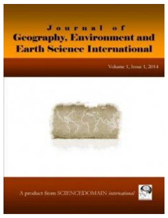

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Water Erosion Risk Mapping and Materials Transfer in the Smir Dam Watershed (Northwestern Morocco)

Ahmed Raissouni[1*], Lamiae Khali Issa[1], Khadija Ben Hamman Lech-Hab[1] and Abdelkrim El Arrim[1]

[1]Department of Earth Sciences, Laboratory of Environment, Oceanology and Natural Resources, Faculty of Sciences and Technology, University of Abdelmalek Essaâdi, Tangier, B.P. 416, Morocco.

Authors' contributions

This manuscript is a product of excellent teamwork; all members have contributed in various steps from the analytical methods used, to the research concept, and the experiment design. Each author has participated sufficiently in this work and made substantial contributions. All authors read and approved the final version of the manuscript to be published.

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ABSTRACT

Over the last three decades, soil erosion phenomenon has grown to be the most serious and significant geo-environmental problem in Morocco as in the whole Mediterranean area. As a matter of fact, it damages both soil functions and quality, not to mention the magnification of the surface waters pollution along with the siltation of Dams and reservoirs.
The Geographic Information System (GIS), in addition to other tools, has shown to be one of the key components used to model and assess potential erosion in a given area by estimating the rate of eroded soils and the amount of sediment carried out by either runoff or through rivers.
The main aim of this paper consists, primly, in producing soil erosion risk map of the Smir Dam watershed (Northwestern Morocco) using the Universal Soil Loss Equation (USLE) adapted to Moroccan conditions and integrated into a GIS platform. The aforesaid equation allows the calculation, spatialization and overlying the five factors controlling water erosion, namely rainfall

**Corresponding author: E-mail: ah_raissouni@hotmail.com;*

erosivity, soil erodibility, slope length and steepness, land use and erosion control practices. As a result, a spatial referenced document has been generated, representing, mostly, high erosion rates with an average loss of 45.45 t/ha/year. Furthermore, the spatial analysis of erosion phenomenon, related with other thematic maps, showed that the vegetation cover is the main factor that controls and affects the erosion in the Smir watershed.

Keywords: Water erosion; watershed; GIS; USLE; Smir Dam; Morocco.

1. INTRODUCTION

Soil is a vital component in the functioning of ecosystems and an essential resource for all types of land use and contributes significantly in the development of the world's civilizations. Unfortunately, as a result of the recent economic expansion and the population growth that exceeded every standard, soils fertility is degraded and threatened by erosion. Actually, the current rate of soil degradation threatens the capacity of future generations to meet their most basic needs.

It goes without saying that the problem of water erosion is widespread globally and adversely. It generally impacts differently on the five continents. Several studies have been conducted in different countries around the word in order to highlight the role of different factors controlling the erosion phenomenon under various states of the environment. In fact, high erosion rates are mostly found in the western Mediterranean including Morocco [1,2,3,4,5,6,7,8,9,10]; in northern and eastern Europe [11,12,13,14,15], in the middle East [16,17,18,19,20], in Africa [21,22,23,24], in Asia [25,26,27,28,29,30], in northern America [31,32,33], in Latin America [34,35,36] and In Australia [37,38]. Furthermore, the areas known by clearing and/or overgrazing issues or their mismanagement, have also presented high soil losses. Given that the vegetation cover has a positive influence on reducing soil erosion phenomenon, overgrazing has badly impact soil fertility in several areas [39,40,41,42,43,44,45].

Under Mediterranean climatic conditions, seasonal fluctuations and parent material can greatly control and/or affect the erosional behavior of soils when vegetation is negligible or absent [46]. In Morocco, the rates of soil erosion are exceeding extremely every international standards as well as the rate of pedogenesis under the Mediterranean climate, which leave the country in a worrying situation.

The negative impacts of water erosion witnessed in Morocco are tremendous, including silting of dams, reduction of soil productivity, pollution and turbidity of water courses. Moreover, some agricultural areas have been badly degraded while others have disappeared due to this phenomenon.

In 2001, a preliminary reconnaissance study conducted by the Moroccan Departments of Environment and Water [47] in order to evaluate the overall situation of soil degradation in Morocco. The results showed that for 22.7 million hectares assessed:

- 8.2 million hectares (36%) was cultivated of which 18% requires severe measures of soil conservation;
- 13.4 million hectares (59%) should be enhanced by grazing and forestation;
- 1.1 million hectares (5%) experience intense erosion and therefore should be excluded from all agricultural development;
- consequently, 64% of the total area of ponds should not be cultivated.

As stated above, the phenomenon of overgrazing, clearing and land reclamation, essentially caused by the rapid population growth, are the principal factors of soil degradation. Under these circumstances, the Smir dam watershed that suffered constantly from an intense deterioration over the past few decades [48].

At the national level, the most advanced studies concerning erosion in Morocco are mainly based on the silting of existing dams, turbidity measurements of runoff and courses and erosion risk indices [48,49,50,51].

