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Abreham Berta Aneseyee (abresh1240@gmail.com)

Research

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Abreham Berta Aneseyee1,2*

1. Center for Environmental Science, College of Natural and Computational Science, Addis Ababa University, P. O. Box No: 1176, Addis Ababa, Ethiopia.
2. College of Agriculture and Natural Resource Department of Natural Resource Management, Wolkite, P. O. Box 07, Wolkite, Ethiopia.

Correspondent author email: abresh1240@gmail.com

Abstract

Background: Information on soil loss and sediment export is essential to identify hotspots of soil erosion for conservation interventions in a given watershed. This study aims at investigating the dynamic of soil loss and sediment export associated with land use/land cover change and identifies soil loss hotspot areas in Winike watershed of Omo-gibe basin of Ethiopia. Spatial data collected from satellite images, topographic maps, meteorological and soil data were analyzed. Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) of sediment delivery ratio (SDR) model was used based on analysis of land use/land cover maps and RUSLE factors.

Result: The results showed that total soil loss increased from 774.86 thousand tons in 1988 to 951.21 thousand tons in 2018 while the corresponding sediment export increased by 3.85 thousand tons in the same period. These were subsequently investigated in each land-use type. Cultivated fields generated the highest soil erosion rate, which increased by 10.02 t/ha/year in 1988 to 43.48 t/ha/year in 2018. This corresponds with the expansion of the cultivated area that increased from 44.95 thousand ha in 1988 to 59.79 thousand ha in 2018. This is logical as the correlation between soil loss and sediment delivery and expansion of cultivated area is highly significant ($p<0.01$). Sub-watershed six (SW-6) generated the highest soil loss (62.77 t/ha/year) and sediment export 16.69 t/ha/year, followed by Sub-watershed ten (SW-10) that are situated in the upland plateau. Conversely, the lower reaches of the watershed are under dense vegetation cover and experiencing less erosion.

Conclusion: Overall, the changes in land use/land cover affect significantly the soil erosion and sediment export dynamism. This research is used to identify an area to prioritize the watershed for

immediate management practices. Thus, land use policy measures need to be enforced to protect the hydropower generation dams at downstream and the ecosystem at the watershed.

Key Words: InVEST model, Omo gibe basin, Sediment delivery, Soil loss, Winike watershed

Background

Watershed ecosystems provide multiple services including hydrological cycling, provisioning, regulating of climate and soil erosion (Guo et al., 2019; Seutloali and Beckedahl, 2015; Sun et al., 2014). Soil erosion is a global environmental threat (Sun et al., 2013), which leads to a reduction of provisioning and regulating ecosystem services (Aneseyee et al., 2019; Bezabih et al., 2016; Hassen and Assen, 2018).

Land use and land cover change (LU/LCC) is the major causal factor for driving soil loss in upland watersheds particularly Sub-Saharan Africa (Seutloali and Beckedahl, 2015). Speedy land-use alteration because of exhaustive agronomic practices, population pressure, poverty, the absence of comprehensive land-use policies and land tenure systems upshots intensifying rates of soil erosion (Abebe and Sewnet, 2014; Aster, 2004; Tefera et al., 2002). This soil loss is also activated by an amalgamation of topographic factors such as slope length and steepness, and climate change along with land cover patterns and the intrinsic properties of soil (Gelagay and Minale, 2016). Reports indicate that soil erosion is highest in cultivated land and lowest under forest land suggesting, the importance of soil cover (C-factor of erosion) and land management (P factor) (Nigatu, 2014; Tadesse et al., 2017). Many research reports show that land use/land cover change result in soil erosion and sedimentation processes that disrupt the hydrological balance of a watershed, e.g, Chaleleka wetland, Central Rift Valley of Ethiopia (Wolka et al., 2015) and the level of Hawassa lake has increased due to erosion and the sedimentation processes in the surrounding river watersheds (Ayenew et al., 2007; Kebede et al., 2014).

Hence, quantifying soil erosion and sediment delivery (i.e., sediment that essentially arrives at the watershed outlet) is important to design appropriate conservation measures (Hamel et al., 2015). The study indicated that 10% of total soil erosion is delivered to an outlet that reaches a natural water body in Ethiopia high land (Constable and Belshaw, 1986). This exported soil offers the downstream influences of sediment deposition affecting the ecosystem and siltation of water reservoirs and hydroelectric dams (Baral et al., 2014).

In Ethiopia, a large body of scientific literature and research reports are available on soil erosion (Bewket and Teferi, 2009; Haregeweyn et al., 2015; Hurni, 1988; Hurni et al., 2005). Although variations in soil loss estimates vary depending on the methods used (measurement versus model estimation), the general agreement is that soil erosion in the Ethiopian highlands is among the highest in sub-Saharan Africa (Elias, 2017). The most of the report agreed that the average soil loss in Ethiopia high land is greater than 80 t/ha/year (Bewket and Teferi, 2009; Constable and Belshaw, 1986; Haregeweyn et al., 2015; Haregeweyn et al., 2017). However, information on the soil loss and sediment export and its spatial variation associated with LULC change in a watershed is limited in Ethiopia (Sadeghi et al., 2008).

Many soil erosion models such as the Revised Universal Soil Loss Equation (RUSLE) predict soil loss are not capable of predicting the sediment exported from a given watershed (De Vente et al., 2013). Several studies have used the Revised Universal Soil Loss Equation (RUSLE) to examine soil loss (Hamel et al., 2015) but the factors of RUSLE are continuously changing conditions by the land use type. For instance, the different spatial distribution of the crop cover (C factor) and land management (P factor) are directly linked to changing land-use types. Often, reductions in C and P factors are reported to have increased soil loss and sediment export and it is related to higher loss of regulating functions of the ecosystem (Durigon et al., 2014). Conversely, models such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) sediment delivery ratio (SDR) model overcomes such limitations with the conventional soil erosion models and it enables characterizing the hydrological connectivity of the watershed (Sharp et al., 2018). InVEST model has followed a compressive approach by analysing the soil loss and loading sediment at the outlet of the watershed (sediment export) at the same times.

