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Soil Erosion Risk Assessment Due to Land Use/Land Cover Changes (LULC) in Hangar River Watershed, Northwest Ethiopia

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Abstract

Soil erosion is a major environmental and economic concern affecting all continents around the world. Soil loss facilitates land degradation, threatening both agricultural and natural environments. This problem is severe in Ethiopia due to its topographic features. To evaluate the effect of land use and land cover changes on soil erosion, we studied land use changes of the Hanger River watershed, NW Ethiopia, from 2005 to 2017, using remote sensing and estimating soil erosion using the Revised Universal Soil Loss Equation. The results of land-cover changes have revealed a decrease in open forest areas, grazing land, shrub land and grass land by 33.16%, 9.20 %, 3.22 %, and 7.62 %, respectively in a fourteen years period. In the same period, there was an increase in agricultural areas by 48.73 % and dense forest by 4.74 %. The estimated mean soil erosion potential in Hanger River watershed, between 2005 and 2017, was about 55.5 and 70.5 t ha^{-1} $year^{-1}$, respectively. For the High and Very high classes, the values increased from 33.40% to 35.74% and 6.36% to 12.81%, respectively from 2005 to 2017. Therefore, it can be concluded that there is an increasing tendency for soil erosion in the area due to changes in land cover, particularly deforestation due to agricultural land expansion. This trend should receive attention aiming to keep the stability and sustainability of this ecosystem in the future. Management interventions are necessary to improve the status and utilization of watershed resources by applying sustainable land management practices for sustainable livelihood of the local people.

Keywords: GIS. Hanger basin. Land use and land cover changes. RUSLE. Soil erosion.

1. Introduction

Land use/land cover changes (LULCC) have become more complicated and multidimensional (Latocha et al., 2016) in recent years. This situation has given rise to special LULCC contrary to nature, resulting in a large number of changes in the global climate system and the biosphere (Riebsame et al., 1994). These changes primarily include soil erosion by water, which is considered the most important geo environmental hazard (Kavian et al., 2017). This phenomenon responds very rapidly to LULCC and has caused serious damage throughout the World (Conforti and Buttafuoco, 2017).

Soil erosion is a natural process that contributes to the evolution of the Earth's surface and is governed by the underlying geology and soil characteristics, rainfall, topography, vegetation, land use and management practices. The ability to measure soil erosion and resultant land degradation is important because soil erosion has a range of environmental impacts, including loss of organic matter and nutrients, and reduction of landscape productivity and downstream water quality (Newcombe and Macdonald, 1991). Soil loss by runoff is a severe ecological problem occupying 56% of the world-wide area. Soil loss is accelerated by human-induced soil degradation (Gelagay et al., 2016).

According to Hurni (1985), degradation and loss of soil resulting from soil erosion was estimated to be about 20 t per hectare in Ethiopia, i.e., about 1 mm of soil depth per year. Ethiopia loses about 1.9 billion metric tons of fertile soil from the highlands every year and the degradation of land through soil erosion is increasing at a high rate (Hagos et al., 1999).

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Studies in Ethiopia indicated that 57% and 28% of the area are moderately and severely affected by soil erosion respectively (Lambin and Geist, 2006). Higher soil erosion rates have occurred in the western areas where the high amount of rainfall is recorded than in the relatively low rainfall regions of the northern, central and eastern parts of Ethiopia (Hurni, 1988). In the highlands of Ethiopia, rates of annual soil loss reached as high as 200 – 300 t ha^{-1} year^{-1}, reaching tons of soil loss annually (Hurni, 1993). However, the severity of soil erosion increases on steeper topographic position and poor vegetation cover (Shiferaw, 2011).

A Geographic Information System (GIS) have become an increasingly important means for understanding and dealing with the pressing problems of water and related resources management like spatiotemporal analysis of LCLU and soil loss rate estimation in large areas in world (Wang et al., 2014).

