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Araştırma Makalesi / *Research Article*

Sediment Assessment Using Coupled RUSLE-SDR Models of Future Mellegue2 Dam in Tunisia

Tunus'ta Gelecekteki Mellegue2 Barajının Birleştirilmiş RUSLE-SDR Modelleri Kullanılarak Sediman Değerlendirmesi

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ABSTRACT

Over the last 60 years, the Mellegue1 Dam has lost approximately 80% of its original 268 million cubic meter capacity to siltation, reflecting broader Mediterranean basin patterns in which climate-driven erosion has exacerbated dam sedimentation rates. In response, the strategic building of the upstream Mellegue2 Dam intends to address water scarcity, improve flood management, and assure a continuous supply of water for agricultural and domestic purposes. This study fills critical knowledge gaps by integrating climate change projections with sediment modeling in Mediterranean semi-arid environments, developing spatially explicit conservation strategies using combined RUSLE-SDR and SWAT modeling, and evaluating management interventions under future scenarios using drought-flush erosion mechanisms documented across the Mediterranean basin. This study evaluates sediment dynamics in the Mellegue2 Dam watershed from 1993 to 2019 using an integrated RUSLE-IC-SDR modeling approach, with model validation performed using a three-tiered framework that includes SWAT comparison, historical sedimentation records, and regional correlation analysis. The model performed well (NSE=0.78, R^2=0.82), with an average annual prediction error of 12.3%, similar to verified Mediterranean erosion models. Monte Carlo simulation with 1000 iterations, accounting for parameter variability in R-factor (±15%), K-factor (±20%), and C-factor (±25%), yielded confidence intervals of -18% to +22% for annual forecasts. Temporal study demonstrates drought-flush erosion mechanisms common to Mediterranean climates, with post-drought sediment outputs increasing by 40-60% above normal years, consistent with regional research from Spain, Italy, and Greece. According to the management scenario study, Mellegue2 Dam will lose 50% of its capacity within 24 years if no intervention is implemented. However, comprehensive watershed management based on proven Mediterranean basin conservation practices has the potential to increase operational lifespan to 75 years while also delivering broader environmental benefits. The study finds three priority management zones that require distinct conservation approaches, with the largest return on investment found on northwestern slopes with erosion rates of more than 12 t/ha/year. These findings contribute to a

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better knowledge of climate-driven erosion processes across the Mediterranean and offer management solutions that can be applied to similar semi-arid watersheds.

Keywords: Sediment export, soil erosion, RUSLE, SDR, SWAT, index of connectivity, watershed management, Tunisia.

ÖZ

Son 60 yılda, Mellegue1 Barajı, iklim kaynaklı erozyonun baraj sedimantasyon oranlarını artırdığı Akdeniz havzasındaki genel eğilimi yansıtarak, orijinal 268 milyon metreküp kapasitesinin yaklaşık %80'ini siltasyon nedeniyle kaybetmiştir. Buna yanıt olarak, membada stratejik olarak inşa edilen Mellegue2 Barajı, su kıtlığını gidermeyi, sel yönetimini iyileştirmeyi ve tarımsal ve evsel amaçlar için sürekli su teminini sağlamayı amaçlamaktadır. Bu çalışma, iklim değişikliği tahminlerini Akdeniz yarı kurak ortamlarındaki sediman modellemesiyle entegre ederek, RUSLE-SDR ve SWAT modellemesini birleştirerek mekansal olarak açık koruma stratejileri geliştirerek ve Akdeniz havzasında belgelenen kuraklık-akış erozyon mekanizmalarını kullanarak gelecek senaryoları altında yönetim müdahalelerini değerlendirerek kritik bilgi boşluklarını doldurmaktadır. Bu çalışma, entegre RUSLE-IC-SDR modelleme yaklaşımı kullanılarak 1993'ten 2019'a kadar Mellegue2 Barajı havzasındaki sediman dinamiklerini değerlendirmekte ve model doğrulaması SWAT karşılaştırması, tarihsel sedimantasyon kayıtları ve bölgesel korelasyon analizini içeren üç aşamalı bir çerçeve kullanılarak gerçekleştirilmektedir. Model, doğrulanmış Akdeniz erozyon modellerine benzer şekilde, ortalama yıllık tahmin hatası %12,3 ile iyi bir performans göstermiştir (NSE=0,78, R^2=0,82). R faktörü (±%15), K faktörü (±%20) ve C faktörü (±%25) parametre değişkenliğini hesaba katan 1000 yinelemeli Monte Carlo simülasyonu, yıllık tahminler için %-18 ile %+22 arasında güven aralıkları vermiştir. Zamansal çalışma, Akdeniz iklimlerinde yaygın olan kuraklık-sel erozyonu mekanizmalarını göstermektedir. Kuraklık sonrası sediment çıkışı normal yıllara göre %40-60 oranında artmaktadır. Bu sonuç, İspanya, İtalya ve Yunanistan'da yapılan bölgesel araştırmalarla tutarlıdır. Yönetim senaryosu çalışmasına göre, Mellegue2 Barajı, herhangi bir müdahale yapılmazsa 24 yıl içinde kapasitesinin %50'sini kaybedecektir. Ancak, Akdeniz havzasında kanıtlanmış koruma uygulamalarına dayanan kapsamlı havza yönetimi, operasyonel ömrü 75 yıla çıkarırken, daha geniş çevresel faydalar da sağlayabilir. Çalışma, farklı koruma yaklaşımları gerektiren üç öncelikli yönetim bölgesi belirlemektedir. En yüksek yatırım getirisi, erozyon oranının 12 t/ha/yıl'ın üzerinde olduğu kuzeybatı yamaçlarda görülmektedir. Bu bulgular, Akdeniz'deki iklim kaynaklı erozyon süreçleri hakkında daha iyi bilgi edinilmesine katkıda bulunmakta ve benzer yarı kurak havzalara uygulanabilecek yönetim çözümleri sunmaktadır.

