Assessment of Environmental Changes for Natural Resources Management in the Koga catchment, Northwestern Ethiopia

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Vienna Doctoral Programme on Water Resource Systems

Doctoral Thesis

Assessment of Environmental Changes for Natural Resources Management in Northwestern Ethiopia

submitted in satisfaction of the requirements for the degree of

Doctor of Science in Civil Engineering
of the Vienna University of Technology, Faculty of Civil Engineering
as part of the

Vienna Doctoral Programme on Water Resource Systems

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Vienna, February 2015

Abstract

This PhD study assessed the impacts of land use/cover changes over the past few decades on runoff and soil loss in a watershed in Northwestern Ethiopia. In chapter 2, land use/cover changes for the past 5 decades were generated from remotely sensed data after the input data were reconciled for the differences in spatial scales. The remotely sensed data analysis was complimented by ground truth data through field survey and interviews with elders that have observed the land use/cover changes in the study area for the considered time period. Results indicate that woody vegetation cover in the study area has tremendously decreased from the 1950s to 2010. Most of the changes took place between the 1970s and 1980s. The area used for settlement significantly increased from the 1950s to 2010. Population pressure and land use policies accounted for the changes in land use/cover.

In Chapter 3, high temporal resolution measurement of turbidity and discharge data, accompanied by sediment-discharge hysteresis analysis enabled us to estimate the seasonal variation and sources of sediment in the study area. While agricultural areas and hill slopes contribute most of the sediment yield in the study area, most of the sediment loss occurs in the high rainfall months between June and mid-August when the agricultural areas have very little vegetation cover. The following high rainfall months of the year between mid-August and the end of September contributed only a small portion of the total yearly sediment yield as the agricultural areas are completely covered with vegetation within this time period. 25 t $yr^{-1}ha^{-1}$ rate of suspended sediment transport was estimated in the study area.

In chapter 4, the decadal trends in runoff and soil loss for changes in land use/cover were simulated using the Annual Agricultural non-point source (AnnAGNPS) model. The model was calibrated with measured yearly runoff and soil loss data and then with daily data for one year followed by validation on the following year. The model predicted runoff and soil loss well with good correlation coefficients between measured and modeled values and satisfactory Nash-Sutcliffe coefficients. Model simulations for changes in land use/cover over the past 5 decades produced runoff and soil loss maps for that time period. Simulation results indicated a tremendous increase in soil loss and runoff from the 1950s to 2010. The modeling output enabled delineation of the areas that were at high erosion risk throughout the entire past 5 decades, as well as the current high risk erosion areas, for planning appropriate soil and water conservation measures that may reduce soil loss and runoff. In chapter 5, selected soil and water conservation measures were simulated with the calibrated and validated AnnAGNPS model in chapter 4. Simulation results indicate that soil loss in the study area can be reduced by up to 88% and runoff by up to 22% when combinations of reforestation, contour farming and terracing were applied, each of them on areas with different levels of erosion risk. Chapter 6 summarizes the findings and conclusions of this study.

Acknowledgements

I would like to extend my sincere thanks to my primary supervisor Prof. Günter Blöschl who, in addition to his unreserved professional guidance and support, has been understanding and kind throughout the PhD study. His input contributed tremendously to my development as a water resource research professional. My heartfelt gratitude also goes to Prof. Wolfgang Wagner for his professional support and understanding throughout the PhD study and for his encouraging words that helped me step forward at times when the research was not timely progressing as expected.

I would like to pass deepest thanks to the Faculty for the Future Programme of the Schlumberger Foundation for granting me a scholarship for this PhD study. Besides my PhD study, the grant has also enabled me to fulfill my motherly duties by bringing my children to Austria. I also would like to thank the Vienna Doctoral Programme on Water Resources Systems for hosting me and, through the Austrian Science Fund, for purchasing the instruments needed to set up a hydrological monitoring station at my research catchment in Ethiopia. My thanks also go to Alexander Eder for the successful installation of the hydrological monitoring station at my research site in Ethiopia. This research would not have been possible without the good data sets I got from the hydrological monitoring station.

I thank the Koga Watershed Irrigation Project team, especially Ato Zerihun Balcha, for doing their best for the success of my research, considering this research as an important contribution to the project. I would also like to extend my thanks to my colleagues from Addis Ababa University - Ato Tessema Bekele, Dr. Solomon Mulugeta, Dr. Tesfaye Shiferaw and Dr. Muluneh Woldetsadik - for their encouragement from quite a long distance.

