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Sustainable Land Management for Mitigating Soil Erosion at the Catchment Scale

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Abstract: This study addresses this challenge by focusing on the Revised Universal Soil Loss Equation (RUSLE) to combat excessive soil erosion rates within the Kayacık Dam Basin, located in the semi-arid region of the Tigris-Euphrates Basin in Türkiye. The primary objective is to maintain an average annual soil loss of no more than 10 tons per hectare. To achieve this, the RUSLE model is employed to evaluate sustainable land management (SLM) strategies. These strategies encompass agronomic, vegetative, and structural measures, all of which are intricately linked to RUSLE's C and P factors. Spatial analysis reveals that severe erosion (10-20 t ha^{-1} y^{-1}) is predominantly concentrated in agricultural areas, spanning 2536.37 hectares. In contrast, very severe erosion (>20 t ha^{-1} y^{-1}) affects 834.13 hectares of grassland. Statistical analyses underscore the significant contributions of various model factors to predicted soil losses (A). LS, C, K, and R factors account for 80.24%, 44.68%, 0.97%, and 0.27% of the effect, respectively. Remarkably, topography exerts the most substantial influence on agriculture, pasture, and forest/other land uses, contributing 84.46%, 57.29%, and 39.27% to the variation, respectively. These findings highlight the pivotal role of effective agronomic and vegetative practices in ecosystems management, especially within steep-slope landscapes encompassing agriculture, grassland, and forest. Furthermore, the semi-arid regions under investigation contend with the intricate interplay of heightened drought risk and the ramifications of intensive irrigated agriculture on soil erosion. This complex dynamic presents distinct challenges for implementing SLM strategies in the face of evolving climatic conditions and underscores the need for climate-resilient solutions.

Keywords: Erosion modelling, land use, sustainable soil management, sustainable land management, soil loss

1. Introduction

Soils are vital components of terrestrial environments, essential for delivering critical ecosystem functions and services that underpin global food security. According to the report from the Food and Agriculture Organization (FAO) (Anonymous, 2015a), a significant majority of the world's soil currently faces fair to very poor conditions (e.g. soil carbon and biodiversity losses, nutrient imbalance, soil sealing, acidification, contamination, compaction and salinity), largely due to soil erosion, a primary threat to these ecosystems.

In semi-arid and semi-humid regions, human-induced soil erosion disrupts ecological balance, leading to significant consequences for water resources, reservoir capacity, agricultural yields, and freshwater ecosystems (Bakker et al., 2008; Xiong et al., 2013; Prostocimini et al., 2016; Borrelli et al., 2017; Sokouti and Nikkami, 2017). The depletion of soil resources poses a threat to ecosystems, as soil plays a crucial role in determining the presence and health of ecosystems. Additionally, the increased frequency and severity of droughts, exacerbated by climate change, further intensifies soil erosion (Dardel et al., 2014; Garcia-

Ruiz et al., 2017). According to the FAO Global Soil Partnership (GSP), global arable lands experience an annual erosion of 75 billion tonnes (Pg), resulting in an estimated financial loss of US $400 billion annually (Anonymous, 2017). Alarmingly, accelerated water erosion affects one-sixth of the Earth's land area (Schröter et al., 2005).

Soil erosion worsens due to climate and land cover changes, posing lasting risks to agriculture and its ecosystem services. Increased fertilizer uses and technological advances can mask soil degradation, limiting agro-ecosystems' service capabilities (Poesen, 2018). In addition to affecting agriculture, soil erosion contributes to land degradation, disrupting habitats and threatening biodiversity. An in-depth analysis of soil erosion risks across various land use types in fragile ecosystems can unveil dynamic indicators of soil erosion. These scientific insights, deeply rooted in erosion research literature, serve as essential guides for soil and water conservationists in formulating effective measures to combat land degradation at different scales. This heightened awareness of soil erosion has resonated with policymakers and land use planners globally, emphasizing the necessity for comprehensive conservation strategies that align with the Sustainable Development Goals (SDGs) and promote development-oriented policies. These strategies encompass climate change mitigation, adaptation efforts, as well as the battle against desertification and land degradation, fostering a shared agenda for a sustainable future. Soil and water conservation measures, aiming to prevent soils from eroding, are well-oriented with new generation Sustainable Land Management (SLM) technologies and practices. This alignment ensures that soil erosion prevention is systematically designed and integrated into land management approaches, creating a synergy between environmental protection and sustainable land use. Therefore, prioritizing soil erosion as one of the main issues for SLM approaches and practices offers a strategic pathway to simultaneously address the interconnected challenges of land productivity and soil organic matter dynamics. This prioritization strategy entails conducting comprehensive soil erosion risk assessments at the watershed scale, which would serves as the foundational step.

Assessing the impacts of soil erosion resulting from shifts in land use and unsustainable land management is essential, especially within the context of climate change. Recent research spanning various spatial scales highlights the profound influence of these changes on soil erosion and sediment levels in drainage basins (Van Rompaey et al., 2002; Pruski and Nearing, 2002; Dunjo et al., 2004; Başaran, 2005; Bakker et al., 2008; Bayramin et al., 2008; Chou, 2010; Jain and Das, 2010; Xiong et al., 2013; Madenoğlu et al., 2018; Pınar et al., 2018). Crucially, these studies underline the potential for reducing unsustainable soil loss through effective SLM practices (Cerda et al., 2010; Anonymous, 2015a, 2018; Panagos et al., 2015). In the context of agriculture, pasture, and forest management, understanding the extent and severity of soil erosion is consequential. Once the risk assessment is completed, tailored SLM practices can be developed and implemented to mitigate erosion effectively. These practices may include contour farming, terracing, agroforestry systems, and cover cropping, among others.

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) offers valuable methodological insights for designing soil and water conservation measures in regions vulnerable to water erosion. The determination of the tolerable soil loss threshold varies depending on global soil conditions and to prevent, reduce, and reverse land degradation caused by soil erosion depends on sustainable use of soil resources. Various Geographic Information Systems (GIS)-based RUSLE methodologies have been used extensively for land use planning with conservation practices (Borrelli et al., 2017; Diwediga et al., 2018; Yesuph and Dagnew, 2019). Erpul et al. (2018) conducted a national-scale assessment of water erosion risk in Türkiye using the RUSLE-based system for major river basins. Their findings, published in the 1st Edition of the Water Erosion Atlas of Türkiye, showed that within the Tigris and Euphrates basin, around 160 million tons of soil are transported annually, with 84 million tons lost to rivers each year, factoring in the sediment delivery ratio (SDR).

Türkiye's national-scale Basin Monitoring and Evaluation System (Anonymous, 2015b) provides a suite of analytical tools and services, encompassing data visualization, data mining, and predictive modeling. Its primary focus is the sustainable management of natural resources and land across different spatial scales. Within this framework, the "RUSLE-based Dynamic Erosion Model and Monitoring System" (Erpul et al., 2018) operates alongside the Desertification Risk Map of Türkiye (Türkeş et al., 2019). Furthermore, a collaborative effort with FAO under the national-scale Global Environment Facility (GEF) project (GCP/TUR/065/GFF) is ongoing, aimed at developing a Decision Support System for Land Degradation Neutrality (LDN). This project integrated erosion severity as a crucial indicator in assessing land degradation, alongside considerations of land use changes, land productivity dynamics, and soil organic carbon

(Anonymous, 2019). In summary, soil erosion, which is closely linked to land use practices, significantly affects land productivity by depleting valuable topsoil and reducing its fertility. Additionally, erosion contributes to soil organic carbon (SOC) loss, by removing organic matter with eroded soil particles. Therefore, effectively mitigating soil erosion through tailored SLM practices is inherently aligned with LDN objectives (Cowie et al., 2018). Ultimately, integrating soil erosion risk assessment into the LDN approach helps neutralize land degradation.

