Estimation Of Soil Loss Using Remote Sensing And GIS-Based Universal Soil Loss Equation In Northern Catchment Of Lake Tana Sub-Basin, Upper Blue Nile Basin, Northwest Ethiopia

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ABSTRACT

Background: Soil erosion, one of the major environmental challenges, is influenced by topography, climate, soil characteristics, and human activities and has a significant impact on potential land productivity and food security in many highland regions of Ethiopia. The present study attempts to estimate soil erosion risk in the Northern catchment of Lake Tana basin, situated in northwest part of Ethiopia, with available data through the application of the Universal Soil Loss Equation model integrated with Geographic Information System and remote sensing technologies to identify priority areas for controlling soil erosion. In addition, it analyzes the effect of land use and land cover, topography, erodibility, and drainage density on soil erosion potential of the catchment, and the possible relationships among them.

Results: The results show that the mean annual soil loss of catchment is estimated at 37.89 ± 59.2 t ha⁻¹ yr⁻¹ with a total annual soil loss of 1,705,370 tons. The topography (LS-factor), followed by the support practice (P-factor) and the soil erodibility (K-factor) were the most sensitive factors affecting soil erosion in the catchment. To identify high priority areas for management, the study area was subdivided into five major sub-basins and further categorized into five erosion classes based on erosion severity. The mean soil erosion rates of the Derma, Megech, Gumara, Garno, and Gabi Kura River sub-basins are 46.8, 40.98, 30.95, 30.04, and 29.66 t ha⁻¹ yr⁻¹, respectively. About 58.9% of the area was found in very low erosion risk which extends from 0-1 t ha⁻¹ yr⁻¹ and accounted only 1.1% of total soil loss, while 12.4% of the area was found to be under high and extreme erosion risk with erosion rates of 10 t ha⁻¹ yr⁻¹ or more that contributes about 82.1% of total soil loss warrant high priority for reducing the risk of soil erosion.

Conclusions: This study permits the understanding of the soil erosion process and the various factors that lead to the spatial variability of the risk in the catchment, and thus enhances the effectiveness of proposed conservation strategies for sustainable land management.

Keywords: Soil erosion, Universal Soil Loss Equation, Geographical information system, Remote sensing, Northern catchment, Lake Tana basin
1. Background

Soil erosion, one of the severe land degradation problems in many parts of the world, is a natural process that varies according to natural and anthropogenic factors, leading to loss of nutrient-rich topsoil, soil productivity, biodiversity, and increased runoff from more impermeable subsurface, along with indirect damage to the environment (Kim et al. 2005; David Pimentel, 2006). Estimates show that about 85% of land attenuation, globally, is because of soil erosion reducing crop productivity by about 17%, affecting the soil fertility initially and in the long term resulting in land desertion (Singh and Panda, 2017). This is commonly regarded as a major environmental problem and has become a serious threat to sustainable agricultural production and water quality, which has effects on the country’s economy. Soil degradation remains a serious and widespread problem in many developing countries, where soil fertility is inherently low, infrastructure for soil management is poorly developed as well as high population growth, intensified use of already stressed resources and expansion of agricultural frontiers to marginal and fragile lands are quite common.

Land degradation is a major concern in many African countries that lack adequate data, infrastructure, scientific support, and land concentration to combat the problem. With Ethiopia, it is a common feature of landscape with severely eroded highlands that many view this issue as the country’s primary environmental problem and have significant effects on the crop yields, the productivity of the agricultural lands, and their overall sustainability. Hurni (1993) estimated that the gross soil loss for cropland was at 42 t h⁻¹ yr⁻¹, while the average soil loss for all land in the highlands was at 100 t h⁻¹ yr⁻¹ (Jan Bojo and David Cassells 1995). It estimates the annual crop production losses to soil erosion to be 1 to 2% (Bezuayehu et al. 2002; Anbes Tenaye, 2020) and these losses represent an annual decline of 0.3% in the value of global production (Scoones, 2001). This would, therefore, pose a major threat to food security, the livelihood of farmers, and poverty in the country since 80% of its population solely depends on agriculture as a source of employment and income. According to Hurni (1985), the soil erosion rates are extreme, with about 3.5 billion tons of soil eroded each year from the highlands, of which a considerable portion (1.5 billion tons) leaves the country through its rivers. Already in the early 1990s, FAO (1986) reported that about half (27 million hectares) of the highland area was significantly eroded, and over 14 million hectares of the highland area was seriously eroded and over 2 million hectares are described as beyond the point of no return (Moges et al. 2019).

Soil erosion by water is the dominant degradation process in the highlands of Ethiopia (Bekele Tsegaye, 2017) and has its major impact on soils because of diverse physiographic features, soil characteristics, and unique climatic conditions (Barber, 1984). The area of most intense population and livestock density and the area of land degradation, recorded measurements of soil loss by water erosion range from 3.4 to 84.5 t h⁻¹ yr⁻¹ with a mean of 32 t h⁻¹ yr⁻¹ (Berry et al. 2003) Decades of continuous population growth rates (current estimate at 2.7% per annum between 1950 and 2019) (CSA, 2019) have induced an increasing demand for crop and livestock food products, causing over-farming, intensive grazing, deforestation (currently the rate at 15000
ha/yr in the period 2010-2020 and only less than 3% have closed forest cover) (FAO, 2015; Temesgen et al. 2014) and agricultural expansion towards steep slopes and marginal lands (Negasi et al. 2018). As a result, the area is characterized by shallow soils, diminished water holding capacity, secondary salinization, and greatly reduced forest (current estimate at 1.25 ha/yr) and woody vegetation cover (1.8 ha/yr) (Asefa et al. 2003; FAO, 2015). Furthermore, FAO (2015) stresses that over the last five decades, the impact of land degradation on soil productivity has been declining at an alarming level, and many habitable areas are transforming into drylands and wastelands as well as high soil erosion rates on steep and marginal lands. However, inappropriate land management practices and land-use changes as well as intense road construction in fragile areas are among the most well-known causes of land degradation and desertification. It is, therefore, important to estimate the soil loss, the spatial pattern, and extent of soil erosion risk within the watershed. This provides a detailed understanding of the processes and factors that affect soil erosion as well as potential soil losses in relation to land-use change and landscape position. Such an understanding is essential to improve land management practices for planning and implementation of effective soil conservation measures for sustainable management and thereby reducing the soil erosion risk.

Soil erosion models have been used widely all over the world for the assessment and prediction of soil loss due to water runoff. The most widely applied soil erosion models are Universal Soil Loss Equation (USLE), its improved version the Revised Universal Soil Loss Equation (RUSLE), the European Soil Erosion Model (Euro SEM), the Soil Loss Estimation Model for Southern Africa (SLEMSA), the Water Erosion Prediction Project model (WEPP), the Agricultural Non-Point Source Pollution Model (AGNPS), and the Revised Morgan-Morgan-Finney model (RMMF). Most of these models were developed to predict soil loss in particular conditions, but applying these models to any other location is problematic essentially it requires particular validation and specific local data (Smit, 1999; Jim, 2005). Among various models developed globally, USLE (Wischmeier and Smith, 1978) is the most widely known and used empirical model and represents simple to understand and easy to apply technology which has been of substantial benefit to soil conservation and land management in temperate regions (Smit, 1999). However, most of the improvements from the RUSLE model (Renard et al. 1997) are difficult to adapt to the new locations that lack decades of continuous requisite data (Kim et al. 2005), such as rainfall kinetic energy, maximum 30 min rainfall intensity, and soil erodibility. As such essential input data are scarce in our research site, the available data sources such as remote sensing image, climate, soil type, digital elevation model (DEM), and land use/land cover maps were used with the USLE to predict the spatial distribution of soil erosion. Pham et al. (2018) also pointed out that the combination of available data sources used with the USLE and geographic information system (GIS) technology is a viable option to calculate soil erosion, which would allow targeted attention toward a solution to reduce future soil erosion. Furthermore, Kim et al. (2005) reported that the USLE and GIS together provide a first-order method for prioritizing areas to be examined and remediated, yet despite some problems in applying USLE for a large area and/or the tropic regions since it was developed at the unit plot
scale and temperate environment. Keeping in view of the above aspects, the present study carries out estimation of soil loss in the Northern catchment of Lake Tana sub-basin, NW Ethiopia through the USLE using remote sensing technologies and GIS.

As the estimation of soil erosion risk in the research site, it was still not well established, our study aimed (i) to identify and characterize areas with high erosion potential, (ii) to identify the probable spatial relationships between erosion rates and geographic factors namely topography, altitude, land use, soil erodibility, drainage density, and land cover, (iii) to understand the soil erosion due to land transformations in the catchment, (iv) to calculate soil erosion potential during the dry and the wet seasons; and (v) to determine the most important USLE factors that control the soil erosion risk in the study area. This paper provides information about the erosion process, quantitative and spatial analysis of soil losses, and area prioritization essential for sustainable soil management in the northern catchment of Lake Tana.

2. Study Area

The northern catchment of Lake Tana, sub-basin of the Blue Nile basin (known as the Abbay river basin), is located in the northwestern highlands of Ethiopia, between longitudes 37°00’ and 37°48’E, and latitudes 12°08’ and 12°46’N. It covers an area approximately 292,230 ha (about 22.1% of the total catchment area of the lake) having Gabi Kura, Derma, Megech, Gumero, and Garno river catchments at an elevation range of 1751–3014 m a.m.s.l. (Fig.1). Several streams along with the major rivers rise in the Ethiopian highlands and flow southward through the North Gondar region and drain to Lake Tana. Most of the rivers are perennial but highly seasonal in their flow and act as the tributaries to the lake. About 27.6% of the total northern catchment area is located in the Megech sub-catchment, followed by the Derma (20.6%), Gabi Kura (19.3%), Gumero (18.5%) and Garno (14%). The total annual runoff from the northern catchment of Lake Tana is $689.2 \times 10^6$ m$^3$ and it is about 9.7% of the total inflow to Lake Tana sub-basin (Mekete Dessie et al. 2015).

The study area has a complex topography, which was formed by a large-scale tectonic and volcanic activity (Mohar, 1971), marked by the extension of north-south trending highlands, descending north to hilly terrain and the south to flat-to-rolling plains (Fig.2). It is composed of rugged topography with broken and undulating hills, mountainous ridges, steep slopes, uplands, deep valleys, lowland plains and occasional rocky peaks in the upper part of the study area. This area has many low hills and volcanic ridge chains bordering the sub-catchments and also acting as a drainage divide, whereas the lower part of the catchment is relatively flat and gently sloping, covered by alluvial plains (acting as floodplains). The plains border the lake along the reaches of downstream of the river. The catchment gradients are influenced by hill slopes and are explicitly related to regional climatic and geological conditions. It has a major influence on the physical attributes of stream ecosystems. The slope gradient of the study area varies from flat to very steep slopes. About 34% of the catchment that exists on the steep and hilly slopes, tends to have a very rapid runoff, causing severe floods and considerable disturbance to the stream-banks. Conversely, about 66% of the area that falls on the strong and gentle slopes tends to have a high
diversity of channel structures. The study area was categorized into three major altitude zones based on geology: the lowland zone (1751-2000 m a.m.s.l, 61.7%), the middle zone (2000-2400 m a.m.s.l, 24%), and highland zone (2400-3010 m a.m.s.l, 14.2%). These altitudinal zones are characterized by fast-changing topography which leads to a range of slope gradients. The lowland zone shows gentle slopes, strong slopes, hilly slopes and steep slopes 16.8%, 66.1%, 15.4% and 1.7% respectively; middle zone shows 4.8%, 36.5%, 36.5% and 22.1% respectively; and highland zones 3.1%, 27%, 36%, and 34% respectively. A typical dendritic drainage pattern was observed in the study area. However, the curious river course follows the original drainage pattern radiating from volcanic ridges in the mountainous part.

