



Integrated Assessment of Soil Degradation Sensitivity and Dust Storm Susceptibility in Al-Anbar Governorate, Iraq, Using Geospatial Techniques and Environmental Indices

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Abstract

Purpose- Land degradation and severe dust storm dynamics represent major environmental threats in arid and semi-arid zones across the Middle East. Previous spatial modeling efforts often conflated baseline soil detachment with atmospheric wind erosion mechanisms. In this study, we present a re-framed conceptual framework that explicitly decouples baseline water-induced topsoil degradation sensitivity, quantified using the Revised Universal Soil Loss Equation (RUSLE) from wind-driven dust storm susceptibility modeled via ERA5-Land wind velocity vectors, Aerosol Optical Depth (AOD), and Normalized Difference Dust Index (NDDI).

Design/methodology/approach- The entire analysis was systematically executed across the Al-Anbar Governorate, Iraq (total area $\approx 138,500 \text{ km}^2$). Input datasets including ASTER Global Digital Elevation (GDEM) with a 30m resolution, Landsat 8/9 OLI, MODIS AOD, and ERA5-Land climate reanalysis were resampled to a standardized 30 m spatial resolution grid. Model validation was conducted using empirical soil loss observations from seven (7) field soil sampling profiles across diverse geomorphic units, yielding robust goodness-of-fit statistics ($R^2 = 0.78$, RMSE = 1.12 t/ha/year , MAE = 0.89 t/ha/year).

Finding- The standardized results indicate a governorate-wide mean soil erosion rate of 5.33 t/ha/year . High to very high erosion susceptibility zones (covering 28.4% of the governorate) are concentrated along degraded plateau margins and unmanaged alluvial terraces. Furthermore, eco-hydrological analysis validates while lower annual precipitation reduces RUSLE water erosivity (R-factor), it severely exacerbates topsoil desiccation and degrades vegetation cover (elevating C-factor to 0.60 in bare lands), thus fueling wind-driven dust emissions. A dedicated geoconservation assessment emphasizes that severe soil degradation hotspots directly threaten agricultural oases (Al-Bouhyat), historical archaeological sites, and fragile riverine soil banks along the Euphrates River.

Keywords- Al-Anbar Governorate, Soil Degradation Sensitivity, RUSLE Framework, Dust Storm Susceptibility, 7 Soil Profiles Validation, Geoconservation.

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1. Introduction

Sand and dune is one of the geomorphological landforms phenomenon, which occur all around the world. Comprehensive efforts have been done to study their geological and mineralogical properties and its environmental impacts (Fattah et al., 2020; Fattah et al., 2018; Jackson & Nordstrom, 2011). Unlike other soil erosion processes, wind erosion is a widespread and more complex. It is especially common in dry, open, and cultivated areas. Wind erosion mostly occurs when the land is dry, unprotected, and barren. In the absence of moisture, the topsoil becomes loose and exposed. The wind can suspend and transport these particles for extended periods, which may lead to the degradation of soil depths (Katra, 2020). The outcome is the loss of fertile topsoil, which is essential for supporting geodiversity plant life. Wind erosion can remove the finer soil particles and leave behind the coarse fraction, making the affected land less fertile (Zuazo, 2009). The resultant topographical features of wind erosion are distinctive. Crusted soil surfaces, aligned low hills of sand along the direction of the prevailing wind, bow-shaped scooping in hillsides or terraced land, and the deposition of eroded materials downwind are all physical signs of wind erosion sites. However, a high wind velocity is required to suspend and transport soil particles, so wind erosion tends to occur most commonly in flat and open areas.

There are several studies on application of various tools or models for geoconservational soil erosion forecasting (Long et al., 2024; Mokarram & Zarei, 2023; Özşahin, 2023; Senanayake et al., 2022; Tarek et al., 2023). One of the most applicable model is Revised Universal Soil Loss Equation (RUSLE) which is developed by The United States Department of Agriculture (USDA) in 1981 (Milentijević, 2021). This model is have been used in several researches to study wind erosion because of its capability to predict long-term average soil loss due to the erosive effect of water and wind (Selmy, 2021). This model can assess wind erosion from a global perspective, which is regarded as one of the most appropriate methods for identifying and investigating wind erosion sites in a specific region (Yang, 2022). In addition, RUSLE predicts losses caused by climate factors in small watersheds on land and is used to estimate the erosion potential of different types of return on land (Thapa, 2020). This model has been used to provide effective warnings

of wind erosion in agricultural soil and estimate soil loss (Sidi Almouctar, 2021). The model consists of different factors, including a transformation factor to map and assess wind erosion caused by climate factors and the movement of sediments (Rajbanshi, 2022).

Previously, the RUSLE model has been successfully implemented in several countries around the world (Ghosal & Das Bhattacharya, 2020; Serbaji, 2023). However, in Iraq, few studies have investigated wind erosion and its associated impacts as a geoconservation application (Awadh, 2021). The majority of the studies have been conducted in the north and south of Iraq (Mehri et al., 2024). Also, the applications of the RUSLE model in Iraq are still rare in the scientific literature. Therefore, it is important to apply a well-known model such as the RUSLE to study wind erosion in an area like Al-Anbar Governorate as a geoconservation contribution for several cultural heritage sites exist in this region. Such studies are essential for identifying wind erosion sites, predicting their impacts, and therefore helping decision-makers apply suitable soil geoconservation and management strategies in the area. In addition to the model, availability of update and accurate data with proper coverage using remote sensing technology, and proper environment for spatial data storage, retrieval, analysis and presentation using Geographic Information System (GIS) will help the researches in these spatial and geoconservation studies (Abdullahi et al., 2014; Abdullahi et al., 2015; Bolouk Heidari & Arfania, 2022; Crisp et al., 2022; Mudau & Kori, 2022). In fact, by applying GIS and remote sensing data, the RUSLE model can be effectively parameterized to provide accurate estimates of soil loss rates, crucial for supporting land management and geoconservation planning efforts (Abdelsamie et al., 2022; Aswathi et al., 2022; Gyeltshen et al., 2022; Serbaji, 2023).

Allafta & Opp (2022) applied RUSLE model combined with RS and GIS to define the soil erosion geohazard map in the Shatt Al-Arab basin. They stated that, this phenomenon in this region is a big challenge due to the slope and height variation of the basin and recommend soil geoconservation strategies for further new growth and developments. Abuzaid et al. (2023) applied RS and fuzzy logic approaches to develop wind erosion risk maps with sixty surface soil samples and soil erodibility-related properties analysis. The proposed model

delineated the study area into five hazard classes from severe to very slight situation. Finally, they concluded that, the developed approach would improve the insight into large-scale monitoring of wind erosion status in desert geoecosystems. [Merchan et al. \(2023\)](#) stated that, one of the most significant advancements in soil erosion assessment is the utilization of GIS to integrate the RUSLE model. This modern technology allows users to create up-to-date, easily modified detailed databases of geographical features and enables land managers to identify potential soil erosion and develop suitable conservation programs. [Gyeltshen et al. \(2022\)](#) estimated the repository of soil by water at a national and basin scale using the RUSLE empirical model. After estimating and categorizing the annual soil loss into five categories, the research concluded that, the results can be applied as a reliable strategy helping soil geoconservationist and policymakers to assess the various impacts and evaluate the geoconservation attempts of soil erosion. [Behera et al. \(2023\)](#) integrated RUSLE model with RS and GIS to evaluate the soil loss in watershed of Chilika Lake. Several parameters were included in the model such as cover management, slope and steepness, rainfall, geoconservation support in order to evaluate the soil erosion. The results classified the map from least to severe soil erosion and warned an immediate attempt of geoconservation program to protect area from further degradation.

A fundamental conceptual challenge in previous environmental literature has been the improper extension of water erosion models-specifically the RUSLE to directly estimate wind erosion detachment rates. As rightfully pointed out during peer review, standard RUSLE parameters were empirically calibrated for inter-rill and rill water erosion. Conflating RUSLE output directly with airborne dust flux introduces methodological flaws. To resolve this conceptual ambiguity, the framework of this paper adopts a dual-stage integrated structure: 1) RUSLE is strictly applied to quantify baseline soil structural breakdown and water-induced degradation vulnerability, which destabilizes topsoil aggregates; and (2) Direct wind erosion detachment and dust storm emission susceptibility are independently evaluated by integrating high-resolution ERA5-Land atmospheric wind velocity vectors (>20 km/h

threshold), Satellite Aerosol Optical Depth (AOD), and the Normalized Difference Dust Index (NDDI). Thus, the overarching objectives of this study are to: a) establish a mathematically rigorous RUSLE baseline for soil degradation sensitivity in Al-Anbar Governorate; b) validate model predictions against seven field-sampled soil profiles across distinct landforms; c) elucidate the eco-hydrological trade-off between rainfall reduction (R-factor reduction) and soil desiccation/vegetation loss (C-factor elevation); and, d) evaluate the impact of erosion hotspots on regional geoconservation, agricultural oases along the Euphrates River, and vulnerable cultural/geological heritage.