Sediment delivery to watercourses in many areas of the world is increasing as catchments are progressively modified through human activities such as agriculture expansion, deforestation, construction, and the urbanization (Duerdoth et al., 2015). This increase of sediment has resulted in modification of the structure and chemical composition of the river bed (Gieswein et al., 2019), aquatic pollution (Dalu et al., 2019), habitat modifications (Ysebaert et al., 2019) and siltation and nutrient enrichment of the reservoirs and dams (Devi et al., 2008; Sutcliffe et al., 2012). Reports show that there is a loss of about 2% of the designed storage volume of reservoirs each year due to sedimentation (Aga et al., 2019). The soil erosion results in the decline of soil fertility in the upslope of land that is washed away (exported) from farmlands and these erosion-based constraints significantly reduce the agricultural productivity (Bashagaluke et al., 2018; Kurothe et al., 2014; Sahoo et al., 2015). The exported soil also affects in the downward ecosystem degradation like sedimentation of dams, the burial of fertilizing cultivation fields with boulders and stone etc. The Omo Gibe basin is one of the twelve major river basins in Ethiopia and it is the most important basins because of series of hydropower power dams that have been constructed on Omo and Gibe rivers. The dams (Gibe I, Gibe II and Gibe III and Gibe IV) have a total power generation capacity of more than 2600 MW thus contributing towards the green economic development of Ethiopia (Aneseyee et al., 2019) with the estimated life span of 70 years (Sutcliffe et al., 2012). However, sedimentation and nutrient enrichment emanating from high surface runoff in the surrounding watersheds are becoming the major threats to the dams (Sutcliffe et al., 2012; Takala et al., 2016; Woldemariam et al., 2018). Winike watershed is located on the upper stream of the Omo River delivering sediment to Gibe II, IV and IV dams (Figure 1). In this watershed, the densely populated inhabitants depend on cereal cultivation of the rugged and rolling topography, which aggravates soil erosion and subsequent sediment yield in the area (Bezabih et al., 2016). Hence concerted effort in conserving and protecting the watershed is a high priority agenda for Ethiopia and to maintain soil fertility but abate siltation of the Gibe hydropower dams at the same time. Quantifying and documenting the extent and sediment implies of a case study watershed is a major priority for landscape managers (Demissie et al., 2013). Besides, to overcome the challenges of sedimentation in the reservoirs downstream, stakeholders require understanding where the sediment is produced in a given watershed. This was analyzed using the Sediment Delivery Ratio (SDR) of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Sharp et al., 2018). Therefore, the objectives of this study are (1) to explore the changes in land use and land cover and ensuing soil loss and sediment export under different land-use types; (2) to assess the influences of changes in individual land use/land cover types on soil loss and sediment export; 3) to prioritize the sub-watershed for immediate conservation action.

Methods and Materials

Description of the study area

The study site is straddling the regions of South Nation and Nationalities People Region state (SNNRP) of Ethiopia in the Omo Gibe Basin within coordinate bounds of7°40’N to 8°20’N latitudes and 37°40’E to 38°10’E longitudes, covering an area of 1091.8 km2 (Figure 1). Winike River is one of the tributaries of the Omo Gibe basin, which found in five districts of the Guraghe zone (Cheha, Ezha, Gumer, Geta, Enemor) and one district of Silte zone (Merab Azernet Berbere).

The entire watershed is divided into 10 sub-watersheds based on altitude and drainage density using ArcSWAT for further spatial analysis and identification of priority watersheds for immediate interventions (Figure 1).

The altitude ranges between 1022 m and 3324 having a wide range of slope gradient from the lowest of zero to the highest of 89.9°. Average annual rainfall for a period of 30 years (1988–2018) for the five weather stations (Agena, Emdiber, Enemore, Gumer and Merab Azernet) varies from 856 mm to 1,600 mm with a bimodal distribution. The main rainy season *Kiremt*, which extends from June to September and the short season *(the Belg*) between from March to April. The annual mean temperature is 19.1°C, where the maximum and minimum values are given by 22.5 °C & 6.7 °C, respectively. Acacia vegetation (Acacia polyacantha) is dominantly found in the lower part of the watershed, whereas Eucalyptus plantation is found dominantly in the upper part of the watershed.

Analysis of Land Use/Land Cover Change

Based on the existing land use type in the watershed, the area was initially categorized into eight broad LULC classes. These are cultivated land, built-up area, woodland, forest land, grazing land, bare land, shrubland, and water body. GPS coordinates of the target eight LULC types were collected, with 320 total Ground Control Points (GCPs). Thematic layers of towns, topographic maps, regional administration maps, and roads were used to collect the information in the watershed.

Satellite images were obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov) of earth explorer, for the years 1988, 1998, 2008, and 2018. All the images were projected to the Universal Transverse Mercator (UTM) of WGS84 with the location of 37 N, and Ethio GIS data were used to clip the study area. The multi-date multi-sensor satellite imagery was collected for successive cropping seasons during the study years. Dataset selections were fixed in the dry season (February and January), with the lowest percent monthly cloud cover (0-3%). A 30 m resolution digital elevation model (DEM) was used, which is downloaded from the ASTER GLOBAL DEM site (https://earthexplorer.usgs.gov).

The supervised image classification method was employed using Mahalanobis distance classification and the region of interest (ROI) has been a signature for the analysis in each LULC type. The radiometric correction was applied to reduce haze removal, sensor noise, loss of data correction, solar position effect on missing line and calibration of the satellite (Hilker et al., 2012; Lyapustin et al., 2012).

Confusion matrix was employed to measure the reliability of the LULC classification. The overall accuracy for the land use classification was 87.23% in 1988, 90.45% in 1998, 92.21% in 2008 and 95.3% in 2018 for land use. Besides, the Kappa coefficient, 0.88 in 1988, 0.89 in 1998, 0.92 in 2008 and 0.95 in 2018, was found to be an agreement with the classified image and the referenced data was applied.

According to Hassen and Assen (2018), the rates of change of LULC classes (proportion) for each land use/land cover overtimes were calculated by Eq. (1).

$$C = \frac{A_{f2} - A_{f1}}{A_{f1}} \times 100 \qquad \text{Eq. (1)}$$

Where Af 1= the area of one type of land use in f1 time; Af2 = the area of the same type in f2 time and C = the rate of change in percent.