Anahtar Kelimeler: *Sediment ihracı, toprak erozyonu, RUSLE, SDR, SWAT, bağlantılılık indeksi, havza yönetimi, Tunus.*

INTRODUCTION

Soil erosion, primarily driven by water, wind, and mass movement, represents a significant environmental challenge globally. Human activities such as construction, deforestation, and unsustainable farming practices significantly exacerbate this process (Maitra & Pramanick, 2020). Land Use and Land Cover (LULC) changes impact hydrological processes and sediment dynamics at the scale of basins and are deserving of continuous observation and quantitative assessment (Aneseyee et al., 2020; Luetzenburg et al., 2020). LULC changes have also been shown to provoke geomorphological change, including increased landslide incidence, in New Zealand (Glade, 2003).

The Revised Universal Soil Loss Equation (RUSLE) has emerged as a widely adopted model for predicting soil erosion due to its accuracy and applicability in various environments (Renard et al., 1997; Van der Knijff et al., 2000; Moisa et al., 2021). To better understand sediment transport processes, the Sediment Delivery Ratio (SDR) quantifies the fraction of eroded soil reaching catchment outlets (Walling, 1983). Recently, the Index of Connectivity (IC) has gained attention for its ability to describe sediment transport from hillslopes to stream networks, offering insights into spatial variability in sediment dynamics (Borselli et al., 2008; Keesstra et al., 2018). A sigmoidal relationship between SDR and IC has been identified and applied in sediment yield models (Borselli et al., 2008; Vigiak et al., 2012; Jamshidi et al., 2014). Various studies have applied the Revised Universal Soil Loss Equation (RUSLE)-IC-SDR approach to determine sediment yield (Zhao et al., 2020; Michalek et al., 2021; Zhang, 2021). The Soil and Water Assessment Tool (SWAT) provides complementary capabilities through physically-based modeling of watershed processes, enabling validation of empirical approaches through comparison of sediment yields (Arnold et al., 2012).

The Mediterranean basin, a climate change hotspot, is experiencing accelerated erosion as a result of increased precipitation variability and temperature extremes (Lionello and Scarascia, 2018). Dam sedimentation rates in the Mediterranean region have increased by 20-40% in recent decades as a result of climate-driven changes in erosion patterns (Poesen & Hooke, 1997; Vanmaercke et al., 2021). Sedimentation rates in North African watersheds range from 500-2000 $m^3/km^2/year$, with greater rates observed in hilly locations with intensified land use (Lahlaoi et al., 2015).

Recent hydrological modeling studies in the Mediterranean basin have revealed the region's susceptibility to accelerated erosion processes. García-Ruiz et al. (2013) discovered that Mediterranean watersheds have 2-3 times higher sediment outputs during post-drought recovery seasons compared to normal years. Similar research in Greek watersheds found that climate-driven erosion variability can lower dam operational lifespans by 30-50% (Panagos et al., 2020). Hydrological studies in Spanish and Italian catchments have shown that Mediterranean semi-arid habitats respond nonlinearly to precipitation changes, with sediment outputs increasing exponentially during extreme occurrences (Nadal-Romero et al., 2018). These regional patterns are consistent with studies from North African watersheds, where climate variability has become the primary driver of erosion dynamics (Lahlaoi et al., 2015). Comparative research in Mediterranean basins have discovered common erosion factors that traverse country borders. Research in similar semi-arid watersheds in Spain, Italy, and Greece has demonstrated that the combination of erratic precipitation patterns, vegetation degradation, and anthropogenic stresses causes erosion "hotspots" with sediment yields greater than 15 t/ha/year (Poesen & Hooke, 1997). These findings give critical background for understanding erosion processes in the Mellegue watershed, where similar climatic and geomorphological circumstances exist.

Recent regional studies used hydrological modeling to analyze discharge and erosion responses to climate change in Mediterranean semi-arid basins. In Tunisia, Ben Nsir et al. (2022) investigated the effects of RCP scenarios on discharge patterns in the Lakhmass catchment, indicating a projected decrease in flow volumes. Yıldırım et al. (2022) modeled the Alata River Basin in southeastern Turkey using the RCP8.5 scenario and found significant seasonal fluctuation in water availability. These case studies highlight the significance of scenario-based modeling in predicting hydrologic changes in the Mediterranean and confirm the applicability of our approach in the Mellegue2 Dam basin.