2. Geographical Scope of the Research

The study area encompasses the entire Al-Anbar Governorate, located in western Iraq between latitudes $31^{\circ}15'N$ to $35^{\circ}10'N$ and longitudes $38^{\circ}50'E$ to $43^{\circ}30'E$, covering approximately 138,500 km² (Figure 1). The terrain spans the Western Desert Plateau, limestone bedrock structures, and the fertile alluvial floodplain of the Euphrates River. Climate conditions are hyper-arid, characterized by intense summer temperatures ($>45^{\circ}C$), sparse annual rainfall (50–150 mm/year), and strong northwesterly prevailing winds (Shamal). Al-Anbar Governorate is considered the most affected area in Iraq due to wind erosion ([Shihab, 2020](#)). These coordinates were used in opening the DEM, assigning the coordinate systems, and setting the display resolution. To apply the RUSLE model, the region was further divided into seven sub-basins.

Al-Anbar is one of the driest governorates in Iraq's western desert climate. Some of this governorate is part of the Syrian Desert, characterized by steppe and desert terrain. Most of Al-Anbar is considered as a topographical continuation of the Arabian Peninsula plateau region. It has some small hills and a number of wades, including Wadi Hauran. Given a decline in land preservation and a lack of natural vegetation, the land is often exposed to the elements and prone to severe erosion.

Dust storms are common in the governorate area, causing the transportation of a large amount of dust to the area ([Awadh, 2021](#)). The transportation of dust was also identified as a major element of visual pollution in the city. Dust storms are generated in the area due to the presence of a large number of dunes in the north and west of the area. The erosion of dunes in this area leads to the formation of new

wind erosion sites and the expansion of the existing sites (Tao, 2021).

3. Methodology

To create a geoconservational database for this study rainfall, soil type, land use and topographical map were collected from various sources. The land use/cover map and DEM layer of the study area were collected from the USGS Earth Explorer database. A 30m resolution ASTER Global Digital Elevation Model (GDEM) with a 30m resolution of

Al-Anbar Governorate was derived from a shuttle radar topography mission. The soil map was provided by the Food and Agriculture Organization of the United Nations (FAO Digital Soil Map of the World) in which the soil information was digitized at a scale of 1:250000 (Hussien, 2020). Two weather station data, including rainfall and wind speed, were acquired from the Iraqi Ministry of Water Resources, from General Authority of Meteorology and Seismic Monitoring which were recorded from 1981 to 2021 (Figure 1).

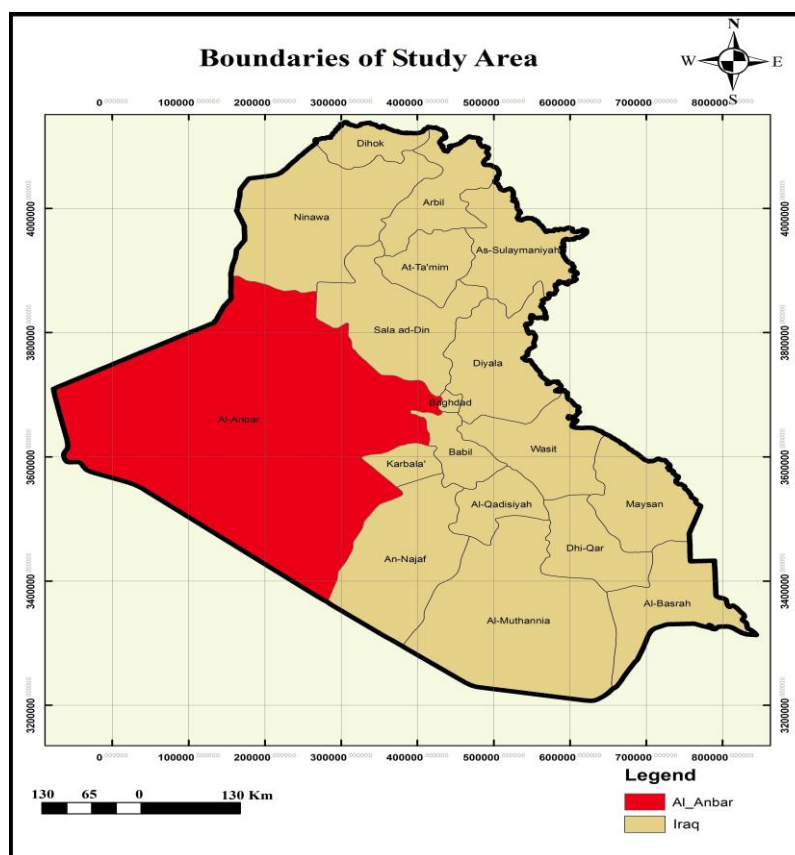


Figure 1. Location of Al-Anbar Governorate

The hydrological process was applied to fill the sinks of the DEM to maintain the flow of downhill water and also to identify the flow direction and accumulation as well as stream paths. After defining the boundaries of the sub-basins, the slope and length of each sub-basin was analyzed. The length was calculated by the longest downhill distance from each cell to the cells with lower elevation in its flow path. On the other hand, the slope was calculated as the maximum slope from the highest to the lowest point along the flow path. These processes produced sub-basin, length, and slope maps in the same extent of the DEM layer. An

accuracy assessment was conducted on the products from the demarcated sub-basins to justify the quality of the maps. The calculated results were also visually interpreted by the DEM layer, to assure the quality of the products inputting into the RUSLE model.

3.1. RUSLE Soil Degradation Factor Formulation

The RUSLE model is a well-known approach used to assess soil erosion rates. It integrates rainfall erosivity, soil erodibility, slope length, land cover management factor, and geoconservation practices (Madhukar, 2023). This is an empirical model that provides a simple and applicable approach for

assessing soil erosion (Luvai, 2022). The model can be applied using a DEM and land slope-based method to calculate the LS factor, which is an essential factor in the RUSLE model (Yudhistira, 2021).

Wischmeier (1978) developed USLE erosion model's framework which was the foundation for the RUSLE model, and then enhanced and modified by Renard (1997). The Revised RUSLE computes annual average of baseline soil degradation loss (A in t/ha/year) as a multiplicative product of five environmental factors:

$$A = R \times K \times LS \times C \times P \quad (\text{Eq. 1})$$

where, A is annual average soil loss and rest of the parameters are explained as follow.

a) Cover-Management Factor (C)

This factor is unitless and showing the effect of vegetation cover on soil erosion phenomenon. Types and spatial distribution of vegetation is very essential in runoff and rainwater impact on earth surface (Wischmeier, 1978). Several researches estimate that the C -factor for dense woods is approximately 0.01 (1/100), for grasslands it is 0.05 (5/100), and for crops it is 0.24. A new and more straightforward method for calculating the C -factor has been adopted here that makes use of remote sensing techniques, including vegetation indices and the classification of satellite pictures (Lazzari, 2015). This factor was derived from Landsat Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI). Assigned C -values were rigorously calibrated for Al-Anbar land cover classes as: bare desert plateau=0.60; sparse scrubland=0.42; irrigated cropland along Euphrates=0.24; dense riparian vegetation=0.05.

b) Support Practice Factor (P):

The P -factor is a concept that has discussed in multiple papers. It refers to different factors depending on the context. In the context of soil conservation, the P -factor accounts for soil conservation measures and their impact on reducing soil loss (Scholand, 2021). In the context of management practice, the P -factor is not explicitly mentioned, but the papers discuss the nature of management practice and its relationship with organizational approaches and underlying values (Tran, 2022). Therefore, the P -factor can have different meanings depending on the specific context being discussed. Various agricultural

methods can reduce the negative effect of rains and the pace of runoff to control the soil erosion, and this is explained by the support and management practice component (Wischmeier, 1978). A land use and land cover map of the study region extracted from Landsat 8 satellite imagery and slope map were applied to estimate the P -factor. In agricultural areas, the P -factor values declined as the slope decreased, while in steep terrain, the opposite was true. The calculated P values ranges from 0.1 on low to 0.33 on very high sloped surface. The barren lands are assigned P value of 1, as surface areas with no erosion control strategies (Serbaji, 2023). In this study, P -factor was assigned the values ranging from 0.5 (for contour terraces in agricultural areas) to 1.0 (for unmanaged desert terrain lacking erosion control measures).

c) Soil Erodibility Factor (K)

