Integrating RUSLE, GIS, and Remote Sensing for Soil Erosion Assessment in Morocco's Raouz Watershed

Lhoussaine Ed-daoudy[1*], *Abdessalam* Ben Harra[1], *Yousra* Rghif [1], *Ayoub* El Bakkali[2], and *Brahim* Damnati [1]

[1]EMRN, FSTT, Abdelmalek Essaadi University. Tangier, Morocco
[2]Applied Geosciences Research & Development Laboratory, Abdelmalek Essaadi University, Tétouan

Abstract. Soil erosion threatens sustainable development in Morocco's Rif Mountains, causing severe land degradation and reservoir sedimentation. This study quantifies erosion rates in the Raouz watershed (46.89 km²) using the Revised Universal Soil Loss Equation (RUSLE) integrated with GIS and remote sensing. We analyzed five erosion factors: rainfall erosivity (R), soil erodibility (K), topography (LS), cover management (C), and conservation practices (P). Results reveal a mean annual soil loss of 16.53 t ha^{-1} yr^{-1}, with severe erosion (>20 t ha^{-1} yr^{-1}) affecting 26.4% of the watershed. Critical hotspots (7.3% of area) contribute 35-40% of total sediment yield. Validation against Caesium-137 measurements shows strong agreement (R^2=0.76). Topography (52% variance) and vegetation cover (31% variance) emerge as dominant erosion controls. The Moulay El Hassan Ben Mehdi Dam faces annual sedimentation of 23-31 t yr^{-1}, threatening water security for 500,000 inhabitants. Findings support targeted conservation strategies prioritizing steep, sparsely vegetated upper watershed areas. **Keywords**: Soil erosion; RUSLE; GIS; Remote sensing; Watershed management; Morocco

1 Introduction

Soil erosion by water constitutes a critical environmental challenge in Mediterranean watersheds, causing land degradation, reservoir sedimentation, and substantial economic losses [1, 2]. In Morocco, erosion affects approximately 20 million hectares, with specific rates reaching 2,000-4,000 t km^{-2} yr^{-1} and annual reservoir capacity losses of 0.5% [3, 4, 5]. The Rif region, despite occupying only 6% of national territory, accounts for 60% of Morocco's soil losses due to steep slopes, erodible soils, and intensive land use [6, 7].

The Raouz watershed feeds the Moulay El Hassan Ben Mehdi (MHBM) Dam (capacity: 30 million m^3), which provides drinking water to Tetouan city and supports agricultural irrigation. Accelerated sedimentation threatens this critical infrastructure and regional water security. While previous studies employed Caesium-137 (^{137}Cs) techniques for point-specific erosion assessment [8, 9, 10], comprehensive spatial analysis remains limited.

This study addresses this gap by integrating the RUSLE model with GIS and remote sensing to: (1) quantify spatially-distributed erosion rates; (2) identify critical erosion hotspots; (3) validate predictions against ^{137}Cs measurements; and (4) inform targeted conservation strategies. The RUSLE-GIS approach enables watershed-scale assessment while maintaining computational efficiency and leveraging freely available data [11, 12].

2 Study Area

The Raouz watershed (46.89 km²; 35°33′ N, 5°23′ W) is located in the northwestern Rif Mountains, approximately 15 km from Tetouan (Figure 1). The area experiences a semi-arid Mediterranean climate with mean annual precipitation of 600-800 mm, concentrated in October-April. The hydrological network exhibits typical Mediterranean intermittent flow, with pronounced seasonal variability and rapid response to rainfall events.

Elevation ranges from 50 to 600 m a.s.l., creating moderate to steep topography. Geologically, the watershed lies within the External Rif domain, characterized by complex nappe structures with sandstone ridges and marly formations. Soils include Regosols, Cambisols, and Leptosols, with variable depth and moderate to high erodibility. Land use comprises cultivated areas (cereals, legumes), olive groves, Mediterranean shrublands, and degraded forests, with recent agricultural intensification contributing to accelerated erosion.