The climate in the study area is typical of the region showing tropical highland monsoon characteristics with different climate zones: Humid subtropical (Cwa) and Subtropical highland oceanic (Cwb) in the highland regions, and Tropical wet and dry or savanna climate (Aw) in the lowland regions (Köppen and Geiger,1930). Seasonal rainfall patterns of the study area, driven mainly by the migration of the Inter-Tropical Convergence Zone (ITCZ), are characterized by a unimodal pattern of rainfall with a mean annual rainfall of 1453 mm, peaking in July and August. Most precipitation occurs in a single wet season (called ‘Kiremt’) between June to September, when the ITCZ is at its northernmost position over northern Ethiopia. It follows this is followed by the dry season (lesser rainfall in October to December called ‘Bega’ and considerably lesser rainfall in January to early May called ‘Belg’). There is no statistically significant trend observed in the mean rainfall in any season/month during the period 1997−2018 of the study area. Generally, the precipitation increases with elevation varying from 618 to 3259 mm. However, a vast contrast between ridges and valleys leads to a strong alternation in climate within short distances as rainfall depends on wind speed and direction which is modified by the fast-changing topographic conditions. The mean annual temperature of 22 years was 19°C, ranging from 15–22°C in the high altitude and 24–30°C in low altitude regions of the study area, whereas the mean monthly temperatures range from 15.1°C in August to 32.5°C in April.

The area around Lake Tana has been the site of volcanic activity since the initiation of the East African Rift System and is associated with the oldest volcanic rocks of NW Ethiopian Plateau. The major geologic units in the study area have occurred in four distinct episodes of Afro–Arabian Large Igneous Province volcanism (34.05–23.75Ma) onto the timeline of the Eocene–Oligocene transition during the Cenozoic and are underlain by the oldest geologic units of Mesozoic and Precambrian rocks. The dominant rock types in the study area are: Eocene-Oligocene basalts (lower mafic volcanic unit); Oligocene felsites (felsitic volcanic unit); Oligocene sedimentary rocks, fine basalt and amygdal basalts (sedimentary-basalt association unit); and Oligocene-Miocene basalts (upper mafic volcanic unit). The compositions of these rocks are bimodal: sub-alkaline to mildly alkaline, olivine - to plagioclase-phyric basalts, and dacites to rhyolites including banded finely crystalline to glassy rocks, vitric/lithic tuffs, obsidian-rich agglomerates and coarse ignimbrites (Prave et al. 2015). The N-S and NW-SW trending centroclinal fault blocks are present around the lake area, but northern and eastern areas of the lake exhibit a more jumbled fault pattern relative to western areas.
The physiographic setting, unique climate conditions, mineral composition of the parent rock, drainage characteristics, and soil depth of the study area cause various types of soils. There are six major soil types: Eutric vertisols (VRe, 38.1%), Lithic leptosols (LPq, 28.5%), Haplic luvisols (LVh, 20.5%), Chromic luvisols (LVx, 7.4%), Humic nitisols (NTu, 5.1%), Eutric leptosols (LPe, 0.5%) characterized by loam, clay loam, sandy clay loam, and clay texture (medium to fine granular). Most of the soils occur within 100 cm of the soil surface in the catchment except the Lithic and Eutric leptosols as they occur within 10 cm and 30 cm of the soil surface, respectively. The larger part (67%) of the study area is characterized as imperfect to poor drainage class while the remaining area is moderately well. There are seven land-use types in the study area namely, cropland, grassland, shrubland, plantation forest, forest, barren land, and the built-up area. Agriculture land-use was widespread in the catchment area, mostly dependent on rainfall and it is the main economic activity and source of livelihood.

3. Materials and Methods

USLE is an empirical soil loss model that is widely used all over the world for calculating the long-time average soil losses. This equation computes soil erosion (sheet, rill erosion) on-field slopes using values representing the five major factors affecting erosion: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and support practice (P). RUSLE retains the conceptual use of the USLE factors, but it uses the process-based equations derived from the science of fundamental erosion and professional judgment to make it applicable beyond the scope of the USLE. Nevertheless, USLE is believed to be applied wherever the numerical values of its factors are available (Wischmeier and Smith, 1965 &1978). Universal Soil Loss Equations to estimate soil erosion by water were used in this study by multiplying all the required input thematic layers to obtain a grid of estimated erosion in tons per year as:

$$A = R \times K \times LS \times C \times P$$  \hspace{1cm} (1)

where,

- $A$ is the average annual soil loss (tons ha$^{-1}$yr$^{-1}$),
- $R$ is the rainfall erosivity (MJ mm ha$^{-1}$h$^{-1}$yr$^{-1}$),
- $K$ is the soil erodibility factor (tons ha h$^{-1}$MJ$^{-1}$mm$^{-1}$),
- $LS$ is the topographic factor (dimensionless),
- $C$ is the land cover management factor (dimensionless), and
- $P$ is the support practice factor (dimensionless).

The requisite inputs of the USLE equation were collected from various sources, and the methodology used in this study was by implementing the USLE equation in a raster-based GIS environment for the calculation of specific factors and annual soil erosion on a cell-by-cell basis which was brought under thorough investigation.

3.1. Rainfall erosivity factor (R)
Rainfall erosivity is the erosive power caused by rainfall that causes soil loss and it can be determined by the product (EI\textsubscript{30}) of the total kinetic energy (E) of the storm times the maximum 30-minute intensity (I\textsubscript{30}) [21]. R factor is also an index of rainfall erosion which is the average annual total of the storm El values in a particular locality. In this study, the annual rainfall erosivity was calculated using the empirical equation proposed by Hurni (1985), because the R factor of USLE requires long-term rainfall intensity data (I\textsubscript{30}) which are not available for the study area. The equation used to calculate the annual rainfall erosivity is:

\[
R = 0.55 \times P - 4.7
\]

where, P is the average annual precipitation (mm).

Rainfall data from 35 rainfall stations within and around the study area over a period of 21 years (1997–2018) were used to estimate the rainfall erosivity (R) in the catchment. The spatial distribution of mean annual rainfalls at all stations of the study area is shown in Fig.3. The correlation between rainfall, altitude, and topography was assessed. The R-factor was calculated based on Eq. 2 for each rainfall station and the results interpolated in a GIS using the ordinary Kriging method. Many others also established various relationships to calculate the R-factor using annual and monthly rainfall data (Renard and Freimund, 1994; Diodato and Bellocci, 2007). In addition, we calculated the R-factor also using the other mostly accepted erosion index methods such as Fournier Index (FI), Modified Fournier Index (MFI), and Precipitation Concentration Index (PCI) to study the effect of rainfall length on erosivity are:

\[
\text{Fournier Index (FI)} = \frac{p^2}{P}
\]

where, \(p\) is the precipitation in the wettest month and \(P\) is the total annual rainfall.

\[
\text{Modified Fournier Index (MFI)} = \frac{\sum_{i=1}^{12} p_i^2}{P}
\]

where, \(p_i\) = the monthly rainfall depth (mm) in \(i\) month, and \(p\) = the annual rainfall (mm).

\[
\text{Precipitation Concentration Index (PCI)} = 100 \times \frac{\sum_{i=1}^{12} p_i^2}{P^2}
\]

where, \(p_i\) is the monthly rainfall and \(P\) is the total annual rainfall.

3.2. Soil Erodibility Factor (K)

The soil erodibility factor (K) is one of the key factors of soil erosion which expresses the susceptibility of a soil type to erosion and is usually regarded as the rate of soil loss per erosion index unit (Wischmeier and Smith, 1978). The major soil properties affecting the K-factor are soil texture (sand, silt and clay composition), organic matter content, soil structure index, and the soil permeability index which are used in soil erodibility estimation. Therefore, K is one of the most challenging factors, requiring substantial time, cost, and resources for field surveys and analyses (Bahrami et al. 2005). However, some researchers found a relationship between soil
organic matter content, soil texture, and the K factor (Nguyen and Thai, 1999). In our study, the harmonized world soil database (HWSD) version 1.21 (FAO/IIASA/ISRIC/ESBN/ISS–CAS/JRC, 2013) was used because the above-mentioned field survey data of soil profiles are not available for the study area. The HWSD is composed of a GIS raster image file linked to an attribute database that provides information about the composition of each soil mapping unit, and standardized soil parameters for top- and subsoil. The K values for soil types in the study area were estimated based on percent sand, silt and clay composition (soil texture) relative to percent organic matter (i.e., organic carbon multiplied by a factor value, 1.72) at <2 and ≥2 as per the USDA technical manual (USDA, 2008). The dominant soil types and associated soils of the catchment are shown in Fig. 4.

3.3. Topographic Factor (LS)

Topographic Factor (LS) is the slope length-gradient factor that represents the effect of topography on soil erosion rates and is defined as the estimated ratio of soil loss per unit area from a field slope to soil loss from a 22.13 m length of uniform 9 percent slope (Wischmeier and Smith, 1978). Of the five factors used in the USLE, the LS factor is the most problematic (Renard et al, 1997). The USLE was originally developed on gentle slopes and the LS factor was one-dimensional in calculating the average annual sheet and rill erosion per unit area at the watershed or even larger scales. However, since the topography was shown as two-dimensional, the LS factor is more difficult to estimate than the other terms in the equation (Ligonja and Shrestha, 2015; Van Remortela et al. 2004). Nevertheless, many researchers agreed that the amount of soil loss depended on the three-dimensional distribution of terrain (Mitasaova et al, 1996; Moore and Wilson, 1992). Numerous methods were proposed to calculate the combined LS factor for complex terrain over the past few decades (McCool et al, 1987; Desmet and Govers, 1996; Zangh et al. 2013). A simplified equation suggested by Moore and Wilson (1992) using a unit contributing area to calculate the LS for three-dimensional terrain as follows:

$$\text{LS} = \left( \frac{A_s}{22.13} \right)^m \left( \frac{\sin \beta}{0.0896} \right)^n$$

(3)

where, $A_s$ is the upslope contributing area that can characterize the effect of converging as well as diverging terrains on soil erosion unlike the horizontal slope length ($\lambda$) in the USLE and RUSLE which is only applicable to 2-dimensional and uniform hill slopes, $m$ (0.4-0.6) and $n$ (1.2-1.3) are the slope length and steepness exponents respectively, and $\beta$ is the slope angle (radian), The values 22.13m (72.6ft.) and 0.0896 radian (5.14°) are the length and slope of the standard USLE plot. For predicting erosion at a point, Eq.3 should be multiplied by (m+1) as proposed by Griffin et al. (1988). Pham et al. (2018) reported that $A_s$ can also be calculated based on the multiple-flow direction algorithm using the digital elevation model (DEM) along with the ArcGIS as suggested by Freeman (1991). DEM data for this study was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM 2011) with a spatial resolution of 30 m. In this study, the LS factor was computed using the following equation suggested by Mitasova et al. (1999):
\[ LS = (m + 1) \times \left( \frac{FA \times \text{cell size}}{22.13} \right)^{m} \times \left( \frac{\sin (\text{slope angle} \times 0.01745)}{0.0896} \right)^{n} \]  

where FA is the flow accumulation, cell size is the size of DEM data (30×30 m), slope angle in radians, and m=0.5 (0.4–0.7) and n =1.3 (1.0–1.4) are the exponent values assigned as recommended by Mitasova et al. (1996) and Liu et al. (2000) because the study area has a very complicated terrain with dense stream network resulting in dominating rill erosion and also gully erosion. Determination of the flow direction followed by calculating a raster layer of accumulated flow to each cell was performed using Arc Hydro tools.

