Use of geomatics, Simulating the Impact of Future Land Use and Climate Change on Soil Erosion in the Tigrigra watershed (Azrou region, Middle Atlas, Morocco)

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Abstract. Soil losses need to be quantified in watersheds to implement erosion protection measures. The main objective of this work is to quantify soil loss in the Tigrigra watershed over the reference period 1985-2020 and two future periods 2050-2070, A Revised Universal Soil Loss Equation (RUSLE) model supported by geographic information systems (GIS) and remote sensing was used. GIS's model generator can automate various operations of creating thematic layers of model parameters. For future climatic periods (2050-2070), precipitation was produced using a classical statistical downscaling model (SDSM). On the other hand, Automata/Markov models (CA Markov) are used to characterize future land use through modeling in Idrisi software. Over the two periods, the results showed that annual erosivity varies decreases, or increases. The annual soil loss maps showed that 50% of our study area was in the very low class (<5 t/ha/year), while 20% was in the severe class (>80 t/ha/year). These fluctuations are primarily due to the effects of climate change and deforestation/reforestation in the region. This leads to changes in soil erosion due to the important role played by these two factors.

1. Introduction

Soil erosion by water has become one of the most serious global environmental challenges. It negatively affects soil conditions, water quality, species habitats, and the provision of ecosystem services [1], [2]. This damages natural resources such as soil fertility, drainage, and water quality. It also contributes to a reduction in reservoir capacity and, through the sediments it contains, adversely affects aquatic habitats, hydrological systems, and downstream water quality. To minimize the effects of erosion, it is necessary to carry out in-depth studies of areas prone to water erosion in Morocco, to find solutions to this problem. Our study area is the Tigrigra watershed, part of the Middle Atlas hydrographic unit. It's considered one of the most eroded regions of Morocco.

The C factor is calculated using the INDVI or the land use map, while the R factor is calculated using equations based on the value of annual or average precipitation, depending on the equation used. LS based on the DEM of the study area to obtain the slope, the P factor calculated by slope or land use. In our study area, the calculation of the spatial distribution of erosion will be carried out for a base period and a future period.

In the future period, the R factor will be estimated by projecting future precipitation for the years 2050 and 2070 using SDMS software, and the factor will be estimated by projecting future land-use maps for the years 2030 and 2070 using Markov chain in TerSset software. The results can help to establish priority intervention criteria for each sub-basin to prevent siltation of the dam at the outlet. The step-by-step adaptation of the RUSLE model to the study site, described in this article for the test catchment, can easily be applied to other catchments

2. Study area

The geological structure of the Middle Atlas can be subdivided into two parts. On the one hand, the Middle Atlas Causse or tabular Middle Atlas to the northwest, and on the other, the folded Middle Atlas to the southeast (Figure 1). The studied area is part of north-west Morocco. Its large surface area encompasses several plains and mountainous areas. It is the watershed of the Tigrigra River, located approximately 160 km SE of Rabat. The Tigrigra River drains the Tigrigra plain, with a total surface area of 6,000 ha. This extends in an indentation of the Middle Atlas causse from Ras El Ma to the Amghas area. This area is accessible via the main road RP n°24 from Fez to Marrakech via Azrou (Figure 1).

The relief of the Middle Atlas forms the eastern part of the basin. These reliefs culminate at a maximum altitude of 2165m. The confluence of the Tigrigra wadi with the Amghas, Aïn Leuh, and Ifrane wadis forms the Beht wadi. This is a narrow strip of a few kilometers, stretching over more than 30 km, with a very steep gradient upstream downstream (1600m in the Ougmès plateau area, 1000m in the Amghas area).