I thank my colleagues Mike Exner-Kittridge, Gemma Car, Jose Luis Salinas, and Jan Podrouzek from the Doctoral Programme for their consistent efforts to create a pleasant social atmosphere within and outside the institute, and for being good friends throughout my stay in Austria. I also would like to thank Peter Haas for his unreserved IT support throughout the study period. My thanks also goes to Jürgen Koma, Maria

Cardenas Gaudery, Michael Vetter, Alberto Viglione, Julia Derx and Philip Nester for their contribution in one way or another towards a comfortable work environment within the institute.

I thank my late mom W/o Tiyint Mekonnen and my father Ato Yeshaneh Ayehu for their loving parenting that taught me the principles of life. I wish my mom was still alive to witness this step in my life. My deepest thanks go to my children, Eyasu and Kenean, who have always been my sources of motivation and passion, and gave my life a meaning. I would also like to thank my husband Mogesie Ayele for his encouragement and for his tolerance, staying in Addis Ababa without me and our children for such a long time for the sake of my career. I also would like to thank my brothers and sisters for their encouragement.

I owe lots of thanks to Mrs. Dana Basnar for editing the English of my PhD thesis. In addition to Mrs. Dana, I would like to thank some of the parents from my children's school, namely Huda Azhari and Valerie Duruz Michaud for narrowing the language barrier information gap during my life in Austria and for offering me help regarding my children whenever I was in need.

Last but not least, I thank the Lord my God Jesus Christ, whose presence I always felt, whom I shall always proudly witness for his grace in getting me through every difficulty.

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1. Introduction

Environment includes all those natural features such as flora and fauna, water quality and quantity, tree cover and soil fertility that can be affected by natural processes or human induced factors (UNHCR, 2002). Environmental change is a continuous process that has been in operation since the Earth first came into existence (Mannion, 1997). Environmental change has occurred as humans by their ingenuity, i.e. technology, have transposed components of the Earth's surface into resources (Mannion, 1997). Their impact has been direct as natural ecosystems have been cleared to provide land for agriculture and urbanization, and as land-based resources, such as minerals, have been extracted. Human communities have also brought about indirect and often inadvertent environmental change as a result of resource use and agricultural and technological innovations.

In developed countries, environmental problems are generally related to industrialization and technological advance. In developing countries, in contrast, underdevelopment itself is an environmental problem (UN Dept. of International Economic and Social Affairs, 1980). An uncontrolled population rise in developing countries has an impact on the environment. This is due to the fact that, in developing countries like Ethiopia, where technological advancement is yet undeveloped, countries could not offer energy substitutes. Hence vegetation has been the main source of fuel, house heating and construction material, that in turn implies that vegetation depletion is highly related to population growth. More population means more demand for the utilization of natural resources that leads to environmental degradation (UNHCR, 2002).

Ethiopia is one of the poorest countries in Africa and faces major problems. Many of Ethiopia's problems have environmental origins and/or effects. Deforestation, and the resulting soil erosion, are Ethiopia's greatest environmental threats and have had a severe impact on soil and water resources. In recent years, particularly after the 1950s, there has been an increasing degradation of natural resources. Nearly one billion tons of fertile soil is eroded each year (Tamene and Vlek, 2008) because of deforestation, over-cultivation and overgrazing. The country loses up to 140,000 hectares of forest annually (FRA, 2005).

The fast growing population of Ethiopia is playing a significant role in hastening environmental degradation. The population of Ethiopia has tripled in the last 50 years. The pressure of an increasing population has increased the rate of deforestation, overgrazing, and rising demand for cropland. The huge animal population has also contributed to land degradation in no small way. Ethiopia has made great efforts in ecological conservation in the fast deteriorating highlands since the 1970s, though most of the efforts were ineffective (Dubale 2001, Tesfaye et al. 2014). Large-scale reforestation projects and catchment preservation programmes with thousands of kilometers of terraces were constructed with peasant labour. Unfortunately most of these structures are not in place today. As a result environmental problems constitute a major constraint to development, and there is an urgent need for conservation of the natural resources. Planning for conservation requires information on the current status of the available natural resources, and their past, current and expected future use.

Land use/cover change is increasingly recognized as an important driver of environmental change on all spatial and temporal scales (Turner *et al.*, 1994). It has become one of the major issues for environmental change monitoring and natural resource management. Predicting how land use/cover changes affect land degradation and the vulnerability of places and people in the face of land use/cover changes requires an understanding of the dynamic human-environment interactions associated with land use/cover change (Lambin et al, 2003).

Land use/cover characteristics in many ways reflect the hydro-meteorological conditions of an area. Generally land use/cover varies slowly over time. However, occasionally this variation can be rapid, for example following land-use transformation, forest fires or extensive deforestation by man that may result in dramatic modifications in the hydrological and soil erosion processes. Therefore, for obtaining inputs in hydrological models, as well as for detecting modifications in the hydrological regime, it is important to generate time series land use/cover maps.