Estimation of soil loss and sediment delivery analysis

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST 3.3.6) and sediment delivery ratio (SDR) modelling is used to model sediment delivery and soil loss (Hamel et al., 2017; Sharp et al., 2018). The rationale for employing this model include (1) the model is relatively less data-intensive and flexible than other models like SWAT; and (2) it can easily be adapted to a specific context (Gao et al., 2017). The unique characteristics of the InVEST model can analyze land-use types of soil loss and sediment export independently based on RUSLE factors, DEM, Maximum SDR and Borselli parameters.

Potential soil loss in the watershed was estimated using the Universal soil loss equation (Wischmeier and Smith, 1978) based on six factors - rainfall erosivity (R), soil erodibility (K), topographic factors (length and gradient – LS), cover (C) simulated by means of Normalized Vegetation Index (NDV) as shown in Eq. (6) and management (P).

$$USLE_i = (R * K * LS * C * P)_i \qquad \text{Eq. (2)}$$

Where, R is the rainfall erosivity factor (MJ Mm/ha/year), K is the soil erodibility (MJ mm/t/ha), LS is the topographic factor (dimensionless), C is the crop management (dimensionless) and P is the conservation practices (dimensionless). Each RUSLE parameter was prepared for the InVEST model input according to the model’s requirement. To be perfectly run the model, the input RUSLE parameters were projected to UTM of WGS84 with the location of 37 N.

Rainfall erosivity factor (R)

The erosivity factor was calculated according to the Eq. (3)**,** as given in Hurni (1985) derived from spatial regression analysis for Ethiopian conditions, based on the available mean annual rainfall (P). Thirty-year of monthly total rainfall data were obtained from five meteorological stations in the watershed (Emdiber, Gubre, Gunchre, Agena and Gumer). The interpolation techniques of IDW (Inverse Distance weighted interpolation) was used to create spatial raster map. The raster interpolated R factor was used as input for InVEST model for the year 1988, 1998, 2008 and 2018.

$$R = -8.12 + 0.562P \qquad \text{Eq. (3)}$$

Where R is the erosivity factor and P is the mean annual rainfall in mm/year.

Soil erodibility (K factor)

The FAO (1984) soil and geomorphological map of Ethiopia (1: 2 million scales) was used to identify major soil types in the watershed. The shapefile of the legacy soil map was obtained from the FAO and complimented by the Omo - Gibe river basin master plan soil database that was made available by the Ethiopia Water, Irrigation and Electric Ministry. Accordingly, five soil types were identified Chromic Luvisols, Pellic Vertisols, Eutric Nitosols, Leptosols, and Orthic Acrisols. In each soil type, plot soil samples were taken to determine the K factor using Eq. (4), based on the four soil characteristics that determine erodibility (sand, clay, silt, and soil organic matter content). After calculating the soil erodibility, its value was assigned for each soil type and soil map of the watershed was delineated for the watershed. The K factor values of watershed ranged from 0.33 to 0.62 (Table 1).

According to, soil erodibility (K factor) were calculated using Eq. (4)

$$Soil\ Erodibility\ (K) = \frac{2.1M^{1.14}(10^{-4}(12-OM)}{7.59} \qquad \text{Eq. (4)}$$

Where, K = soil erodibility, OM = soil organic content (%) and

$$M = ((\%\text{silt} + \%\text{sand}) \times 100 - \%\text{clay}) \qquad \text{Eq. (5)}$$

Cover Factor (C)

The corresponding average C-value was determined for each land use/land cover classes of the years (1988, 1998, 2008 and 2018) based on NDVI value Eq. (6), suggested by Durigon et al. (2014).

$$C = \frac{(-NDVI+1)}{2} \qquad \text{Eq. (6)}$$

$$NDVI = \frac{(NIR-RED)}{(RED+NIR)} \qquad \text{Eq. (7)}$$

Where NIR is the surface spectral reflectance in the near-infrared band and RED is surface spectral reflectance in the red band. The C-value ranged from 0.0 to 0.27 in the watershed (Table 2).

Land management Practices (P factor)

Management practices (P) were determined based field observation in the upper, middle and lower sub-watersheds of the area focusing on the practices of conservation. The various soil and water conservation practices employed by farmers were identified and documented in treated or untreated areas of the watershed. Depending on the different conservation practices, the value of the P factor ranges from 0 to 1, as suggested by Hurni (1985) and Ganasri and Ramesh (2016). Assigning highest P-value indicates good conservation practices while the lowest values associated with the land required conservation practices. The agricultural land p-value is assigned based on slop classification (Annex 1), using ArcGIS.

Sediment export

The sediment load or export from given pixel i, Ei (t ha−1yr−1) is given in Eq. (8)

$$Ei = \text{USLEi}^{*}\ SDRi \qquad \text{Eq. (8)}$$

Where,

SDRi= sediment delivery ratio (SDR) for a pixel i

The sediment delivery ratio (SDR) is the proportion of fine sediment produced in a given area that travels with the overland flow and researches natural waterways (Hamel et al., 2015; Sharp et al., 2016). It is computed as a function of the hydrologic connectivity of the area following an approach proposed by Vigiak et al. (2012). It has a default value of 0.8 to reduce the number of parameters (Hamel et al., 2015; Vigiak et al., 2012) and the Borselli k and Borselli ICo parameters are taken the default value of 0.5 and 0.2, respectively (Sharp et al., 2016).

The total catchment sediment export /load, (tha-1yr-1) is given by Eq. (9).

$$\text{E} = \sum_{i=0}^{n} E_i \qquad \text{Eq. (9)}$$

Where, Ei= sediment export/load, calculated from Eq. (8)

Model Validation

For validation, the observed data obtained from Ethiopia Ministry of Irrigation, Water and Electric Ministry was compared against with InVEST model output. To determine the observed data, the empirical relationship between streamflow and associated sediment concentration was estimated (Asselman, 2000; Sadeghi et al., 2008) using Eq. (10) of six stations.

$$SC = b \times Q^c \quad \text{Eq. (11)}$$

Where SC (t/day) = Suspended sediment concentration (g/ml), Q is stream flow rate (m3/s), b & c are constant to be determined from the observed sediment concentration and streamflow.