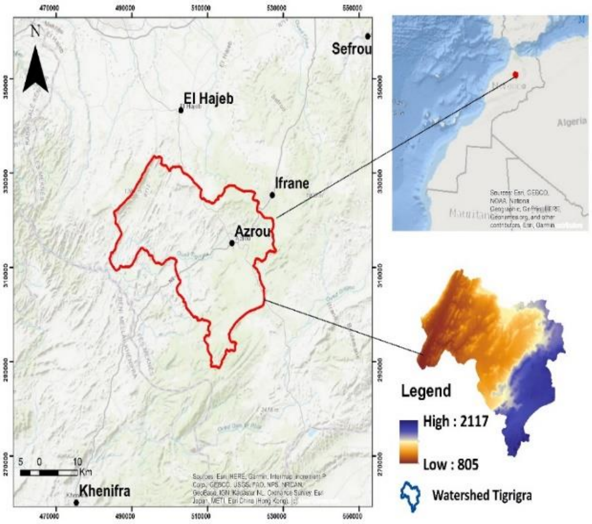

Fig. 1. Geographical location of Tigrira watershed.

3. Material and methods

Data

Different types of data from diverse sources were used to achieve the main objectives: (1) Precipitation data from 10 rain gauge stations distributed throughout the basin over 35 years (1985/2020) were used.

(2) Topographic data obtained from the Shuttle Radar Topography Mission (SRTM) website at a resolution of 30 meters were used to generate the digital elevation model (DEM) (3) 30 meters resolution Landsat 8 OLI, Landsat 7 ETM, and Landsat 5 TM satellite images were obtained from http://earthexplorer.usgs.gov/.

Description of the model

Soil Loss Modelling

The RUSLE (Revised Universal Soil Loss Equation) module has been incorporated into the Idrisi GIS. This module calculates soil erosion not only for individual grid cells but also for groups of cells within uniform polygons, taking into account slope parameters, orientation, and slope length, which can be adapted The RUSLE equation model is outlined below:

$$A = R * K * LS * C * P \quad (1)$$

A denotes the soil loss rate (t/ha/year); R signifies the rainfall erosivity factor (MJ.mm/ha.hr.year); K denotes the soil erodibility factor (t. hr/ha.MJ.mm); LS indicates the topographic factor; C represents land cover factor and P represents a factor of the anti-erosion techniques (Figure 5).

Creation of sub-watersheds using SWAT

The SWAT model has been adopted for this study because of its successful application in the northern region of Morocco [3], [4]. What's more, its "open source" nature opens up the possibility of adapting it to the specificities of the environment under study. In this study, SWAT is implemented through the dedicated Arc GIS interface (Arc SWAT), which facilitates the management of heterogeneous watersheds in terms of landscape, land use, and pedology.

Hydrological modeling with SWAT takes place in two phases. First, the watershed is subdivided into sub-catchments linked by a hydrographic network. Each sub-catchment is then divided into hydrological response units (HRUs), characterized by a unique combination of slope, land use, soil type, and cropping practices representing the spatial heterogeneity of the environment studied [5] (Figure 3).

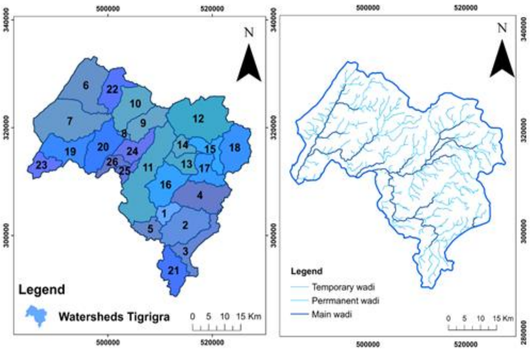

Fig .2. Sub-watershed and hydrographic networks

4. Results and discussions

RUSLE Model

Climatic aggressiveness factor (R)

In general, the results of the R factor (Figure 3) show large values with great temporal variability. During the reference period, the minimum value of the R factor (364.66 Mj.mm/ha/year) was obtained in station 6 for the year 1985, while the maximum value (725 Mj.mm/ha/year) was found in station 7 for the year 2020. In the forecast periods, the average erosion value is 570.74 and 543.12 for the RCP 2.6 (2021-2050) and RCP 2.6 (2050-2070), respectively.

