Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Environmental Implications of Soil Erosion and Sediment Yield in Lake Hawassa Watershed, South-central Ethiopia

Arega Degife (aregad2015@gmail.com)
PhD candidate for Environmental Planning Program, Ethiopian Institute of Architecture, Building Construction, and City Development, Addis Ababa University (AAU), P.O.Box:518, Addis Ababa, Ethiopia
Hailu Worku
New York City Charter High School for Architecture Engineering and the Construction Industries
Shumete Gizaw
Federal Government of Ethiopia, Ministry of Innovation and Technology

Research

Keywords: Lake Hawassa, sediment yield, soil erosion, sediment retention

Posted Date: January 28th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-153847/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Environmental implications of soil erosion and sediment yield in Lake Hawassa watershed, south-central Ethiopia

Author names and affiliations:

Arega Degife[1,2], **Hailu Worku**[3] , **Shumete Gizaw**[4]

[1]PhD candidate for Environmental Planning Program, Ethiopian Institute of Architecture, Building Construction, and City Development, Addis Ababa University (AAU), P.O.Box:518, Addis Ababa, Ethiopia

E-mail: aregad2015@gmail.com

[2]Department of Geography and Environmental Studies, Dilla University, Dilla, Ethiopia.

[3]Professor at Ethiopian Institute of Architecture, Building Construction and City Development (EiABC), Addis Ababa University (AAU), P.O.Box:518, Addis Ababa, Ethiopia.

E-mail: hailu.worku@eiabc.edu.et

[4]Federal Government of Ethiopia, Ministry of Innovation and Technology, Addis Ababa, Ethiopia. P.O.Box 2490, Addis Ababa, Ethiopia.

E-mail: Shumete.gizaw@pmo.gov.et

Abstract

Background: Assessing soil erosion, sediment yield and sediment retention capacity of watersheds is one of the under researched areas in watersheds of developing countries like Lake Hawassa watershed. The study examined soil erosion, sediment yield and sediment retention and their environmental implications in Lake Hawassa watershed. The quantification and mapping was carried out using Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. Data such as Land Use Land Cover (LULC), Digital Elevation Model (DEM), rainfall, soil, and management practice were used as input parameters.

Results: The empirical analysis confirmed that the watershed has a total soil loss of about 5.27 Mt annually. The mean annual erosion rate from the watershed was estimated to be 37 t ha^{-1} yr^{-1}. The estimated erosion rate was greater than the maximum tolerable erosion limit in Ethiopia (2-18 t ha^{-1} yr^{-1}). The total amount of sediment which was exported to the nearby streams and lakes in the watershed was estimated to be 1.6 t ha^{-1} yr^{-1}. The water bodies receive a total of 226,690.3 t of sediment annually. Although higher soil loss and sediment export per unit of area were estimated from the highest slope gradients, greater contributions to the total soil loss and sediment export were computed from slopes with 5-30% gradients. In terms of LULC, the highest contribution to the total soil loss was computed from cultivated land while the highest rate of soil loss per hectare was observed from bare land. Due to the existing vegetative cover, a total of 18.65 Mt (130.7 t ha^{-1} yr^{-1}) of sediment was retained. Vegetation-covered LULCs such as forest, woodland, shrub land, and agroforestry revealed the highest sediment retention capacity. As a result of the increasing soil erosion and sediment yield in the watershed, a drying of a small lake and the rise in the water level of Lake Hawassa were identified.

Conclusion: Most of the soil loss and sediment yield were contributed by small part of the watershed. Thus, the results underscore the urgent need for targeted soil and water conservation measures of various types to ensure sustainability of the watershed resources.

Key words: Lake Hawassa, sediment yield, soil erosion, sediment retention

1. Introduction

Lakes and the associated watershed resources have various environmental and economic benefits (ILEC, 2003; Huang and Cai, 2009). Despite their multifaceted importance, lake and their watersheds are facing growing threats due to increasing anthropogenic pressures (Holdren et al., 2001; Olson and Maitima, 2006; Huang and Cai, 2009). The major threats that lake watersheds are facing today are soil erosion and the associated sedimentation problems. Soil erosion is a main global environmental problem and it is a major concern in developing countries including the sub-Sahara African countries (Lal, 2001; Borrelli et al., 2017).

Soil erosion and the associated sediment yield have many environmental repercussions and have received the attention of many scientists (Ionita et al., 2015). It has the impacts of reducing ecosystem services and functions (Angassa, 2014; Haregeweyn et al., 2012, 2015). In addition, it has not only on-site impacts of increasing soil nutrient loss and reduced productivity of land (Pimentel, 2006; Haregeweyn et al., 2008, 2015, 2017; Fenta et al., 2020) but also has off-site impacts like damaging of infrastructure and deposition of sediment in downstream water resources (Tamene et al., 2011; Haregeweyn et al., 2017). Soil erosion and the resulting sedimentation have also undesirable impacts on water holding capacity, water quality and recreational value of downstream lakes and reservoirs (LIA, 2011; Haregeweyn et al., 2012; deNoyelles and Kastens (2016), Desta and Lemma, 2017; Issaka and Ashraf, 2017).

A quantified estimation of soil erosion and sediment yield is very important to better understand the impacts of land use or climatic changes (Ambers, 2001; Navas et al., 2009) and helps to address the problems through planning (Xiaoqing, 2003). Although there are many studies on sediment yield estimations at global level (Jansson, 1988; Syvitski and Milliman, 2007), the number of studies in tropical environments, particularly in sub-Saharan Africa, is generally scanty (Vanmaercke et al., 2010). In addition, most of the studies on erosion and sediment yield conducted so far have focused mainly on the use of sophisticated instruments and well experienced experts in data-rich environments. Such approaches are largely less practical in the context of developing countries such as Ethiopia, where there is data scarcity and lack of experienced experts (Haregeweyn, et al., 2012).

In Ethiopia, studies show that soil erosion and the resulting sediment yield are common problems (Hurni, 1993; Bantider, 2007; Erkossa et al., 2015; Gelagay, 2016; Desta and Lemma, 2017; Haregeweyn, et al., 2017). However, the levels of erosion and sediment yield reported have shown spatial variation depending on the type of soil, climate, topography, population density and farming and management practices. Such variations signify that site-specific studies and locally adaptable erosion and sediment mitigation strategies are necessary in order to minimize the impacts of accelerated erosion and sedimentation. Additionally, although the studies indicate that soil erosion and related sediment yield in the country have been leading to various environmental problems, there were very limited studies which were conducted on the estimations of erosion, sediment yield and retention capacity in the rift-valley lake watersheds of Ethiopia.

Thus, this study was conducted in an environmentally fragile watershed of Lake Hawassa, which is located in the south-central rift-valley region of Ethiopia. The lake and its watershed resources play significant role in supporting the livelihoods of many people. However, the watershed is currently exposed to various pressures due to uncontrolled anthropogenic activities. The expansion of small- and large-scale farms, conversion of wetlands in to various land uses, and rapid expansion of population and unplanned settlements have been leading to the growing deterioration of land and water resources in the watershed (Dessie, 2007; Van Dijk, 2016; Degife et al., 2019). There were studies conducted on the degradation of Lake Hawassa (Geremew, 2000; Gebre-Mariam and Desta, 2002; Gebreegziabher, 2004; Esayas, 2010). However; the source, magnitude, and spatial distribution of soil erosion, sediment yield and sediment retention capacity at watershed scale have not been sufficiently studied. This has made it difficult to understand the impacts of anthropogenic activities on land and water resources of the watershed. It is scientifically proved that identifying the magnitude and spatial variation of sources of pressure on natural resources are the major requirements for making proper conservation planning and management (FEI, 2003). Hence, the purpose of this study is to quantify and map the spatial variations of erosion and sediment yield and examine their environmental implications in Lake Hawassa watershed. This will help to understand the degree of stress on natural resources and make informed decision before irreversible damage happen to the Lake and the associated watershed resources.

2. Materials and methods

2.1. Study site description

Lake Hawassa watershed is located in a closed drainage system with an area of 142,661ha. Its formation is associated with the tectonic activity which formed the Great East African Rift System and the Lakes Region in Ethiopia (Chorowicz, 2005; Macgregor, 2015). Geographically, the watershed is situated between 6º 45’N and 7º 15' N Latitude and 38º 15' E and 38º 45' E Longitude (Fig. 1). The dominant landscapes characterizing the watershed are the volcanic mountains forming the surrounding escarpments and flat plains lying at the foothills of the mountains. In terms of elevation, the watershed ranges from 1680m to 2550m above sea level.

Prior to early settlement and agricultural land expansion, the watershed was predominantly covered by *Podocarpus falcatus* and *Juniperus procera* in the moist *Woina Dega* (moist mid-highland) and by acacia and shrubs in the Dry *Woina Dega* (dry mid- highland) (Dessie, 2007). The watershed consists of important ecosystems such as lakes and wetlands and small streams (Fig. 1). The streams flow from the eastern escarpment and later collected into one major river called Tikur Woha that finally joins Lake Hawassa.

The watershed is characterized by high population growth. According to the estimate by the Federal Government of Ethiopia (Ministry of Water, Irrigation and Energy (MoWIE)), in 2007, the total Population of the watershed was estimated to be 839,585, of which 23% was urban. In 2020, the projected population, by Rift valley Lakes Basin Master Plan Studies, was 2,491,295.

The dominant economic activity in the watershed was agriculture, which was characterized by subsistence level mixed cropping with some commercial farming and livestock production.

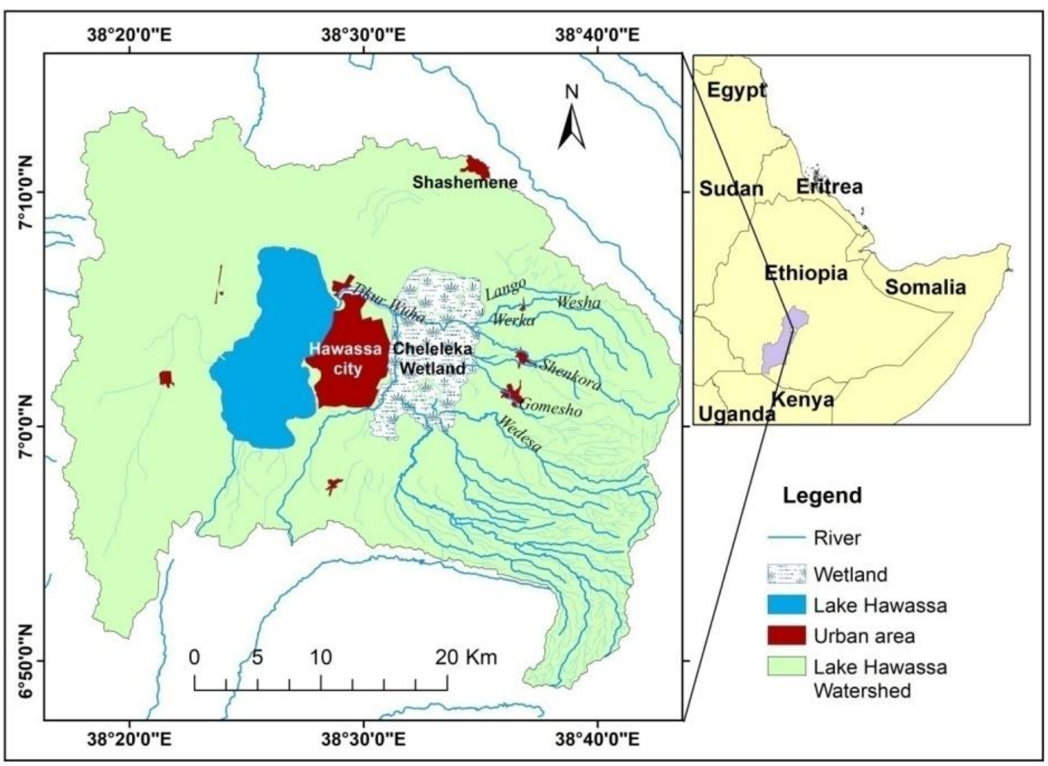


Fig. 1 Location map of the study area

2.2. Data analysis tool

Various supporting models are available for quantifying and mapping erosion and sediment yield in a watershed (Morgan, 2009; Biggs et al., 2015; Farhan and Nawaiseh, 2015; Karabulut et al., 2016; Redhead et al., 2016; Schmalz et al., 2016). Some of the models have little data requirements (e.g. USLE) and others are sophisticated which require intensive data and resources (e.g. WEAP) (Sharp et al., 2018). The choice of a model is dependent up on the requirement and availability of input data and the type of output required. Hence, considering the serious data scarcity in the study area, InVEST model was selected to quantify and map runoff, erosion and sediment yield for this study.

The InVEST model estimates the relative contributions of sediment from each parcel of a landscape in a spatially explicit manner, offering insight into how changes in LULC patterns affect the annual sediment yield. However, the model has some limitation as it is based on annual averages, which disregard extremes and sub-annual patterns of sediment delivery (Sahle et al., 2018; Sharp et al., 2018). However, the model still provides a useful assessment of how landscape scenarios may affect the annual delivery of sediment (Sharp et al., 2018). Compared to other sophisticated and data intensive models, InVEST model was preferred for this study due to its requirement of less number of input parameters, availability of the required input spatial data and its compatibility with various GIS data. Most importantly, the model uses the Revised Universal Soil Loss Equation (RUSLE) and some of the input parameters of the RUSLE equation were calibrated for the Ethiopian context (Hurni, 1985) which can readily be used in the model. Above all, very limited studies in Ethiopia (e.g. Sahle et al. (2018)) and probably no other studies in Lake Hawassa watershed were conducted employing this model.

2.3. Data used

Various factors including LULC, soil, topography, climate, and management and support practices affect the rate of soil erosion, sediment yield and sediment retention in a watershed. In this study, multiple data including spatial and non-spatial such as field observation with the purpose of triangulating data were utilized. The data used in the study includes watershed boundary, LULC data, rainfall erosivity (R-factor), soil erodibility factor (K-factor), DEM, and biophysical table.

2.3.1. Watershed Boundary

A shapefile of Lake Hawassa watershed was one of the inputs to InVEST model. It was extracted from the DEM using ArcGIS and used to determine the boundaries of the watershed.

2.3.2. LULC data

In the sediment delivery ratio module of InVEST model, a raster LULC dataset with an integer LULC code for each cell is required. The LULC dataset was extracted from Landsat image 2017 which was downloaded from USGS website (http:// earth explorer.usgs.gov) (fig. 2). Before classifying; image sub-setting, layer stacking, and image enhancement were made as image pre-processing. The LULC dataset was then created by employing supervised classification using maximum likelihood algorithm in ERDAS IMAGIN 2014 environment (Fig.2). The accuracy of the LULC classification was 93% with over all kappa of 0.90.

