The influence of land use change on soil erosion in the Genale catchment, Southern Ethiopia

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Abstract

Soil erosion forms one of the main causes of land degradation in third world countries. The subject of this research was the influence of land use and land use change on soil erosion in the upper Genale catchment, Southern Ethiopia. A land use classification was implemented for Landsat satellite images from 1985, 1993, 2003 and 2015. Using a hydrological model of the catchment, created with the Soil and Water Assessment Tool (SWAT), an erosion model was developed. The results of an erosion survey, which focused on different land uses, were used for calibration and validation. Using a continuation of land use changes in the past decades, erosion predictions were made for 2025. Land use change within the area was substantial with an increase of farmland from 10 percent to 62 percent between 1985 and 2015. Forest and grassland cover decreased from 76 percent to 32 percent. Besides population growth as the main driver of land use change, financial opportunities and government policies have been observed to influence land use dynamics in the region. During the erosion survey the average soil erosion was 3.9 $\mathrm{t\,ha^{-1}}$ during 5 weeks. An average annual erosion of 41 $\mathrm{t\,ha^{-1}\,y^{-1}}$ was predicted for 2015. Both the erosion survey and the model revealed agricultural land to be the biggest influence on soil erosion. Especially annual crops which exhibited soil erosion up to 10 times as high as other farms. The erosion was estimated to have increased by 189 percent between 1985 and 2015. When land use changes continue linearly, erosion will increase to 50 $\mathrm{t\,ha^{-1}\,y^{-1}}$ in 2025. Soil and water conserving measures in combination with irrigation projects are needed but should be strategically chosen. Good decision making is necessary to maintain agricultural potential in the area.

Contents

1 Introduction

Soil degradation forms an important problem that many third world countries face. Decrease in the top soil layer depth and the soil organic matter content have a substantial negative influence on crop yield, which is especially threatening when yield is already critically low (Lal, 1990). The importance of soil degradation and its extensive consequences on yield have been reported by the World Meteorological Organization (Sivakumar, 2011). According to their report, productivity on more than 16 percent of the agricultural land in the world is threatened, from which the largest parts are in Asia and Africa. Productivity has decreased as much as 20 percent in, for example, sub Saharan Africa in the last 40 years. Furthermore, a continuation of a productivity loss up to 1 percent per year is expected for regions which are already vulnerable (Sivakumar, 2011).

Soil erosion forms one of the most important factors in soil degradation, due to soil particles and organic matter being eroded by flow of water or wind over the soil (Lal, 2001). Especially high precipitation in combination with vulnerable soil can cause problems that cannot be neglected. Acceleration factors such as decrease in soil structure due to land use also play an important role. The removal of vegetation in an area, for example, drastically decreases soil strength (Lal, 1990). It also may reduce infiltration rates and cause increased amounts of surface runoff (Hurni et al., 2005). These reasons make land use change one of the driving forces of soil erosion, which has on many occasions been pointed out as an important and threatening influence (Virgo & Munro, 1987; Lal, 1990; Hurni et al., 2005; Tamene & Vlek, 2007; Sisay et al., 2014). While control measures such as terracing and strip farming can be taken to reduce soil erosion, both application and research into these control measures are below a level that would create sustainable agriculture in many third world areas (Morgan, 2009). Especially with the possible impact of population growth, and thus likely land use change, on the behavior of soil erosion (Tamene & Vlek, 2007). More insight into the critical influence of land use change on soil erosion is required to control its consequences. Optimal locations for creation of control measures could then also be located to ensure maximum benefit from these costly projects (Yang, 2010). If not built correctly, local support for these erosion-control projects might decrease rapidly which will cause even more problems in finding the local funding for building and maintaining these measures (Shiferaw, 1999).

Ethiopia has been plagued by struggle in many aspects. A general low productivity of agricultural land and a rapid population expansion both combine into a major permanent food shortage (Clay et al., 1999; Yang, 2010). Furthermore, over-grazing and deforestation, which have been common practice for decades, precipitate alarming rates of soil erosion, which far exceed other complications such as salinization and depletion of nutrients (Tekle, 1999; Taddese, 2001). Not only deforestation but land use change in general has a high rate in the Ethiopian highlands (Zeleke & Hurni, 2001). This high rate of land use change has been linked to the high values of soil erosion in Ethiopia (Bewket, 2002; Bewket & Sterk, 2005; Hurni et al., 2005). It is estimated that on average a mass of 42 $\mathrm{t\,ha^{-1}}$ erodes from sloping agricultural land in Ethiopia annually (Hurni, 1985).

While general principles considering land use, soil erosion and land degradation are known (Lal, 2001), specific studies about this topic are scarce, especially for regions within Ethiopia. Soil erosion and land degradation in Ethiopia have been the subject of studies, but besides some low detail models for the entire country, most of Ethiopia only has some crude estimations of soil erosion and land degradation (Munro et al., 2008; Setegn et al., 2009). In general it is concluded that soil erosion values are reason for concern. Land use has also been the subject of studies but only for certain regions in Ethiopia such as the upper Ghibe Valley (Reid et al., 2000), the Kalu district (Tekle & Hedlund, 2000), the Beressa watershed (Amsalu et al., 2007), and for deforestation in the Southern Central Rift Valley (Dessie & Kleman, 2007). In general it was concluded that land use changes take place rapidly, mostly due to population increase, and the rate of deforestation has been high when compared to other countries. Detailed studies on the relation between land use changes and soil erosion are scarce for Ethiopia. There exist only four studies for some parts of the Ethiopian Highlands (Bewket, 2002; Bewket and Sterk, 2005; Hurni et al., 2005; Tefera and Sterk, 2010).

Bewket (2002) focused mainly on land use change and concluded that while it has an important influence on soil erosion, the percentage of vulnerable land (land without permanent vegetative cover) remained constant between 1957 and 1998 in the Chemoga watershed. He concluded, however, that this is not representative for other parts of Ethiopia. Bewket and Sterk (2005) focused mainly on hydrology and how it has been influenced by land use change in the Chemoga watershed. An erosion survey was also performed combined with an analysis of the land use change. They concluded that especially a decrease in infiltration and thus an increase in surface runoff due to land use change could increase soil erosion. Hurni et al. (2005) also concluded that in the upper Blue Nile basin in Ethiopia the population increase led to intensification of agricultural land use and thus increased runoff. This could lead to an increase of soil erosion. Tefera and Sterk (2010) focused on the effectiveness of soil and water conservation measures. An erosion survey was executed which showed that both crop type, slope and soil texture influenced soil erosion. They concluded that in the Fincha's watershed, slope and land use type have an important influence on soil erosion and rill density after precipitation events. In their study only fields with annual crops were however surveyed. None of the above mentioned studies focused on the direct influence of land use change on soil erosion while it was frequently mentioned as an important influence. The influence of land use change on soil erosion and thus land degradation is therefore unknown in many regions. The aim of this research project was to determine the influence of land use change and land management on soil erosion in the Genale river catchment within the Sidama zone in Ethiopia.

The specific objectives were:

1. Create land use maps for different time periods to investigate land use changes.
2. Quantify soil erosion and relate it to land use, topography and soil characteristics.
3. Investigate possible relations between soil erosion, land use, land use change and land management using modeling.

2 Site Description

The Southern Ethiopian hydrological system is highly influenced by two rivers; the Genale and Dawa rivers. Part of the basin of the these rivers lays within the Sidama zone, a 50,000 km^2 area with Awassa as its capital. The population of the zone is estimated to be approximately 2.1 million with a population density of 451.8 people per square kilometer (CSA, 2013). This research was conducted within the upper part of the Genale river catchment within the Sidama zone (1).

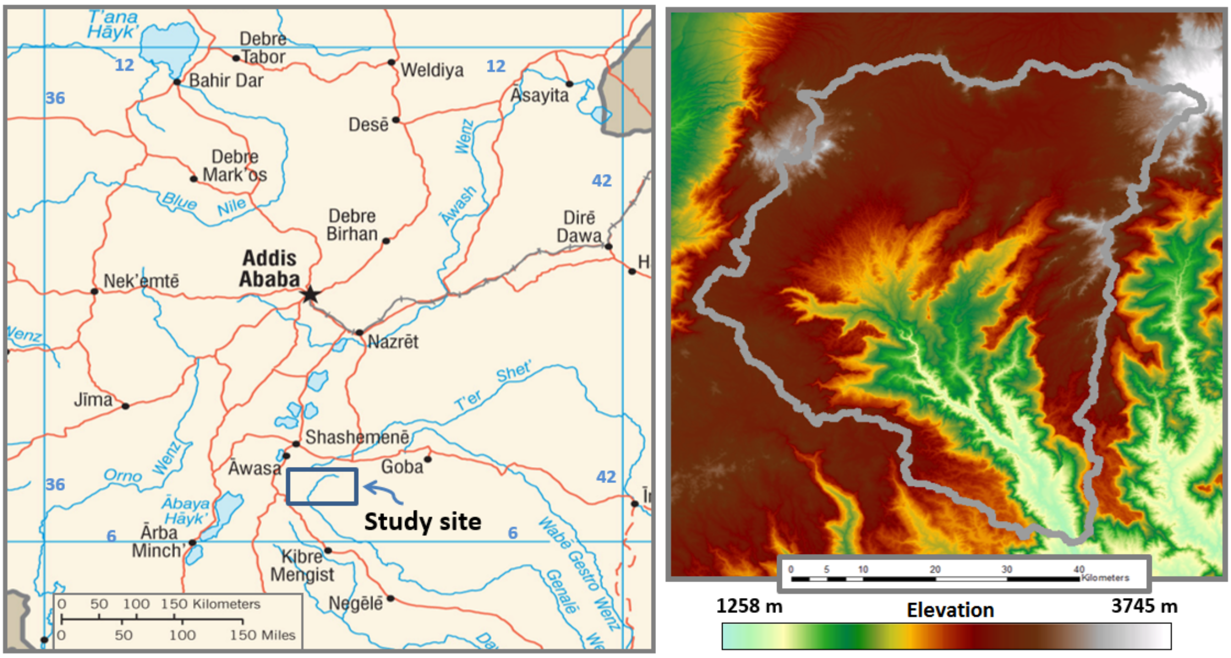

Figure 1: The location of the upper Genale catchment within Ethiopia and a digital elevation model of the study site.

The Genale river has its origin in the Ethiopian highlands, nearby Awassa. It receives the vast majority of its water from the Sidama and Bale highlands. The study site is the upper Genale basin, which covers the districts: Arbegona, Bensa and Bona Zuria. The Genale river originates near the great Rift Valley and flows from the northwest to the southeast (Grab, 2002). It has a total basin area of approximately 172,000 square kilometers and a length of nearly 860 km (CSA, 2012). The altitude of the study site varies between 1,258 and 3,745 meters above sea level. Altitudes of the surrounding province vary from 800 meters to up to 4,600 meters (CSA, 2013). A Digital Elevation Model (DEM) is given in Figure 1. The slopes are reported to be steep within the Ethiopian highlands (World bank, 2004). The average slope of the catchment is 9.57 degrees. Of the total area, 33 percent has a slope between 8 and 15 degrees, 16 percent has a slope between 15 and 30 degrees and 1 percent has a slope above 30 degrees. From the districts that form the study site, the Arbegona district is the highest, with altitudes between 2600 and 3700 meters. The Bona and Bensa districts are lower, going down to 1500 meters above sea level. The dominant crops in the catchment are coffee (Coffea arabica), enset (Ensete ventricosum) and annual crops such as maize (Zea mays L.) and sugar cane (Saccharum officinarum

L.). The coffee is grown in agroforestry systems with trees providing shade to the coffee shrubs. Due to the higher altitude, no coffee is grown in the Arbegona district since temperatures are below the necessary climatic conditions for coffee growth.

A variety of climate systems exist within the zone, with various levels of rainfall and diverse land use characteristics throughout. Within the study site the average temperature ranges between 19 and 26 degrees Celsius. Annually, temperatures in the lower altitudes vary between 23 and 30 degrees Celsius and temperatures in the higher altitudes range between 15 and 20 degrees Celsius (CSA, 2012). The annual precipitation in the catchment varies between 1200 and 2000 mm with an average of 1700 mm. The climate at the study site is dominated by one dry (Nov - Mar) and one wet season (Apr - Oct) (Figure 2). Between April and May a the first and minor part of the rainfall season takes place, after which the more intense part of the rainfall season happens between June and October. The dry season lasts from September until February. Within the rainfall seasons the temperatures go down. Because of these climatological properties, conditions for vegetation are favorable and agricultural potential is high (NMA, 2014).

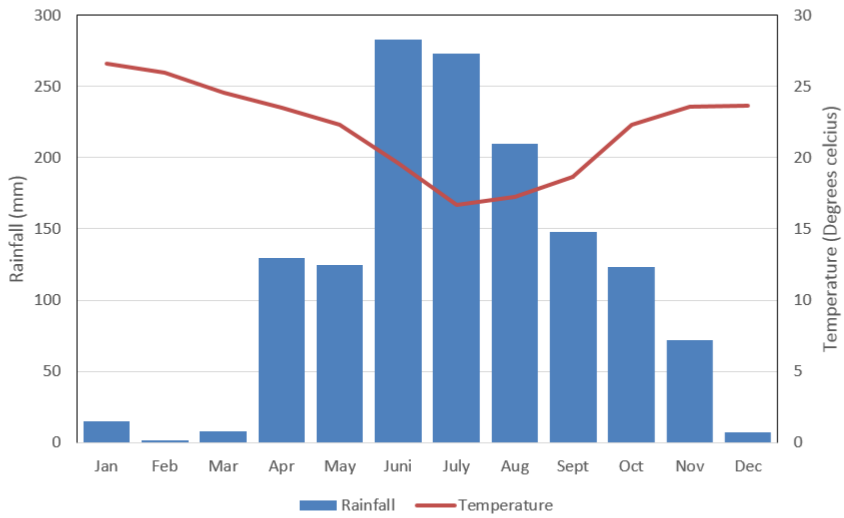

Figure 2: Monthly rainfall and temperatures averaged for the last 15 years in the upper catchment of the Genale river, Southern Ethiopia.

The local economy is mainly based on subsistence farming. Enset forms the staple crop and the main cash crops are coffee and annual crops. The local farms are responsible for the high presence of agroforestry (World Bank, 2004). While the generally impoverished people have no financial means to pay for soil erosion control measures, substantial humanitarian aid is present in Ethiopia. Therefore, some control measures have been constructed, and possibilities of implementing more of these measures do exist within the area (FAO, 2014).

3 Materials and Methods

3.1 Land Use Changes

Since no detailed land use maps existed for the study site, such maps were created to use for both the modeling and analysis of land use change in the region. In order for classification to work correctly, images with a spatial resolution appropriate for the spatial variability of land use are needed (Woodcock & Strahler, 1987). A resolution of 30 meters was chosen since this has been used successfully in other research in similar regions (Reid et al., 2000; Teferi et al., 2010). Landsat TM and ETM+ images with this resolution and at least 5 spectral bands were available since 1985 (USGS, 2015). To examine the change in land use, images from four different moments in time were used. Images from February had minimal cloud cover and were available for a sufficient number of years. Images where the study site was best visible, with a maximum cloud cover of 10 percent, were available from February 1985, 1993, 2003 and 2015.

To compare spectra from different sattelite types, radiometric consistency is required (Vincente-Serrano et al., 2008). Radiometric calibration was therefore performed using the equations of Vogelmann et al. (2001). Atmospheric correction was performed with the Quick Atmospheric Correction Code (QUAC) developed by Bernstein et al., (2012). Both the calibration and the classification methods were available in the ENVI remote sensing software package (ITT Visual Information Solutions SA, 2008).

