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ORIGINAL ARTICLE

Soil erosion assessment using the RUSLE model for better planning: a case study from Morocco

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Abstract
Wise decisions depend on accurate and up-to-date scientific guidance. The ability to react, the accuracy, and the effectiveness of the measures adopted depend on it, particularly in the face of insurmountable structural risks. Among them, soil erosion is a persistent problem that generates so much damage and all indications are that it will continue to do so almost everywhere, including in Morocco. There, the three identified knowledge gaps have been addressed in this article: (i) spatially assess magnitude across regions, (ii) identify key drivers, and (iii) periodically update plans to maintain land productivity and infrastructure. Through the RUSLE model, it was found in the mountainous watershed of Nekor (in the North) an average rate of 37.8 t/ha/year of soil losses, which equates to a massive gross amount of 3.8 kg/m^2/year. The highest erosion rates are observed upstream in the hills and high mountains. The rugged topography and aggressive precipitation are the two main factors that accentuate erosion processes. It is anticipated that updating the plans is thwarted by several constraints that need to be addressed through sound planning that benefits from research and co-creation for better mitigation, preparedness, and response.

Keywords Watershed · Soil erosion · Modeling · RUSLE · Planning

Introduction

Policymakers need to better understand the state of soil erosion because of the constraints it places on the achievement of several Sustainable Development Goals, including ending hunger (SDG 2), ensuring clean water and sanitation (SDG 6), eradicating poverty (SDG1), achieving sustainable cities and communities (SDG 11), and sustaining life on land (SDG 15) (Quine and Van Oost 2020). This is all the more important in the persistence of major challenges to maintaining the role of soil in food, water and human security, in the face of its degradation that continues to exceed record rates (Amundson et al. 2015). Therefore, there is an urgent need to map the state of soil erosion to guide mitigation strategies and management/conservation practices, especially in view of future scenarios (climate change and accelerated urbanization) (Alewell et al. 2019).

As in many Mediterranean countries, it is a challenge in Morocco to mitigate the impacts of soil degradation by improving management and planning decisions (Salhi et al. 2020c). However, the challenge is becoming more and more complicated due to many structural constraints such as irregular rainfall and long and repetitive droughts, water shortage, abandonment of cultivable land and deforestation, degradation of conservation infrastructure, and pollution (Benabdelouahab et al. 2020; Hadria et al. 2019, 2021; Lebrini et al. 2021; Salhi and Chikhi 2018). Despite intensified prevention and control measures, and vulgarization campaigns, significant public efforts have failed to slow the effects of soil degradation (Badraoui 2006). Therefore, three knowledge gaps were identified to capitalize on these efforts and meet the challenge: there is a need to assess the magnitude spatially and periodically in all regions of the country, identify key

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drivers, and update future development plans with accurate information to maintain land productivity and infrastructure (Benabdelouahab et al. 2021; Panagos and Katsoyiannis 2019; Salhi et al. 2023).

Here, these gaps were addressed by assessing soil loss from one of the major watersheds in the north of the country. The objective is to assess the soil loss, spatialize the risk zones, and identify the influential parameters for a better orientation of the decision-making.

Materials and methods

Study area

The study area (Fig. 1) is a 916 km^2 coastal watershed in northern Morocco that shares its name with the Nekor River, which crosses it from southwest to northeast for 112 km. It is a high-folded mountainous watershed of the eastern Rif, dominated by argillaceous limestone, marly schists, and marls. The importance of the friable component of these formations, combined with the steep slopes and the retreat of the forest favor the erosive processes which generate a high sedimentary yield, responsible for the siltation downstream of the Al Khattabi dam (10 km from the coast line) (Arrebei et al. 2019; Chalouan et al. 2008; Niazi et al. 2005; Salhi 2008).

