Research Article

Modeling soil erosion susceptibility and LULC dynamics for land degradation management using geoinformation technology in Debre Tabor district, Northwestern highlands of Ethiopia

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Abstract: Land degradation manifested in landscape change is triggered by soil erosion and it is a thoughtful environmental threat. Nationally, soil loss costs 23% of the national annual GDP. Thus, identifying and prioritizing land degraded areas for conservation in regional planning and resource conservation is the priority of land degradation management. Therefore, identification of erosion hazard area and land use and/or land cover (LULC) dynamics are the overall objectives of the study. GIS and Remote Sensing technology was used to identify erosion hazard areas. K-factor, R-factor, LS factor, P-factor, and C-factor, parameters were derived from mean rainfall, Digital Elevation Model, soil map, LULC map, and ground truth points of all the parameters used to identify erosion hazard areas. At the last, the aggregate effect of those parameters had been analyzed and erosion hazard areas were identified. The Revised Universal Soil Loss Equation (RUSLE) was employed to estimate the annual soil loss of the area. The analysis result unveils that within 20 years interval cultivated land, urban land, and bare land show that a dramatically increasing and forest land shows that decreasing rate. The district has undergone significant changes. Portions of the study area that has the highest slope gradient, the highest amount of rainfall, and consist of Nitosols on agricultural land are the most erosion hazard areas. Statistically, nearly 49%, 19.78%, 9.58%, and 5.45% of the study area coverage lower than moderate, high, very high, and severe soil erosion class correspondingly. Annually losses on average of 41.07 t/ha/year soil loss because the area is intensively cultivated and experiences relatively high rainfall, and steep slope. The share of the study area, southern part, and northeastern portion of Debre Tabor district are exposed to high erosion hazard class compared to other parts.

Keywords: GIS, land degradation, remote sensing, RUSLE, soil erosion

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Introduction

Environmental hazards and jeopardies in the world are strictly related to the misuse of environmental resources, mostly terrestrial resources (Boardman et al., 2009; Gashaw et al., 2014). However, unwise use of these resources disrupts the land and induces natural hazards, such as soil erosion (Bishaw, 2001; Nigussie et al., 2017; Tanto and Laekemariam, 2019). Soil erosion is one of the greatest severe types of land degradation, in which it affects agricultural productivity, food security, and the national economy of the country (Mhiret et al., 2019; Thapa, 2020). Accelerated erosion due to anthropogenic factors at a global scale was causing reservoir sedimentation, river morphology changes, and river bed siltation (Hailu, 2017; Tessema et al., 2020), and it had been a chronic problem ever since the beginning of settled agriculture and remained the same in the 21st
century, especially in developing countries like Ethiopia (Megersa, 2014).

Land degradation is a key hazard to growth in most economies of developing countries (Bishaw, 2001; Molla and Sisheber, 2017) spatially, it is a serious environmental problem and risk to the highlands of Ethiopian (Gashaw et al., 2014; Nigussie et al., 2017; Tanto and Laekemariam, 2019). Annually, 1900 million tons of soil was eroded from the uplands of Ethiopia, which is comparable to a regular disposable soil loss of 100 t/ha/year (Phinzi and Ngetar, 2019; Thapa, 2020). Ethiopia’s exaggerated population growth over the last 50 years and future predictions of a growing population has placed risky pressure on the land, which resulting in accelerated soil erosion (Hawando, 1997). Soil erosion and land degradation happened because the production system was based on unceasingly expanding land for cultivation, rather than increasing the production per unit area (Marques et al., 2007). According to the Ethiopian highland reclamation study (Wolka et al., 2015) 14 million hectares of highland area seriously eroded. This implies that soil erosion is sensitive in most high land parts of Ethiopia. To control extra degradation on erosion hazard area, recent information on the extent and spatial distribution of erosive area is important (Mhiret et al., 2019). This information is vital for cost-effective soil conservation planning (Anejionu and Nwilo, 2013).