1. Introduction

Effective control of soil erosion requires an ability to quantitatively predict the amount of soil loss that would occur under alternate management strategies and practices. Modeling runoff and soil erosion is important to determine their spatial and temporal distribution, and in turn for devising the optimal soil and water conservation and management practices (Kothyari et al, 1997; Quan, 2006). Catchment models are important not only for better understanding of hydrologic behaviors of a catchment and of how changes in the catchment may affect these behaviors, but also to provide valuable information for studying the potential impacts of changes in land use (Quan, 2006).

The aim of this PhD research is therefore to assess watershed-scale environmental changes in the Koga catchment which is located in the Northwestern part of Ethiopia. Chapter 2 determines land use/cover changes over the past 50 years in the selected catchment. Different types of satellite images coupled with aerial photos and ground truth data were used for generating the land use/cover changes. An attempt was made to reconcile the differences in the spatial scales of the remotely sensed data inputs. In Chapter 3, high temporal resolution measurement of discharge and sediment accompanied by sediment-discharge hysteresis analysis enabled us to quantify the temporal variation of suspended sediment transport in a hydrological year and identify the dominant sources of sediment in the study area. In chapter 4, the distributed physically based AnnAGNPS (Annual Agricultural Non-point Source) model was used to analyze the decadal trends of soil loss and runoff in the study area and to delineate the high erosion risk areas for development of improved land management. AnnAGNPS was also used in chapter 5 to simulate selected soil and water conservation measures to determine the best management practices that should be implemented for sustainable natural resource management. Chapter 6 summarizes the findings and conclusions in this study.

2. Identifying land use/cover dynamics in the Koga catchment, Northwestern Ethiopia, from multi-scale data, and implications for environmental change

Abstract: This study analyzed more than 50 years of land cover and land use changes in the 260 km^2 Koga catchment in North Western Ethiopia. The data used includes 1:50,000 scale aerial photographs, Landsat MSS, TM and ETM images, and ASTER images together with ground truth data collected through field surveys and community elders' interviews. Aerial photographs have high spatial resolution but provide lower spectral resolution than satellite data. While most land use/cover change studies compare changes from different spatial scales, this study applied land use/cover classification techniques to bring the data to a relatively similar scale. The data revealed that woody vegetation decreased from 5,576 ha to 3,012 ha from the 1950s to 2010. Most of the deforestation took place between the 1970s and 1980s, but there is an increasing trend since then. No significant changes were observed in the area used for agriculture that comprises the pastures and crop fields since the 1950s, while there is an enormous increase in the area used for settlement, due to a tremendous increase in population from one point in time to another. The bare lands that used to exist in previous years were found to be totally covered with other land cover/use classes and no bare lands were observed in the study area in the year 2010. Population pressure and land use policies were found to be reasons for the changes in land use/cover while soil degradation, decrease in the indigenous woody vegetation and erosion were the observed consequences of the land use/cover changes.

2.1 Introduction

Land use change trends in many developing countries are both extremely rapid and the direction of changes and rates are in flux (Olson et al., 2004). Land use/cover changes are the primary source of soil degradation (Lambin et al., 2001; STAP, 2006); and by altering ecosystem services, affect the ability of biological systems to support human needs (Lambin et al., 2001; Loveland et al., 2003, Turner et al., 2007). Before remedial policies and programs can be effective, it is useful to understand in what way land use has changed and what are the principal causes (Olison et al., 2004, Anderson et al., 1976; Dawn et al., 2001).

Africa is said to have the fastest rate of deforestation in the world as a result of overdependence on primary resources (Ademiluyi et al., 2008). Climate changes and rapid population growth cause increasing pressure on the East African highlands. The results of the pressure are manifold: intensified agriculture, decreasing amount of forest land, loss of biodiversity, intensified land degradation and soil erosion (Pellikka et al., 2004). Deforestation rates in East Africa, including Ethiopia, were the second highest in Africa: 0.94% for 1990–2000 and 0.97% for 2000–2005 (Garedew et al., 2009). A study conducted in North Western Ethiopia indicated 99% clearing of the forest cover of the 1950s until the year 1995 (Zeleke et al., 2001). The population of Ethiopia, which is currently 79 million people, increases by almost two million annually under highly unfavorable economic and environmental conditions (Garedew et al., 2009). Population pressures in Ethiopia have decreased the size of holdings, including both arable and pasture lands, leading to conversion of forested and marginal areas into agricultural lands (Bishaw, 2001). Farm sizes in Ethiopia have been declining over time, and roughly a quarter of the agricultural households are virtually landless, controlling less than 0.1 ha per capita (Jayne et al., 2003). Awulachew *et al.* (2008) also indicated high population pressure induced deforestation, overgrazing, land degradation and declining agricultural productivity in the upstream part of the Blue Nile basin.