The climate is Mediterranean with dry and long summers resulting in several arid months with great water stress which affects the soil and vegetation. Winters and autumns are moderately rainy, although precipitation can exceptionally reach a high intensity, with abundant runoff (Salhi et al. 2019). The annual variability of precipitation is also high, with a great contrast between dry and rainy years (Salhi et al. 2022b). It is also observed an increase in the average temperature and increasingly long droughts over the last decades correlated with global warming (Salhi et al. 2022c). Continental influence and the Foehn effect are most clearly

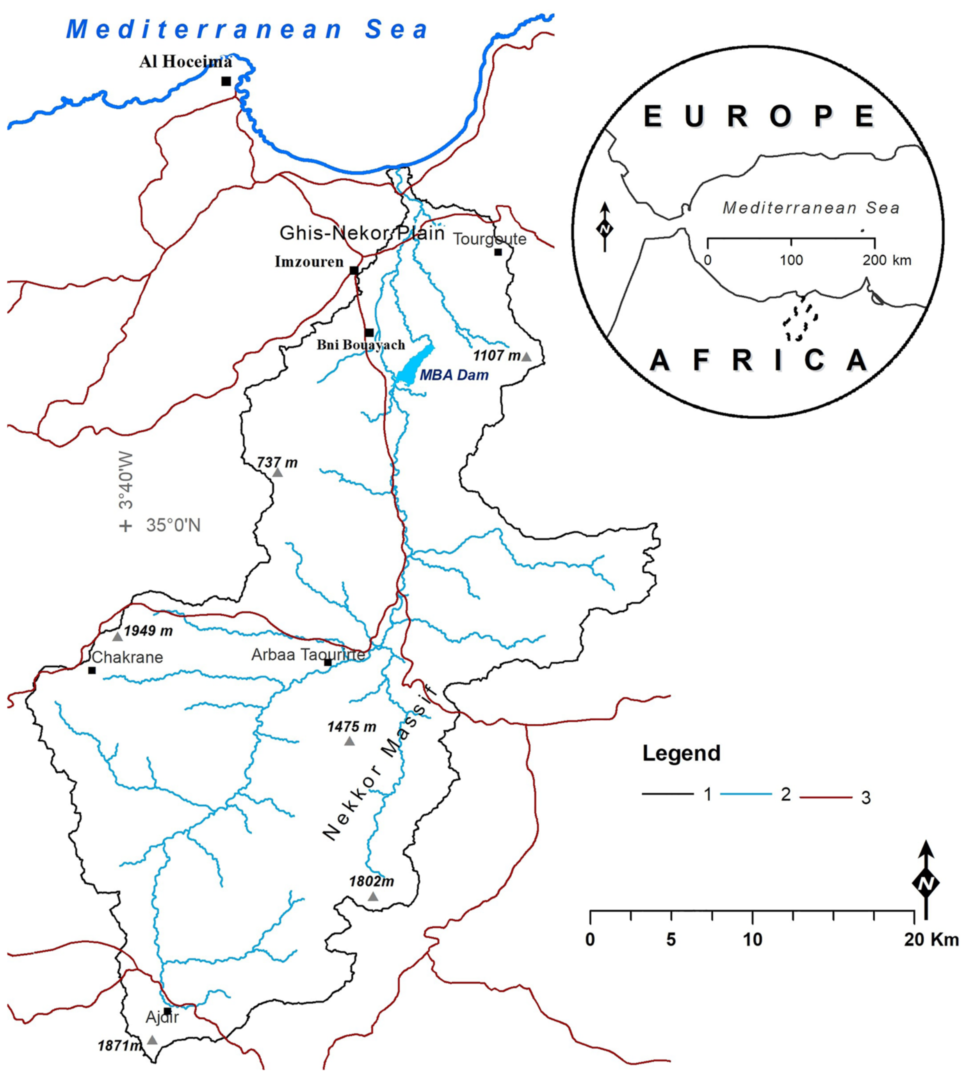

Fig. 1 Geographic location of the study area. 1: Drainage divide of the Nekor watershed. 2: Hydrographic network. 3: Road network

observed upstream of the watershed where the drought trend is most acute (Okacha 2020).