The InVEST model output was compared against the observed data (Eq. 10) to obtain the accuracy of the model using Eq. (12).

$$RRMSE = \frac{RMSE}{\sum_{i=1}^{n} \frac{O^i}{n}} \quad \text{Eq. (11)}$$

$$RMSE = \sqrt{\frac{1}{n}} \sum_{j=1}^{n} (P_i - O_f)^2 \quad \text{Eq. (12)}$$

Where, O= Observed data, P=predicted and n= number of samples

Results

Land Use/Land Cover dynamisms

Land conversion and cover change between 1988 and 2018 resulted in the expansion of cultivated lands and built-up areas at the expense of forest, grazing land, and shrubland (Table 3). This is consistent with the ever-increasing number of human populations in the area needing more land for food production habitation (residence). The conversion of grazing, forest and shrubland into cultivated land over 30 years was by 19%, and 1.84%, 0.28%, respectively. As a result of deforestation and overgrazing, there is a steady increase in the area of bare land was increased by 0.91% suggesting the ensuing problem of desertification. The waterbody like constructed ponds, lakes (Areket, Dweshe and Yezebeze) and rivers are insignificant declined by -0.01%. The portion of the watershed that remained enact was 45.89% that remained under forest, shrub, wood and grazing land. The most dramatic land-use conversion and cover change took place from the 1990 to 2018 period. This is partly associated with the fall of the *Dergue* regime in 1991 and the subsequent disbandment of the military who returned from the civil war and started clearing forests and expanded the settlement. Besides, there was a population boom during this period, compared with the period before 1988 when the nation was on civil war. After the fall of *Dergue* regime, the EPRDF government implement agricultural policy (ADLI) that help for investment expansion and motivate the farmer to increase agricultural production. This was contributed to the degradation of the forest and pristine environment for searching for land.

Change in soil loss and sediment export

Change in soil loss

As would be expected, the drastic change in the land use and cover from the forest, grazing and shrubland to cultivated land resulted in corresponding high soil loss compared to other land-use types. The estimated total soil loss of the watershed increased from 774.86 thousand metric ton in 1988 to 951.21 thousand metric tons in 2018 with the mean annual soil loss 11.88 t/ha/year (Table 4). Major soil loss occurred within 2008 to 2018 With the maximum soil loss of 270.6 t/ha/year recorded in 2018 suggesting progressively increasing levels of soil loss in the watershed.

The major source of increase means soil loss was from cultivated land that ranged between 10.02 t/ha/year in 1988 to 43.48 t/ha/year in 2018. This is followed by an average loss of 33.47 t/ha/year, from the bare land in the same period. The data suggests that cultivated land make the most significant contribution to the total soil loss in the watershed due to poor cultural practices including cultivation of steep slopes (>34% gradient) without appropriate conservation measures. Repeated cultivation of the land with the last pass up and down the slope to facilitate drainage of excess water contributes to the large soil loss in the cultivated fields, it implies the need for immediate conservation intervention in this land-use type. Comparing the sub-watershed, the maximum soil loss was observed in the sub-watersheds (SW-6) situated within the eastern part of Winike watershed. This is related to the expansive area of cultivated land in the upland plateau with high slope gradient, compared to the western and central part of the watershed that is characterized by a relatively higher vegetative cover and little cultivation. Moreover, soil erosion rate decreased in grazing and forest lands by 1.92 t/ha/year in grazing land 0.12 t/ha/year in the forest land when reference years (1998) is compared with the experimental year (2018). This is related to expanding canopy cover of the maturing above-ground vegetation.

Change of sediment export

Sediment export is the net losses to the stream network and considers the soil loss potential mitigation effects of topography and land cover. Between 1988 to 2018, the proportion of soil loss increased by 9.79% and sediment export increased by 3.45% (Figure 2, B and C). In other words, the data suggest an increasing trend in the sediment export which is consistent with the increasing trend of soil loss. The total sediment exported from the watershed was 0.050 t/ha/year and total export was 3.85 thousand metric ton over the past 30 years (Table 4). Consistent with the soil loss pattern, the largest contributor to the total sediment export (0.42 t/ha/year) is the cultivated land followed by bare land (0.37 t/ha/year) while forestland woodland, grazing land and shrubland had the lowest 0.01 t/ha/year. This is the amount of sediment that directly joins the hydropower dams thus contributing towards their siltation. Eventually, this can threaten the life span of the dams and significantly compromise the hydropower generation capacity of the nation over time.

Sub-watersheds that contributed the largest share of the sediment export were those that are situated on the upper sub-watershed including Megecha river (SW-6), Fugiro river (SW-10), Gogob river (SW-8), Kecher river (SW-9), Mitirekat river (SW-7) (Figure 1).The highest sediment export in these sub-watersheds is associated with expansion in cultivation in these upland plateaus by clearing the natural vegetation. Sub-watersheds in the downstream catchments such as Chat, Zizat, Gotam, and Wuze river catchments are less accessible for cultivation due to alternative economic sources of the farmer rather dependent crops cultivation and hence remain covered with forests resulting in little soil loss in these sub-watersheds.

Land-use/land cover change associated with soil loss and sediment export change

Soil loss and sediment expert is directly proportional to the land conversion. Relationships between the proportion of change in soil loss within land use/land cover showed that the soil loss increased as land use/land cover change increased except in the shrubland (Figure 2, A). There was a consistent increase in sediment export rate (0.01 t/ha/year) in all the land use/land cover types except for the cultivated and bare lands.

The soil loss and sediment export increased as the proportion of cultivated land increased. Conversely, shrubland proportion decreased and soil loss increased. The extent of forest and shrubland were inversely related to soil loss, but it has no relation with sediment export. Moreover, a woodland and bare land proportion showed a significant positive correlation with the proportion of soil loss and sediment export. The overall result showed that soil loss was lower in the watershed dominated by forest, grazing and shrubland and high in the cultivating and shrubland. Land conversion and clearing of forests to expand cultivated land was highest between 1998 and 2018 resulting in concurrent high soil loss and sediment export for the period.