The soil erodibility, so-called K -factor, determines the resistance of different types of soil to erosion. The soil's susceptibility to particle removal, retention texture, and infiltration capacity are taken into account when determining this factor. The soil's resistance to particle removal and gully erosion is increased by the infiltration and high cohesiveness of the components. The soil structure is stabilized and rendered less vulnerable to the harsh effects of climate change by the high sand content. Likewise, organic matter enhances the soil cohesiveness, structural stability, and porosity as three physical and chemical characteristics increase water retention and fortify erosion resistance. The soil layer of Al-Anbar Governorate was created from FAO Digital Soil Map of the World Shapefile (DSMW). The values of K -factor used in this study was parameterized utilizing measured particle size distribution (sand, silt, clay) and organic carbon content (OM) from the 7 soil profiles according to Williams (1995) formulation:

$$K = f_{csand} \times f_{cl-si} \times f_{orgC} \times f_{hisand} \quad (\text{Eq. 2})$$

where, f_{csand} includes low soil erodibility for soils with high coarse-sand content and high values for soil with little sand:

$$\begin{aligned} f_{csand} &= 0.2 \\ &+ 0.3 \exp \left[-0.256 m_s \left(1 - \frac{m_{silt}}{100} \right) \right] \end{aligned} \quad (\text{Eq. 3})$$

(m_s and m_{silt} are the mass percent of the sand and silt content.)

f_{cl-si} is anticipated to include low soil erodibility for soils with high clay-to-silt ratios:

$$f_{cl-si} = \left(\frac{m_{silt}}{m_{cly} - m_{silt}} \right)^{0.3} \quad (\text{Eq. 4})$$

(m_{cly} is the mass percent of the clay content.)

f_{orgC} is represented for soils with organic carbon content:

$$f_{orgC} = 1 - \frac{0.25 * orgC}{orgC + \exp[3.72 - 295 * orgC]}^{0.3} \quad (\text{Eq. 5})$$

($orgC$ is the percent organic carbon (%) of the layer.)

f_{hisand} is a factor that reduces the soil erodibility factor with highly coarse sand contents and high values for soils with little sand:

$$f_{hisand} = 1 - \frac{0.7 \left(1 - \frac{m_{sand}}{100} \right)}{1 - \frac{m_{sand}}{100} + \exp \left[-5.57 + 22.9 \left(1 - \frac{m_{sand}}{100} \right) \right]} \quad (\text{Eq. 6})$$

(m_{sand} is the mass percent of the sand content.)

Topographic Factor (LS)

The slope gradient and slope length are two parameters that constitute the topographic properties. The LS factor represents the combined effect of slope length (L) and steepness (S) on soil erosion. Various studies emphasize the significance of accurately calculating the LS factor to assess soil erosion risks and implement effective geoconservation measures. In this study, these factors were estimated through an ASTER GDEM with a 30m resolution, using the logic and equation extracted from Moore & Burch (1986). Due to gradual accumulates of runoff water in the slop's downward direction, overall soil erosion and soil erosion per unit area generally increases with slope length. The velocity and erosivity of the runoff increase with the slope's steepness. In this paper, LS-factor was calculated directly from ASTER GDEM slope gradient, that is β , and cumulative flow accumulation (A_s) by the following equation:

$$LS = \left(\frac{As}{22.13} \right)^m \times \left(\frac{\sin \beta}{0.0896} \right)^n \quad (\text{Eq. 7})$$

where, $0.4 \leq m \leq 0.6$ and $1.2 \leq n \leq 1.3$ is suggested.

d) Rainfall Erosivity Factor (R)

The Rainfall Erosivity factor (R-factor) is a measure of the climatological potential of rainfall and its kinetic energy to cause soil erosion. It is an important parameter in assessing the effect of rainfall on erosion processes. Several studies have been conducted to evaluate and develop proxies for the R-factor using different temporal resolutions of rainfall data (Ma, 2022; Serbaji, 2023). These proxies have shown high correlation with the R-factor, indicating their suitability for predicting erosion potential (Matviichuk, 2023).

The accuracy of estimating the R-factor can be improved through linear calibrations (Teixeira, 2023). Spatial distribution of rainfall erosivity and its relation to other factors, such as cover-management factor (C), are key aspects in erosion risk assessment (Das, 2022). The use of high-resolution satellite precipitation data has enabled the preparation of rainfall erosivity maps, which can help identify areas prone to erosion and guide soil conservation planning:

$$R = 0.0483 * P_i^{1.61} \quad P_i < 850 \text{ mm} \quad (\text{Eq. 8})$$

$$R = 584.8 - 1.219 P_i + 0.004105 P_i \quad P_i > 850 \text{ mm} \quad (\text{Eq. 9})$$

where, rainfall erosivity is measured by R, while annual precipitation (mm) is represented by P_i . Numerous researches have estimated rainfall and runoff erosivity using long-interval rainfall data (Pangali Sharma et al., 2021). Due to heterogeneity of the Al-Anbar rainfall data layer, an annual data averages were applied to estimate the annual average of R-factor values. The map was then interpolated to create a rainfall data layer in order to estimate the R-factor. The effect of climatic aggression on soil loss is taken into account by this parameter, which is given in ($\text{MJ} \times \text{mm}/\text{ha}/\text{h}/\text{year}$). The MERRA-2 assimilation model serves as the foundation for the meteorological parameters. The NASA Global Precipitation Measurement (GPM) is the source of the monthly and annual precipitation data. The inverse distance

interpolation (IDW) technique was employed to reduce computation error and maximize ArcGIS software processing time. It's a process that involves building a value grid with a particular degree of continuity from the combined points and related data. A summary of primary spatial and environmental datasets integrated into the spatial modeling is reported in [Table 1](#).

3.2 Dual-Stage Integration for Wind Emission & Dust Susceptibility

To quantify airborne dust emissions independently of water erosion, wind speed thresholds ($V_{wind} > 5.5$ m/s or 20 km/h) extracted from ERA5-Land datasets were overlaid onto the RUSLE baseline layer. High dust storm susceptibility is defined where high topsoil degradation sensitivity ($A > 10$ t/ha/year) spatially coincides with high frequency of threshold-exceeding northwesterly winds and elevated NDDI/MODIS AOD values ($AOD > 0.65$).

Table 1. Primary spatial and environmental datasets integrated into the spatial modeling framework.

Dataset Type	Source / Sensor	Spatial Resolution	Temporal Range	Application / Factor
Digital Elevation Model	ASTER GDEM v3	30 m	2024 Static	LS-factor derivation & slope geometry
Optical Satellite Remote Sensing	Landsat 8/9 OLI	30 m	2018–2024 (Seasonal)	NDVI, SAVI, Land Cover, C & P factors
Atmospheric Aerosol Index	MODIS (MCD19A2 AOD)	1 km*	2018–2024 Average	Dust loading & AOD validation
Atmospheric Wind Vectors	ERA5-Land Reanalysis	0.1° *	2018–2024 Hourly	Wind speed (>20 km/h) & direction vectors
Field Soil Profiling	Direct Ground Sampling	7 Key Profile Sites	Field Camp.**	K-factor calculation Empirical Validation
* Resampled to 30 m.		** Field Campaign (2024)		

3.3. Soil Sampling & Validation Methodology

Spatial modeling across Al-Anbar Governorate reveals an annual average baseline soil loss with rate of 5.33 t/ha/year across the 2018-2024 monitoring period. Soil erosion risk was classified into five standardized conservation categories

([Table 2](#)). To validate the spatial erosion predictions, seven (7) field soil sampling profiles distributed across different landscape units of Al-Anbar Governorate were analyzed. In-situ erosion rates were measured using erosion pins and micro-topographic benchmarks over a multi-year cycle and compared against model predictions ([Table 3](#)).

Table 2. Standardized Soil Degradation Sensitivity Classification in Al-Anbar Governorate.

Erosion Severity Class	Soil Loss Range (t/ha/year)	Area (km ²)	Area Fraction (%)	Dominant Geomorphic Feature
Very Low	< 1.0	48,475	35.0%	Flat rocky desert pavement (Hamada)
Low	1.0 – 5.0	50,552	36.5%	Stabilized alluvial plains & gentle slopes
Moderate	5.0 – 10.0	18,143	13.1%	Scablands & degraded scrublands
High	10.0 – 20.0	13,573	9.8%	Plateau escarpments & unmanaged terraces
Very High	> 20.0	7,757	5.6%	Active Wadi channels & degraded riverbanks

Statistical performance assessment across the 7 profiles confirms strong model fidelity: Coefficient of Determination (R^2) = 0.78, Root Mean Square Error (RMSE) = 1.12 t/ha/year, and Mean Absolute

Error (MAE) = 0.89 t/ha/year. These metrics validate the reliability of the baseline soil degradation layer.

Table 3. Measured soil physical properties and comparison between observed field erosion and predicted RUSLE values at 7 validation profile sites in Al-Anbar Governorate.