Due to increased migration (rural–urban and to Europe), the population fell from 73 to 61 thousand between 1994 and 2014, respectively (HCP 2014). The reasons for migration are related to the natural structural constraints that disadvantage large rural mountains lacking infrastructure compared to narrow coastal fringes (clearly favored) with urban and peri-urban characteristics (Salhi et al. 2020b, 2023). This causes a growing imbalance in population density between upstream (depopulation and rural exodus) and downstream (growth of urban centers) which is transmitted to a disproportion in the distribution of resources and needs (Salhi et al. 2022c, 2023).

RUSLE model

RUSLE combines the physical and anthropogenic elements that affect soil erosion caused by raindrops and surface runoff (Renard 1997). It is a widely used model for estimating average annual soil loss (A in t/ha/y) (Aswathi et al. 2022). The latter is the product of the five key factors of soil erosion according to Eq. 1 (Renard 1997). These are rainfall erosivity (R), slope steepness (S) and length (L), cover management (C), soil erodibility (K), and support practice (P).

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

Rainfall erosivity (mm/ha/h/year) is an estimate of soil detachment at a location by splash erosion of raindrops. Several papers have shown effective and approved R-factor estimation equations, especially in data-scarce areas (Dutta 2016). In our case, it was assessed according to Eq. 2 on the basis of monthly (P_i) and annual precipitation (P) (Rango and Arnoldus 1987), which are spatially and temporally abundant data. Both parameters were extracted from historical precipitation data (1975–2015) from nine local precipitation stations.

$$R = e^{1.74 \cdot \log \sum_{j=12}^{i=1} \left(\frac{P_i^2}{P} \right) + 1.24}. \tag{2}$$

The effect of topography (LS-factor) has a major role in the process of soil erosion. It combines the effects of slope steepness and length based on inclination (θ) and extent (λ) according to Eq. 3 (Wischmeier and Smith 1978). Both parameters were extracted from Aster GDEM Version 2 digital terrain model.

$$\mathrm{LS} = \left((\frac{\lambda}{22.3} \right)^m \cdot \left(0.0065 \cdot \theta^2 + 0.045 \cdot \theta + 0.0065 \right). \tag{3}$$

The cover management (C) factor is the subsequent significant factor. It was assessed on a pixel-based scale according to Eq. 4 (Van der Knijff et al. 2000). Normalized Difference Vegetation Index (NDVI) values were extracted from Landsat 8 imagery retaining the average pixel value of 2020 scenes for each path/row with less than 20% of cloud cover. The C-factor varies between 0 and 1 with higher values for covers likely to increase soil loss.

$$C = e^{\left[-2 \cdot \frac{\mathrm{NDVI}}{1 - \mathrm{NDVI}} \right]}. \tag{4}$$

Soil erodibility (K-factor) is its inherent vulnerability to erosion due to runoff and the impact of raindrops (Bekele and Gemi 2021). Key parameters are percentage of silt and fine sand (M), percentage of organic matter (a), soil permeability (b) and structure (c) according to Eq. 5 (Wischmeier and Smith 1978). These parameters were derived from open-source data of the Geological Maps of Morocco, the National Soil Map Geodatabase, and the Soil Mapping Database of Morocco (Fertimap) (Fig. 2a–c).

$$K = \frac{1}{100} \cdot \left[2.1 \cdot 10^{-4} \cdot M^{1.14} \cdot (12 - a) + 3.25 \cdot (b - 2) + 2.5 \cdot (c - 3) \right]. \tag{5}$$

The support practice (P) factor estimates the effect of implementing conservation practices. It is a dimensionless factor with a value between 0 (no soil erosion) and 1 (no conservation measures or failure thereof) (Ganasri and Ramesh 2016). Data were extracted from the Esri land use and land cover (LULC) layer derived from Landsat 8 imagery of 2020 (Fig. 2d). Later, a P-factor value was assigned to each pixel based on the LULC category as shown in Table 1 (USDA 1981).

Results

The Rainfall erosivity (R-factor) map (Fig. 3a) shows a gradual north–south increase in erosivity. This is linked to the spatial distribution of precipitation, which is greater toward the high mountains upstream of the watershed (Salhi et al. 2019). This is explained by the phenomenon of drying of the wet cloud masses coming from the west throughout their passage in the mountainous convex axis of the Rif, which means that they pour very little rain during their descent on the eastern continental slope (Foehn effect) (Salhi et al. 2022b). Rainfall erosivity varies from 27 to 104 mm/ha/h/year with lower values (≤ 36) downstream of Arbaa Taourirt, from where the values increase rapidly to more than 83.