3.4. Land Cover management Factor (C)

The C-factor represents the combined effect of all the interrelated cover, crops, and crop management variables on soil erosion rate. It is the most important factor required for land-use policy decisions as it represents conditions that can be most easily managed to reduce erosion. The C-factor is the ratio of soil loss from land cultivated under specific conditions to the corresponding loss from clean-tilled and continuous fallow lands (Wischmeier and Smith, 1978). The C-factor values range between 1 and 0 where C equals to1 indicates lack of cover and the C near zero indicates a very strong cover. Assigning the C values for the type of various land covers by choosing representative values from Tables given by (Wischmeier and Smith, 1965) is widely applied in some studies in Ethiopia. By adapting the USLE to the Ethiopian highlands, Hurni also suggested in 1985, the C-factor values for various land cover types. However, for this study, we used satellite images to compute the Normalized Difference of Vegetation Index (NDVI), which is an index of vegetation abundance, for calculating the C values. We chose time-series 30 m resolution of Landsat 8 OLI images: path 170, row 51 from January 11, April 17, June 20, September 24, and December 13 of the year 2018. Remote sensing technology can provide a lot of information about the land surface through the NDVI which is positively correlated with the amount of green biomass and gives an indication of differences in green vegetation coverage (Van der Knijff et al. 2000). We computed the NDVI for each satellite image using the following equation:

\[ NDVI = \frac{NIR - RED}{RED + NIR} \]  

NIR and RED are the surface spectral reflectances in the Near-infrared (0.85–0.88µm) and Red bands (0.64–0.67µm). The spectral response depends on many factors that may be affected by various surface conditions. The spectral reflectances were extracted from the selected Landsat-8 imageries. Several studies have established linear relationships between NDVI and USLE C-factor, but the correlations are still quite low (De Jong, 1994; Van der Knijff, 1999). Many researchers calculated the C-factor with NDVI values by developing different equations (Durigon, 2014; Karaburun Ahmet, 2010). However, in this study, the C-factor was calculated using Van der Knijff’s et al. (2000) equation who found the relationship between them in an
exponential function that is more realistic than the linear equation. We generated the mean NDVI from the time series Landsat 8 images data for five months: January, April, June, September, and December of the year 2018 and used to create the C-factor map with the following equation:

\[ C = \exp \left( -\alpha \frac{NDVI}{\beta - NDVI} \right) \]  

(7)

where, \( \alpha = 2 \) and \( \beta = 1 \).

An estimate of \( C_i \) for each pixel was also obtained from NDVI of \( i^{th} \) time-series map using Eq. 7 to study the trend of soil erosion risk according to the seasonal variation of the C-factor so that variability during dry and wet months can be estimated.

3.5. Support Practice Factor (P)

The support practice factor (P) is defined as the impact of land use or farming system on soil erosion (Pham et al. 2018). It represents erosion prevention practices such as contouring, strip-cropping, and terracing to reduce the amount of soil erosion by the runoff. P-factor is the ratio of soil loss by a particular support practice to that of straight-row farming up and down the slope. P-factor is considered the most uncertain value due to difficulties in its estimation of specific land-use types and farming systems of the specific land plot (Morgan and Nearing, 2011). Further, it is time and cost-intensive. P-value equal to 1 indicates no erosion control solution. Soil conservation practices are very poor in the study area. Some researchers suggested that the P-value is rather dependent on the slope inclination (Shin, 1999; Lufafa et al. 2003), while others used farming practices on the slope to calculate P values (Stone and Hilborn, 2012).

It is observed that the soil conservation practices are very poor in the study area, and significant measures are yet to be implemented. Some areas in the lowlands of the catchment have adopted the use of stone walls and eucalyptus trees, but they are poorly maintained. Moreover, the map of conserved areas was not available for the study area and hence this study adopted the P-factor values as suggested by Shin (1999), which includes cultivation method, land-use types, and land slopes. In this, the P-factor is calculated based on the relationship between terracing and slope in the agricultural field areas and is estimated according to the relation of both the farming type and the slope. Slope gradient ranges (in degrees) and types of land-use for this study were generated from Landsat-8, OLI imagery of December 2018 (pan merged 15 m), and DEM of the study area respectively. To generate a LULC map of the study area, the imagery was first preprocessed to convert raw DN values to top of atmosphere (TOA) reflectance that minimizes spectral differences caused by different factors. The unsupervised classification was performed on NDVI imagery as well as all-original bands of the Landsat data to classify the satellite image (bands 3,4,5) into 15 land-use classes and in turn, these classes were classified into 11 classes using supervised classification. Supervised-Maximum Likelihood classification was used for this analysis using ERDAS IMAGINE 2014 software. LULC classes identified in the catchment were: dense forest, plantation forest, shrubland, cultivated land, cash crops, perennial crops, grassland, bare land, bare rock, urban built-up area, and water. After classification, the accuracy
of the LULC map was assessed by computing the error matrix. The classification had an overall accuracy of 0.905 (90.5%) with a kappa coefficient of 0.897 and this indicates a strong agreement with the reference data according to Landis and Koch (1977) classification. To assign the P-factor value, we combined the LULC type and slope range maps in raster using spatial analyst tools in Arc GIS and assigned P values to each combination by choosing representative values proposed by Shin (1999).

3.6. Estimation of soil erosion risk

The thematic layers for factors R, K, LS, C, and P were created before were re-sampled into raster layers of 100 m spatial resolution (1ha cell size). The soil erosion estimation using the USLE model was generated by multiplying the required input thematic layers of the model together in a GIS platform. These input raster layers were used as data files to run the model to obtain a grid of estimated erosion in tons per year. The potential soil erosion map was derived by multiplication of the thematic layers in raster calculation in Arc GIS using the R, K, LS, C, and P factors respectively. The total erosion for each sub-catchment in the study area was calculated by adding together the estimated erosion for all the cells within each sub-catchment. The Grid cells were classified into five erosion potential levels based on the estimated erosion rates namely, cells with very low erosion (0-1), low erosion (1-5), moderate erosion (5-10), high erosion (10-50), and extreme erosion (≥50) proposed by Pham et al. (2018).

3.7. Descriptive Statistics

The log-linear regression analysis was used to determine the sensitivity of each input factor of the USLE for the soil erosion rate. In this technique, we selected 100 erosion locations from soil erosion susceptible areas in the derived A-factor map and those values were superimposed with all other independent factors, R, K, LS, C and P. Those values were exported to IBM SPSS Statistics 20 using multiple linear regression analyses. The Logarithmic transformation of Eq.1 was:

\[
\ln(A) = \ln \left( R \times K \times LS \times C \times P \right) \\
= \ln (R) + \ln (K) + \ln (LS) + \ln (C) + \ln (P)
\]

where, ‘\(\ln\)’ is the natural logarithm.

To identify the effect of each input factor on soil erosion rate, a multiple linear regression was applied to determine the relationship between those factors; then the Eq. 8 can be expressed as:

\[
\ln \left( A \right) = \beta + \beta_i \ln (X_i) + \beta_j \ln (X_j) + \beta_k \ln (X_k) + \beta_l \ln (X_l) + \beta_m \ln (X_m)
\]

where, \(\beta\) value is a standardized coefficient due to different units of the input factors; \(\beta_i\) is the estimated regression coefficient which quantifies the association between the factor \(X_i\) and \(A\); \(\ln (X_i)\) is the natural logarithm of \(i^{th}\) input factor.

The conditions for the multiple linear regressions (Eq.9) are: significance (Sig) must be <0.05 (with 95% confidence), multicollinearity must be absent, and Variance Inflation Factor (VIF) must be <10 to standardize the coefficients.
3.8. Drainage density (Dd)

Drainage density (Dd) was defined as the ratio of the total length of streams in a watershed over its contributing area (Horton, 1945). During the past decades, drainage density was analyzed with many parameters like slope gradient, soil type, elevation, soil erosion, soil erodibility as well as sediment yield (Collins and Bras, 2010; Gregory and Walling, 1968). Total drainage density for the entire catchment was calculated with the following equation proposed by Horton (1945):

\[
Dd = \frac{L_u}{A}
\]

where, Dd = Drainage density; \(L_u\) = Total stream length in a catchment; A = total contributing area of the catchment.

The levels of Dd were derived. The dry and wet drainage densities of the catchment also were calculated using focal statistics in ArcGIS as the terrain was complex. On the basis of field observations, we considered the Dd values less than 0.86 km/sq.km as low drainage densities while the Dd values were greater than 0.86 km/sq.km as high drainage densities. The effects of Dd together with other geographical parameters such as elevation, slope, and soil conditions on soil erosion were estimated.

3.9. Stream Power Index (SPI)

Although the USLE model accounts for rill and inter-rill erosion, it does not account for soil loss from gullies or mass wasting events such as landslides (Rubianca, 2018). Stream power index (SPI) is a measure of the erosive power of flowing water and it appropriates the locations where the gullies are likely to form on the landscape. There are several models to predict gully erosion by considering various factors like topographical, hydrological, geological, and environmental conditions. DEM and GIS techniques were used to map the gully-erosion susceptibility in the study area. Drainage density, slope, soils, and rainfall are critical factors promoting gullying (Alireza Arabameri et al. 2019). The effects of these factors on gully erosion were analyzed. The SPI was calculated using the following equation:

\[
SPI_i = \ln (DA_i * \tan (G_i))
\]

where, SPI \(_i\) is the stream power index at grid cell \(i\); DA\(_i\) is the drainage basin area (flow accumulation at grid cell \(i\) multiplied by grid cell area), and G\(_i\) is the slope at grid cell \(i\) in radians. The critical zones were classified into two: gully erosion and no gully erosion by using a threshold 7.2. The areas of extreme erosion potential in the catchment were compared with the areas of gully formation.

3.10. Land cover change detection

In this study, Spatio-temporal satellite data were used to evaluate the effect of a typical land cover change on soil erosion rate. Some land cover features, like water bodies and vegetation, have very specific spectral reflectance characteristics that facilitate the separation
from other features as per spectral indices. However, it is challenging in the study area to effectively separate the built-up areas (especially rooftops) from barren lands (bare soils, bare rock, and sands), sandy gravel grounds, and shallow stream beds using a single index due to similarities in the spectral properties of the land use classes. Using the spectral indices derived from satellite images for land use mapping is an operational approach as it enables the mapping at a higher degree of accuracy which is highly comparable to the above mentioned indistinguishable land use areas (Xu, 2007; Zha et al. 2003). The characteristics of the reflected energy in different regions of the spectrum for a specific land cover can be utilized to produce various indices that are used as an alternative data source for land cover characterization. In this study, a multiple index approach was constructed using three-band combinations of spectral indices for mapping seven different land cover classes.

The normalized difference tillage Index (NDTI), the soil adjusted vegetation index (SAVI), and modified normalized difference water index (MNDWI) were used as the first, second and third components of the multi-index data set following several combinations of other indices such as the existing built-up indices: NDBI, BUI, BAEI, BSI, vegetation index: NDVI, and water index: NDWI and their performances were evaluated in pre-classification. The maximum likelihood supervised classification technique was employed to create the spectral signatures of significant land cover categories (waterlogged, crop fields, barren land, grassland, shrubland, forest, plantation forest, and built-up area). After ensuring accuracy for each classified image, a detailed post-classification land-use change detection analysis was performed to assess the resultant change from 1986 to 2018. The equations for the above multispectral indices used in this study are:

\[
\text{NDTI} = \frac{(\text{SWIR 1} - \text{SWIR 2})}{(\text{SWIR 1} + \text{SWIR 2})} \\
\text{SAVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red} + 0.5)} * 1.5 \\
\text{MNDWI} = \frac{(\text{Green} - \text{SWIR 1})}{(\text{Green} + \text{SWIR 1})}
\]

In this study, classification accuracy assessment was conducted by comparing the reference satellite image with the classified image using some random sampling points. A total of 320 random sampling points of the reference image were used for accuracy assessment of every classified image. A stratified random sampling of the image was adopted to calculate the classification accuracy of each classified image in this study. Because in this sampling method, each land cover class is found equal probability to be observed (Inzamul Haque and Rony Basak 2017). The accuracy assessment result of each classified image (2018, 1986) was quantified by using the error matrix. According to the error matrix reports, these classifications had an overall accuracy of 93.4% with a kappa coefficient of 0.925, and 88.12% with a kappa coefficient of 0.864 for the satellite images 2018 and 1986 respectively.