The Rif Chain, to which belongs our study area, is generally constitutes of limestone and friable formations such as marls, shales and flyschs. Besides these soil characteristics that made it more exposed to torrential rains and poorly evolved, rugged topography and friable facies, in addition of the exacerbating anthropogenic factors, are the main causes leading to the increase of soil sensitivity against erosion.

The Rif Mountains, which cover only 6% of the Moroccan area, provide alone over 60% of annually mobilized sediment all over the country [52]. Erosion may reach 30 to 60 t/ha/yr in some Rif basins [48,53,54] not to mention the very high amount of the degraded land in those areas that range from 2500 to 5000 t/km2/yr. This negative aspects contribute, in a way or another, in silting dams that are receiving about 50 million tons of sediments annually [55,56,57] and consequently, reducing their water storage capacity estimated at -0.5% per year [57]. This results in the loss of 10,000 ha of agricultural land [58].

As a result to the growing awareness of the importance of problems related to erosion in Mediterranean environments, several studies are conducted to develop and test numerous models designed to quantify soil loss or indicate areas that are suffering from soil erosion.

In this context, the identification of erosion factors and vulnerable areas to soil erosion could be very helpful to evaluate the expansion of the phenomenon and the level of risk. Modeling and mapping erosion phenomenon has become a necessity for policy makers in order to target the major risk areas and implement preventive and/or corrective appropriate actions, to develop conservation measures and soil/water management plans [59].

The combination of existing models with new spatial techniques such as remote sensing and geographic information systems (GIS) helped to minimize financial costs and gain mapping time and therefore, wise and quick intervention are made. In this study, we use the universal model of soil loss (USLE) adapted to Moroccan conditions and integrated into a GIS platform to quantify and map the water erosion risk in the Smir dam watershed.

The benefits that could offer the possibility to integrate these models in GIS and generalize the results on large area made them easier and more efficient for studies at catchment or regional scale.

2. MATERIALS AND METHODS

2.1 Study Area

Covering a geographical area of 66.4 Km^2, the Smir dam watershed is located in the eastern part of the Tangier peninsula on the Mediterranean coast between 35°37'43' to 35°45'4,99' of North latitudes and 05°22'1,06' to 05°27'11,04' of West longitudes (Fig. 1).

The dam is almost located downstream, a few miles from the embouchure of the river. The climate of the area can be classified as sub-humid characterized by dry hot summer and rainy cold winter. The area is generally flat to gently sloped with an elevation ranging from 23 m at the outlet to approximately 830 m at the

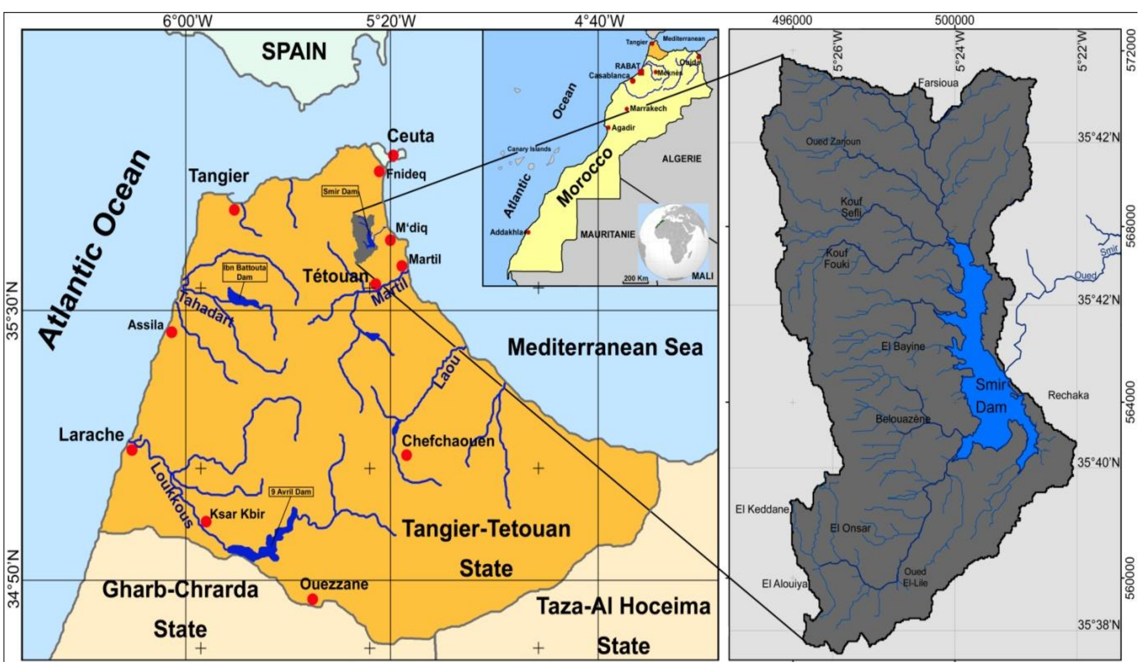

Fig. 1. Location map of the Smir Dam watershed

mountainous peaks in the east, north east and south east boundaries (Figs. 2 A and B). From geological point of view, the area belongs to the Rif chain; with calcareous and dolomotic formations developed in the West, schists and Paleozoic clastic formations and flysch in the center, quaternary formations in the East and finally sandstones and flysch in the top North East part of the basin (Fig. 2C). The land use/cover mainly consists of agricultural areas characterizing the center, followed by hardwood forests in the north, south east and centre and highly to entirely degraded areas mainly located in the West (Fig. 2D).