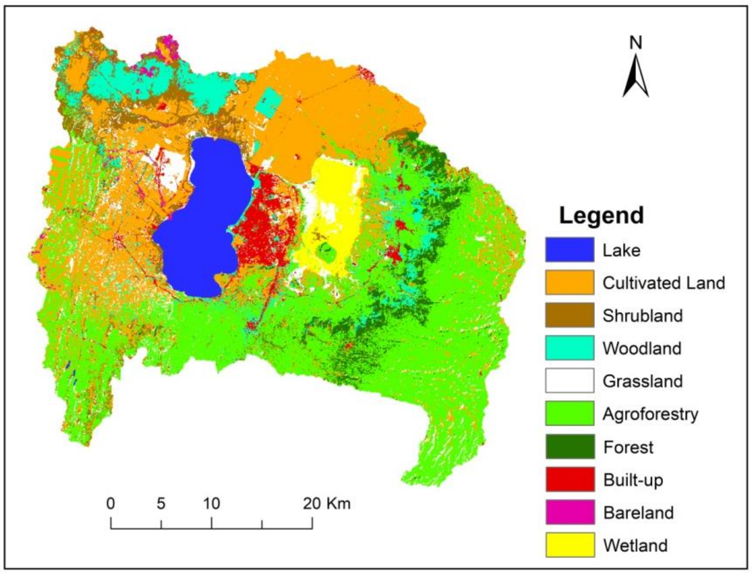


Fig. 2 LULC map of Lake Hawassa Watershed

2.3.3. Rainfall erosivity (R-factor)

The Rainfall erosivity (R) factor is the power of rain to initiate soil erosion. It is the energy of a given storm that depends on the amount, duration, intensity, energy and size of rain drops, pattern of rainfall and rate of the resulting runoff (Renard et al., 1997; Farhan and Nawaiseh, 2015). It is considered as the most prominent factor that affects soil erosion and sediment yield (Wischmeier and Smith, 1978). It is derived from rainfall intensity records of an area (Kouli et al., 2009; Renard et al., 1997). However, such data are not readily available at weather stations of most third world countries, including Ethiopia, owing to lack of automatic rain gauges (Hurni, 1985). Hence, R-factor is alternatively estimated from the long-term mean annual rainfall values of a watershed (Renard et al., 1997). In this study, R-factor was computed based on the regression equation developed by Hurni (1985) for the highlands of Ethiopia (Eq.1).

$$R = -8.12 + (0.562 * P) \quad \textbf{Equation (1)}$$

Where, R is the rainfall erosivity factor and P is the mean annual Precipitation (mm).

In the process of calculating R, first, the daily average precipitation data was summed to obtain the mean annual rainfall amount (in mm) at each station. However, since the annual rainfall erosivity value significantly fluctuates at spatial and temporal scales, a minimum of 15 years of data is required to achieve proper estimates of rainfall erosivity of a watershed (Panagos et al., 2015; Yusuph and Dagnew, 2019). The variation in altitude may also cause the variation in the distribution of rainfall. Hence, to adequately consider the variation of rainfall in the entire watershed, more than 30 years of rainfall data from 6 weather stations (from within and around the watershed with varied altitudinal locations) were used following a method employed by Wolka et al. (2015), Esa et al (2018), and Yusuph and Dagnew (2019).

Therefore, the mean annual rainfall data at each station was used to generate gridded rainfall data using inverse distance weighted (IDW) interpolation technique in ArcGIS 10.3. The IDW geo-statistical interpolation method was preferred because it makes it easier to generate relatively accurate rainfall gridded data from known sample points located at closer distances than those located far from the points of unknown values. The method was also selected for the reason that it enables better interpolation of the required data from grid based irregularly spaced samples (Li and Heap, 2008).

Finally, the raster rainfall data which was generated using the IDW method was used to compute rainfall erosivity (R) raster data using eq. 1 in a raster calculator of ArcGIS. A similar approach was used to compute R factor in Ethiopia by Bewket and Teferi (2009), Shiferaw (2011), Wolka et al. (2015), Esa et al. (2018), and Yusuph and Dagnew (2019). The computed R value ranged from 457.6 to 646.4 MJ mm $ha^{-1} h^{-1} year^{-1}$ (Fig. 3).

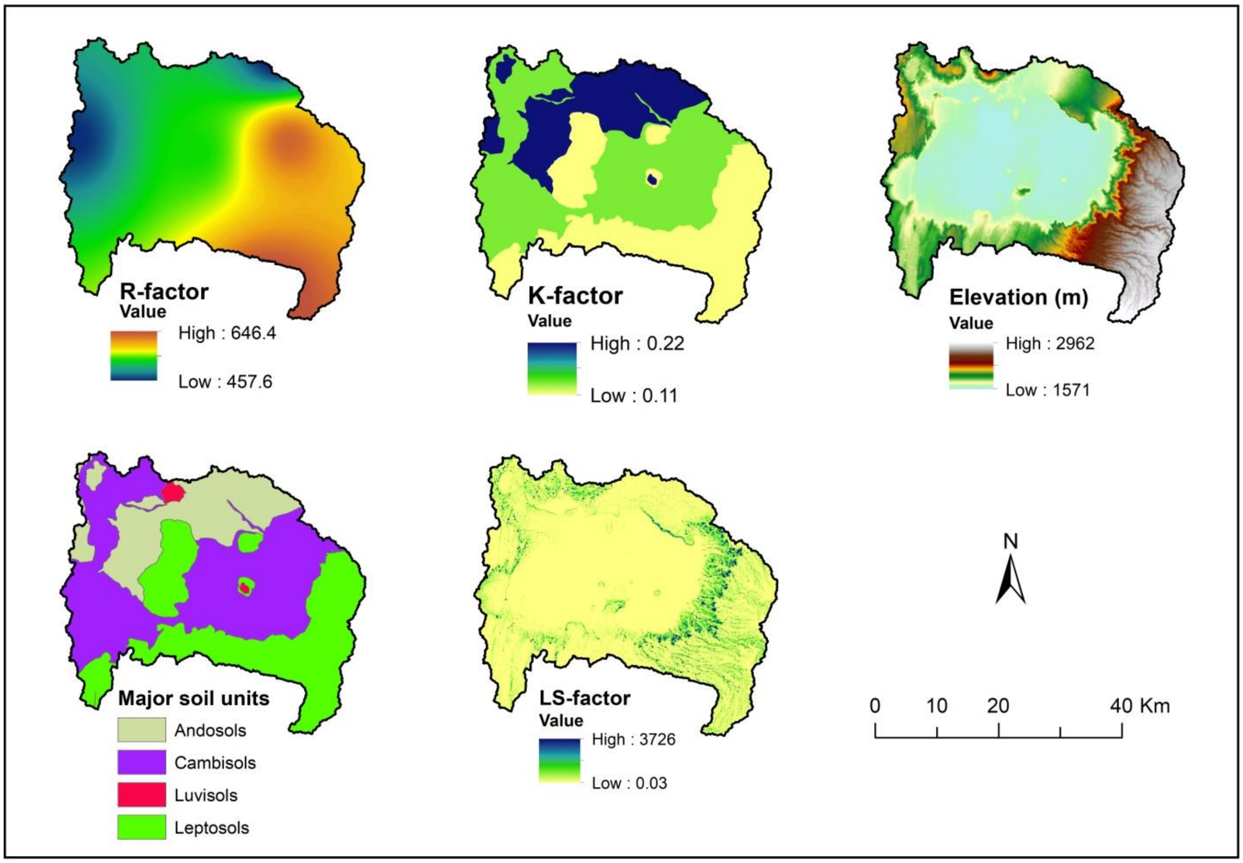


Fig. 3 Spatial distributions of R-factor, K-factor, Elevation, Major soil units, and LS-factor

2.3.4. Soil erodibility (K-factor)

One of the requirements for InVEST model is soil erodibility data. Soil erodibility (K) is the biophysical and chemical properties of the soil indicating the susceptibility of soil to erosion (Renard et al., 1997; Farhan and Nawaiseh, 2015; Panagos et al., 2015). The K-factor reveals the ease with which the soil is removed by splash and surface flow. It also indicates the effect of soil properties on soil loss and the susceptibility of soil to erosion.

Literatures reveal that various approaches have been used by scholars to determine erodibility of soil depending on data availability (Hurni, 1985; Romkens et al., 1997). For instance, a study by Hurni (1985) indicated that k-factor can be determined depending on soil texture, organic matter content, permeability, grain size distribution and other factors. In the present study, due to paucity of data, the K-values for each soil type were determined by using the values adopted by the Ethiopian Rift valley Lakes Basin Master Plan Studies from Hurni (1985). The soil units' spatial data of the watershed was extracted from the Rift valley Lake Basin Master Plan study. The soil data contains four dominant soil units namely; Andosols, Cambisols, Luvisols and Leptosols (Fig. 3).

Finally, the soil erodibility (K) map of the watershed having a grid size of 30 m was produced using ArcGIS 10.3 "Spatial Analyst" tool. The K value ranges from 0 to 1, where 0 indicates less and 1 reveals high susceptibility to erosion risk (Farhan and Nawaiseh, 2015). The K-factor values for the soil types of Lake Hawassa watershed were presented in Table 1 and Fig. 3.

Table 1 Soil erodibility factor

Soil type	K-factor
Andosols	0.2
Cambisols	0.13
Luvisols	0.11
Leptosols	0.22

2.3.5. Digital Elevation Model (DEM)

One of the requirements for RUSLE equation was LS factor. A DEM with 30m spatial resolution which was corrected by filling-in sinks was used as a major input to InVEST model to calculate slope length (L) and slope gradient (S) in sediment delivery calculations. The LS-factor is a combined factor that indicates the effects of slope length and slope gradient and determines the velocity and volume of runoff and the transport of soil particles (Prasannakumar et al., 2012). The steepness and length of slope determines the rate of soil erosion (Gashaw et al., 2017), through greater accumulation of runoff (Wischmeier and Smith, 1978).

In RUSLE, the LS-factor represents a ratio of soil loss per unit area on a site to the corresponding loss from a "standard" 9% slope steepness and 22.13 m long plot (Renard et al., 1997; Kaltenrieder, 2007). LS-factor increases with slope length and slope gradient. The higher the value of LS-factor of a land the higher will be the velocity and erosive power of runoff (Wischmeier and Smith, 1978; Renard et al., 1997).

Since it is difficult to make direct field measurements to determine LS-factor in a complex topography, the InVEST model computes the slope LS value from the input DEM. In line with this, many studies suggest using DEM in the calculation of LS-factor (Moore and Wilson, 1992; Mitasova and Mitas, 1999; Simms et al., 2003; Yusuph and Dagnew, 2019). Hence, in this study a 30m spatial resolution SRTM DEM was used as input for the calculation of LS factor.

As indicated by Sharp et al. (2018), InVEST model calculates the *LS*-factor from the input DEM using an equation developed by Desmet and Govers (1996):

$$LSi = Si\frac{(A_{i-in}+D^2)^{m+1}-A_{i-in}^{m+1}}{D^{m+2}*x_i^m*22.13^m}$$ **Equation (2)**

Where, S_i represents the slope of a grid cell computed as function of slope radians θ, with S = 10.8 ・ sin(θ) + 0.03 for θ < 9% while S = 16.8 ・ sin(θ) – 0.50 for $\theta \geq$ 9%; A_{i-in} represents the contributing area in m^2 at the inlet of a grid cell which is computed based on the d-infinity flow direction method; D indicates the grid cell linear dimension in m; $xi = |sin\alpha i| + |\cos\ \alpha i|$ where αi stands for the aspect direction for grid cell i; m is the RUSLE slope length exponent of LS factor which is based on Oliveira et al. (2013), where: m = 0.2 for slope <= 1%, m = 0.3 for 1% < slope <= 3.5%, m = 0.4 for 3.5% < slope <= 5%, m = 0.5 for 5% < slope <= 9%, and $m = \beta/(1+\beta)$ where β = sin θ/0.0986/(3 sin $\theta^{0.8}$ + 0.56) for slope >= 9%.

Finally, the calculated LS-values rage from 0.03 in low flow concentration level slope land to 3,725.98 in very steep slope areas (Fig.3).

2.3.6. Biophysical table

For the calculation of erosion and sediment yield, a ".csv" table containing information on cover-management and support practice factors corresponding to each of the LULC classes was required. In the table, rows were LULC classes and columns were named as "lucode", "rusle_c" and "rusle_p", where they represent land use code, land cover and management factor, and support practice factor, respectively.

The "lucode" was land use code of a unique integer for each LULC class (e.g., 1 for cultivated land, 2 for agroforestry, etc.) which was matched to the LULC raster input.

The "rusle_c" values indicate how the covers of the land types (such as cultivated land, agroforestry, etc.) affect soil loss (Renard et al., 1997; Haregeweyn et al., 2017). Determining "rusle_c" values entails data related to soil management condition, the nature of plant canopy and crop residues as a soil cover, soil surface roughness, and the level of soil moisture. However, estimating each of these parameters was difficult due to paucity of data (Renard et al., 1997; Farhan and Nawaiseh, 2015). In most cases, LULC map and normalized difference vegetation index (NDVI) are used for "rusle_c" value estimation (Karaburun, 2010; Lin et al., 2017). In this study, the LULC map approach was selected since it gives comparatively precise "rusle_c" value than the NDVI (Lin et al., 2017). To assign C-factor value for each LULC class, the raster data was converted to vector format using ArcGIS10.3. The "rusle_c" values were assigned based on literature suggestions for the highlands of Ethiopia (see table 2). The values were floating point values between 0 and 1.

Table 2 Adopted values of "rusle_c" factor for different LULC classes

LULC type	"rusle_c" values	References
Lake	0	Girma and Gebre (2020)
Cultivated land	0.15	Hurni (1985), Bewket and Teferi (2009)
Shrub	0.05	Tamene et al. (2014), Haregeweyn et al. (2013)
Woodland	0.06	Eweg and van Lammeren (1996)
Forest	0.01	Hurni (1985); Zerihun et al. (2018)
Grassland	0.05	Hurni (1985), Bewket and Teferi (2009);
Agroforestry	0.06	Eweg and van Lammeren (1996)
Wetland	0.001	Wischmier and Smith (1978); Hurni (1985) and Kaltenrieder (2007)
Bareland	1	Eweg et al. (1998); Hurni (1985)
Built-up	0.05	Moges and Bhat (2017)

The "rusle_p" factor reveals the role of land conservation practices in minimizing the level of soil erosion (Renard et al., 1997). It is determined by the type of conservation measures implemented in the field. However, the "rusle_p" factor is the least reliable factor due to the difficulty in measuring the characteristics of conservation practices in the field (Renard et al., 1991). In fact, some soil and water soil conservation measures have been practiced in the watershed. However, the observed conservation practices in the field were either scanty, poorly designed and implemented or totally damaged due to poor follow-up and maintenance. As a result, it is difficult to use these support practices as an input data to determine soil erosion in the watershed. Hence; as suggested by Wischmeier and Smith (1978), Hurni (1985), Sharma et al. (2011), and Yusuph and Dagnew (2019); "rusle_p" values of various LULC classes were used.

To this end, the watershed was classified into cultivated land and other LULC types as recommended by Wischmeier and Smith (1978). In addition, as suggested by scholars who carried out similar studies in the Ethiopian context (Gelagay and Minale, 2016; Esa et al., 2018; Gashaw et al., 2018; Yusuph and Dagnew, 2019), cultivated lands were further categorized into six slope classes (Table 5) for the reason that land management activities are highly dependent on slope classes. Then, the cultivated lands under each slope class were given p-values while the remaining LULC classes were assigned with a uniform default value of 1 based on the literatures' recommendation.

The resulting values vary between 0 and 1 with the lower values indicating a comparatively better soil erosion control measures (Table 3).

Table 3 Adopted values of “rusle_p” factor

LULC	Slope category	“rusle_p” factor	References
Cultivated land	0-5	0.10	Wischmeier and Smith (1978), Bewket and Teferi (2009), Gelagay and Minale (2016), Esa et al. (2018), Gashaw et al. (2018); Yusuph and Dagnew (2019).
	5-10	0.12	
	10-20	0.14	
	20-30	0.19	
	30-50	0.25	
	50-100	0.33	
Non-cultivated LULCs	All	1	

2.4. Model structure

InVEST sediment yield model helps the mapping and quantification of annual soil erosion, sediment export and sediment retention in a watershed. It calculates soil erosion and sediment delivery in a spatially-explicit manner working at the spatial resolution of the input DEM raster. For each cell of the output data, the model primarily calculates the amount of eroded soil and then computes the sediment delivery ratio (SDR), which is the amount of soil loss that reaches a watershed’s outlet (Sharp et al., 2018). The approach was developed by Borselli et al. (2008) and has received an increasing attention in recent years (Cavalli et al., 2013; López-vicente et al., 2013).