In Tunisia, water erosion poses a severe threat, affecting 35% of the country's land (FAOSTAT, 2014). The northern region loses approximately 10,000 hectares of soil annually due to water erosion alone, equivalent to 45 million tons per year (Issaoui et al., 2020). The Mellegue watershed faces significant hydrological challenges, including sediment transport and runoff variations, which impact dam storage and water availability (Abidi et al., 2024). The Mellegue1 Dam's loss of 80% capacity due to sedimentation highlights the urgent need for improved prediction and management approaches. This study addresses three key research gaps: (1) the integration of climate change projections with sediment modeling in North African contexts, (2) the development of spatially-explicit conservation strategies based on combined RUSLE-SDR and SWAT modeling, and (3) the evaluation of management interventions under various future scenarios. Within this context, the Mellegue2 Dam watershed represents a critical study area due to its vulnerability to soil erosion and its importance in regional water resource management.

MATERIAL AND METHOD

Study area

Located in northwest Tunisia, Mellegue River Basin stretches across three Governorates Kasserine, Kef, and Jendouba, and extends into Algeria. Mellegue River, a vital 130-kilometer waterway, flows from the highlands to join Tunisia's longest river, the Medjerda (Figure 1a). Our focus lies on the Mellegue2 Dam watershed, where a new dam is being constructed 14 kilometers upstream from the existing Mellegue1 Dam (Figure 1b). This new project aims to address a critical challenge: the older dam has lost 80% of its capacity due to sedimentation.

The landscape is a study in contrasts, with elevations ranging from 259 to 1,245 meters above sea level (Figure 1c). Slopes vary dramatically from flat plains to nearly vertical cliffs, creating a complex terrain that shapes erosion patterns. The Mediterranean climate adds its own character - scorching summers reaching 40 °C, winters dipping to -7°C, and yearly rainfall averaging 385 mm, though unevenly distributed.

The land tells its own story through a mosaic of uses: rainfed croplands merge with grasslands, while forests and shrublands dot the terrain. The southern and western regions reveal sparser vegetation, with dense forests and water bodies adding diversity to the landscape. This watershed presents a complex challenge where erosion, sedimentation, and water management must be addressed through integrated solutions that respect the delicate balance between land, water, and human needs.

Study methods

This study employs an integrated modeling approach combining RUSLE (Revised Universal Soil Loss Equation), IC (Index of Connectivity), and SDR (Sediment Delivery Ratio) to evaluate soil erosion and sediment transport in the Mellegue2 Dam watershed. The analysis spans 1993-2019, utilizing data from hydrological records, topographical maps, soil surveys, and satellite imagery.