Universal Soil Loss Equation (USLE) and its revised form i.e., Revised Universal Soil Loss Equation (RUSLE) are principally used to estimate the rate of soil loss from the landscape and guide the priority areas of conservation practices to a soil loss tolerance (SLT) level. SLT is the average erosion rate that can occur with little or no long-term degradation of the soil with values ranging from 5 to 11 t ha^{-1} year $^{-1}$ (Renard et al., 1997). Studies in northwestern highlands of Ethiopia reported that the mean SLT value was 6-10 t ha^{-1} year^{-1} where soil erosion value below this is assumed not to be a problem of sustainability (Hurni, 1983). Morgan (2005) also estimated the average African SLT value at the rate of 10 t ha^{-1} year^{-1} over which farmers should be concerned.

The study area has experienced spatiotemporal land cover dynamics. These changes were largely caused by unsustainable land use practices such as overgrazing, expansions of farmlands at the expenses of other land cover classes, and deforestation. The agricultural practices, in the study area, are largely characterized by small-scale, fragmented and traditional tillage with low fertility level. Alternatively, farming operations are usually performed during intense rainfall events where weak soil surface caused by tillage and absence of vegetative cover exposing farmlands to direct rainfall impact and hence, increased stream loads.

The result of this research is crucial to sustainably enhance the benefits of land resources and diminish the adverse impacts of land degradation. Therefore, the aim of this work was to map land uses and the risk of erosion in the Hanger watershed, and to highlight the role of land use and vegetation cover in regulating erosion risks. The mapping of erosion factors and identifying areas of vulnerability to soil erosion would help assess the risk of erosion for the different land uses and vegetation cover densities in order to develop measures and conservation of water and soil.

2. Description of Study Area

Hanger watershed found in North - West part of Ethiopia in Oromia regional state, East Wollega Zone at about 400 km of Addis Ababa. It located between 9^{0}01'26”- 9^{0}59'50” N latitudes and 36^{0}02'21”- 37^{0}58’50” E longitudes as shown in Fig. 1. It covers a total drainage area of 7805 km^2 in the Blue Nile river basin. The altitude of the study area ranges between 849 – 3215 m above sea level.

From Hanger river basin, high rainfall was recorded in months, May to September whereas the lower rainfall was recorded in months, October to April in all stations. The watershed is characterized by different landforms: flat plains, undulating plains, rolling land and steep areas. We have used rainfall data from 6 meteorological stations in the region, digital elevation model with 30 meters resolution, and soil type data were obtained from the Ministry of Water Irrigation and Energy (MWIE) of Ethiopia. Also, for the assessment of land use changes, the images of TM and OLI sensors of Landsat satellite of the study area for the years 2005 and 2017, have been used after geometric corrections.

3. Materials and Methods

In this research, the RUSLE approach was employed in geographic information system to estimate the mean annual soil loss. The RUSLE model was broadly applied for forest and agricultural watersheds to predict the average annual soil loss by integrating the various erosion factors. In the RUSLE, the mean annual soil loss is expressed as a function of six erosion factors (Renard et al., 1997):

$$\mathbf{A = R \times K \times L \times S \times C \times P} \qquad \mathbf{(1)}$$

In this relation, **A** is the average of soil erosion (t ha-1year-1), **R**: rainfall erosivity, **K**: soil erodibility, **L**: gradient length, **S**: slope steepness, **C**: the crop management factor and **P** the erosion control practice factor (Fig. 2).

During the simulation, the RUSLE method was used in two-time steps in the years 2005 and 2017, which were relatively assigned in the dynamic parameters. In fact, the LS-factor and K-factor controlling erosion in the RUSLE method are more constant factors through years, while the R-factor, C-factor, and P-factor are more dynamic parameters (Renard et al., 1997).