When terrain is rough, the illumination changes due to a difference in angle between the sun, the surface and the sensor (De Jong, 2004). To correct for these illumination changes a correction was performed. For this research the c-correction model was applied. This empirical model is based on reflection of both diffusive and direct light and is location dependent (Teillet et al., 1982). Other models exist but the c-correction was used as the method has been shown to give the best results for most Landsat images (McDonald et al., 2002; Riano et al., 2003). The c-correction is based on the following procedure: For each band n, a regression line through all the combined digital numbers and incident angles is fitted:

$$DN_n(i) = b_n + m_n i \tag{1}$$

Where DN is the Digital Number value for the reflection of light for the n^{th} band, i is the sun's incident angle (angle relative to surface normal), b_n is the interception of the regression line, and m_n is the slope of the regression line. This gives an approximate linear relation between the illumination and the incident angle. The correction that was done using this relation is as follows:

$$Lh_n = Lr_n(\frac{cos(a_{ze}) + \frac{b_n}{m_n}}{cos(i) + \frac{b_n}{m_n}}) \tag{2}$$

Where Lh_n is the illumination a horizontal surface would have, Lr_n is the illumination on the sloped surface, and a_{ze} is the sun's zenith angle (angle relative to the normal vector of an horizontal surface). The incident angle is calculated from the slope and solar angles:

$$cos(i) = cos(a_{ze})cos(s) + sin(a_{ze})sin(s)cos(a_{az} - a_{as}) \tag{3}$$

Where s is the slope angle of the surface, a_{az} is the azimuth angle of the sun, and a_{as} is the aspect angle of the surface. All the corrections on the used remote sensing images were accomplished with the exclusion of clouds from the image as they have a negative effect on the

Table 1: The land use types used for classification of the Landsat satellite images

Land Use Class	Description
Forest	Dense tree cover, high leaf cover percentage. Forest should cover more than 80 percent of the surface.
Grassland	Areas covered with grass. Forest or bushes may only cover up to 20 percent of the surface.
Agroforestry	Combination of enset, coffee and annual crops. All three must at least cover 80 percent of the surface. For agroforestry the combination of the crop and trees in between must cover at least 80 percent of the surface.
Enset	Enset trees
Coffee	Coffee plants, often mixed with trees to provide shade.
Annual crops	Any crop that causes the land to lie bare at least once a year. Mainly maize, sugar cane and chad.
Water	Area completely inundated by water.
Bare soil	Barren land, maximum 20 percent surface cover by grass or trees.
Town	Urban land use, roads and bare soil used for markets are included.

performed algorithms (De Jong, 2004). The sun's zenith and azimuth angles were provided with the meta-data from the Landsat satellite images used. For the DEM, the Aster world-wide 90 meter digital elevation model was interpolated to 30 meters resolution. From this digital elevation model both the slope and the aspect angle have been calculated. Research by Gao and Zhang (2009) showed that the use of a down-scaled 90 meter resolution DEM for Landsat correction is possible and has successfully given similar results when compared to a real 30 meter DEM.

The land use maps were created by using a supervised classification on remote sensing images. The spectral angle mapping, minimum distance, maximum likelihood and spectral information divergence methods were tested (Sabins & Lulla, 1987; De Jong, 2004). For validation and comparison of accuracy both the confusion matrices and the kappa coefficients were used. The kappa coefficient is calculated from the confusion matrix (De Jong, 2004):

$$\kappa = \frac{N \sum_{i=1}^{n} -m_{i,j} \sum_{i=1}^{n}(G_i C_i)}{N^2 - \sum_{i=1}^{n}(G_i C_i)} \tag{4}$$

Where κ is the kappa coefficient, N is the total number of pixels being classified, $m_{i,j}$ is the amount of pixels belonging to class i and classified into class j, G_i is the total number of classified pixels belonging to class i and C_i is the number of ground truth pixels belonging to class i. The spectral angle mapping method showed the highest accuracy and was therefore used.

The classes that have been used for the classification process, and their descriptions are given in Table 1. These types of land use have been observed to be present in Ethiopian highlands by other research (Zeleke & Hurni, 2001; Bewket 2002). The agroforestry class was subdivided into enset, coffee and annual crops since these were mainly grown throughout the study site. Other types were assumed to be present in such a way that they can be neglected in the classification process.

To calibrate and validate the classification process, land use observations were done. For the most recent image, control points were established on site. At least 20 control points were used for each class, which resulted in 328 control points. Using these points, groups of pixels were selected, of which the class was known. After half of these pixels were used to create sample spectra for all the classes, validation was done using ground truth polygons created from the other half. In order to further validate the generated land use map, a total of 10 transects of 2 kilometer length were taken throughout the catchment, observing land use. Because the use of ground truth polygons is only possible for a recent image, the older images from 1985 and 2003 were classified using the same sample groups as were used for the 2015 image. Calibration of the older maps was done with information considering land use history from elderly farmers in the study site. For this, informal interviews were held with ten elderly farmers who have lived in the study area for more than 25 years. The farmers were asked questions referring to the history of the land use of both their own fields and the area in which they lived. For the older maps to be in accordance with the information from elderly farmers, thresholds were set for the spectral angle mapper. These thresholds limited the spectral difference that a pixel could have with a sample group, while still being able to be classified to that group. Effectively this can shift the percentages of land use classes, distributing pixels without classification to their second most likely land use class combined, the four land use maps have been used to analyze land use change and the influence on soil erosion in the erosion model. To analyze the the causes of land use change, the distribution of land use classes over multiple slope classes was analyzed for each created land use map.

3.2 Soil Erosion Assessment

In order to relate land use change to land degradation, soil erosion measurements were done in the field. Soil erosion was quantified by using the assessment of current erosion damage (ACED) method by Herweg (1996). This method is based on surveying erosion features such as rills and gullies. By measuring the amount of features and their average depths, widths and lengths, the total eroded volume is estimated. The forms that are provided in the method were used for the survey. The possible presence of water and soil conservation measures is also noted. Herweg (1996) states that the following assumptions underlay the ACED method; 1) Sheet and splash erosion are assumed to have such a small contribution to sediment yield that they can be neglected. 2) Rainfall must be mostly concentrated in intense events and not evenly distributed throughout the year. Since the method was tested and created partially in Ethiopia, it is mentioned that the assumptions are correct for most parts of that country (Herweg, 1996). This includes the study site of this research.

The survey method was applied on 62 fields. These fields were located in the middle and lower district within the study site. This way all four dominant land use types were present: enset, coffee, annual crops and grazing land. In order to relate soil erosion to topography and soil characteristics, these properties were variable for the 62 fields. The 62 fields were evenly distributed over the following slope classes:

- Very steep (> 20%)
- Steep (10% - 20%)
- Moderately steep (5% - 10%)
- flat (0% - 5%)

The inclination of slopes was determined by using a set of marked poles combined with an inclinometer. Each combination of land use and slope class had 4 fields, except enset, for which 2 fields with a very steep slope and 6 fields with a steep slope were used.

Average width and length of the fields was approximately 30 meters. The total surveyed area was thus 5.7 ha. The length of rills was measured from their starting point to the end of the field, or the point of sedimentation. If a smaller rill joined a larger rill, the volume of the smaller rill was estimated from the starting point to the point where the rill entered the larger rill. Since rills change in depth and width, averages of multiple measurements were taken for each rill. The width was measured at 1 to 5 points along the length of the rill. For each of these points the depth was measured between 1 and 5 times along the intersection of the rill at that point. This was necessary to obtain a good average value for depth. The number of measurements depended on the actual width and length. The measurements for the volume of the eroded soil were done twice between March and May 2015 for every field. Similarly to other studies, one month was chosen to be between the measurements (Tefera & Sterk, 2011; Bewket & Sterk, 2003). Since erosion features might be removed due to tilling of the fields, the farmers were asked to report the dates when tillage happened. The eroded volume was then measured for the days following the date of tillage.

3.3 SWAT Modeling

The SWAT (Soil & Water Assessment Tool) model is a public domain modeling tool that simulates hydrological systems and soil erosion. In a second master research, De Gier (2015) implemented the SWAT model for the same study area. He calibrated and validated the model using discharge data of the Genale river, and focused only on the hydrology of the catchment. In the current study the validated model was used to quantify erosion in the upper Genale catchment. To use the hydrological model, ArcSwat, a SWAT version integrated in Arcmap software, was used (Winchell et al., 2007; Esri, 2009). Since SWAT does not include the entire hydrological cycle in its model but merely a catchment leading to a certain user-defined outlet point on a river, input and output fluxes for this area were needed. During conversion into the model the study area was divided twice. First subcatchments were created based on topography and the stream network. Each subcatchment leads to a single reach of the Genale river. Within each subcatchment a division was made into hydrological response units (HRU's). These exist out of all combined areas that have the same soil type, slope class and land use type. SWAT uses a water balance equation for each layer in every HRU. These layers are, from top to bottom: the unsaturated top layer, subdivided into a root zone and a rootless unsaturated zone, the shallow unconfined aquifer and the deep confined aquifer (Arnold et al., 1996).

For the water content in the unsaturated zone, every HRU uses the following equation (Arnold et al., 1996):

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day,i} - Q_{surface,i} - E_{a,i} - W_{seep,i} - Q_{lat,i}) \quad (5)$$

Where SW_t and SW_0 are the final and initial water storages in the unsaturated zone of the HRU (mm), R_{day} is the daily rainfall (mm), $Q_{surface}$ is the daily runoff in mm, E_a is the actual daily evapotranspiration (mm), W_{seep} is the daily outflow of water out of the unsaturated zone into the shallow unconfined aquifer (mm), Q_{lat} is the daily amount of lateral outflow (mm), and t is the time (days). For each component of the water balance a routine is used. For runoff, which is highly influential on erosion, the soil conservation service curve number (SCS-CN) and Manning's equation for water flow are used (Arnold et al., 1996). For other layers, such as the shallow unconfined aquifer, terms are similar but involve groundwater flow and deep groundwater recharge. These are simulated using a base flow recession constant (Arnold et al., 1996). Sediment deposition or degradation in a channel is also included in the model. Which one of these occurs depends on the ratio between the sediment capacity of the channel and the incoming sediment load.

To model soil erosion, the SWAT model uses an HRU based approach. For this the modelled area is divided into sub-catchments which are assumed to behave in a similar way and can thus be approximated using the equations in the model. In order to calculate sediment yield (soil loss in a certain region) the Modified Universal Soil Loss Equation (MUSLE) is used. This equation is defined for a single HRU as (Williams, 1975):

$$SE = 11.8 * (Q_{surface} * q_{peak} * A_{HRU})^{0.56} * K * LS * C * P * CFRG \quad (6)$$

Where SE is the total sediment yield for a given day in the HRU ($10^3\,kg$), $Q_{surface}$ is the surface runoff volume ($mm\,ha^{-1}$), q_{peak} is the peak runoff rate ($m^3\,hr^{-1}$), A_{HRU} is the area of the hydrological response unit (ha), K is the soil erodibility factor ($0.013 * 10^3\,kg\,m^2\,hr$) ($m^3\,10^3\,kg\,cm)^{-1}$, LS is the topographic factor (-), C the cover and management factor (-), P the support practice factor (-), and $CFRG$ the coarse fragment factor (-). Because of the HRU-based approach to soil erosion, sediment is routed directly from the fields to the reach within the same subcatchment. Because of this, no deposition can occur within the simulation.

The difference with the original Universal Soil Loss Equation (USLE) is the term related to the strength of the erosive force (Wischmeier & Smith, 1960). Instead of rainfall, surface runoff is used to drive the soil erosion process. From the factors in the MUSLE equation, only the management related factors C and P were estimated for the study site. Both the physical and the runoff factors were estimated from the DEM, land use map or the output from the hydrological part of the model. The management and support practice factors were estimated from research by Stone and Ontario (2000). They created tables of values for a variety of tillage practices, tillage directions and management practices. Research has shown that the empirical formula used for the topographic factor of the MUSLE equation, which was derived using slopes below 9 °, does not compare well with experimental data for slopes steeper than 9 °(Liu et al., 1994; Liu et al., 2000). In the study site more than a third of the area has a steeper slope than was used to develop the MUSLE topographic factor (Williams, 1975). The Revised Universal Soil Loss Equation (RUSLE) uses a different topographic factor which is more accurate for steeper slopes (Liu et al., 2000). Since this topographic factor is not a part of the SWAT model, it was manually calculated and used in the erosion calculations. The RUSLE topographic factor was calculated with the following equations (McCool et al., 1987):

$$LS = L * S \quad (7)$$

where L is the length factor (no unit) and S is the slope factor (no unit).

$$L = (\frac{\lambda}{22.1})^{\frac{\beta}{1-\beta}} \quad (8)$$

Where λ is the horizontal length of the field in the direction of the steepest slope (meter) and $\frac{\beta}{1-\beta}$ is the ratio between rill and non-rill erosion (no unit). This ratio is given by:

$$\beta = \frac{sin(\frac{\theta}{0.0896})}{3sin(\theta)^{0.8} + 0.56} \quad (9)$$

Where θ is the slope angle. Furthermore:

$$S = 10.8sin(\theta) + 0.03 \ (\theta \leq 9°) \tag{10}$$

$$S = 16.8sin(\theta) - 0.50 \ (\theta > 9°) \tag{11}$$

The values for these factors were calculated using the built-in tools from the Arcmap software (Esri, 2009).

The methods that are used by the SWAT model need weather conditions for the entire study site. Rainfall was measured throughout the fieldwork period by two already present rain gauges. Because of the use of daily weather data, the simulation was set to also use daily time steps. In order to provide the model with all the soil parameters and land use properties that were required for the MUSLE equation, the created land use and soil maps were reclassified using soil and land use classes from the built-in SWAT library. For the parameters canopy height, leaf cover, leaf area index, root dept and plant density, the values from the SWAT library were checked against the values that were gathered during the erosion survey.

In order to calibrate the erosion model, the calculated erosion values were compared with the erosion measurements. Based on this the model parameters were changed to minimize the difference between the measured and modeled soil erosion values. To determine which parameters had to be altered, a sensitivity analysis was performed. Since the hydrological part of the model was calibrated by de Gier (2015), only parameters directly influencing erosion were considered. The parameters that the model was the most sensitive to, and that also had the highest uncertainty, were changed. Erosion was not measured for steeper slopes than 30 degrees and other land use types than annual crops, grazing land, enset and coffee. Due to this, areas with these properties cannot be directly calibrated. An average of the calibrated parameters was used for other land uses and the areas with a slope above 30 degrees were given the same slope factor as the steepest calibrated slope class.

For the comparison, an average of the measurements that matched the slope class, land use type and soil type of an HRU within the same subcatchment was used. As an error function the Root Mean Square Error (RMSE) was used (12):

$$RMSE = \sqrt{\frac{\sum_{i=0}^{n}(x_{i,obs} - x_{i,mod})^2}{n}} \tag{12}$$

Where $x_{i,obs}$ is the observed value, $x_{i,mod}$ is the modelled value and n is the number of observations.

For calibration of the erosion part of the model, half of the gathered data form the erosion survey was first used. After that, validation was done using the other half. As a significance criteria, $p = 0.05$ will be used. After the performance of the model was validated, it was calibrated for the entire data set. Both the calibration and the validation were done using the SWAT-CUP software, which allowed for use of automated calibration by Sequential Uncertainty Fitting (SUFI-2) routine (Abbaspour et al., 2007).

After calibration and validation, the erosion model was executed for the four created land use maps to relate the land use change in the study site to the soil erosion determined by the model.

For the calibration and validation, weather data from the months of the survey was used. All other simulations were performed with the weather conditions from 2007 (de Gier, 2015). With a total rainfall of 1650, that year showed a distribution of rainfall close to the average. Finally a future scenario was made where both the land use change of the past 10 years, and the change in distribution of land use over slope classes were continued. A program was written in Wolfram Mathematica in order to do this. The statistics of land use change between 2003 and 2015 were used to calculate chances for pixel conversion. Pixels neighboring to a certain class were set to have a higher chance to be converted to that same class.

4 Results and discussion

4.1 Land Use

The resulting land use statistics and land use maps, that were created with the spectral angle mapper method using images from 2015, are given in Figure 3 and Table 2. Land use and land use change percentages are given as percentage of the total catchment area.