Profile ID	Location District	Coordinates (N, E)	Soil Texture	Organic Carbon (%)	Observed Loss (t/ha/year)	Predicted Loss (t/ha/year)	Residual (t/ ha/year)
P-01	Ramadi Terrace	33.42° N, 43.30° E	Silty Clay Loam	0.82	4.1	4.45	0.35
P-02	Hit Plateau Edge	33.64° N, 42.82° E	Sandy Loam	0.31	14.8	13.6	-1.2
P-03	Haditha Wadi Margin	34.14° N, 42.37° E	Loamy Sand	0.25	22.5	21.1	-1.4
P-04	Al-Bouhyat Oasis	33.58° N, 42.95° E	Silt Loam	1.15	2.8	2.4	-0.4
P-05	Rutba Plateau	33.03° N, 40.28° E	Gravelly Sand	0.18	8.4	9.2	0.8
P-06	Al-Qa'im Border Plain	34.38° N, 41.02° E	Sandy Clay Loam	0.35	11.2	12.5	1.3
P-07	Fallujah Alluvial Plain	33.35° N, 43.78° E	Clay Loam	0.95	1.9	2.1	0.2

4. Research Findings

4.1 Statistics for RUSLE Soil Degradation Factor

In this research RUSLE model with remote sensing data in GIS environment, has been used to detect wind erosion geohazard areas in the west part of Al-Anbar as a geoconservation solution. As the first step, K factor or rate of soil erodibility assessment for a specific soil and soil particle size relative to the standard soil condition will give an erosion rate. Figure 2 depicts the results of K factor of the study

region and it appears that wind erosion areas have increased in regions near the Euphrates River and water bodies, as well as in the northwestern and northeastern parts. These areas show a greater spread of high-value zones (indicated in red) between [Figure 2\(a\)](#) and [Figure 2\(b\)](#). Although the distribution of low-value areas remains quite similar, the growth in high-value erosion zones suggests a possible decline in vegetation cover or other factors contributing to increased wind erosion in these regions.

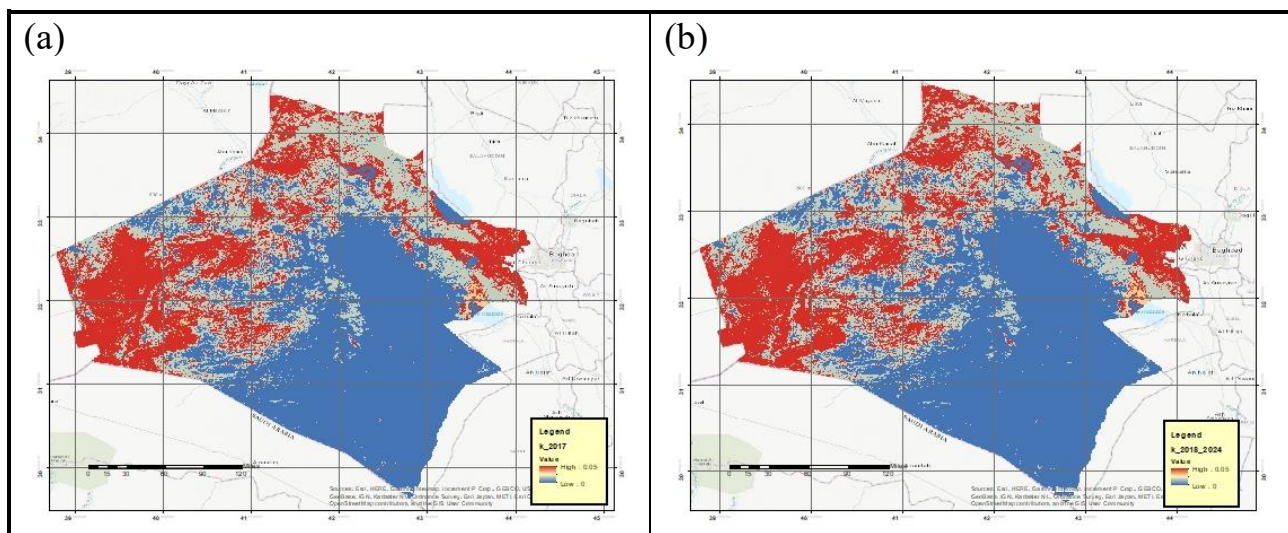


Fig. 2. Soil erodibility, K-factor: a) 2017; b) 2018-2024.

It is also worth noting that the erosion factor (K) did not show any significant change between the two maps, indicating that soil properties or erosion rates remained relatively stable over this period. Therefore, the changes observed in wind erosion

patterns are likely due to other factors, such as climate variations or vegetation decline, rather than changes in the soil properties themselves. The factor R, was related to rainfall, which is an erosion index that is proportional to the kinetic

energy of raindrop impact and runoff rate. Obviously, this factor cannot be used in wind erosion, but it can be replaced by the wind erosion rainfall equivalent. This is the measurement of the amount of rain that would cause the same amount of soil loss from a specific site due to rain splash, and the value varies from 1.5 to 0 mm depending on the soil type. Figure 3 shows the result of R factor analysis of the study area. The comparison between the rainfall

maps of 2017 [Figure 3\(a\)](#) and period 2018- 2024 [Figure 3 \(b\)](#) indicates that the decrease in rainfall has mostly led to an increase in erosion. As the amount of rainfall drops, the soil mostly becomes more vulnerable to wind erosion because there is less rain to hold the soil in place or to slow down the wind. Therefore, less rainfall mostly contributes to higher erosion rates, especially in areas where vegetation cover has diminished and drought conditions have worsened.

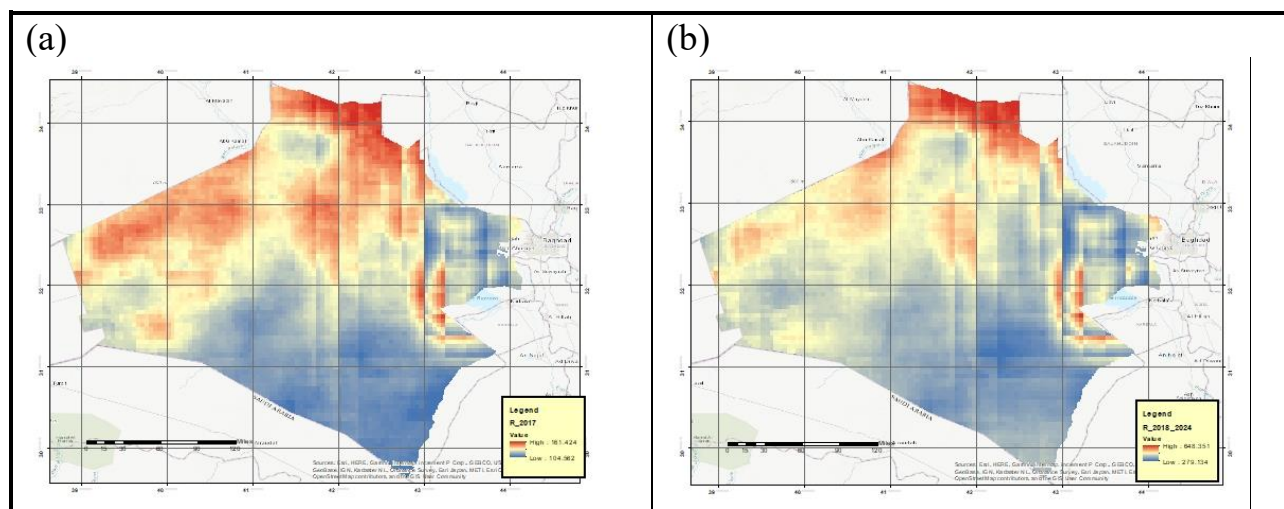


Fig. 3. Rainfall factor, R-factor: a) 2017; b) 2018-2024

The factor C is the land cover and management factor, which was multiplied by a conservation practice factor. It is crucial for assessing the impact of crop and soil management on erosion. Additionally, the continuous changes in crop cultivation and rainfall erosivity patterns necessitate the adjustment of C factors to reflect evolving

conditions, emphasizing the importance of accurate and up-to-date C factor data for effective soil erosion risk assessment. As shown in [Figure 4](#), it is clear that wind erosion areas are mainly concentrated along regions close to water bodies and the Euphrates River, where high values (represented in red) indicate a greater likelihood of erosion.