The combination of increased interest in environmental changes over large areas and improved data and interpretation methodologies is leading to an increasing number of studies and projects using land use change analysis (Olson et al., 2004). Satellite data, appropriately calibrated and validated with ground data, provide spatial information on the distribution of land cover types and changes over time (Loveland et al., 2003; Hansen and DeFries, 2004). Whereas such information could previously only be obtained over small areas from ground surveys or aerial photographs, satellite data extend the coverage over larger areas at more frequent time intervals (DeFries and Eshleman, 2004; Lambin et al., 2004). On the other hand, historical aerial photographs have much longer temporal history than satellite images, and are an important source of data for long term land cover change analysis (Carmel and Kardon, 1999). In addition, aerial photographs have generally higher spatial resolution and therefore offer the possibility of providing more detailed local and regional vegetation information for landscape ecological assessments (Zhang et al., 2008).

Remotely sensed data need to be supported and validated with ground truth data that is achieved through either field surveys or documented data. Interviews with the local people can be an additional option when either of the two previous ways is not possible. Conducting group or key informant interviews is one way of gathering information on the past land use changes and the root causes. Critical information may be obtained from interviews with local people from mainly community elders concerning their impressions of the patterns of land use change that have occurred, and the reasons behind those changes (Olson et al., 2004).

One of the challenges of land use/cover research is to maintain continuous time series of data to generate uninterrupted time series for analysis. This need is and will continue to be impeded by the malfunction of Landsat 7 since 2003, given that the Landsat system, with its spatiotemporal resolution (900 square meters, every 16 days) and relatively low costs, has been the “workhorse” data base for so much of the land cover classification (Turner et al, 2007). The other challenge is when remotely sensed data come from different sensors MSS with TM, different pixel size affects the classification as a given land cover is not seen in the same way at different pixel sizes. The classifications differ because some elements are not detected in the coarser resolution images, which do appear in the finer resolution images (Serra et al., 2003). Similarly, spectral reflectance properties of natural surfaces at a given moment often prevents consistent identification and mapping of a large range of cover classes such as agricultural crops or detailed natural vegetation communities (Serra et al., 2003), which is another challenge to the remotely sensed image using community.

The purpose of this paper is to quantify the land use/cover changes that have happened over the past 50 years on the Koga catchment, to identify the drivers of the land use/cover changes and assess implications of the changes by the environment.

2.2 Materials and Methods

2.2.1 The Study Area

2.2.1.1 Location, Climate and Topography

The selected study area is the Koga catchment in northwestern Ethiopia, which is a typical catchment for the Ethiopian Highlands. The Koga catchment is situated in the North Western Ethiopian Highlands between latitudes of 11°9.7' and 11°30'N and Longitudes of 37°02' and 37°18'E. The catchment area is 260 km^2; 72% of which is used for subsistence agriculture. Figure 2-3 shows some parts of the catchment. The Koga River originates in the Wezem mountain area and is a tributary of the Gilgel Abbay, which flows northwest in to Lake Tana, and lies in the upper part of the Blue Nile (Abbay) watershed.

The climate of Koga catchment falls within the Woina Dega (cool semi-humid, 1,500 to 2,400 masl) and Dega zones (cool, above 2,400 masl). The majority of the catchment area lies within the Woina Dega zone and is characterized by distinct dry and wet seasons. The dry seasons occur between November and April and the Wet season between May and October; small rains occur sporadically during April and May. The mean daily temperature is 18.25 ℃. The monthly mean maximum temperature varies from 30.0 ℃ in March to 23.7 ℃ in August. The monthly mean minimum temperature varies from 5.4 ℃ in December to 13.1 ℃ in May and June. Figure 2-1 shows the air temperature and precipitation of the Bahirdar station located 35 km northeast of the catchment. Apparent is high July and low January precipitation. It also appears that air temperature has increased through years.