The RUSLE model was run for 2005 and 2017 separately. To run the RUSEL model in Geographic Information System (GIS), first, rainfall raster layer, soil, slope, Digital Elevation Model (DEM), and also layers of land-cover were created. The five raster layers were produced from the attribute values of the RUSLE model and processed by overlay analysis to generate the annual soil loss rate of each cell using “raster calculator” of Spatial Analyst Tool. During each model run, all parameters remained the same except values of the C-factor, which was changed according to the land cover of the respective year.

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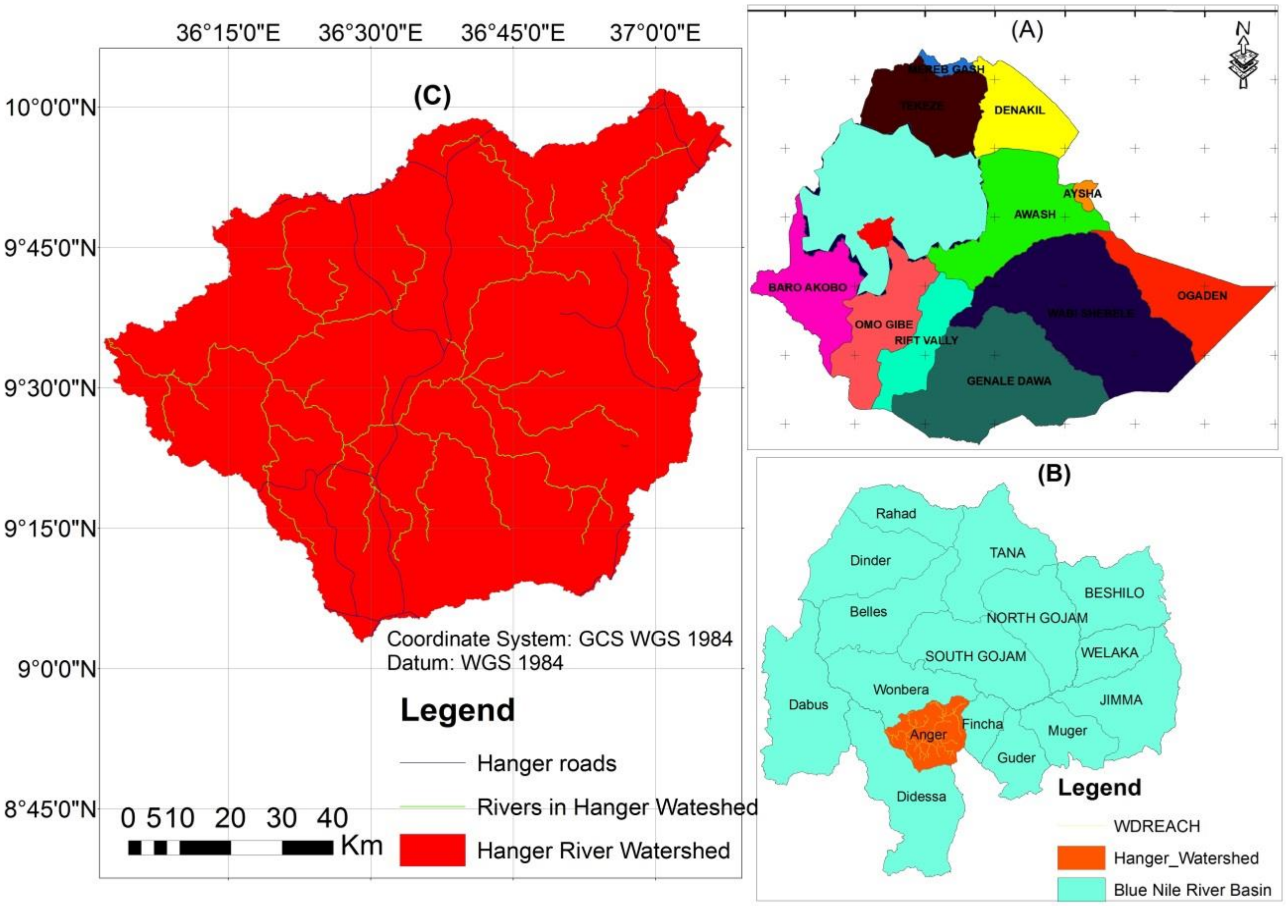

Fig. 1. Location map of the study area.