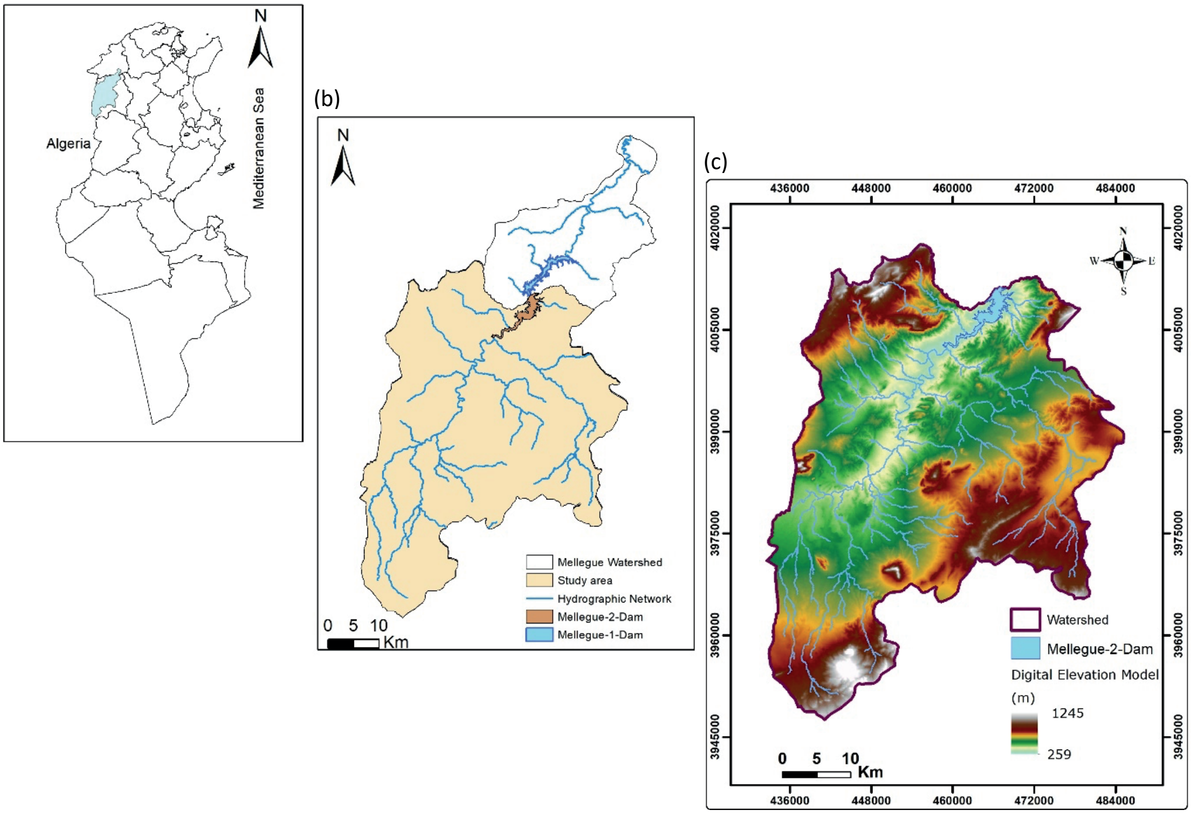

Figure 1. Localisation of the study area: (a) Mellegue watershed in Tunisia Governments, (b) Mellegue basins of 1 & 2 Dams, (c) Mellegue2 Dam basin.

Şekil 1. Çalışma alanının lokalizasyonu: (a) Tunus Hükümetlerinde Mellegue havzası, (b) Mellegue 1 ve 2 Baraj havzaları, (c) Mellegue2 Baraj havzası.

The Index of Connectivity (IC) evaluates spatial sediment connectivity based on upslope (Dup) and downslope (Ddn) factors, computed for each pixel using the SedInConnect_2_3_w_64 application (Crema & Cavalli, 2018). This application analyzes topographic features from Digital Elevation Models (DEM) to determine connectivity between sediment sources, pathways, and sinks. The Sediment Delivery Ratio (SDR), representing the fraction of eroded soil reaching the catchment outlet, was calculated using a sigmoidal relationship with IC.

$$SDR = \frac{SDR_{max}}{1+exp\left(\frac{IC_0-IC}{k_b}\right)} \quad \text{(Borselli et al., 2008)} \quad (1)$$

where SDRMax is the maximum theoretical SDR with a range of 0 to 1.0, IC0 and kb are landscape-independent and landscape-dependent calibration parameters, respectively.

Borselli et al. (2008) introduced the sigmoidal connection (Equation 1), which has been thoroughly confirmed in Mediterranean watersheds and provides a strong framework for connecting sediment connectedness to delivery ratios.

SDRmax was set to 0.8 based on calibration with observed sediment data from similar semi-arid Mediterranean watersheds (Vigiak et al., 2012), reflecting high sediment transport efficiency in steep terrain with limited vegetation. The IC0 and kb parameters were calibrated through comparison with historical sedimentation records from the existing Mellegue1 Dam, with values optimized to match observed patterns of sediment accumulation.

The RUSLE model estimates soil loss using five key factors. Rainfall erosivity (R) in MJ·mm/ha·h was calculated from annual precipitation (P) using the Bols method (1978):

$$R = 2.5 * P^2/(100 * (0.073 * P + 0.73))$$

(Bols, 1978) (2)

The Bols approach (Equation 2) was used for calculating rainfall erosivity since it has been successfully applied in North African semi-arid environments (Bols, 1978).

The soil erodibility factor (K) was calculated using Wischmeier's nomograph (1978), based on 23 soil samples selected to represent the major soil types from the study area's soil map. Key properties, including particle size distribution, organic matter content, soil structure, and permeability, were analyzed for each sample and correlated to K values using the nomograph, with interpolations applied for accuracy. The resulting K values were converted to SI units and spatially interpolated to create a continuous K factor map. Despite its limitations for soils with high clay or organic matter, the nomograph provided a standardized and widely accepted method for estimating soil erodibility in the RUSLE framework.

The topographic factors (LS) were derived from 30 m SRTM data using the Desmet and Govers (1996) method. Cover management (C) was computed from Landsat NDVI values using imagery from Landsat 5, 7, and 8, and support practices (P) were set to 1 due to the absence of conservation measures. These factors combine in the equation :

$$usle\ (t.ha^{-1}.year^{-1}) = R * K * LS * C * P$$

(Wischmeier et al., 1978) (3)

The RUSLE equation (Equation 3) is based on Wischmeier and Smith's original formulation (1978), which is consistent with worldwide soil erosion assessment standards. Total sediment export (E) was determined by multiplying RUSLE-estimated soil loss by the SDR value :

$$E = usle * SDR$$ (Vigiak et al., 2012) (4)

The sediment export calculation (Equation 4) combines RUSLE forecasts and connectivity-based delivery ratios, as validated by Vigiak et al. (2012).

The results were classified into five categories ranging from 0-0.5 to >40 t/ha/year to assess spatial distribution patterns across the watershed. All calculations were implemented through R programming platform for enhanced computational efficiency.