Correlation analysis between land use type and sediment export showed a strong positive correlation ($R2 = 0.89$, $P < 0.001$) between cultivated land and soil loss and sediment export a (Figure 3 a & b). The forest land change had a weak correlation with soil loss (inversely proportional) but no correlation with sediment export (Figure 3 c & d). The existing grazing land had also a correlation with soil loss but weak correlation sediment export. This is expected due to large canopy cover effect under the forest cover and root regulating capacity of the vegetation. On the contrary, there was an inverse relationship between changes in soil loss and shrubland

(R^2=0.02, P= -0.41) due to degradation of vegetation by fire and dry out but its sediment export did not correlate (land (R^2=0.031, P= 0.26). The dynamics of sediment export is also a significant correlation with changes in LULC of bare land (R^2=0.72, P< 0.01) and built-up area (R^2=0.61, P < 0.01).

Priority sub-watersheds for soil and water conservation

Erosion severity was rated as slight (<5 t/ha/year), moderate (5-15 t/ha/year), high (15-30 t/ha) and severe (>50 t/ha) based ratings suggested by Haregeweyn et al. (2017). The InVEST model analysis identified erosion severity and priority areas for immediate intervention. As shown in Table 5 there is a significant variation of the vulnerability of soil erosion among sub-watersheds. Very high vulnerability to soil erosion is observed in the Megecha river catchment (SW-6) accounting for about 21.02% of the entire watershed. The soil loss and sediment export in this sub-watershed is 62.77 t/ha/year and 16.69 t/ha/year, respectively. Since this watershed is situated in the upland plateau encompassing cultivated, cultivation is the major land-use accounting for 47.05% of the entire watershed. For this reason, it warrants immediate attention for soil waters conservation intervention.

Mitirekat (SW-7), Gogeb (SW-8), Kecher (SW-9), and Fugiro (SW-10) rivers represent 42.04% of the entire watershed, showing severe soil loss and sediment export from these watersheds which have huge implications for the entire river basin by contributing dam's siltation and ecosystem degradation. The average soil erosion and sediment export of the SW-7, SW-8, SW-9 and SW-10 is soil loss (45.47 t/ha/year) and sediment export (10.77 t/ha/year) followed by those moderate soil erosion rates of SW-3 and SW-5 at Zizat river, with soil average soil loss and sediment export of 23.19 t/ha/year and 3.77 t/ha/year.

The study also found that Yechat (SW-2), Gotam River (SW-4) and Wuze River (SW-1), catchments had shown a slight and very slight soil erosion rate (15.66 t/ha/year) and sediment export (1.77 t/ha/year) (Table 5 and Figure 4), that are situated in the lower reaches of the river which are less accessible for people and they are under permanent vegetative cover.

The analysis shows that soil loss and sediment export in the sub-watersheds have a significant difference in altitude (P<0.01). SW-6 is found in the higher altitude (2,707 m), has average soil loss of 25.2%), and its total sediment export was 41.65%, while SW-1 found in the lower altitude (1,772 m) has soil loss and sediment export of 13 thousand t/year and 0.5 t/year, respectively,

(Figure 4). Therefore, the sub-watersheds found in the high altitude had a higher soil loss and sediment export than lower altitudes.

Validation of the model

The watershed which was susceptible to erosion of the soil was validated using the resulted of InVEST model output of sediment export and the calculated observed sediment form daily streamflow and sediment concentration. Therefore, the accuracy of the model's R2 is 0.82 and RRMSE is 0.39 (39%) (Figure 5). This analysis shows that the observed data of sediment export from the hydrological station of the watershed have been provided with a good fit with the InVEST model output (P>0.001).

Discussion

The results of the current study highlight the increasing trends in soil erosion and sediment export which is aggravated by land conversion and LULC changes over the past 30 years. This is consistent with the findings of Hassen and Assen (2018) that showed that land-use changes result in the corresponding change in soil erosion rates. Conversion of forest, shrub and grassland into cultivated land is the major driver of the soil erosion. Research undertaken in one of the basin tributaries of Gilgel Gibe river headwaters found that the average soil loss for cultivated fields was 39 t/ha/year (Demissie et al. (2013). This is in agreement with this current study in Winike watershed that found average soil loss of 43.48 t/ha/year for cultivated fields, which is the major contributor for soil erosion in the basin. Compared to Hurni (1983) soil loss tolerance (SLT) rate of 6–10 t/ha/year, the erosion rate reported in the study can be rated as severe. We have reported 17.91 t/ha/year in the watershed and maximum soil loss rate of 270 t/ha/year in sub-watersheds (SW-6). This is associated with the accelerated conversion of natural vegetation into cultivated land for stakholder farmers to have their ends met. To meet domestic food demands, farmers are clearing natural forests, shrub and grassland and it is supported with extension service that provides seed and fertilizer inputs to boost agricultural production (Aneseyee et al., 2019). However, the cultivation of steep slopes (as high as 34%) without installing soil and water conservation measures is detrimental. Downstream effects of sediment delivered from the watershed is siltation of the hydropower dams. The total soil loss and sediment export increased by 176.35 thousand ton and 3.85 thousand ton, respectively, in the last three decades (1988 to 2018) of the study watershed. This is consistent with previous research in the basin that suggested accelerated soil erosion in the catchments resulting in siltation of dams (Getahun et al., 2013; Karki et al., 2018) According to Devi et al. (2008), Gilgel Gibe river catchment has been contributing 277 thousand tons of silt per year to the Gibe dam I.

The eastern part of the watershed is situated on the upland plateau (higher altitude) and is more prone to soil erosion than the western part of the watershed (lower altitude). The high altitude upland eastern half of the watershed is conducive for agricultural activities and is highly populated. This along with high rainfall in the area leads to severe soil erosion loss and sediment export compared to the western half. The western half of the watershed is part of the Gibe Sheleko National Park with the natural vegetation remains intact, as result, it contributes much lesser tot eh overall soil loss and sediment export of the watershed.