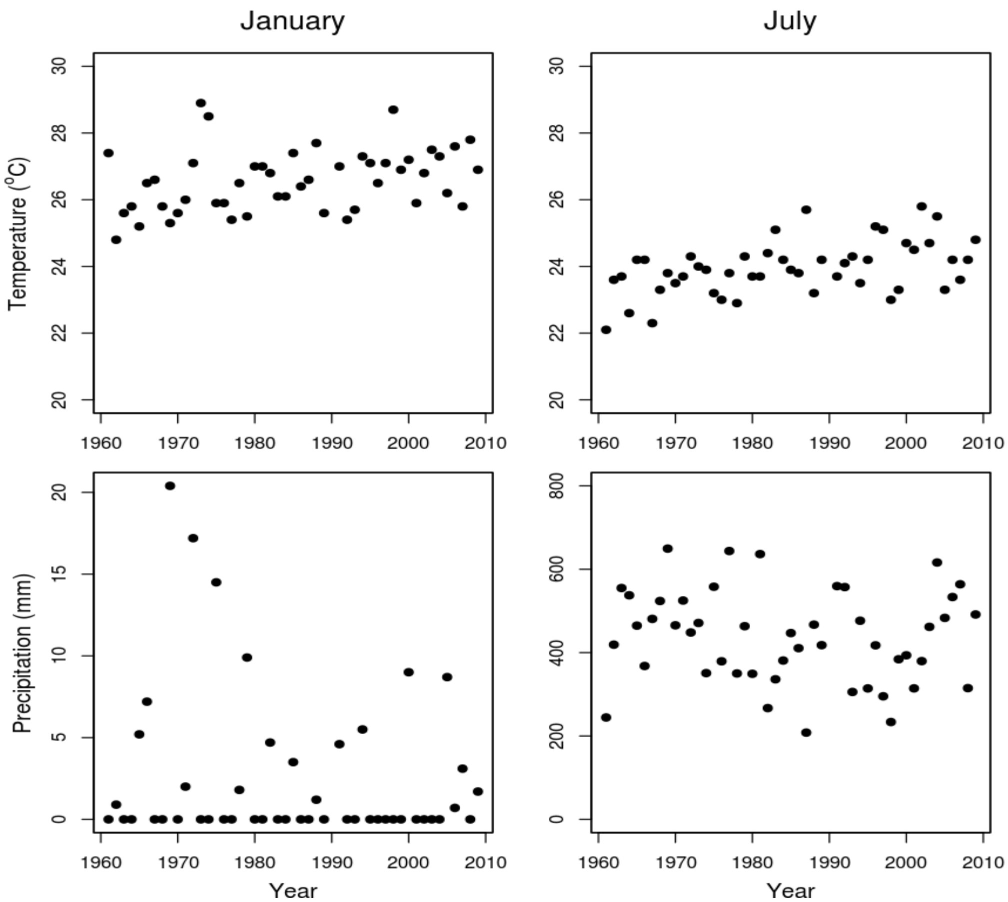

Figure 2-1: Mean maximum temperature (in ℃) and rainfall (in mm/month) for the years 1961–2009 at Bahirdar Station

The land elevation of the Koga catchment varies from 1,875 masl at the mouth of the Koga River to 3,215 masl at its highest point on the watershed divide. The Koga River rises in the hills north of the Wezem Mountains and flows a distance of some 49 km to where it joins the Gilgel Abbay, which eventually flows in to Lake Tana. The total catchment area from source to mouth is 260 km^2 and the course of the main river is northerly up to the village of Rim then westerly to Wetet Abbay. The catchment is generally elongated with a pronounced narrowing above Rim where the mean width of the basin is only 3.8 km.

2.2.1.2 Geology and Soils

The regional geology of the Koga catchment comprises extensive flow type, volcanic (extrusive) rocks of the Ashangi Group; these were deposited during the palaeocene-Oligocene-Miocene (Teritiary) stages of geological time. The Ashangi group comprises the older volcanic rocks, which were formed by lava and debris, ejected from fissural volcanic eruptions. It covers over 50 percent of the Koga river sub basin and consists predominantly of alkaline basalts with interbedded pyroclastic and rare rhyolite. The Koga catchment can be divided in to two major units based on slope gradient: the upper catchment and the lower catchment. The upper catchment is a soil complex and consists of a number of different soil sub groups. The main soil types within the upper catchment are Luvic Phaeozems (Typic Argiustolls), Chromic Cambisols (Fluventic and Typic Ustropepts) and Lithic Leptosols (Lithic Ustortents) on shallow steep slopes. The lower catchment consists of three major soil groups; the reddish brown and yellowish brown Haplic Alisols (Typic Paleustults) in the well-drained and moderately well drained upland areas, Eutric Vertisols (Ustic Epiaquarts) in the convex poorly drained plains and Eutric Gleysols (Typic Tropaquepts) in the poorly and very poorly drained concave flat flood plains of the Koga tributaries.

2.2.1.3 Population

The total population of the Mecha woreda, within which the Koga catchment is located, is 292,000 of which 269,404 live in the rural part while 22,677 live in the urban part (CSA, 2007). The population density in the lower catchment is extremely higher than the population density in the upper catchment. Subsistence rain fed production of cereals comprising teff, maize, barley and millet, as well as pulses, oilseeds and some legumes is dominant in the area while irrigated agriculture takes up a small percentage of the cultivated area of the Koga catchment. Income from livestock also contributes to the livelihood of the small scale poor farmers in the area.