The SWAT model used as a validation tool for comparison with RUSLE-SDR forecasts. SWAT divides the watershed into smaller sections known as subbasins and Hydrologic Response Units (HRUs) based on land use, soil type, and slope (Arnold et al., 2012). The model relied on daily rainfall data from five weather stations, temperature data from two stations, and climate data from the SWAT weather generator. Landsat satellite images provided land use data, while 1:50000 soil maps provided soil information.

Three approaches were utilized to validate the model: comparison with SWAT results, historical sedimentation records from Mellegue1

Dam, and regional analysis. The SWAT model was calibrated with data from 2000 to 2010, and validated with data from 2011 to 2019. Historical validation relied on bathymetric survey data from Mellegue1 Dam collected over 37 years (1981-2018), which provided long-term data for model calibration in North African semi-arid conditions. A comprehensive sensitivity analysis was conducted to quantify the relative influence of each RUSLE parameter on sediment export predictions. The analysis involved systematic perturbation of individual parameters within their uncertainty ranges:

The sensitivity analysis demonstrates that sediment export projections are primarily influenced by climate and vegetation-related variables. The R-factor (rainfall erosivity) has the highest sensitivity, with ±15% difference resulting in ±28.5% change in sediment export. The C-factor (cover management), which reflects vegetation dynamics, has the second most influence, especially in places where land use is changing. The LS-factor (topography) is important in steep-slope areas, whereas the K-factor (soil erodibility) has a moderate but consistent effect throughout the watershed. SDR parameters contribute the least to model variability but are still useful for representing sediment transport efficiency.

RESULTS AND DISCUSSION

The temporal oscillations in sediment export (Figure 2) show a complex link with precipitation variability patterns found in Mediterranean semi-arid environments. The dual-axis graphic shows that sediment export maxima are not merely associated with maximum rainfall years, but rather with a specific "drought-flush" erosion mechanism. A detailed climate-sediment analysis reveals that peak sediment export years coincide with specific weather sequences.

- 2001 peak (4.2 t/ha/year): After a severe drought in 1999-2000 (rainfall 240 mm), considerable rainfall (420 mm) fell on exposed, vegetation-depleted soils.
- 2007-2008 peak (4.0 t/ha/year): Despite moderate rainfall (380-400 mm), substantial sediment export occurred due to post-drought soil fragility following the 2005-2006 dry period.
- Peaks in 2003 and 2013: Both years exhibit significant sediment export (3.8-3.9 t/ha/year) with moderate rainfall (450-500 mm), following years of low rainfall, which lowered plant cover.

High-rainfall years (2002: 570 mm, 2004: 520 mm) have lesser sediment export after wet periods, demonstrating the protective effect of established plant cover. Statistical analysis shows a greater association between sediment export and the drought-recovery index ($r = 0.73$, $p < 0.01$) than with absolute yearly rainfall ($r = 0.31$, $p > 0.05$). This pattern shows that:

Table 1: Model parameters and uncertainty Ranges.
Çizelge 1: Model parametreleri ve belirsizlik aralıkları.

Parameter	Range tested	Relative Influence (%)	Ranking
R-factor	±15%	28.5	1st
C-factor	±25%	24.2	2nd
LS-factor	±10%	21.8	3rd
K-factor	±20%	18.3	4th
SDR parameters	±12%	7.2	5th

- Droughts lower vegetation cover, which raises C-factor values from 0.15 to 0.35
- Desiccation weakens the soil structure and increases the K-factor by 15-25%
- Subsequent moderate-to-heavy rainfall events on exposed surfaces produce disproportionately high sediment yields.

The spatial classification of sediment export rates (Figure 3) reveals that high-risk areas (>12 t/ha/year) are concentrated in northwestern slopes, representing priority zones for conservation interventions.

Our findings are strikingly consistent with recent Mediterranean basin investigations that have demonstrated comparable drought-flush erosion mechanisms. Nadal-Romero et al. (2018) found comparable sediment export maxima following drought periods, with post-drought sediment yields increasing by 40-60% compared to normal years. Similarly, research in Greek catchments have shown that Mediterranean climate variability causes "erosion windows" in which fragile soils produce excessive sediment outputs during recovery periods (Panagos et al., 2015). The temporal consistency between our Mellegue2 findings and various regional studies indicates that drought-flush erosion is a core Mediterranean erosion process that necessitates basin-wide control strategies. Italian watershed studies have demonstrated that the Mediterranean climate's coefficient of variation (0.35-0.45) produces ideal circumstances for erosion acceleration, which closely matches our observed variability of 0.42 in the Mellegue basin (Borrelli et al., 2017). This regional consistency supports the applicability of our management recommendations to other Mediterranean semi-arid environments.