In the realm of land management and combating land degradation as a part of integrated catchment management programs, the choice between process-based and state-based indicators carries significant implications for our ability to comprehend and address complex environmental challenges effectively. State-based indicators, such as those employed in the LDN approach, provide valuable insights into the current conditions of land productivity dynamics (LPD) and SOC. However, they inherently lack the temporal and mechanistic depth necessary to reveal the intricate cause-and-effect relationships shaping land degradation processes. Soil erosion, as a process-based indicator, enables us to explore the intricate interactions between land management practices, climatic factors, and geomorphological processes at catchment scales where hydrological processes play a key role. It offers a comprehensive view of how these components interplay, leading to land degradation. Soil erosion, for instance, reflects the consequences of land use decisions, such as deforestation, inappropriate agricultural practices, or overgrazing, on soil structure, nutrient balance and water-holding capacity. This real-time understanding of causality empowers us to make informed decisions, develop targeted strategies, and implement effective SLM practices.

The primary objective of this study is to explore spatial disparities in erosion severity and formulate conservation goals to mitigate the detrimental impacts of soil erosion. This was achieved through the implementation of SLM technologies and practices within the Kayacık Dam Basin, located in the Tigris-Euphrates Basin of Türkiye.

2. Materials and Methods

2.1. Material

This study is located within the Tigris and Euphrates Basin, specifically in the Southeastern Anatolia Project (GAP) region, covering about 22.6% of Türkiye's national territory, totaling approximately 17.615.280,33 hectares. This region is currently experiencing increased drought uncertainties due to recent climate changes, making the sustainable use of soil and water resources of utmost importance. The primary focus of this study is the Kayacık Dam, situated on the Ayfinar stream, one of the two tributaries forming the Sacır (Alleben) River. The Sacır River originates from the Sof Mountains in Gaziantep, Türkiye, within the Euphrates and Tigris Basin (Figure 1). The Kayacık Dam basin covers approximately 42484.30 hectares, with diverse land uses, including agriculture, forests, pastures, and others. The construction of the Kayacık Dam began in 1993 and was completed in 2006 as part of the GAP. Geographically, the dam is located at coordinates 36°49'20.96" N and 37°34'7.01" E, serving as an irrigation source for a vast area spanning 200 square kilometers. The GAP is a prominent regional development initiative covering nine provinces in the Euphrates-Tigris Basin and the upper Mesopotamia plains.

2.2. Methods

The RUSLE model, as proposed by Renard et al. (1997) and depicted in Figure 2, uses various independent variables, including soil characteristics, rainfall patterns, topography, land use, and soil and water conservation practices. This model quantifies average annual soil loss (A) in metric tons per hectare per year (t ha^{-1} y^{-1}). For this study, we utilized the Water Erosion Atlas of Türkiye database established by Erpul et al. (2018). This database served as the basis for applying the RUSLE model to the Kayacık Dam Basin. The primary goal was to assess erosion risk and classify it into severity categories. Subsequently, erosion reduction targets were defined within each category, creating a strategic framework for sustainable land management aimed at mitigating soil erosion in the basin.

A factor level analysis: To evaluate the individual impact of RUSLE parameters (R, K, LS, and C) on predicting soil losses (A, t ha^{-1} y^{-1}), an analysis was performed using Equation 1. This analysis established criteria for optimizing the utilization of practices related to the C (Cover and Management) and P (Support Practice) factors, supporting the implementation of sustainable land use practices as described in Equation 2.

$$r^2 = 1 - \frac{SS\ Error}{SS\ Total} = 1 - \frac{\sum(A_i - \hat{A}_i)^2}{\sum(A_i - \bar{A}_i)^2} \quad (1)$$

Where A_i is the observed response value (referring to the predicting soil loss), $\hat{A}_i$ is the i^{th} fitted response and $\bar{A}$ is the mean response.

Equation 1 calculates the incremental increase in the R-squared value when each RUSLE factor is

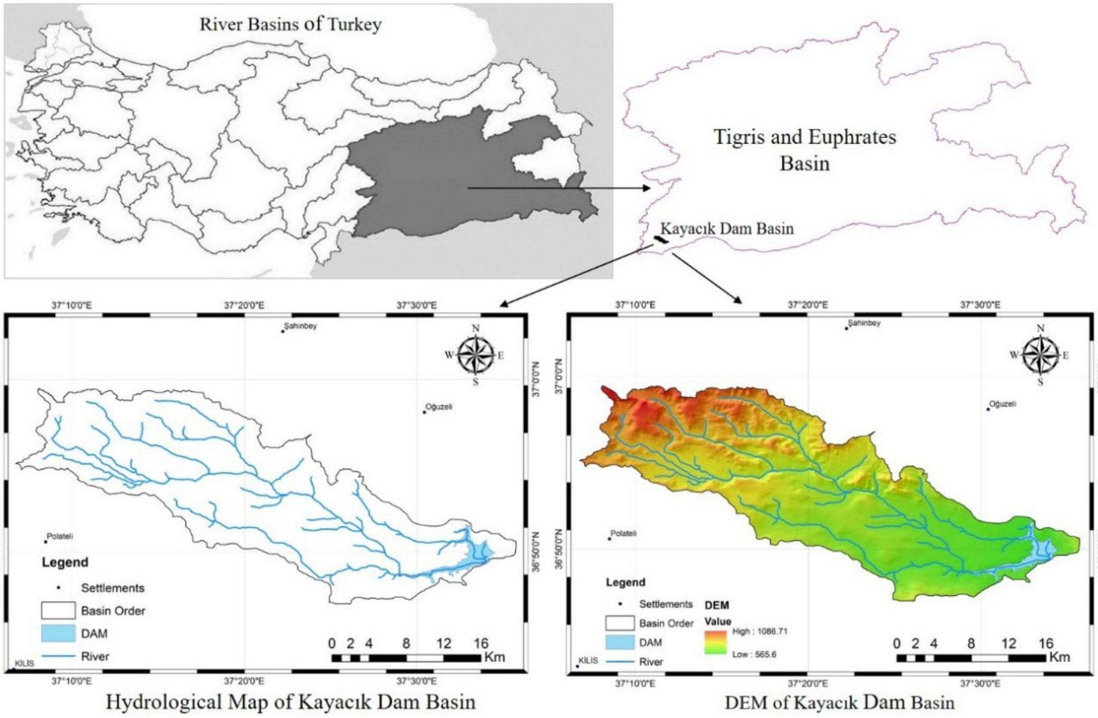

Figure 1. Location of Kayacık Dam in Türkiye

A
- The mean annual soil loss (Wischmeier and Smith, 1978; Renard et al., 1997)
- t ha^{-1} year^{-1}
- $A = R \cdot K \cdot L \cdot S \cdot C \cdot P$