The loss of soil in Debre Tabor district from cultivated land can prime to a decrease in crop yield manufacture potential, degrade drainage networks, and minor surface water quality (Hailu, 2017; May et al., 2005). Debre Tabor district, some area gets a high amount of rainfall on an arable steep slope that causes high runoff generation (Molla and Sisheber, 2017; Tessema et al., 2020). By way of a consequence, soil wearing away is a serious problem in the area. This problem leads to the formation of gullies from time to time in many parts of the woreda. So, these situations have their effect on the agricultural and socio-economic activities of the people. Hence, the impartial of the research was, modeling Soil erosion vulnerable area and LULC dynamics for land degradation management with peasant associations using geo-informatics technology within 20 years’ interval (2000-2020) at Debra Tabor district in the highlands of Ethiopia.

This research was supposed to find out the extent of soil erosion problems and recommend giving attention to extremely eroded areas in Debre Tabor district to apply appropriate conservation practices.

Method and Materials

Study area

Debre Tabor was found in the north-central highland of Ethiopia and it was the capital of Ethiopia under Emperors Tewodros II, the town was now, one of the districts of South Gonder Zone, Amhara region after 1991 of the new regimes of Ethiopia. It is positioned within astronomical coordinates of 37°50′–38°10′ East Longitude and 11°45′–11°55′ North Latitudes. It covers 11088.42 hectares. It is relatively situated in the Amhara Regional State of Ethiopia. It is 100 km far away from the southeast of Gondar, 667km from Addis Abeba (the capital city of Ethiopia), and 50 kilometers east of Lake Tana, this historic town has an average elevation of 2,706 meters (8,878 ft) above sea level (Figure 1).

Dataset, processing, and analysis

The dataset for the study was collected from ground control points, filed observations. Sentinel-2A Satellite image with a resolution of 10m was used for LULC classification, which was downloaded from the website: www.earthexplorer.usgs.gov. A Geo-informatics application was employed for all variables of soil erosion identification, which are rainfall, slope, land use land cover, and soil data by applying the basic image preprocessing techniques. The study used interpolation, regression, re-classify, weighted overlay analyzing, combining, map algebra of GIS Spatial Analysis technologies to identified eroded areas. The satellite data of the area was clipped from 169 path and 52 rows that, were preprocessed, manipulated, and analyzed by using Geospatial Packages. The LULC of the study area change matrices was done quantitatively. Finally, the amount of area exposed to high erosion hazard quantified, and peasant association vulnerable to high erosion hazard was expressed quantitatively. All the primary and secondary data was collected, preprocessed, manipulated, analyzed, and interpreted in three phases: Pre-fieldwork, fieldwork, and post fieldwork. Pre-fieldwork was the initial step and was include the Literature review of existing reports, journals, publications, and in the final stage ground points was collected for accuracy assessment of LULC and soil erosion risk identification.

Sampling techniques and size

The sampling frame and sample size for this particular study are rural peasant associations that are found in the study area by using stratified random sampling. Stratified random sampling is
good to make sure that small, but important LULC are represented in the frame (Fothergill et al., 1971; Geen et al., 2000; Wolka et al., 2015). Respectively LULC class was measured as a layer. The number of model schemes was spatial resolution multiplayer by the number of bands, (Wim, et al 2001) in this case 10 × 12. Circular shape units were employed for the gain of its extent limit and fewer edge tree consequence and relaxed of arrangement.

![Map of Debre Tabor District](image)

Figure 1. The map of Debre Tabor District.

**Modeling of RUSLE and erosion susceptible**

Modeling soil erosion is the procedure of statistically recitation soil element detachment, transportation, and confession on terrestrial surfaces and it can be castoff as extrapolative apparatuses for evaluating soil erosion aimed at management preparation, soil loss records when soil erosion is happening, and for sympathetic erosion processes (Marques et al., 2007; Tessema et al., 2020). Sophisticated and properly standardized models provide good estimations of soil erosion risks. Universal Soil Loss Equation (USLE) was advanced reviewed in 1997 to improved the evaluation of the values of several restrictions and developed Revised Universal Soil Loss Equation (RUSLE) (Biswas and Pani, 2015; Desalegn et al., 2018; Kamaludin et al., 2013). The RUSLE integrates perfections in the influences founded on original and improved data but preserves the foundation of the USLE equation. RUSLE model stood established as a comparison representing key issues affecting soil erosion, specifically rainfall, soil types, slope, LULC characteristics (Bagwan, 2020; Balabathina et al., 2019; Boardman et al., 2009; Kheir, 2007).