2.2.2 Land use Policy and Interview of Locals

In Ethiopia, land is a public property and has been administered by the government since 1975. Before 1775 was the imperial era in which land was controlled by the King and the ruling elites (Ambaye, 2012). The emperor of that time and his family, together with the barons and lords in both houses of parliament were owners of vast tracts of land in the country (Ambaye, 2012). Since 1975, all rural and urban land became under public ownership and the possession of rural land plots has been conditional upon residence in a village (Gebreselassie, 2006).

Historical long time ground truth data is difficult to collect unless there is documented data or through people that knew the area during the considered time period. Aerial photographs do sometimes serve as an alternative way of collecting ground truth data whenever there is no other way of getting it. Getting aerial photographs for all the years required is not possible. In addition, aerial photo interpretation itself need to be supported by ground truth data from some other sources due to the difficulty in distinguishing some of the land use/cover classes using normal aerial photo interpretation techniques. For this reason it was important to discuss with selected local people in the study area. The key informants were selected community elders that did and still reside in the catchment and who are older than 75 years. The catchment lies within 18 kebeles (sub-division of district) of the Mecha Woreda (district) (Figure 2-2). Discussions were made in person with one key informant from each Kebele about how the land use/covers in their vicinity evolved through time and about their observations of the causes of the changes. The elders were mostly priests, and some of them were farmers who have an in depth knowledge of the area while having lived there for a long time. Finding the right elders for discussion from each kebele was a tough task due to some reasons. In the first place there were not many elders in each kebele and secondly, a few of the existing elders were illiterate, which made topographic map or aerial photo based discussions difficult in addition to their unwillingness to walk a little distance away from their place to explain the land use/cover changes within their kebeles. Some others were not fit to make dependable discussion due to the inconsistent information they provided, which was believed to be associated with aging. Regardless of all these difficulties, sufficient data was collected through key informants, who were willing to walk for a considerable distance within their kebeles in order to explain the land use/cover changes. As far as it enabled collection of enough data, selection of location for ground truth data was mainly based on the respondents' choice due to accessibility and distance from their place.