* Lhoussaine Ed-daoudy: leddaoudy@uae.ac.ma

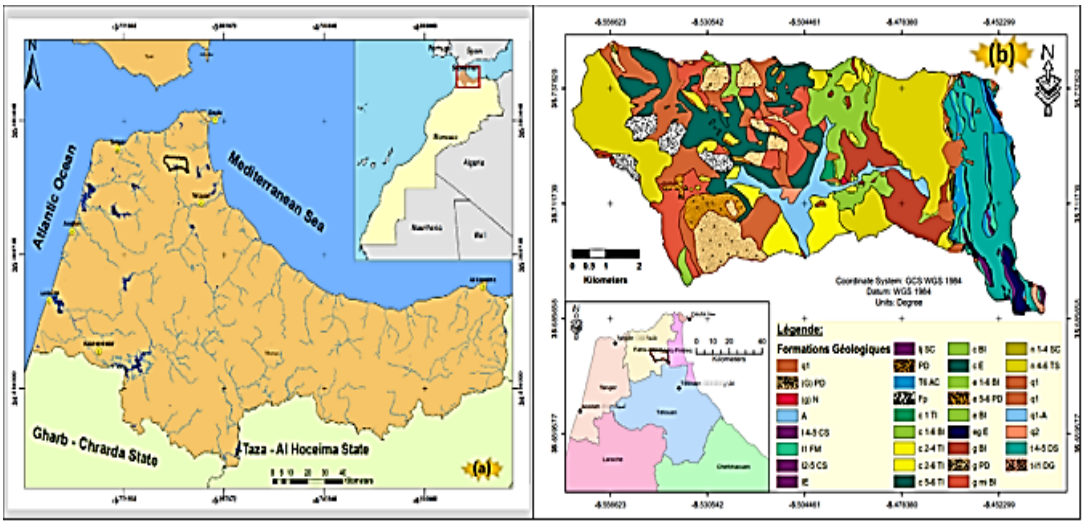

Fig. 1. Location map of the Raouz watershed showing (**a**) the regional setting and drainage network in Morocco, and (**b**) the geological map of the study area.

3 Materials and Methods

3.1 RUSLE Model Framework

The RUSLE model estimates mean annual soil loss as (Figure 2) [13]:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where **A** = soil loss (t ha^{-1} yr^{-1}); **R** = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}); **K** = soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}); **LS** = topographic factor; **C** = cover-management factor; **P** = support practice factor.

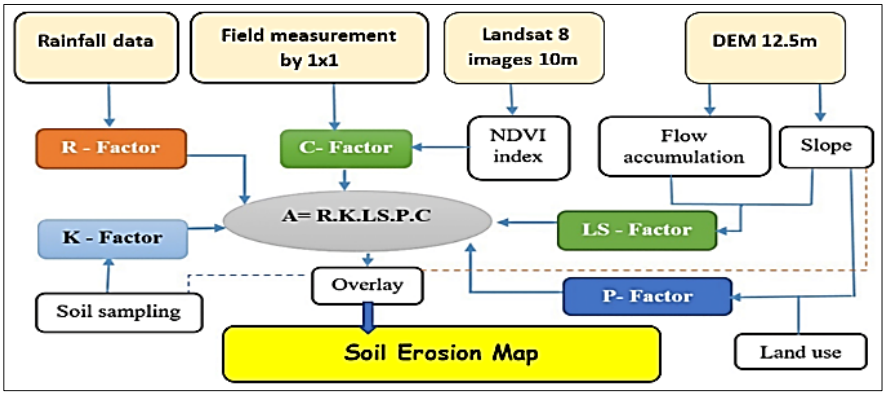

Fig. 2. Methodology flowchart

3.2 Data Sources and Processing

- **Remote Sensing:** Landsat 8 OLI/TIRS imagery (30-m resolution, January 31, 2021) from USGS Earth Explorer, atmospherically corrected (Level-2 Surface Reflectance).
- **Topography:** ASTER GDEM V3 (30-m resolution; vertical accuracy ±8.5 m), preprocessed to fill depressions.
- **Climate:** Monthly/daily precipitation data (2000-2020) from four meteorological stations (Loukkous Hydraulic Basin Agency).
- **Soil:** Field sampling (45 georeferenced sites, 2019-2021) for texture, organic matter, structure, and permeability analysis.