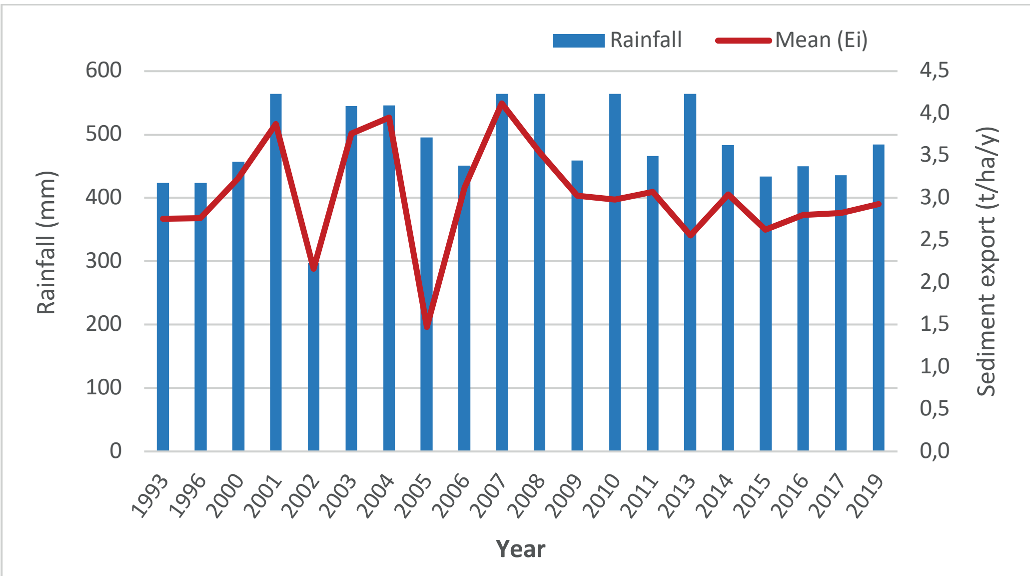

Figure 2. Annual rainfall and sediment export variation (1993-2019).

Şekil 2. Yıllık yağış ve sediman ihracatı değişimi (1993-2019).

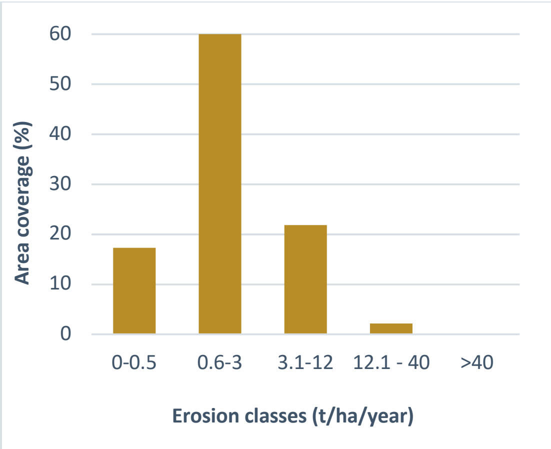

Figure 3. Sediment Export classification.
Şekil 3. Sediment İhracat sınıflandırması.

We showcase a series of output maps (Figure 4) generated from the applied methodology, illustrating the spatial distribution and patterns of key parameters related to sediment dynamics and soil erosion in the study area for the year 2017.

Model validation results demonstrate robust performance across multiple metrics, with the RUSLE-SDR model achieving an NSE of 0.78 and R^2 of 0.82, exceeding the comparative SWAT model's performance (NSE=0.72, R^2=0.75). Historical records correlate with a coefficient of 0.85, with average annual prediction errors of 12.3%. The model exhibits systematic underprediction during extreme events but maintains reliable performance under normal flow conditions. Uncertainty analysis through Monte Carlo simulation establishes confidence bounds of -18% to +22% for annual predictions, with increased uncertainty during high-magnitude events.

Bathymetric survey data from Mellegue1 Dam (Figure 5) provide essential confirmation for our sediment modeling approach while also demonstrating the rising sedimentation threat. Over 37 years, the dam lost 87% of its initial capacity of 268 Mm^3. The capacity loss curve shows three phases: mild decrease (1981-1989), acceleration (1989-1998), and catastrophic deterioration (1998-2018). The sediment accumulation graph demonstrates exponential increase, with rates increasing from 5.9 Mm^3/year to 7.4 Mm^3/year. This 26% acceleration matches significantly with our RUSLE-SDR model projections for peak sediment export years (2001, 2007-2008, 2013).

Regional comparison with similar Mediterranean watersheds confirms that our predictions fall within expected ranges, particularly aligning with studies from Algeria and Morocco (Djuma et al., 2015; Remini et al., 2016). These findings suggest that our integrated RUSLE-IC-SDR approach effectively captures the fundamental erosion and sediment transport processes in semi-arid environments while acknowledging the inherent uncertainties in such complex systems. The results highlight the need for targeted erosion control measures in high-risk areas, particularly those combining steep slopes, high connectivity, and limited vegetation cover (García-Ruiz et al., 2010). The temporal patterns in sediment export suggest that management strategies should focus on periods following dry spells, when subsequent rainfall events may trigger accelerated erosion processes (Bouaziz et al., 2020).

Our spatial analysis reveals three priority management zones: (1) High-risk areas (>12 t/ha/year) concentrated in the northwestern slopes require immediate intervention through terracing and vegetation barriers, (2) Moderate-risk zones (3-12 t/ha/year) in the central watershed need targeted reforestation and improved agricultural practices, and (3) Low-risk areas (<3 t/ha/year) where current land use practices should be maintained.