In the study watershed, the woodland is increased by 783.1 hectares in the last 30 years, which is encroached by eucalyptus plantation. Farmers are obtaining their short-term economic benefit from eucalyptus by selling the wood (pole) of Eucalyptus. Therefore, they are planting this tree in their parcel of land at the edge of the farm plot, road, and riverside. Studies showed that soil quality reduced due to eucalyptus plantation (Dessie, 2011; Zewdie, 2008). This is supported by Zerga (2015), soil erosion and gully formation are increased in eucalyptus woodlots. Therefore, due to Eucalyptus plantation couple with continuous cultivation and undulating topography, the eastern part of the watershed is highly affected by soil erosion than the western and central part of the watershed.

Soil loss in the watershed has a downstream effect of sediment deposition in the hydropower dams. The InVEST model output of this study indicates that the sediment delivery is controlled by the cover (C), rainfall erosivity (R) and soil erodibility (K) factors in that order of C, R, K and P factors. The sensitivity of each RUSLE factor to cause soil erosion is not similar and the parameters are changed over time as the LULC has changed. As a result, the RUSLE parameter uncertainties have been widely observed in many study areas (Merritt et al., 2003; Wang et al., 2001). For example, a land-use has a lower C factor, shows the higher capability of reducing soil erosion possibility. According to Hamel et al. (2017), the C values for cultivated land had the highest C values among all LULC types. However, in the study area, the C value is highest in the bare land (0.27) next to cultivated land (0.25). The C- factor depends on the resistance of soil loss by vegetation, it is determined by NDVI and it has a significant influence on soil loss and sediment export. The lower NDVI value, the C factor is higher (e. g, In the bare land NDVI=-0.142 and C

=0.27 and the forest land NDVI=0.073 and C=0.01). In other words, the forest has a lower C value than cultivated land but it has a higher resistance to erosion.

Soil erodibility (K) is influenced by land conversion due to the conversion of soil erodibility parameters. For example, the loss of forest land leads to loss of the soil organic matter (SOM). If the soil is become lost its organic matter, it is susceptible to soil erosion. Regarding the study watershed, the SOM value in the Leptosols soil types (eastern part of the watershed) is 1.5% and its K value is 0.62 and the SOM in Eutric Nitosols (central part) is 3.21% and its K value is 0.44 (Table 1). The Orthic Acrisols (western part of the watershed) SOM and K value is 2.87% and 0.33, respectively. This indicates that the higher SOM, the lower soil erosion (lower soil erodibility). Organic matter of the soil decreases K's values because it can bind particles of soil together and increases cohesiveness by decreasing the detaching effect of rainfall droplet, decreasing runoff and increasing infiltration (Hassen and Assen, 2018; Renard et al., 1997; Wischmeier and Smith).

The average annual rainfall for the years 1988 and 2018 was 1129 mm and 1234 mm, respectively. Over some time, the erosion power of the high rainfall is strong to cause erosion, due to the increased amount of runoff (Pimentel, 2006). Thus, erosion changed from 1988 to 2018 in the watershed. However, Gumer station has higher rainfall. This is supported by Makaya et al. (2019),which showed higher rainfall characterized the higher vulnerability of soil erosion. As a result, Gumer station (eastern part of the watershed) is showing high soil erosion and sediment export rate than other stations (Emdiber, Agena, Gubre, Enemore and Geta).

The government of Ethiopian implemented exhaustive soil and water conservation structure at the national level in recent times like Productive Safety Net Programs (PSNP), Community Mobilization through free-labour days, and the National Sustainable Land Management Project (SLM) (Haregeweyn et al., 2015; Okereke et al., 2019). These are supported by the extension program of the government and the mass participation of the community. These mass movement of Soil Water Conservation (SWC) by the cooperation of the society is showing important progress in the land management practices in the study area. However, the maintenance of the SWC structures and following a scientific methodology to implement SWC is still left to achieve sustainable ecosystem services conservation in the area.

Conclusion

The InVEST model analysis indicated that a historical fluctuation of soil loss and sediment export due to the considerable conversion of land use/land cover changes. The study analysis shows that the reduction of the forest, grazing and shrubland were predominantly substituted by cultivated lands in the last 30 years (1988 to 2018). This resulted in the reduction of regulatory capacity of the land which aggravates increased soil erosion. The total soil loss and export in the watershed increased by 176.35 thousand tons and 3.85 thousand tons, respectively, in the last 30 years.

Soil loss and sediment export have largely increased in the cultivated land and bare land while soil loss of forest and grazing land decreased, but sediment was constantly exported in the forest, grazing and shrubland. This show that soil erosion change is directly proportional to each land use/land cover except for shrubland. However, the shrubland was an inversely proportional and negative correlation with soil loss and the non-significant correlation with sediment export.

Soil loss and sediment export are found more in the eastern than the western and central part of the watershed. Sub-watersheds (SW-6) at Megecha river was the most severely affected by soil erosion and sediment export among the sub-watershed found in the watershed. Therefore, the research finding suggests need more conservation practices in the highly vulnerable sub-watershed and reduce continuous cultivation in the higher altitude of the watershed to overcome the challenges of dam siltation and ecosystem degradation in the lower part of the watershed. The research finding also suggests policy instruments need to be enforced by making a buffer zone and urgent conservation activities in the Omo-river so that the dams will not get silted up.

Abbreviations

InVEST: Integrated Valuation of Ecosystem Services and Tradeoffs; LULC: Land Use/Land Cover; SW: Sub-watershed, NDVI; Normalized Difference Vegetation Index; SDR; sediment delivery ratio; RUSLE: Revised universal soil loss equation

Authors detail

[1]Center for Environmental Science, Addis Ababa University, P. O. Box No: 1176, Addis Ababa, Ethiopia. [2]College of Agriculture and Natural Resource Department of Natural Resource Management, Wolkite, P. O. Box 07, wolkite, Ethiopia.

Author Contributions

AB has been collected field and analyzed the data, written the paper. The author read and approved the final manuscript.

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Competing interests

The authors declare no conflict of interest.