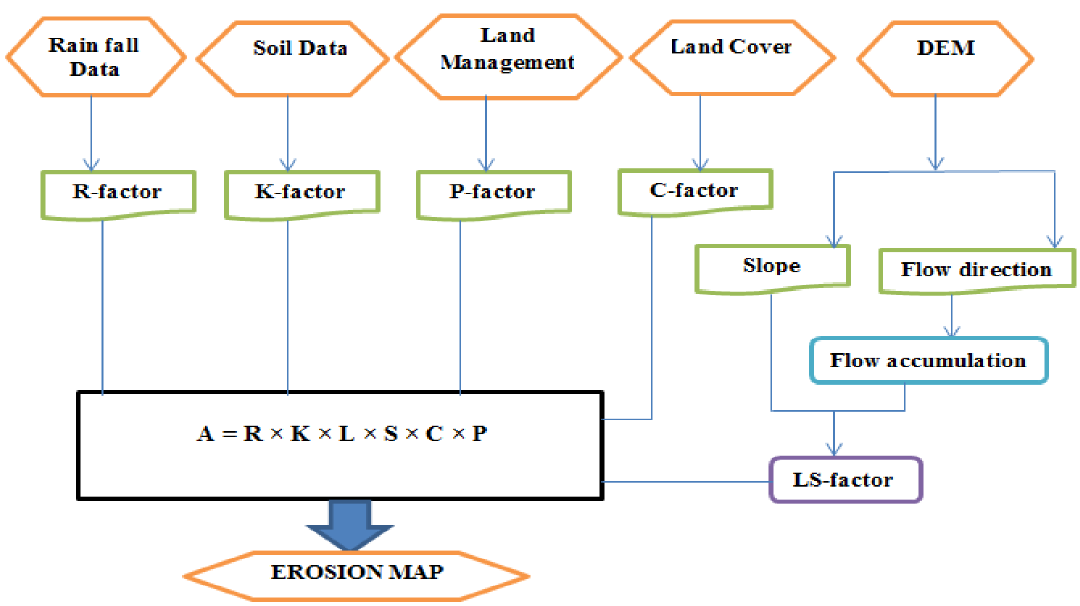

Fig. 2. Chart of research process.

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3.1. Rainfall erosivity factor (R-factor)

The rainfall erosivity factor R, combining the effects of the duration, magnitude, and intensity of rainfall events, can be used to measure the potential ability of rain to cause erosion. It reflects the potential effect of variations in climate and precipitation on soil erosion keeping all other factors constant. It is the basis for quantitative studies of soil erosion. We chose the formula suggested by (Hurni, 1985) which has been proven suitable for Ethiopia. The R-value is estimated according to the following equation:

$$R = -8.12 + 0.562P \quad \textbf{(2)}$$

Where **R** is the rainfall erosivity factor in MJ mm ha^{-1} h^{-1} $year^{-1}$ and **P** is the mean annual rainfall in millimeters.
For this study, mean annual rainfall data of six stations found in and around the study area, between 1984 and 2017, were obtained from National Meteorological Service Agency and used for the analyses. As a result, mean annual rainfall of the six stations were used to describe the spatiotemporal soil erosion patterns for the 14 years study period where the land cover map is used to determine C factors.