3.3 RUSLE Factor Computation

- **R-factor:** Calculated using the modified Fournier index [14]:

$$\log Re = 1.74 \log \sum_{i=0}^{n} \left(\frac{Pi^2}{P}\right) + 1.29 \quad (2)$$

where $\mathbf{P_i}$ = monthly precipitation, **P** = annual precipitation. Spatial interpolation via Ordinary Kriging (exponential semivariogram).

- **K-factor:** Determined from soil analysis using [15]:

$$K = \left[2{,}1M^{1{,}14.10^{-4}(12-OM)} + 3{,}25(S-2) + 2{,}5(P-3)\right] \div 100 \quad (3)$$

where **M** = particle size parameter, **OM** = organic matter (%), **S** = structure code, **P** = permeability class.

- **LS-factor:** Computed from DEM using flow accumulation algorithm [16]:

$$LS = \left[\left(FlowAccumulation \times {}^{12.5}/_{22.1}\right)^{N} \times (0.065 + (0.045 \times slope) + (0.0065 \times slope) \times slope)\right] \quad (4)$$

where **m** = slope length exponent (0.2-0.5 based on slope gradient).

- **C-factor:** Derived from NDVI using supervised classification (overall accuracy 87%, Kappa 0.83):

$$C = \exp[-\alpha \times NDVI / (\beta - NDVI)] \quad (5)$$

where **α**=2, **β**=1 for Mediterranean conditions [17].

- **P-factor:** Assigned value of 1.0 (no conservation practices) based on field surveys.

All spatial processing implemented in ArcGIS 10.8 at 30-m resolution.

3.4 Model Validation

RUSLE predictions compared with independent ^{137}Cs erosion measurements from previous studies at nine sites [8], [18]. Statistical metrics (R^2, mean absolute error, relative error) calculated to assess model performance.

4 Results and Discussion

4.1 RUSLE Factor Spatial Distribution

- **R-factor** ranges from 485 to 687 MJ mm ha^{-1} h^{-1} yr^{-1} (mean = 573), showing relatively uniform spatial distribution (CV = 12%). Higher values occur in western areas influenced by Atlantic Ocean proximity (Figure 3a).
- **K-factor** exhibits substantial heterogeneity (0.015-0.042 t ha h ha^{-1} MJ^{-1} mm^{-1}; mean = 0.028; CV = 35%), with highest erodibility in fine-textured marly soils and lowest in coarse sandstone-derived soils (Figure 3b).
- **LS-factor** shows pronounced variability (<0.5 to >20; mean = 4.8; CV = 185%), with 35% of watershed exhibiting LS>5. Highest values occur in steep, dissected upper catchment reaches (Figure 3c).
- **C-factor** ranges from 0.02 (dense vegetation) to 0.85 (bare soil/sparse vegetation), with mean = 0.38 (CV = 78%). Approximately 28% of watershed shows C>0.5, indicating inadequate vegetation protection, particularly in upper agricultural and degraded rangeland areas (Figure 3d).