The methodology described above was implemented in the study of the northern catchment of Lake Tana to develop substantial data inputs into the future database for soil erosion in Ethiopia.
4. Results

4.1. Rainfall erosivity factor (R)

The mean annual rainfalls were obtained from the past 21 years (1997–2018) recorded at the 35 weather stations within and around the study area, ranging from 643–3259 mm. A weak positive correlation between the rainfall and altitude was found (r =0.20) but do not show any significant differences between them (at .05 level, p =0.254) (Fig. 5a); whereas, nearly moderate positive correlation between the rainfall and topography was found (r =0.35) and showed significant differences between them (at .05 level, p =0.024) (Fig. 5b). This inconsistency is due to the fast-changing topography of the catchment, which is surrounded by a chain of mountain ridges and low hills, and alternation between valleys and ridges within short distances (Veeranarayana et al. 2019). The estimated R-factor value ranges from 349–1788 MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$ and showed that the distribution of rainfall was uneven in the study area (Fig.13 a). About 66.63% of the research site is comprised of the R values greater than 1000 MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$. The other erosivity indices namely Fournier Erosivity Index (FI), Modified Fournier Erosivity Index (MFI) and Precipitation Concentration Index (PCI %) results showed that the FI values ranged from 20.1 to 225.12 (avg. 112.63) that indicated low to extremely severe erosion risk (Oduro–Afriyie, 1996), and the MFI values ranged from 109.4 to 613.7 (avg. 291.5) that indicated moderate to very high risk (CEC, 1992) and the PCI % values ranged from 10.9 to 40.66 % (avg. 20.97%) that indicated moderately seasonal to highly seasonal (Oliver, 1980). Erosivity values from various indices at all stations, annual rainfall, and altitude are shown in Fig.6a. A correlation between annual rainfall (P) and erosive indices showed significant at 0.01 level.

The trends of monthly average rainfall at various stations are shown in Fig.6b. The most precipitation events occurred between June and September that confirm the Köppen climatic classification showing no alternation of humid and dry months within the wet season (Köppen and Geiger, 1930). The mean annual rainfall during the wet season for the study area was 1173 mm and the R-factor value ranges from 272-1305 MJ mm ha$^{-1}$ h$^{-1}$ yr$^{-1}$ (Fig.7a). Therefore, soil loss mostly occurs during the rainy season and particularly during major storms, however, the post- and pre-monsoon months that have less intense events with low rainfall also cause some extent of erosion. During the dry season (October-May), the mean annual rainfall for the total catchment was 260 mm (range 135-478 mm) and the R-factor value ranged from 69-256 MJmmh $^{-1}$ h$^{-1}$ yr$^{-1}$ (Fig.7b). The dry months, March, April, and November have light precipitation (21-33 mm) that occurred in two or three nonconsecutive days in each of these months whereas, less intense events with low rainfall in May (105 mm) and October (66 mm). During this time, soil especially from the areas where the agricultural land is left as it is without any soil conservation measures after sowing or harvesting, and where the land is prepared for new plantation forest, is being eroded considerably even by small rainfall intensities. The Megech sub-catchment has the highest R values followed by the Gumero and Derma sub-catchments while the Garno and Gabi Kura sub-catchments have the lowest R values (Table1).
4.2. Soil Erodibility Factor (K)

The results also indicate that soil erodibility factor (K) in the study area ranges from 0.20 to 0.34 t ha\(^{-1}\) MJ\(^{-1}\) mm\(^{-1}\) (Fig.13 b). The results presented in Table 2 show that about 66.8% of the study area has a K-factor value of 0.24, 0.33 and 0.34 for the soil types Eutric vertisols (clay) Lithic leptosols (clay loam), and Eutric leptosols (loam) respectively and is considered as high due to having low permeability, organic matter and imperfect drainage, whereas K-factor value of 0.2 and 0.21 for the soil types Chromic-Haplic luvisols and Humic nitisols respectively and is considered as low due to having acceptable soil permeability, moderately well drainage. The high K-factor value soil types are naturally more prone to soil erosion due to their physical structure, texture, permeability, and organic matter content. The organic matter (OM) content of the soils in the study area ranges from 0.67-4.2% and the bulk density ranges from 1.18-1.51kg/dm\(^3\). The K-factor values for the sloping landscapes are significant. The area about 60% of the high altitudes, 89% of the mid-altitudes, and 55% of the lowlands in the study are comprised of the high K-factor values that indicated more prone to soil erosion. The results also showed that the high K-factor value of 0.33 and above occurred in the sub-catchments Megech, Gumero, and Garno causing severe soil erosion rates (Table 3).

4.3. Topographic Factor (LS)

DEM data show that the terrain of the study area is very complex, with 20% of the area having a slope steeper than 25\(^\circ\). The spatial distribution of the combined LS-factor was derived from flow accumulation and slope using the DEM of the study area (Fig.13 c). The LS-factor values vary from 0 to 96.47. The results presented in Table 4 show that nearly 98.4% of the study area showed the LS-factor value 1 and below which indicates the slope is very complex and gentle, and slope lengths are shorter, resulting in a very high flow rate and extreme soil erosion potential. The high LS values occurred only 1.6% of the study area on steep slopes and high flow accumulation areas particularly in the upper parts of all sub-catchments. It indicates that this area is highly vulnerable to soil erosion. The LS values 1 and below were found in more than 98% of all sub-catchment areas, whereas the LS values 10 and below were in more than 1% of the Megech, Garno, and Gumero.

4.4. Land Cover management Factor (C)

The five months average of time series NDVI varies from −0.194 to 0.48 (Fig.8), while the C-factor in the study area varies from 0.20 to 0.91 (Fig.13 d). The results presented in Table 5 show that about 45.3% of the study area comprised higher C values ranging from 0.63-0.91, whereas lower C values comprised only 19.3% ranging from 0.20-0.53. This indicates the effects of cropping and management practices, vegetation canopy, and ground cover on soil erosion rates are high in the half of the study area. The results also show that the trend of C-factor change in the study area was due to the seasonal variation of the various land cover (Fig.9). The range of C-factor values during the wet (0.037-1.46) and dry season (0.18-1.35) indicated that there was a huge variation in the cropping management practices particularly in highlands to low-lying flood
 plains of the study area (Fig.10a and b). Consequently, about 46.1% of the lowland area and 41% of the highland area has a higher C value of 0.63 and above. The higher C values indicate high soil erosion risk.

4.5. Support practices factor (P)

P-factor depends on the erosion control practices at each land use type. However, land-use type impacts the rate of soil erosion through farming support practices (P) on the slope and the land cover management (C) (Fig. 11 and Fig.12). The P-factor map for the study area is shown in Fig. 13e and the area under different support practice factors are shown in Table 6. The P-factor in the study area varied between 0.003 and 1.0. P-value 1 indicates that there are no conservation practices. About 21% of the study area has a P-value of 1. The results indicate that the significant soil conservation measures are to be implemented in the study area for controlling the soil erosion and protecting the soil on marginal and steep slopes.

4.6. Estimated soil losses and area prioritization

The raster layers of the USLE factors R, K, LS, C, and P were used to obtain a grid of estimated erosion in tons per year. The total annual estimated soil loss from the northern catchment of Lake Tana was 1,705,370 tons and the mean estimated erosion rate was 37.89 t ha\(^{-1}\)yr\(^{-1}\), with a standard deviation of 59.2 t ha\(^{-1}\)yr\(^{-1}\). The grid cells were classified into five rates of erosion severity levels in the study area: very low erosion (0–1 t ha\(^{-1}\)yr\(^{-1}\)), low erosion (1–5 t ha\(^{-1}\)yr\(^{-1}\)), moderate erosion (5–10 t ha\(^{-1}\)yr\(^{-1}\)), high erosion (10–50 t ha\(^{-1}\)yr\(^{-1}\)), and extreme erosion (≥ 50 t ha\(^{-1}\)yr\(^{-1}\)). The annual soil erosion rate for each erosion class is shown in Fig. 14. The estimated soil erosion rates and total annual soil losses in the northern catchment of Lake Tana are shown in Table 7. This helps to prioritize areas for better conservation measures according to their level of risk. The erosion risk map shows that the spatial distribution of soil loss in the study area was variable. The soil loss estimated for the study area ranges from 0 in the flat areas to over 50 t h\(^{-1}\)yr\(^{-1}\) in degraded lands, along the steep channel banks, marginal and very steep slopes. About 51.5% of the study area has a soil loss value of 0. This indicates that the soil erosion from these areas is negligible. The mean estimated soil erosion rate from the study area was 37.89 t ha\(^{-1}\)yr\(^{-1}\) and this rate is comparable with the mean rate in similar studies that have been conducted in Ethiopia as shown in Table 8: soil losses were estimated to be 39.8 t ha\(^{-1}\)yr\(^{-1}\) from the Ribb watershed (Estifanos, 2014), 42.67 t ha\(^{-1}\)yr\(^{-1}\) from the Gumara watershed, Lake Tana basin (Mengie et al. 2019), 49 t ha\(^{-1}\)yr\(^{-1}\) from the Demeche (Mengesha et al. 2018), 42–47.4 t ha\(^{-1}\)yr\(^{-1}\) from the Koga watershed,( Tegegne and Biniam, 2017; Gelagay and Minale, 2016), and 37.9 t ha\(^{-1}\)yr\(^{-1}\) from Beshillo catchment, Blue Nile basin (Asnake and Amare, 2019) while this rate is low compared to the estimated soil loss of 100 t ha\(^{-1}\) y\(^{-1}\) from all land in Ethiopian highlands by FAO (1986). Hence, our result is in line with the previous works that have been carried out in the neighboring watersheds in the Lake Tana and the Blue Nile basins. The mean rate is greater than the tolerable soil loss of about 2-18 t ha\(^{-1}\)y\(^{-1}\) estimated for Ethiopia by Hurni (1985).
The results presented in Table 7 show that the cells with estimated erosion rates of 50 t ha\(^{-1}\)yr\(^{-1}\) or more comprised 2.9% of the total study area and is classified as extreme erosion potential. The soil loss under this class accounts for 47.1% of the total estimated soil loss in the study area (809,848 tons). About 87.6% of the study area was classified as being under very low, low, and moderate soil erosion potential and has a soil loss value of less than 10 t ha\(^{-1}\)yr\(^{-1}\). The total soil loss from these areas combined accounts for only 17.9% of the total soil loss of the study area (298,136 tons). Cells with extreme and high erosion potential represent high-priority areas for the implementation of the soil conservation measures in the study area and have a soil loss value of 10 t ha\(^{-1}\)yr\(^{-1}\) and more. Although such classes together comprised only 12.4% of the total study area (36,317ha), they contributed 82.1% of the total estimated soil erosion in the study area (1,407,234 tons) with a mean soil erosion rate of 38.75 t ha\(^{-1}\)yr\(^{-1}\), which is greater than the tolerable soil loss was estimated for Ethiopia by Hurni (1985). It was also observed that the extent and magnitude of soil erosion in the study area were spatially varying.

In this study, we also calculated the total soil erosion for each sub-catchment by adding together the soil erosion for all the cells within each sub-catchment and were classified into five soil erosion rate classes proposed by Pham et al. (2018). The results presented in Table 9 show that the soil erosion rates in each sub-catchment of the study area. The Megech sub-catchment comprised 27.6% of the total study area. The total annual soil loss from this area was 848,756 tons (sharing 49.9% of the total soil loss), with a mean erosion rate of 40.98 ±69.91 t ha\(^{-1}\)yr\(^{-1}\). The Derma sub-catchment comprised 20.6% of the total study area and the total annual soil loss from this area was 207,933 tons (accounted 12.2% of the total soil loss), with a mean erosion rate of 46.80 ±71.89 t ha\(^{-1}\)yr\(^{-1}\). The Gabi Kura sub-catchment comprised 19.3% of the total study area and the total annual soil loss from this area was 73,392 tons (accounted 4.3% of the total soil loss), with a mean erosion rate of 29.66 ±25.78 t ha\(^{-1}\)yr\(^{-1}\). The Gumero sub-catchment comprised 18.5% of the total study area and the annual soil loss was 325,656 tons (accounted for 19.1% of the total soil loss) with a mean erosion rate of 30.95 ±36.17 t ha\(^{-1}\)yr\(^{-1}\). The Garno sub-catchment comprised 14.1% of the total study area and the annual soil loss was 244,832 tons (accounted for 14.4% of the total soil loss) with a mean erosion rate of 30.01±28.17 t ha\(^{-1}\)yr\(^{-1}\).