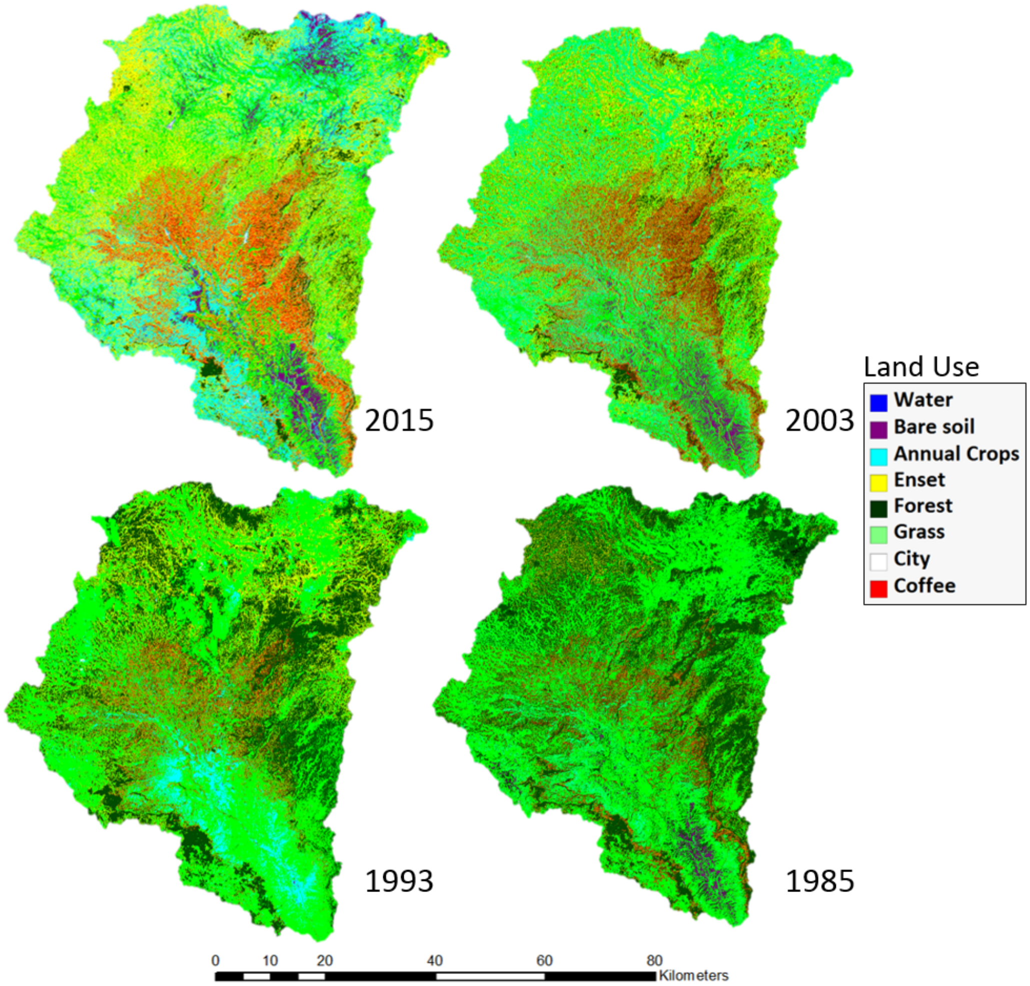

Figure 3: Land use maps for the upper Genale catchment, Southern Ethiopia, for the years 1985, 1993, 2003 and 2015.

Table 2: Land use distribution and change for the upper Genale catchment, Southern Ethiopia, for the years 1985, 1993, 2003 and 2015.

	Area in 1985		Area in 1993		Area in 2003		Area in 2015		Change		
									1985	1993	2003
Land Use Class	%	10^3 Ha	%	10^3 Ha	%	10^3 Ha	%	10^3 Ha	1993	2003	2015
City	0.0	5.6	0.0	12.3	0.1	16.7	0.1	47.4	0.02	0.01	0.10
Forest	39.5	12636.8	29.6	9474.0	13.3	4255.9	5.8	1845.5	-9.90	-16.33	-7.54
Grass	48.9	15623.5	48.4	15481.5	40.6	12969.8	26.7	8529.7	-0.44	-7.86	-13.89
Bare Soil	1.2	385.8	0.0	4.9	2.1	660.8	4.6	1470.1	-1.19	2.05	2.53
Enset	5.2	1660.9	13.6	4360.0	24.2	7733.5	36.0	11490.8	8.44	10.55	11.76
Annual Crops	2.3	723.8	4.8	1534.1	12.2	3909.5	19.0	6064.9	2.54	7.43	6.74
Coffee	2.9	926.1	3.4	1095.6	7.6	2416.4	7.9	2514.0	0.53	4.13	0.30

4.1.1 Calibration and Validation

The validation results for different types of classification methods for the most recent satellite image are given in Appendix A. The c-correction that was applied changed the kappa coefficient of the land use map from 0.74 to 0.83. The confusion matrix for an uncorrected classification is also given in Appendix A. The spectral angle mapper method performed optimal within the study site. The confusion matrix for the resulting land use map for 2015 is given in Table 3.

Table 3: Confusion matrix for the spectral angle mapper classification of the 2015 image of the upper Genale catchment, Southern Ethiopia, with a kappa coefficient of 0.83

Land Use Class	Bare Soil	Annual Crops	Enset	Forest	Grass	City	Coffee	Total
Bare Soil	14	0	0	2	0	5	0	21
Annual Crops	1	11	1	3	1	8	1	26
Enset	0	6	15	16	5	0	6	48
Forest	0	0	0	160	0	0	0	160
Grass	0	1	3	11	19	0	0	34
City	0	0	0	2	0	20	0	22
Coffee	0	8	1	7	4	1	7	28
Total	15	26	20	200	29	25	14	328

The kappa coefficient of 0.83 indicates that the pixels were generally classified correctly. Generally a minimum value of 0.8 for the kappa coefficient is used as a criterion for a good classification process (De Jong, 2004). Since no inundated areas were detected within the catchment, the water land use class was omitted from the results. Without this class, 75 percent of all the pixels were classified correctly. The least accurate land use type in the classification was coffee for which only 56 percent was correctly classified. Within the catchment, especially the strong presence of agroforestry with coffee and enset causes spectral similarity of the both these classes and forests, leading to classification errors. The combination of forest, enset and coffee however performed above average with 76 percent of pixels being correctly classified. In general, both the strong presence of trees and the highly mixed nature of land use/cover in the catchment due to the small farm size complicated the process of classification. The vast majority of farms are smallholder farms. Fields with an area of more than 0.25 ha are encountered sporadically and commercial farming is completely absent. For some fields with coffee intercropping systems are furthermore present with, for example, avocado trees. Lastly, the locations of ground truth points were predominantly in the center of the catchment, and thus not ideal for classification of the outer parts.

4.1.2 Land Use Distribution

The main types of land use in the catchment are enset, annual crops and coffee. Annual crops and coffee are especially present surrounding the larger villages within the study site. Most of the farmers live in traditional huts and have some small pieces of land next to their homes with enset and grazing land. The southern part of the catchment is more arid due to higher temperatures and consists mainly of annual crops and bare soil. The northern part of the catchment, which has a higher altitude and is thus cooler, mainly consists of grazing land, enset, forest and annual crops because of this. The western part of the catchment is more mountainous and therefore consists of many of the remaining pieces of forest. While new types of fruits and vegetables such as apples have been introduced in the Sidama zone by organizations such as ILRI, the presence of these is not yet substantial enough to be visible on remote sensing images.

4.1.3 Land Use Change

Land use and land cover have changed dramatically over the past 30 years within the Genale river catchment in the Sidama zone (Figure 3, Table 4). Forest decreased from 39.54 percent in 1985 to 5.77 percent in 2015. Grazing land decreased from 48.88 percent in 1985 to 26.69 percent in 2015. The first large deforestation projects started early in the 20th century. After that there were multiple attempts by the government to replant parts of the national forests but eventually the much more extensive deforestation projects caused a substantial decrease in natural forest. Deforested areas were first converted into grasslands and after 1993, the percentage of grass in the catchment dropped drastically while forest area remained stable. Decrease in grazing land was 7.86 percent between 1993 and 2003 and 13.89 percent between 2003 and 2015. Decrease in forest was 16.33 percent between 1993 and 2003 and 7.54 percent between 2003 and 2015. Grazing land was mostly converted into enset and annual crops.

While the Sidama zone is particularly proud of its traditionally produced and unique varieties of coffee, the growth of the areas that are used for coffee within the catchment has stopped after 2003. Between 2003 and 2015 the area of coffee grew with 0.31 percent while growth between 1993 and 2003 was 4.13 percent. It is losing the previously important role it had as a cash crop due to changes in it's price. Especially chat (Catha Edulis) has increased in popularity by taking on the role as the new cash crop for local farmers. Within the study site chat is grown as an annual crop. Its presence can, however, not be detected from satellite images due to its similarity to other land use classes. Especially new smallholder farms are used to cultivate chat. Consumption of the leaves is said to increase in popularity with the younger generation in the country due to its stimulating properties. Strengthened by the increased presence of chat, annual crops have been growing in popularity rapidly during the past decade. Other important annual or bi-annual crops are sugar cane and maize, which have also thrived between 2003 and 2015. These also take on the role of cash crop for numerous farmers. Annual crops have had an increase from 2.26 percent in 1985 to 18.98 percent in 2015.

Both in the past and in recent years, one of the most important crops grown in the Sidama region has been enset. Praised for its ability to withstand droughts, it is the staple crop of a vast majority of the population (Mohammed et al., 2013). Between 1985 and 2015 the percentage of land dedicated to it increased from 5.2 percent to 35.9 percent. Especially the North of the catchment, where coffee is not able to grow efficiently, the crop is widely produced. The southern part of the catchment has fewer smallholders farmers focused entirely on enset. Generally, however, most households do have at least a small field of enset next to their homes of around 0.05 - 0.15 ha for their own consumption. With the large decrease in area for grazing land in especially the southern part of the catchment, the ability to allow for livestock to graze has disappeared entirely around larger villages. Due to this, the majority of livestock there is fed with enset. During the past 30 years, enset has remained the most important crop in the catchment.

The distribution of land use classes over different slope classes is, for the majority of land use classes, similar to the distribution of slope classes within the entire catchment. Exceptions are, for example, residential areas. As expected they are present substantially more in lower slope classes. While on average the catchment has 49 percent of its area with a slope lower than 8 degrees, 86.5 percent of the residential areas lie within that slope class. The distribution of forest also differs from the total distribution of slope classes. Instead of 49 percent, 27.1 percent of the forest lies on areas with slopes below 8 percent. The percentage of forest on areas with a slope above 15 degrees increased from 16 percent to 37 percent in the last 40 years. This was expected as deforestation is more probable to occur when the remaining soil is more advantageous for cultivation. Annual crops, a growing land use, has increased much in the moderate slopes. Both enset and coffee, also growing land uses, have increased more in the areas with steeper slopes. This is due to the majority of the forest already being removed before enset and coffee had the majority of their growth. Steeper slopes had to be used since most of the more moderate sloped areas with forest were already deforested.

Lastly, due to both the lack of remaining forest and the protection of it by the government, the recent increase in cereals originated mostly from converted grazing land. Due to the lack of available land in the catchment the remaining forest is likely to eventually disappear. Areas with steep slopes have often been last in the area to be deforested and converted into either grassland or smallholder farmland. These areas will gradually be occupied by farms that cultivate popular crops. This would result in a high percentage of fields with annual crops, which have been increasing recently, on steep slopes, which would lead to more erosion and less irrigation potential.

4.1.4 Drivers of Land Use Change

The population of Ethiopia is estimated to have tripled in the past 60 years. Between 1985 and 2015 the population of Ethiopia increased from 41 million to 99 million (UN, 2013). Since population data for the districts within the catchment was not available, population growth is assumed to have been identical to the national increase. Consequences of this are visible in the trend of both a decrease in forest and grass, and an increase in coffee enset and annual crops. A combination of growth of the population and different land use classes within the upper Genale catchment is given in Figure 4.Agricultural land forms the combination of annual crops, coffee and enset.

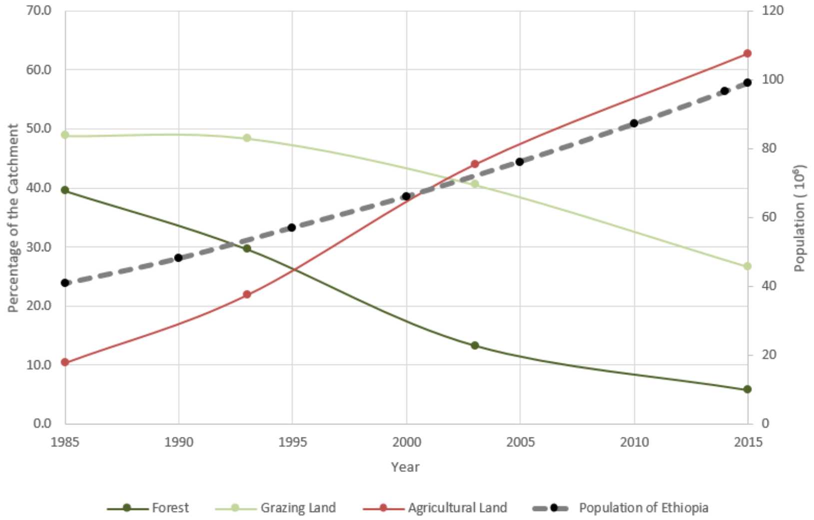

Figure 4: Land use changes in the upper Genale catchment, Southern Ethiopia, compared to population growth in Ethiopia. Population data for Ethiopia from the UN (2013).

The percentage of the catchment used for villages and cities furthermore exhibits exponential growth similar to the estimated population growth in the region. The area of the catchment covered by cities has grown from 0.02 percent to 0.05 percent between 1985 and 2003. After that the area of cities grew to 0.15 percent in 2015, leading to a total increase from 2 to 18 hectares. The land use change in the catchment in the past 40 years thus seems to be driven mainly by population growth.

The amount of bare soil strongly fluctuates between the different moments captured by the land use maps. A possible reason for this could be the presence of more intense dry seasons in those years. Both old farmers and other studies (Hameso, 2014) mention that extreme dry years do take place in the Ethiopian highlands. Severe droughts that lasted for multiple years are said to be the cause of significant migrations, leading to land use change (Reid et al, 2000). In order to investigate the relationship between the presence of droughts and the percentage of dry/bare soil in the catchment the annual averaged rainfall is given together with the dry/bare soil percentage in Figure 5.

Compared to the average rainfall of 1700 mm, 2002, 2003 and 2014 were substantially dryer. While the publicly available data stops in July 2014, from interviews with farmers and data from the Ethiopian National Meteorological Agency it is known that 2014 and the first months of 2015 have been the dryest in twenty years. This complies with the high percentage of bare soil in the 2015 land use map. Therefore, for the land use in both 2015 and 2003, rainfall correlates well with the percentage of bare soil. In 1993 and 1985 no evident correlation is however present. In the land use map of 1993, annual crops are present in areas where they are not detected in 2003. Therefore, the lack of correlation between bare soil and rainfall in these years is probably due to classification errors between bare soil and annual crops.