The spatial distribution is similar in both predicted periods. Predicted periods show the highest values in the central parts and the lowest values in the watershed boundaries. Compared to the reference period, average rainfall erosion will decrease by 11.9% and 16.2% for the periods 2050 and 2070, respectively. The decrease in precipitation will influence the loss of soil through the reduction of erosion because precipitation or raindrops attack the upper part of the soil and remove soil particles and therefore increase soil erosion.

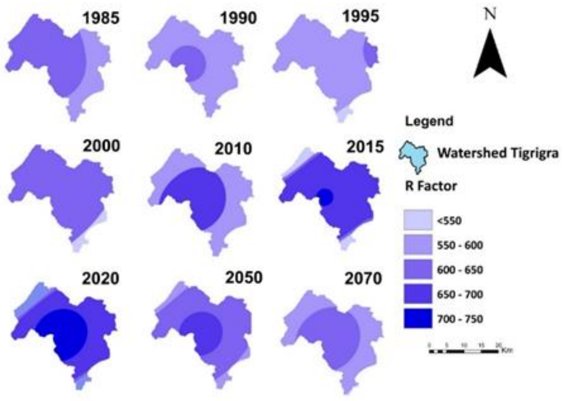

Fig. 3. Spatial distribution of R factor for the different scenarios.

Soil erodibility factor, Topographic Factors, and Support practice

- **Factor K**

The susceptibility of soil particles to erosion by rainfall and runoff is assessed by the soil erodibility factor K. This factor depends on the soil's physical and chemical properties. It is determined by soil texture, structure, organic matter content, and permeability. [6]. The K-factor map (figure 4) shows values ranging from 0.15 to 0.32. The map indicates the presence of three different soil types: Low-erodibility soils, with K values between 0.15 and 0.22, located in the center of the basin, soils with a K value between 0.22 and 0.28 at the southern extremities of the basin, soils with an erodibility value between 0.28 and 0.32, situated in the northern section of the basin. The high value of k indicates a soil sensitive to erosion; therefore, the northern part of the soil is the most erodible according to the value of K.

- **Factor LS**

Topography has a major influence on soil water erosion. Various considerations need to be factored in when evaluating the influence of topography. These include length, surface condition, topographic position, and slope shape. Slope rigidity accentuates the erosive force of runoff.

The topographical factor is calculated from the combination of slope inclination and slope length. This factor was calculated using digital terrain model (DTM) processing, based on 30 m resolution ASTER GDEM radar images, in ArcGIS: The topographical factor (Figure 4) ranges from zero to 27.

According to the LS factor, the majority of the Tigrigra watershed is between zero and four. Therefore, erosion is low in these regions. But in parts of the area, especially in the center, we have a very high LS value reaching up to 27, which indicates a very high sensitivity to erosion.

- **Factor P**

The most soil-friendly practices are all cultivation techniques implemented to reduce runoff and erosion. These include contour cultivation, bench planting, natural or artificial covering, and alternating strips or terraces. Values of P are less than or equal to one. If none of these practices exists in the region studied, the value of P is equal to one. Depending on the agricultural or erosion control practices used and the slope gradient, the P factor will vary. In this scenario, P-factor values were established based on slope characteristics (figure 4).

In this context, the P factor values were determined based on the slope. Low and medium values correspond to areas of low to moderate slope. The P factor values vary between 0.55 for areas with gentle slopes and 0.6 for areas with moderate slopes. These values become important for areas with steep slopes and vary between 0.8 and 1. The largest P values (P> 0.5).

In our region, the majority of the watershed surface has a value of 0.5 indicating low erosion but there are parts with very high P values which are the most erodible parts.