Availability of data and materials

All authors declare that the data used in this research are available upon request.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

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Figures

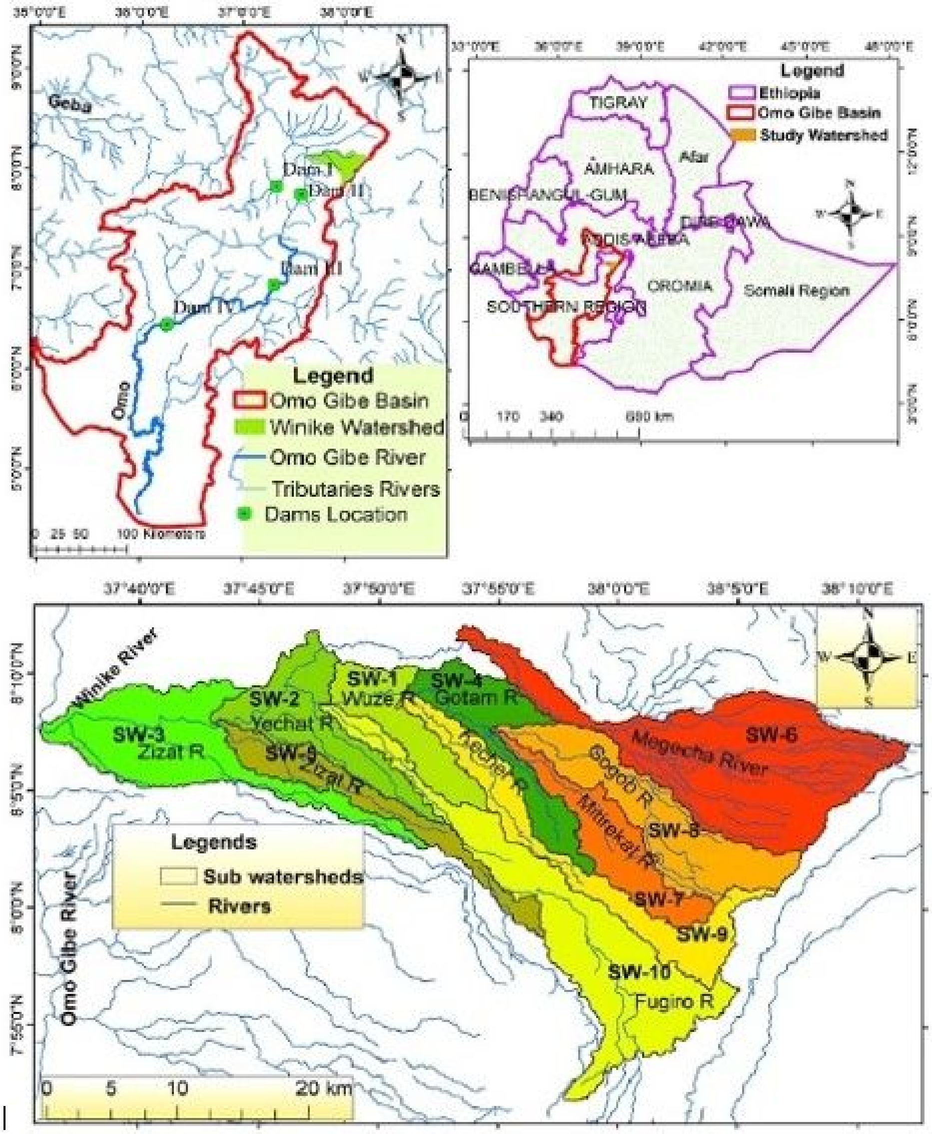

Figure 1

Map of the study watershed showing the sub-watersheds (bottom) and hydropower dams

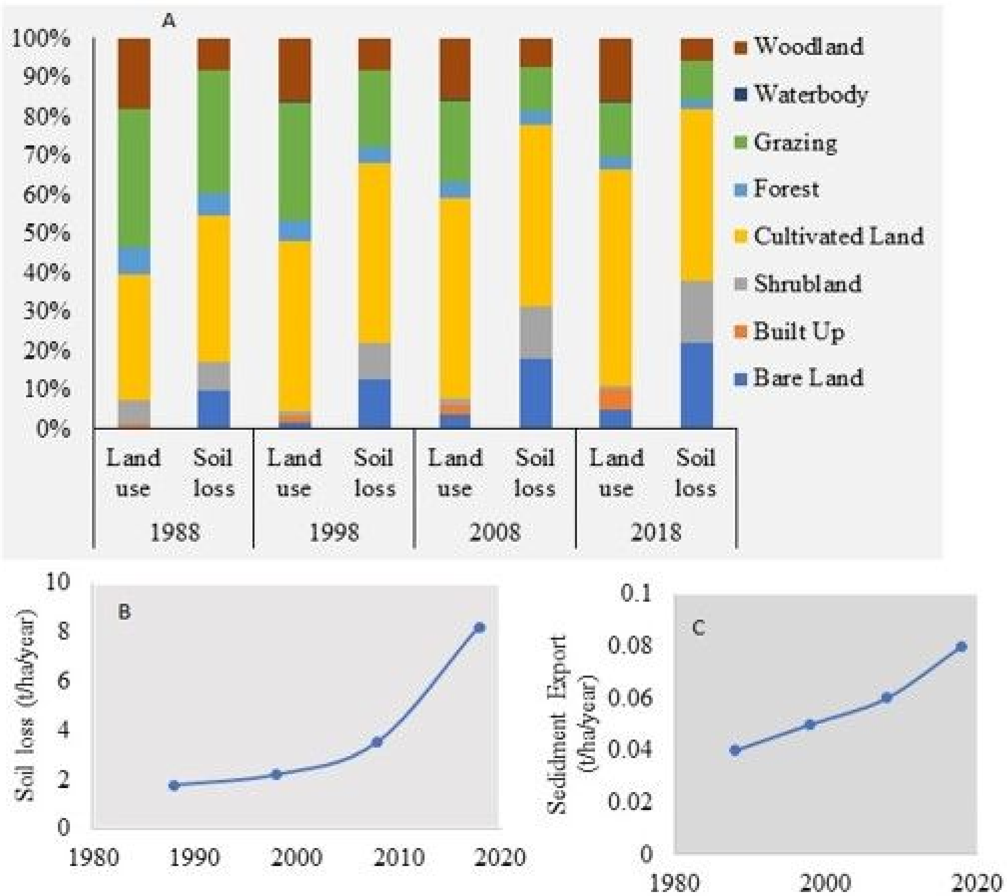

Figure 2

The proportion (%) of soil loss and land use/land cover changes.