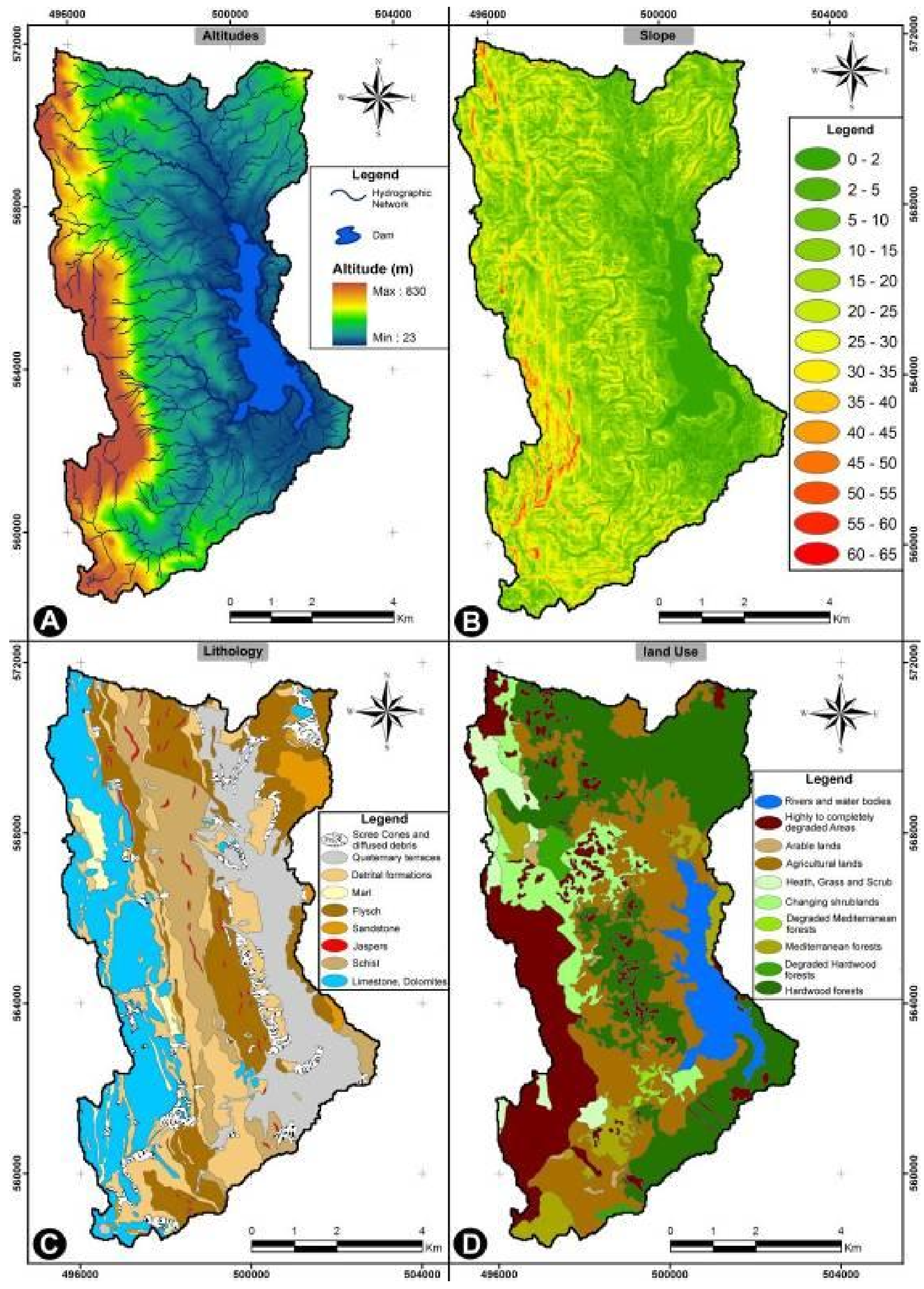

Fig. 2. Maps of physical parameters in the Smir Dam catchment

2.2 Methodology

Since the dust bowl era in 1930s known as a period of severe dust storms that greatly damaged the ecology and agriculture, researchers took the issue of assessing and predicting soil erosion as a challenge and succeed to develop several models to overcome it [60]. Actually, the deterioration of land fertility and the dissemination of soil loss, in the early 30s, are the main causes that led the scientists to carry out more research on this phenomenon. Since then, Researchers, farmers, local authorities and policy makers have become more and more concerned by soil loss problem, thenceforth multiple studies are conducted to assess, control erosion phenomenon and detect its effects on agricultural productivity.