Other studies in and near the Ethiopian highlands reported similar changes in land use. The percentage of grazing land in the upper Genale catchment has been the subject of a study by Bi-

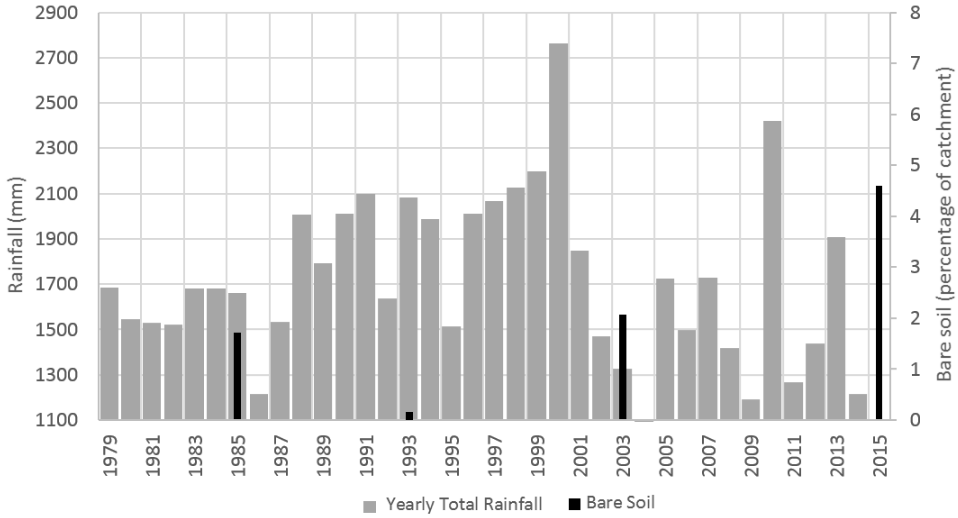

Figure 5: The percentage of the upper Genale catchment, Southern Ethiopia, that was classified as bare soil against total annual rainfall in that area.

azin et al. (personal communication, May 11, 2015). They performed a survey in three districts within the same catchment. These districts take up at least two thirds of the total area. The results from this survey showed that on average, the amount of grazing land decreased by 50 percent between 1994 and 2014. This exhibits a high likeliness with the decrease of 48 percent in the Genale catchment between 1993 and 2015. Similar studies in Ethiopia also point to population growth as a primary driver of land use change (Bewket & Sterk, 2005; Tefera & Sterk, 2008). In a study by Bewket (2002), grazing land decreased in area, similarly to the Genale catchment, in a catchment in the Northern Ethiopian highlands. The area was predominantly converted into farmland. Due to classification errors there was a minor decrease in area of settlements between 1982 and 1998. However, the increase between 1957 and 1982 followed population growth similar to the Genale Catchment. In a similar study in Ethiopia, Zeleke & Hurni (2001) also observed a decrease in natural forest and grassland since 1957. In their catchment residential area and cultivated land increased substantially, as in the Genale catchment, mainly due to population growth. In another similar catchment Tefera & Sterk (2008) observed a decrease in grassland and an increase in cropland. In this catchment grazing land however grew in area from 20.7 to 25.2 percent of their catchment between 1980 and 2001. They state this growth is caused by dynamics between swamp areas, grazing land and the construction of a dam within the catchment. Permanent grazing land decreased in area, similar to the trend in grazing land in the Genale catchment.

Other important drivers of land use change in Ethiopia are said to be policies introduced by the government such as the forest protection policies (Reid et al, 2000; Tesema, 1997). Within the upper Genale catchment, interviews with inhabitants revealed multiple mentions of protection of forested areas against migrating population. The governments forest protection policies, that originated from the derg regime between 1974 to 1987, have been mentioned both to have a negative, and positive effect on forest protection. Tesema (1997) stated that afforestation by the derg regime was more efficient than the more recent projects. Bewket & Sterk (2005) observed that the area of forest increased in their catchment between 1957 and 1998 due to government forest protection and afforestation. Bewket (2002) reported that government policies contributed to the steady increase in area covered with forest. Biazin & Sterk (2013) observed a decrease in dense since 1965 in a much more arid and warm area. Due to government policies and a change in government they observed "severe forest losses". Similar to the Upper Genale catchment, cultivated land took the place of much of the forest there. Grassland was barely present in the catchment they studied and increased slightly. The more gradual decrease in forest within the upper Genale catchment in the last 10 years suggest that the protection of forests is generating results. Between 1985 and 2003 deforestation however took place at an alarming rate, indicating that the protection has only recently been efficient. In other catchments deforestation took place before any aerial photos were made (Bewket & Sterk, 2005). In some regions deforestation is said to have happened before the 20th century (Ritler, 2003). In the upper Genale catchment only a small percentage of the deforestation was reported to have happened before 1985, and a part of these deforested areas were reported by farmers to have been afforested again after government changes.

Other policies that are said to have influenced land use are the resettlement and revillagization policies (Reid et al, 2000). While they state that farmers did not change the area of land they cultivated because of their migration, the population distribution throughout regions changed. Especially the relocation of the majority of the population into villages could result in livestock being kept in close proximity to the villages, causing it to be fed more with enset. This could have helped in the decrease of grazing land in the past 30 years. Revillagization is reported to have happened within Ethiopia in 1986 and in the decades before. Since the decrease in grazing land between 1985 and 1993 is insignificant, smallholder grazing land was most likely left untouched after the revillagization.

Another driver for land use change within the catchment could be climate change. Studies report that temperatures are likely to rise in the Ethiopian highlands. This could mean that the 2400 meters altitude boundary for coffee could shift allowing for more coffee cultivation. While the amount of coffee has risen, no farmers have reported that they were able to grow coffee on higher altitudes. In the future coffee presence might increase due to rising temperatures. Lastly, with the more arid and therefore less inhabitable rift valley nearby, the relatively more fertile Genale catchment is a logical choice for migration. The capital of the province, Awassa, has grown to at least three times its earlier population in only 10 years according to the local government. However, since the catchment is already densely populated, migration could eventually lead to deforestation of the last areas with forests.

4.2 Erosion

The total area of the fields that were visited for the erosion survey was 4.7 ha. The average erosion during the fieldwork was 3.9 $t\,ha^{-1}$ with an estimated rainfall during this period of 120 mm. The average values for erosion for each combination of slope and land use class are given in figure 4. The measured erosion values from the erosion survey, plotted against slope, are given in Figure 6 including regression lines for each land use class. An example of the erosion is given in Figure 7.

Table 4: The average values for erosion for each combination of slope and land use class in the Genale catchment during 5 weeks ($t\,ha^{-1}$).

Land Use Class	Slope Class 0-5°	5-10°	10-20°	20-30°
Grazing Land	0.3	0.1	0.1	0.1
Enset	2.1	0.4	1.4	12.9
Coffee	0.1	1.1	0.9	6.3
Annual Crops	0.2	1.6	8.7	20.7

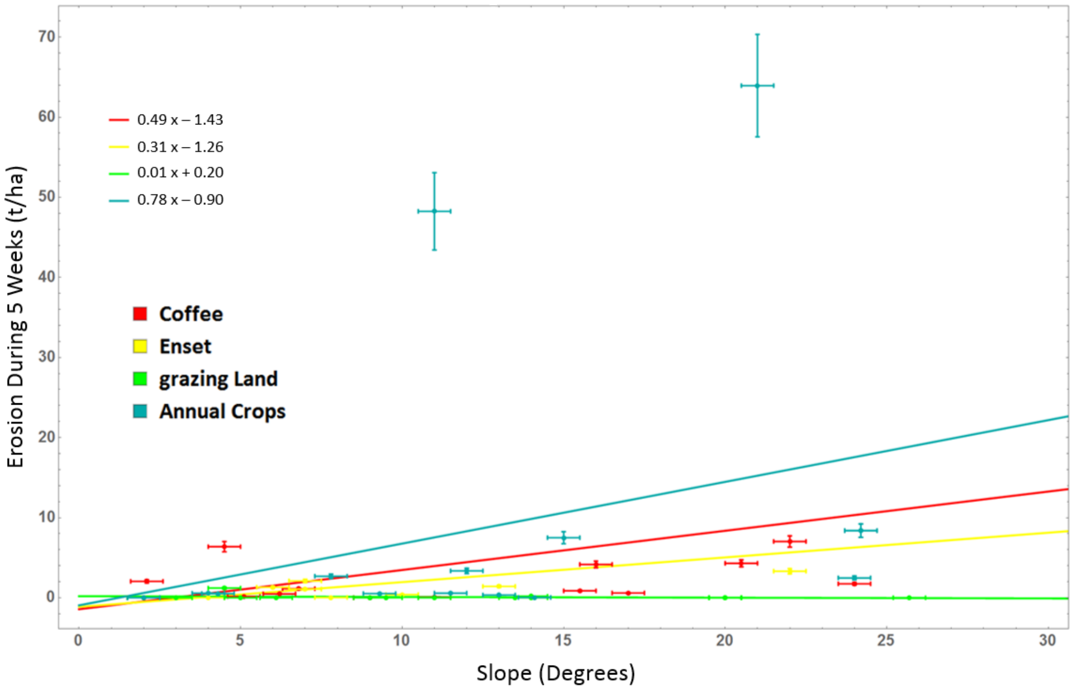

Figure 6: The erosion values, measured on 4 different land uses during 5 weeks, plotted against slope. Regression lines and their equations are included.

4.2.1 Erosion and Land Use

Annual crops have shown the highest amount of erosion with increasing slope. This was expected because the soil is bare for the part of the year after harvesting the crops. The annual crops within the catchment furthermore do not develop sufficient leaf area and root density to efficiently catch rain and prevent erosion. Coffee and enset exhibited less erosion, which can be explained by their much higher leaf area index. Especially enset, with its vertically structured leaves and often fully covering layer of dead leaves on the soil, prevents rain from causing splash detachment. Coffee is frequently planted less densely which allows for rills and gullies to form during intense rain. Coffee and enset furthermore cover the soil more permanently than annual crops. Farmers reported replanting coffee every 25 years and enset every 7 years on average.

As expected, grazing land displayed the lowest amount of erosion. Due to the dense cover and tight roots relatively few erosion features were visible on field with grass as cover. Tillage practices differ throughout the study site. For an estimated 60 percent of the study site tillage is performed. All observed practices were either done by hand or with an ox plow without any regularity or direction. Fields with enset that were recently tilled showed 2.5 t ha^{-1} erosion and the fields that were not tilled showed only 0.3 t ha^{-1} . Besides the removal of dead leaves that cover the soil and reduce the impact of rain, the grass that grows between the plants is removed, reducing soil structure in between the plants.

1) 
2) 

Figure 7: 1) An example of erosion in the Genale catchment. Taken on the 13^{th} of May, erosion features formed in 5 weeks. Width of rills approximately 0.3 meter. 2) An example of soil and water control measures in the Genale catchment. Taken on the 21^{st} of March.

4.2.2 SWC Measures

Existing soil and water conservation measures were present within the study site. Generally, fences made of the Euphorbia Candelabrum, a plant similar to cacti, were able to partly prevent erosion. Some of the fields with annual crops on slopes steeper than 20 degrees applied other methods. Three of the 62 fields that were inspected had these while 18 fields had fences made of Euphorbia Candelabrum. From all the non-annual crops, the fields with fences had an average slope of 7.6 degrees and an average erosion of 0.59 t ha^{-1} during the fieldwork. The non-annual crops without fences displayed an average of 2.9 t ha^{-1} during the fieldwork, with an average slope of 11.6 degrees. Since the increase in slope is more than 3 times as small as the increase in erosion, this demonstrates that the fences prevent a large part of the erosion from flowing out of the fields. Annual crops were only combined with fences at the down-slope border in 2 of the 16 fields. In these cases they were only present for less than 50 percent of the border, making them less effective. The other present measures were contour ditches. In total 3 farms with these measures were identified. These efficiently caught all the eroded soil during the fieldwork. An example of these measures is given in Figure 7. However, only a small part of the annual erosion occurred during the fieldwork and the ditches were already filled to near their maximum capacity. Ditches were, however, well maintained and it is therefore suspected that the efficiency of the ditches stays high during the remaining part of the wet season. Herweg and Ludi (1999) also report the use of these measures in the Ethiopian highlands but suspect more efficient measures are available such as strips of land perpendicular to the slope direction, covered with elephant grass (Pennisetum Purpureum).

4.2.3 Accuracy

During the erosion survey, two field with extreme erosion features were measured. Both of these were yearly crops, lying bare during the dry season, with slopes of 11 and 22 degrees. Due to the minimal cover and steep slopes these fields exhibited up to 62 $\mathrm{t\,ha^{-1}}$ during the survey period. Existing studies of erosion in the Ethiopian highlands report 42 $\mathrm{t\,ha^{-1}\,y^{-1}}$ (Hurni, 1985) and 40 $\mathrm{t\,ha^{-1}\,y^{-1}}$ (Shiferaw & Holden 1999). Hurni reported a annual rainfall of 830 mm (Hurni, 1985), which is substantially lower than for the Genale catchment. The influence of the slope on the erosion can also be seen from Figure 6. An increase is shown for each land use type with increasing slope. The spread of the erosion values is large, especially for annual crops. Because of this, determining the form of the relationship is difficult and a linear fit was chosen. While a trigonometric relationship is often assumed on physical basis and measurements (Weesies et al., 1997), this is not present in the measurements from the survey.

Due to the nature of the research project, the survey had to be conducted before the second and larger rainy season started. This changed the temporal distribution of rain events, since measurements were not done during the entire year, which would have exhibited a different distribution of rain. Therefore the survey might not comply with the assumptions of the ACED method. The majority of rain fell in more numerous events of more gradual intensity. Such a change in distribution could influence the ratio between erosion originating from rills and sheet erosion (Herweg, 1996). During the survey any sign of sheet erosion at the down-slope border was taken into account, this is however far more imprecise. Other research has also discovered a relationship between the proportionality of rill and inter-rill erosion and the intensity and temporal distribution of rainfall events (Liu et al., 2000). The influence of the mentioned effects are however expected to be insignificant and the results conform to similar research projects.

4.3 SWAT Modelling

4.3.1 Calibration and Validation

The variables that the model was most sensitive to, and that were used in the calibration process, are given in Table 5. The same variables have been determined to be the most important in the process of modelling erosion with SWAT by other research (Wu & Chen 2012).

Table 5: The calibration parameters that were used to model erosion in the upper Genale catchment using the SWAT model.

Variable	Description	Slope	Land Use	Soil
USLE_SLP	Slope factor in the RUSLE equation. One of two variables representative of the linear terms.	0°-5°	All	All
USLE_SLP		5°-10°	All	All
USLE_SLP		10°-20°	All	All
USLE_SLP		20°-30°	All	All
USLE_M	Management factor in the RUSLE equation. One of two variables representative of the linear terms	All	Yearly crops	All
USLE_M		All	Grazing land	All
USLE_M		All	Enset	All
USLE_M		All	Coffee	All
USLE_K	Catchment wide scaling of erosion by the soils erodibility factor.	All	All	All

It was assumed that the total uncertainty in erosion was 50 percent. All parameters were therefore given a relative range from 0.8 to 1.15 times their original value. This leads to a combined relative range of 0.5 to 1.5 times the original erosion values. The final calibrated values for all parameters were within their separate ranges indicating that the model does not significantly deviate from the observations. The parameters with the lowest p-value were the RUSLE slope and management terms for the coffee and enset land use classes. The erosion for these land use classes was underestimated by the model. This was caused by the use of land use classes from the default SWAT library. These classes had to be modified more than expected. The plant density, leaf cover and leaf area were all higher than would be representative for the enset and coffee fields that are common in the catchment. This decreased the rainfall hitting the soil, and thus decreased splash detachment in the erosion model. Due to a larger spread of the plants, the leaf area index of 1.15 and 4.5 for coffee and enset were estimated to be 0.8 and 3.5 m^2. With these changes the parameters for these land uses performed within the desired accuracy, and had a p value higher than the significance criteria of 0.05. Comparison of the survey and the results from the model are given in Figure 8 for the calibration and Figure 9 for the validation.

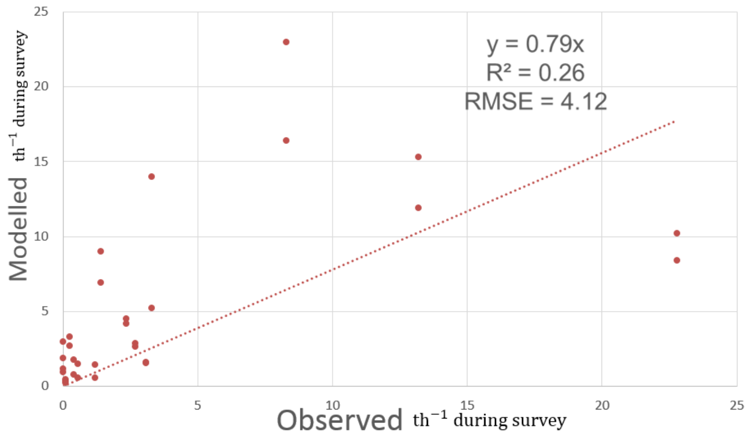

Figure 8: Comparison of the predicted soil erosion by the SWAT model to half of the measurements for the upper Genale catchment for calibration.