After the data of those parameters collected, investigation and meting out were complete by categorizing the compulsory evidence of respectively thematic layer utilizing Geospatial technology. At the last, the influence of all parameters for soil erosion was weighted to map erosion hazard area (Figure 2).

The equation is expressed as: -

$$A = K \ast R \ast LS \ast C \ast P$$

where: A= average annual soil loss (t/ha/year), R= rainfall erosivity factor (MJ mm ha/h/year), K= soil erodibility factor (T ha h ha/MJ/mm), L= slope length and steepness factor, C= LULC factor, P = support management factor.

**K factor (soil erodibility)**

Soil erodibility factor (K) discusses the characteristic of soil vulnerability to the push factor of soil erosion by water (Desalegn et al., 2018; Le Roux, 2011). Soil erodibility was
calculated from soil texture, soil organic substance content, soil structure, and soil permeability data (Kayet et al., 2018; Molla and Sisheber, 2017). Soil record was obtained from the Ethiopian Ministry of Water. Different soils have different capacities to resist soil erosion. According to (Molla and Sisheber, 2017), soil classification, three major soil categories were recognized in the area, which are Vertisols, Luvisols, and Nitosols with a K factor of 0.15, 0.20, and 0.25 correspondingly.

**R factor (rainfall erosivity)**

Rainfall is one of the agents of soil erosion. The rainfall erosivity factor represents the erosive force of specific rainfall events (Kamaludin et al., 2013; Sahu et al., 2017). R factor is resolved by the quantity, strength, and spreading of rainfall (Tadesse et al., 2017; Woldemariam and Harka, 2020). A rainfall data from 57 sample meteorological stations covering the period 2000-2020 obtained from the Ethiopian Metrology Agency was used, that processed and analyzed by using Interpolating methods in ArcGIS.

According to (Ashiagbor et al., 2013; Mitasova et al., 2013), R factor classification, the interpolated rainfall data of Debre Tabor district with the average yearly rainfall varieties from 610.89 to 763.38 mm (Figure 2). The erosivity factor of the area was intended utilizing the equation of a rate of 0.88 tall association for monthly precipitation (x) and monthly erosivity was found in the Ethiopian highlands (Batista et al., 2017; Moges and Bhat, 2017) using the regression equation,

\[
R = -8.12 + (0.502 \times P) \quad \text{Eq (2)}
\]

where R is rainfall erosivity (MJ mm h/ha/year/ and P, are mean annual rainfall (mm)

**LS factor (slope length and steepness)**

The Slope length and steepness factors in RUSLE are a grouping of slope length (L) and slope steepness (S) factors (Bishaw, 2001). The LS influence is measured in the soil loss comparison model because both the length and the steepness of the gradient significantly disturb the rate of soil erosion by water (Lahlaoi et al., 2015; Megersa, 2014).

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**Figure 2. Analytical flow chart of RUSLE soil erosion identification and LULC Matrixes.**
The vertical and the stretched the gradient, the higher is the degree of destruction by water because of the bigger accumulation of runoff (Senanayake et al., 2020). The LS factor was computed from an equation,

$$LS = \left( \frac{A}{10} \right) \times \left( \frac{\sin \theta}{0.033} \right)^{1.4}$$  

Eq (3)

Where: LS = the slope length and steepens, A = the product of flow accumulation and cell size (10m by 10m), $\theta$ is the gradient in degrees that extracted from ASTER–DEM with a spatial resolution of 10m.

**C factor (land cover)**

The capacity of land use to resist soil erosion is dependent on its land cover and use type (Foster et al., 2003; Roslee and Sharir, 2019). According to (Hurni, 1985), different land uses take unlike measurements to resist soil erosion. The LULC of the area 2000 Landsat-5 TM and Sentinel-2A 2020 was used and classification by supervised classifier algorism. After the sorting was done, 86% of accuracy assessment was achieved. Furthermore, field visits were carried out to get the highest possible precision. Five LULC types were found in the area. The two-year within 20 years’ interval of a thematic image of LULC type variation recognition was done quantitatively for change detection to control the changes in LULC.