R factor
- The rainfall-runoff erosivity factor (Wischmeier and Smith, 1958; Foster et al., 1981; Renard et al., 1997)
- MJ mm ha^{-1} h^{-1} year^{-1}
- $E = 0{,}29(1 - 0{,}72e^{0{,}051})$

K factor
- The soil erodibility factor (Torri et al., 1997, 2002; Shirazi and Boersma, 1984)
- t ha h ha^{-1} MJ^{-1} mm^{-1}
- $K_T = 0{,}0293(0{,}65 - D_G + D_G^2) \times \exp\left[-0{,}0021\frac{OM}{C} - 0{,}00037\left(\frac{OM}{C}\right)^2 - 4{,}02C + 1{,}72\,C^2\right]$ &
- $D_G = \sum f_i \log_{10}\left(\sqrt{d_i d_{i-1}}\right)$

LS factor
- Slope Length & Slope stepness factor (Ogawa et al., 1997; Lee, 2004)
- Unitless
- 1/25000-scaled DEM
- $LS = \left(\frac{x\eta}{22{,}13}\right)^{0{,}4}\left(\frac{\sin\theta}{0{,}0896}\right)^{1{,}3}$

C factor
- Cover-management factor (Panagos et al., 2015)
- Unitless
- CORINE 2018

P factor
- Support practice factor
- Unitless
- No conservation practices (=1)

Databases
- DEMIS - Dynamic Erosion Model and Monitoring System of Turkey (Erpul et al., 2018)
- Water Erosion Atlas of Turkey (Erpul et al., 2018)

Figure 2. The RUSLE framework used in the Dynamic Erosion Model and Monitoring System and Water Erosion Atlas of Türkiye (Erpul et al., 2018)

added to a model already containing all other factors. For the analysis, a total of 2020 random sample points were used, distributed proportionally among various land use types in the basin. The distribution percentages for agriculture, forest, pasture, and other land uses were 80.39%, 1.78%, 16.54%, and 1.29%, respectively.

Conservation planning with an adaptive approach: An adaptive approach, integrated with the RUSLE methodology (Figure 3), includes three distinct strategies aligned with erosion severity classes identified in the Water Erosion Atlas of Türkiye (Erpul et al., 2018). These strategies are categorized as: 1) A≤ 10 t ha^{-1} y^{-1}, 2) 10< A ≤20 t ha^{-1} y^{-1}, and 3) A> 20 t ha^{-1} y^{-1}.

In a nutshell, the predictive RUSLE model foresees transformative changes in a diverse set of C and P alternatives relying on the relative magnitude of predicted and targeted soil losses (A1/A2, Equation 2). Often, engineering measures will also require a factorial change in the LS multiplier to break slope length e.g., by alternating crop strips or terracing in the field without altering slope steepness. So, a general formulation of the RUSLE case in a land unit with given R and K factor distributions is formulated by (Equation 2), which is easily re-organized and re-run considering the extent of best-case scenarios for erosion with conservation measures of C & P.

$$\frac{A_{i1}}{A_{i2}} = \frac{RK\left\{\frac{1}{\sum_{i=1}^{n}\forall_i}\left\{\sum_i^n(\forall LSCP)_{i1}\right\}\right\}}{RK\left\{\frac{1}{\sum_{i=1}^{n}\forall_i}\left\{\sum_i^n(\forall LSCP)_{i2}\right\}\right\}} = \frac{\sum_i^n(\forall LSCP)_{i1}}{\sum_i^n(\forall LSCP)_{i2}} \qquad (2)$$

Where,

A_{i1}, soil loss under current land management (t ha^{-1} y^{-1}),

A_{i2}, aimed soil loss under sustainable land management (t ha^{-1} y^{-1}),

LS_{i1}, C_{i1} and P_{i1} are factor values of slope length and steepness, vegetation cover and crop-management, and soil conservation under current land management, respectively.

LS_{i2}, C_{i2} and P_{i2} are factor values of slope length and steepness factor, crop-management factor and soil conservation under adaptive sustainable land management, respectively. The numerical value of

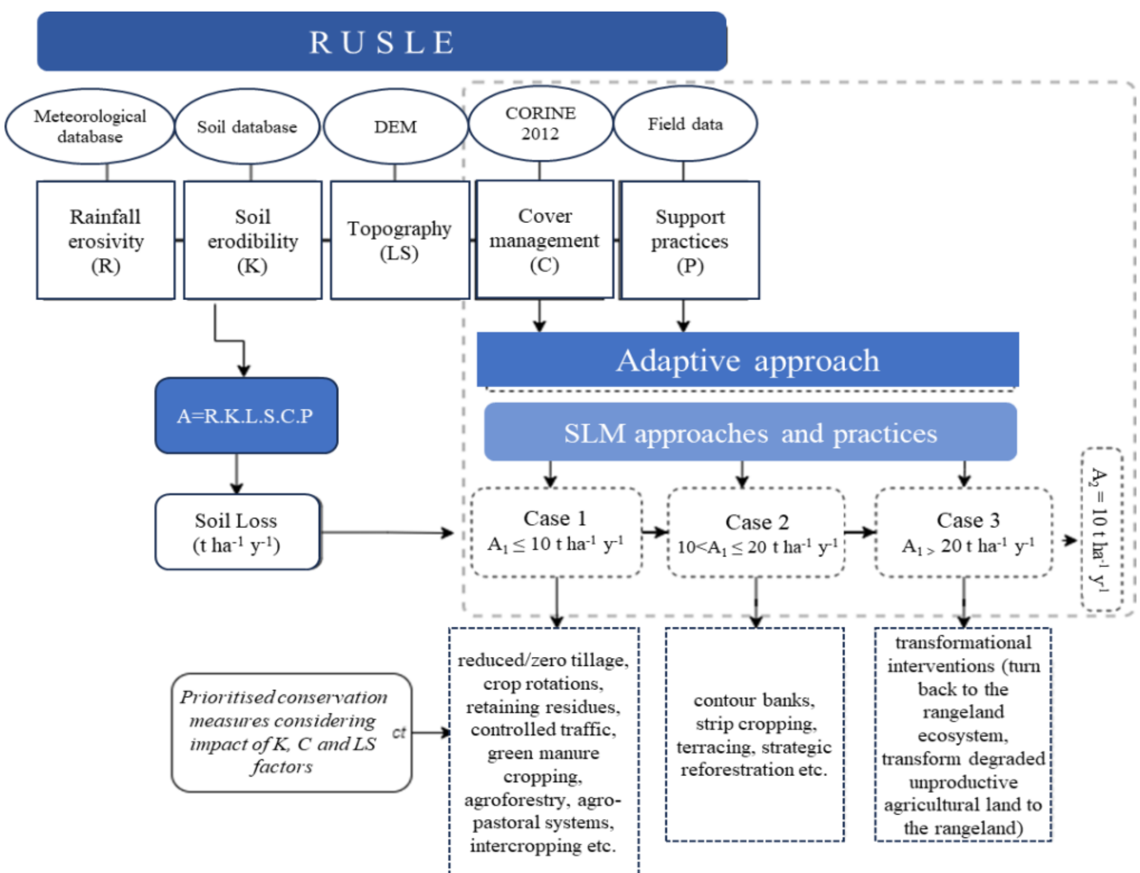

Figure 3. A conceptual framework for scenario setting with the RUSLE methodology along with sustainable land management practices proposed to be implemented under each scenario case

these factors needs to be transformed by introducing adaptive approaches and practices depending upon relative magnitude of A_{i1}/A_{i2},

$\forall_i$, unit area of each land use type and crop pattern in the basin (ha),

i, the numbers of different land use types and crop patterns in the basin (*i= 1, ………n*).