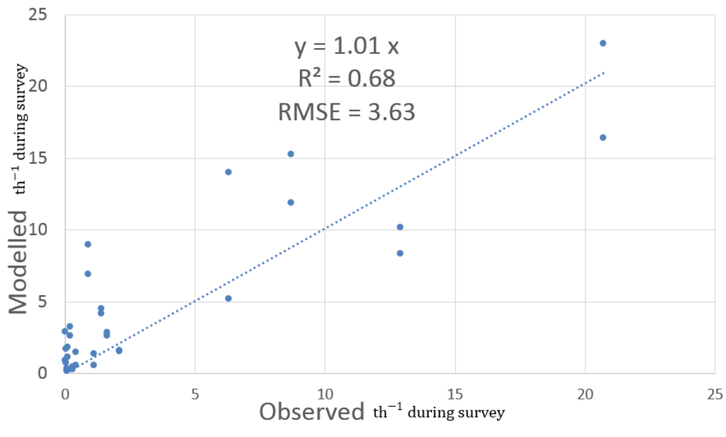

Figure 9: Comparison of the predicted soil erosion by the SWAT model to half of the measurements for the upper Genale catchment for validation.

The average modelled erosion during the survey period was 4.94 t ha^{-1}. The calibrated model showed an RMSE of 4.12 t ha^{-1} , and a regression line with a slope coefficient of 0.79, which indicates a good likelyness between modelled and observed data. Validation gave a better comparison, with a RMSE of 3.63 and a slope coefficient of 1.01. For the full dataset, the RMSE is 3.17 t ha^{-1}. While the predicted values show some spread, both the linear relationship, and the correct slope of this relationship are evident within the validation of the model, indicated by a slope coefficient of 1.01, and an R-squared value of 0.68. This means that both the spatial patterns and the erosion values are generally predicted accurately. The most noticeable relative errors are present where erosion was simulated lower than observations. This is presumably partly due to the distribution of rainfall events during the measurement period.

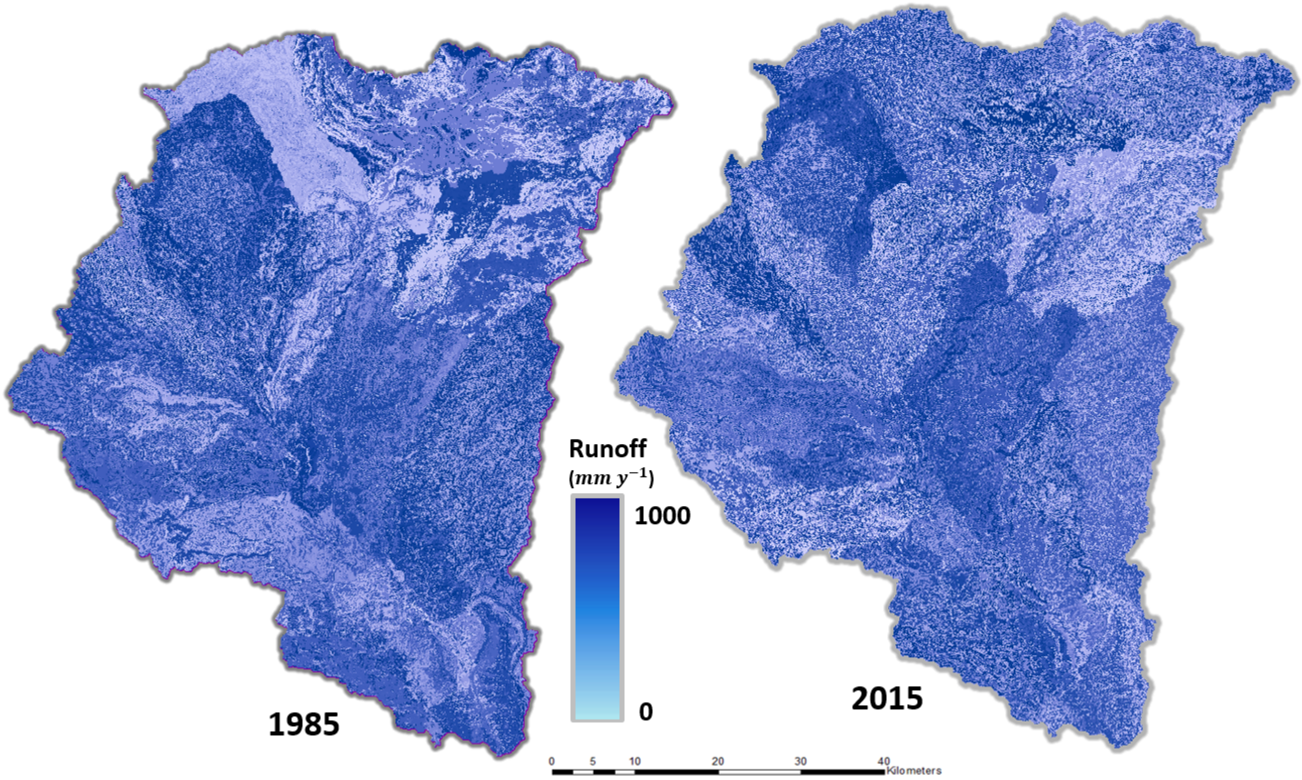

Figure 10: Modelled runoff for the upper Genale catchment for the years 1985 and 2015.

4.3.2 Surface Runoff

To investigate whether the spatial patterns in the increase in erosion were caused by runoff changes or directly by the change in parameters associated with different land use types, the runoff was plotted for 1985 and 2015 (Figure 10). The average annual surface runoff in the Genale catchment increased from 444 mm to 546 mm. While runoff in the main valley of the catchment was not significantly influenced by land use change, runoff in other parts changed substantially. Especially the most northern part of the catchment showed an increase in annual surface runoff and a change in its spatial distribution. Cultivated land has been reported to cause between 5 and 30 times as much runoff as forested areas and 10 times as much as grass covered areas (Hurni, Tato & Zeleke, 2005). Due to the decrease in grazing land, the most northern sub basins display up to double the amount of runoff. Two smaller regions in the center of the catchment also exhibit a similar increase in runoff due to a large decrease in grazing land. The majority of the grazing land in these sub basins was converted to yearly crops. Furthermore, an increase in runoff due to traditional Maresha ploughing practices has been reported (Temesgen et al., 2012; Biazin et al., 2011). Maresha ploughing was shown to reduce the infiltration rate, and thus increase surface runoff. Because the majority of farmland in the Genale catchment is ploughed either with this traditional method or by hand, both giving similar results in soil structure, this could potentially be one of the important factors that cause erosion.

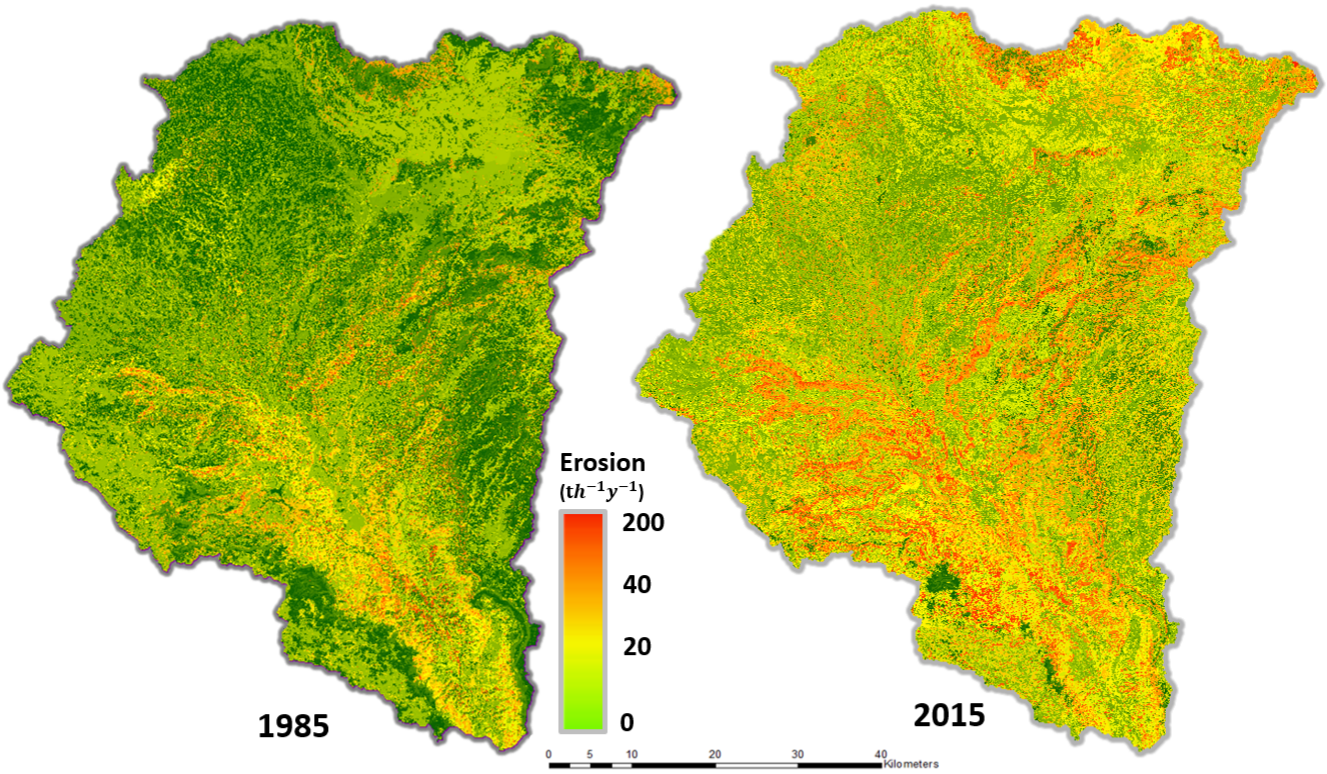

Figure 11: Maps depicting modelled erosion by the SWAT model for the upper Genale catchment, southern Ethiopia, for the years 1985 and 2015

4.3.3 Erosion

The maps with predicted erosion for the years 1985 and 2015 are given in Figure 11. The erosion maps for all other time-periods are given in appendix C. The erosion-map for 1985 has a range from 0 to 160 and an average of 13.8 $\mathrm{t\,ha^{-1}\,y^{-1}}$. The 2015 erosion map has a range from 0 to 200 $\mathrm{t\,ha^{-1}\,y^{-1}}$ and an average erosion for the catchment of 41.0 $\mathrm{t\,ha^{-1}\,y^{-1}}$. An overview of the modeled average values for erosion in the past and the future are given in Figure 12. Comparable to the increase in agro-forestry and agricultural land, the trend shows a shape similar to the population increase in the Ethiopian highlands. With an increase from 13.8 to 41.0 $\mathrm{t\,ha^{-1}\,y^{-1}}$, the erosion has risen by 190 percent between 1985 and 2015. Erosion values above 10 $\mathrm{t\,ha^{-1}\,y^{-1}}$

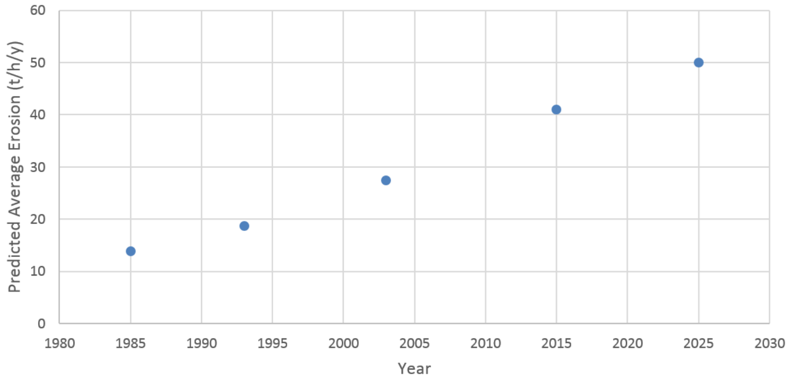

Figure 12: Modeled erosion values, between 1985 and 2025, averaged for the upper Genale catchment.

can be categorized as high, above 20 $\mathrm{t\,ha^{-1}\,y^{-1}}$ as very high and above 40 $\mathrm{t\,ha^{-1}\,y^{-1}}$ as severe (Singh et al., 1992). The erosion in study site in 1985 can thus be classified as high on average, while the 2015 map would almost completely fall into the category very high or severe. In the future scenario for 2025, the land use change trends from the past 12 years were continued with 28 percent annual crops, 11 percent coffee, 46 percent enset and 13 percent grazing land. For this land use, an average soil erosion of 50.0 $\mathrm{t\,ha^{-1}\,y^{-1}}$ was predicted. This is an increase of 263 percent compared to 1985. Both the details and large-scale patterns of the spatial distribution of erosion have furthermore substantially changed. In the 1985 erosion map only the main valley shows an increase in predicted erosion values. In 2015 two main regions within the catchment are notable due to their high values: The main valley in the south and the north-eastern higher region of the catchment.

The average modelled erosion throughout the study site in 2015 agrees with reported values from other studies. Shiferaw & Holden (1999) reported values of approximately 40 $\mathrm{t\,ha^{-1}\,y^{-1}}$ for the Ethiopian highlands, and for the same area Hurni reported 30 $\mathrm{t\,ha^{-1}\,y^{-1}}$ (1985). Both the SWAT model and the modified universal soil loss equation have been used successfully multiple times before in Ethiopia and around the world (Tesfahunegn, 2013; Prasannakumar et al., 2012; Setegn, 2008; Tripathi et al., 2013). The model has furthermore proven to be successful in comparisons and test research projects (Shen et al., 2009; Mosbahi et al., 2013).

4.3.4 Causes

In Table 6, the percentage of the total erosion in the catchment that is caused by each land use type is given for 1985 and 2015. In general, the causes of erosion agree with the erosion survey. The main source of erosion is annual crops. In 2015, 40 percent of the erosion came from annual crops that formed 19 percent of the total area of the catchment. Forest exhibited insignificant amounts erosion and grazing land, which covers 26.7 percent of the catchment, contributed 9.4 percent of the erosion. Both coffee and enset contributed approximately the same percentage of erosion as their land use percentages. For yearly crops, coffee, enset and forests, the erosion in 1985 shows similar values, which indicates that annual crops are by far the most influential contributors to erosion in the catchment. Due to its large presence, enset is the second most important contributor. An exception is grazing land, which was responsible for 52.5 percent of the erosion in 1985. Besides grazing land covering 48.9 percent of the catchment.

Similar distributions of the sources of erosion were measured by other research. Ouyang et al.(2010) reported that an increase in bare soil and/or farm land increased erosion in both their SWAT model and in measurements. A study in Ethiopia by Betrie et al. (2011) also stated that a decrease in forest increased both their modeled and measured sediment load, indicating an increase in erosion.

Table 6: Sources of erosion for 1985 and 2015. For 5 different land use classes the percentage of land use and the percentage of the total erosion that originates from that land use class are given.

	1985		2015	
Land Use Class	% Erosion	% Land Use	% Erosion	% Land Use
Annual Crops	16.2	2.3	39.5	19.0
Coffee	10.5	2.9	10.3	7.9
Enset	11.8	5.2	31.3	36.0
Grazing Land	52.5	48.9	9.4	26.7
Forest	1.4	39.5	0.1	5.7

Spatial patterns in the change in runoff influenced the spatial distribution of erosion throughout the catchment. Due to topography and soil properties of especially annual crops, the north, north-eastern and the most western and south-western regions show higher runoff. This influences the erosive force in the RUSLE equation and increases erosion. Besides the change in runoff due to land use change the main cause of change in the spatial distribution and values of erosion is the direct influence of land use soil erodibility. In 2015, land uses with a relatively high risk of erosion, such as yearly crops and coffee, are dominant in the majority of the catchment. For the erosion map of 1985, land uses such as forest and grass, which have lower erodibility factors, are more predominantly present, leading to a lower average of erosion in the study site. Especially forested areas exhibited insignificant erosion. While the area of forests in the catchment has decreased substantially, the remaining areas in the southern part of the catchment still provide this protection in 2015. The main valley in the south is characterized by steep slopes and a high percentage of coffee and annual crops in 2015. This has led to both a high slope factor and a high crop related erodibility factor in the RUSLE equation. While the north-eastern region of the catchment is characterized by more gradual slopes, the annual crops still cause high erosion. In 2015, grazing land and enset are predominantly present in the north-western part of the catchment, which has caused less increase in erosion.