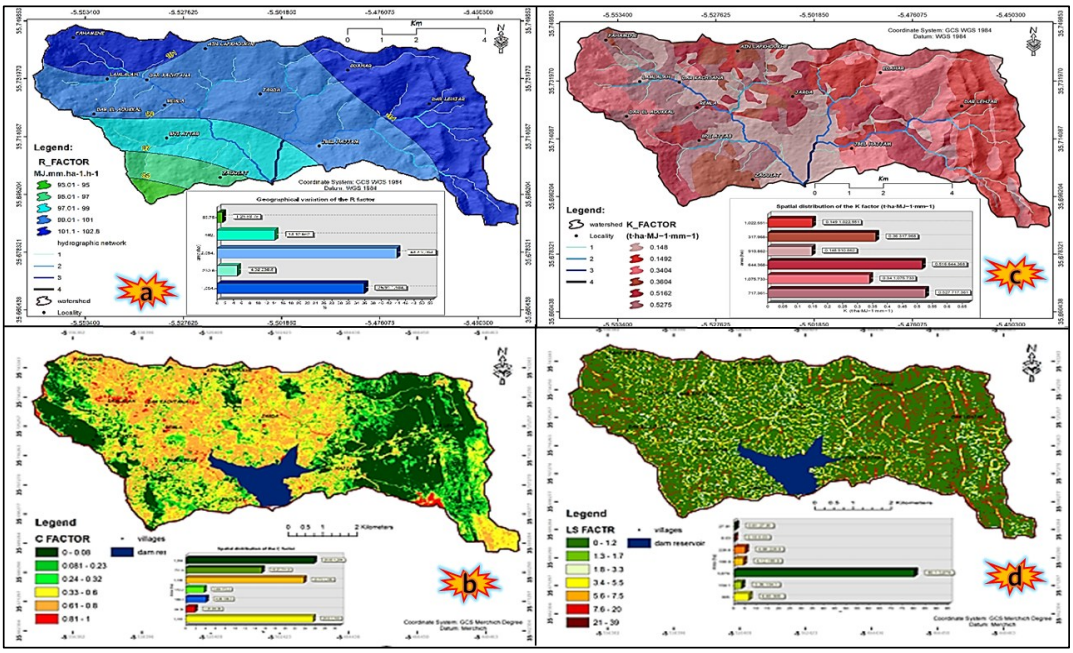

Fig. 3. Spatial distribution of RUSLE factors: (**a**) rainfall erosivity (R), (**b**) cover-management factor (C), (**c**) soil erodibility (K), and (**d**) topographic factor (LS).

4.2 . Soil Erosion Patterns and Hotspots

Mean annual soil loss is 16.53 t ha^{-1} yr^{-1}, substantially exceeding tolerable thresholds (5-10 t ha^{-1} yr^{-1}) and indicating severe degradation risk. Spatial analysis reveals pronounced heterogeneity (CV = 142%), with erosion classified into five severity classes (Table 1; Figure 4).