2.4.1. Annual soil erosion

To determine the amount of annual soil loss on pixel i, $rusle_i$ ($t\ yr^{-1}$), the model uses the Revised Universal Soil Loss Equation (RUSLE) (Sharp et al., 2018). The equation estimates water-caused soil loss for varying climatic, soil, and topographic conditions. Since its development, RUSLE has been continuously improved to more precisely calculate soil loss and to adapt to varying range of geographic areas. The equation is widely applied and is explained by the following equation (eq.3) (Renard et al., 1997):

$$\boldsymbol{rusle_i = R_i * K_i * LS_i * C_i * P_i} \qquad \textbf{Equation (3)}$$

Where, $rusle_i$ is the average annual soil loss in t ha^{-1} yr^{-1}; Ri is the rainfall erosivity in mega joules millimeter per hectare per hour per year [MJ mm, (ha^{-1} h^{-1} year^{-1})] which is derived from daily precipitation data; K_i is the soil erodibility factor in ton hectare hour hectare^{-1} megajoule^{-1} millimeter^{-1} (t ha^{-1} h MJ^{-1} ha^{-1} mm^{-1}) which is derived from data on soil types; LS_i is the slope length-gradient factor which is the length of the slope and percent of the slope steepness derived from DEM (dimensionless); C_i is the land cover and management factor (dimensionless) which is derived from LULC classification of satellite image data; and P_i is the support practice factor which accounts for soil erosion control measures (dimensionless) derived from literature.

2.4.2. Annual sediment export

The sediment export is the proportion of soil loss reaching the nearby streams (Sharp et al., 2018). The model estimates the exported sediment based on the work by Borselli et al. (2008). Since the estimation of SDR at each pixel is determined by the upslope area and downslope flow path, the model first computes the connectivity index (IC) which is given by the following equation:

$$\boldsymbol{IC = log_{10}(\frac{D_{up}}{D_{dn}})} \quad \textbf{Equation (4)}$$

D_{up} is the upslope component and given by:

$$\boldsymbol{D_{up} = \overline{C}\overline{S}\sqrt{A}} \quad \textbf{Equation (5)}$$

Where, $\bar{C}$ is the mean C factor of the upslope contributing area; $\bar{S}$ is the mean slope gradient of the upslope contributing area; and A is the upslope contributing area in m^2, which the model delineates based on the D-infinity flow algorithm (Tarboton, 1997; Sharp et al., 2018).

The downslope component (D_{dn}) is defined as:

$$\boldsymbol{D_{dn} = \sum_i \frac{d_i}{C_i S_i}} \quad \textbf{Equation (6)}$$

Where d_i is the length (in m) of the flow path along the i^th cell based on the steepest downslope direction; C_i and S_i represent the C factor and the slope gradient of the i^th cell, respectively. The model determines the downslope flow path is using the D-infinity flow algorithm (Tarboton, 1997; Sharp et al., 2018).

Then, the model computes the SDR ratio for a pixel i from the connectivity index (IC) based on Vigiak et al. (2012):

$$\boldsymbol{SDR_i = \frac{SDR_{max}}{1+\exp(\frac{IC_0 - IC_i}{k})}} \quad \textbf{Equation (7)}$$

Where SDR_{max} is the maximum hypothetical SDR, set to an average value of 0.8 (Vigiak et al., 2012), and IC_0 and k are calibration values that determine the shape of the SDR-IC relationship (increasing function) (Sharp et al., 2018).

The sediment load from a given pixel i, Ei ($t\ ha^{-1} yr^{-1}$) is given by:

$$\boldsymbol{E_i = usle_i * SDR_i} \quad \textbf{Equation (8)}$$

The total sediment load from the watershed, E ($t\ ha^{-1} yr^{-1}$) is given by:

$$\boldsymbol{E = \sum_i E_i} \quad \textbf{Equation (9)}$$

2.4.3. Annual sediment retention

For estimating the sediment retention service that the watershed provides, the model uses as a benchmark a hypothetical scenario where the whole watershed is cleared to bare soil. The value of the sediment retention service is then estimated based on the difference between the sediment export from this bare soil watershed and that of the watershed under the existing land management and vegetative cover (Sharp et al., 2018).

2.5. Data analysis techniques

In order to combine the datasets and run the model, all the input data were set to the same spatial resolution, projection and reference system. The Landsat image and the DEM used in this study were with 30m cell sizes and all the remaining data were processed to the same cell size and reference system. After preparing and arranging the input data using ERDAS IMAGIN 2014 and ArcGIS 10.3, all the parameters were combined using InVEST 3.8.9 model to generate final estimated values of soil erosion, and sediment yield and retention.

The outputs from the InVEST sediment yield model included the amount of sediment eroded in the catchment, the sediment retained by the vegetation and topographic features as well as the sediment load beyond the retention capacity of the vegetation and topographic features which are delivered to a water body at an annual time scale. These outputs are important to estimate the regulatory capacity of the watershed's LULC for soil erosion and sediment protection services, which are important in studying the management of lake, reservoir and water quality in streams (Sharp et al., 2018).

Finally, the spatial distribution of the estimated mean annual soil erosion and sediment export and retention were presented using maps and tables. The computed results were categorized in to different intensity classes and ranges of soil loss, and sediment export and retention rates following literature recommendations such as FAO guideline (FAO, 2006) and personal expertise, with some adjustment to fit local circumstances as depicted in Table 4. In addition, the spatial variations in rates of soil erosion and sediment export and retention in different LULC categories and slope classes were computed by using the zonal statistics tool of ArcGIS 10.3.

2.6. Validation of model results

Due to lack of measured data specific to the study area, the validity of the model outputs were compared with the results of other studies conducted in Ethiopia. In addition, field observations were conducted to identify a severely erosion affected areas. The field visits were accompanied by color printed model output maps of soil erosion, sediment yield and retention maps to prove it on the ground.

3. Results

3.1. Soil erosion in Lake Hawassa watershed

3.1.1. Spatial variation of annual soil loss in the watershed

The soil loss estimation in each pixel ranged from 0 to 605 t pixel^{-1} (1 pixel = 0.09 ha) (Fig. 4). The computed total annual soil loss from the watershed was 5,275,201 t (37 t ha^{-1} yr^{-1}). As demonstrated in Fig. 4 and Table 4, the annual soil loss was categorized into five erosion intensity classes. The result in the table indicated that 54.8% of the watershed was affected by very slight rates of soil erosion, while 15.7% and 9.9% of the watershed experience slight and moderate rates of soil loss, respectively. The remaining 19.6% of the watershed had severe and very severe soil loss rates (Table 4). The result also reveals that majority of the soil loss (83.1%) was contributed by very small area (13.7%) of the watershed which experience high erosion rates per unit of area.

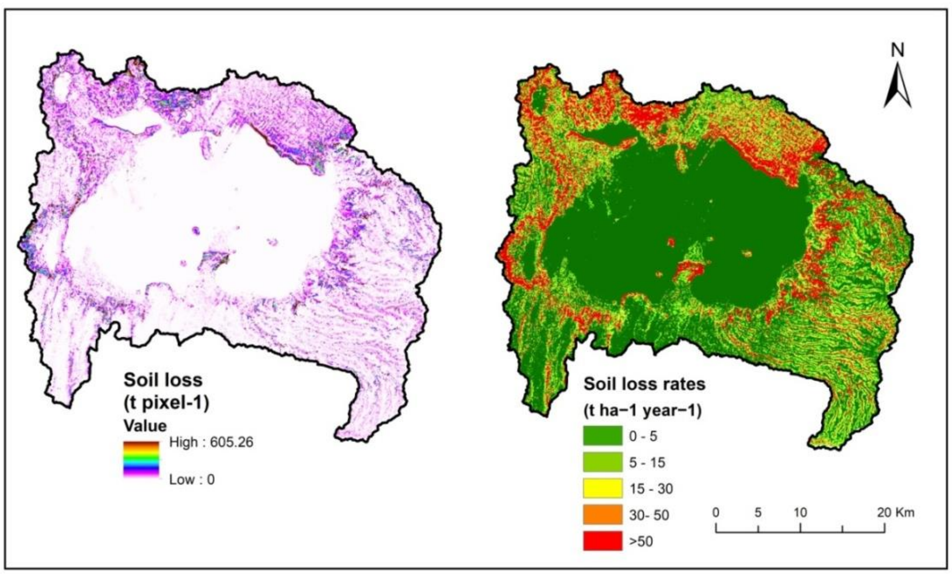


Fig. 4 Soil erosion rate in Lake Hawassa watershed

Table 4. Severity classes, area coverage, magnitude and rates of annual soil erosion

Soil loss rates (t ha^{-1} year^{-1})	Severity classes *	Area (ha)	Percent of total	Estimated annual loss (t)	Percent of total loss
<5	Very slight	78,178.1	54.8	80,425.5	1.5
5-15	Slight	22,328.1	15.7	189,940.6	3.6
15-30	Moderate	14,124.7	9.9	295,228.2	5.6
30-50	Severe	8,440.8	5.9	323,644.0	6.1
>50	Very sever	19,589.3	13.7	4,385,962.7	83.1
Total		142,661	100.0	5,275,201.0	100.0

*This classification was made based on FAO (2006), Haregeweyn et al. (2017) and Yusuph and Dagnew (2019)

3.1.2. Spatial variation of annual soil loss along slope classes

The soil erosion rate varies with slope. The result in table 5 reveals that 83.4% of the watershed is situated on slope <15% and only 16.5% of the watershed is situated on the steeply sloping terrain (slope >15%). The result also indicated that areas with medium slop gradients have the highest contribution to the total annual soil loss compared to areas with lower and higher slope gradients. For instance, 67.8% of the soil loss was contributed by the slope ranging between 5 and 30%. In addition, the result in the table revealed that the mean soil loss per unit of area (ha) increased linearly with increasing slope gradient. As shown in table 5, the highest mean soil loss per unit of area (201.4 t $ha^{-1}year^{-1}$) was estimated on areas with slopes >50% while the lowest (10.6 t $ha^{-1}yr^{-1}$) was observed on areas with slopes <5%.

Table 5. Variation of annual soil erosion rates with slope classes

Slope class (%)	**Area**		**Estimated annual soil loss**		
	ha	%	t yr^{-1}	Contribution to the total soil loss (%)	t $ha^{-1}yr^{-1}$
0-5	77,187.8	54.1	816,977.2	15.5	10.6
5-15	41,819.1	29.3	2,025,774.5	38.4	48.4
15-30	17,147.2	12.01	1,551,541.5	29.4	90.5
30-50	5,590.6	3.9	696,352.8	13.2	124.6
>50	916.3	0.6	184,554.8	3.5	201.4
Total	142,661.0	100.0	5,275,200.9	100.0	37.0

3.1.3. Spatial variation of soil loss with LULC classes

The soil erosion rate also revealed significant variations with LULC. According to the model results indicated in table 6, the highest contribution to the total soil loss was from cultivated land (41.9%) which was followed by agroforestry (18%). The lowest contribution to the total soil loss was from built-up area (7.4%) (disregarding lake and wetlands). However, the highest rate of erosion per unit of area was computed from bare land (599.6 t $ha^{-1}yr^{-1}$).

Table 6. Variation of annual soil erosion rates with LULC types

LULC Class	**Area**		**Estimated annual soil loss**		
	ha	%	ton yr^{-1}	Contribution to the total soil loss (%)	t $ha^{-1}yr^{-1}$
Cultivated	39,172.8	27.5	2,209,089.0	41.9	56.4
Agroforestry	49,188.2	34.5	952,106.0	18.0	19.4
Bare land	863.6	0.6	517,784.3	9.8	599.6
Built-up	5,637.3	4.0	41,706.0	0.8	7.4
Forest	5,745.7	4.0	150,472.0	2.9	26.2
Grassland	8,982.4	6.3	133,821.0	2.5	14.9
Lake	9,512.5	6.7	90.6	0.0	0.0
Shrubs	9,667.7	6.8	556,327.6	10.5	57.5
Wetland	4,376.9	3.1	30.8	0.0	0.0
Woodland	9,513.9	6.7	713,773.8	13.5	75.0
Total	142,661.0	100.0	5,275,201.1	100.0	36.98

3.2. Sediment retention capacity of Lake Hawassa watershed

3.2.1. Spatial variation of annual sediment retention in the watershed

For estimating the amount of avoided soil erosion due to the existing LULC and management practices, the model uses a hypothetical scenario as a benchmark where all land is cleared to bare soil. Then, it calculates the amount of retained sediment based on the difference between the sediment export from the watershed under bare soil and the sediment export from the watershed under the existing LULC.

As indicated in fig. 5, the sediment retention potential of the watershed was in a range of 0–11,231.7 t pixel^{-1}. Due to the existing LULC and management practices, a total of 18,646,116 t yr^{-1} (130.7 t ha^{-1}yr^{-1}) of sediment was retained in the watershed. As it is indicated in table 7, the annual average sediment retention capacity of the watershed was grouped into five sediment retention capacity levels. The result revealed that 51.4% of the watershed had very low sediment retention capacity, while 16.7% and 25% of the watershed had low and moderate sediment retention capacities, respectively. Only 7% of the watershed had high and very high sediment retention capacity. In addition, the result revealed that 84.7% of the total sediment was retained by only 32% of the watershed (Fig. 5 and Table 7).

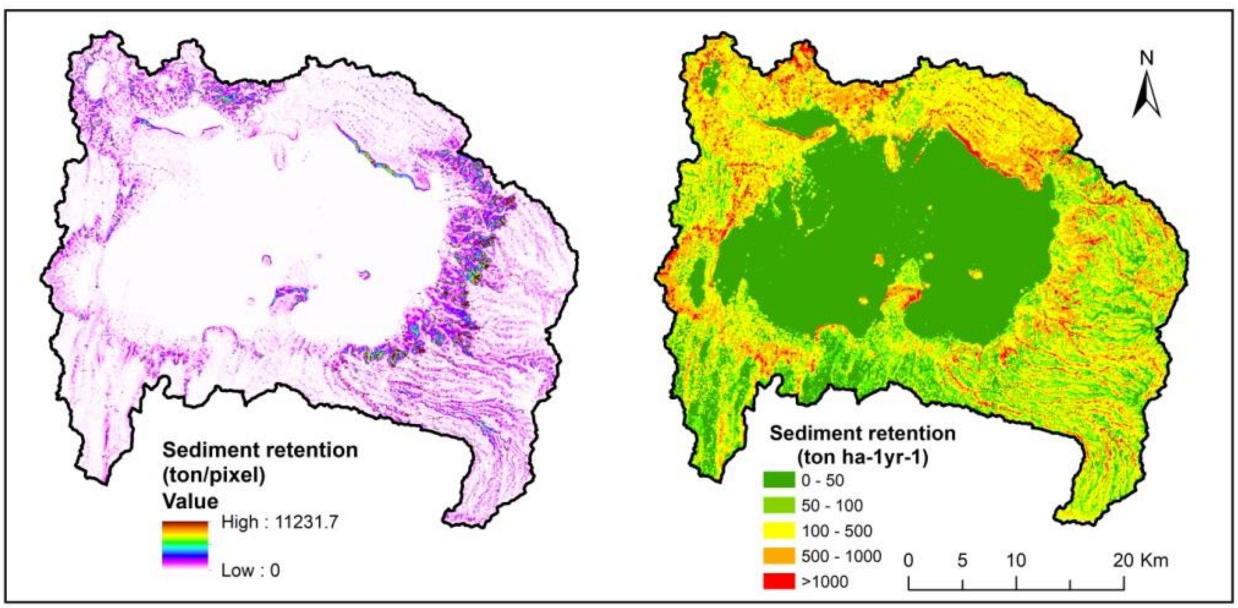


Fig. 5 Sediment retention rate in Lake Hawassa watershed

Table 7. Annual sediment retention levels, rates, and area coverage

Sediment retained ($t\ ha^{-1}\ yr^{-1}$)	Retention levels	Area (ha)	% of the total area	Estimated annual Sediment retention (t)	% of the total retention
0-50	Very low	73,377.2	51.4	734,325.4	3.9
50-100	low	23,768.9	16.7	2,118,433.6	11.4
100-500	Moderate	35,619.5	25.0	6,906,696.0	37.0
500-1000	high	8,515.5	6.0	5,699,354.4	30.6
>1000	Very high	1,379.9	1.0	3,187,306.6	17.1
Total		142,661.0	100	18,646,115.97	100

3.2.2. Spatial variation of sediment retention along slope classes

The spatial distribution of the retained sediment varies with slope gradients. As demonstrated in table 8 the contribution to total watershed's sediment retention was higher in areas with slope ranges of 15-30% followed by 5-15% and 30-50%. Overall, 86% of the sediment was retained by areas within the slope ranges of 5-50%. However, the sediment retention per unit area (ha) revealed an increasing trend with increasing slope gradients, being the highest (1,378.6 $t\ ha^{-1}year^{-1}$) on slopes >50.