Utilizing the approach in Figure 3 and Equation 2, the three cases are systematically designed:

Case 1 (C1) focuses on areas with A1 ≤ 10 t ha^{-1} y^{-1}. It promotes SLM practices to mitigate soil erosion and enhance land use systems, aligning with emerging trends like climate change mitigation, adaptation, land degradation neutrality, biodiversity, and ecosystem services. C1 establishes SLM as the new standard, discouraging unsuitable practices, especially in alluvial flat plains (0-3%) and gently sloping colluvial areas (3-8%).

Case 2 (C2) targets areas with 10 ≤ A1 ≤ 20 t ha^{-1} y^{-1}, implementing soil and water conservation measures to reduce soil loss to A2= 10 t ha^{-1} y^{-1}.

Case 3 (C3) addresses severely degraded areas with A ≥ 20 t ha^{-1} y^{-1}, primarily focusing on arid rangeland systems with communal grazing. It aims to curb past land degradation due to water erosion, but the required investments for rehabilitation or restoration exceed the economic capabilities of governments and communities in this region.

In cases where the A1/A2 ratio is significantly large, composite conservation practices (CP) may not be economically viable. The RUSLE methodology assesses spatially diverse costs of soil and water conservation, facilitating practical planning and informed decision-making. In summary, the three cases systematically leverage opportunities and RUSLE technical approaches while emphasizing stakeholder involvement through social and policy dialogues in basin management. This inclusive approach aligns with SLM technologies and practices, prioritizing economic feasibility as advocated by Schwilch et al. (2012) and Cowie et al. (2018).

3. Results

3.1. Descriptive statistics for RUSLE factors

Table 1 provides an extensive overview of the descriptive statistics for the RUSLE factors, while Figure 4 visually presents their respective map layers, crucial for estimating soil loss (A1, t ha^{-1} y^{-1}) within the Kayacık Dam Basin.

Table 1. Descriptive statistics for the RUSLE factors

RUSLE	Maximum	Minimum	Mean	Standard deviation
R	938.38	612.86	793.20	49.47
K	0.029	0.015	0.020	0.004
LS	15.667	0.002	1.127	1.800
C	0.450	0.001	0.244	0.108

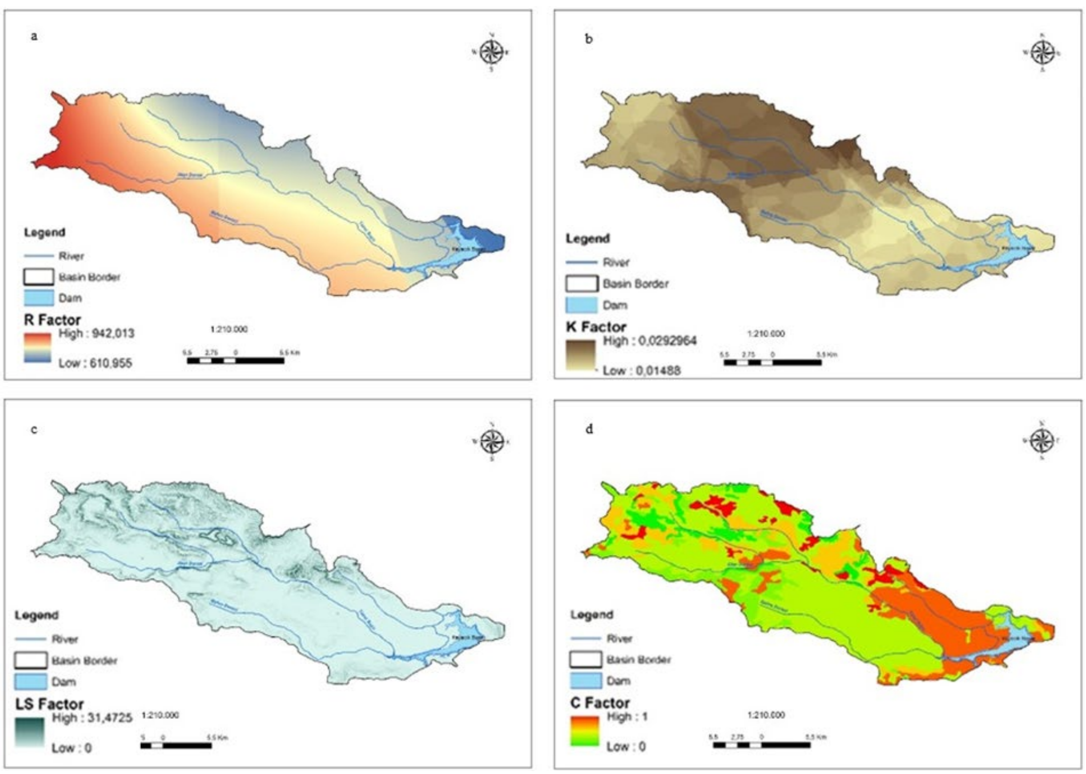

Figure 4. The factor maps of RUSLE model; **(a)** R, **(b)** K, **(c)** LS, and **(d)** C in the Kayacık Dam Basin

The summary statistics for the RUSLE factors are as follows:

a) The R factor ranges from 612.86 to 938.38 (MJ mm ha^{-1} h^{-1} y^{-1}) (Table 1), with particularly high values observed in the northwestern upstream region (Figure 4a).

b) Regions displaying increased susceptibility to soil erosion are primarily located upstream in the catchment (Figure 4b). Here, the RUSLE-K factor ranges from 0.015 to 0.029 (t h MJ^{-1} mm^{-1}) (Table 1).

c) The RUSLE-LS factor reaches its highest value at 15.667 (Table 1), mainly in the mountainous areas spanning from the middle to the upstream reaches of the basin (Figure 4c).

d) Northern regions exhibit comparatively lower vegetative cover and less-established protective cover, resulting in higher RUSLE-C factor values in contrast to other parts of the basin (Figure 4d).

3.2. Erosion severity classes in the Kayacık Dam Basin

The soil erosion risk map (Figure 5) is generated by integrating GIS map layers (Figure 4a, b, c, and d) to estimate soil losses (A1, t ha^{-1} y^{-1}), as shown in Figure 2. Units are categorized into five severity classes, ranging from very light ($0 \leq A1 \leq 1$) to very severe (≥ 20), as outlined in Table 2. Table 2 presents the spatial distribution (%) of erosion severity classes across land use types within the basin. Notably, very light (39.3%) and light (38.7%) categories predominate. However, around 9.9% of the land faces higher erosion risks, falling into severe (6.5%) or very severe (3.3%) categories per the RUSLE model (Table 2). The annual total soil loss for the basin is estimated at 251844.7 t ha^{-1}, averaging 6 t ha^{-1} y^{-1} for the entire area. This highlights the significance of Case 1, covering approximately 90% of the basin.