**P factor (management practices)**

The management factor (P) refers to the proportion of soil loss with a detailed provision preparation to the matching loss with up and fall cultivation (Molla and Sisheber, 2017). The statistics linked to managing performances of the area were together from major land cover and gradient collaboration that adapted by (Collins et al., 1996; Zerihun et al., 2018). Field surveys also other alternative values for this factor. For agricultural lands, the greatest significant conservation preparation factor (P) includes delineation farming, terracing, and strip harvesting (Anejionu and Nwilo, 2013). The consistent P standards were allocated to respectively LULC and gradient class (Figure 2). The P standards variety between 0 and 1 (Hurni 1985), where the highest values correspond to bare land without any support practices (Nigussie et al., 2017).

**Results and Discussion**

**Trends of LULC dynamics and matrix**

Land use arrangement is misinterpreted in Debre Tabor district, without the proper planning of LULC changes influences of climate and weather conditions are high. According to 2000 LULC (Figure 6 (a) and Table 1), the study area was dominated by cultivated land, shrubland, forest land, Bare land, and Urban which covers 3800.85ha, 3693.92ha, 1990.03 ha, 1495.70ha, and 107.92ha of the study area respectively from highest to lowest area coverage. The greatest part covered by vegetation, the summation of shrubland, and forest accounts for more than 51% coverage part of the study, this shows that the study area before 20 years has a balanced ecosystem and land degradation. The LULC result of 2020, (Figure 6(b) and Table 1) showed that the highest coverage of the area is cultivated land, which covers 42.15%, followed by shrubland which covers 35.72%. Generally, from the above result Cultivated land, Urban land, and Bare land show that a dramatically increasing and forest land also shows a decreasing rate with comparing to 2000 LULC class to 2020 land-use class within 20 years gap.

As shown (Table 1), only 94.11ha of an urban area in 2000 keep on the same in 2020. The remaining had altered to other LULC types. Further, only 583ha out of 1990.03ha of the area that was enclosed with forest in 2000, that motionless below the identical cover in 2020, the rest was changed to other LULC types in 2020, 935.02ha to shrubland, 448ha to cultivation, 17.41ha to bare land and 6.54ha to urban land. Mostly, in 20-year, apparent that forest land LULC was most at risk of changing and it decreases the vegetation coverage of the area.

**Erosion risk identification**

Erosion hazard extent identification and prioritization is a significant part of preparation for employment of land degradation and natural resource conservation program (Boardman et al., 2009; Geen et al., 2000). Soil loss is the result of the interaction between different factors such as the amount of rainfall, soil type, slope extent, LULC characteristics, and type of soil and water conservation and management preparation of the area. Therefore, categorizing the whole woreda based on the severity of erosion class is important to detect significant area identification for further terrestrial degradation management concerning soil loss susceptibility based on areal coverage and geographical location were identified. As shown in the RUSLE result (Figure 4(a) and Table 2(a)), the soil type erodibility distribution of K factor of Debre Tabor district, three types of soil, namely Vertisols, Luvisols and Nitosols covers 14.24%, 47.87%, and 37.94% of the area coverage correspondingly. The soil loss distribution of the soil type of Vertisols, Luvisols, and Nitosols also ranges from moderate, high, and
very high erodibility. Subsequently, the rainfall erosivity R factor (Figure 4(b) and Table 2(b)), was computed from the mean annual rainfall data of the entire area using Eq (2). The estimated R factor varieties from 379.52 to 409.51 MJ mm ha/h/year. As per (Figure 4(c) and Table 2(c)), the LS influence classification, the area stood classified into five erosivity class from less than 5, 5 to 10, 10 to 15, 15 to 25, and 25 percent of gradient inclination are leveled to low, moderate, high, very high and sever soil erosivity with an area coverage of 19.41%, 33.80%, 24.08%, 18.28% and 4.43% from the total area coverage of 11088.42ha. An area that has the highest slope gradient above 15% slope gradients needs serious conservation treatment.