Table 8. Variation of annual sediment retention rates with slope classes

Slope class (%)	Area		Estimated annual Sediment retention		
	ha	%	$t\ yr^{-1}$	Contribution to total sediment retention (%)	$t\ ha^{-1}yr^{-1}$
0-5	77,187.8	54.1	1,230,643.7	6.6	15.9
5-15	41,819.1	29.3	5,407,373.6	29.0	129.3
15-30	17,147.2	12.0	6,115,926.0	32.8	356.3
30-50	5,590.6	3.9	4,642,882.9	24.9	830.5
>50	916.3	0.6	1,249,289.8	6.8	1378.6
Total	142,661.0	100.0	18,646,116.0	100	

3.2.3. Spatial variation of sediment retention with LULC classes

Similar to the variations observed in soil loss, the spatial distribution of the retained sediment varied with LULC types. As depicted in table 9; agroforestry, forest, and woodland with their respective 36.5%, 28.2%, and 13.9% contribution to the total sediment retention; had the highest sediment retention capacity while bare land (0.3%) and built-up (0.6%) (disregarding lake and wetlands) had the lowest retention capacity. However, high sediment retention per unit of area (ha) were estimated from forest (915 $t\ ha^{-1}\ yr^{-1}$), woodland (273 $t\ ha^{-1}\ yr^{-1}$), shrubs (143 $t\ ha^{-1}\ year^{-1}$) and agroforestry (138.2 $t\ ha^{-1}\ yr^{-1}$) while lower sediment retention were computed from built-up (20.1 $t\ ha^{-1}\ yr^{-1}$), grassland (55.6 $t\ ha^{-1}\ yr^{-1}$) and bare land (62.1 $t\ ha^{-1}\ yr^{-1}$).

Table 9 Sediment retention by LULC types

LULC Class	Area		Estimated annual sediment retention		
	ha	%	t yr^{-1}	Contribution to the total sediment retention (%)	t $ha^{-1}yr^{-1}$
Cultivated	39,172.80	27.5	1,939,196.1	10.4	49.4
Agroforestry	49,188.20	34.5	6,805,832.3	36.5	138.2
Bare land	863.6	0.6	55,938.3	0.3	62.1
Built-up	5,637.30	4.0	111,876.7	0.6	20.1
Forest	5,745.70	4.0	5,258,204.7	28.2	915.0
Grassland	8,982.40	6.3	503,445.1	2.7	55.6
Lake	9,512.50	6.7	0	0.0	0.1
Shrubs	9,667.70	6.8	1,379,812.6	7.4	143.0
Wetland	4,376.90	3.1	0	0.0	1.1
Woodland	9,513.90	6.7	2,591,810.1	13.9	273.2
Total	142,661.00	100.0	18,646,116.0	100	130.7

3.3. Sediment export in Lake Hawassa watershed

3.3.1. Spatial variation of annual sediment export in the watershed

Exported sediment is the sediment beyond retention capacity of the vegetative cover and management practices which has a potential to reach the nearby streams. It is the sediment amount which can be compared to any observed sediment loading at the outlet of a watershed. For estimating the sediment export for each cell, the model first computed the amount of eroded sediment, then the sediment delivery ratio (SDR), which is the amount of soil loss that actually reaches the nearby streams and outlet of the watershed.

The result revealed that, the computed total annual sediment export from the watershed was 226,690.3 tons (1.6 t ha^{-1} yr^{-1}) (table 10). The sediment export from each pixel in the watershed was in a range of 0-239.9 t $pixel^{-1}$ (Fig. 6). In addition, the result in table 10 shows that 85% of the watershed had a sediment export <1 t ha^{-1} yr^{-1}, contributing only 8.1% of the total sediment export. Whereas, 7.6% of the watershed had a sediment export of 1- 5 t ha^{-1} yr^{-1} while supplying 18.7% of the total sediment. A sediment export >5 t ha^{-1} yr^{-1} was estimated from only 7.4% of the watershed which contributed 73.2% of the total sediment export.

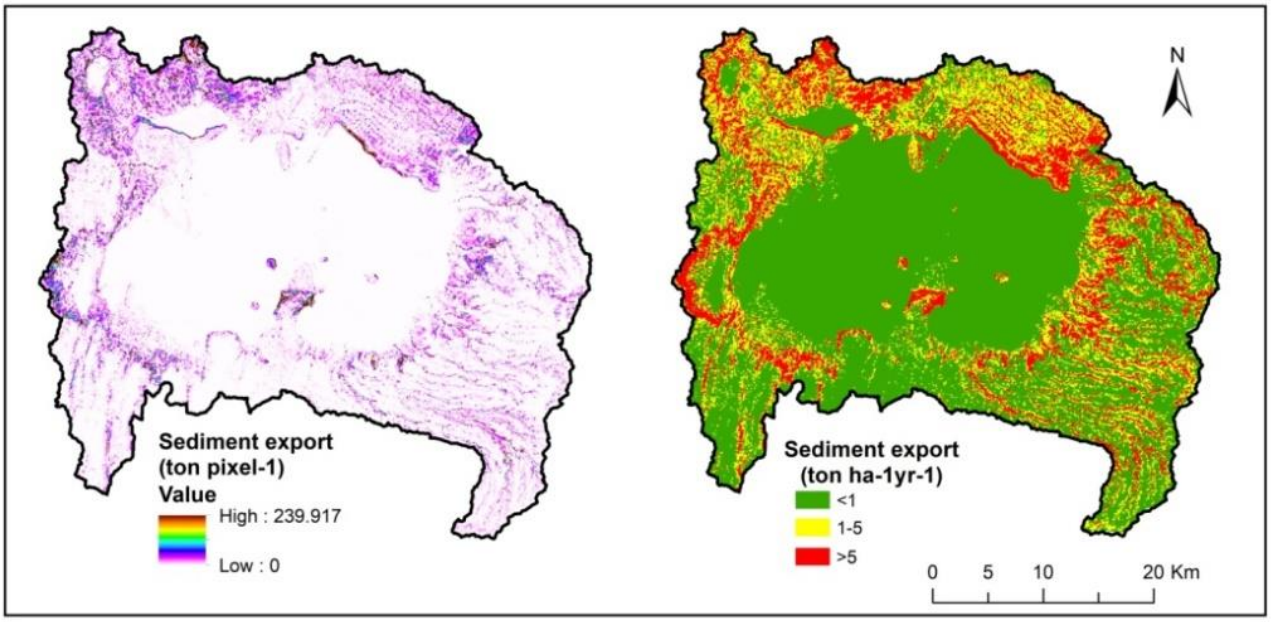


Fig. 6 Sediment export rate in Lake Hawassa watershed

Table 10. Annual sediment export rates, magnitude and area coverage

Exported sediment (t ha^{-1} yr^{-1})	Export level	Area (ha)	Percent of the total area	Estimated annual sediment export (t yr^{-1})	Percent of the total export
0	Low	121,219.0	85.0	18,267.5	8.1
1-5	Moderate	10,864.8	7.6	42,433.5	18.7
5	High	10,577.2	7.4	165,989.3	73.2
Total		142,661.0	100.0	226,690.3	100.0

3.3.2. Spatial variation of sediment export along slope classes

There was variation in the spatial distribution of sediment export with slope. The contribution to the total sediment export was higher for the medium slope areas. For instance, about 70% of the sediment exported to the nearby water bodies was contributed by areas with slopes ranging between 5 and 30% (table 11). Only 15.3 % of the exported sediment was contributed by areas with slopes below 5%, with similar proportion of sediment contributed by slopes >30%. However, it is indicated in the table 11 that the annual mean sediment export per hectare increased linearly with increasing slope gradients. Areas with higher slope gradients contributed greater exported sediment per hectare than areas with lower slope gradients. For example, the highest mean sediment export per hectare was estimated from areas with slopes >50% with the lowest observed from areas with slopes <5%.

Table 11. Variation of annual sediment export rates with slope classes

Slope class (%)	Area		Estimated annual sediment export		
	ha	%	t yr^{-1}	Contribution to the total sediment export (%)	t $ha^{-1}yr^{-1}$
0-5	77,187.8	54.1	34,675.58	15.3	0.5
5-15	41,819.1	29.3	90,087.59	39.7	2.2
15-30	17,147.2	12.01	67,754.61	29.9	4.0
30-50	5,590.6	3.9	28,393.01	12.5	5.1
>50	916.3	0.6	5,779.56	2.5	6.3
Total	142,661.0	100.0	226,690.36	100	1.6

3.3.3. Spatial variation of sediment export with LULC classes

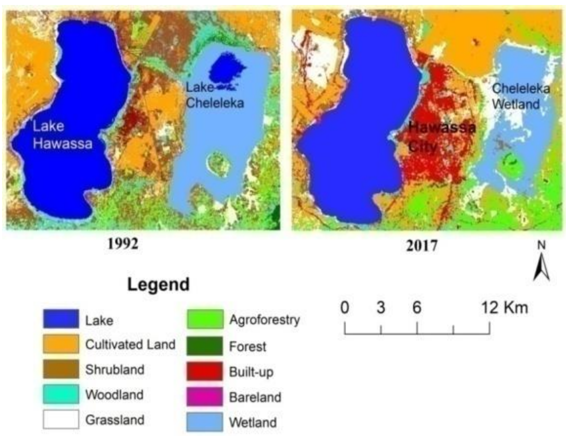
Similar to the result observed in the spatial distribution of soil loss, variation of sediment export was observed with different LULC classes. From the total sediment that reaches the surrounding water bodies, the highest contribution was from cultivated land (40.7%) (table 12). However, the highest sediment export per unit of area (ha) was observed from bareland.

Table 12 Sediment export by LULC types

LULC class	Area		Estimated annual sediment export		
	ha	%	t yr^{-1}	Contribution to the total sediment export (%)	t $ha^{-1}yr^{-1}$
Cultivated	39,172.8	27.5	92,263.0	40.7	2.4
Agroforestry	49,188.2	34.5	34,683.6	15.3	0.7
Bareland	863.6	0.6	28,789.7	12.7	33.2
Built-up	5,637.3	4.0	2,040.2	0.9	0.4
Forest	5,745.7	4.0	5,213.9	2.3	0.9
Grassland	8,982.4	6.3	5,440.6	2.4	0.6
Lake	9,512.5	6.7	-	0.0	0.0
Shrubs	9,667.7	6.8	26,522.8	11.7	2.7
Wetland	4,376.9	3.1	-	0.0	0.0
Woodland	9,513.9	6.7	31,736.7	14.0	3.3
Total	142,661.0	100.0	226,690.4	100	1.6

3.4 The environmental implications of soil erosion and sediment yield

Lake Hawassa is located in a closed watershed. The lake is situated at the lowest elevation in the watershed and it is the end receiver of runoff and sediment from the whole watershed. It was indicated in section 3.3 that the total annual sediment export from the watershed that joins the lake was 226,690.3 t (1.6 t ha^{-1} yr^{-1}). The accumulation of such amount of sediment in the lake has many environmental repercussions. One of the effects was most likely the dry-out of Lake Cheleleka, a small lake which is located in the upstream of Lake Hawassa (Fig. 7). In addition, the rise in the water level and the increase in the surface area of Lake Hawassa are the other effects which are likely or partly related to such sediment accumulation (Fig.8). Lake Cheleleka with a surface area of 570 ha in the 1992 LULC map was not identified in 2017 LULC map, indicating the complete dried-out of the lake (Fig. 7). In addition, the surface area of Lake Hawassa which was 9,249 ha in 1992 increased to 9,481 ha in 2017, signifying the accumulation of sediment in the lake and flow-out of the water to the surrounding areas (Fig. 8). A personal experience of the area indicates that the rise in the lake level and the resulting flooding have been the major environmental concerns threatening the nearby Hawassa city in the last few decades.



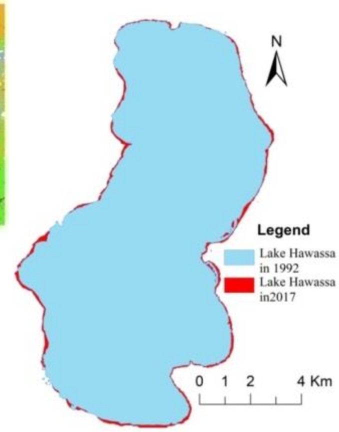


Fig. 7 Lake Cheleleka in 1992 and 2017 **Fig. 8** Surface area of Lake Hawassa in 1992 and 2017

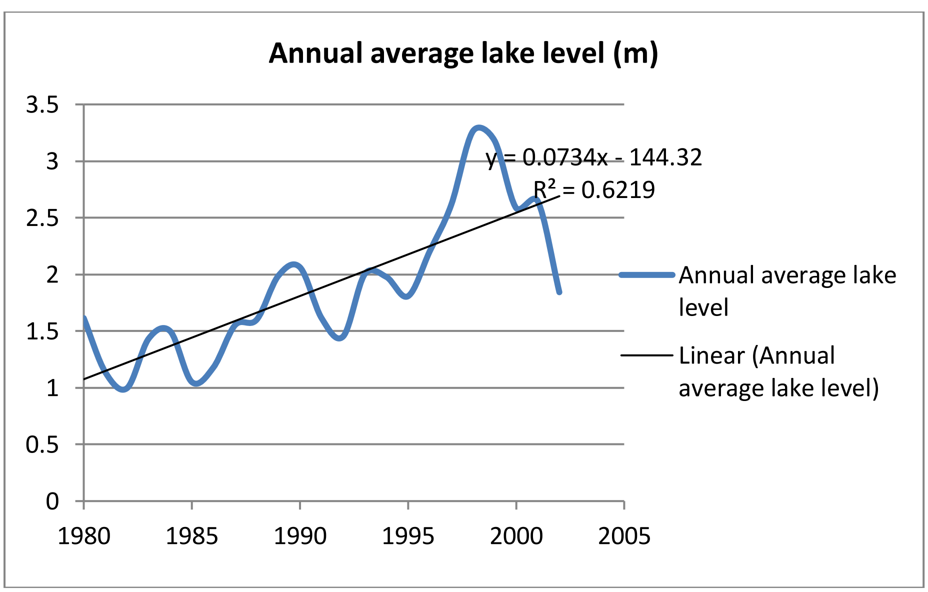


Fig. 9 Water level of Lake Hawassa

4. Discussion

4.1 Soil erosion and sediment retention and export in Lake Hawassa watershed

Soil erosion

Understanding the level of erosion and sediment retention and export is important for science-based sustainable management of natural resources in a watershed. The study found that the average rate of soil loss from the watershed was 37 t ha^{-1} yr^{-1}. The estimated soil loss value is higher compared to the soil formation rates of different places in Ethiopia, which were in a range of 2–22 t ha^{-1} yr^{-1} (Hurni, 1983). In addition, the value is higher compared to the soil loss tolerance limit in Ethiopia, which was suggested by Hurni (1986) to be in a range of 2–18 t ha^{-1} yr^{-1} on agricultural lands, and which was calculated by Morgan (1995) to be 10 t ha^{-1} yr^{-1}. Moreover, the value is higher than the rate that can be reversed within 50 to 100 years time. Kouli et al. (2009) reported that an erosion rate which is above 10 t ha^{-1} yr^{-1} will not be reversed within 50 to 100 years time.