In both agricultural and pasture lands, a significant portion falls within the "very light" and "light" erosion severity classes. However, over 20% of the pastureland is classified under "severe" and "very severe" erosion risk categories. In contrast, agricultural land has a combined risk of 7.2% for these severe categories. When considering conservation efforts, addressing the "moderate" erosion class may be more economically feasible than tackling the "severe" and "very severe" classes. Notably, nearly 40% of the catchment basin's pastures face erosion risks falling within the "moderate," "severe," and "very severe" categories, as indicated in Table 2.

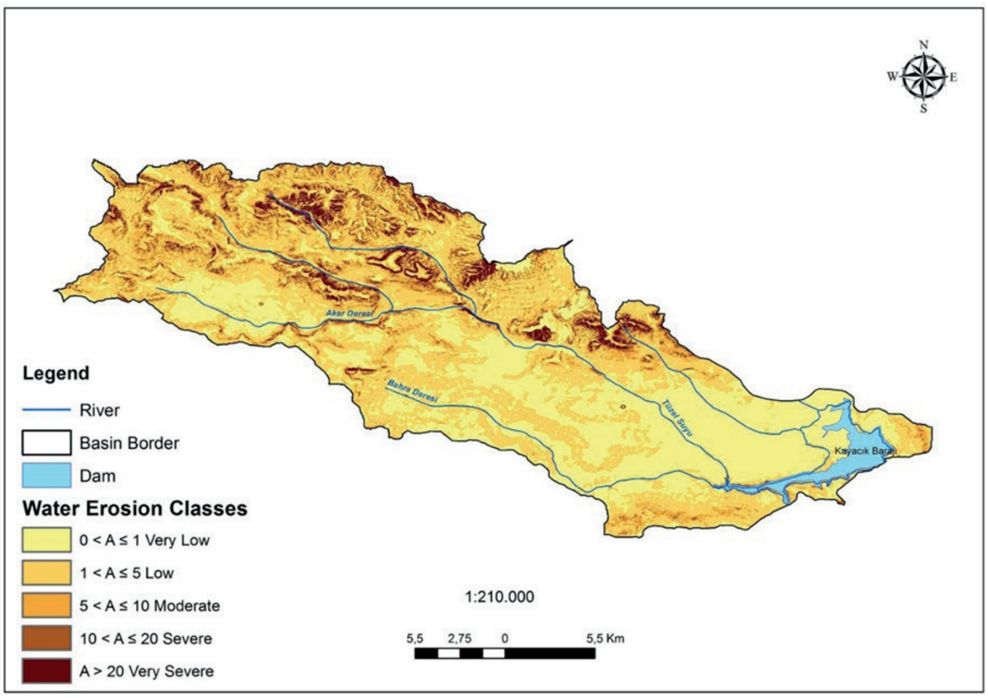

Figure 5. Soil erosion severity map of the Kayacık Dam Basin

Table 2. Spatial distribution of the erosion severity classes by land use types in the Kayacık Dam Basin

Kayacık Dam Basin drainage area (ha)	42.484,3					
Dam surface area (ha)	401.3					
Erosion severity classes ($t\ ha^{-1}\ y^{-1}$)	Very light ($0 \leq A1 \leq 1$)	Light ($1 < A1 \leq 5$)	Moderate ($5 < A1 \leq 10$)	Severe ($10 < A1 \leq 20$)	Very severe (≥ 20)	Total
Area (ha)	16522.6	16304.9	5134.6	2737	1383.9	42083
Overall (%)	39.8	38.4	12.2	6.5	3.3	100.0
Agricultural lands (%)	42.1	39.1	11.6	5.7	1.5	100.0
Pasturelands (%)	21.9	38.7	16.1	10.8	12.5	100.0
Forest (%)		100.0				100.0

3.3. Differential impact analysis of the RUSLE factors on soil loss prediction

The assessment of differential effects, aimed at elucidating the role of each RUSLE predictor variable through linear regression (Equation 1), provides valuable guidance for planning cost-effective SLM technologies and practices in soil erosion management. In the basin area, both the LS and C factors emerged as prominent contributors. Notably, LS had a twice as significant impact (80.23%) as C (39.45%), while R and K factors made relatively minor contributions at 0.27% and 1.09%, respectively (Figure 6, Table 3 and 4). It's important to highlight that the incremental impact of the C factor in pasturelands is approximately 50%, indicating a negative trend in land productivity dynamics and notably low biomass production.

3.4. Planning soil conservation measures

To strategically plan soil conservation measures in the Kayacık Dam basin, we employed a proactive approach was employed, utilizing insights from both the RUSLE-based severity classes and the differential impact analysis (Table 2 and 4). These analyses provided valuable inputs for developing support tools for SLM. These support tools encompass a range of agronomic, vegetative, and structural measures, all addressed within the framework of the RUSLE methodology (Equation 2). They involve strategies such as altering crop patterns, adopting conservation tillage practices, and modifying slope lengths (L) through techniques like vegetative strips or engineering structures.

3.5. The results of the RUSLE approach

The findings of 3 cases to set a target of A2= 10 $t\ ha^{-1}\ y^{-1}$ (Figure 3) (Equation 2) to introduce conservation measures in the catchment are detailed hereinafter.

Case 1 (C1): C1 focuses on cost-effective policies for sustainable land use within approximately 90.3% of the catchment area (37962.1 ha). The objective is to optimize land productivity and economic value by implementing SLM practices. This approach emphasizes effective cover management, reduced and zero tillage, crop rotation, controlled traffic, agroforestry and

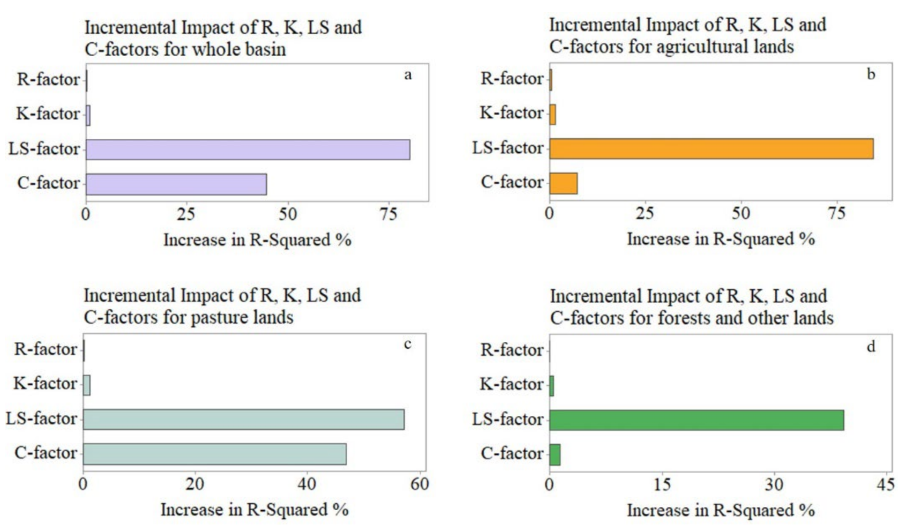

Figure 6. The incremental impact of each (R)USLE factor on total soil loss across the catchment **(a)**, agricultural lands **(b)**, pasture lands **(c)** and forest and other lands **(d)***

*: Long bars represent factors that contribute the newest information to the model.