The results also indicate that soil erosion rates varied across the five sub-catchments in the study area. Megech sub-catchment has the largest amount of area in the northern catchment of Lake Tana and also has the largest amount of area with high and extreme erosion potential (51.5% and 32.7% of the total high and extreme erosion areas of the study area) followed by the Gumero sub-catchment comprised 18.5% of the study area and the amount (16.8% and 23.3%) of the area with high and extreme erosion potential, The Garno sub-catchment comprised 14.1% of the study area and the amount (16.6% and 19.4%) of the area with high and extreme erosion potential, Gabi Kura sub-catchment comprised 19.3% of the study area and the amount (4.3% and 9.8%) of the area with high and extreme erosion potential and Derma sub-catchment comprised 22.9% of the study area and the amount (10.8% and 14.9%) of the area with high and extreme erosion potential. The areas with high and extreme soil erosion potential in each sub-
catchment are the critical areas that require urgent soil and water conservation measures. These differences in reported values could be attributed mainly to the relative strength of influence of erosion governing factors such as topographic, support practices, soil erodibility, land cover, rainfall, and also anthropogenic activities. If measures are not applied to the areas identified as at risk, the agricultural production in these areas will be severely affected, and consequently, this will result in food insecurity (Birhan and Assefa, 2017).

About 88% of the total soil loss occurred alone during the wet season, with a mean erosion rate of 42.4 ±77.1 t/ha whereas, about 12% the total soil loss occurred during the dry season, mostly in pre- and post-monsoon months, with a mean rate 34.2±32.7 t/ha. This indicates that soil erosion is highly seasonal. The annual estimated soil erosion rates during the wet and dry seasons are shown in Fig.15a and b respectively. The soil conditions affected by the previous rainfall of the wet season played a vital role in the following dry season for land cover as was seen in the lower parts of the catchment. The early and receding rains also have a major influence on soil erosion in the sub-catchments; Megech has the highest amount (46%) of the total soil loss during the dry season, followed by Gumero (20%), Garno (16%), and Derma (13%).

4.7. Descriptive statistics

The log-linear regression analysis results showed that the average annual estimated soil erosion rate \( A \) had a significant correlation and there was no multicollinearity with each input factor of the USLE model \( (p <0.043, \text{ VIF} < 10) \). This indicated that the impact of each input factor of the USLE on annual soil erosion rate was significant proposed by Pham et al. (2018). The results presented in Table 10 show that the estimated standardized coefficients, \( \beta \) values ranging from 0.151 to 0.563, and were used in the Eq.9 for multiple linear regressions of the average annual estimated soil erosion rate \( A \) and each input factor of the USLE model for the study area as follows:

\[
\ln (A) = 0.155 \ln (R) + 0.217 \ln (K) + 0.563 \ln (LS) + 0.151 \ln (C) + 0.468 \ln (P) \ldots (15)
\]

The \( \beta \) values in Eq.15 indicate that the relative influential strength of each input factor on the annual soil erosion rate. The LS-factor had the strongest influence on soil erosion rate \( (\beta = 0.563) \) followed by the other factors, \( P (\beta = 0.468), K (\beta =0.217), R (\beta = 0.155), \) and \( C (\beta = 0.151) \).

4.8. Factors influencing soil erosion risk and erosion rates

4.8.1. Land cover

Land use is represented by the values of the land cover factor \( C \). About 45.3% of the study area has a \( C \)-factor value of greater than 0.63. This area comprised 38.6% and 51.7% of the total high and extreme erosion potential area in the study area respectively. It indicates that nearly all high and extreme erosion areas had barren land use. Only 19.4% of the study area has low \( C \)-factor values ranging from 0.2–0.53 and it comprised 29.1% and 16.5% of the total high and extreme erosion potential area respectively (Table 11). About 35.3% of the study area has the \( C \)-factor values ranging from 0.53-0.63 and this comprised 32.3% and 31.8% of the total high and
Extreme erosion potential areas in the study respectively. This indicates that nearly all high and extreme erosion areas had agricultural land use.

4.8.2. Topography

The topography had the strongest influence on soil erosion rates in the study area. The results presented in Table 12 show that various slope gradients and estimated erosion rates in the study area. Strong slopes (3-10°) comprised 54% of the study area with a mean erosion rate of 25.6±28.8 t ha\(^{-1}\)yr\(^{-1}\) and 34.1% of the total estimated soil loss. Moderately steep slopes (10-20°) comprised 22.8% of the catchment with a mean erosion rate of 42±66.2 t ha\(^{-1}\)yr\(^{-1}\) and 32.2% of the total estimated soil loss. Steep slopes (20-45°) comprised only 11.1% of the catchment and 30% of the total estimated soil loss with a mean erosion rate of 46.1±37.6 t ha\(^{-1}\)yr\(^{-1}\). Very steep (>45°) slopes comprised only a small fraction of the entire catchment. Steep and moderately steep lands in the study area comprised more than 30% of the high and extreme erosion potential area. There was a high rate of soil erosion from these slopes and it needs more attention to control such high erosion. This could be due to the agricultural land-use on marginal and steep slopes in the study area.

4.8.3. Land use

Table 13 shows the land use type and estimated erosion rates in the study area. About 27.6% of the catchment comprised the barren land and 24.8% of the total estimated soil loss, with a mean erosion rate of 35.9±57.2 t ha\(^{-1}\)yr\(^{-1}\). This has the highest amount (31.6%) of the area with extreme erosion potential. About 28.7% of the study area comprised agricultural land use and 13.6% of the total estimated soil loss, with a mean erosion rate of 41.1±66.1 t ha\(^{-1}\)yr\(^{-1}\), and having 29.7% of the total extreme erosion potential area. About 15.3% of the catchment comprised the plantation forest and 28.7% of the total estimated soil loss, with a mean erosion rate of 34.9±49.3 t ha\(^{-1}\)yr\(^{-1}\), and having 21% of the total extreme erosion potential area. About 13.4% of the catchment comprised the shrubland and 12.1% of the total estimated soil loss, with a mean erosion rate of 33±47.5 t ha\(^{-1}\)yr\(^{-1}\), and having only 5.9% of the area with extreme erosion potential. 9.7% of the catchment comprised the grassland and 12.4% of the total estimated soil loss, with a mean erosion rate of 41.64±74.2 t ha\(^{-1}\)yr\(^{-1}\), and having 9.9% of the area with extreme erosion potential. The mean channel bank erosion rate for the catchment was 27.2±40.1 t ha\(^{-1}\)yr\(^{-1}\). Much of this erosion occurs as the weakened stream banks fail and break down due to increased runoff. The results indicate that most of the soil loss occurred from the barren land, cropland, plantation forest, and shrubland. Furthermore, these areas have the largest amount of extreme erosion cells and are contributing to high rates of soil loss.

Table 14 shows the land use type and estimated erosion rates in the study area. The extreme erosion cells are found higher in cropland (33.2%), plantation forest (36.3%), and barren land (43.0%) in the Megech sub-catchment than those in all other four sub-catchments. Next to the Megech, Gumero has the areas of extreme erosion potential in the cropland (26.6%), plantation
forest (22.4%), and barren lands (19.1%). The extreme erosion cells are the least in the three land use (8.7%, 5.9%, and 5.7%) in the Gabi Kura.

4.8.4. Land use and Topography

Table 15 shows the slopes, versus land-use type, and estimated erosion rates. Strong slopes (3-10°) comprised 54% of the study area, 61% of the agricultural cells, and have the highest amount (39.3%) of areas with extreme erosion potential, whereas Steep slopes (20-45°) comprised only 8.5% of the agricultural cells, but 27.3% of the cells with extreme erosion potential were located on such slopes. Strong slopes comprised the largest amount (49.3%) of the plantation forest and 27.5% of the cells with extreme erosion potential, whereas, Steep slopes comprised only 21% of the plantation forest and 34.8% of the cells with extreme erosion potential were located on such slopes. Strong slopes comprised the largest amount (52.1%) of barren land and 33.5% of the area with extreme erosion potential, whereas, moderately steep slopes comprised only 29.2% of barren land and the highest amount (41%) of cells with extreme erosion potential on such slopes.

4.8.5. Drainage density (Dd)

The drainage density (Dd) estimated for the study area varies from 0 to 1.5 km/sq.km and the overall drainage density was 0.79 km/sq.km. Fig.16 shows the spatial distribution of the Dd of the study area. The overlying map of drainage density and soil loss reveals that about 44.8% of the study area (131,390 ha) has a high drainage density value of greater than 0.86 km/sq.km. The soil loss of the area under this class accounts for 45.1% of the total soil loss of the study area and has 41.3% of the cells with extreme erosion potential. Whereas, about 55.2% of the study area (160,985 ha) has a low drainage density (Dd < 0.86 km/sq.km) and the soil loss area under this class accounts for 54.9% of the total soil loss and has 58.7% of the cells with extreme erosion potential (Table 16). About 29.5% of the catchment is characterized by wet (active) drainage density (86,297 ha), whereas 70.5% of the catchment is characterized by dry drainage density (206,297 ha). The altitude and soils of the study area also impact on the rate of soil loss from the Drainage density areas (Sumantra and Padmini, 2015). In the high altitudes (upstream section) of the study area, low Dd and soil loss are high. In this study, the C factor and R factor is the reason for high soil loss. In the low altitudes (downstream section), high Dd and soil losses are very high due to the presence of several fingertip streams and the shallow depth of the soils promotes the soil loss. The soils, Lithic leptosols, and Eutric vertisols with high erodibility factors occur in both high and low Dd areas. These areas have the largest amount (65%) of extreme erosion cells.

4.8.6. Soil erodibility and Topography

Strong slopes comprised 68% of the Vertisols (K value 0.24) as well as 64.3% of the Luvisols (K value 0.20), and 57.8% and 48.6% of cells with extreme erosion potential respectively. About 37.8% of the Leptosols (K value 0.33) occurred on moderately steep slopes and 41.2% of cells with extreme erosion potential were located on such slopes. The steep slopes
comprised 32.3% of Nitisols (K value 0.21) and 45.2% of cells with extreme erosion potential thereon.

4.8.7. Gully erosion susceptibility

Drainage density, land-use, topography, soil erodibility, and stream power were considered as influencing factors to gully in our study. The Stream Power Index (SPI) values ranged from -1.71 to 16.29 in the catchment. These susceptible areas were then classified into the gully and no gully erosion by using a threshold value of 7.71 (Fig. 17). The gullies occurred in 15.52% of the study area (45,375 ha). About 44.1% of the gully area was identified in the high Dd areas with the presence of 37.6% of cells with extreme erosion potential (3,969 ha), whereas the remaining 55.9% of the gully area was in low Dd areas with the occurrence of 62.4% of cells with extreme erosion potential (4,606 ha). The gullies in low Dd areas have higher extreme erosion potential than those in high Dd areas in all sub-catchments. The larger areas of gullies were identified in areas of K values 0.24 (Vertisols), 0.33 (Leptosols), and 0.20 (Luvisols) respectively. The gully areas in plantation forest and barren lands were larger as compared with those in the crop-, shrub- and grasslands. 50.5%, 22.2%, 16.5%, and 10.8% of gullies occurred on strong slopes, hilly slopes, steep slopes, and gentle slopes respectively.