3.2. Soil erodibility factor (K-factor)

The K factor is an indicator of soil detachment and transport by raindrop impact and surface flow. It accounts for the influence of soil properties on soil loss during storm events in upland areas. The value of K is closely related to soil texture, organic matter content, structure and permeability. Different soil types have variable susceptibility to erosion. Fine textured clay soils and coarse textured sandy soils have low K values; medium textured silt and loam soils have moderate K values, while soils with high silt content have high K values due to their inherent physical property of soils (McCool et al., 1995; Renard et al., 1997). Therefore, K is a function of particle size, drainage potential, structural stability, organic matter content, and cohesiveness. For the analysis of K factor, standard digital database for soil type classification was obtained from Ministry of Agriculture and Rural Development of Ethiopia (FAO, 1997). According to FAO soil classification, Haplic Arenosols, Haplic Acrisols, Haplic Alisols, Rhodic Nitosols, Dystric Leptosols, Eutric Vertisols, Haplic Nitosols and Eutric Leptosols were identified in the study area. Finally, the vector format soil map was changed into grid and the grid dataset was reclassified with a cell size of 30 m × 30 m resolution into the corresponding K values using Spatial Analyst Tool of ArcGIS 10. The results of analysis indicated that K-factor values of the study area were ranged from 0.15 to 0.35 with the mean value of 0.275.

3.3. Gradient length (L) and slope (S) factors

The L and S factors, which are functions of slope inclination and slope length, are used to evaluate the effect of topography on erosion. Generally, soil erosion correlates with slope. Two factors, the slope length (L) and the slope steepness (S), are widely used to reflect the influence of the slope gradient on soil erosion. In RUSLE, the LS-factor represents a ratio of soil loss under given conditions to that at a site with the "standard" slope steepness of 9% and slope length of 22 m plot (Renard et al., 1997; Kaltenrieder, 2007). The steeper and longer the slope, the higher is the momentum to generate soil erosion. In this study, the technique for estimating the RUSLE LS-factor is computed based on flow accumulation and slope steepness in degree as proposed by (Moore and Burch, 1986 a, b):

$$\boldsymbol{LS} = (Flow\ accumulation * cell\ size/22.13)^{0.6} * (\sin slope * 0.0896)^{1.3} \quad \textbf{(3)}$$

Where flow accumulation denotes the accumulated upslope contributing area for a given cell, LS = combined slope length and slope steepness factor, with a resolution of 30 m × 30 m grid cell size and sine slope value of slope degree.

3.4. Land use/land cover management factor (C-factor)

The land cover and management practice factor C is used to reflect the effect of cropping and management practices on soil erosion rates in agricultural lands, and the effects of vegetation canopy and ground covers on reducing the soil erosion in forested regions (Renard et al., 1997) This factor considers the variability of the vegetation cover and methods of land management, reflecting their protective function to the topsoil (Xiao et al., 2015). Studies in highlands of Ethiopia and Eritrea indicated that the density of the crop cover is of crucial importance to determine the rainfall erosivity (Kaltenrieder, 2007). The C-values can vary from near zero for a very well-protected soil to 1.0 in barren soils before plant growth and 1.5 for a finely tilled surface that produces much runoff and leaves the soil and highly susceptible to rill erosion (McCool et al., 1995; Kim and Julien, 2006; Benzer, 2010).

3.5. Conservation practice factor (P)

In the steep areas, cultivation needs conservation to protect water and soil. This operation decreases waste water to the bottom of erosion threshold, so, it reduces the power of water erosion and it carrying capacity. Conservation operation includes contour cultivation, terracing system, covered streams and so on. P factor is proportion of eroded soil in conditions of protective operations to the erosion created in standard condition, that i's mean plowing in the slope direction (Renard et al., 1997). The P-factor values ranges from 0 to 1 depending on the soil management activities employed in an area. According to Prasannakumar et al. (2012), the highest value is assigned to areas with no conservation practices while minimum values correspond to built-up land and plantation area with strip and contour

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cropping. As a result, the lower P value, the more effective the conservation practices. Evaluation of the practices in RUSLE requires to estimate surface roughness and runoff reduction, but some of the P-factor values are slope dependent (McCool et al., 1995).

After providing required information layers of the model and preparing them as raster maps with pixel size of 30 meters, the map of annual soil erosion potential was extracted.