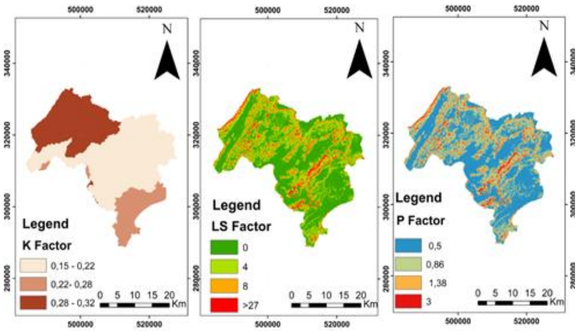

Fig. 4. Spatial distribution of K factor, LS factor, and P factor.

Vegetation cover factor (C)

The C factor stands out as one of the most important RUSLE factors. It can be effectively controlled to minimize soil loss. The C-factor reflects the impact of different land uses on erosion rates and is primarily associated with the proportion of vegetation cover, making it a key determinant of water erosion.

The calibration of the 2020 land use map and the projection of land use for 2050 and 2070 were based on the transition matrix derived from 1985 to 2020 data. All metrics indicated that the LCM module of the TerrSet software has the potential to accurately project land use maps for 2050 and 2070 using the Markov chain principle in this scenario. Based on land use, in output the map of factor C. The results are presented in Figure 6. The value of factor C close to 1 indicates strong erosion. According to the results obtained in the study area C is high in the NW part of the basin applied very high erosion (Figure 8).

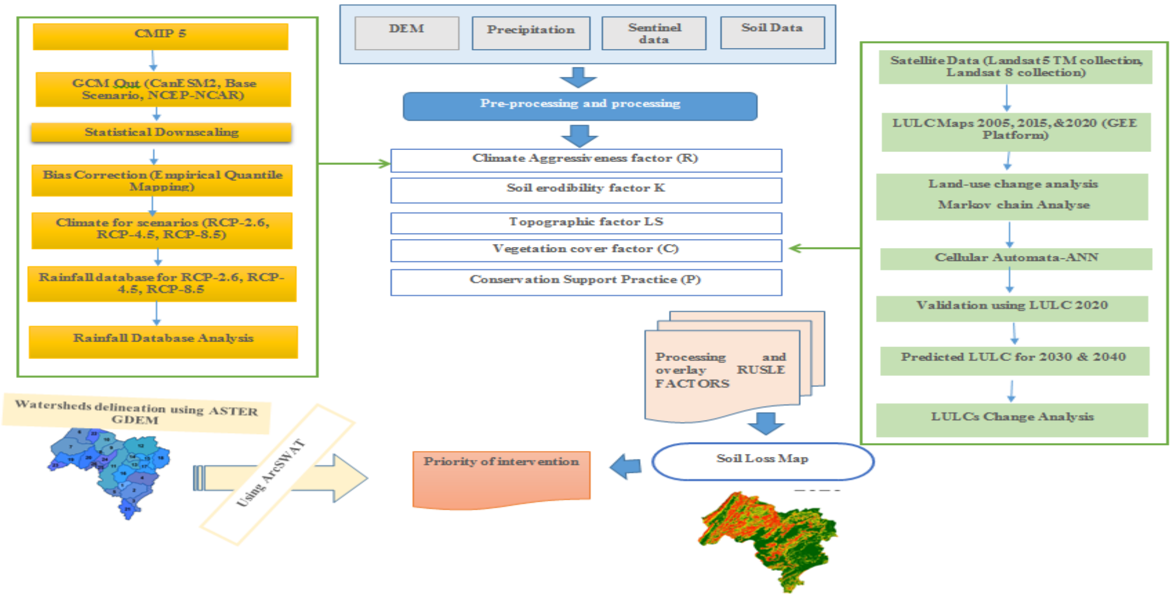

Fig. 5. The methodology employed in the research

Table 1. Priority classes of 26 sub-basins of Tigrigra.