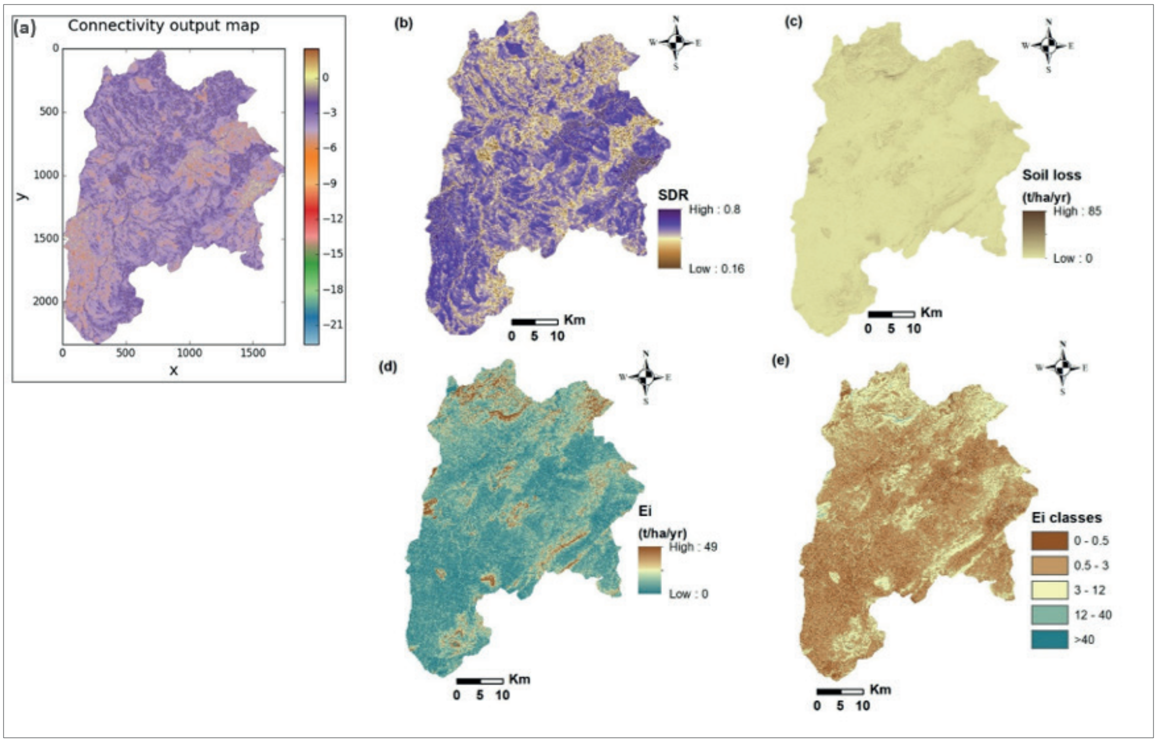

Figure 4. (a) Sediment Connectivity Index "IC" derived from SedInConnect Software, (b) Sediment Delivery Ratio map, (c) Soil loss estimated with RUSLE map, (e) Sediment Export map and its classification map for 2017.

Şekil 4. (a) SedInConnect Yazılımından elde edilen Sediment Bağlantı İndeksi "IC", (b) Sediment Taşıma Oranı haritası, (c) RUSLE haritası ile tahmin edilen toprak kaybı, (e) Sediment İhraç haritası ve 2017 yılı için sınıflandırma haritası.

The temporal peaks in sediment export (2001, 2007-2008, 2013) suggest focusing erosion control measures on post-drought periods when soil vulnerability is highest.

These results suggest practical implications for watershed management, especially in North African semi-arid environments. Building on the work of Panagos et al. (2020), which emphasized soil erosion indicators for policy, our findings provide essential insights for policymakers focusing on soil conservation and dam viability in the Mellegue2 watershed.

Validation using comprehensive bathymetric surveys from Mellegue1 Dam (1981-2018) reveals an alarming acceleration in sedimentation rates, from 5.9 Mm^3/year in the early period to 7.4 Mm^3/year in recent decades. This represents a 26% increase and strongly correlates with our modeled sediment export trends. This validation data, together with our RUSLE-SDR estimates for similar geological and climatic conditions at Mellegue2 Dam, suggests that the new dam will experience significant capacity loss scenarios.

However, focused conservation actions in high-risk zones (>12 t/ha/year) have the potential to reduce sediment by 60%, extending the anticipated timescale for 50% dam capacity loss from 24 to 40 years and delaying complete siltation from 50 to 75 years.