4. Results and Discussion

4.1. Land use land cover change

The land-use/land-cover maps were classified into six classes, such as cultivated land, grazing land, open forest, dense forest, grassland, shrub/bush land and water body with high classification accuracy for each period (2005 and 2017) given in Fig. 3. The spatial distribution of land-use/land-cover categories of the study area during the period 2005 and 2017 shows that agricultural land and dense forest areas have increased, while the extent of open forest land declined continuously from 2005 till 2017. A comparison of different land-use/land-covers during these years is shown in table 1. The detected changes represent either a loss or a gain in some LCLU in each period.

As illustrated in Table 1, the spatial gain extent and growth during 2005 to 2017 were for the dense forest area and agricultural land of, 4.74% (370 km²) and 48.73% (3805 km²), respectively. Moreover, another spatial extent loss between 2005 and 2017 was associated with the conversion of grazing land by 9.20% (719.5 km²), open forest by 33.16% (2588 km²), shrub and grass land by 3.22% (251.5 km²) and 7.62% (594.5 km²), respectively, to agricultural land and dense forest areas. The maximum change is related to the agricultural land, it has grown 6 times during 14 years. This growth indicates cultivation pattern changes and type of plants. Also, open forest cover has been reduced more than 2588 km² during this period of time.

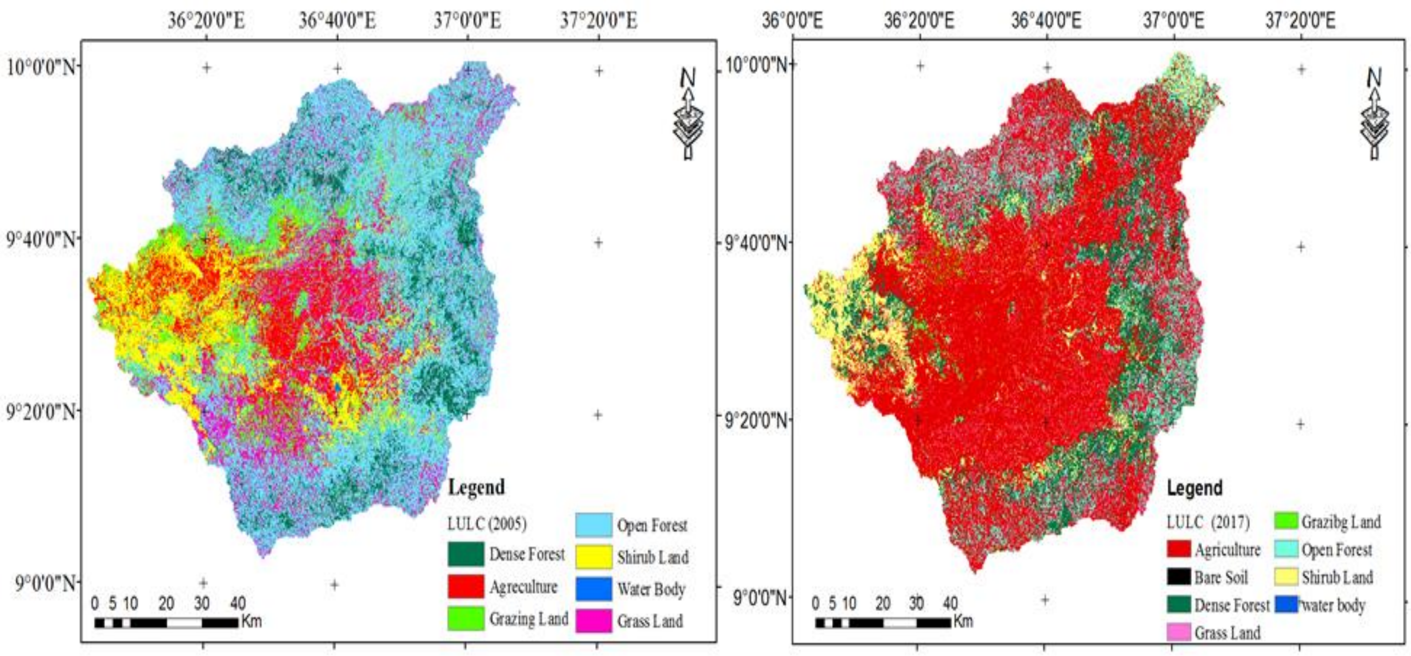

Fig. 3. Land cover classification map in 2005 and 2017.