		A 2020		A 2050		A 2070	
Sub-basin number	**Distance/dam (km)**	**Mean**	**Priority**	**Mean**	**Priority**	**Mean**	**Priority**
1	30	9.85	Moderate	13.32	High	10.06	Moderate
2	30.56	8.56	Moderate	10.45	Moderate	7.04	Moderate
3	26.61	7.9	Moderate	9.2	Moderate	6.07	Moderate
4	20.9	2.99	Low	3.35	Low	2.42	Low
5	24.71	12.38	High	13.69	High	12.22	High
6	27.99	51.97	High	41	High	46.83	High
7	0	43.06	Very high	38.78	Very high	38.94	Very high
8	12.04	31.02	Very high	28.63	Very high	22.52	Very high
9	18.58	57.95	Very high	54.92	Very high	44.86	Very high
10	23.36	36.25	High	35.13	High	28.29	High
11	15.67	23.77	Very high	23.53	Very high	18.32	High
12	25.97	13.44	High	22.04	Very high	12.44	High
13	4.71	23.23	Very high	33.36	High	18	Very high
14	10.47	16.98	High	16.26	High	13.48	High
15	17.96	8.4	High	11.42	High	8.91	High
16	27.49	25.45	High	34.12	High	22.96	High
17	31.43	9.86	Moderate	17.25	High	10.76	Moderate
18	30.32	7.13	Moderate	10.53	High	7.89	Moderate
19	36.1	46.66	High	42.78	High	36.3	Very high
20	9.14	45.87	Very high	42.12	Very high	35.53	Very high
21	18.32	13.32	High	18.47	High	9.8	High
22	19.64	34.8	Very high	28.09	Very high	33.31	Very high
23	30.08	27.89	High	25.31	High	22.26	High
24	18.58	24.45	High	22.72	Very high	19.28	High
25	18.59	9.46	High	8.98	High	7.44	High
26	16.65	16.89	High	15.67	High	13.06	High

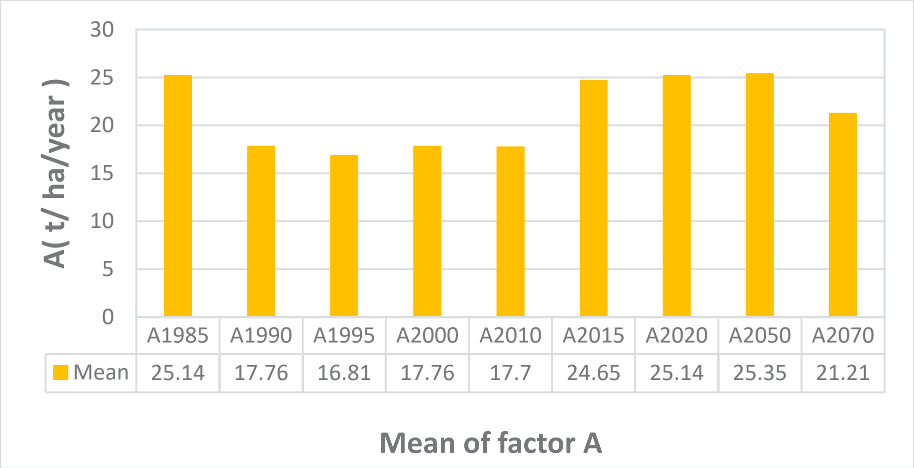

Fig. 6. Mean of the period-based and future period of factors A the RUSLE model

Table 2. Statistics parameters of the period based and future period of factors A the RUSLE model

A (t / ha/ year)	A1985	A1990	A1995	A2000	A2010	A2015	A2020	A2050	A2070
Minimum	0	0	0	0	0	0	0	0	0
Maximum	1371.56	1300.2	1231.1	1300.2	1326.19	1353.04	1371.56	1246.13	1046.69
Mean	25.14	17.76	16.81	17.76	17.7	24.65	25.14	25.35	21.21