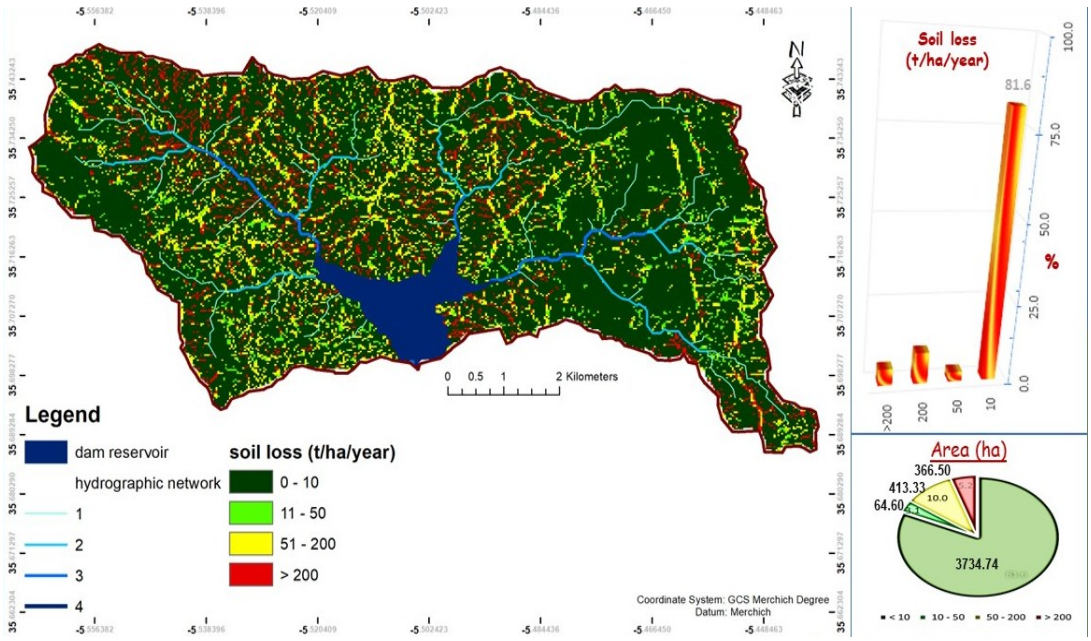

Fig. 4. Spatial distribution of annual soil loss showing erosion severity classes and priority conservation zones.

Table 1. Soil erosion severity classification and spatial distribution.

Class	Rate (t ha⁻¹ yr⁻¹)	Area (km²)	Area (%)	Description
Very Low	0-5	12.45	26.5	Tolerable
Low	5-10	10.82	23.1	Slight
Moderate	10-20	11.27	24.0	Moderate
High	20-40	8.94	19.1	Severe
Very High	>40	3.41	7.3	Very severe

Critical erosion hotspots (>40 t ha^{-1} yr^{-1}) occupy only 7.3% of watershed area but contribute an estimated 35-40% of total sediment yield. These zones coincide with steep slopes (>15°), highly erodible soils (K>0.035), and sparse vegetation (C>0.6). Severe to very severe erosion (>20 t ha^{-1} yr^{-1}) affects 26.4% of the watershed, concentrated in upper reaches.

4.3 Model Validation and Performance

Comparison with ^{137}Cs measurements reveals strong agreement (R^2=0.76, p<0.01; mean absolute error = 4.2 t ha^{-1} yr^{-1}; relative error = 18%). RUSLE slightly underpredicts at high-erosion sites (>30 t ha^{-1} yr^{-1}) and overpredicts at low-erosion sites (<10 t ha^{-1} yr^{-1}), likely reflecting model calibration for moderate conditions and exclusion of gully erosion processes. Despite minor systematic bias, validation confirms RUSLE reliability for watershed-scale assessment in semi-arid Mediterranean environments.

4.4 Erosion Controlling Factors

Statistical analysis reveals differential factor contributions: LS-factor explains 52% of erosion spatial variance (CV=185%), confirming topography as the dominant control. C-factor accounts for 31% of variance (CV=78%), with areas exhibiting NDVI<0.3 showing 3.5× higher erosion than NDVI>0.5 areas. K-factor contributes 12% of variance, while R-factor's limited spatial variability (CV=12%) minimizes contribution to spatial patterns (5% variance). Strong negative correlation between NDVI and erosion (r=-0.68, p<0.001) quantitatively demonstrates vegetation's protective role.

4.5 Sediment Yield and Reservoir Impact

Total annual soil loss is estimated at 77,5 t yr^{-1} (1,653 t km^{-2}). Applying sediment delivery ratio of 0.3-0.4 [19], sediment yield reaching MHBM reservoir ranges from 23,25 to 31 t yr^{-1}, corresponding to annual capacity loss of 18-24 m³ (0.06-0.08%). While seemingly modest annually, cumulative sedimentation over 50-75 years could reduce capacity by 3-6%, threatening water security for Tetouan's 500,000 inhabitants.

4.6 Management Implications

Results support a three-tiered conservation strategy:

- **Tier 1 (Critical zones, >40 t ha□ yr□, 7.3% area):** Priority structural interventions including bench terracing, check dams, and stone bunds on steep slopes, combined with reforestation and controlled grazing.
- **Tier 2 (High erosion, 20-40 t ha□ yr□, 19.1% area):** Moderate conservation measures emphasizing contour farming, conservation tillage, cover crops, and agroforestry systems.
- **Tier 3 (Moderate erosion, 10-20 t ha□ yr□, 24.0% area):** Preventive measures focusing on improved agricultural practices, crop rotation, and vegetation maintenance.