The very first attempts to quantitatively estimate soil erosion were conducted by research scientists during 16 years period of time, from 1940 to 1956, in a large scale area in the United States of America [61]. As a result, Wischmeier, Smith, and others managed to reach that goal, based on the assembled data in previous studies, by developing the universal soil loss equation (USLE), described and published in 1965 [62] and revised in 1978 [63].

Thenceforth, several empirical and physical models have been developed and constantly improved to estimate soil erosion in different regions of the world. The empirical ones includes the Universal Soil Loss Equation), the Unit Stream Power Based Erosion/Deposition model (USPED) [64] and physically based ones includes the Water Erosion Prediction Project [65] and the European Soil Erosion Model [66,67].

The Universal Soil Loss Equation along with its improved version, the Revised Universal Soil Loss Equation (RUSLE) [68] are the most commonly applied models to estimate soil erosion and become the major soil conservation planning tool in the world given that to their simplicity and applicability to different situations. Although originally developed from erosion plot and rainfall simulator and designed for agricultural purposes, their use has been extended to other land uses.

Coupled with new space technology such as GIS, process based models have been developed and proved their ability to spatialize the erosion phenomenon with high accuracy in different scale watersheds and their efficiency in managing georeferenced data, computing input parameters, interactive mapping of various parameters, overlaying of different thematic maps, analyzing results, and the continual updating of data [69,70,71,72,73,74,75,76].

Equally important, remote sensing (RS) has shown to be useful, as well as inexpensive and effective tool in LULC (Land Use/Land Cover) mapping and LULC change detection [31]. In addition, the important and key data used to assess erosion within GIS platform are generated and provided by RS technique, which is more and more used by the researchers, specially for large areas [77,78,79,80,81,82,83, 84,85].

The main purpose for choosing this methodology, compared to other methods, was it high accuracy and ability to provide data that could address the issue. In other words, the approach used involved the implementation of RUSLE modified by [68] in a GIS environment, coupled with other factors obtained mainly from soil surveys, topographic maps, satellite imagery and reviewed literature. A GIS layer was developed for each factor and combined with a cell-by-cell basis in using the ArcGIS software. Calculations were done using capabilities available within the Spatial Analyst extension in ArcMap module.

The equation, expressed in t/ha/yr, is the product of five major erosion factors namely the rainfall erosivity factor (R), the soil erodibility foctor (K), the topographic factor integrating gradient and slope length (LS), the crop and cover management factor (C) and finally the conservation practice factor (P). Based on the Agriculture Handbook written by the USDA and other literature cited, those factor, generated from the digital elevation model (DEM), soil data, land use/cover data, rainfall data, crop and management factor (C-factor) were calculated and digitalized then rasterized within the GIS platform.

In 1978, Wischmeier and Smith [58] announced that rainfall erosivity is directly proportional to the kinetic energy and the maximum rainfall intensity within 30 min. However, due to the lack of rain-gage-based rainfall data in many countries including Morocco, several studies were developed to estimate the R factor based on the pluviometric data [86,87]. In our case study, the rainfall erosivity factor R (MJ/mm/ha) was calculated for 25 weather stations throughout the region by the most appropriate formula for Moroccan conditions, established by [50], which takes only into account the monthly and annually rainfall:

$$R = \Sigma^{1}_{12} (MRi) / RA \quad (1)$$

With: MR: the mean monthly rainfall
AR: the mean annual rainfall.

The soil erodibility factor K (t.ha.H/ha.MJ.mm) was also determined using an adapted formula to Moroccan conditions, based on the soil texture and electrical conductivity [88]:

$$K = 311.63 - 4.48 * (CS\% + S\%) + 613.4 * EC + 6.45 \quad (2)$$

With: CS%: percentage of coarse sand;
S%: percentage of total sand.
EC: electrical conductivity.

A sampling campaign was carried out in different locations of the study area to collect surficial sediment on which granulometry and conductivity analyzes were achieved. Sampling was done according to the homogeneous units map performed by the method of soil-landscapes [89].

A digital elevation model (DEM) extracted from an Aster satellite Image was used to produce slope map. The topographic factor LS was generated, directly by an integrated calculation tool in GIS software, from the Digital Elevation Model (DEM) and its derived maps. We used a simple and adaptable formula to our database [90]. This formula allows calculating LS factor based on slope steepness and flowing accumulation maps. The formula is written as:

$$LS = (\frac{Fl.Acc*PS}{22,1})^{0.4} * (\frac{Sin\ (Sl)*0.01745}{0.0896})^{1.4} * 1.4 \quad (3)$$

With: Fl. Acc: Flow accumulation map
PS: Pixel size
Sl: Slope map in percent rise

The land use/cover map of the study area was generated from (Landsat TM5) satellite imagery. For detailed information on different land uses/land cover, satellite imagery for the year 2010 was used. Initially, the satellite imagery was rectified. ENVI software was used to extract land use/cover data using the supervised method of remotely sensed data. By this method, the data extracted from the imagery is compared with field data.