Table 1. Matrix of LULC change of 2000 up to 2020.

| LULC dynamics matrix | Urban | Cultivation | Bare land | Shrub land | Forest | Total area (ha) |
|----------------------|-------|-------------|-----------|------------|--------|----------------|
| LULC type in 2000 (ha) |       |             |           |            |        |                |
| Urban                | 94.11 | 3.21        | 10.39     | 0.21       | 0.00   | 107.92         |
| Cultivation          | 29.00 | 2681.84     | 216.61    | 780.79     | 92.61  | 3800.85        |
| Bare land            | 35.57 | 482.70      | 573.03    | 115.01     | 289.39 | 1495.70        |
| Shrubland            | 24.01 | 1058.09     | 327.00    | 2130.02    | 154.80 | 3693.92        |
| Forest               | 6.54  | 448.00      | 17.41     | 935.02     | 583.06 | 1990.03        |
| Total area (ha)      | 189.23| 4673.84     | 1144.44   | 3961.05    | 1119.86| 11088.42       |

Figure 4. RUSLE Soil erosion distribution map, (a) soil type K factor distribution, (b) rainfall R factor distribution, (c) slope LS factor distribution.
Table 2. RUSLE soil erosion distribution result, (a) slope K factor distribution, (b) rainfall R factor distribution, (c) slope LS factor distribution.

| Soil Loss Level | Soil Type | (a) K Factor | Area (ha) | Area (%) | (b) Rainfall (mm) | R Factor | Area (ha) | Area (%) | (c) LS Factor | Area (ha) | Area (%) |
|-----------------|-----------|--------------|-----------|----------|-------------------|----------|-----------|----------|---------------|-----------|----------|
| Low             | --        | ---          | ---       | ---      | ---               | ---      | ---       | ---      | ---           | 2152.43   | 19.41    |
| Moderate        | Vertisols | 0.15         | 1578.69   | 14.24    | 14.24             | ---      | ---       | ---      | 3747.67       | 33.80     |          |
| High            | Luvisols  | 0.20         | 5302.59   | 47.82    | 610.89 - 730     | <390     | ---       | ---      | 2670.32       | 24.08     |          |
| Very High       | Nitosols  | 0.25         | 4207.15   | 37.94    | 730 - 750        | 390 - 405| 6068.76   | 54.73    | 2026.52       | 18.28     |          |
| Sever           | ---       | ---          | ---       | ---      | 750 - 763.38     | >405     | 2640.41   | 23.81    | 491.48        | 4.43      |          |
| Total           |           |              | 11088.4   | 100      |                   |          |           | 11088.4  | 100          |           |          |

Table 3. RUSLE Soil erosion distribution result, (a) C factor distribution, (b) P factor distribution.

| Soil Loss Level | LULC Type | (a) C Factor | Area (ha) | Area % | (b) LULC Type | Slope | P Factor | Area (ha) | Area % |
|-----------------|-----------|--------------|-----------|--------|---------------|-------|----------|-----------|--------|
| Low             | Forest    | 0.001        | 1119.86   | 10.10  | Other LULC Type | >15   | 1        | 6414.58   | 57.85  |
| Moderate        | Shrub land| 0.01         | 3961.05   | 35.72  |                |       |          |           |        |
| High            | Bare land | 0.08         | 1144.44   | 10.32  |                |       |          |           |        |
| Very High       | Urban     | 0.09         | 189.23    | 1.71   | Cultivated     | 0-5   | 0.12     | 1937.05   | 17.47  |
| Sever           | Cultivated| 0.15         | 4673.84   | 42.15  |                | 5-15  | 0.25     | 2736.79   | 24.68  |
| Total           |           |              | 11088.42  | 100    |                |       |          | 11088.42  | 100.00 |
According to (Figure 5(a) and Table 3(a)), the result of RUSLE, five LULC types was recognized, forest, shrubland, bare land, urban and cultivated with an erosivity value of 0.001, 0.01, 0.08, 0.09 and 0.15 respectively. In addition to that, the cultivated land and shrubland cover the highest area coverage of 42.15% and 35.72% correspondingly, which is when the area is covered by cultivation land the rate of erodibility is high with comparing to other land use land cover class. A Land that has a vegetation cover is categorized by low overflow, whereas land with poor vegetation protection is categorized by high overflow, runoff, and sensitive to soil erosion for the reason that of low external irregularity. Subsequently, the result also shows that (Figure 5(b) and Table 3(b)), the management and conservation practices of P factor were extracted based on LULC type and gradient of the LULC class. P factor was grouped into three classes of erodibility cultivated 1, cultivated 2, and other LULC classes with extended exposure of 17.47%, 24.68%, and 57.85% of the area coverage from the total area of 11088.42ha, and the P-value was assigned to be equal to 1 for this study except for agricultural land.