However, the computed erosion rate in the watershed is less than the highest rates of erosion in Ethiopia which were reported by Zeleke (2000) in northwestern highlands of Ethiopia (243 t ha^{-1} yr^{-1}), Sahle et al. (2018) in Wabe river catchment (165 t ha^{-1} yr^{-1}), and Haregeweyn et al. (2015) in Anjeni (110 t ha^{-1} yr^{-1}) and Chemoga (102 t ha^{-1} yr^{-1}) watersheds in Ethiopia. On the other hand, the value is greater than the rate reported by Haregeweyn et al. (2015) who reported the average soil erosion rate in Ethiopia to be 29.9 t ha^{-1} yr^{-1}.

Overall, compared to the soil loss estimated values in this study, the figures in the literature have disparity and inconsistency. Such disparity may arise from the use of different methods and the variations in biophysical environment and management practices. Nevertheless, the estimated value and spatial distribution of the estimated soil loss were comparable to what is observed in the field and to that reported by SCRP (1996) (35 t $ha^{-1}yr^{-1}$) and Yusuph and Dagne (2019) (37 t $ha^{-1}yr^{-1}$) in the northern Ethiopia where high erosion rates were reported to exist.

With regard to the spatial distribution of the estimated soil loss, the study revealed that about 18% of the watershed had a severe and very severe soil loss rates, contributing 88% of the soil loss. In addition, the study indicated large part of the watershed had slight and very slight soil loss rates. This implies that most of the total soil loss was contributed by small part of the watershed which experienced high erosion rates. Hence, there is a need to implement targeted soil and water conservation measures of various types to ensure sustainability of the watershed resources. The soil loss map (Fig. 4) also revealed that the extent of soil loss is the highest in the upper reaches of the watershed. This could be due to the expansion of agricultural activities into marginal steep slope areas which cleared large areas of forest, woodland and shrubs and exposed the soil for the direct forces of raindrops.

From slopes perspective, the study revealed a considerable effect of slope gradient on the rate of soil erosion. Although higher soil loss per unit of area was identified on the highest slope gradients, the study found greater contribution to the total soil loss from medium ranging slopes (slopes with 5-30%). This is mainly because of the smaller proportion of the watershed with very steep slope gradients. For instance, only 4.5% of the watershed exists on slopes >30%. Hence, the contribution of such steep slope gradients to the total soil loss was small (only 16.7% of the total soil loss). On the other hand, part of the watershed with 5-30% slope gradients covers significant proportion of the watershed (41.3%) that contains relatively optimal slope gradients which were accessible to agricultural practices and contributed 67.8% of the total soil loss. This is an indication that apart from slope gradient, the proportion of area with relatively higher slope gradient is the major factor that affected the soil loss in the area. Therefore, stabilizing slopes using various soil and water conservation structures and considering slope classes in the efforts towards controlling soil erosion should be given priority.

In connection with LULC, the study indicated that the type of LULC has significant effect on the extent of soil erosion in the watershed. The highest contribution to the total soil loss was from cultivated land while the highest rate of soil loss per hectare was observed from bare land. It appears that the higher soil loss from cultivated land was related to the intensive farming of large area on higher slopes of the watershed which caused removal of the natural vegetative cover that exposed the soil to direct forces of raindrops and running water. Similar results were found by Bewket (2003), Bantider (2007) and Yusuph and Dagnew (2019) who reported higher soil erosion rates of cultivated lands. In addition, although the study revealed higher rate of soil loss per hectare on bare land, its contribution to the total soil loss was minimal because of its small coverage in the watershed.

Sediment export

The study reported that the sediment export to the water bodies in the watershed was 1.6 t ha^{-1} yr^{-1}. The figure is comparable to other sediment yield estimations in Ethiopia. For instance, Haregeweyn et al. (2012) estimated a 2 to 19 t ha^{-1} yr^{-1} of sediment export from 14 micro-dam watersheds in northern Ethiopia. Sahle et al. (2018) also identified a sediment export of 0–33 t ha^{-1} yr^{-1} from the Wabe river catchment of the Gibe basin. The estimated sediment export value was generally reasonable compared to the reported figures and to what is observable in the field which indicates considerable mass of soil materials which were removed from steep slopes of the watershed have been accumulated in downstream areas. Such sediment export created problems of lake sedimentation, pollution of water bodies and sediment deposition on the active agricultural lands.

The spatial distribution of the sediment export along the slope and LULC classes was in line with the results observed in the spatial distribution of soil loss. Similar to the values observed in the soil loss, the sediment export per unit of area increased linearly with increasing slope gradient with the highest values observed on very steep slopes. The contribution to the total sediment export from the watershed was also proportional to the amount of the estimated soil loss. The highest sediment export was observed from the slopes ranging between 5 and 30%. Areas within this slope class contributed 69.6% of the total sediment export. This is mainly due to the relatively increasing slope gradient and the fact that significant part (41.3%) of the watershed is located within this slope category. Although, large part (54.1%) of the watershed is situated within a slope range <5%, the contribution to the total soil loss and sediment export from this slop class was only 15.5% and 15.3%, respectively. This is mainly due to the plain nature of the area that made it less liable to running water. In addition, the sediment contribution of the area located on slopes >30% is only 15% of the total sediment export because of the fact that small part (4.5%) of the watershed was located within this slope category.

The estimated sediment export along the LULC classes was also in line with the results observed in the spatial distribution of soil loss. The result revealed that the highest contribution to the total sediment export comes from cultivated lands. The result is in conformity with the findings of Haregeweyn et al. (2015) who found higher sediment export from cultivated lands. This is associated with cultivation of steep slopes, intensive plowing and mono cropping practices and poor land management activities. Hence, the result gives a reason to suggest the need for promoting sustainable land management practices in the watershed.

Sediment retention

The estimation of the sediment retention capacity of the watershed shows that large volumes of sediment, which could impose great environmental problems on the downstream lake ecosystem were maintained because of the existing vegetative cover and management practices in the watershed. The estimated average annual sediment retention was 130.7 t ha^{-1} yr^{-1}. This value is greater than the rate of soil loss (37 t ha^{-1} $year^{-1}$) and sediment export

($1.6\ t\ ha^{-1}\ yr^{-1}$) in the watershed. This means that the watershed has high sediment yield potential but large part of it was retained by the existing vegetative cover. High level of sediment was also retained by slopes ranging between 5 and 50%, where high soil loss and sediment export potential were estimated. This implies that much of the sediment retention was observed on high sediment yield potential areas; indicating the requirements for protecting, retaining and enhancing the existing vegetation cover and targeted management practices on this slope range to sustain and enhance the sediment retention capacity of the watershed.

In addition, the estimated sediment retention along the LULC classes revealed that vegetation-covered LULCs such as forest land, woodland, shrub land, and agroforestry had the highest sediment retention capacity. It appears that the remnant vegetation and expanding agroforestry practices may have supported the protection of such significant volumes of soil from being further exported to the water bodies.

4.2. Environmental implications of soil erosion and sediment export

The study revealed that the expansion of cultivation on higher slopes combined with meager land management practices are continuing to erode the top fertile soil and causing sediment deposition in the water bodies. It appears that the rise in the water level and expansion of surface area of Lake Hawassa are likely related to such accumulation of sediment. In support of this, studies indicate that the horizontal expansion of Lake Hawassa is resulting in flooding of lakeshore areas, damaging of properties, and displacement of people due to the rising lake level (Belete, 2013; Degife et al., 2019). It has to be noted that the pressure on natural resources will continue to increase tremendously as the watershed is being occupied by more people, settlements, farms, industries and increasing population. For instance, according to the estimate by the Federal Government of Ethiopia, Ministry of Water, Irrigation and Energy (MoWIE) and the Rift valley Lakes Basin Master Plan Studies the population of watershed increased from 839,585 in 2007 to 2,491,295 in 2020 with an annual population growth rate of over 4%. This implies that there is a highly increasing population in the area and this is a clear indication that the watershed will continue to be under pressure in the coming years with such population increase. Hence, the sustainability of sensitive ecosystems such as lake, wetlands and related fauna and flora will continue to be under threat unless appropriate and integrated interventions are implemented.

4.3 Management and policy implications

The study revealed that anthropogenic activities affected the state of erosion and sediment yield in the watershed. In line with this result a study by Bewket (2003) in Chemoga watershed indicated that loss of vegetation and the consequent soil erosion in upstream areas resulted in agricultural land degradation, sedimentation, and pollution of water bodies and increased flood flows in downstream areas. Hence, as it is suggested by De Graff (1996) and Bewket (2003), a well-coordinated conservation measures are required to avert the problem. The measures may include: afforestation, reforestation, soil and water conservation and limiting further expansion of bare and degraded lands. The conservation activities measures should be designed to tackle worst cases which cause greater soil losses. For the measures to be effective, active participation of the community during planning and implementation is mandatory. As Sharma (1999) and Bewket and Sterk (2002) suggested, participation of the local people is at the center of resource conservation. People are also required to be provided with options of conservation technologies and be allowed to opt on what is suitable for the biophysical and socioeconomic situation of their landscape. Without active participation of people, conservation activities mostly end up with a failure (Bewket, 2003). Moreover, the delivered technologies should also address people's priorities and be able to provide perceivable, quick and direct benefits that address the issues of food security and poverty. As Blaikie (2016) confirmed, resource degradation is a cause, sign and outcome of poverty. Without addressing rural poverty, sustainable management of natural resources is very difficult. Hence, providing farmers with economically rewarding conservation activities is important. Finally, the study indicated that there is high population growth in the watershed while the watershed resources are degrading critically. Although there is a policy in the country for the control of rapid population growth since 1994, little or no success has been achieved in this regard. Thus, there is a need to revise the existing population policy and strategies and enhance political commitment to control the ever-increasing population number against the economic growth and deteriorating natural resources.

5. Conclusion

Soil erosion and sediment yield are critical environmental problems in Lake Hawassa watershed. This study not only mapped and quantified the spatial distribution of the annual soil erosion and sediment yield and retention capacity of the watershed but also identified their downstream and management implications.

The study revealed much of the soil erosion and sediment export were contributed by cultivated lands and higher slopping areas in the watershed. This is an indication that the soil erosion and sediment yield in the watershed were mainly induced by human activities through the cultivation of higher slopes. In fact, it is not disregarded that other factors such as soil type, rainfall, and vegetation also have a great influence on the rate of soil erosion and sediment yield in the watershed.

The estimated average annual soil loss was 37 t ha^{-1} $year^{-1}$ and found to be higher than the soil loss tolerance limits for Ethiopian highlands. In addition, the estimated exported sediment to the nearby water bodies was 1.6 t $ha^{-1}year^{-1}$, which was generally reasonable compared to the reported figures in Ethiopia and to what is observable in the field. Greater contributions to the total soil loss and sediment export were observed from cultivated lands and slope gradients ranging between 5 and 30% while the highest soil loss and sediment export per hectare were estimated from bare lands and higher slope areas in the watershed. Although, greater part of the watershed has low contribution to the total soil loss and sediment export, extreme and very extreme soil erosion and sediment export were observed in parts of the watershed with scanty vegetative cover, poor conservation practices, cultivated and bare lands, steep slopes and mountainous areas.

Large volumes of soil which had a potential to be exported to the water bodies in the watershed were also retained due to the existing vegetative cover and management practices. The estimated average annual sediment retention was 130.7 t ha^{-1} $year^{-1}$, which was higher than the rate of soil loss and sediment export in the watershed. The sudy showed very small part of the watershed retained the great majority of the sediment that has a potential to be exported to the water bodies. Areas with a slope range of 5-50% and vegetated LULCs such as forest land, woodland, shrub land, and agroforestry had the highest contribution to the retained sediment.

The study signifies that the soil erosion and sediment export from the watershed had led to lake surface expansion, lake level rise and dry-out of a small lake. The information obtained from the estimated soil loss and sediment export and retention was found to be useful for implementing a sustainable lake watershed management in general and planning soil conservation measures in particular. The study demonstrated that InVEST model is useful to better estimate soil loss and sediment yield and retention in data-sparse watersheds like Lake Hawassa. The result helps to identify hotspot areas and prioritize areas for effective planning of sustainable lake watershed management. The study also gives a lesson on how to ease and systematize watershed planning and management and prioritize intervention areas for decision making through the use of modeling, GIS and remote sensing tools. Finally, for effective conservation of watershed resources, the study recommends that there is a need to plan for sustainable lake watershed management through effective soil and water conservation activities with active participation of the local people.

Recommendations for future research

The model represents rill and inter-rill erosion processes only and has a limitation of estimating gully erosion. This limitation suggests the need for further studies using other possible modeling approaches to identify and measure gullies in the watershed to improve the accuracy of soil loss and sediment yield estimations for better planning and management in the future. In addition, given the simplicity of the model and small number of input parameters, it is likely that outputs are very sensitive to most input parameters. However, sensitivity analysis was not carried out to identify the most sensitive input parameters that may help selective and targeted interventions. Hence, further studies are recommended to conduct sensitivity analyses to investigate how the confidence intervals in input parameters influence the study outputs and identify most sensitive parameters.

Acknowledgements: The first author would like to thank Addis Ababa University Thematic Area Research Fund for supporting the cost of data collection.

Authors' contributions: Mr. Arega Degife (main author) collected, analyzed, and interpreted the data and wrote the manuscript. Professor Hailu Worku and Dr. Shumete Gizaw edited, commented and suggested ideas in the manuscript preparation process. All authors read and approved the final manuscript.

Availability of data and materials: All data and materials used in the study are presented in the main paper.

Ethics approval and consent to participate: "Not applicable".

Consent for publication: "Not applicable".

Competing interests: The authors declare that they have no competing interests.

Financial competing interests: "Not applicable".

Ethical statement: All ethical practices related to the development, writing, and publication of the article have been followed.

References

Ambers, R.K., 2001. Using the sediment record in a western Oregon flood-control reservoir to assess the influence of storm history and logging on sediment yield. *Journal of Hydrology*, *244*(3-4), pp.181-200.

Angassa, A., 2014. Effects of grazing intensity and bush encroachment on herbaceous species and rangeland condition in southern Ethiopia. *Land Degradation & Development*, *25*(5), pp.438-451.

Bantider, A., 2007. Landscape Transformation and Opportunities for Sustainable Land Management along the Eastern Escarpment of Wello (EEW), Ethiopia (PhD dissertation). University of Bern, Switzerland.

Belete, M.D., 2013. The Impact of Sedimentation and Climate Variability on the Hydrological Status of Lake Hawassa, South Ethiopia (PhD dissertation). University of Bonn, Germany.

Bewket, W. and Sterk, G., 2002. Farmers' participation in soil and water conservation activities in the Chemoga watershed, Blue Nile basin, Ethiopia. *Land Degradation & Development*, *13*(3), pp.189-200.

Bewket, W. and Teferi, E., 2009. Assessment of soil erosion hazard and prioritization for treatment at the watershed level: case study in the Chemoga watershed, Blue Nile basin, Ethiopia. *Land Degradation & Development*, *20*(6), pp.609-622.

Bewket, W., 2003. Towards integrated watershed management in highland Ethiopia: the Chemoga Watershed case study (Ph.D dissertation). Wagningen University.

Biggs, E.M., Bruce, E., Boruff, B., Duncan, J.M., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow, J. and Haworth, B., 2015. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science & Policy*, *54*, pp.389-397.

Blaikie, P., 2016. *The political economy of soil erosion in developing countries*. London, UK.

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V. and Bagarello, V., 2017. An assessment of the global impact of 21st century land use change on soil erosion. *Nature communications*, *8*(1), pp.1-13.