The crop/cover management factor C was assigned for each unit on a land cover map. This latter was obtained through the classification of the satellite image. According to literature [91,92], the values of C factor ranges from 0 to 1.

The conservation practice factor P corresponds to the practices used to conserve soil and reduce land degradation. It ranges from 1 on uncultivated soil without any erosion control practices to 1/10th on soils where the ridging is practiced. Since there is no erosion control practices applied in the entire basin, the P value was considered equal to 1.

3. RESULTS AND DISCUSSION

3.1 Thematic Mapping of Erosion Factors

3.1.1 Rainfall erosivity factor (R)

The R values in the Smir Dam catchment range between 98 and 108 $MJ.mm.ha^{-}1.h^{-}1.year^{-1}$. They are among the highest values in the region, which clearly reflects the influence of its situation overhanging the Mediterranean coasts and bounded by the high mountains of the limestone chain. This Mediterranean influence appears in the spatial distribution map of the R factor in the watershed (Fig. 3), which shows a decrease in factor R values towards the internal areas.

3.1.2 Soil erodibility factor (K)

According to calculated K value for each unit, the soil erodibility map (Fig. 4) was developed through the rasterization of homogenous units map. The values range between 0.43 and 0.82 (Table 1).

Table 1. Distribution of K factor values in the Smir Dam watershed

Factor K classes	Area (ha)	% area
No data	418.91	6.31
0.43-0.48	1551.35	23.36
0.48-0.53	359.68	5.42
0.53-0.58	421.55	6.35
0.58-0.63	408.49	6.15
0.63-0.68	467.16	7.04
0.68-0.73	1141.64	17.19
0.73-0.78	142.17	2.14
0.78-0.82	1728.84	26.04
Total	6639.79	100%

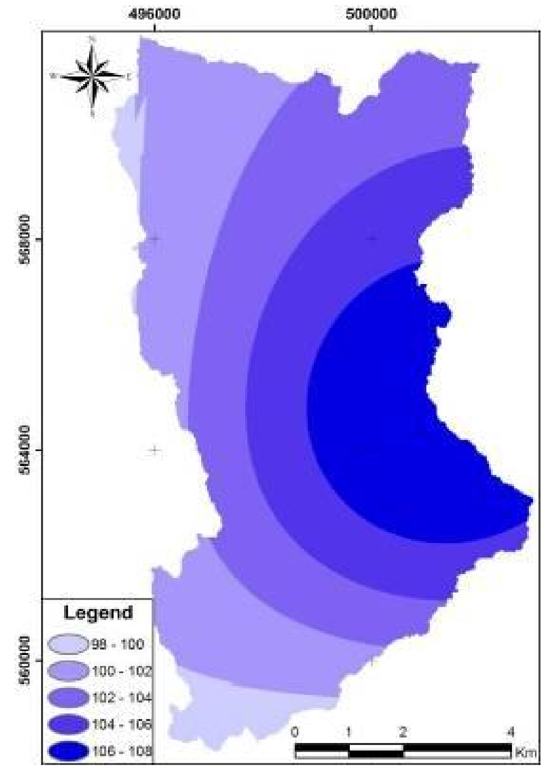

Fig. 3. Spatial distribution map of R factor

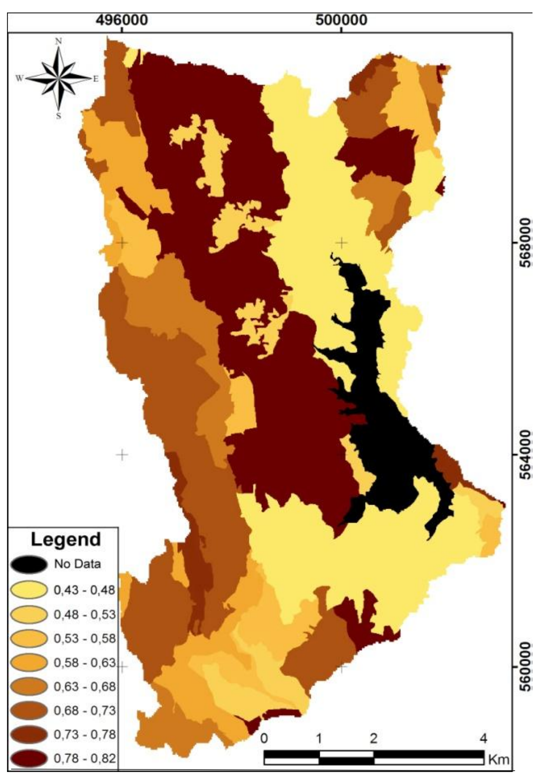

Fig. 4. Spatial distribution map of K factor

The lowest values are located in the east part of the basin, specifically along the sides of the main tributaries, which corresponds to fluvial terrace deposits usually very friable. The average values correspond mainly to sandstone or detrital formations while the highest ones correspond to the flysch formations.