4.7 Regional Context and Limitations

The estimated erosion rate (16.53 t ha^{-1} yr^{-1}) aligns with regional studies reporting 12-35 t ha^{-1} yr^{-1} for Rif watersheds [6, 8, 20], confirming moderate to high erosion severity. However, limitations include: (1) RUSLE excludes gully erosion and mass movements, potentially underestimating total erosion by 10-20%; (2) temporal variability not captured in long-term averages; (3) P-factor assumption may overestimate erosion where informal conservation exists; (4) DEM accuracy (±8.5m) and soil sampling density introduce ±15-25% uncertainty. Climate change projections suggest 15-30% increases in rainfall erosivity and reduced vegetation cover could elevate erosion rates by 40% by mid-century, emphasizing urgent need for adaptive management strategies [21].

5 Conclusion

This study successfully applied an integrated RUSLE-GIS-remote sensing approach to quantify and spatially characterize soil erosion in Morocco's Raouz watershed. Mean annual soil loss (16.53 t ha^{-1} yr^{-1}) substantially exceeds tolerable thresholds, with severe erosion affecting 26.4% of watershed area. Critical hotspots representing 7.3% of area contribute 35-40% of sediment yield, providing clear targets for conservation prioritization. Strong validation against ^{137}Cs measurements (R^2=0.76) confirms model reliability, while factor analysis reveals topography (52% variance) and vegetation cover (31% variance) as dominant erosion controls.

Results provide actionable intelligence for implementing cost-effective, spatially-targeted conservation strategies in steep, sparsely vegetated upper watershed reaches. The three-tiered management framework balances immediate intervention in critical zones with preventive measures in moderate-erosion areas. Annual reservoir sedimentation (23-31 t) threatens long-term water security, emphasizing urgent need for watershed management implementation.

The methodology demonstrates effective integration of freely available remote sensing data with empirical modeling for erosion assessment in data-limited watersheds, offering replicable framework for similar Mediterranean mountain environments. Future research should incorporate climate change scenarios, sediment connectivity modeling, and economic assessment of conservation practice effectiveness to support adaptive watershed management under changing environmental conditions.

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References

1 L. A. Mounirou et al., "Hydrologic similarity: Dimensionless runoff indices across scales in a semi-arid catchment," J Arid Environ, vol. 193, p. 104590, 2021, doi: 10.1016/j.jaridenv.2021.104590.

2 J. M. García-Ruiz, S. Beguería, E. Nadal-Romero, J. C. González-Hidalgo, N. Lana-Renault, and Y. Sanjuán, "A meta-analysis of soil erosion rates across the world," Geomorphology, vol. 239, pp. 160–173, Jun. 2015, doi: 10.1016/J.GEOMORPH.2015.03.008.

3 M. A. Ezzaouini, G. Mahé, I. Kacimi, and A. Zerouali, "Comparison of the MUSLE Model and Two Years of Solid Transport Measurement, in the Bouregreg Basin, and Impact on the Sedimentation in the Sidi Mohamed Ben Abdellah Reservoir, Morocco," Water (Basel), vol. 12, no. 7, p. 1882, 2020.

4 A. Hachemaoui, A. Elouissi, B. Benzater, and S. Fellah, "Assessment of the hydrological impact of land use/cover changes in a semi-arid basin using the SWAT model (case of the Oued Saïda basin in western Algeria)," Model Earth Syst Environ, vol. 8, no. 4, pp. 5611–5624, Nov. 2022, doi: 10.1007/S40808-022-01422-6/METRICS.

5 K. K. Kusi, A. Khattabi, and N. Mhammdi, "Evaluating the impacts of land use and climate changes on water ecosystem services in the Souss watershed, Morocco," Arabian Journal of Geosciences, vol. 16, no. 2, p. 126, 2023, doi: 10.1007/s12517-023-11206-6.