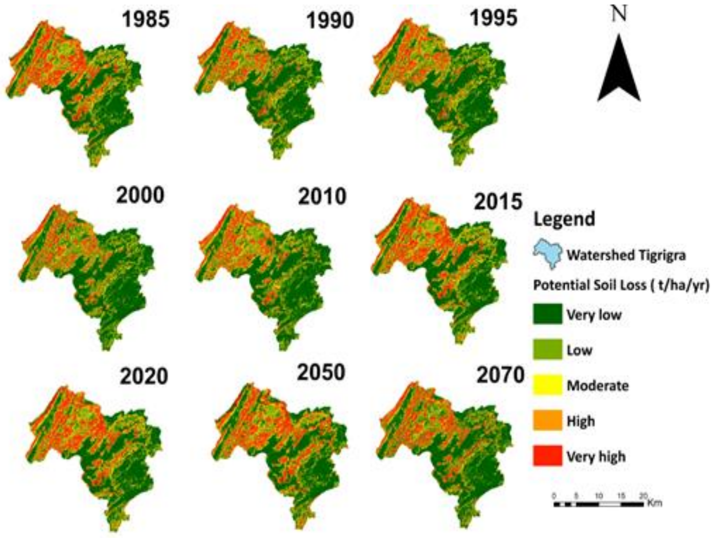

Fig. 7. Spatial distribution of A factor for the different scenarios

Table 3. Decision matrix of the priority intervention

Distance/dam (km	Soil loss rate (t/ha/year)				
	0–5	5–7.4	7.4–12	12–20	> 20
> 100	**NU**	**L**	**L**	**M**	**M**
50–100	**L**	**L**	**M**	**M**	**H**
20–50	**L**	**M**	**M**	**H**	**H**
10–20	**L**	**M**	**H**	**H**	**V h**
0–10	**L**	**M**	**H**	**V h**	**V h**

NU: Not urgent; L: Low; M: Moderate; H: High; Vh: Very high

Annual soil loss rate

Erosion risk rates were classified into five classes: low erosion risk (A<6 t/ha/year), medium erosion risk (6<A<11 t/ha/year), high erosion risk (11<A<33 t/ha/year), very high erosion risk (33>t/ha/year). The annual soil loss maps showed that 50% of our study area was in the very low class (<5 t/ha/year), while 20% was in the severe class (>80 t/ha/year) (figure 8). The mean soil loss found using the RUSLE model for the different scenarios: baseline period (1985, 1990, 1995,2000,2010,2015, and 2020) and future period (2050 and 2070) was 25.14, 17.76, 16.81, 17.76, 17.70, 24.65, 25, 14, 25.35 and 21.21 t/ha/year respectively (Table 2 and Figure 7).

Priority of intervention

The prioritization of interventions was developed for 26 sub-basins (Figure 2). To prioritize the action plan by sub-basin (Figure 2), a strategy is required that depends on two primary conditions: (1) the average soil loss rate in the sub-basin and (2) the distance between the sub-basin outlet and the dam reservoir (Table 3) [9].

In this context, a decision matrix was developed to define priority levels for each sub-basin, with five classes defined, from non-urgent to very urgent action (Table 1). The results are shown in Table 1 and Figure 2.

Discussion

In this study, we highlighted precipitations and vegetation cover impact on soil erosion in the watershed Tigrigra. The mean soil loss found using the RUSLE model for the different scenarios: baseline period (1985, 1990, 1995,2000,2010,2015, and 2020) and future period (2050 and 2070) was 25.14, 17.76, 16.81, 17.76, 17.70, 24.65, 25, 14, 25.35 and 21.21 t/ha/year respectively (Table 2). These values take place within the range (0 to 258.19t/ha/year) of erosion assessments done on the country scale by Gourfi et al., 2018 [8] using the same model. This comparison indicates that our study area falls into the regions the riskiest to erosion.

Taking into account the results of previous studies, the results from the Sebou watershed for the period 2000-2013 showed that 71.90% of the total watershed area experienced minimal erosion, while only 0.20% of the area faced significant erosion risk [8].

The results for the period between 2014 and 2027 indicate that approximately 58.33% of the study area is expected to be at low erosion risk, while only 0.27% of the total area is expected to be at high erosion risk. It can be seen that the erosion risk is very low in the basin, particularly in the central part. In the same region and studies using the SWAT model, findings for the period of 2000 to 2013 indicated that 35.57% of the entire catchment area experienced minimal erosion, with only 9% of the area facing a significant risk of erosion [8].