4.8.8. Land use cover change (LUCC) detection analysis

The output of thematic change detection analysis (Fig. 18) and the corresponding statistics of the land use cover change from 1986 to 2018 (Table 17) showed that the highest amount of land use cover conversion had taken place from barren land to cultivated land (4.29%) and to plantation forest (3.69%). A considerable amount of land cover changed from the shrub-, grass- and natural forest lands to cultivated land and plantation forests (1.01-1.30%). Other land changes or conversions were below 1% and not exempt from extreme erosion potential because much of the cells with extreme erosion potential were located even in such smaller land cover changed areas. Results of land use cover change (LUCC) statistics for 1986 and 2018 showed the typical behavior of each land cover type considering the change dynamics with remarkable precision. In summary, forest, barren land, grassland, and shrublands decreased by 64%, 23.4%, 19.0%, and 17.5% of the total land-use area respectively during the 32 years (1986-2018). Conversely, plantation forests and cultivated land increased (56.6% and 32.4% respectively). Artificial surface and waterlogged areas also increased (101.6% and 37.1% respectively) Table 18). The calculated accuracy assessment result of each classified image (2018, 1986) is shown in Table 19. The results in the table were summarized and quantified by using the error matrix. The accuracy results indicate that the classifications in this study had a strong agreement (kappa statistics >0.8) with the reference data.

5. Discussion

The annual soil erosion risk map shows that 12.4% (36,617 ha) of the northern catchment of Lake Tana can be classified as extreme and high erosion potential areas. These areas together contributed 82.1% of the total estimated soil loss in the catchment. The areas with extreme
erosion potential though comprised only 2.9% of the catchment, contributed 47.1% of the total estimated soil loss with a mean erosion rate of 156.8±285 t ha$^{-1}$ yr$^{-1}$. Therefore, both the extreme and high erosion potential areas shall be considered as high priority areas for soil erosion prevention and control measures and better land-use cover management.

The mean estimated soil erosion rate in the northern catchment was 37.89 t ha$^{-1}$yr$^{-1}$ with a standard deviation of 59.2 t ha$^{-1}$ yr$^{-1}$. This mean rate is comparable with the erosion rates of other catchments of Lake Tana and Blue Nile basin published in the literature. Of the five sub-catchments in the present study, Megech has the highest amount (49.9%) of the total estimated soil erosion and the highest amount (32.7%) of the cells with extreme erosion potential followed by other sub-catchments Gumero (19.1% and 23.3%), Garno (14.5% and 19.4%), Derma (12.2% and 14.9%) and Gabi Kura (4.3% and 9.8%). The northern and eastern parts of the catchment, as well as the areas of the riverine outlets, have the extreme erosion potential values whereas, the western parts of the catchment do not show such high values. The climate, altitude, topography, drainage density, soil conditions, soil types, geology, sediment delivery, sizes of sub-catchments, and land uses are markedly different in these parts. The differences in these features lead to the spatial and temporal variability of soil erosion potential. The main USLE factors that influence the soil erosion risk in the catchment are the slope length and steepness factor (LS-factor), the support practice factor (P-factor), as well as the land cover factor (C-factor). The land cover depends on climatic factors (e.g., rainfall) and soil conditions (texture, organic matter, structure, permeability, and topography). There is a close relationship between the soil erodibility and topography that indicates the susceptibility of the catchment area to erosion. The susceptibility is dependent on land cover and their relationship indicates the sensitivity of the area to the erosion.

In turn, the relationship between the sensitivity and rainfall erosivity indicates erosion risk in the catchment. These relationships varied during wet and dry seasons, however, showing soil erosion risks even during dry seasons. As the K and R factors, that are dependent on the natural soil types and the rainfall, cannot be altered (Stone and Hilborn, 2012), interventional catchment management strategies to prevent and control soil erosion shall focus on the LS, P, and C factors.

The relationship between rainfall and altitude has no significance in the catchment due to the complex and highly varied topography. As the topography of the catchment has an imposing effect on the rainfall distribution, it is important to consider the topography factor in soil erosion studies to evaluate the impact of land management practices in areas sensitive to land degradation. The altitude in the catchment does not directly influence the rainfall erosivity index, but the altitudinal gradient of precipitation does. The highly significant correlation between rainfall and other erosivity indices indicated that high and extreme erosion risk was seasonal. The catchment has a unimodal rainfall pattern during June-September that peaks in July and August, and it clearly shows that these critical months are more susceptible to erosion.

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The rainfall has a good relationship with land cover. During the dry season (October-May) the rate of vegetation growth and agricultural activities are limited. The strong contrasts between the dry and wet seasons, the land covers, the drainage density of soil, and the slopes played a vital
role in soil erosion in the study area. According to the climatic seasonality, June, July, August, and September are the months with the highest risk of soil erosion in scattered barren lands and croplands. In May when usually rainy season starts and in October when the season ends in Ethiopia the soil erosion risk was though low, but considerable. During these months also, erosion in grassland areas, plantation forests, temporarily abandoned agricultural lands, tilled lands on slopes, and near the river, outlets occur in the catchment.

The high soil erosion risk in the highland area of the catchment is confirmed from a high-resolution satellite image and found evidence of colluvial–alluvial formations deposited in the downstream banks of the lowland area of the catchment. These flooded areas with scarce land cover, the sandy formations without consistency, and the undulating slopes produced the morpho-dynamic conditions in the lowland area. However, once the intensity of the flood is reduced, these areas are being used for cultivation from October onwards. The relationship between rainfall and soil erodibility, drainage density, topography, and land cover can be seen as a key factor to understand the soil erosion in the lower parts of the catchment. Here, though the land cover is dependent primarily on the rainfall, the soil conditions also promote the growth of the land cover. The seasonal variation of the land covers such as natural forest, plantation forest, shrubs, seasonal grasses, and agriculture causes a change in the C factor for any given specific month of erosion risk in the catchment. No agricultural activities are conducted in the croplands in upper parts of the catchment during the dry season (December–April). The land is mostly devoid of any cover during the dry season. The first abundant rainfall that starts in May initiates vegetative growth. However, these initial rains cause severe erosion in highland parts of the catchment due to less land cover, improper tillage methods, and poor practices of conservation and management of land and terraces. Basic physical conditions in Ethiopia, which impact land degradation, include topography and rainfall variability from year to year and place to place, particularly in the drier parts of the highlands. The sequence of drier years with reduced vegetation cover followed by wetter years with heavy rainfall is conducive to high levels of soil loss (Berry et al. 2003).

The higher C values in nearly half of the northern catchment indicate the occurrence of less vegetation cover and high estimated erosion there. A large area of the catchment is on strong slopes. However, the areas with extreme erosion potential are mostly located on moderately steep and steep slopes. Of all the land use types, most of the estimated erosion occurred in barren lands followed by the agricultural lands and plantation forests. The relationship between topography and land use is another key factor to understand the soil erosion in the catchment. Very steep slopes were sparse in the catchment comprising only 0.1% agricultural cells of extreme erosion potential. Moderately steep and steep slopes together comprised 34% of the entire basin and 20% of the agricultural areas; yet, 52% of the cells with extreme erosion potential were located on those slopes. Of course, agriculture seemed to favor flat areas with 80% of agriculture occurring on 0-10% slopes and comprised 66% of the catchment. These flatter slopes were not exempt from extreme erosion potential because 48% of the cells with extreme erosion potential were located on them. Moderately steep and steep slopes comprised
40% of the plantation forest, yet 67% of the cells with extreme erosion potential were located on such slopes. 40% of the barren land occurred on moderately steep and steep slopes, but 62% of the cells with extreme erosion potential were located on them.

The wet and dry densities in the study area indicate that the drainage density (Dd) of the catchment depends on the precipitation, infiltration capacity, underlying rock, soil texture, slope, altitude, vegetation, and hydraulic conductivity of the underlying soil. Higher Dd values indicate lower infiltration rates and higher surface flow velocity (Yalcin, 2008) and are often related to a high sediment yield transported through the river network, high flood peaks, steep hills, and low suitability for agriculture. The largest area (55.8%) of the catchment is characterized by low Dd and 58.7% of cells with extreme erosion potential, whereas 44.2% of the catchment is characterized by high Dd and 41.3% of cells with extreme erosion potential.

A large percentage of the catchment, concentrated at low altitudes (1751-2000 m a.m.s.l), is characterized by 77.5% of the high Dd, strong slope gradient (3-10˚), and the largest (47.8%) of the area with extreme erosion potential. Such lower parts of the catchment area associated with the presence of several extremely narrow and scattered streams, and shallow depth of the Eutric vertisols and Luvisols. Thus, the fine clay soil and a number of streams promote soil loss in this area. Very less percent of the catchment occurred in high altitudes (2400-3100 m a.m.s.l) on moderately steep–steep slopes of >10˚ and is characterized by high Dd and the least (12.8%) of the area with extreme erosion potential. It is associated with the rough soil surface and very shallow depth of the Leptosols and Nitosols. About 48.6% of the low Dd area in the catchment occurred at low elevations (1751-2000 m a.m.s.l) having only 8.8% of the cells with extreme erosion potential, whereas 51.4% of the low Dd area occurred at high elevations (2000-3014 m a.m.s.l) having 91% of the cells with extreme erosion potential.

The LS, C, and R factors are found in this study as the causative factors for high soil loss. At the river outlets, the high Dd is not related to high soil loss as the elevation and slope of this region are too low. In many areas of the northern catchment, the slopes are irregular and lead to runoff's into small drainage ways and flow at a velocity sufficient to detach and transport soil particles and thus further the hazard of soil erosion. Gully erosion occurs in the catchment due to highly erodible soils such as Vertisols and Leptosols, and misuse of soil and water resources. The plantation forests, barren lands, croplands, moderately steep and steep slopes, and low Dd areas were very susceptible to gully erosion that has been matched with the generated erosion risk map.

The high soil erosion in the catchment is associated with the highland fringe areas where the critical slopes exist. Field observations also showed the degradation and transformation of agricultural lands into wastelands. The presence of low clay content in loamy soils indicates that soil erodibility tends to be high. In the upper part of the catchment, the drainage forms relatively steep narrow gorges that can attribute to small soil depth and high flow permeability that lower the drainage density and increase the surface runoff to lower parts of the catchment. The high soil loss in the upstream parts of the catchment is due to the shallow depth of the leptosols and
the deeply weathered rocks, whereas, in the downstream parts of the catchment, the high soil loss is the result of the poor agricultural practices in croplands and high rainfall erosivity of uplands. The high percentage of barren lands in the hilly terrains, the presence of leptosols, fallow lands, and rainfall erosivity of the uplands caused moderate to the high amount of soil loss in the downstream sections of the catchment. The rate of increase in the human population of Ethiopia (from 42 to 109 million between 1986 and 2019) continues to put a great demand for agricultural land. Such demand has a negative impact on the natural resource conditions and ecosystems of grasslands, shrublands, and natural forests in the highlands as they are being converted to agricultural lands. The thematic change analysis helps to understand such land cover conversions with remarkable precision.

6. Conclusions

Soil erosion risk in the northern catchment of Lake Tana basin was moderate to high with a mean erosion rate of 37.9 t ha$^{-1}$ yr$^{-1}$. Although the areas with extreme and high erosion potential comprised only 12.4% (2.9% and 9.5% respectively) of the catchment area, they contributed about 82.1% (47% and 35% respectively) of the total soil loss in the catchment, which should be priority areas for better practices of land use and land cover management. Megech comprised the highest percent (i.e. 47.1%) of areas with extreme and high erosion potential followed by the other sub-catchments Gumero (18.4%), Gano (17.2%), Derma (11.7%), and Gabi Kura (5.6%) in the study area. Spatial relationships between soil erosion rates and geographical factors such as slopes, land cover, land-use, drainage density, and soil erodibility that were found in the catchment were inconsistent because of highly complex terrain conditions. The descriptive statistics results revealed that the soil erosion was most sensitive to the topographic factor followed by the other factors i.e., the support practice, soil erodibility, crop management, and rainfall erosivity. Soil erosion risk in the catchment showed the high influence of climatic seasonality and was high during the rainy season only. Barren land exhibited the highest soil erosion rates, followed by the croplands and plantation forest in the catchment. The results showed that gully erosion was constrained in the steep slopes of all sub-catchment areas, which could be attributed to higher steep slopes in land-use. But also it expanded significantly to the middle and lower parts of the catchment. Therefore, Land uses, land cover conversions, and support practices shall be regularized, implemented, and frequently monitored by the concerned departments of agriculture, forest, river water management, and environment. Watershed management and flood control measures also can significantly reduce the riverine soil erosion caused during wet seasons. Farmers shall be provided with appropriate awareness and resources for the implementation of scientific agricultural practices and farm management.