3.1.3 Topographic factor (LS)

As observed in Fig. 5, LS factor ranges from 0 to over 80 reflecting clearly the topography of the study area. The lowest values that rarely exceeding 20 are limited to the east part of the watershed. In the surrounding areas, there are usually very low values ranging between 0 and 5, with the exception of some very limited areas along the edges of the dam lake, where the value increases proportionately with the slope.

In the West, the northern and southern boundaries of the watershed, the relief is high and characterized by steep to even very steep slopes, which results in high LS values exceeding 55 or even 80 in some areas. These values can also be explained by long slopes due to the homogeneity of their surface.

According to the spatial distribution classes table (Table 2), the lowest slope class (0-3) occupies more than half of the basin total area, followed by low to medium values (10 to 35). The very high values (from 35) cover only 11.26% of the area.

Table 2. Distribution of LS factor classes in the Smir Dam watershed

LS factor classes	Area (ha)	% area
0-3	3555.06	53.54
3-5	268.32	4.04
5-10	610.56	9.20
10-20	811.05	12.22
20-35	646.44	9.74
35-55	372.23	5.61
55-80	182.83	2.75
> 80	193.30	2.91
Total	6639.79	100%

3.1.4 The land use/cover factor (C)

In the Smir basin, we can clearly recognize the preponderance of two major land cover types: Agricultural activity which dominate the lowlands around the dam and the southern areas, generally with low relief, covering 28.9% of the basin area; and dense hardwood forests, covering 27.39% of the total area and located mainly in the northeastern and the southeastern high mountains. In the western part, there is a large degraded region covering 17.58% of the basin (Fig. 6 and Table 3).

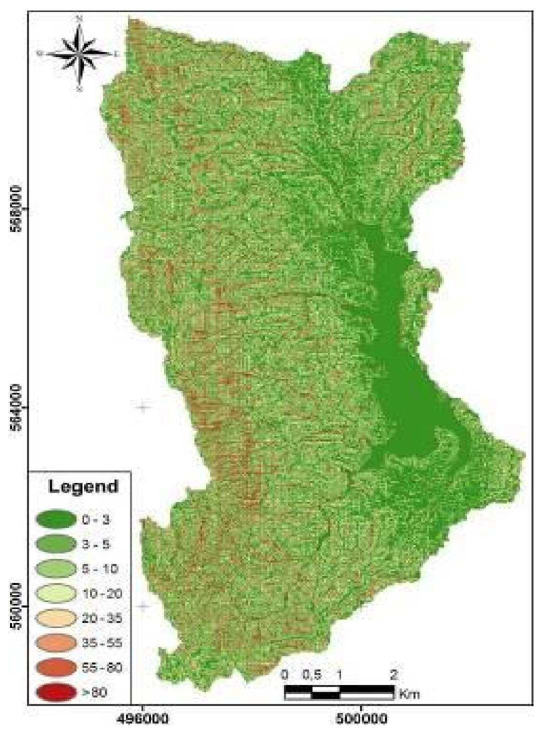

Fig. 5. Spatial distribution map of LS factor

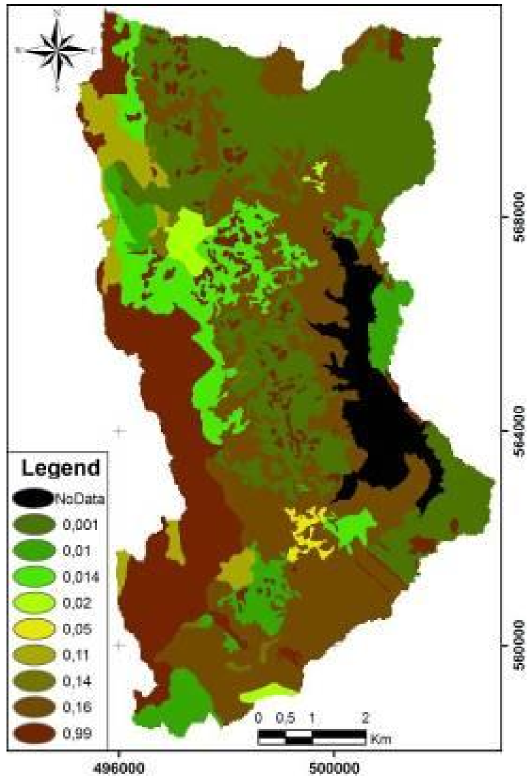

Fig. 6. Spatial distribution map of C factor

Table 3. Distribution of C factor classes in the Smir Dam watershed

Vegetation classes	Area (ha)	% area	C factor
Rivers and water bodies	414.17	6.24	0
Hardwoods forest	1818.39	27.39	0.001
Degraded hardwoods forest	91.85	1.38	0.02
Changing shrublands	510.62	7.69	0.014
Heath, Grass and Scrub	238.72	3.60	0.11
Arable lands	43.32	0.65	0.14
Mediterranean forests, woodlands	403.22	6.07	0.01
Degraded Mediterranean forests and woodlands	33.44	0.50	0.05
Agricultural areas	1918.93	28.90	0.16
Areas highly to completely degraded	1167.13	17.58	0.99
Total	6639.79	100%	

3.2 Erosion Risk Map

The soil erosion risk map (Fig. 7) obtained by overlaying different factors previously calculated and mapped, shows that the erosion in the watershed is generally high, with an average loss of 45.45 t/ha/year.