Borselli, L., Cassi, P. and Torri, D., 2008. Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment. *Catena*, *75*(3), pp.268-277.

Cavalli, M., Trevisani, S., Comiti, F. and Marchi, L., 2013. Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. *Geomorphology*, *188*, pp.31-41.

Chorowicz, J., 2005. The east African rift system. *Journal of African Earth Sciences*, *43*(1-3), pp.379-410.

De Graff, J., 1996. The price of soil erosion: an economic evaluation of soil erosion and watershed development (Ph.D. thesis). Wageningen Agricultural University, Wageningen, The Netherlands.

Degife, A., Worku, H., Gizaw, S. and Legesse, A., 2019. Land use land cover dynamics, its drivers and environmental implications in Lake Hawassa Watershed of Ethiopia. *Remote Sensing Applications: Society and Environment*, *14*, pp.178-190.

deNoyelles, F. and Kastens, J.H., 2016. Reservoir sedimentation challenges Kansas. *Transactions of the Kansas Academy of Science*, 119(1), pp.69-81.

Desmet, P.J.J. and Govers, G., 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. *Journal of soil and water conservation*, *51*(5), pp.427-433.

Dessie, G., 2007. Forest Decline in South Central Ethiopia: Extent, history and process (Doctoral dissertation). Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden.

Desta, H. and Lemma, B., 2017. SWAT based hydrological assessment and characterization of Lake Ziway sub-watersheds, Ethiopia. *Journal of Hydrology: Regional Studies*, *13*, pp.122-137.

Erkossa, T., Wudneh, A., Desalegn, B. and Taye, G., 2015. Linking soil erosion to on-site financial cost: lessons from watersheds in the Blue Nile basin. *Solid Earth*, *6*(2), pp765-774.

Esa, E., Assen, M. and Legass, A., 2018. Implications of land use/cover dynamics on soil erosion potential of agricultural watershed, northwestern highlands of Ethiopia. *Environmental Systems Research*, *7*(21).

Esayas, Y., 2010. Evaluating the Impact of Land Use/Land Cover Change on Soil Erosion Runoff Using SWAT Model at Tikur Wuha Watershed (master's thesis). Addis Ababa University, Ethiopia.

FAO (2006) Guidelines for soil description. FAO, Rome.

Farhan, Y. and Nawaiseh, S., 2015. Spatial assessment of soil erosion risk using RUSLE and GIS techniques. *Environmental Earth Sciences*, *74*(6), pp.4649-4669.

FEI (Finnish Environment Institute), 2003. Guidelines on monitoring and assessment of transboundary and international lakes, Part B: Technical guidelines, Helsinki, Finland.

Fenta, A.A., Tsunekawa, A., Haregeweyn, N., Poesen, J., Tsubo, M., Borrelli, P., Panagos, P., Vanmaercke, M., Broeckx, J., Yasuda, H. and Kawai, T., 2020. Land susceptibility to water and wind erosion risks in the East Africa region. *Science of the Total Environment*, *703*, p.135016.

Gashaw, T., Tulu, T. and Argaw, M., 2018. Erosion risk assessment for prioritization of conservation measures in Geleda watershed, Blue Nile basin, Ethiopia. *Environmental Systems Research*, *6*(1), p.1.

Gebreegziabher, Y., 2004. Assessment of the water balance of Lake Awassa catchment, Ethiopia (Master's thesis). ITC, Enschede, The Netherlands.

Gebre-Mariam, Z. and Desta, Z., 2002. The chemical composition of the effluent from Awassa textile factory and its effects on aquatic biota. *SINET: Ethiopian Journal of Science*, *25*(2), pp.263-274.

Gelagay, H.S. and Minale, A.S., 2016. Soil loss estimation using GIS and Remote sensing techniques: A case of Koga watershed, Northwestern Ethiopia. *International Soil and Water Conservation Research*, *4*(2), pp.126-136.

Gelagay, H.S., 2016. RUSLE and SDR model based sediment yield assessment in a GIS and remote sensing environment; a case study of Koga watershed, Upper Blue Nile Basin, Ethiopia. *Hydrology: Current Research*, *7*, p.239.

Geremew, Z., 2000. Engineering geological investigation and lake level changes in the Awassa basin (Master's thesis). Department of Geology and Geophysics, Addis Ababa University, Addis Ababa, Ethiopia.

Girma, R. and Gebre, E., 2020. Spatial modeling of erosion hotspots using GIS-RUSLE interface in Omo-Gibe river basin, Southern Ethiopia: implication for soil and water conservation planning. *Environmental Systems Research*, *9*(1), pp.1-14.

Haregeweyn, N., Melesse, B., Tsunekawa, A., Tsubo, M., Meshesha, D. and Balana, B.B., 2012. Reservoir sedimentation and its mitigating strategies: a case study of Angereb reservoir (NW Ethiopia). *Journal of soils and sediments*, *12*(2), pp.291-305.

Haregeweyn, N., Poesen, J., Deckers, J., Nyssen, J., Haile, M., Govers, G., Verstraeten, G. and Moeyersons, J., 2008. Sediment-bound nutrient export from micro-dam catchments in Northern Ethiopia. *Land Degradation & Development*, *19*(2), pp.136-152.

Haregeweyn, N., Tsunekawa, A., Nyssen, J., Poesen, J., Tsubo, M., Tsegaye Meshesha, D., Schütt, B., Adgo, E. and Tegegne, F., 2015. Soil erosion and conservation in Ethiopia: a review. *Progress in Physical Geography*, *39*(6), pp.750-774.

Haregeweyn, N., Tsunekawa, A., Poesen, J., Tsubo, M., Meshesha, D.T., Fenta, A.A., Nyssen, J. and Adgo, E., 2017. Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River. *Science of the Total Environment*, *574*, pp.95-108.

Holdren, C., Jones, W. and Taggart, J., 2001. Managing lakes and reservoirs. North American Lake Management Society, Madison, Wisconsin.

Huang, Y. and Cai, M., 2009. Methodologies guidelines: Vulnerability assessment of freshwater resources to environmental change. United Nations Environment Programme (UNEP) & Peking University, China in collaboration with Mongolian Water Authority and Asian Institute of Technology (AIT), Khlong Nueng.

Hurni, H., 1983. Soil formation rates in Ethiopia. Ethiopian highlands reclamation study. Soil Conservation Research Project, FAO, UTF/ETH/037/ETH Working Paper 2

Hurni, H., 1985. Erosion-productivity-conservation systems in Ethiopia. Proceedings of the 4^{th} International Conference on Soil Conservation. Maracay, Venezuela.pp654–674.

Hurni, H., 1986. Guidelines for development agents on soil conservation in Ethiopia. Soil conservation research project, Community Forests and Soil Conservation Development Department, Ministry of Agriculture, Addis Ababa, Ethiopia.

Hurni, H., 1993. Land degradation, famine, and land resource scenarios in Ethiopia. In: D.Pimentel (ed.) world soil erosion and conservation. Cambridge University Press, Cambridge, 27–62.

ILEC (International Lake Environment Committee Foundation), 2005. Managing Lakes and their Basins for Sustainable Use: a Report for Lake Basin Managers and Stakeholders. International Lake Environment Committee Foundation: Kusatsu, Japan.

Ionita, I., Fullen, M.A., Zgłobicki, W. and Poesen, J., 2015. Gully erosion as a natural and human-induced hazard. *Natural Hazards,* 79, pp.1–5.

Issaka, S. and Ashraf, M.A., 2017. Impact of soil erosion and degradation on water quality: a review. *Geology, Ecology, and Landscapes*, 1(1), pp.1-11.

Jansson, M.B., 1988. A global survey of sediment yield. *Geografiska Annaler: Series A, Physical Geography*, 70(1-2), pp.81-98.

Kaltenrieder, J., 2007. Adaption and Validation of the Universal Soil Loss Equation (USLE) for the Ethiopian-Eritrean Highlands (MSc Thesis). Centre for Development and Environment, Geographisches Institut, University of Bern, *Bern*.

Karabulut, A., Egoh, B.N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J. and Vandecasteele, I., 2016. Mapping water provisioning services to support the ecosystem–water–food–energy nexus in the Danube river basin. *Ecosystem services*, *17*, pp.278-292.

Karaburun, A., 2010. Estimation of C factor for soil erosion modeling using NDVI in Buyukcekmece watershed. *Ozean journal of applied sciences*, *3*(1), pp.77-85.

Kouli, M., Soupios, P. and Vallianatos, F., 2009. Soil erosion prediction using the revised universal soil loss equation (RUSLE) in a GIS framework, Chania, Northwestern Crete, Greece. *Environmental Geology*, *57*(3), pp.483-497.

Lal, R., 2001. Soil degradation by erosion. *Land degradation & development*, *12*(6), pp.519-539.

Li, J. and Heap, A.D., 2008. A review of spatial interpolation methods for environmental scientists. Geoscience Australia 2008/2003.

LIA (Lake Illawarra Authority), 2011. Lake Illawarra Authorit's Annual Report 2010/11, Sydney, Australia.

Lin, D., Gao, Y., Wu, Y., Shi, P., Yang, H. and Wang, J.A., 2017. A conversion method to determine the regional vegetation cover factor from standard plots based on large sample theory and TM images: a case study in the eastern farming-pasture ecotone of northern China. *Remote Sensing*, *9*(10), p.1035.

López-Vicente, M., Poesen, J., Navas, A. and Gaspar, L., 2013. Predicting runoff and sediment connectivity and soil erosion by water for different land use scenarios in the Spanish Pre-Pyrenees. *Catena*, *102*, pp.62-73.

Macgregor, D., 2015. History of the development of the East African Rift System: A series of interpreted maps through time. *Journal of African Earth Sciences*, *101*, pp.232-252.

Mitasova, H. and Mitas, L., 1999. Modeling soil detachment with RUSLE 3D using GIS. *University of Illinois at Urbana-Champaign*, Champaign.

Moore, I.D. and Wilson, J.P., 1992. Length-slope factors for the Revised Universal Soil Loss Equation: Simplified method of estimation. *Journal of soil and water conservation*, *47*(5), pp.423-428.

Morgan, R.P.C., 2009. *Soil erosion and conservation*. John Wiley & Sons.

Navas, A., Valero-Garcés, B., Gaspar, L. and Machín, J., 2009. Reconstructing the history of sediment accumulation in the Yesa reservoir: an approach for management of mountain reservoirs. *Lake and Reservoir Management*, *25*(1), pp.15-27.

Oliveira, A.H., da Silva, M.A., Silva, M.L.N., Curi, N., Neto, G.K. and de Freitas, D.A.F., 2013. Development of topographic factor modeling for application in soil erosion models, in: Intechopen (Ed.), *Soil Processes and Current Trends in Quality Assessment*. *Rijeka: InTech*, (4), pp.111-138.

Olson, J.M. and Maitima, J.M., 2006. Sustainable Intensification of Mixed Crop-Livestock Systems, Land Use Change Impacts and Dynamics (Lucid). *Nairobi: International Livestock Research Institute*.

Panagos, P., Borrelli, P., Meusburger, K., van der Zanden, E.H., Poesen, J. and Alewell, C., 2015. Modelling the effect of support practices (P-factor) on the reduction of soil erosion by water at European scale. *Environmental science & policy*, *51*, pp.23-34.

Pimentel, D., 2006. Soil erosion: a food and environmental threat. *Environment, development and sustainability*, *8*(1), pp.119-137.

Prasannakumar, V., Vijith, H., Abinod, S. and Geetha, N.J.G.F., 2012. Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo-information technology. *Geoscience Frontiers*, *3*(2), pp.209-215.

Redhead, J.W., Stratford, C., Sharps, K., Jones, L., Ziv, G., Clarke, D., Oliver, T.H. and Bullock, J.M., 2016. Empirical validation of the InVEST water yield ecosystem service model at a national scale. *Science of the Total Environment*, *569*, pp.1418-1426.

Renard, K.G., Foster, G.R., Weesies, G.A. and Porter, J.P., 1991. RUSLE: Revised universal soil loss equation. *Journal of soil and Water Conservation*, *46*(1), pp.30-33.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and Yoder, D.C., 1997. *Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. Washington, DC: United States Department of Agriculture. 703.

Sahle, M., Saito, O., Fürst, C. and Yeshitela, K., 2019. Quantifying and mapping of water-related ecosystem services for enhancing the security of the food-water-energy nexus in tropical data–sparse catchment. *Science of the Total Environment*, 646, pp.573-586.

Schmalz, B., Kruse, M., Kiesel, J., Müller, F. and Fohrer, N., 2016. Water-related ecosystem services in Western Siberian lowland basins—analysing and mapping spatial and seasonal effects on regulating services based on ecohydrological modelling results. *Ecological Indicators*, 71, pp.55-65.

SCRP (Soil Conservation Research Project), 1996. Soil erosion hazard assessment for land evaluation. Research report. SCRP, Addis Ababa.

Sharma, A., Tiwari, K.N. and Bhadoria, P.B.S., 2011. Effect of land use land cover change on soil erosion potential in an agricultural watershed. *Environmental monitoring and assessment*, *173*(1-4), pp.789-801.

Sharma, P.N.,1999. An overview of recent concepts and participatory integrated watershed management (PIWM) processes. In: B. R. Bhatta, S. R. Chalise, A. K. Myint and P. Sharma (eds.) Recent concepts, knowledge, practices and new skills in participatory integrated watershed management: trainers' resource book. Kathamandu, Nepal.

Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M. Mandle, L., Hamel, P., Vogl, A.L., Rogers, L., Bierbower, W., Denu, D., and Douglass, J. 2018. InVEST 3.5.0.post225+h6aabb7740548 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Shiferaw, A., 2011. Estimating soil loss rates for soil conservation planning in the Borena Woreda of South Wollo Highlands, Ethiopia. *Journal of Sustainable Development in Africa*, *13*(3), pp.87-106.

Simms, A.D., Woodroffe, C.D. and Jones, B.G., 2003. Application of RUSLE for erosion management in a coastal catchment, southern NSW. In: Proceedings of the international congress on modeling and simulation: integrative.

Syvitski, J.P. and Milliman, J.D., 2007. Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *The Journal of Geology*, *115*(1), pp.1-19.

Tamene, L., Abegaz, A., Aynekulu, E., Woldearegay, K. and Vlek, P.L., 2011. Estimating sediment yield risk of reservoirs in northern Ethiopia using expert knowledge and semi-quantitative approaches. *Lakes & Reservoirs: Research & Management*, *16*(4), pp.293-305.

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water resources research*, *33*(2), pp.309-319.

Van Dijk, P.M., 2016. Modelling the hydrology in the Lake Awassa catchment, Ethiopia: Influences of irrigation and the swamp effect (Master's thesis). Utrecht University.

Vanmaercke, M., Zenebe, A., Poesen, J., Nyssen, J., Verstraeten, G. and Deckers, J., 2010. Sediment dynamics and the role of flash floods in sediment export from medium-sized catchments: a case study from the semi-arid tropical highlands in northern Ethiopia. *Journal of Soils and Sediments*, *10*(4), pp.611-627.

Vigiak, O., Borselli, L., Newham, L.T.H., McInnes, J. and Roberts, A.M., 2012. Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. *Geomorphology*, *138*(1), pp.74-88.

Wischmeier, W.H. and Smith, D.D., 1978. *Predicting rainfall erosion losses: a guide to conservation planning*. US Department of Agriculture, Science and Education Administration, Agriculture Handbook, vol. 537, Washington DC.

Wolka, K., Tadesse, H., Garedew, E. and Yimer, F., 2015. Soil erosion risk assessment in the Chaleleka wetland watershed, Central Rift Valley of Ethiopia. *Environmental Systems Research*, *4*(1), pp.1-12.