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**Authors’ contributions**

Authors made a valuable and unreserved contribution. VN wrote the methodology used, carried out the data analysis process, USLE model running and the manuscript; RR, WM and GT engaged on the spatial data collection, LULC classification process and accuracy assessment. All authors read and approved the final manuscript.

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**Competing interests**

The authors declare that they have no competing interests.

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### Table 1 Average annual rainfall and rainfall erosivity (R) of sub-catchments of the northern catchment of Lake Tana (1997-2018)

| Sub-catchment | Area (ha) | Average Annual Rainfall (mm) | R (MJ mm ha\(^{-1}\) h\(^{-1}\) yr\(^{-1}\)) |
|---------------|-----------|-------------------------------|---------------------------------------------|
| Gabi Kura     | 56341     | Min: 618.2, Max: 2092.5, Mean: 940.4, SD: 283.2 | Min: 335.3, Max: 1146.2, Mean: 512.7, SD: 156.2 |
| Derma         | 60118     | Min: 689.5, Max: 2105.9, Mean: 1337.3, SD: 338.2 | Min: 374.5, Max: 1153.5, Mean: 731.2, SD: 186.2 |
| Megech        | 80727     | Min: 944.1, Max: 3282.9, Mean: 1807.3, SD: 378.0 | Min: 515.1, Max: 1850.3, Mean: 989.7, SD: 208.0 |
| Gumero        | 54029     | Min: 971.4, Max: 3121.4, Mean: 1610.2, SD: 432.9 | Min: 529.6, Max: 1712.1, Mean: 881.2, SD: 238.3 |
| Gano          | 41016     | Min: 1005.0, Max: 1261.8, Mean: 1089.0, SD: 50.1 | Min: 548.1, Max: 687.8, Mean: 594.2, SD: 27.6 |

### Table 2 Soil types and soil erodibility in the northern catchment of Lake Tana

| Dominant Soil type (FAO, 1990) | USDA Soil Textural class | Organic matter content (%) | K-factor (t ha h h\(^{-1}\) MJ\(^{-1}\) mm\(^{-1}\)) | Area ha (%) | Associated soils & inclusions |
|---------------------------------|--------------------------|---------------------------|-----------------------------------------------|-------------|-------------------------------|
| Eutric Leptosols (LPe)          | Loam (coarse)            | 1.2384                    | 0.34                                          | 1,195 (0.4) | NTu, LVh, LPq                  |
| Lithic Leptosols (LPq)          | Clay loam (medium)       | 0.6708                    | 0.33                                          | 82,925 (28.4)| LPe, CMe, NTu, LVx, VRe     |
| Eutric Vertisols (VRe)          | Clay (medium)            | 1.8404                    | 0.24                                          | 111,166 (38)| FLe, NTu, LVh, LPq          |
| Humic Nitisols (NTu)            | Clay (fine)              | 4.2140                    | 0.21                                          | 15,721 (5.4)| VRe                           |
| Chromic Luvisols (LVx)          | Sandy clay loam (fine)   | 1.0836                    | 0.20                                          | 21,602 (7.4)| VRe, LPq                      |
| Haplic Luvisols (LVh)           | Sandy clay loam (medium) | 1.0320                    | 0.20                                          | 59,621 (20.4)| VRe                           |

### Table 3 K-factors for the northern catchment and its sub-catchments of Lake Tana

| K factor | Entire catchment ha (%) | Gabi Kura subcatchment ha (%) | Derma subcatchment ha (%) | Megech subcatchment ha (%) | Gumero subcatchment ha (%) | Gano subcatchment ha (%) |
|----------|-------------------------|-------------------------------|---------------------------|---------------------------|---------------------------|------------------------|
| 0.34     | 1,959 (0.4)             | 0 (0)                         | 725 (1.2)                 | 1803 (2.2)                | 0 (0)                     | 0 (0)                  |
| 0.33     | 82,925 (28.4)           | 0 (0)                         | 3997 (6.6)                | 36251 (44.9)              | 22122 (40.9)              | 19877 (48.5)           |
| 0.24     | 111,166 (38.0)          | 34011 (60.4)                  | 30993 (51.6)              | 27248 (33.8)              | 14229 (26.3)              | 3971 (9.7)             |
| 0.21     | 15,721 (5.4)            | 0 (0)                         | 8184 (10.1)               | 2492 (4.6)                | 4881 (11.9)               | 12291 (30.0)           |
| 0.20     | 81,223 (27.8)           | 22331 (39.6)                  | 24399 (40.6)              | 7276 (9.0)                | 15184 (28.1)              | 12291 (30.0)           |
Table 4 Distribution of LS-factors in the northern catchment of Lake Tana

| LS factor Class | Entire catchment ha (%) | Megech area ha (%) | Derma area ha (%) | Garno area ha (%) | Gumero area ha (%) | Gabikura area ha (%) |
|-----------------|-------------------------|-------------------|------------------|------------------|--------------------|---------------------|
| 0 ≤ LS ≤ 1     | 287559(98.4)            | 79730(98.6)       | 59557 (99)       | 40205 (98.0)     | 53250 (98.5)       | 56001 (99.3)        |
| 1 < LS ≤ 10    | 4373 (1.50)             | 1018 (1.25)       | 564 (0.93)       | 806 (1.95)       | 730 (1.35)         | 368 (0.65)          |
| 10 < LS ≤ 20   | 229 (0.08)              | 81 (0.1)          | 48 (0.07)        | 21 (0.05)        | 23 (0.1)           | 11 (0.02)           |
| LS > 20        | 100.5 (0.03)            | 42 (0.05)         | 18 (0.03)        | 6 (0.01)         | 8 (0.01)           | 4 (0.01)            |

Table 5 C-factor values for sub-catchments of the northern catchment of Lake Tana

| C-factor values | Entire catchment ha (%) | Megech subcatchment ha (%) | Derma subcatchment ha (%) | Garno subcatchment ha (%) | Gumero subcatchment ha (%) | Gabi Kura subcatchment ha (%) |
|-----------------|-------------------------|-----------------------------|---------------------------|---------------------------|---------------------------|-----------------------------|
| 0.2<C≤0.53      | 56,664 (19.3)           | 30,538 (37.8)               | 12,083 (20.2)             | 7,839 (19.1)              | 8,903 (16.5)              | 10,070 (17.9)              |
| 0.53<C≤0.63     | 103,267 (35.4)          | 17,873 (22.1)               | 18,452 (30.7)             | 14,827 (36.1)             | 21,077 (39.0)             | 19,223 (34.1)              |
| 0.63<C≤0.91     | 132,251 (45.3)          | 32,316 (40.1)               | 29,577 (49.2)             | 18,360 (44.8)             | 24,051 (44.5)             | 27,048 (48.0)              |

Table 6 P-factor values for land use groups on slope gradients (Shin 1999)

| Land-use group | Slope (degree) | Area ha (%) |
|----------------|---------------|-------------|
|                | 0–5° | 5–8° | 8–10° | 10–15° | >15° |         |
| Dense forest, Grassland | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 31,981 (10.9) |
| Plantation forest, Shrub land, Perennial & Cash crops | 0.55 | 0.6 | 0.8 | 0.9 | 1.0 | 79,963 (27.4) |
| Seasonal & Yearly crops (Pulses), Crop fields (Teff, Barley, Wheat, Rice, Maize, Sorghum, Corn, etc.) | 0.27 | 0.3 | 0.4 | 0.45 | 0.5 | 149864(51.3) |
| Built-up area, Bare rock, Bare soil | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 30,400 (10.4) |

Table 7 Estimated soil loss and erosion rates in the northern catchment of Lake Tana

| Soil erosion class (tons ha⁻¹ yr⁻¹) | Area, ha (%) | Soil loss tons/yr (%) | Mean erosion rate (tons/ha/yr) ± SD |
|-------------------------------------|--------------|-----------------------|-----------------------------------|
| Very low (0–1)                      | 172,106 (58.9) | 18,879 (1.1)         | 0.11 ± 0.27                      |
| Low (1–5)                           | 53,110 (18.2)  | 129,676 (7.6)        | 2.44 ± 1.16                      |
| Moderate (5–10)                     | 30,699 (10.5)  | 149,581 (9.2)        | 7.12 ± 1.54                      |
| High (10–50)                        | 27,800 (9.5)   | 597,386 (35.0)       | 20.80 ± 9.87                     |
| Extreme (> 50)                      | 8,517 (2.9)    | 809,848 (47.1)       | 156.83 ± 285                     |
### Table 8: Comparison of soil loss estimations with results of various studies conducted in Ethiopia

| Study area                              | Mean annual precipitation (mm) | Mean annual soil loss (t ha\(^{-1}\) yr\(^{-1}\)) | Reference                      |
|-----------------------------------------|-------------------------------|-----------------------------------------------|---------------------------------|
| Northern catchment of lake Tana         | 1453                          | 37.89                                         | This study                      |
| Ribb watershed, lake Tana basin         | 2004                          | 39.80                                         | Estifanos (2014)                |
| Gumara watershed, lake Tana basin       | 2078                          | 42.67                                         | Belayneh et al.(2019)           |
| Upper Blue Nile basin                   | 1680                          | 16.0 & 27.50                                  | Daniel et al. (2015), &         |
|                                         |                               |                                               | Haregeweyn et al.(2017)         |
| Dembecha, Blue Nile basin               | 1531                          | 49.00                                         | Zerihun et al.(2018)            |
| Koga watershed, Blue Nile basin         | 1640                          | 42.0 & 47.40                                  | Tegegne and Biniam (2017), &     |
|                                         |                               |                                               | Gelagay and Minale (2016)       |
| Beshillo catchment, Blue Nile basin     | 930                           | 37.90                                         | Yesuph and Dagnew, (2019)       |
| Gelana sub-watershed, Northern highlands | 1024                          | 24.30                                         | Mihretu and Yimer, (2017)       |
| Guder sub watershed, Central highlands  | 1445                          | 30.30                                         | Kidane et al. (2019)            |
| Ethiopian Highlands as a whole          | Variable                      | 100.00                                        | FAO (1986)                      |

### Table 9: Estimated erosion rates and annual soil loss in sub-catchments of the northern catchment of Lake Tana

| Sub catchment | Entire catchment ha (%) | Very low erosion cells ha (%) & Soil loss tons/yr (%) | Low erosion cells ha (%) & Soil loss tons/yr (%) | Moderate erosion cells ha (%) & Soil loss tons/yr (%) | High erosion cells ha (%) & Soil loss tons/yr (%) | Extreme erosion cells ha (%) & Soil loss tons/yr (%) |
|---------------|-------------------------|--------------------------------------------------------|--------------------------------------------------|------------------------------------------------------|---------------------------------------------------|------------------------------------------------------|
| Derma         | 60118(20.6)             | 39549(22.9) & 4912(25.9)                              | 12619(23.8) & 31541(24.3)                          | 3685(12.0) & 21883(14.6)                             | 2998(10.8) & 4923(8.2)                             | 1267(14.9) & 100360(12.5)                             |
| Gabi Kura     | 56341(19.3)             | 41154(23.8) & 6105(32.2)                              | 8695(16.4) & 18651(14.4)                           | 4462(14.5) & 9234(6.2)                              | 1196(4.3) & 1782(3.0)                              | 834(9.8) & 21574(2.7)                                 |
| Gorno         | 41016(14.1)             | 21033(12.2) & 1794(9.5)                               | 7151(15.3) & 21140(16.3)                           | 6582(21.4) & 3217(21.5)                             | 4601(16.6) & 107314(18.0)                          | 1649(14.9) & 82406(10.2)                              |
| Gumero        | 54029(18.5)             | 29289(17.0) & 2962 (15.6)                             | 10563(19.9) & 25086(19.4)                          | 7509(24.5) & 33295(22.3)                            | 4682(16.8) & 136306(22.8)                           | 1986(23.3) & 128007(15.9)                             |
| Megech        | 80727(27.6)             | 41081(24.1) & 3194(16.8)                              | 14082(26.5) & 33201(25.6)                          | 8461(27.6) & 52969(35.4)                            | 14322(51.5) & 286709(48.0)                          | 2781(32.7) & 472683(58.7)                             |