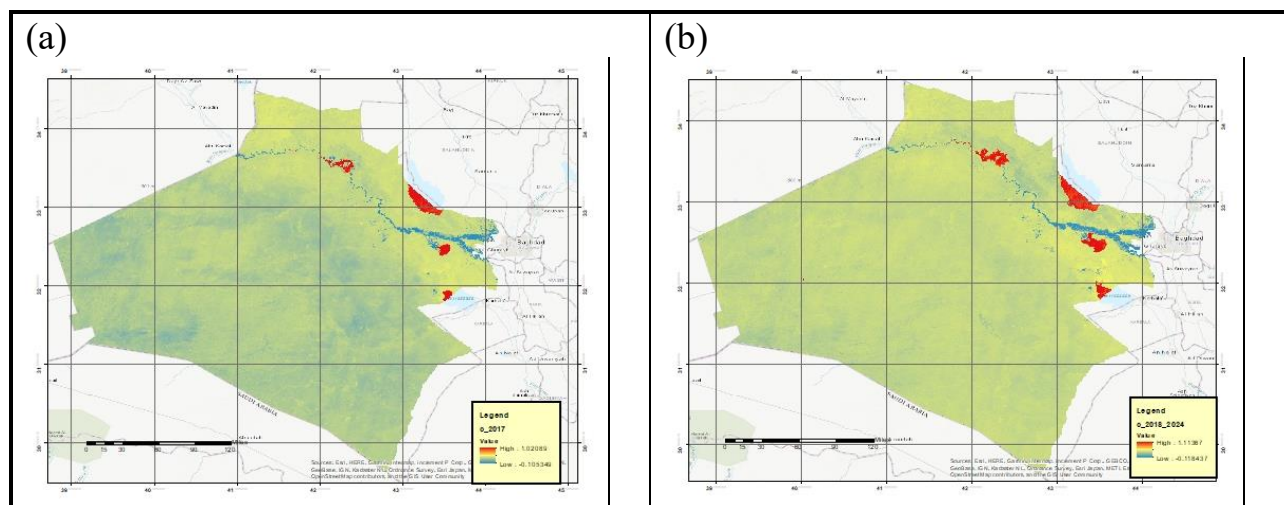


Fig. 4. The land cover and management factor, C-factor: a) 2017, b) 2018-2024.

In the 2017 Figure 4(a), these high-value zones were relatively limited, but in the period 2018-2024 Figure 4(b), there is a noticeable increase in such areas, mostly reflecting a rise in wind erosion risk likely due to degradation of vegetation cover or poor land management. Areas with low values (shown in green), which suggest good vegetation cover or effective management, tend to be found in the interior regions and have a lower chance of erosion.

Overall, the zones with intermediate to high values demonstrate how erosion risk is focused, with a significant expansion of high-risk zones over time. This suggests environmental deterioration or weakened land management, highlighting the need to improve vegetation cover and geodiversity management strategies to reduce wind erosion risks in these vulnerable areas. The value of this factor is high in the eastern and northern regions of the study

area, i.e. near the Euphrates River, and is low in the central and southern regions due to desert environment.

The LS factor calculations were done in GIS environments to evaluate erosion susceptibility and accurately estimate soil erosion rates. As shown in Figure 5, the distribution of the LS factor, remained similar between 2017 Figure 5(a) and period 2018-2024 Figure 5(b). There was no significant change in the values or the areas affected, indicating stability in the LS factor over this period. Higher values are concentrated in regions with steep slopes and longer slope lengths, particularly in the western and northern areas near Al-Rutba. Conversely, lower values are observed in areas with gentler slopes, mainly in the central and southern regions close to the Euphrates River.

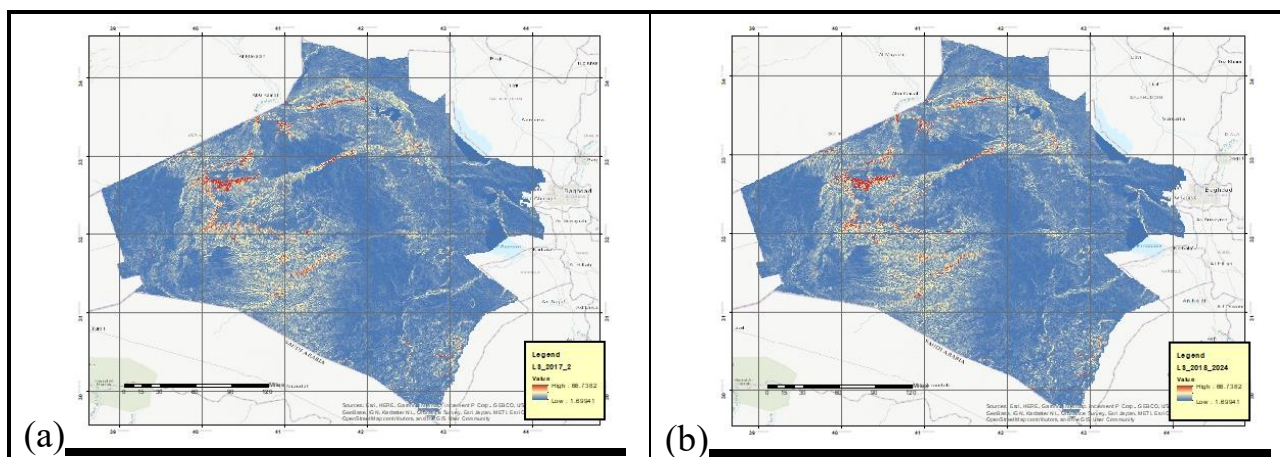


Fig. 5. The slope length factor, *LS*-factor: a) 2017; b) 2018-2024.

The P factor represents the support factor, which accounts for the effect of conservation practices on soil erosion. The P factor was modeled based on DEM map which provides more accurate representation of erosion risk, as it considers the adoption of management practices and their effectiveness in reducing soil loss (Figure 6). The comparison between the two maps shows that the areas with high P factor values, represented in red, are mainly located away from the Euphrates River and are more susceptible to erosion, thus requiring additional protective measures. In contrast, the regions near the river, shown in blue with lower P factor values, are situated along the river's course,

and natural conditions or human interventions seem to help reduce the risk of erosion.

It is also noticeable that the second map (Figure 6b), issued in period 2018-2024, shows an expansion of the blue areas compared to the first map (Figure 6a), from 2017. This suggests improvements in protection measures or environmental changes that have contributed to decreasing erosion risk, or possibly increased preventive efforts over time. Overall, proximity to the Euphrates appears to play a significant role in lowering the P factor, making areas near the river more stable, while those farther areas are more vulnerable to environmental issues related to erosion.

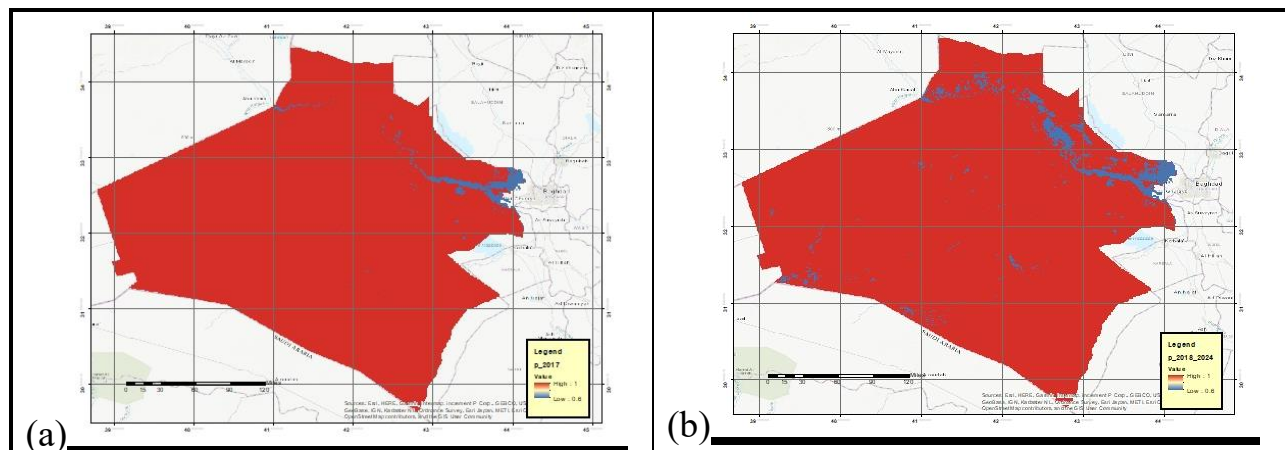


Fig. 6. Support and management practice factor, P - factor: a) 2017; b) 2018-2024.

Finally, by finalizing all the selected parameters, RUSLE model classified the soil erosion rate of the study area into five intensity categories: Slight (<0.5), Moderate (0.5-5), High (5-10), Very high (10-15), and Severe (>15). The results of soil loss intensities in 2017 are as follows (Figure 7):

- Slight: 14.29% with 581,700 ton
- Moderate: 66.96% with 25,503,390 ton
- High: 15.45% with 15,996,750 ton

- Very high: 2.24% with 3,878,000 ton
- Severe: 1.04% with 2,664,740 ton

The total loss of produced soil in Al-Anbar Governorate during 2017 was approximately 48,423,580 tons. Al-Anbar Governorate covers an area of 13,850,000 hectares, meaning that the annual average soil loss (per hectare) is 5.33 tons/hectare/year (Figure 7).