The findings for the period between 2014 and 2027 indicated that approximately 36.97% of the study area is expected to have minimal erosion risk, while a significant risk of erosion is projected for 9.24% of the total surface area [8].

In the Sebou watershed region, other research utilizing the RUSLE model indicates that 78.83% of the study area faces a low erosion risk, 17.36% faces a moderate risk, 3.04% faces a high risk, and 0.77% faces a very high risk [6].

The minimum value of the R factor (364.66 Mj.mm/ha/year) was obtained at station 6 for the year 1985, while the maximum value (725 Mj.mm/ha/year) was found at station 7 for the year 2020. In the forecast periods, the average erosion value is 570.74 and 543.12 for RCP 2.6 (2021-2050) and RCP 2.6 (2050-2070), respectively.

The spatial distribution of the C factor shows that the majority of the study area has a C value between 0.2 and 1, indicating strong erosion. The C factor is closely linked to land use. Land use shows that forests are only present in areas between 11 and 16% of the total surface area of the study area and that these are characterized by very low erosion. The other factor has, also, a significant effect on soil erosion risk:

The schist soils in the study area are highly vulnerable to erosion;

The watershed elevation is very high in some areas;

The LS factor has values higher than 16.

Against this backdrop, adopting on-site soil conservation practices is recommended [9]. When the distance between, the sub-catchment outlets (main outlet dam) is taken into account. The results show that sub-watershed 4 is subject to low erosion in the three years 2020, 2030, and 2070. On the other hand, sub-basins 1, 2, 3, 17, and 18 show moderate erosion.

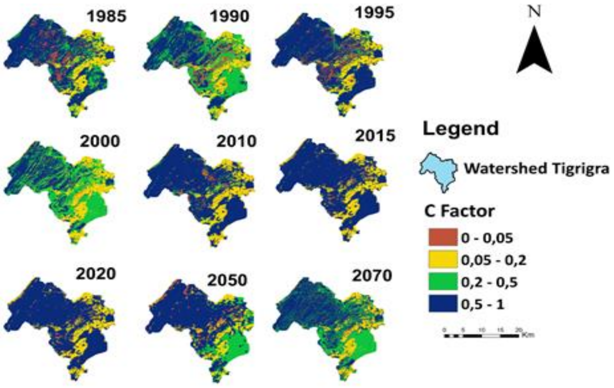

Fig. 8. Spatial distribution of C factor for the different scenarios.

5. Conclusion

Soil erosion poses a threat to the agricultural soil heritage, impacting the environment. This study presents the quantitative assessment and mapping of local soil losses in the Tigrigra watershed using the RUSLE model.

The use of GIS proved to be instrumental and extremely valuable in mapping this particular parameter. The mean soil loss found using the RUSLE model for the different scenarios: baseline period (1985, 1990, 1995, 2000, 2010, 2015, and 2020) and future period (2050 and 2070) was 25.14, 17.76, 16.81, 17.76, 17.70, 24.65, 25, 14, 25.35 and 21.21 t/ha/year respectively.

In this study, the effects of climate change, land use change, and their synergistic impacts on soil loss in the Tigrigra catchment are simulated. A multi-climate model and a multi-emission scenario approach are employed to assess the impacts of climate change. The delta change method serves as the downscaling technique to project future precipitation. The study utilized the Revised Universal Soil Loss Equation (RUSLE) model to simulate current and future soil erosion dynamics in the study area. The results indicate that soil erosion, climate change, and land use interact in complex ways, varying with different greenhouse gas emissions and land use scenarios. Climate change has the potential to increase soil loss rates, erosion, and deposition in future periods, while significant reductions in soil erosion and deposition are expected with increased land use compared to baseline periods. An integrated analysis of climate change and land use highlights the potential of strategic land use planning to mitigate future soil erosion and deposition, in addition to the direct impacts anticipated from climate change.

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