The effect of topography (LS-factor) map (Fig. 3d) shows values between 0 and 55. The lowest values are common downstream (Ghis-Nekor plain and low slopes near it) and in the floodplains of the hydrographic network. On the contrary, the high values (> 6) are more abundant, especially in

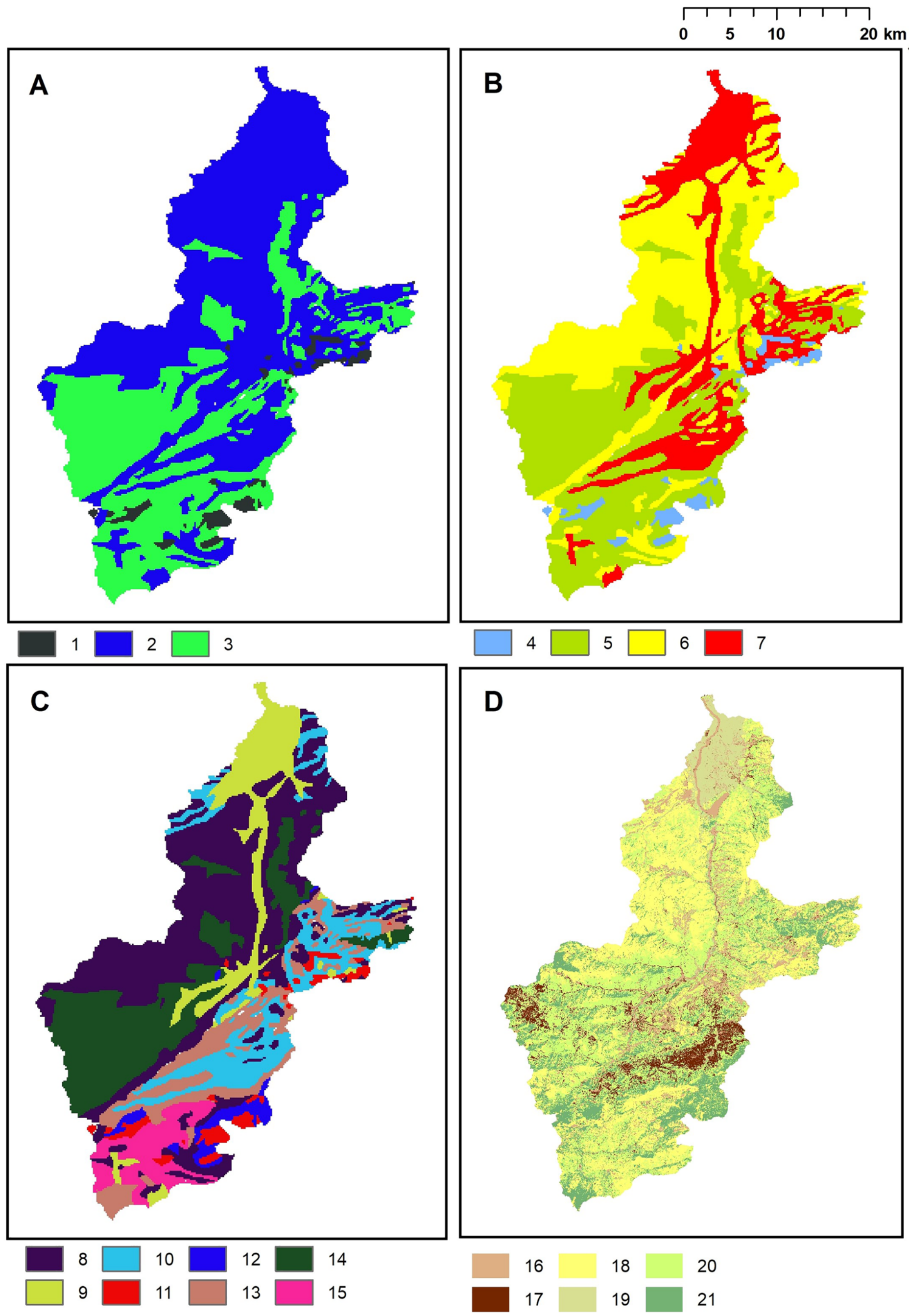

Fig. 2 Soil and Landuse maps for the Nekor watershed. **a** Soil structure code, 1: 0; 2: 2; 3: 3. **b** Soil permeability code, 4: 0; 5: 3; 6: 4; 7: 5. **c** Soil M value, 8: 200; 9: 260; 10: 1,932; 11: 2,250; 12: 3,600; 13: 4,225; 14: 4,422; 15: 5,625. **d** Landuse/Land cover classes, 16: Bare land; 17: Sparse vegetation; 18: Agricultural cropland; 19: Irrigated areas; 20: Reforestation and shrubs; 21: Forest

Table 1 P-factor values for the various Landuse/Land cover categories (USDA 1981)

Landuse/Land cover classes	P Factor
Bare land	1
Sparse vegetation	0.8
Agricultural cropland	0.5
Irrigation	0.5
Reforestation and shrub land	1
Forest	1

the hills and mountains, which reflects the dominant rugged aspect of the watershed.

The cover management (C-factor) map (Fig. 3e) emphasizes the preponderance of sparse vegetation and barren land with high (≥ 0.4) dominant values. Neither the scattering of rural houses nor the small farmlands allow for a large grouping of juxtaposed pixels to clearly discern low values.

It is worth recalling that the organic matter content is a key parameter for assessing soil erodibility (K-factor). In our case, the soils are poor in organic matter, with