Tab. 1. Land use- land cover area in 2005 and 2017 (km²)

Land use – land cover	Area (2005)		Area (2017)		Changes (2005-2017)
	Km²	%	Km²	%	
Dense forest	747	9.57	1117	14.31	4.74 %
Agricultural land	826	10.60	4631	59.33	48.73 %
Grazing land	776	9.94	56.5	0.74	-9.20 %
Open forest	3412	43.71	824	10.55	-33.16 %
Shrub land	971.5	12.44	720	9.22	-3.22 %
Grass land	1050.5	13.46	456	5.84	-7.62 %
Water body	22	0.28	0.5	0.01	-0.27 %

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4.2. Soil loss rates

According to the results of RUSLE model, the basin was divided into six classes in terms of soil erosion in two study years and it indicates soil sensitivity to erosion. The results for the year 2005 presented in Fig. 4 show that about 30.91 % (2413 km²) of the study area was of low potential erosion risk, while the rest of the area was under moderate to very sever erosion risk. In terms of actual soil erosion risk, 28.43% (2219 km²) of the area was of moderate risk, 33.40% (2607 km²) was of high risk and 0.04% (3 km²) was of very sever risk table 2.

In the year 2017, 20.43% (1595 km²) of the area was of low potential for erosion risk, 29.62% (2310 km²) was of moderate potential for erosion risk, 35.74% (2790 km²) was of high potential for erosion risk and 0.24% (19 km²) area of very sever potential for erosion risk. There was an increase of very high and moderate soil erosion risk compared with the year 2005.

The mean soil erosion potential in Hanger river watershed for 2005 and 2017 has been estimated about 55.5 and 70.5t ha^{-1} year^{-1} respectively. For the High and Very high classes, the values increased from 33.40% to 35.74% and 6.36% to 12.81% respectively from 2005 to 2017.

The results of 2017 indicated that 78.17% of the watershed area was subject to soil loss between 5-50 t ha^{-1}year^{-1} while 1.40% of the area was subject to soil loss greater than 50 (>50) t ha^{-1}year^{-1}. Soil loss below the tolerance level (<5 t ha^{-1}year^{-1}) represented only 20.43% of the watershed area.