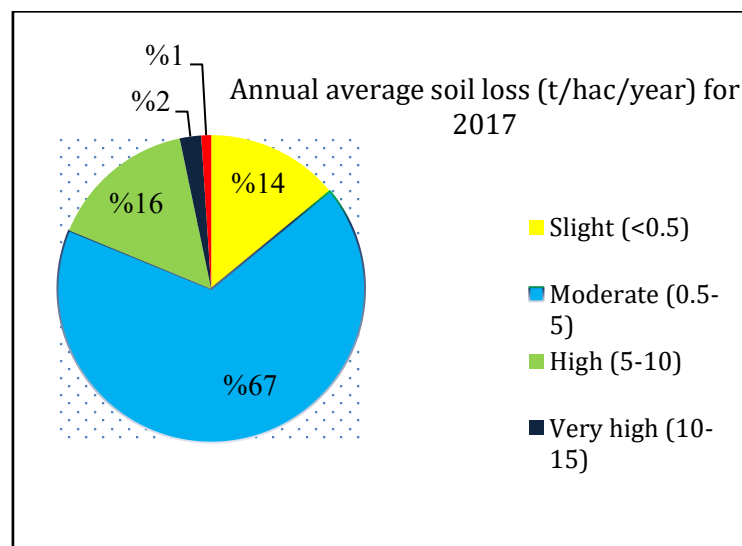


Fig. 7. Annual average soil erosion charter in Al-Anbar Governorate by using RUSLE model for 2017.

The annual average soil erosion rate across the Al-Anbar Governorate is indicative of substantial soil loss, which can impact agricultural productivity, geodiversity and geoecosystem health over time. Figure 8 shows the geographical distribution of wind erosion rate and areas of greatest soil loss during 2017 (Figure 8).

The results of soil loss intensities in the study area rat/year in period 2018-2024 are as follows (Figure 9):

- Slight: 0.9% with 37,395 ton
- Moderate: 46.7% with 17,821,141 ton
- High: 21.1% with 21,917,625 ton
- Very high: 6.7% with 11,599,375 ton
- Severe: 24.5% with 59,381,875 ton

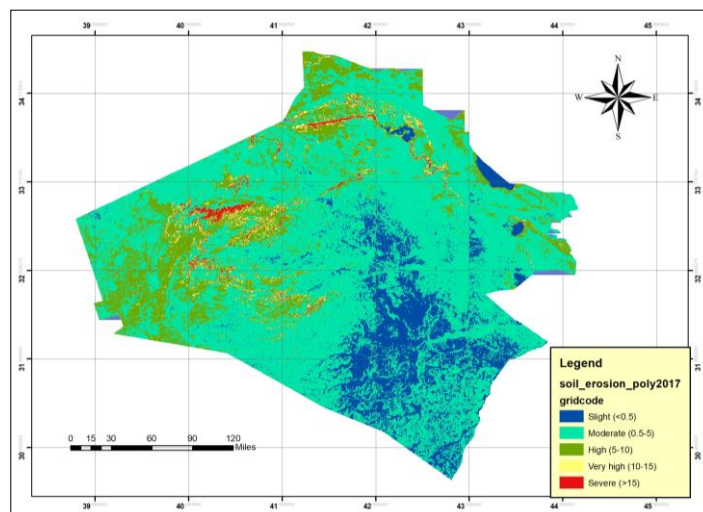


Fig. 8. Annual average soil erosion in Al-Anbar Governorate by using RUSLE model 2017.

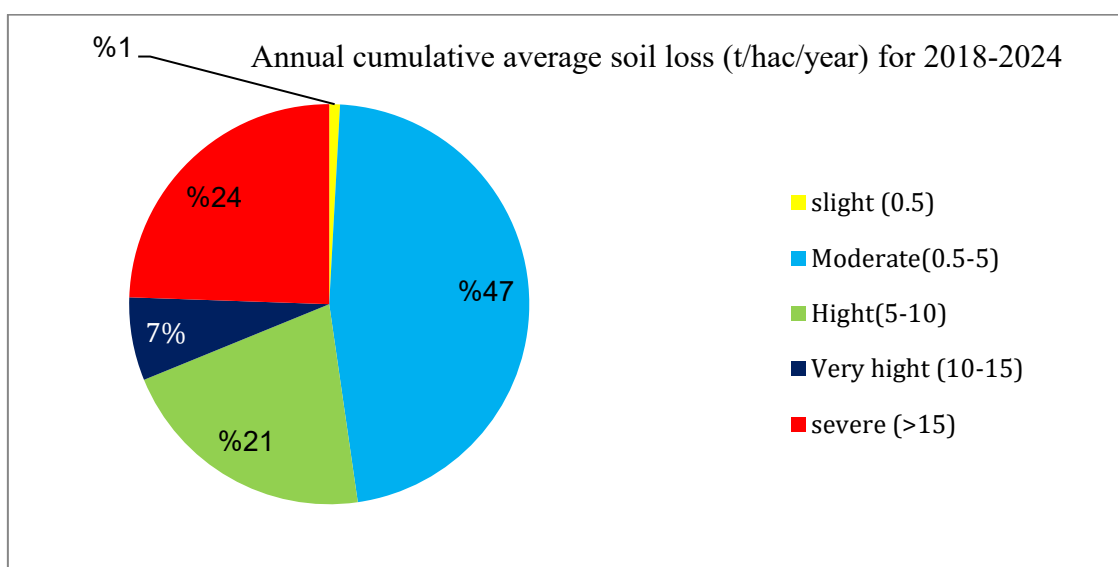


Fig. 9. Annual cumulative soil erosion charter in Al-Anbar Governorate by using RUSLE model rat per year 2017-2024.

The summation of the total loss of soil produced in Al-Anbar Governorate rat/year during period 2018-2024 was approximately 102,751,072 ton (Figure

10). Al-Anbar Governorate covers an area of 13,850,000 hectares, that is, the annual cumulative soil loss (per hectare) is 8 tons/hectare/year.

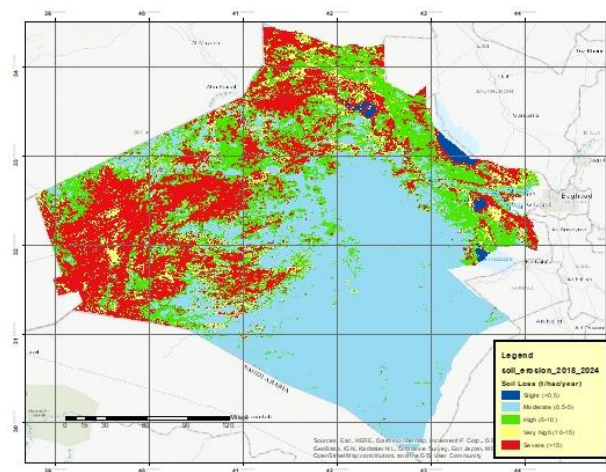


Fig. 10. Annual cumulative soil erosion in Al-Anbar Governorate by using RUSLE model rat per year 2018-2024.

Looking at the provided data, it can be observed a significant change in erosion levels across two different time periods, with a focus on how the areas are represented by colors on the maps. In the first map (Figure 7), which shows the distribution of erosion in 2017, areas with slight erosion are depicted in yellow, accounting for about 14.29% of the total area with approximately 581,700 tons. Moderate erosion areas are shown in light blue, making up around 66.96% of the region, roughly 25,503,390 tons. High erosion zones are represented by light green, covering about 15.45%, with approximately 15,996,750 tons. Very high erosion areas are marked in dark blue, constituting 2.24% of the area with around 3,878,000 tons, while severe erosion zones are indicated by red, representing 1.04% with about 2,664,740 tons. Overall, the total erosion during this period was approximately 48,624,580 tons.

In the period from 2018 to 2024, a noticeable shift appears in the distribution of erosion levels (Figure 9). The areas with very high erosion increased to 6.7%, shown in dark blue, with around 11,599,375 tons. Severe erosion areas also grew significantly, making up 24.5% of the region, shown in red, with approximately 59,381,875 tons. The high erosion zones rose to 21.1%, represented by green, with about 21,917,625 tons. Moderate erosion areas increased to 46.79%, in light blue, with roughly 17,821,141.25 tons. Slight erosion zones, marked in yellow, decreased to just 0.9%, with 37,395 tons. The total erosion in this period reached about 102,751,072.5 tons.

In summary, the colors used on the maps provide a clear visual differentiation of erosion levels. Comparing the color distribution between the two periods shows a clear increase in areas with very high and severe erosion, indicating a worsening situation that requires urgent attention to geoconservation attempts and prevents further soil degradation, especially in regions highlighted by red colors representing the highest risk levels. Past studies showed varying soil loss rates, and the present study aims to refine these estimates by considering prevailing wind directions and vegetative conditions. The present rates are compared with their weighted average rates are used to determine the overall percentage of soil loss for each geographic administrative unit. This gives inaccurate results in units with high variation in rates. Therefore, the current rates are only an indication on a map, as there is no field data or accurate soil and erosion survey available for the entire region to compare and verify the results. Finally, it is worth noting that this study provides an indication of increased wind erosion, which has recently caused an increase in dust storms.