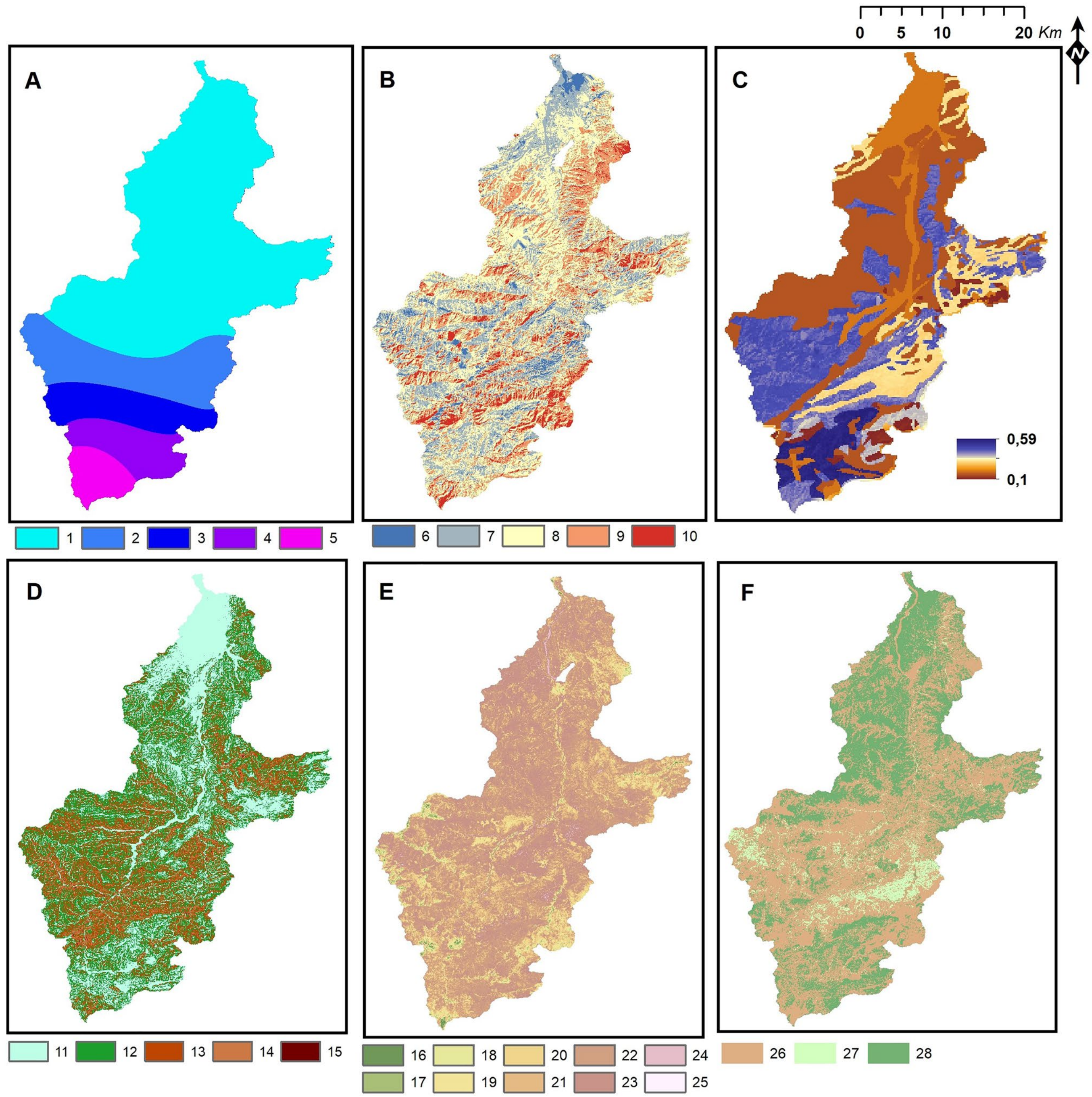

Fig. 3 Parametric maps of the RUSLE model for the Nekor watershed. **a** R-factor, 1: ≤ 36; 2: ≤ 47; 3: ≤ 63; 4: ≤ 83; 5: > 83. **b** Percentage of organic matter, 6: ≤ 1; 7: ≤ 1.5; 8: ≤ 2; 9: ≤ 2.5; 10: > 2.5. **c** K-factor. **d** LS-factor, 11: ≤ 3; 12: ≤ 6; 13: ≤ 9; 14: ≤ 12; 15: > 12. **e** C-factor, 16: ≤ 0.1; 17: ≤ .2; 18: ≤ 0.3; 19: ≤ 0.4; 20: ≤ 0.5; 21: ≤ 0.6; 22: ≤ 0.7; 23: ≤ 0.8; 24: ≤ 0.9; 25: > 0.9. **f** P-factor, 26: 1; 27: 0.8; 28: 0.5

slight spatial variations (Fig. 2b). The highest contents are observed in forest areas where plant productivity increased carbon levels. The percentage of silt and fine sand is another key parameter, evaluated by the granular fraction of lithological formations. The lowest values were found in soils derived from hard rocks (limestone, sandstone, conglomerates), while the highest values were found in marl-clayey soils or mixed soils with a dominance of the latter. From there, the soil erodibility map (Fig. 3c) shows low values (< 0.3) linked to soils that are predominantly friable and/or very poor in organic matter. In contrast, high values (≥ 0.3) are observed in high-folded mountains as an outcome of the conjunction of hard rock soils and productive soil forests.

The support practice (P-factor) map (Fig. 3f) has been divided into three categories, namely agricultural land (0.5), sparse vegetation (0.8), and the absence or failure of conservation measures (1). This last category is widespread in the hills and high mountains upstream, disadvantaged in infrastructure and therefore sparsely populated.

The spatial mathematical superimposition of the different factorial maps resulted in the average annual soil loss map (A) (Fig. 4). The estimated average of 37.8 t/ha/year agree with regional results (Sadiki et al. 2007; Salhi et al. 2020c). This is equivalent to a gross amount of soil loss of 3.5 Mt/year. This huge amount of soil potentially eroded on average per year has severe off-site effects related to increased sediment mobilization and transport to rivers and dams. This leads to rapid sediment siltation which results in the reduction of storage capacities of the Al Khattabi Dam downstream. The latter's storage capacity has dropped exponentially over the past 20 years (shortening its lifespan), and its water quality has also deteriorated (Benabdelouahab et al. 2019; Gourfi et al. 2018; Niazi et al. 2005; Salhi et al. 2020c).