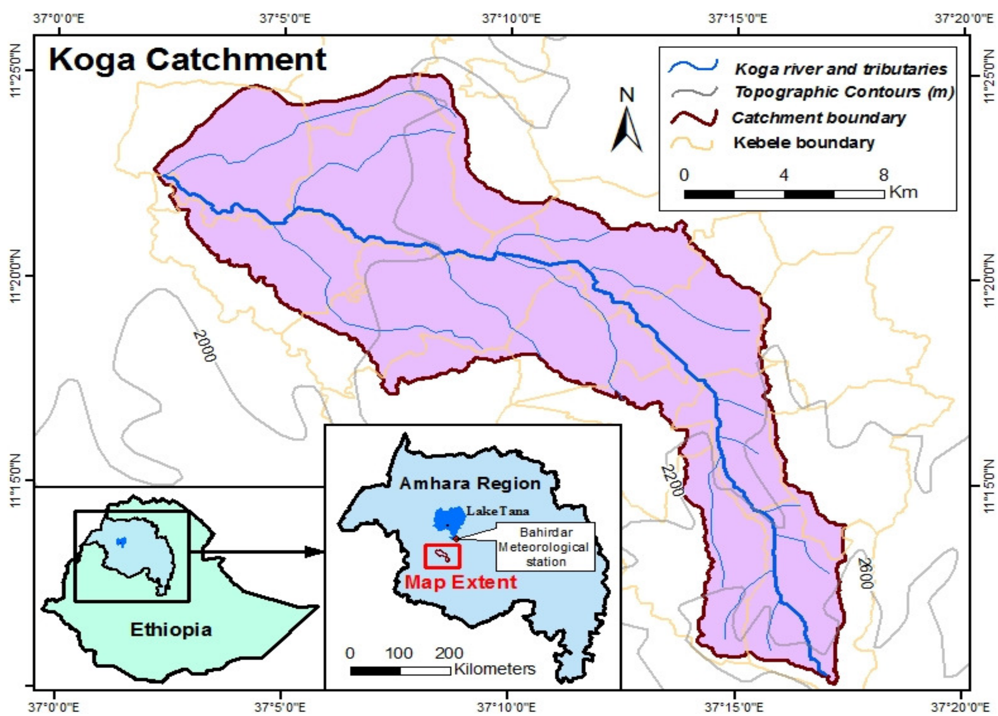

Figure 2-2: Location Map of the Koga Catchment

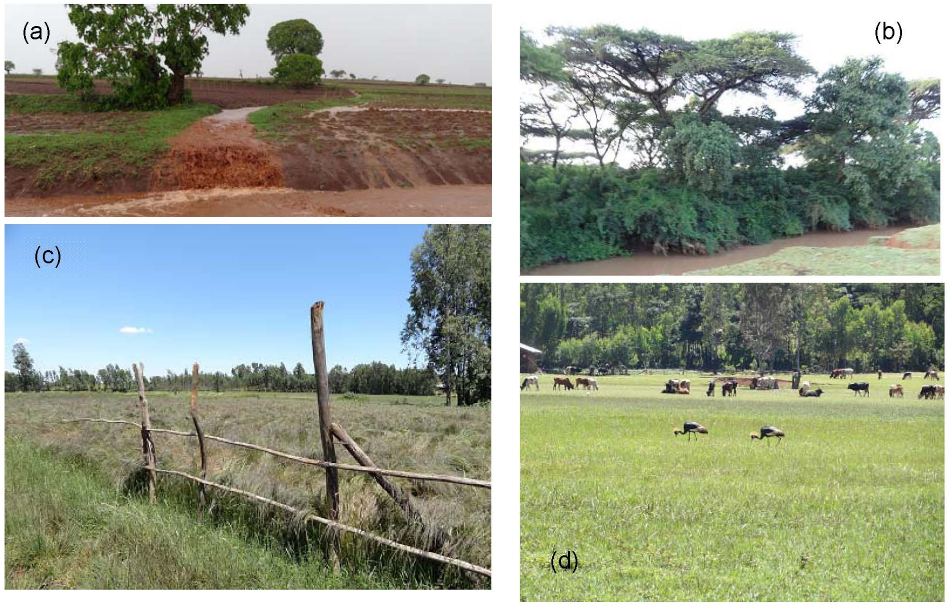

Figure 2-3: **Sediment laden runoff from ploughed fields in the Koga watershed during a rainfall event** (a), **remaining natural woody vegetation along the Koga river** (b), **small crop farm plots and homestead eucalyptus trees** (c), **pasture land and eucalyptus tree plantations** (d).

2.2.3 Remote Sensing Data Analysis

Aerial photographs of the scale 1:50,000 were acquired for the months of December 1957 and January 1982 from the Ethiopian Mapping Agency. Landsat ETM image for the month December 1999, Landsat TM for the months of December and September 1999, and Landsat MSS for the month of December 1979 were downloaded from NASA's GLOVIS website. The ASTER visible and near infrared level 1A product data was obtained from NASA'S Land Processes Distributed Active Archive Center (LP DAAC) website. Selection of the years for land use/cover classification was based on availability of data and the relatively good gap between the years for assessing the land use/change dynamics. Landsat Multispectral Scanner (MSS) images consist of four spectral bands with 80 m spatial resolution. The approximate scene size is 170 km by

185 km. Landsat Thematic Mapper (TM) images consist of seven spectral bands with a spatial resolution of 30 m for Bands 1 to 5 and 7. The spatial resolution for Band 6 (thermal infrared) is 120 m, but is resampled to 30-m pixels. The approximate scene size is 170 km by 183 km. Landsat Enhanced Thematic Mapper (ETM) images consist of eight spectral bands with a spatial resolution of 30 m for Bands 1 to 7. The resolution for Band 8 (panchromatic) is 15 m. All the bands can collect one of two gain settings (high or low) for increased radiometric sensitivity and dynamic range, while Band 6 collects both high and low gain for all scenes. The approximate scene size is 170 km by 183 km. ASTER covers a wide spectral region with 14 bands from the visible to the thermal infrared with high spatial, spectral and radiometric resolution. The spatial resolution varies from 15 m in the visible and near-infrared (VNIR), 30 m in the short wave infrared (SWIR), and 90 m in the thermal infrared (TIR) (Abrams, 2001). The scene size of ASTER images is 60 km by 60 km.

For the year 1957, stereo photo interpretation was done to generate the land use/cover classes. Texture, pattern, tone of the aerial photos and data from key informants were used for stereo photo interpretation. The stereo photo interpretation was made as detailed as possible. Individual patches of woody vegetation as small as about 100 m^2 were separately traced during the stereo interpretation of the aerial photographs. The aerial photos were then scanned with a high resolution scanner and ortho-rectified using ASTER derived DEM that has a resolution of 15 m. Though there is some data production time gap between the aerial photos and the ASTER DEM, ASTER DEM was used for ortho-rectification of the aerial photos due to its relatively better resolution over the data generated topographic maps. In addition, there still is a time gap between the production of the aerial photos and the local topographic map that made preference of using the ASTER DEM to the local topographic map. The nearest neighborhood was used for resampling. This whole process was done using ENVI 4.7. The stereo-interpreted data on transparent paper was then scanned and geo-referenced, and vector data was generated through onscreen digitizing. This vector data was overlaid on the rectified aerial photos and edited according to the 15 m photo resolution. The land use/cover description in Table 2-1 was used for interpreting the aerial photos. This same land use/cover description was also used in classification of the satellite images for the other years.