### Table 10: Standardized coefficients (β) for USLE model-independent factors

| Independent factors | Standardized Coefficients | Sig. * | Collinearity Statistics |
|---------------------|---------------------------|--------|-------------------------|
|                     | Beta, β                   |        | Tolerance | VIF   |
| R                   | 0.155                     | 0.018  | 0.825       | 1.213 |
| K                   | 0.217                     | 0.002  | 0.808       | 1.237 |
| LS                  | 0.563                     | 0.000  | 0.887       | 1.128 |
| C                   | 0.151                     | 0.043  | 0.613       | 1.631 |
| P                   | 0.468                     | 0.000  | 0.626       | 1.597 |
Table 11 C-factor and estimated erosion in the northern catchment of Lake Tana

| C factor | Entire catchment (ha (%)) | Very low erosion cells (ha (%)) | Low erosion cells (ha (%)) | Moderate erosion cells (ha (%)) | High erosion cells (ha (%)) | Extreme erosion cells (ha (%)) |
|----------|---------------------------|---------------------------------|----------------------------|---------------------------------|----------------------------|-------------------------------|
| 0.2-0.53 | 56664(19.4)               | 30946(16.6)                     | 9044(19.9)                 | 8383(30.0)                      | 6851(29.1)                 | 1441(16.5)                   |
| 0.53-0.63| 103267(35.3)              | 70630(37.9)                     | 14037(30.9)                | 8207(29.4)                      | 7616(32.3)                 | 2771(31.8)                   |
| 0.63-1.0 | 132251(45.3)              | 84868(45.5)                     | 22392(49.2)                | 11366(40.7)                     | 9113(38.6)                 | 4512(51.7)                   |

* Level of significance @0.05 (95%)

Table 12 Slopes* and estimated erosion in the northern catchment of Lake Tana

| Slope gradient | Entire catchment (ha (%)) & Soil loss tons (%) | Moderate erosion cells (ha (%)) & Soil loss tons (%) | High erosion cells (ha (%)) & Soil loss tons (%) | Extreme erosion cells (ha (%)) & Soil loss tons (%) |
|----------------|-----------------------------------------------|-----------------------------------------------------|---------------------------------------------------|-----------------------------------------------------|
| Gentle slopes (0-3°) | 35030 (12.0) & 60379 (3.6)                  | 2837(8.4) & 2610(0.4)                               | 879(4.5) & 35043(19.4)                             | 210(4.1) & 12069(1.5)                              |
| Strong slopes (3-10°) | 157754 (54.0) & 581022 (34.1)               | 9144(26.9) & 121269(20.6)                           | 6525(33.3) & 48601(26.9)                           | 1443(28.0) & 322975(41.5)                           |
| Moderately steep slopes (10-20°) | 66533 (22.8) & 548350 (32.2)                | 10210(30.1) & 183917(31.2)                          | 7356(37.6) & 57774(32.0)                           | 1650(32.0) & 261493(33.6)                           |
| Steep slopes (20-45°) | 32573 (11.1) & 502227 (29.5)                | 11634(34.3) & 277685(47.2)                          | 4789(24.5) & 39201(21.7)                           | 1823(35.3) & 176355(22.6)                           |
| Very steep (>45°) | 328 (0.1) & 9186 (0.6)                      | 133(0.5) & 3085(0.5)                               | 27(0.1) & 56(0.1)                                 | 35 (0.7) & 6045(0.8)                               |

* Gentle slopes (flat to undulating); Strong slopes (rolling); Moderately steep slopes (hilly)

Table 13 Land-use type and estimated erosion in the northern catchment of Lake Tana

| Land-use type      | Entire catchment (ha (%)) & Soil loss tons (%) | Moderate erosion cells (ha (%)) & Soil loss tons (%) | High erosion cells (ha (%)) & Soil loss tons (%) | Extreme erosion cells (ha (%)) & Soil loss tons (%) |
|--------------------|-----------------------------------------------|-----------------------------------------------------|---------------------------------------------------|-----------------------------------------------------|
| Grassland          | 28481(9.7) & 210872(12.4)                     | 2884(9.9) & 66556 (11.1)                             | 1697(8.6) & 13352(8.9)                             | 1826(9.9) & 121611(15.1)                             |
| Cropland           | 83750(28.7) & 231879(13.6)                     | 8619(29.5) & 64098(10.7)                             | 5820(29.6) & 13885(9.3)                             | 5486(29.7) & 129280(16.1)                             |
| Plantation Forest  | 44645(15.3) & 488572(28.7)                     | 3257(11.1) & 182775(30.5)                            | 1741(8.8) & 44537(29.8)                            | 3867(21.0) & 216959(27.0)                             |
| Shrub land         | 39050(13.4) & 2190922(12.1)                    | 4763(16.3) & 95038(15.9)                             | 3539(18.0) & 26594(17.8)                            | 1095(5.9) & 81499(10.1)                              |
| Baren land         | 80828(27.6) & 421847(24.8)                     | 8580(29.3) & 158134(26.4)                            | 6047(30.7) & 45631(30.5)                            | 5834(31.6) & 174233(21.7)                             |
Table 14 Land-use type and estimated erosion in sub-catchments of the northern catchment of Lake Tana

| Sub-catchments | All land-use area ha (%) | Cropland | Plantation forest | Barren land |
|----------------|--------------------------|----------|-------------------|-------------|
|                |                          | Cropland cells ha (%) | Extreme erosion cells ha (%) | Plantation forest cells ha (%) | Extreme erosion cells ha (%) | Barren land cells ha (%) | Extreme erosion cells ha (%) |
| Derma          | 60118(20.6)              | 18471(22.1) | 467(17.6)       | 10513(23.6) | 1184(15.7)    | 15934(19.7) | 905(12.2)      |
| Gabi Kura      | 56341(19.3)              | 20057(23.9) | 231(8.7)        | 8911(20.0)  | 448(5.9)      | 14462(17.9) | 423(5.7)       |
| Garno          | 41016(14.1)              | 8597(10.3)  | 369(13.9)       | 5166(11.6)  | 1492(19.8)    | 12801(15.8) | 1493(20.1)    |
| Gumero         | 54029(18.5)              | 20154(24.1) | 707(26.6)       | 6223(14.0)  | 1693(22.4)    | 13856(17.1) | 1418(19.1)    |
| Megech         | 80727(27.6)              | 16477(19.7) | 883(33.2)       | 13783(30.9) | 2739(36.3)    | 23758(29.4) | 3192(43.0)    |

Table 15 Slopes, land use types and estimated erosion in the northern catchment of Lake Tana

| Slopes         | Entire catchment ha (%) | Cropland | Plantation forest | Barren land |
|----------------|-------------------------|----------|-------------------|-------------|
|                |                          | Cropland cells ha (%) | Extreme erosion cells ha (%) | Plantation forest cells ha (%) | Extreme erosion cells ha (%) | Barren land cells ha (%) | Extreme erosion cells ha (%) |
| Gentle         | 35030 (12.0)            | 15466(18.5) | 246(8.8)         | 4446(10.0)  | 308(4.7)      | 6489(8.0)  | 331(4.5)       |
| Strong         | 157754(54.0)            | 51216(61.1) | 1105(39.3)       | 22015(49.3) | 2039(27.5)    | 42097(52.1) | 2455(33.5)    |
| Moderately steep | 66533 (22.8)         | 9910 (11.8)  | 684(24.4)        | 8715(19.5)  | 2440(32.7)    | 23648(29.2) | 3010(41.0)    |
| Steep          | 32573 (11.1)            | 7108 (8.5)  | 766(27.3)        | 9389(21.0)  | 2597(34.8)    | 8568(10.6) | 1535(20.9)    |
| Very steep     | 328 (0.1)               | 64 (0.1)   | 7(0.2)           | 83(0.2)     | 21(0.3)       | 71(0.1)   | 8(0.1)        |

Table 16 Drainage densities and Soil erosion in the northern catchment of Lake Tana

| Drainage density (Dd) | Entire catchment ha (%) & Soil loss tons (%) | Moderately erosion cells ha(%) & Soil loss tons (%) | High erosion cells ha (%) & Soil loss tons(%) | Extreme erosion cells ha (%) & Soil loss tons(%) |
|-----------------------|-----------------------------------------------|-----------------------------------------------------|-----------------------------------------------|---------------------------------------------------|
| High Dd               | 131393(44.2) & 768110(45.1)                    | 9948(33.6) & 198680(33.2)                           | 8156(38.3) & 58295(38.1)                        | 2733(41.3) & 378825(46.1)                         |
| Land-use type       | 1986 Area (ha) | 2018 Area (ha) | Net LUCC area (1986-2018) | Relative Net change percent |
|--------------------|---------------|---------------|----------------------------|-----------------------------|
| Artificial surface | 6437          | 12974         | 6537                       | 101.6                       |
| Barren land        | 105575        | 80828         | -24747                     | -23.4                       |
| Grassland          | 35145         | 28481         | -6664                      | -19.0                       |
| Shrub land         | 47330         | 39050         | -8280                      | -17.5                       |
| Cultivated land    | 63235         | 83750         | 20515                      | 32.4                        |
| Plantation forest  | 28502         | 44645         | 16143                      | 56.6                        |
| Forest             | 6251          | 2250          | -4001                      | -64.0                       |
| Waterlogged        | 1869          | 2562          | 693                        | 37.1                        |
| Class name       | Reference totals | Classified totals | No. correct | Producers accuracy | Users accuracy | Reference totals | Classified totals | No. correct | Producers accuracy | Users accuracy |
|-----------------|------------------|-------------------|-------------|--------------------|----------------|------------------|-------------------|-------------|--------------------|----------------|
| Artificial surface | 40 | 41 | 35 | 87.5 | 85.4 | 40 | 39 | 31.0 | 77.5 | 79.5 |
| Barren land     | 40 | 44 | 37 | 92.5 | 84.1 | 40 | 43 | 33.0 | 82.5 | 76.7 |
| Cultivated land | 40 | 38 | 38 | 95.0 | 100.0 | 40 | 38 | 36.0 | 90.0 | 94.7 |
| Forest          | 40 | 42 | 40 | 100.0 | 95.2 | 40 | 42 | 40.0 | 100.0 | 95.2 |
| Grassland       | 40 | 41 | 39 | 97.5 | 95.1 | 40 | 40 | 36.0 | 90.0 | 90.0 |
| Plantation forest | 40 | 38 | 38 | 95.0 | 100.0 | 40 | 35 | 35.0 | 87.5 | 100.0 |
| Shrub land      | 40 | 41 | 40 | 100.0 | 97.6 | 40 | 45 | 40.0 | 100.0 | 88.9 |
| Waterlogged     | 40 | 35 | 32 | 80.0 | 91.4 | 40 | 38 | 31.0 | 77.5 | 81.6 |
| Overall accuracy of classification | 0.9344 | | | | | 0.8812 | | |
| Overall Kappa   | 0.9250 | | | | | 0.8643 | | |