**Peasant association exposed to erosion hazard**

The spatial distribution of soil loss hazard areas in Debret Tabor district is uneven. It is known that conserving the whole peasant association effectively is difficult. So, identifies peasant associations which are exposed to severe erosion hazard classes were necessary for land degradation and natural resource conservation program. A result of the erosion risk map in (Figure 6 and Table 4) showed that 48.70% and 19.78% of the total area is subject to moderate and high risk for soil erosion respectively. Furthermore, most of the kebeles including Debret Tabor town, Tsegur Adiko, and Debret Tabor Eyesus in the part were subjected to high and very high hazard of soil loss and erosion that received a higher amount of rainfall on a steep slope and consisted of susceptible soil on agricultural land. The southern part of the area is categorized by high soil erosion risk due to the relatively high slope steepness, rainfall, and soil with high erosion vulnerability. Whereas, the central and northeastern parts of the study areas were labeled as low and moderate soil erosion risk areas.

The quantified soil loss in Debret Tabor district was identified and mapped into five soil erosion risk levels such as: low, moderate, high, very high, severe with consideration of a country’s tolerable soil loss rate (5 - 12 t/ha/year) besides the degree of soil formation (Hurni, 1985). In the study area, nearly 49% (5399.60ha), 19.78% (2193.79ha), 9.58% (1062.19ha), and 5.45%(604.85ha) reduction below moderate, high, very high, and severe soil loss class correspondingly (Table 4). Only 16.49% (1827.99ha) of the extent coverage is below a low soil erodibility degree. Debret Tabor district annually losses on average of 41.07 t/ha/year soil with all most more than the extent is under moderate and high soil erodibility class because the area is intensively cultivated and experiences relatively high rainfall, and steep slope (Figure 6 and Table 4).
Table 4. Soil loss and soil erosion class of Debre Tabor district.

| Soil erosion class | Soil loss (t/ha/year) | Mean soil loss (t/ha/year) | Area (ha) | Area (%) | Total soil loss (t/ha/year) |
|--------------------|-----------------------|-----------------------------|-----------|----------|-----------------------------|
| Low                | 0-5                   | 1827.99                     | 16.49     | 2812.00  |
| Moderate           | 5 - 10                | 5399.60                     | 48.70     | 4323.12  |
| High               | 10 - 20               | 2193.79                     | 19.78     | 2828.60  |
| Very high          | 20 - 40              | 1062.19                     | 9.58      | 937.49   |
| Sever              | 40 – 82.14            | 604.85                      | 5.45      | 187.20   |

Conclusion
GIS and Remote sensing technology are vital for derivation of the different geospatial constraints, such as rainfall, slope, soil, and LULC for overlay analysis, geospatial problem solving to investigate areas that are sensitive to soil erosion at Debre Tabor district. The LULC change of the area within 20-year from 2000 up to 2020 shows that urban land, bare land, and cultivation land illustration a growing LULC alteration exposure and forest land were most at risk of changing and it decreases the vegetation coverage of the area. In the west, south, and southwest parts of the area, most peasant associations are highest exposed to serious erosion hazards. So, peasant associations which are exposed to high erosion hazard classes, spatially Tsegur Adiko, Debre Tabor Eyesus should have given due attention during land degradation, soil, and water conservation program.

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