5 Conclusions

In the past three decades, land use change in the Genale catchment has been substantial. Agroforestry with the local staple crop enset has increased from 5.2 to 36 percent of the study site between 1985 and 2015. Annual crops have taken over the role of coffee as the most important cash crop, and have increased in area from 2.3 to 19 percent. The area of coffee itself has also grown substantially from 2.9 to 7.9 percent. These land uses have been increasing in area at the cost of a large part of the grazing land and forest, which have respectively decreased in area from 48.9 to 26.7 and from 39.5 to 5.8 percent of the Genale catchment. Besides population growth as the largest driver of land use change in the region, government policies and financial opportunities have contributed to the dynamics of land use in the catchment. The price changes of coffee and annual crops such as maize, sugar cane and especially chat have motivated many farmers to build new or change existing farms to grow these more profitable crops. The government's policies for protecting forest have protected the last remaining patches of forest that are scattered throughout the area.

The land use survey has revealed that annual crops, followed by coffee, enset and grazing land, have shown the most erosion. This was confirmed by the erosion model that was created. In 1985, the average predicted soil erosion in the Genale catchment was 13.8 $\mathrm{t\,ha^{-1}\,y^{-1}}$. Between 1985 and 2015, the average predicted soil erosion has increased by 190 percent to 41 $\mathrm{t\,ha^{-1}\,y^{-1}}$, which can be classified as severe (Singh et al., 1992). An evident increase in erosion is present throughout the catchment. Land use has been shown to be the most important cause of increase of soil erosion in the Genale catchment. Especially the increase in annual crops has, both through its influence on runoff and direct properties, contributed to the high increase in average soil erosion. Spatial patterns in erosion maps were determined mainly by land use and slope. With land use change continuing as in the past decade, an average soil erosion of 50.0 $\mathrm{t\,ha^{-1}\,y^{-1}}$ was predicted, an increase of 25 percent compared to 2015.

Land management has been shown to have an important influence on soil erosion. Sustainable SWC measures are however rarely present in the catchment, while the current erosion values indicate that they are necessary and that their absence is a cause for concern. Biological fences made of Euphorbia Candelabrum have been shown to block a significant part of eroded soil from flowing downstream on moderate slopes. These fences are however not maintained to a sustainable level and for steeper slopes they do not offer a functioning SMC measure. Areas with steeper slopes and higher risks of erosion are thus left exposed. The combination of popular annual crops, pressure from population growth, and the steep slopes in the region create high erosion values and a high risk of land degradation. The created erosion maps can provide a useful tool for management and decision making in the region. Especially the main valley and north-eastern regions of the catchment should be focussed upon, since steep slopes and annual crops combine to give the highest risks of land degradation. More risk comes from the last remaining areas with forest. Located especially on steep slopes, deforestation will cause extensive land degradation, especially when popular crops such as chat are to be grown there. Protection of the remaining forest should be a high priority. Currently, irrigation potential is barely utilized in the catchment. Although the potential is high, the steep slopes, combined with annual crops, require well-chosen options for irrigation based on FAO guidelines (Nachtergaele, Petri & Biancalani, 2011).

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8 Appendix

8.1 Appendix A

Accuracy = 87.9 %
Kappa = 0.74

Confusion Matrix

Spectral Angle Mapper
No Illumination Correction

Land Use Type	Water	Bare Soil	Annual Crops	Enset	Forest	Grass	City	Coffee	Total
Water	852	0	0	0	1	0	0	0	853
Bare Soil	0	11	0	0	0	0	0	0	11
Yearly Crops	0	0	11	0	8	0	3	3	25
Enset	0	1	8	6	40	8	1	4	68
Forest	0	0	0	5	125	0	0	0	130
Grass	0	1	1	7	13	10	0	0	32
City	0	2	0	0	1	0	18	0	21
Coffee	0	0	6	2	12	11	5	7	43
Total	852	15	26	20	200	29	25	14	1181

Accuracy = 91.2 %
Kappa = 0.81

Confusion Matrix

Minimum Distance

Land Use Type	Water	Bare Soil	Annual Crops	Enset	Forest	Grass	City	Coffee	Total
Water	852	0	0	0	0	0	0	0	852
Bare Soil	0	11	0	0	1	1	1	0	14
Yearly Crops	0	1	16	4	2	3	4	0	30
Enset	0	0	3	13	23	3	5	7	54
Forest	0	0	0	0	149	0	0	1	150
Grass	0	1	1	2	9	16	0	0	29
City	0	2	0	0	1	0	14	0	17
Coffee	0	0	6	1	15	6	1	6	35
Total	852	15	26	20	200	29	25	14	1181

Figure 13: Confusion Matrix and accuracy for the classification.

Accuracy = 91.2 %
Kappa = 0.81

Confusion Matrix

Maximum Likelihood

Land Use Type	Water	Bare Soil	Annual Crops	Enset	Forest	Grass	City	Coffee	Total
Water	852	0	0	0	0	0	0	0	852
Bare Soil	0	12	0	0	5	0	3	0	20
Yearly Crops	0	2	13	2	4	2	14	2	39
Enset	0	0	2	15	10	3	7	6	43
Forest	0	0	0	0	159	0	0	1	160
Grass	0	0	3	0	10	16	0	0	29
City	0	1	8	3	12	8	1	5	38
Coffee	0	0	6	1	15	6	1	6	**35**
Total	852	15	26	20	200	29	25	14	1181

Accuracy = 92.1 %
Kappa = 0.82

Confusion Matrix

Spectral Information Divergence

Land Use Type	Water	Bare Soil	Annual Crops	Enset	Forest	Grass	City	Coffee	Total
Water	852	0	0	0	0	0	0	0	852
Bare Soil	0	14	0	0	2	0	4	0	20
Yearly Crops	0	1	12	0	4	1	7	1	26
Enset	0	0	5	15	16	7	0	7	50
Forest	0	0	0	0	158	0	0	0	158
Grass	0	0	2	4	9	19	0	1	35
City	0	0	1	0	1	0	20	0	22
Coffee	0	0	7	1	10	2	1	5	26
Total	852	15	26	20	200	29	25	14	1181

Figure 14: Confusion Matrix and accuracy for the classification.

8.2 Appendix B

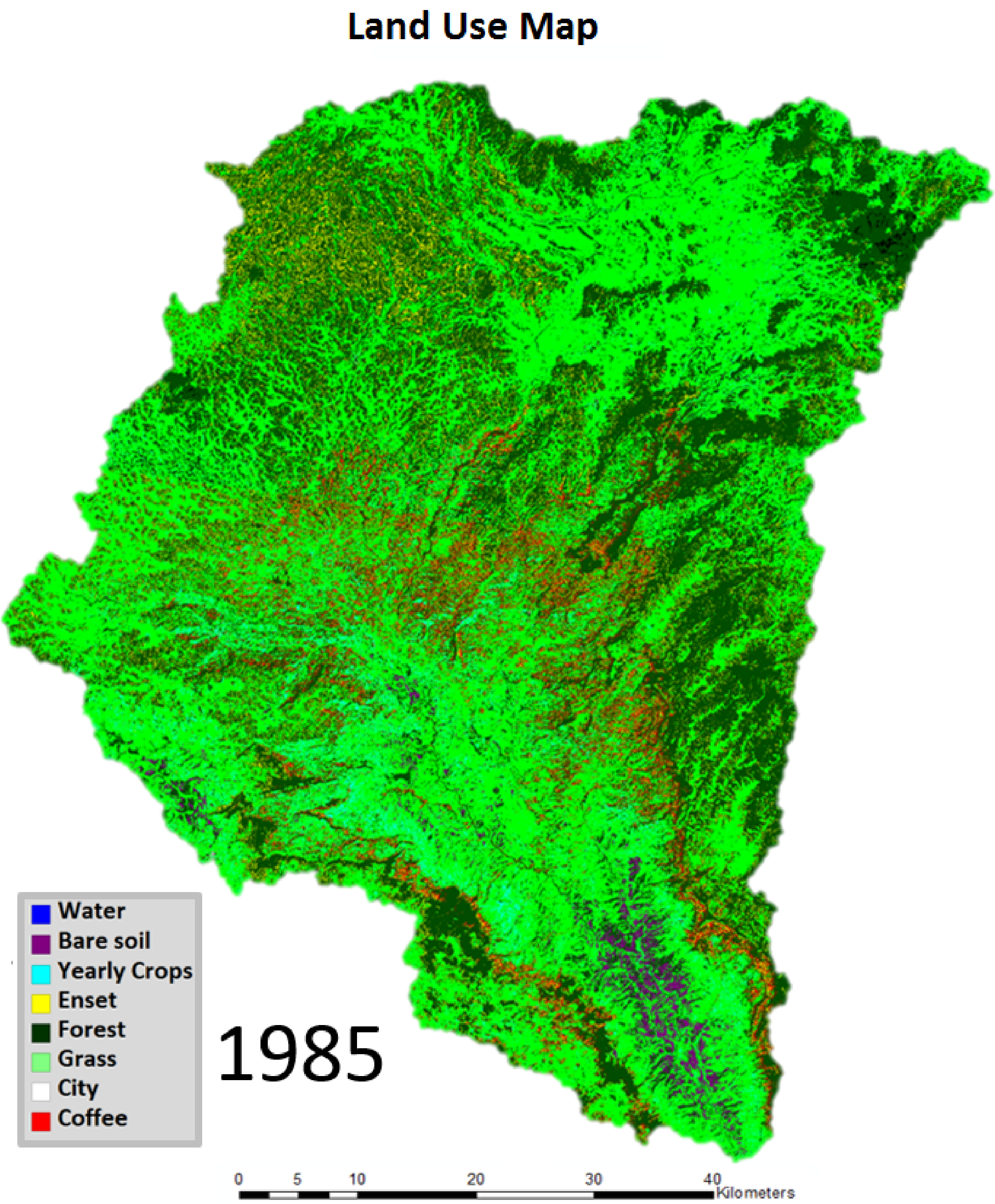

Figure 15: Land use map for the upper Genale catchment.

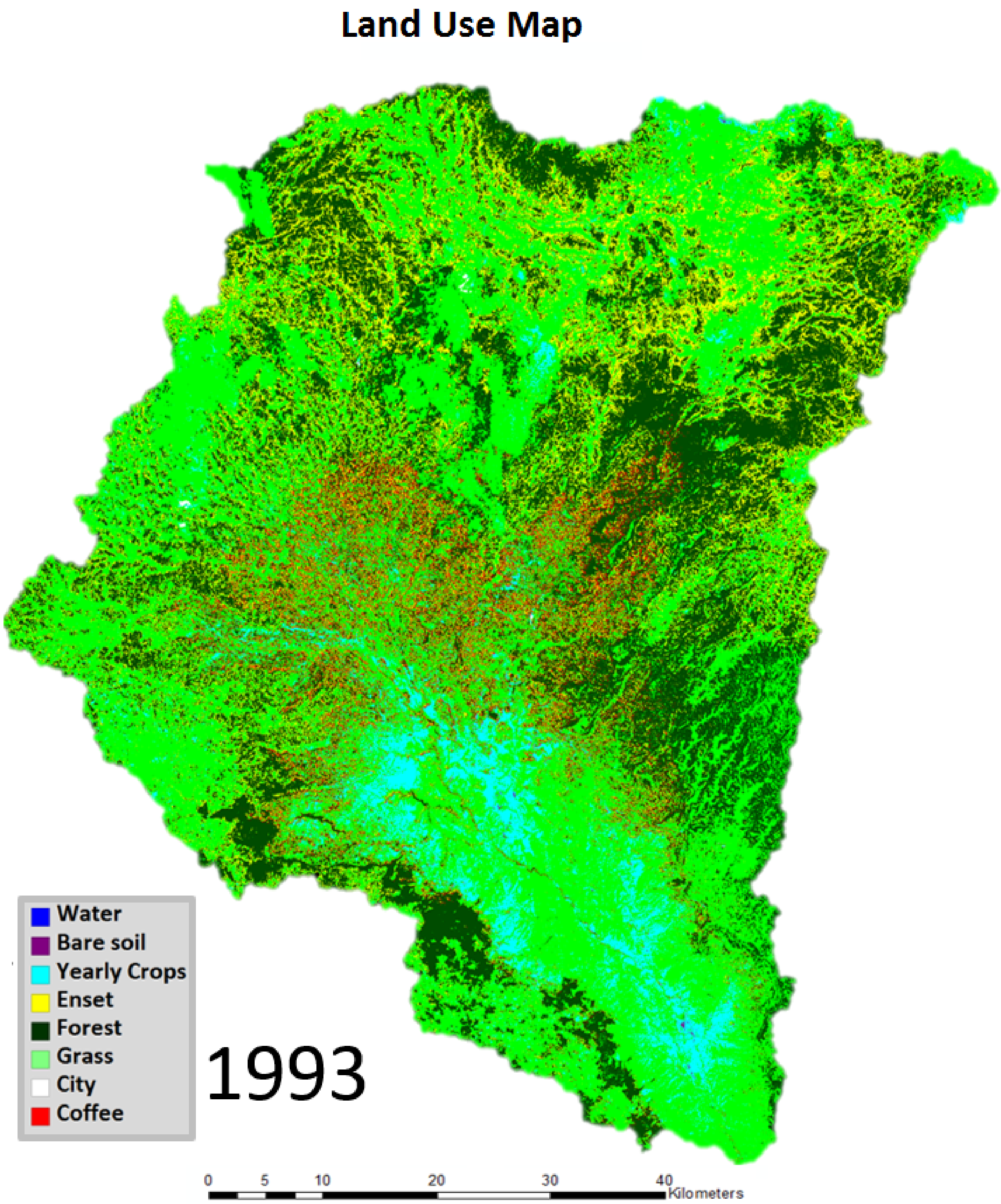

Figure 16: Land use map for the upper Genale catchment.

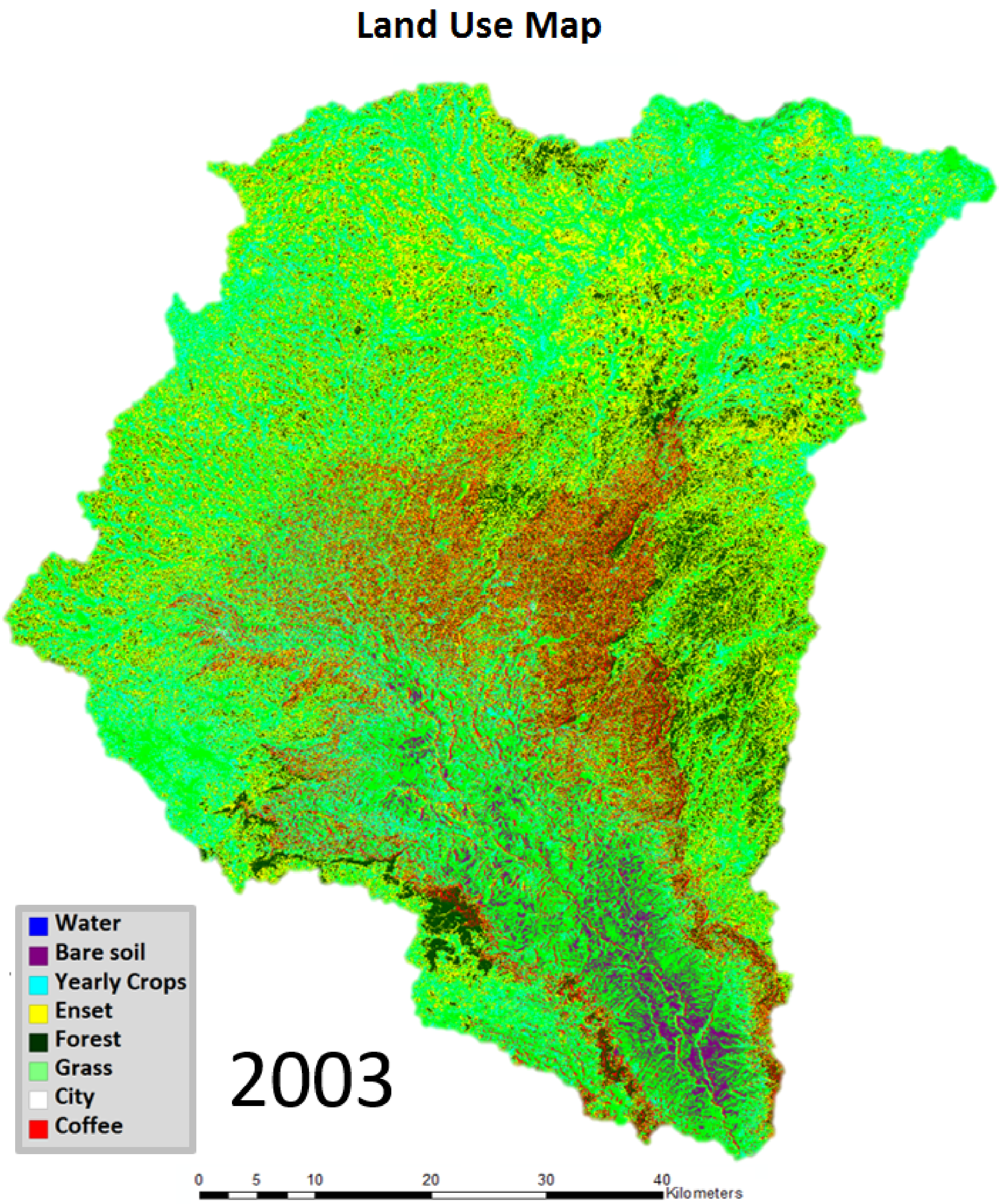

Figure 17: Land use map for the upper Genale catchment.