6 N. Aouichaty, Y. Bouslihim, S. Hilali, A. Zouhri, and Y. Koulali, "Estimation of water erosion in abandoned quarries sites using the combination of RUSLE model and geostatistical method," Sci Afr, vol. 16, p. e01153, 2022, doi: 10.1016/j.sciaf.2022.e01153.

7 M. Manaouch, M. Sadiki, and I. Fenjiro, "Integrating GIS-based FAHP and WaTEM/SEDEM for identifying potential RWH areas in semi-arid areas," https://doi.org/10.1080/10106049.2021.2007295, vol. 37, no. 25, pp. 8882–8905, 2021, doi: 10.1080/10106049.2021.2007295.

8 L. Ed-Daoudy, M. Moustakim, … M. B.-E., and undefined 2024, "A GIS-based modified PAP/RAC model and Caesium-137 approach for water erosion assessment in the Raouz catchment, Morocco," Elsevier, 2024, Accessed: Jul. 04, 2024.

9 L. Mabit, S. Chhem-Kieth, P. Dornhofer, and A. Toloza, "{sup 137} Cs: A Widely Used and Validated Medium Term Soil Tracer," 2014, Accessed: Jun. 17, 2023.

10 M. Benmansour et al., "Assessment of soil erosion and deposition rates in a Moroccan agricultural field using fallout 137Cs and 210Pbex," J Environ Radioact, vol. 115, pp. 97–106, 2013, doi: 10.1016/j.jenvrad.2012.07.013.

11 V. Prasannakumar, H. Vijith, S. Abinod, and N. Geetha, "Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo-information technology," Geoscience frontiers, vol. 3, no. 2, pp. 209–215, 2012.

12 B. P. Ganasri and H. Ramesh, "Assessment of soil erosion by RUSLE model using remote sensing and GIS - A case study of Nethravathi Basin," Geoscience Frontiers, vol. 7, no. 6, pp. 953–961, Nov. 2016, doi: 10.1016/J.GSF.2015.10.007.

13 K. G. Renard, Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). US Department of Agriculture, Agricultural Research Service, 1997.

14 W. H. Wischmeier and D. D. Smith, Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Department of Agriculture, Science and Education Administration, 1978.

15 J. M. Van der Knijff, R. J. A. Jones, and L. Montanarella, "Estimation du risque d'érosion en Italie," Eur. Soil Bur, 2000.

16 H. Mitasova, J. Hofierka, M. Zlocha, and L. R. Iverson, "Modelling topographic potential for erosion and deposition using GIS," International journal of geographical information systems, vol. 10, no. 5, pp. 629–641, 1996.

17 L. Ed-daoudy, N. Lahmam, M. Benmansour, H. Afilal, A. Ben harra, and B. Damnati, "Hydric erosion rates in Raouz watershed, Morocco: RUSLE, GIS, and remote sensing," Remote Sens Appl, vol. 32, 2023, doi: 10.1016/j.rsase.2023.101056.

18 B. Damnati, S. Ibrahimi, O. Benhardouze, H. Benhardouze, H. Reddad, and O. Radakovitch, "Notes et Mémoires du service Géologique du Maroc," N°, vol. 575, pp. 74–80, 2012.

19 D. Walling and T. Quine, "Use of caesium-137 as a tracer of erosion and sedimentation: Handbook for the application of the caesium-137 technique. UK Overseas Development Administration," 1993, Accessed: Sep. 01, 2024

20 S. Keesstra, S. Visser, and M. De Cleen, "Achieving land degradation neutrality: A robust soil system forms the basis for nature-based solutions," Land (Basel), vol. 10, no. 12, Dec. 2021, doi: 10.3390/LAND10121300.

21 F. Giorgi and P. Lionello, "Climate change projections for the Mediterranean region," Glob Planet Change, vol. 63, no. 2–3, pp. 90–104, Sep. 2008, doi: 10.1016/J.GLOPLACHA.2007.09.005.