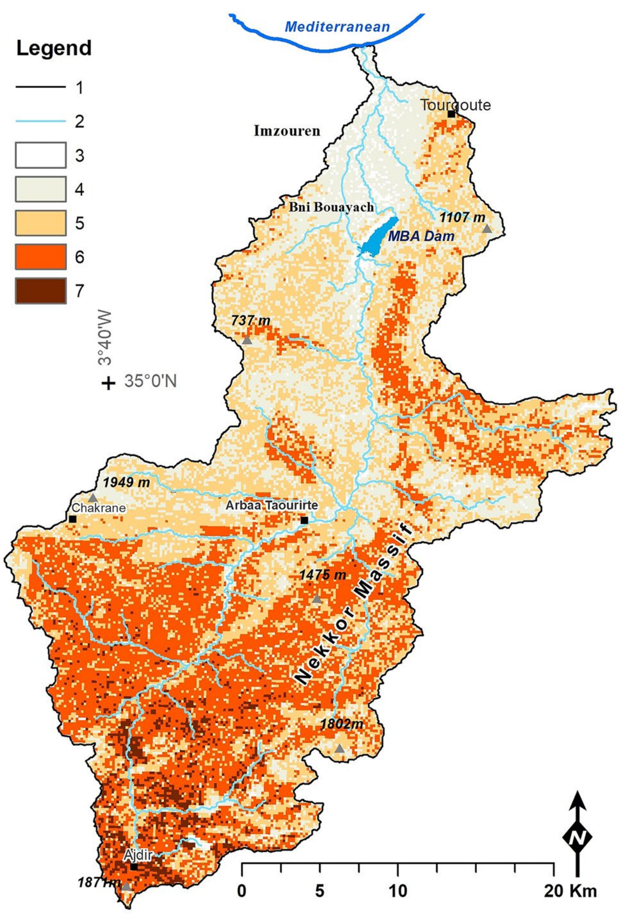

Fig. 4 Map of potential erosion risk of Nekkor watershed. 1: Drainage divide; 2: Hydrographic network; 3: Very low erosion (≤ 1.3); 4: Low (≤ 13); 5: Medium (≤ 39); 6: High (≤ 130); 7: Very high (> 130)

Soil loss has been divided into five classes according to an indicative color scale (from green to red) (Zachar 1982). Three groups emerge:

- Low to very low erosion (green) with rates of less than 13 t/ha/year. It covers 249 km^2 (27.2% of the watershed) downstream, in the center and around the Nekor wadi and its main effluents. The determining factors are the low slope (LS-factor) and the low precipitation (R-factor).
- Medium erosion (yellow) with rates ranging to 39 t/ha/year which covers 336 km^2 (i.e., 36.7%). It often frames the previous group (hills and mountainsides) as the result of a combination of different factors.
- High to very high erosion (orange and red) with rates above 39 t/ha/year covering 331 km^2 (i.e., 36.1%). They are observed in the high mountains upstream as an outcome of the combination of greater rainfall erosivity (R factor), high soil erodibility (C factor) and the absence or failure of conservation measures (P factor).

It should be emphasized that the Rif Mountain range is known for the abundance of factors favoring erosive processes (i.e., friable lithology, poor soils, and lack of conservation measures). Thus, steep slopes (LS-factor) and rainfall erosivity (R-factor) appear to be the predominant factors which accentuates the effect of other factors for the detachment and transport of particles and debris. This results in spatially variable erosion rates but all quite high (Gourfi et al. 2018; Sadiki et al. 2007; Salhi et al. 2020c, 2021b).

Discussion and conclusions

Northern Morocco has been a major gateway for transition and migration flows throughout its history. Its rich stock of water–soil-vegetation has made it a land of cultural permeability, economic stability, and social diversity (Salhi et al. 2020a). Nevertheless, this role has recently been threatened by declining water, soil, and plant resources due to changes in precipitation patterns, intrinsic geomorphologic factors, and anthropogenic pressure (Benabdelouahab et al. 2020; Salhi et al. 2022b). The consequences jeopardize economic and socio-ecological sustainability, especially given the expected increase in immigration flows (Cramer et al. 2020; Salhi et al. 2022c).