Xiaoqing, Y., 2003. Manual on sediment management and measurement world meteorological organization. Operational Hydrology Report No. 47. Secretariat of the World Meteorological Organization, Geneva

Yesuph, A.Y. and Dagnew, A.B., 2019. Soil erosion mapping and severity analysis based on RUSLE model and local perception in the Beshillo Catchment of the Blue Nile Basin, Ethiopia. *Environmental Systems Research*, *8*(17).

Zeleke, G., 2000. *Landscape dynamics and soil erosion process modelling in the north-western Ethiopian highlands*. African Studies Series A16. Geographica Bernensia, Berne.

Figures

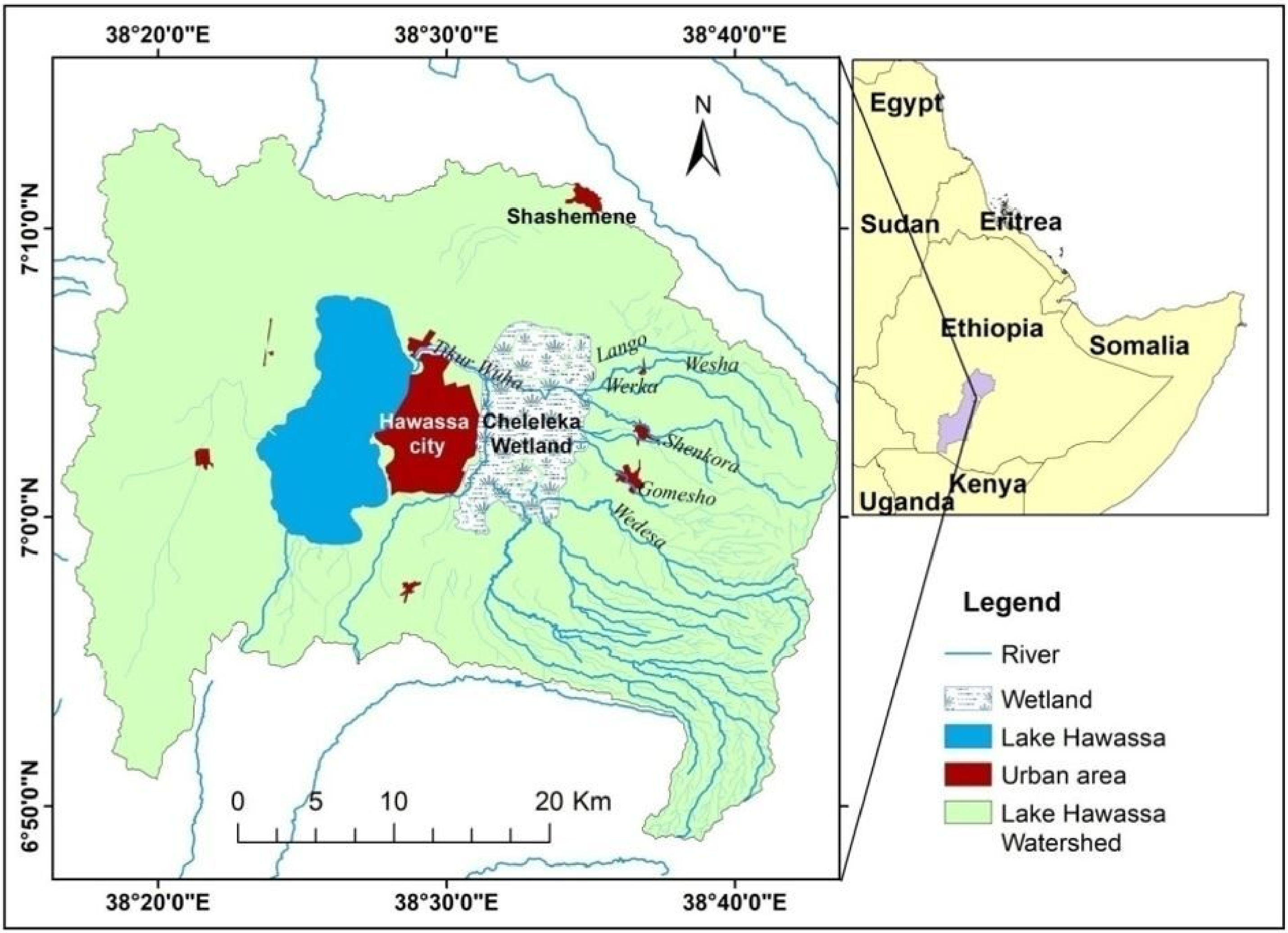


Figure 1

Location map of the study area Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

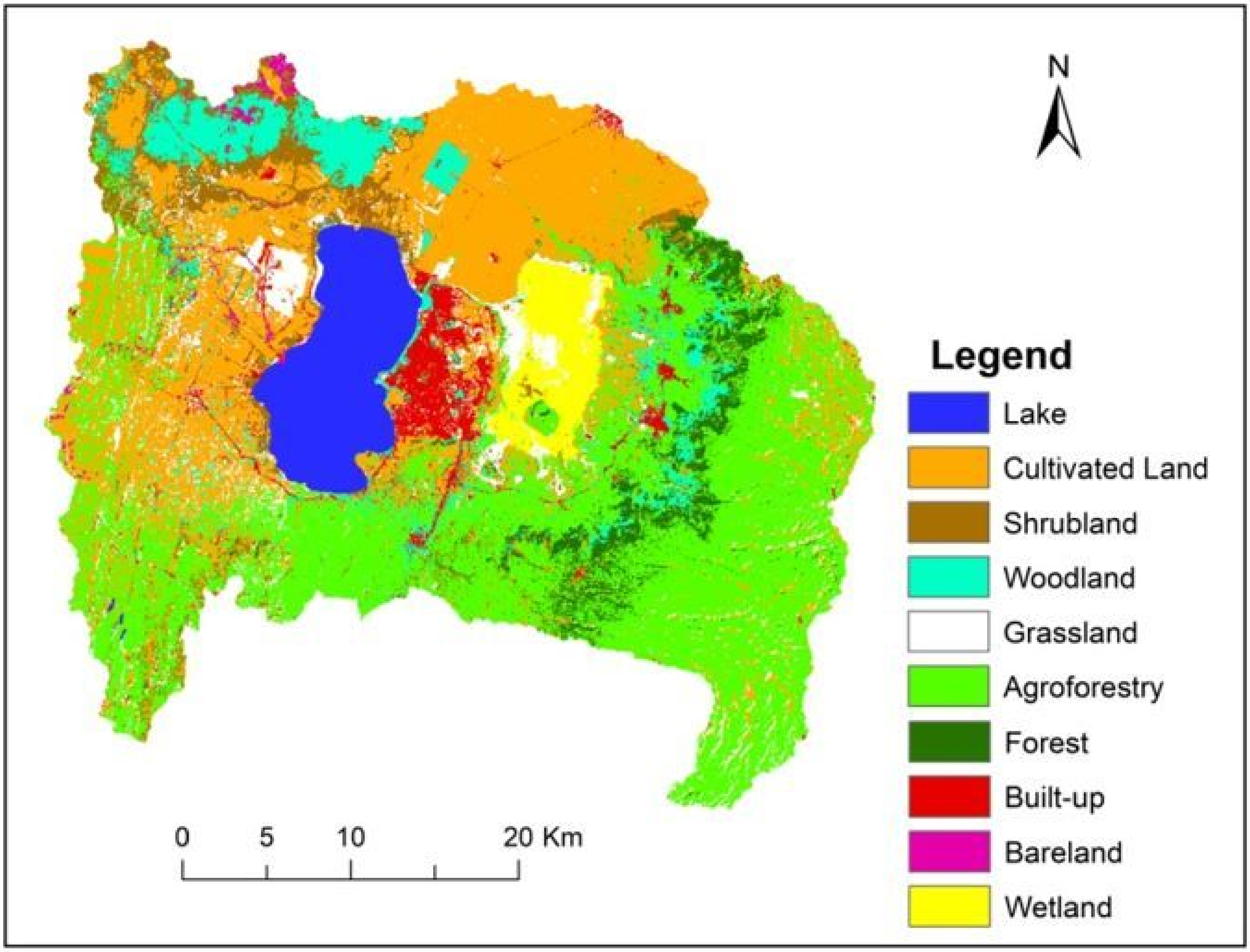


Figure 2

LULC map of Lake Hawassa Watershed Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

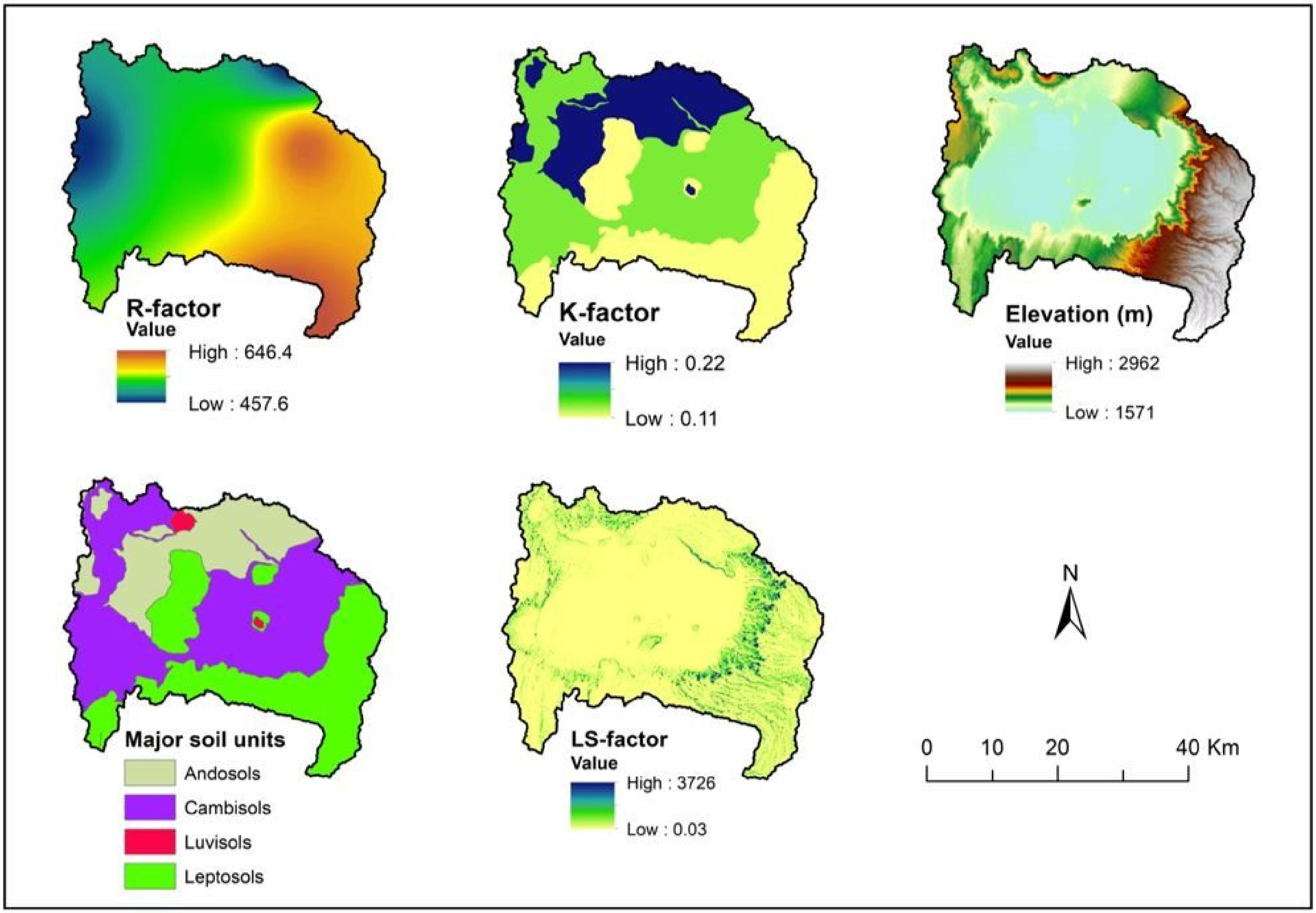


Figure 3

Spatial distributions of R-factor, K-factor, Elevation, Major soil units, and LS-factor Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

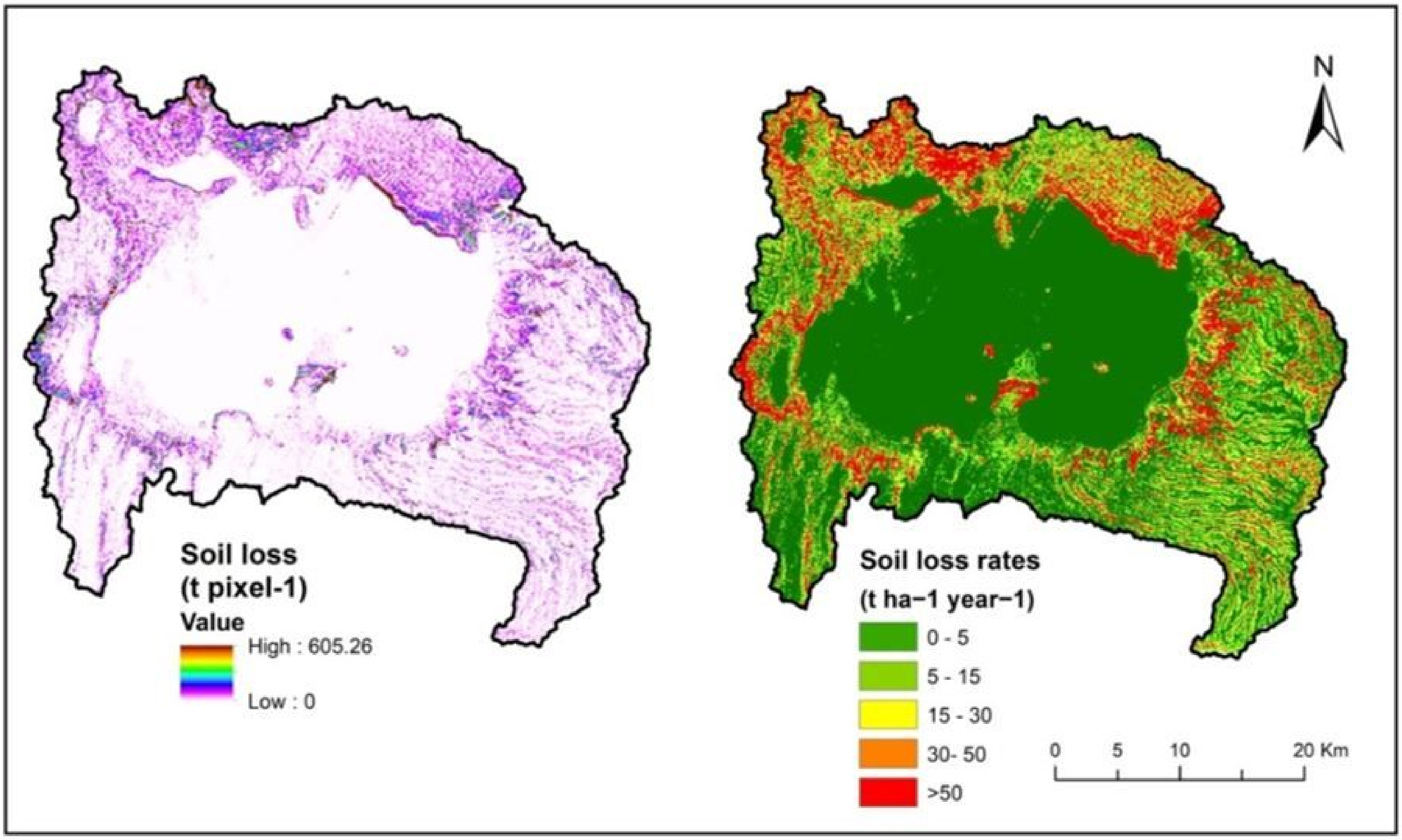


Figure 4

Soil erosion rate in Lake Hawassa watershed Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