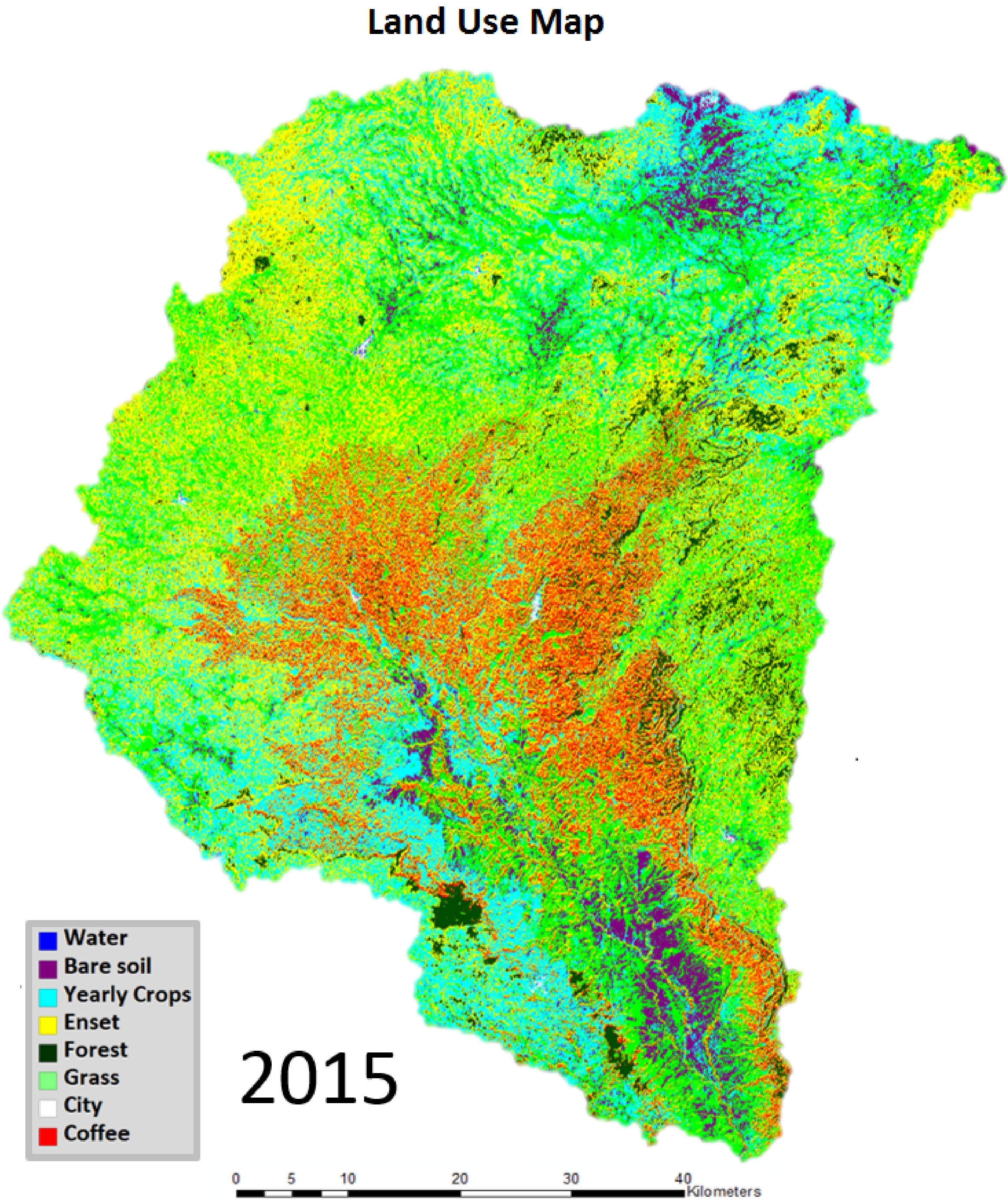

Figure 18: Land use map for the upper Genale catchment.

8.3 Appendix C

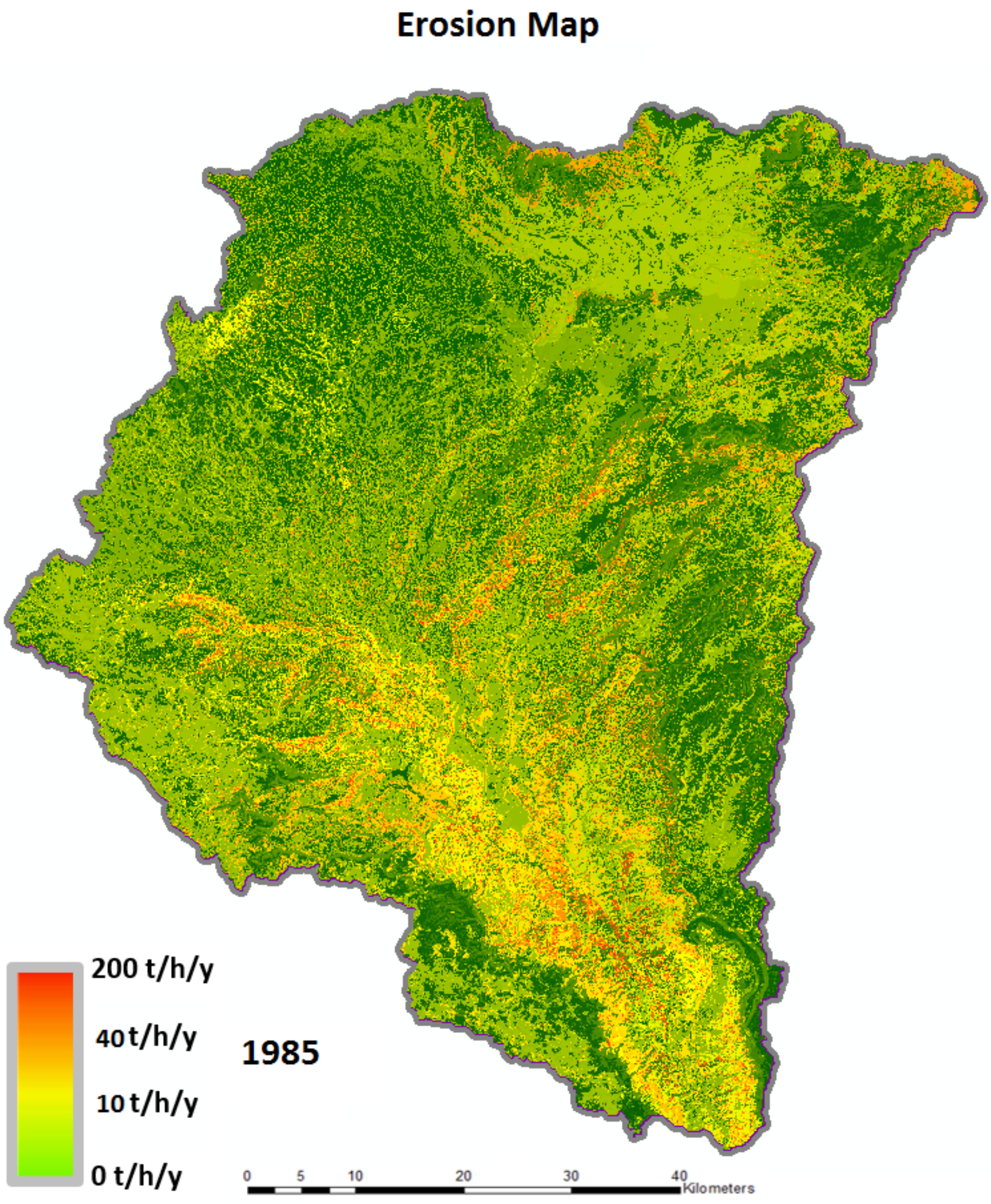

Figure 19: Erosion map for the upper Genale catchment.

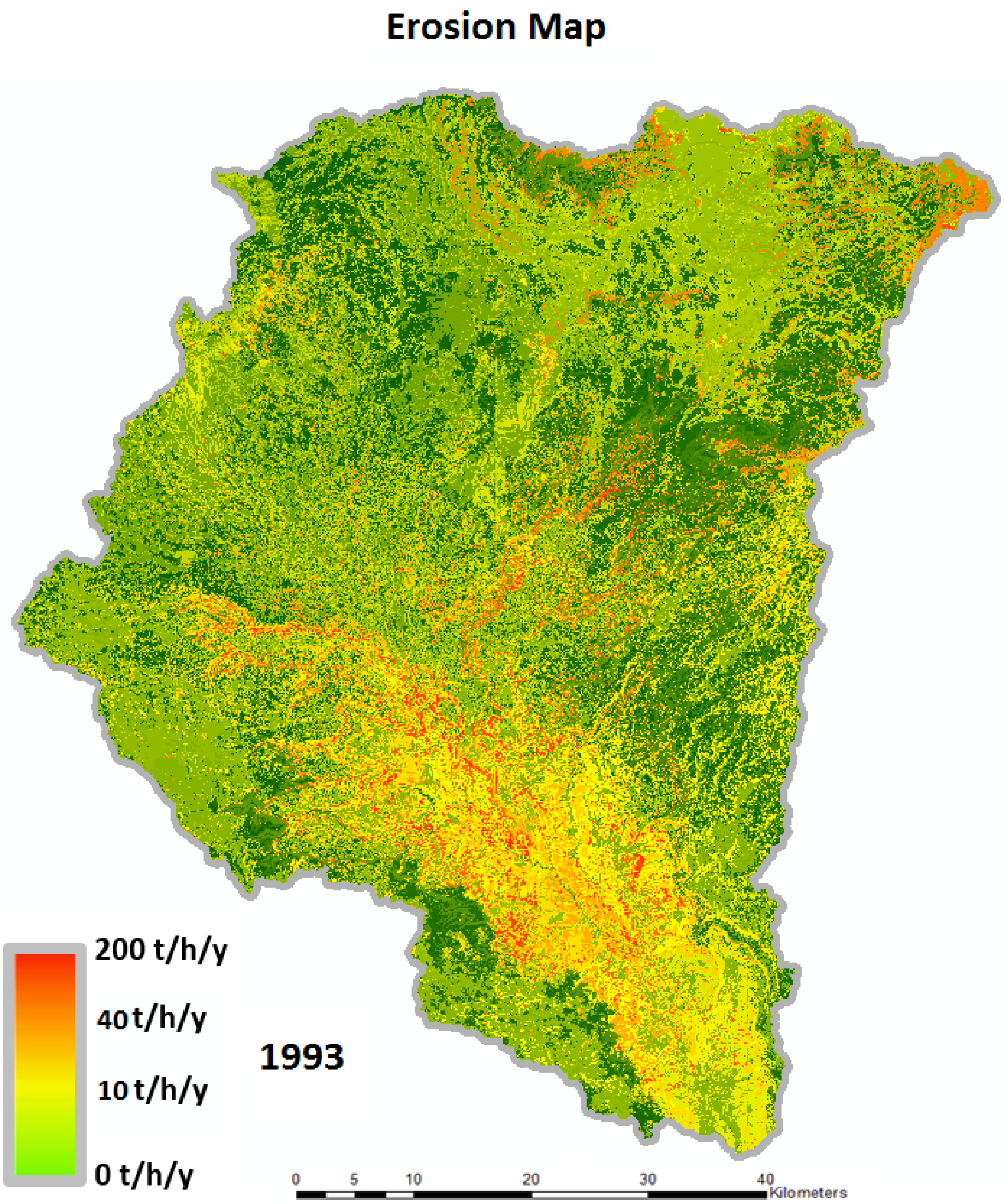

Figure 20: Erosion map for the upper Genale catchment.

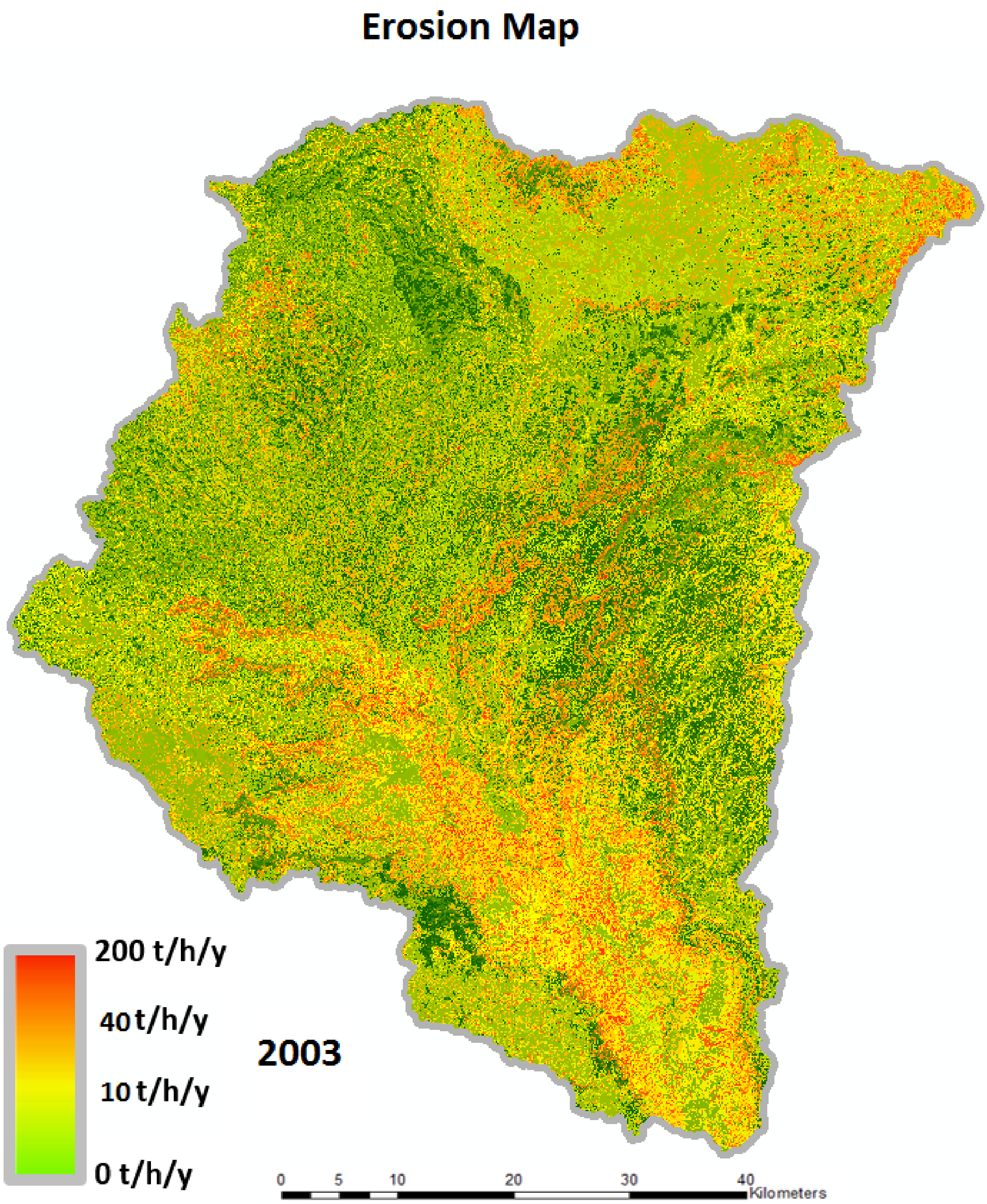

Figure 21: Erosion map for the upper Genale catchment.