The very high risk classes (> 60 t/ha/yr) are generally located in the western part and occupy 38,1% of the total area of the basin (Table 4). This part of the basin, even if it is generally formed by hard and massive formations (limestones and dolomites, Fig. 2C), is characterized by a high (Fig. 2A) and rugged (Fig. 2B) relief and shows bare lands or highly degraded soils (Fig. 2D).

The moderate and high erosion risk classes (12 to 60 t/ha/yr) cover small areas (14.03%) and are located in the center of the basin, coinciding perfectly with moderate to steep altitudes and slopes, and where an intense agricultural activity is developed on flysch, clay and mudstone formations.

Table 4. Soil loss classes (t/ha/year) in the Smir Dam watershed

Soil loss (T/ha/yr)	Area (ha)	% area
0	507.40	7.64
0-3	1969.02	29.65
3-6	359.70	5.42
6-12	342.54	5.16
12-20	276.66	4.17
20-30	240.38	3.62
30-45	242.10	3.65
45-60	172.29	2.59
60-90	245.64	3.70
90-120	175.87	2.65
120-150	132.30	1.99
150-200	168.36	2.54
> 200	1807.54	27.22
Total	6639.79	100%

Low to very low erosion is also observed in the center, affecting areas with hardwood forest which plays the role of soil protective against rainfall erosive effects. Very low and low risk classes (0-12 t/ha/yr) are mainly concentrated in the North and the East parts of the basin and cover 40.23% of the total area even if the average value is relatively high. This is due to the large area affected by very high erosion values. By superimposing on the maps in Fig. 2, these areas, despite their lithological composition susceptible to erosion, have a dense canopy, which highlights the importance of vegetation cover in the preservation of soils against erosion.

In the Smir watershed, as in all the Moroccan Western Rif, precipitations are characterized by their torrential nature that gives them a significant aggressiveness against soils. Therefore, the main factor responsible of launching the erosion process is the rain. Along with other factors, these latter are affecting directly on the annual amount of soil erosion, causing either the decrease or the increase of erosion rates in watersheds in the region.

The comparison of potential erosion map (Fig. 7) with different thematic maps of physical characteristics of the basin (Fig. 2) approves the aforesaid statement, that the vegetation is the main factor controlling the erosion in this area.

At first sight, the comparison between the vegetation cover map (Fig. 2D) and erosion hazard map has revealed that areas with very low risk of erosion are all covered by dense vegetation (hardwood forests). Bare lands are experiencing very severe erosion even if their lithological formations are the least sensitive to erosion (limestone).

In the center part of the basin, agricultural land, grass and shrublands on friable formations like river terraces, flysch and other detrital formations present a medium to high erosion rates, which increases on arable lands. Finally, in Mediterranean forests or degraded hardwood forests, the erosion is low to average, which indicates additional effects of soil erodibility and topography.

In comparison with other basins, studies [93] on the northern Rif basins showed that land degradation varies between 5.85 t/ha/yr on woodlands, 18.5 t/ha/yr on half bare and cultivated land and 94 t/ha/yr on a completely cultivated land. Others said that the average soil loss in fragile Rif areas is 17 t/ha/yr [94] to upper than 49 t/ha/yr [95]. For example, the average potential loss in the Raouz Dam watershed is 35 t/ha/yr [96], 46 t/ha/yr in the Bni Hlou Watershed [97], 48 t/ha/yr in the Mgaz Sebt Watershed [98] and 41.7 t/ha/yr in the Ajras Dam Watershed [99]. These four basins are part of the Khmiss River Watershed, where the average potential loss is 37 t/ha/yr [100]. Another study [77] has revealed that the potential soil loss in the Alian River watershed is 43,5 t/ha/yr and 39.6 t/ha/yr in the Ibn Batouta Dam, and according to [101], the Nakhla Dam loses an average of 38.7 t/ha/yr. The comparison of these averages with those obtained in this study shows the relative reliability of the applied model.

In like manner, a study at the embouchure of the Smir river showed, apart from the humid season, concentrations of suspended solids of 760 mg/l in 2010 and 800 mg/l in 2011. These values, with an average flow of 13.85 m^3/s, are respectively corresponding to 311,575 and 327,974 t/year. They are very close to those obtained by other authors in the same region (200 to 1100 mg/l) [54]. Studies made by [102] gave the result of 1 million t/ha of loss for the Martil river and 8.15 Mt/year for practically all the rivers leading into the Moroccan Western Mediterranean.

The results obtained and their comparison with other studies realized in the Northern Morocco, obviously under same conditions, has shown a strong reliability. Despite some uncertainties and / or gaps that inevitably persist in the application, due to either lack of data or field difficulties, the quantitative map obtained can probably serve to decision makers to target high priority areas.