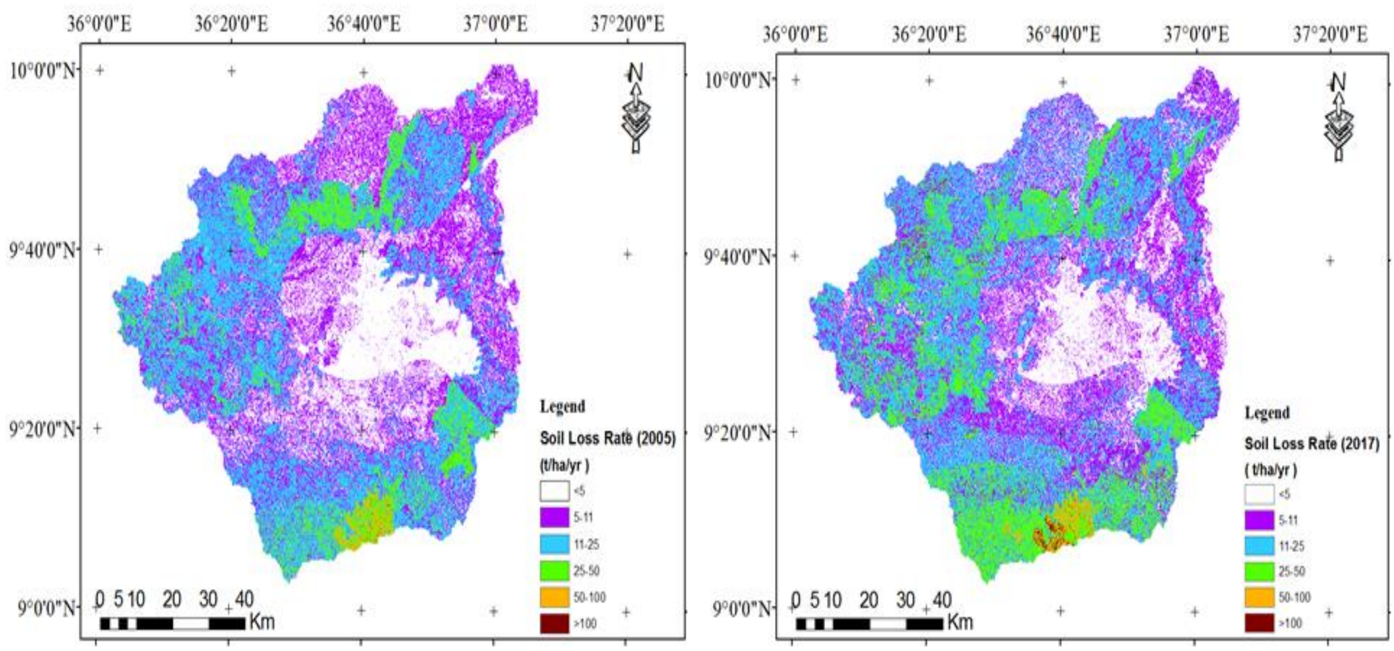

Fig. 4. Spatial distribution map of annual soil erosion potential for 2005 and 2017 (t ha^{-1}year^{-1})

Tab. 2. The area of soil erosion potential classes (t ha^{-1}year^{-1}) for two study years

Soil erosion potential (t ha^{-1}year^{-1})	Area (2005)		Area (2017)		Changes rate percent
	Km²	%	Km²	%	
Low (0-5)	2413	30.91	1595	20.43	- 10.48 %
Moderate (5-11)	2219	28.43	2310	29.62	1.19 %
High (11-25)	2607	33.40	2790	35.74	2.34 %
Very high (25-50)	496	6.36	1000	12.81	6.45 %
Sever (50-100)	67	0.86	91	1.16	0.30 %
Very sever (> 100)	3	0.04	19	0.24	0.20 %

5. Conclusion

The study of risks of erosion in the Hanger watershed was done using the Revised Universal Soil Loss Equation (RUSLE) integrated into a GIS. The various factors involved in the processes of erosion were identified and their combination into a GIS environment resulted in soil loss results of the watershed. All the identified land use/land cover (LULC) types have undergone both spatial and temporal changes over 14 years (2005–2017): sharp

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decrement for open forest (33.16%) and grazing land (9.20%) lands and increment for farm (48.73%) and dense forest (4.74 %) lands. Various open forest and grazing lands were changed to agricultural lands following the change of land use policy in Ethiopia in the 1970s for food self-sufficiency. Consequently, there was a significant shifting of natural vegetation areas to agricultural, grazing and other land use types.

In general, the expansion of agricultural land is at high rate, causing formation of erosion prone areas highly susceptible to soil erosion. Improvement of present agricultural and livestock management practices and introduction of appropriate soil conservation measures are essential for mitigating erosion and for improving the welfare of the community in the watershed. The cultivation practice, in the study area, is mainly dependent on a traditional rain fed agriculture, and the livestock are fed entirely on natural grassland. If this condition is allowed to continue in same way in the future, land degradation could endanger the sustainability of agriculture and the availability of natural resources in the area. Current procedures may in future be a major cause of land degradation in the watershed, leading to decline in crop production as well as shortage of forage for livestock; unless measures to conserve natural resources are taken.

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