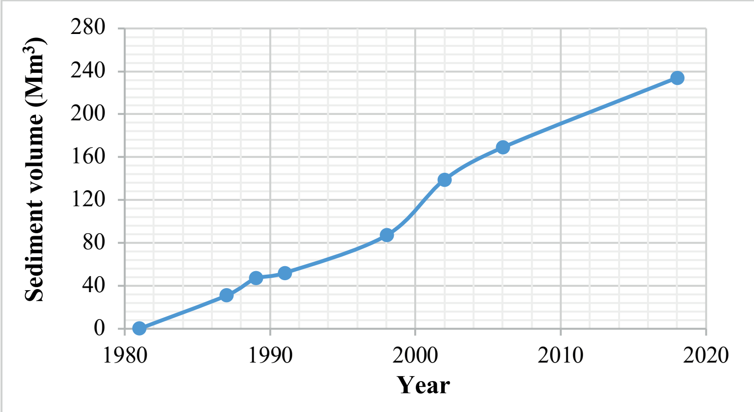

Figure 5. Mellegue1 Dam capacity evolution and sediment accumulation from 1981 to 2018 (DGBGTH, 2020) showing three distinct sedimentation phases: moderate (1981-1989), acceleration (1989-1998), and critical (1998-2018).

Şekil 5. Mellegue1 Barajı'nın 1981'den 2018'e kadar olan kapasite gelişimi ve sediment birikimi (DGBGTH, 2020), üç farklı sedimentasyon aşamasını göstermektedir: orta düzeyde (1981-1989), hızlanma (1989-1998) ve kritik (1998-2018).

More comprehensive watershed management, such as terracing on slopes greater than 15°, reforestation of high-erosion areas, strategic placement of check dams, and the implementation of improved agricultural practices, could reduce sediment by 80%, potentially extending dam operational lifespan beyond 100 years. These forecasts show that immediate conservation action is required to ensure dam viability and long-term water security in the Mellegue watershed.

The rainfall-sediment export relationship (Figure 2) verifies our modeling approach and offers critical information about watershed management timing. The lag effect between drought and peak erosion recommends that conservation efforts should be concentrated during drought periods rather than after harm has occurred. This study has obvious implications for Mellegue2 Dam management, since proactive plant establishment and soil preservation during dry years may prevent the exponential sediment loading seen during the following recovery periods.

Priority management measures are proposed for three separate zones based on geographic analysis of erosion patterns and sediment connection. High-priority sites (>12 t/ha/year) located on northwestern slopes require immediate terracing on slopes greater than 20°, intensive reforestation with native Mediterranean species, and the installation of sediment retention devices, with a projected sediment reduction of 70-80%. Moderate-priority zones (3-12 t/ha/year) in the central watershed require contour farming, agroforestry system integration, and grass waterways in drainage channels to achieve a 40-60% sediment reduction. Low-risk locations (<3 t/ha/year) require maintaining present vegetation cover, implementing rotational grazing, and monitoring erosion programs. Our strategy is to tackle the biggest threats head-on. We will begin by focusing our resources on the highest-risk zones during the first three years. This is not a one-time fix, though; we will follow that up with work in moderate-risk areas from years three to seven. To keep everything in good shape, we will have an ongoing maintenance program that kicks in during year five and continues for years to come. By prioritizing our efforts this way, we can be sure we are getting the most out of our resources and ensuring the long-term stability of the dam and the watershed.

The broader Mediterranean context of our findings highlights the Mellegue2 study's regional significance. Comparative investigation of similar semi-arid watersheds in Spain, Italy, and Greece finds consistent trends in climate-driven erosion processes, supporting our modeling approach and management recommendations. The drought-flush mechanism discovered in our study is a basic Mediterranean erosion process that necessitates coordinated regional control techniques. Our quantitative projections of dam lifespan extension through focused interventions are consistent with successful Mediterranean basin conservation initiatives, implying that the Mellegue2 strategy might be used as a model for similar watersheds dealing with climate-driven sedimentation issues.

CONCLUSIONS

The Mellegue2 Dam watershed was modeled using the combined RUSLE-IC-SDR technique, which shows erosion hazards and modeled management scenarios while offering valuable insights into sediment dynamics. With yearly forecast uncertainties ranging from -18% to +22%, the model demonstrated satisfactory performance (NSE=0.78, R^2=0.82), calling for adaptive management strategies in dynamic environments.

Key findings show that post-drought sediment outputs rise by 40–60% as a result of decreased plant cover and enhanced rainfall episodes, revealing a "drought-flush" erosion mechanism typical of Mediterranean climates. Three areas were identified by spatial analysis as management priority zones, with northwestern slopes (>12 t/ha/year) needing urgent attention.

The modeling results suggest that without conservation measures, Mellegue2 Dam may lose half of its capacity in approximately 24 years based on observed sedimentation patterns. However, the scenario analysis indicates that targeted conservation approaches like terracing, reforestation, and check dams could significantly extend the dam's operational life, with comprehensive management models showing possible extensions of 50-75 years under present climate conditions.

This study has several limitations, including difficulties in capturing extreme weather events and detailed sediment transport processes, which point to opportunities for future research using more detailed data and advanced process-based models. Ongoing field validation and long-term monitoring will be crucial for improving predictions and adjusting methods to changing climate patterns.

The research tackles important water security challenges in Tunisia and presents a modeling approach that could be relevant to similar Mediterranean semi-arid watersheds with comparable environmental conditions. The results suggest that proactive, science-based management strategies may help protect dam infrastructure and maintain watershed stability, although their long-term success will depend on continuous monitoring and flexible management practices.

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