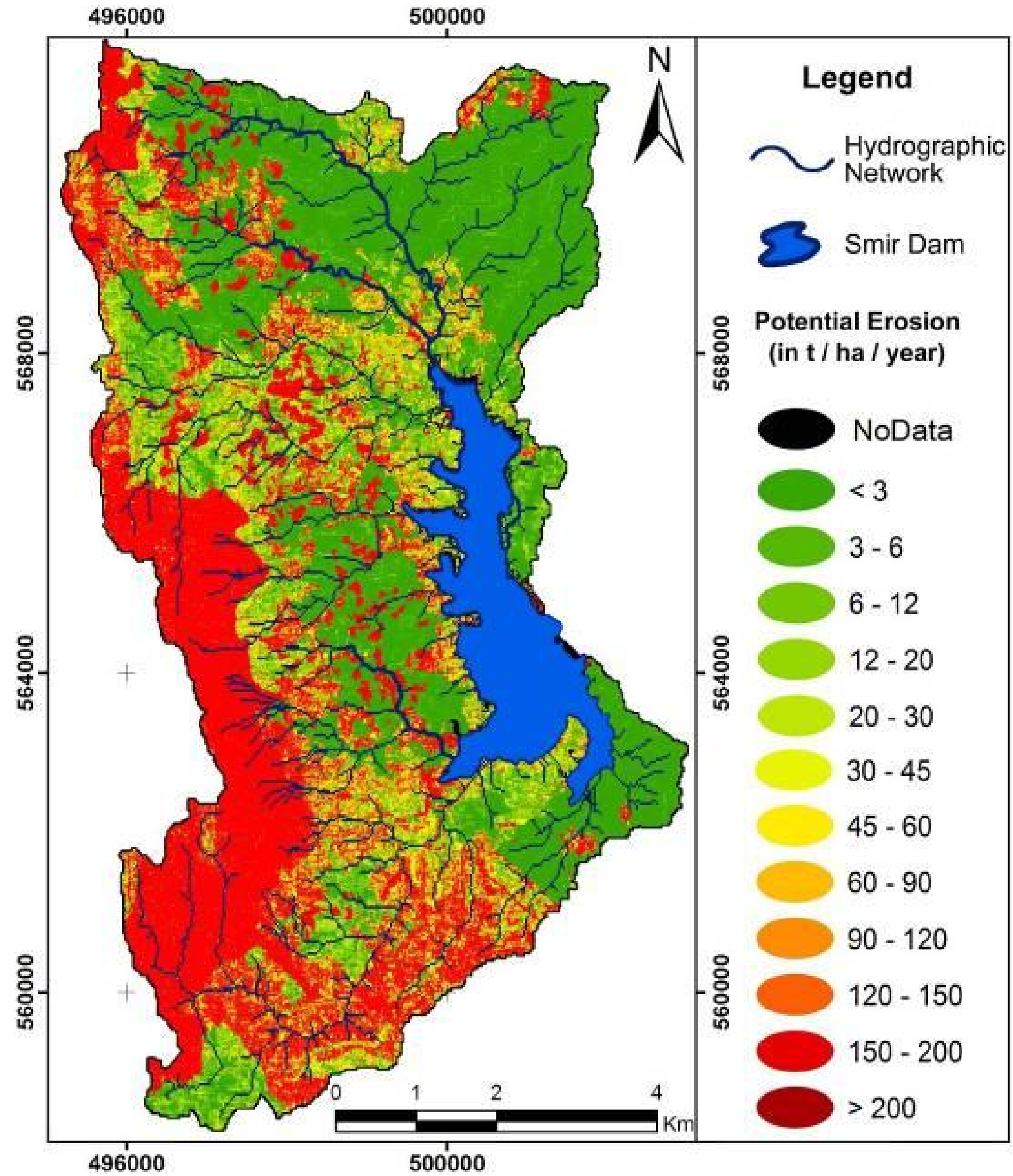

Fig. 7. Erosion hazard map in t/ha/yr in the Smir dam watershed

4. CONCLUSION

The multi source approach, combining empiric models with GIS techniques, allowed us mapping and modeling water erosion risk at the Smir dam watershed and consequently, identifying areas which require the highest priority interventions for the protection of soils and, equally important, the reduction of sediments transportation at the Dam closures.

The resulting map was obtained by overlying different thematic maps, representing the calculated results of the five USLE factors and showing an average rate of 45.45 T/ha/yr.

The application has shown many advantages, especially those related to the results which highlight the local factors involved in the erosion process. GIS allows a rational management of multiple data, respecting the various factors responsible of land degradation. In fact, we concluded that the main factors in the Smir Dam watershed are the vegetation cover followed by soil erodibility. In addition, GIS also allows an easy enrichment and continuous updating of the database, not to mention, it permits, at whatever time, the integration of new spatial data and the development of small-scale management plans that are sufficient to target areas vulnerable to water erosion for a political overall protection.

Finally, we may state that, in the absence of an intensive monitoring program and with comparison to more localized accomplished studies in the region or in other parts of the Mediterranean, the estimates provided by this approach are mostly pleasant and the spatial distribution of the erosion risk seems to be reasonable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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