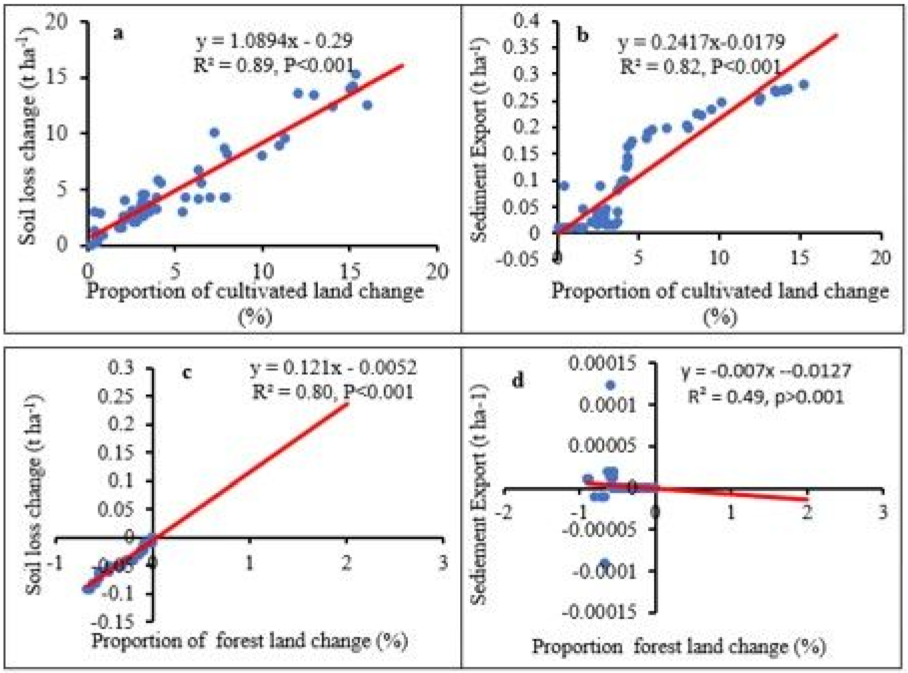

Figure 3

Area of proportion for LULC changes associated with soil loss and sediment export change: (a) Cultivated land proportion vs soil loss;(b) Cultivated land proportion vs sediment export;(c) forest land proportion vs soil loss; (d) forest land proportion vs soil loss

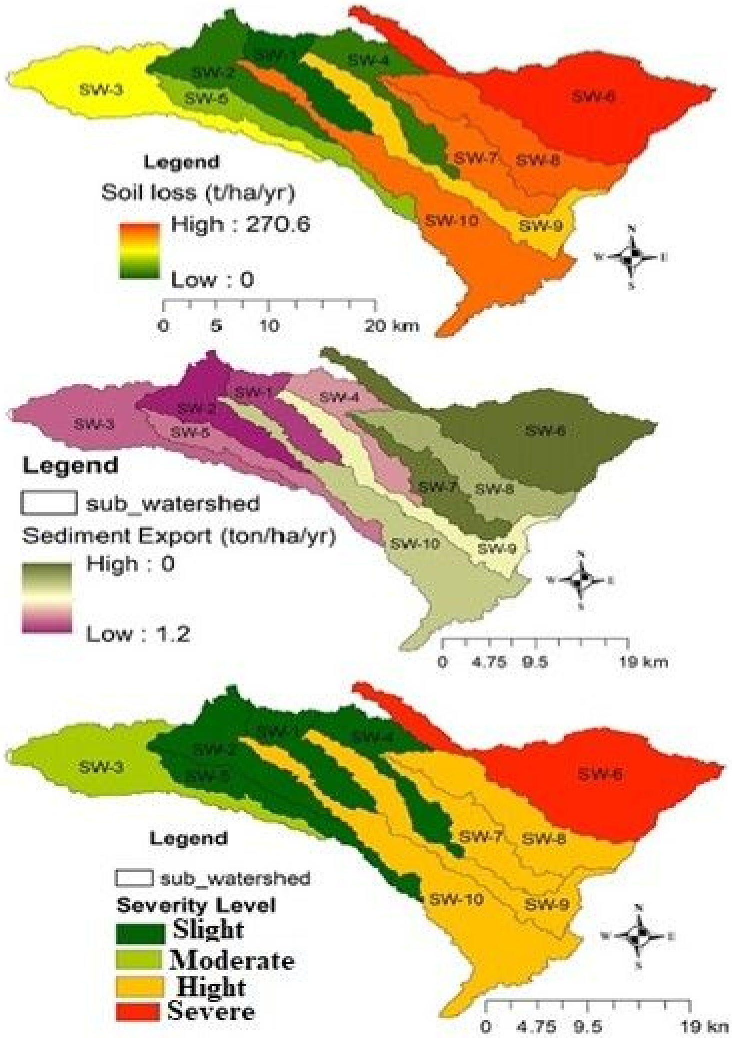

Figure 4

Sub-watershed soil loss, sediment export and severity rate

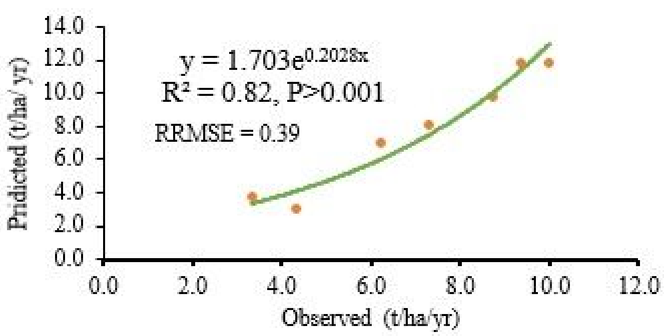

Figure 5

Validation of the InVEST model