Table 3. Increases in R-squared of RUSLE factors effecting the amount of erosion for land use types in the Kayacık Basin

Land use	R	K	LS	C	Total
	R-squared (%)	R-squared (%)	R-squared (%)	R-squared (%)	
Agriculture	0.58	1.50	84.84	7.19	100
Pasture	0.20	1.23	57.29	46.89	100
Forest and others	0.009	0.56	39.37	1.43	100
Overall	0.27	1.09	80.23	39.45	100

Table 4. Weighted impacts of the RUSLE factors in agricultural and pasture lands differentiated by the erosion severity classes

Erosion classes	Erosion rate ($t\ ha^{-1}\ y^{-1}$)	Area (%)	Number of points	R (%)	K (%)	LS (%)	C (%)
Agricultural lands							
Very light	0-1	42.1	641	0.24	1.42	96.43	4.56
Light	1.01-5	39.1	659	2.25	7.12	90.41	23.91
Moderate	5.01-10	11.6	202	6.87	20.84	89.49	52.00
Severe	10.01-20	5.7	94	3.64	14.12	92.94	40.25
Very severe	20.01- +	1.5	22	0.14	1.49	61.13	11.62
Pasture lands							
Very light	0-1	21.9	61	1.08	1.35	72.97	7.73
Light	1.01-5	38.7	143	0.90	3.03	89.74	38.95
Moderate	5.01-10	16.1	46	3.31	12.20	86.63	71.86
Severe	10.01-20	10.8	39	2.34	8.73	64.38	57.94
Very severe	20.01 - +	12.5	43	0.23	4.89	92.51	18.62

agricultural diversification etc. to reduce soil erosion within the moderate erosion severity class. Key factors include the significant influence of LS in agricultural lands and both LS and C in pastures. The economic consideration centers on deriving economic value from biomass and crop production diversity and quantity. The anticipated impact is a substantial reduction in soil erosion and improved land productivity.

Case 2 (C2): C2 aims to reduce soil loss to the lower boundary limit (A2= 10 $t\ ha^{-1}\ y^{-1}$) within highly degraded areas covering 2737 ha, with an initial soil loss of 16.92 $t\ ha^{-1}\ y^{-1}$, compared to the basin's 5.98 $t\ ha^{-1}\ y^{-1}$. This case employs SLM practices to achieve its objective, focusing on optimizing LS to reduce soil erosion. While more conservative, C2 targets significant soil loss reduction within its scenario area, with the economic consideration being cost-effective solutions to meet the specified soil loss reduction. The anticipated impact is a substantial reduction in soil erosion within the targeted area. Figure 7a and 7b respectively illustrate soil loss maps before and after conservation practices to be prescribed by C2.

Case 3 (C3): C3 addresses severely or very severely degraded areas within the basin where soil loss exceeds 20 $t\ ha^{-1}\ y^{-1}$. Covering 1383.9 ha, including agricultural and pasture lands, this case necessitates extensive interventions, including mechanical and engineering structures, to reverse degradation and restore ecosystem functions. However, high associated costs make large-scale rehabilitation economically unfeasible. The primary focus is on implementing SLM practices to achieve a significant reduction of 80.51% within the scenario area, resulting in a soil loss of 10 $t\ ha^{-1}\ y^{-1}$. The anticipated impact is the substantial reduction of soil erosion and the restoration of severely degraded areas. Figure 8a and 8b show maps of soil loss distribution before and after C3 for the basin, respectively.

The study employed target-seeking scenarios to address soil erosion vulnerability across various land use types, aiming to develop cost-effective and environmentally sensitive erosion prevention strategies. Table 5 provides an overview of the case areas' percentages and soil loss calculations before and after implementing cases 2 and 3, demonstrating the effectiveness of SLM practices in mitigating soil erosion in the Kayacık Dam basin. Cases 2 and 3 specifically targeted areas with soil loss (A1) exceeding 10 $t\ ha^{-1}\ y^{-1}$, previously lacking specific conservation measures under the status quo case 1 (Table 3). In summary, the practical relevance of prioritizing soil erosion as a process-based indicator in land degradation assessment lies in its dynamic nature, its close association with land management, direct impact on critical land uses, and its potential to inform integrated and targeted interventions. By addressing soil erosion, we can proactively manage land degradation, promote sustainable land management, and ensure the well-being of both ecosystems and humans.