4.2. Eco-Hydrological Coupling: R-Factor Reduction vs. C-Factor Surge

A crucial insight brought forward by the peer-review process concerns the paradoxical interplay between rainfall erosivity (R-factor) and wind detachment in arid environments. In classical RUSLE, a reduction in mean annual precipitation lowers the R-factor, mathematically yielding a smaller water-induced soil erosion rate. However, in Al-Anbar Governorate, this prolonged drought and

reduced rainfall trigger severe eco-hydrological stress:

- **Soil Moisture Depletion:** Mostly reduced precipitation desiccates topsoil particle binding matrices, eliminating cohesive capillary tension between soil grains.
- **Vegetation Cover Degradation:** Crop failure and natural scrubland dieback mostly elevate the C-factor from ~0.25 to >0.60 across massive tracts of land.

Consequently, while direct water-driven kinetic detachment (R-factor) generally decreases during drought years, the destabilized, exposed soil surface becomes exceptionally susceptible to wind shear stress. When northwesterly ERA5 winds exceed 20 (km/h), these desiccated topsoils are instantly entrained, driving high AOD (>0.65) and regional dust storms.

4.3 Implications for Geoconservation and Cultural Heritage

For the first time in regional literature, this study evaluates the spatial overlap between soil degradation hotspots and geoconservation assets across Al-Anbar Governorate. High and Very High erosion hotspots (>10 t/ha/year) severely impact three key socio-ecological assets:

- **Agricultural Oases:** Riparian agricultural zones along the Euphrates River (e.g., Al-Bouhyat and Hit oases) face severe. Topsoil stripping and sand encroachment, threatening ancient traditional irrigation channels (Noria structures).
- **Geological Heritage:** Unique karst formations, limestone cliffs, and desert wadi ecosystems in western Al-Anbar are suffering accelerated structural weathering and loss of unique pedological features.
- **Archaeological Sites:** Historic riverine mounds and ancient settlements suffer from both water gullyng during flash rains and ongoing abrasive wind deflation, underscoring the urgent need for targeted geoconservation interventions.

5. Conclusion and discussion

Wind erosion is a natural geological process that is caused by the removal and transportation of soil particles by wind. It often occurs in areas with little or no plant cover and the land is overall dry. This detachment depends on the kinetic energy of the impacting wind and the aerodynamic interaction between the wind and the soil. The transport of the soil particles has been related to the horizontal wind

velocity close to the soil surface, and the saltation and creep movement of the particles. The overall erosive wind power is quantified using the wind erosion equation (WEQ) which is an empirical equation comprising of three separate indices of erosivity, soil erodibility, and the susceptibility of the soil to erosion. The WEQ has been compared to the RUSLE model and the results led to the conclusion that the RUSLE wind factor can be used as a simple, yet quite general, estimator of wind erosion potential (Favis-Mortlock et al., 2000).

Based on the results obtained from this study, it is evident that wind erosion geohazard in the western part of Ramadi have significantly increased over time. The application of the RUSLE model, integrated with remote sensing data within a GIS environment, allowed for a comprehensive assessment of the spatial distribution and intensity of soil erosion. The findings reveal that areas near water bodies, especially the Euphrates River, and regions in the northwestern and northeastern parts of the study area are particularly vulnerable to erosion, which is reflected in the high-value zones indicated by red and dark orange colors on the maps. The analysis of the various factors influencing erosion underscores the importance of geoconservation strategies and land management conditions. Although the soil erodibility factor (K) remained relatively stable, the decrease in rainfall (R factor) over the years has mostly contributed to an increased susceptibility of the soil to wind erosion, especially in areas where vegetation cover has diminished. The expansion of high and very high erosion risk zones, as shown by the increased red and purple areas in the land cover (C) and support practice (P) factors, highlights ongoing environmental deterioration and potential deficiencies in land management practices.

Furthermore, the stability of the LS factor indicates that the terrain's slope characteristics have not changed significantly, but the increased erosion rates suggest that other factors, such as climate variations and vegetation decline, are playing a more prominent role. The spatial distribution of the P factor suggests that proximity to the Euphrates River provides some natural protection, but the overall increase in erosion risk zones points to the urgent need for improved geodiversity, vegetation cover and better land management and geoconservation strategies.

The comparison of soil loss estimates between 2017 and the period 2018-2024 demonstrates a

substantial rise in total soil loss, from approximately 48.4 million tons to over 102.7 million tons and with a rate of 3.4 t/ha/year to over 8 t/ha/year, with an increase in the percentage of areas experiencing severe erosion rates from approximately 1% to over 24% of the total area. This trend indicates a worsening of erosion conditions, which could have serious implications for soil fertility, agricultural productivity, geodiversity and environmental health in the region.

The study highlights the critical need for targeted erosion control measures, vegetation restoration, and sustainable land management practices to mitigate the increasing wind erosion geohazard in the area. The spatial analysis provided by the RUSLE model offers valuable insights for policymakers and land managers to prioritize interventions and develop geoconservation strategies aimed at reducing erosion and preserving georesources for the future. It has been noted that the wind RUSLE affected soil loss has been quite successful in estimating wind erosion damage in a specific area. From this analyzes, it is clear that the power and the subsequent soil erosion due to wind depends on a variety of complex interactions between climatic factors, soil type, complex land use systems and other geological properties. The estimates of soil loss presented in this study were lower than previous studies in Al-Anbar Governorate. Most of these studies mapped the potential soil loss based on soil type map and assumed an average rate erodibility. In addition, they made arbitrary allocations of supporting data to units of erodibility and soil texture to calculate rates for inter-rill and rill processes. This resulted in rates from less than 1 to more than 16 t/ha/year. The present rate of 5.33 t/ha/year is close to the average for the whole area but is not comparable with existing map. The main reason for this is that the prevailing wind directions were not known to them. As the wind is the main factor of erosion in Iraq in forms ranging from mass movement to abrasion, it is an important input to erosion models. These prevailing wind directions lead us to calculate potential erosion rates both with and without the presence of vegetation. The present paper considers the latter to be the potential under present conditions with a fully vegetated state. The soil loss rates were also calculated under past and present land uses, but this is considered to be future work which will

involve making new land cover maps with the same resolution of the soil and vegetation maps.

It is also concluded that, the implementation of the Revised Universal Soil Loss Equation (RUSLE) for studying wind erosion in regions like Iraq, specifically in areas such as Al-Anbar Governorate can provide valuable insights into soil loss dynamics and erosion impacts. By understanding the spatial distribution and intensity of erosion, researchers and policymakers can develop targeted interventions to mitigate soil loss, enhance agricultural productivity, geodiversity, geoheritage sites and preserve the environmental health of the region. This discussion encapsulates the critical aspects of soil and wind erosion in Al-Anbar Governorate, highlighting the importance of continued research and targeted geoconservation efforts. By utilizing the RUSLE model in this context, researchers and decision-makers can better understand the factors contributing to wind erosion and develop strategies for soil geoconservation and sustainable land management practices.

In summary, this study successfully restructured the environmental modeling framework for Al-Anbar Governorate by explicitly decoupling water-induced baseline soil degradation sensitivity (RUSLE) from wind-driven dust storm susceptibility. Empirical validation against 7 field soil sampling profiles demonstrated robust model accuracy ($R^2 = 0.78$, RMSE = 1.12 t/ha/year) with a governorate-wide mean soil erosion rate of 5.33 t/ha/year. Key recommendations for land management in Al-Anbar Governorate include:

- Prioritizing conservation interventions across the identified 21,330 km² of High and Very High erosion hotspots.
- Establishing windbreak shelterbelts and native drought-resistant vegetation strips along wadi margins and agricultural oasis perimeters.
- Integrating geoconservation protection plans into municipal regional planning for historical and geological heritage sites along the Euphrates corridor.

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Author Contributions

The authors contributed equally to the development and preparation of this research.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the authorship or publication of this article.

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ارزیابی یکپارچه حساسیت به تخریب خاک و استعداد وقوع طوفان‌های گرد و غبار در استان الانبار عراق با استفاده از تکنیک‌های مکانی-فضایی و شاخص‌های زیست‌محیطی

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چکیده مبسوط

۱. مقدمه

تخریب خاک و افزایش فراوانی و شدت طوفان‌های گردوغبار از مهم‌ترین مخاطرات محیطی در مناطق خشک و نیمه‌خشک خاورمیانه به شمار می‌روند که پیامدهای گسترده‌ای برای پایداری منابع طبیعی، بهره‌وری کشاورزی، سکونتگاه‌های انسانی و حفاظت از میراث طبیعی و فرهنگی دارند. در چنین مناطقی، کاهش بارندگی، خشکی سطح خاک، تخریب پوشش گیاهی و وزش بادهای شدید می‌توانند شرایط را برای جداسدن و انتقال ذرات خاک و تشدید گردوغبار فراهم کنند. با وجود اهمیت این مسئله، در برخی مطالعات، حساسیت خاک به فرسایش آبی و استعداد انتشار گردوغبار ناشی از فرسایش بادی به‌صورت یکسان ارزیابی شده‌اند؛ درحالی‌که این دو فرایند، اگرچه با یکدیگر ارتباط دارند، از سازوکارهای متفاوتی پیروی می‌کنند. ازاین‌رو، پژوهش حاضر با هدف ارزیابی یکپارچه حساسیت تخریب خاک و استعداد وقوع طوفان‌های گردوغبار در استان الانبار عراق، با بهره‌گیری از سامانه اطلاعات جغرافیایی، سنجش‌ازدور و شاخص‌های محیطی انجام شده است. شناسایی کانون‌های بحرانی تخریب خاک و تعیین مناطق اولویت‌دار برای اقدامات حفاظتی، از اهداف کاربردی این پژوهش است.