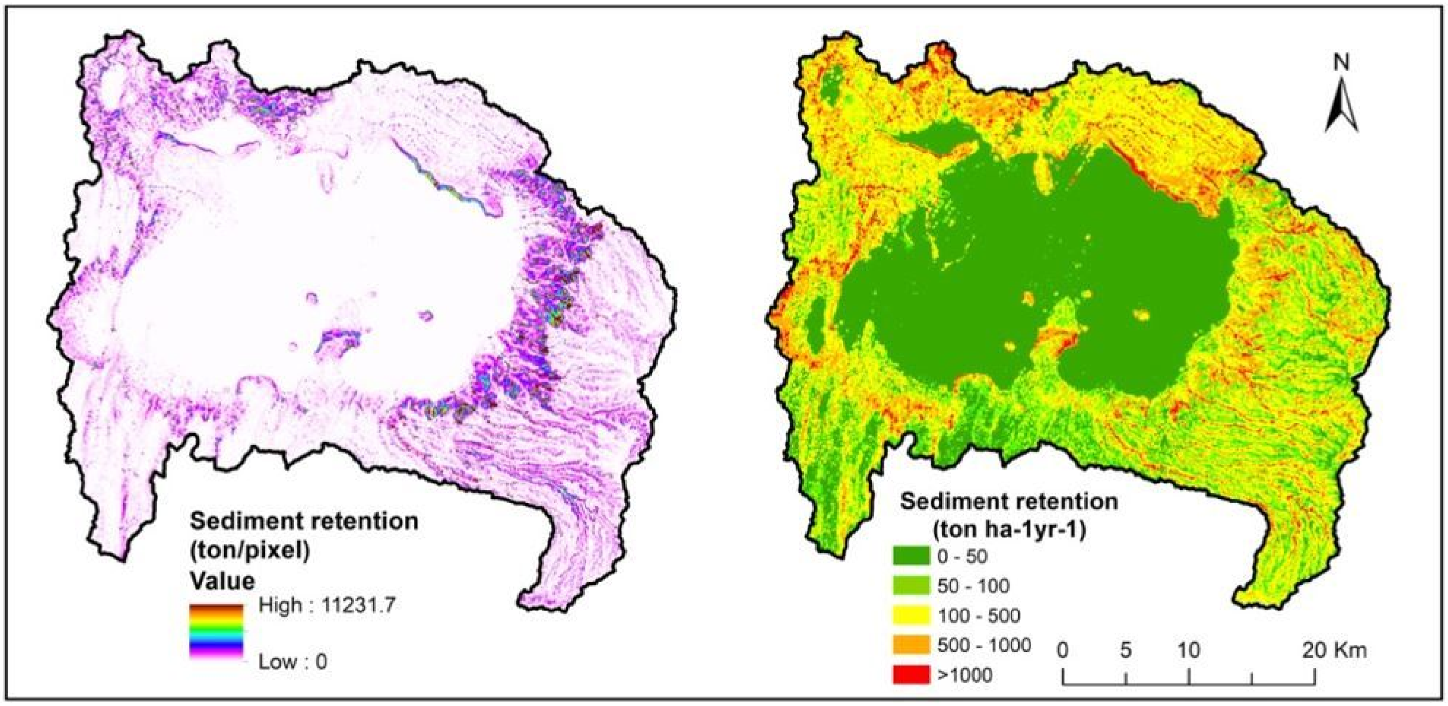


Figure 5

Sediment retention rate in Lake Hawassa watershed Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

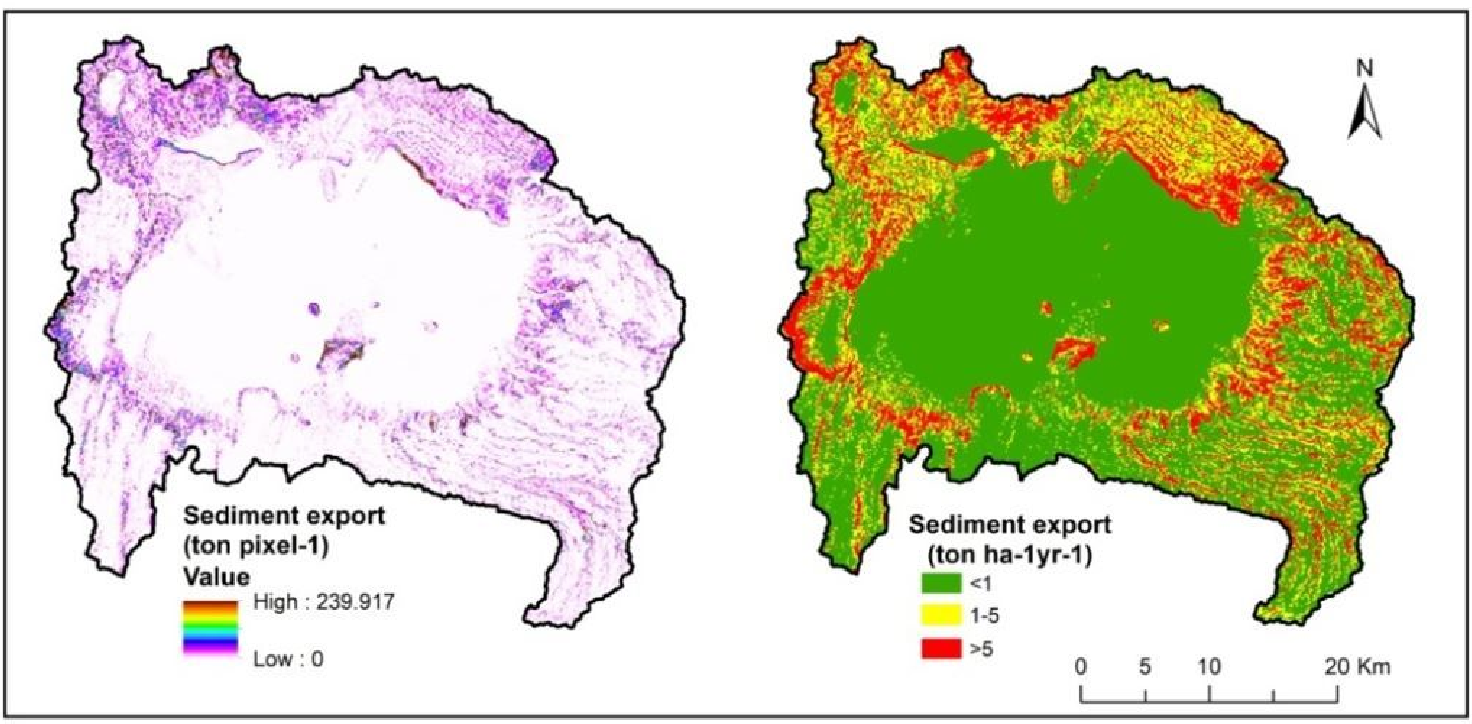


Figure 6

Sediment export rate in Lake Hawassa watershed Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

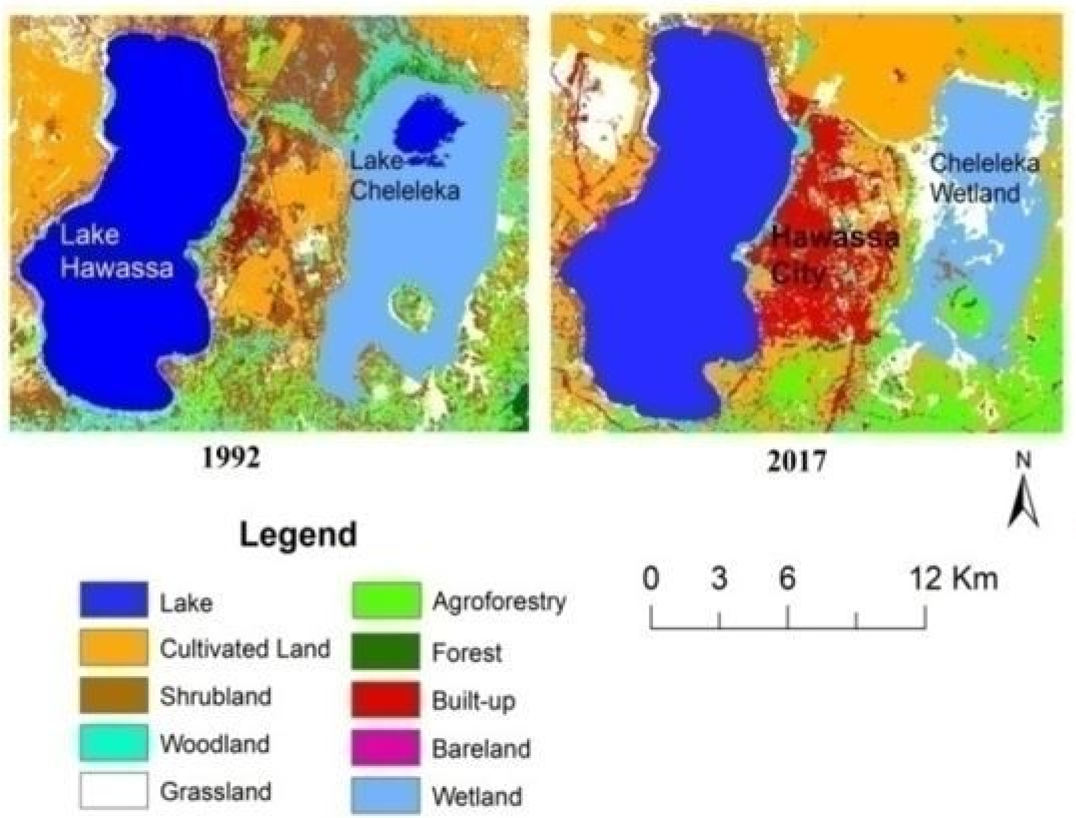


Figure 7

Lake Cheleleka in 1992 and 2017 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

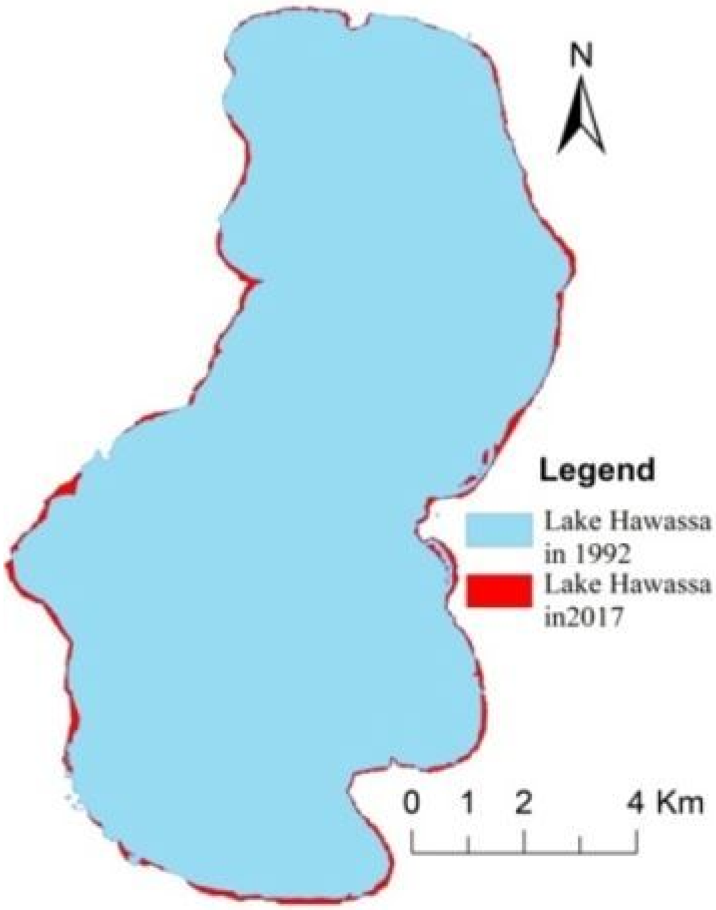


Figure 8

Surface area of Lake Hawassa in 1992 and 2017 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

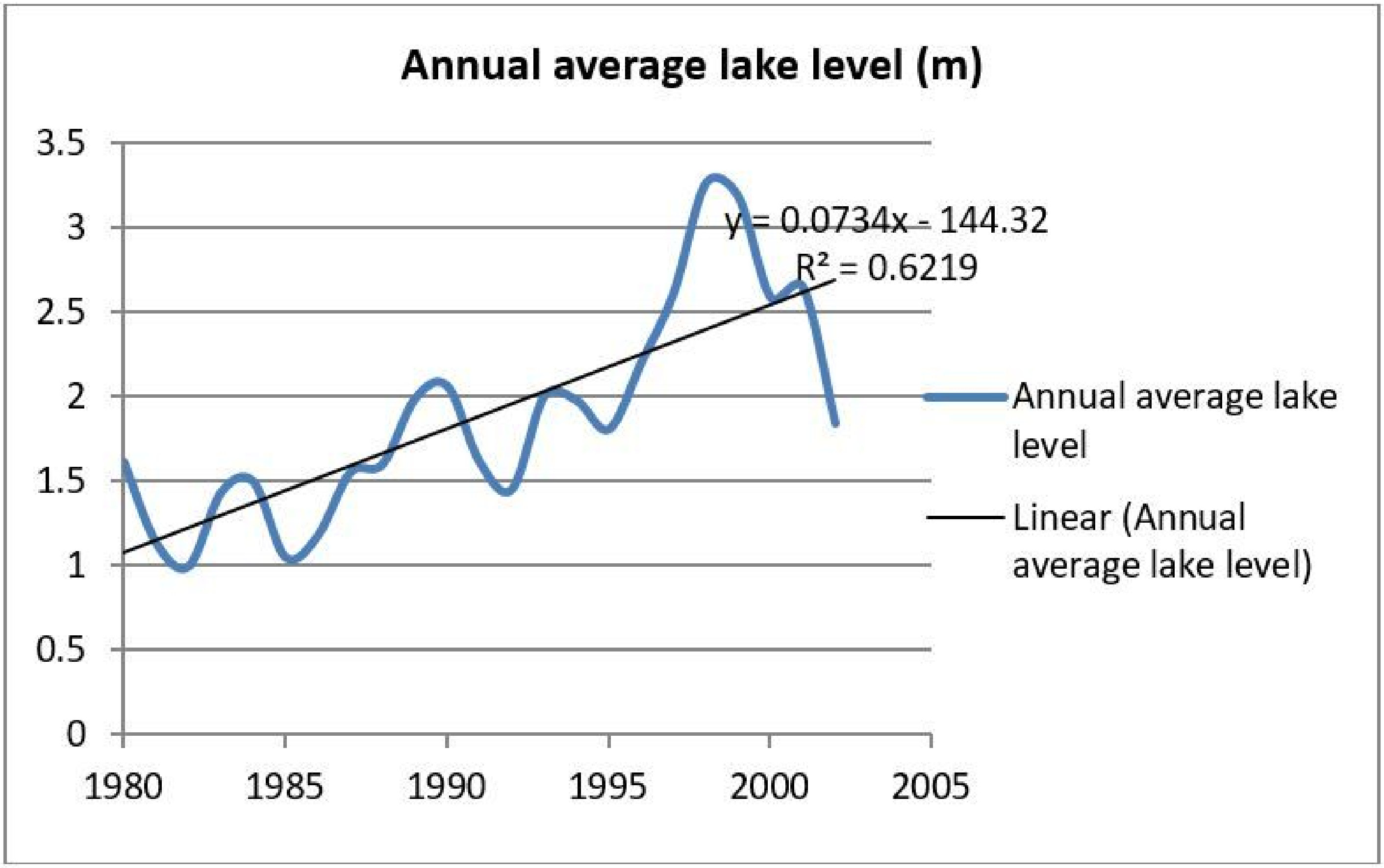


Figure 9

Water level of Lake Hawassa