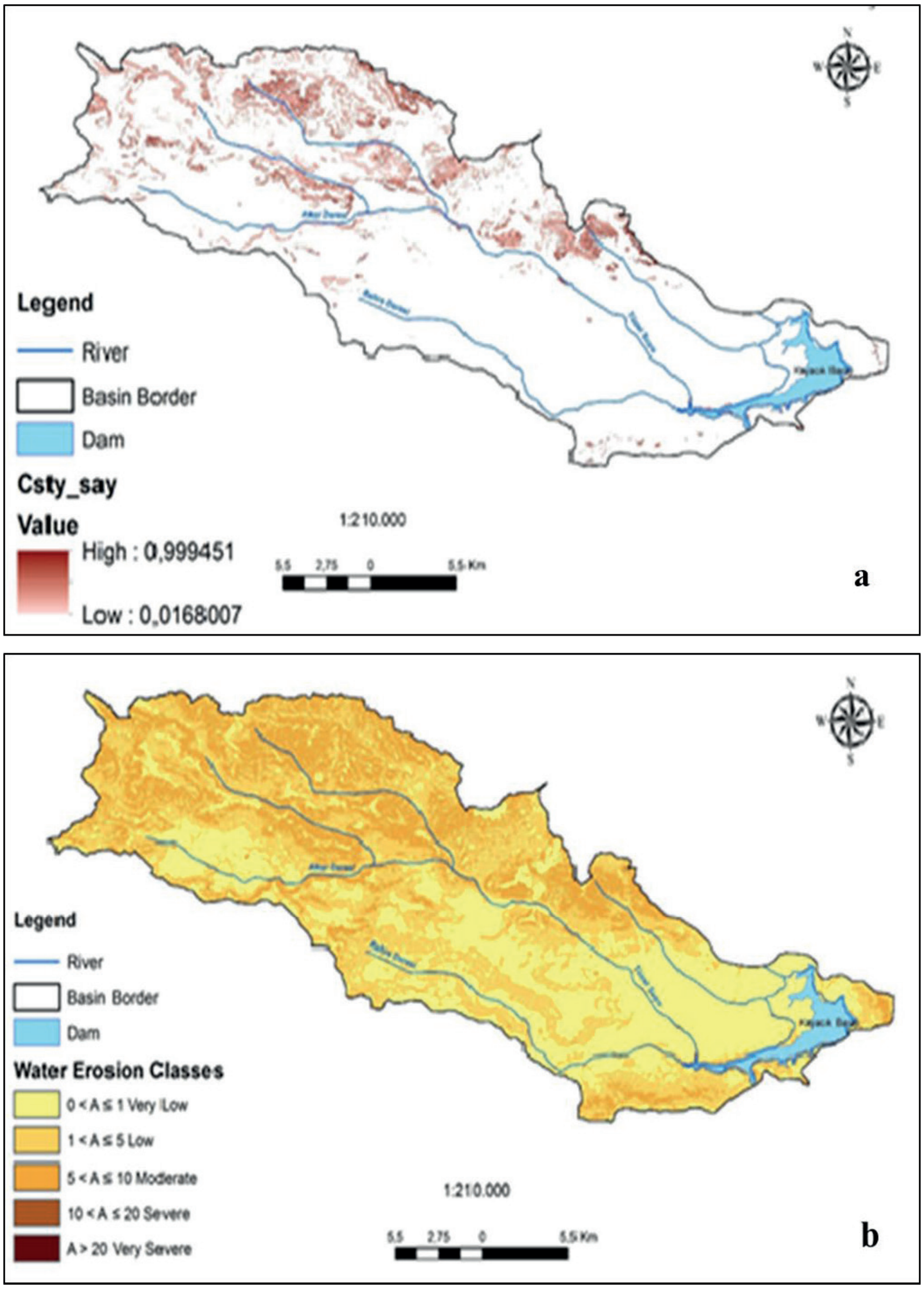

Figure 7. The C2 map **(a)** and soil loss map after C2 **(b)** in the areas with 10< A1 ≤20 t ha^{-1} y^{-1} for A2= 10 t ha^{-1} y^{-1}

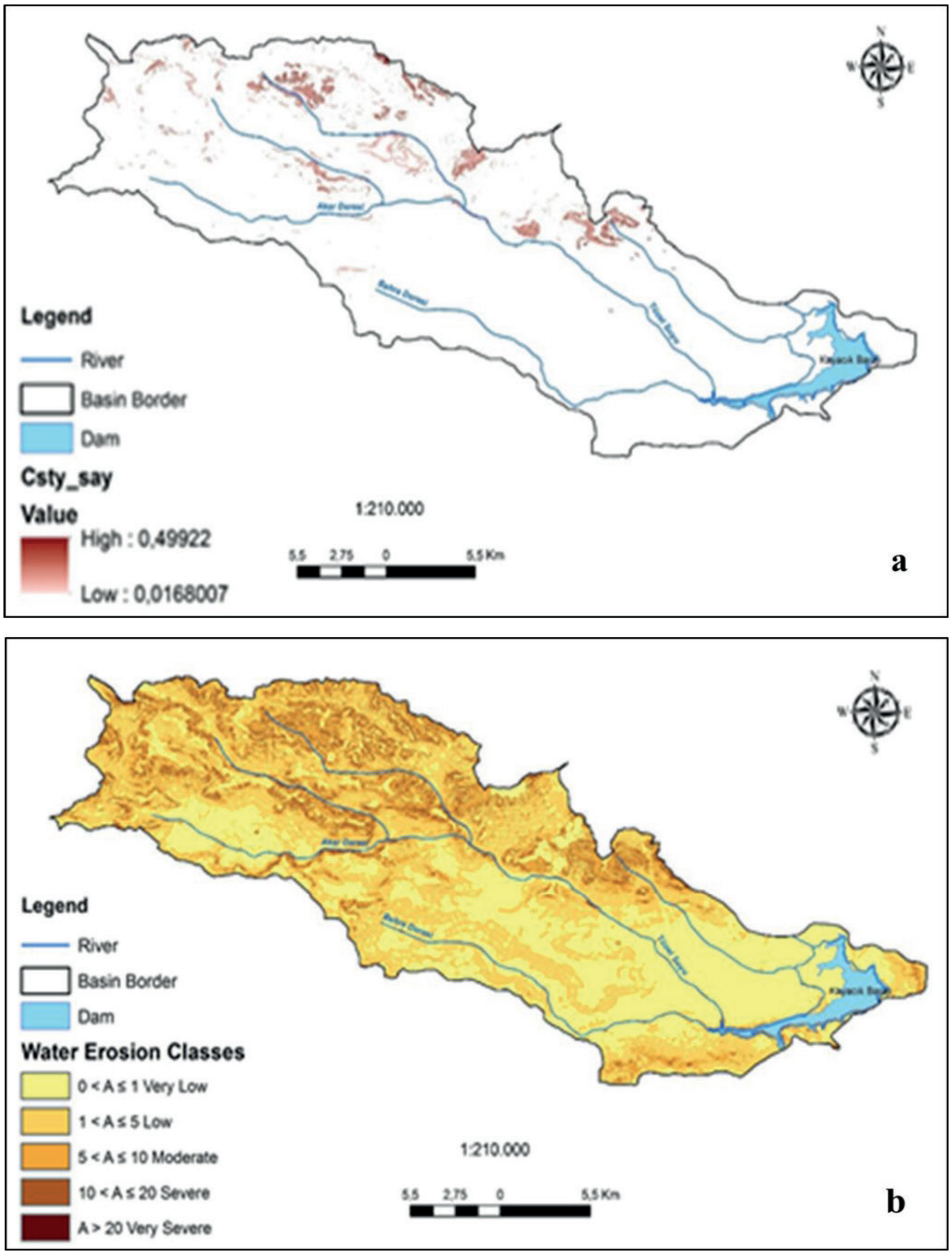

Figure 8. The C3 map **(a)** and soil loss map after C3 **(b)** in the areas with A1 >20 t ha^{-1} for A2= 10 t ha^{-1} y^{-1}

Table 5. The average amounts of soil losses predicted before and after the cases

Area (ha)	Case 1 (A1 ≤ 10 t ha^{-1} y^{-1})	Case 2 (10 < A1 ≤ 20 t ha^{-1} y^{-1})	Case 3 (A1 > 20 t ha^{-1} y^{-1})	Total
	37962.1	2737	1383.9	42083
Adaptive approaches	Soil loss in the area (t ha^{-1} y^{-1})			Total soil loss in the basin (t ha^{-1} y^{-1})
Case 1	5.41			5.98
Before Case 2		16.92		5.98
After Case 2		10		5.53
Decreasing		6.92		0.45
Before Case 3			51.32	5.98
After Case 3			10	4.63
Decreasing			41.32	1.35

4. Discussion and Conclusion

The basin's agricultural and pastureland areas, facing soil erosion rates (A1) exceeding 5 t ha^{-1} y^{1}, require a focused application of SLM practices. The construction of the Kayacık Dam, primarily for energy and irrigation, led to a shift towards intensive agriculture with irrigation infrastructure. This shift had complex results, boosting agricultural productivity and providing energy and water resources while also causing land degradation marked by reduced genetic diversity and increased pesticide use. It had diverse impacts on local communities and ecosystems, including displacement, biodiversity loss, and water availability changes. Given these intricate consequences, it's crucial to thoroughly assess the potential effects on agricultural systems and implement SLM practices.