۲. مبانی نظری تحقیق

چارچوب نظری پژوهش بر این استوار است که تخریب خاک و انتشار گردوغبار، ضمن برخورداری از پیوندهای محیطی، باید از نظر مفهومی و روش‌شناختی از یکدیگر تفکیک شوند. در این چارچوب، مدل اصلاح‌شده معادله جهانی هدررفت خاک (RUSLE) برای برآورد حساسیت پایه خاک به فرسایش و تخریب، با استفاده از پنج عامل فرسایش‌پذیری بارندگی (R)، فرسایش‌پذیری خاک (K)،

توپوگرافی (LS)، پوشش و مدیریت زمین (C) و اقدامات حفاظتی (P) به کار گرفته شده است. در مقابل، استعداد انتشار گردوغبار با استفاده از سرعت و جهت باد، عمق نوری هواویزها (AOD) و شاخص نرمال‌شده گردوغبار (NDDI) ارزیابی شده است. بر این اساس، کاهش بارندگی، با وجود کاهش بالقوه فرسایش‌پذیری باران، می‌تواند از طریق کاهش رطوبت خاک و تضعیف پوشش گیاهی، سطح خاک را در برابر تنش باد آسیب‌پذیرتر کند. بنابراین، ارزیابی هم‌زمان وضعیت خاک، پوشش گیاهی و شرایط جوی، مبنای شناسایی دقیق‌تر کانون‌های مستعد تخریب و گردوغبار قرار می‌گیرد.

۳. روش تحقیق

پژوهش حاضر از نظر هدف، کاربردی و از نظر روش، مبتنی بر تحلیل‌های مکانی و مدل‌سازی محیطی است. محدوده مطالعه، کل استان الانبار عراق با مساحتی حدود ۱۳۸۵۰۰ کیلومتر مربع را در بر می‌گیرد. داده‌های مورد استفاده شامل مدل رقومی ارتفاع ASTER GDEM با قدرت تفکیک مکانی ۳۰ متر، تصاویر ماهواره‌ای Landsat 8/9، داده‌های عمق نوری هواویز MODIS، داده‌های بازتحلیل اقلیمی ERA5-Land، اطلاعات خاک و داده‌های بارندگی و باد است. تصاویر و لایه‌های مکانی پس از آماده‌سازی و هم‌مقیاس‌سازی، در محیط سامانه اطلاعات جغرافیایی پردازش شدند. شاخص‌های پوشش گیاهی و ویژگی‌های سطح زمین برای محاسبه عوامل مدل RUSLE به کار رفتند و نقشه حساسیت تخریب خاک تهیه شد. سپس، با تلفیق نتایج مدل با داده‌های سرعت و جهت باد و شاخص‌های گردوغبار، مناطق مستعد انتشار گردوغبار شناسایی شدند. همچنین، برای ارزیابی اعتبار برآوردهای مدل، داده‌های حاصل از هفت

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البوحیات، حاشیه‌های رودخانه‌ای و محوطه‌های تاریخی و زمین‌شناختی را در معرض تهدید قرار می‌دهد.

۵. بحث و نتیجه‌گیری

یافته‌ها نشان می‌دهند که ارزیابی حساسیت تخریب خاک، بدون توجه مستقل به سازوکارهای فرسایش بادی و شرایط جوی، نمی‌تواند تصویری جامع از خطر توفان‌های گردوغبار در مناطق خشک ارائه دهد. تلفیق مدل RUSLE با داده‌های سنجش‌ازدور و شاخص‌های جوی، امکان شناسایی مکانی کانون‌های بحرانی و تعیین اولویت‌های حفاظتی را فراهم می‌کند. با این حال، از آنجاکه RUSLE اساساً برای برآورد فرسایش آبی توسعه یافته است، نتایج آن باید به‌عنوان برآورد حساسیت پایه تخریب خاک تفسیر شود و نه اندازه‌گیری مستقیم شار انتشار گردوغبار. همچنین، محدود بودن اعتبارسنجی میدانی به هفت پروفیل و ناهمگونی قدرت تفکیک داده‌های جوی، ضرورت تفسیر محتاطانه نتایج و توسعه داده‌های میدانی را برجسته می‌کند. بر این اساس، پیشنهاد می‌شود اقدامات حفاظتی در پهنه‌های دارای حساسیت زیاد و بسیار زیاد در اولویت قرار گیرند؛ احیای پوشش گیاهی بومی مقاوم به خشکی، ایجاد بادشکن‌های زیستی، بهبود مدیریت اراضی و حفاظت از واحه‌های کشاورزی و میراث طبیعی و تاریخی در دستور کار قرار گیرد. در مجموع، چارچوب تلفیقی پژوهش می‌تواند به‌عنوان ابزاری برای پشتیبانی از تصمیم‌گیری محیطی، برنامه‌ریزی کاربری زمین و مدیریت پایدار منابع خاک در مناطق خشک مورد استفاده قرار گیرد.

کلیدواژه‌ها: تخریب خاک؛ فرسایش بادی؛ توفان گردوغبار؛ مدل RUSLE؛ سنجش‌ازدور؛ سامانه اطلاعات جغرافیایی؛ استان الانبار.

تشکر و قدردانی

مطالعه حاضر برگرفته از رساله دکتری اسیل مزر حسین، گروه مهندسی عمران، دانشکده فنی و مهندسی، دانشگاه آزاد اسلامی، واحد اصفهان (خوراسگان)، اصفهان، ایران است.

پروفیل نمونه‌برداری خاک در واحدهای ژئومورفولوژیک مختلف با نتایج مدل مقایسه شدند. ارزیابی آماری با استفاده از ضریب تعیین، ریشه میانگین مربعات خطا و میانگین قدرمطلق خطا انجام گرفت. تحلیل تغییرات نیز با مقایسه وضعیت سال ۲۰۱۷ و دوره ۲۰۱۸ تا ۲۰۲۴ صورت پذیرفت.

۴. یافته‌های تحقیق

نتایج مدل‌سازی، میانگین برآوردشده هدررفت خاک را در سطح استان حدود ۵/۳۳ تن در هکتار در سال نشان داد. بر اساس طبقه‌بندی حساسیت تخریب خاک، حدود ۲۸/۴ درصد از مساحت استان در طبقات حساسیت زیاد و بسیار زیاد قرار گرفت؛ این مناطق عمدتاً در حاشیه فلات‌های فرسایش‌یافته، تراس‌های آبرفتی فاقد مدیریت حفاظتی مناسب، آبراهه‌های فعال و حاشیه‌های تخریب‌شده رودخانه‌ای متمرکز بودند. اعتبارسنجی مدل بر اساس هفت پروفیل خاک، ضریب تعیین ۰/۷۸، ریشه میانگین مربعات خطا برابر با ۱/۱۲ تن در هکتار در سال و میانگین قدرمطلق خطا برابر با ۰/۸۹ تن در هکتار در سال را نشان داد. مقایسه نقشه‌های زمانی نیز از گسترش پهنه‌های دارای شدت زیاد و بسیار زیاد تخریب حکایت داشت؛ به‌طوری‌که سهم طبقه تخریب شدید از حدود ۱ درصد در سال ۲۰۱۷ به حدود ۲۴/۵ درصد در دوره ۲۰۱۸ تا ۲۰۲۴ افزایش یافت. همچنین، سهم مناطق دارای تخریب بسیار زیاد از ۲/۲۴ به ۶/۷ درصد رسید. این تغییرات با کاهش سهم پهنه‌های دارای تخریب خفیف و گسترش مناطق دارای پوشش گیاهی ضعیف همراه بود. تحلیل عوامل محیطی نشان داد که عامل فرسایش‌پذیری خاک (K) و عامل توپوگرافی (LS) در مقایسه زمانی تغییر چشمگیری نداشته‌اند؛ درحالی‌که کاهش بارندگی و افت پوشش گیاهی، به‌ویژه در اراضی برهنه، با افزایش آسیب‌پذیری سطح خاک در برابر فرسایش بادی همراه بوده‌اند. کانون‌های بحرانی عمدتاً در بخش‌های شمالی و غربی استان، حاشیه فلات‌ها و برخی پهنه‌های مجاور رود فرات مشاهده شدند. این شرایط، واحه‌های کشاورزی، به‌ویژه

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