Recall that the objective is to assess potential soil loss in one of the main regional watersheds (i.e. Nekor) as a decision-making tool for erosion control. It was found a high annual average of 37.8 t/ha/year, which equates to a massive gross amount of 3.8 kg/m^2/year. The highest erosion rates are observed upstream in the hills and high mountains.

Rugged topography and aggressive precipitation are the two main factors that accentuate erosion processes.

In another era, this massive erosion was an excellent source of soil renewal and natural fertilization of the agricultural plain of Ghis-Nekor downstream. Except that the vocation of this plain is currently in accelerated change which transforms its rural character toward another urban and industrialized. There are several continuously growing urban centers and a dam (i.e., Al Khattabi) just at the entrance to this triangular plain (open to the sea) which requires now more water and energy than soil sources. This contradicts immediate needs with real events and gives decision-makers very few options to seize:

- Implement long, costly, and vast (approximately 400 km^2) soil conservation measures.
- Establish an efficient system of check dams (Piton et al. 2019) across rivers and tributaries to reduce slope, retain sediment and regulate their transport, considering the restoration and conservation of the mountainous terrain upstream.
- Develop eco-effective and sustainable alternatives (for water and electricity supply, reduction of water losses, and eco-agriculture).

The ideal seems to be a judicious planning that combines the last two options through urgent interventions and others deferred (programmed) according to realistic and visionary long-term action plans. Clearly, this cannot succeed in the current situation due:

- The administrative fragmentation of the territory in response to a large-scale problem (watershed) which splits interests, and economic and human powers (Salhi and Benabdelouahab 2023; Zetland 2011).
- The existence of structural obstacles, in particular the multiplicity of actors (institutional and elected) and the overlapping of sectors of intervention and responsibilities (Salhi et al. 2021a).
- The spread of imprecise or false information, perception gaps, and communication obstacles add to the informal rules of decision-making (political price) to privilege the management of the present by assuming that the problems of the "distant future" are the responsibility of others (Salhi et al. 2022a; Zetland 2011).

There is no doubt that the intensity of erosion and its impacts are increasing and will continue to do so for the foreseeable future in the Nekor watershed. The factors are already described here as well as the spatial distribution. In response, more research should be drawn into co-creation and the quality of stakeholders in mitigation, preparedness, response and recovery. Currently, resources dedicated to community information and engagement are weak and the evaluation of efforts is not systematic (Ryan et al. 2020). In general, co-creating to engage is useful for improving knowledge, personalizing risk impacts, and increasing preparedness activities in the community. Therefore, more work needs to be done to organize community engagement and the programs they are part of. This will allow the sharing of lessons learned between all stakeholders and, what is more important, the implementation of know-how. The latter must necessarily call upon local knowledge for a smoother integration. For instance, the construction of "Matfia" (a traditional technique for harvesting rainwater and runoff) should go together with planting, placing retaining walls and contour farming.

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Author contributions AO led the research, modeling, mapping, and analysis under the supervision of AS. AO wrote the first draft. AS wrote the final version. KA, KE, and KL provided support in the field study.

Data availability All the datasets that support the findings of this study are open access. The Land use/Land cover dataset is available from ESRI at https://livingatlas.arcgis.com/landcover/, Aster GDEM dataset is available in https://asterweb.jpl.nasa.gov/, Fertimap dataset is available in http://www.fertimap.ma/, and Landsat series datasets are available in https://eos.com/landviewer.

Declarations

Conflict of interest The authors declare no competing interests.

Informed consent The Land use/Land cover dataset is available from ESRI at https://livingatlas.arcgis.com/landcover/, Aster GDEM dataset is available in https://asterweb.jpl.nasa.gov/, Fertimap dataset is available in http://www.fertimap.ma/, and Landsat series datasets are available in https://eos.com/landviewer.

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