These practices should aim to mitigate negative outcomes and promote long-term environmental and social sustainability. Key components include transitioning to more sustainable agricultural systems that prioritize soil health, biodiversity conservation, community engagement, and efficient water resource use to support and improve irrigated agriculture. Effective policies and practices are essential for enhancing dryland ecosystem resilience to climate change and drought. Strategies include crop diversification through rotations and cover crops. Prioritizing regions with moderate erosion ($5< A \leq 10$) is vital due to the potential for accelerated erosion from land use and climate change impacts. Intensive agricultural practices, like excessive tillage, monoculture cropping, and crop residue removal, increase soil erosion rates, causing topsoil loss and reduced fertility. Clearing natural vegetation leaves soil vulnerable to erosion, while heavy machinery can compact soil, reducing infiltration and root growth, increasing runoff and erosion. Intensive farming can also lower soil organic matter, destabilizing soil aggregates and elevating erosion risk.

To mitigate these impacts, farmers can employ conservation practices like reduced tillage, cover cropping, and conservation tillage to preserve or boost soil organic matter and minimize disruption. Techniques like contour farming, terracing, and soil conservation methods further decrease runoff rates and erosion risk. The analysis highlights LS and C factors as key drivers of soil degradation. Combining vegetative, agronomic, and mechanical measures is crucial in agricultural and grassland areas. Regulatory actions within the SLM approach are necessary to prevent further degradation. Engaging local communities in economic planning and promoting awareness of SLM practices, climate-resilient farming, and environmental strategies are pivotal in these regions. In areas where Case 1 (C1) is applied, effective management measures are essential to prevent soil loss and improve soil quality. Implementing regulations like contour farming and controlled grazing is vital, especially in semi-arid grasslands susceptible to degradation due to factors like overgrazing and reduced biodiversity.

Sustainable pasture management practices, such as rotational grazing, soil health maintenance, water resource management, and biodiversity promotion, are crucial for long-term pastureland health and productivity. Proper management can lead to improved water quality, enhanced soil health, reduced erosion, and better manure handling. In areas under Case 2 (C2), forests remain erosion-free, while agricultural lands benefit from cost-effective measures like strip cropping, terracing, and contour banks to minimize soil erosion. Implementing managerial and management practices, along with medium-cost vegetative and agronomic conservation measures, proves economically viable for reducing soil losses. Cultural practices like mixed cropping, intercropping, contour tillage, strip cropping, and mulching, along with vegetative measures such as planting barriers (vegetative strips), live fences, high-density planting, grass buffer lines, and windbreaks, effectively bring soil losses to sustainable levels (A2= 10 t ha^{-1} y^{-1}). These measures also foster agricultural biodiversity management suitable for semi-arid climates and provide soil erosion control. Pasture areas, often on sloping terrain, are vulnerable to excessive soil erosion due to animal activity and grazing intensity, leading to soil compaction and increased runoff.

In regions subject to Case 3 (C3), the emphasis is on enhancing pasture ecosystems and preventing further land use alterations. The conversion of dryland pastures into agriculture is unsustainable and damaging, given the marginal nature of these pastures with shallow topsoil and steep slopes, rendering them highly susceptible to water erosion. Therefore, it is advisable to revert these unsustainable cultivated lands close to their original state as semi-arid pastures or steppe ecosystems. This approach is more favorable than implementing costly agronomic, vegetative, and structural measures in heavily eroded basin areas. Cases 2 and 3 highlight the effectiveness of integrated soil and water conservation measures, guided by the RUSLE methodology, in reducing soil loss. Administrative actions specific to the basin are essential for optimizing soil and land management, considering both on-site and off-site impacts. In erosion-affected regions, a combination of agronomic and vegetative methods, supported by structural practices like terraces and check dams, should be considered. However, large-scale engineering structures, as in the Kayacık Dam basin, require cost-benefit analysis. Alternatives as land use changes and rotational grazing may be more practical based on budget and erosion severity. Economic analysis is vital, accounting for implementation costs and the benefits from reduced soil losses.

Soil erosion, especially in productive areas, indicates soil and land degradation. National efforts, like the Global Environment Facility project (GCP/TUR/065/GFF) in partnership with FAO, aim to integrate this indicator into land degradation assessments. Therefore, as a general approach that is also valid in the Kayacık Dam Basin, it can be said that using soil erosion as a prioritized process-based indicator in the context of land degradation and SLM approaches and practices holds robust practical relevance for several key reasons.

Firstly, soil erosion is a dynamic process that directly impacts land productivity dynamics and soil organic carbon levels. Its practical relevance lies in the fact that it serves as a leading indicator of ongoing land degradation processes. Soil erosion can be readily assessed and monitored at different spatial and temporal scales, making it a valuable tool for timely intervention and adaptive management.

Secondly, soil erosion is closely linked to land use and land management practices. Its prioritization allows for the identification of specific land management interventions that can effectively reduce erosion rates, thereby mitigating land degradation. By focusing on soil erosion, practical strategies can be developed to prevent further degradation and promote sustainable land management practices.

Thirdly, soil erosion has direct implications for agricultural, pastoral, and forestry systems, which are critical for livelihoods and food security. Prioritizing soil erosion as a process-based indicator aligns with the practical goal of ensuring continued land productivity. This is especially relevant in regions where land degradation threatens agricultural production and ecosystem services. Furthermore, understanding the interactions between soil erosion and other land degradation indicators, such as land productivity dynamics and soil organic carbon, allows for the development of holistic and integrated management approaches. Practically, this means that interventions can be designed to simultaneously address multiple aspects of land degradation, leading to more efficient and effective outcomes.

In this study, we applied the RUSLE model to the Kayacık Dam Basin in Türkiye, a part of the Tigris-Euphrates Basin. Our goal was to assess water erosion-induced soil loss and implement three target-seeking cases using SLM strategies for dryland management. Our analysis, conducted through GIS-based RUSLE methodology, revealed severe erosion in agricultural areas and very severe erosion in grasslands within the basin. The scenarios we implemented successfully reduced soil losses in these highly erosive areas. Notably, the LS factor had the most significant impact on soil erosion in agriculture, pastureland, and forest/other land uses. Our study emphasized the importance of combining structural, agronomic, and vegetative measures to achieve targeted reductions in soil erosion. To ensure the effectiveness of soil and water conservation strategies, it is crucial to integrate them into modern SLM practices. These should include conservation agriculture, climate-friendly farming, and adapted dryland management practices to promote sustainability in agriculture, rangeland, and forest management. Aligned with overarching policies addressing climate change, desertification, land degradation, biodiversity, and ecosystem services, SLM approaches with erosion control strategies will play a pivotal role in shaping future land use and management programs. This will help safeguard soil and water resources and ensure food and energy security in basins where erosion is a significant contributor to land degradation.

Ethical Statement

The authors declare that ethical approval is not required for this research.

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Declaration of Author Contributions

Investigation, Formal Analysis, Visualization, Writing-Original Draft Preparation, Writing-Review & Editing, *S. MADENOĞLU*; Investigation, Data Curation, Formal Analysis, Visualization, Writing-Review & Editing, *M.Ö. PINAR*; Investigation, Data Curation, Formal Analysis, Visualization, *S. ŞAHİN*; Conceptualization, Material, Methodology, Investigation, Formal Analysis, Writing-Original Draft Preparation, Writing-Review & Editing, *G. ERPUL*. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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