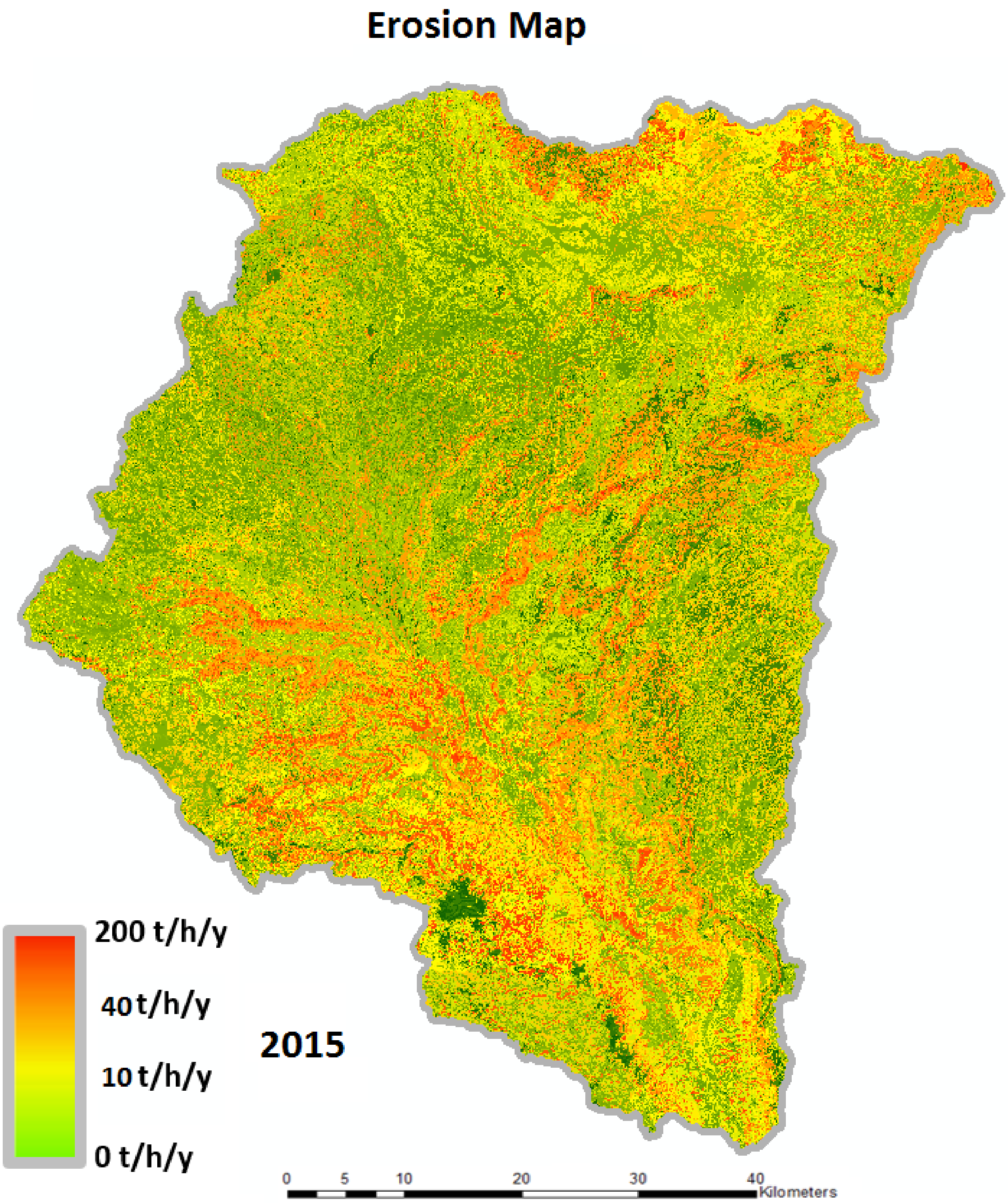

Figure 22: Erosion map for the upper Genale catchment.

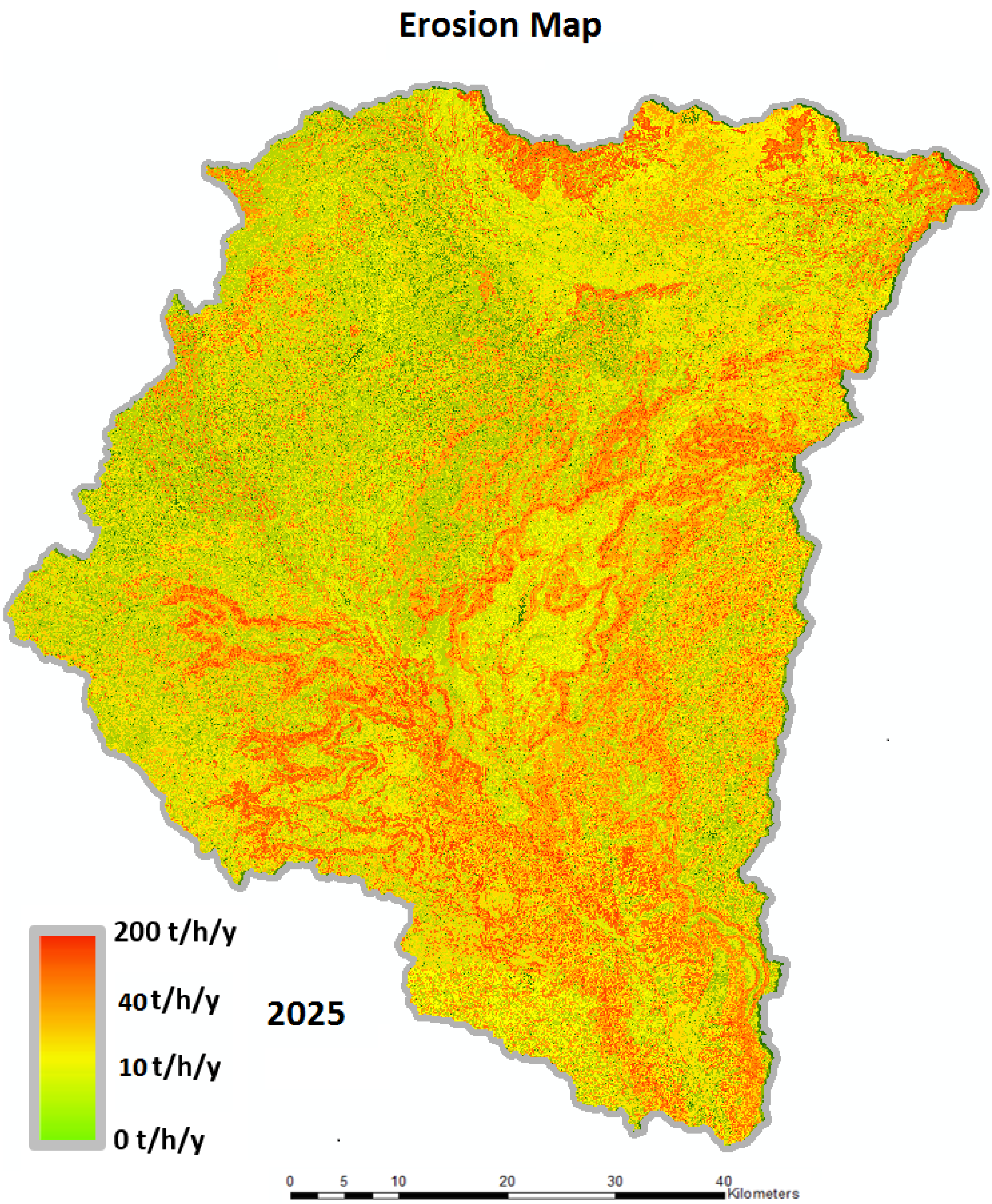

Figure 23: Erosion map for the upper Genale catchment.

8.4 Appendix D

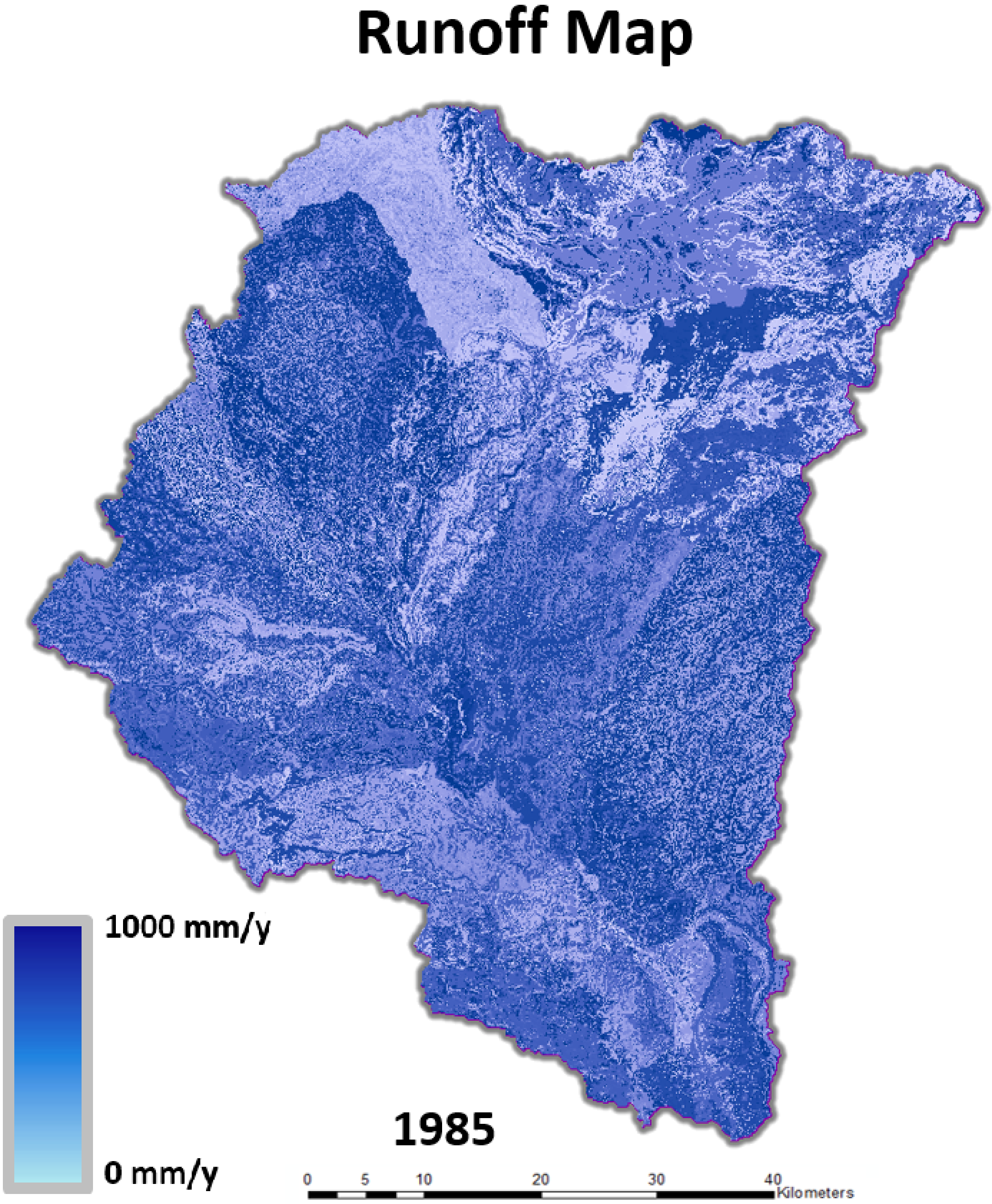

Figure 24: Surface runoff map for the upper Genale catchment.

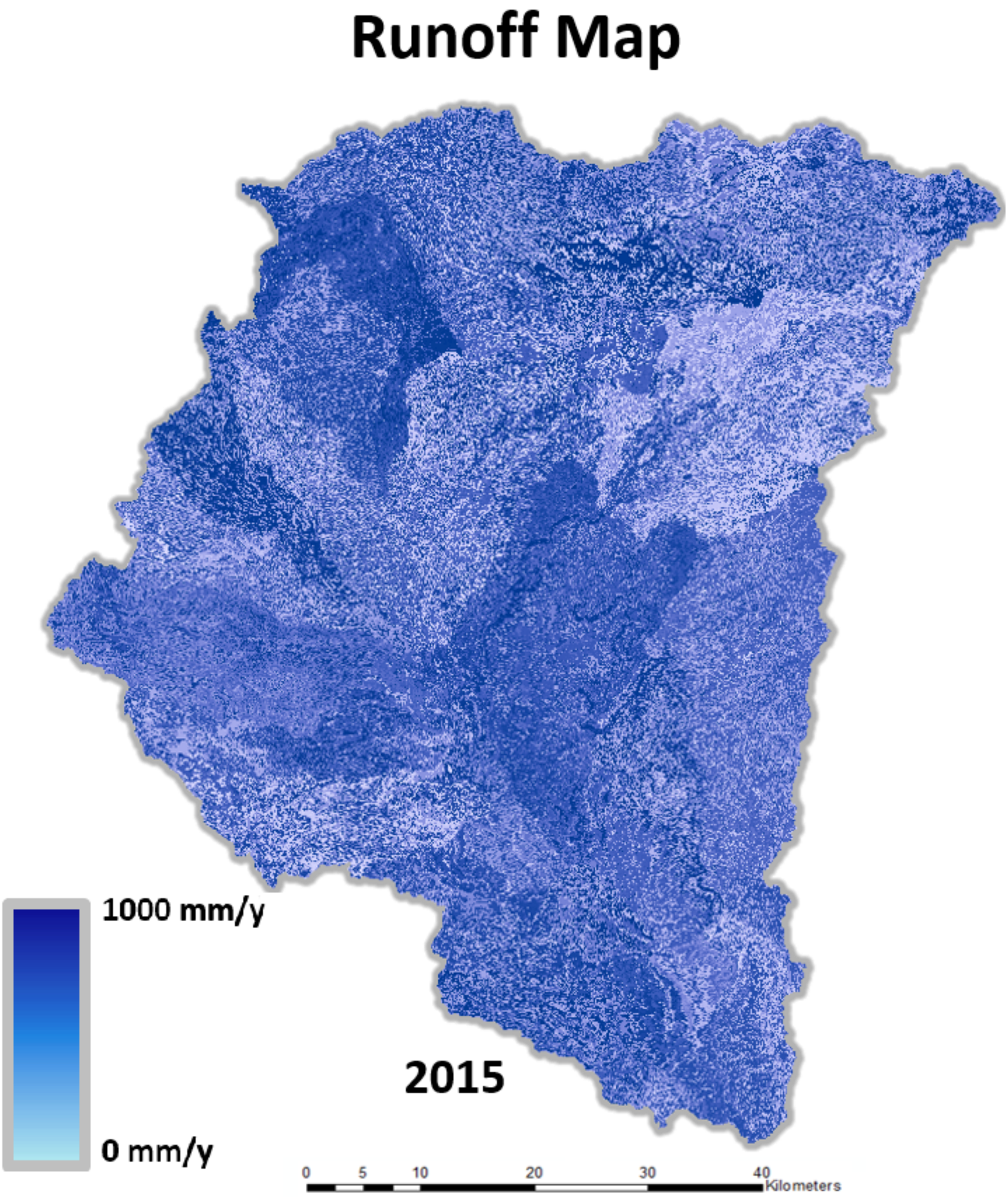

Figure 25: Surface runoff map for the upper Genale catchment.