Table 2-1: Definition of the land use/cover classes in the Koga catchment

Land Use/Cover Class	Description
Woody vegetation	trees and shrubs with 20% or more crown cover that are taller than 2 m.
Crop field	land used for production of food
Bare land	areas characterized by bare rock, gravel, sand, silt, clay or other earthen material, with little or no green vegetation present
Pasture	areas used for cattle grazing including partially wet lands.
Settlement	Residential areas

The Landsat MSS data for the year December 1979 has a spatial resolution of 60 m. Regardless of the relatively lower spatial resolution of the 1979 Landsat MSS data as seen from Figure 2-4, an image with a better spatial and spectral resolution was produced by pansharpening the Landsat MSS image using large scale aerial photographs of January 1982. Pansharpening is an image fusion method in which high resolution panchromatic data is fused with lower resolution multispectral data to create a colorized high-resolution dataset. It is a pixel-level fusion technique that increases the spatial resolution while simultaneously preserving the spectral information in the multispectral image, giving the best of both worlds: high spectral resolution and high spatial resolution (Amro et al., 2011). This enables to produce images with improved interpretability. Though there is a one year difference in the time the MSS image and aerial photographs were taken, both data sets were used for generating the land use/cover map of 1979. This is due to the fact that there cannot be sudden significant changes in the land use/land cover classes within one year as long as there is no change in the policy of the government at that time, as confirmed by key informants and from personal observation of historical happening of such facts in the country. Principal Component Spectral Sharpening technique was used to sharpen the false color composite of December 1979 Landsat MSS multispectral data with a mosaic of high spatial resolution scanned aerial photographs of January 1982 that were ortho-rectified and resampled with a spatial resolution of 15 m. Principal Component Spectral Sharpening assumes that the low spatial resolution spectral bands correspond to the high resolution panchromatic band (ITT visual Information Solutions, 2009) and relies on the Principal Component Analysis (PCA) mathematical transformation (Amro et al., 2011). Ortho-rectification of the January 1982 aerial photos was done in the same way as that of the 1957 aerial photographs. The output image had a relatively better spectral and spatial resolution (see Figure 2-4). The ground truth data for some points of the study area at that particular time was obtained from the key community elders accompanied by data from the aerial photograph for supervised image classification. Supervised classification is the process of using samples of known identity from training samples (spatially explicit field work data) or secondary data (maps, literature, or knowledgeable informants) to classify areas of unknown identity (Castro et al., 2002). The most commonly applied supervised classification method is the maximum likelihood procedure because of its robustness (Serra et al., 2003). In a maximum likelihood supervised classification procedure, each pixel is evaluated for its statistical probability of belonging in each category of the land use/cover classes and assigned to class with maximum probability. Maximum likelihood classifiers, which are a widely used form of supervised classification, assume the training data statistics for each class in each band are normally distributed and calculates the probability that a given pixel belongs to a specific class. Maximum likelihood classifier was used in ENVI 4.7 for supervised classification of the pansharpened 1979 image and the classification had an overall accuracy of 96.17% with a kappa coefficient of 0.94. The kappa coefficient represents the level of agreement between the training samples and land use/cover values in the classified image. The maximum value for kappa occurs when the observed level of agreement is 1. A kappa coefficient of 0.60–0.80 represents good level of agreement while a kappa coefficient of greater than 0.80 represents very good level of agreement. When the same ground truth data were used to do the classification on 60 m spatial resolution false color composite of the 1979 LandSat MSS image, the classification has an overall accuracy of 77.78% with a kappa coefficient of 0.67 (Appendix A).

Pansharpening has improved the overall accuracy of the classification from 77.78% to 96.17% (Appendix B). In satellite based classifications using Landsat imagery, most authors have claimed accuracy of between 60 to 90 percent (Mango, 2010).

A false color composite of the December 1986 LandSat TM has the spatial resolution of 30 m. No pansharpening was done to this image, as there was no aerial photo of that area that time. Maximum likelihood classifier was used for supervised image classification using ground truth data achieved through the same techniques as that of the 1979 imagery. The classification has an overall accuracy of 87.97% with a kappa coefficient of 0.82.

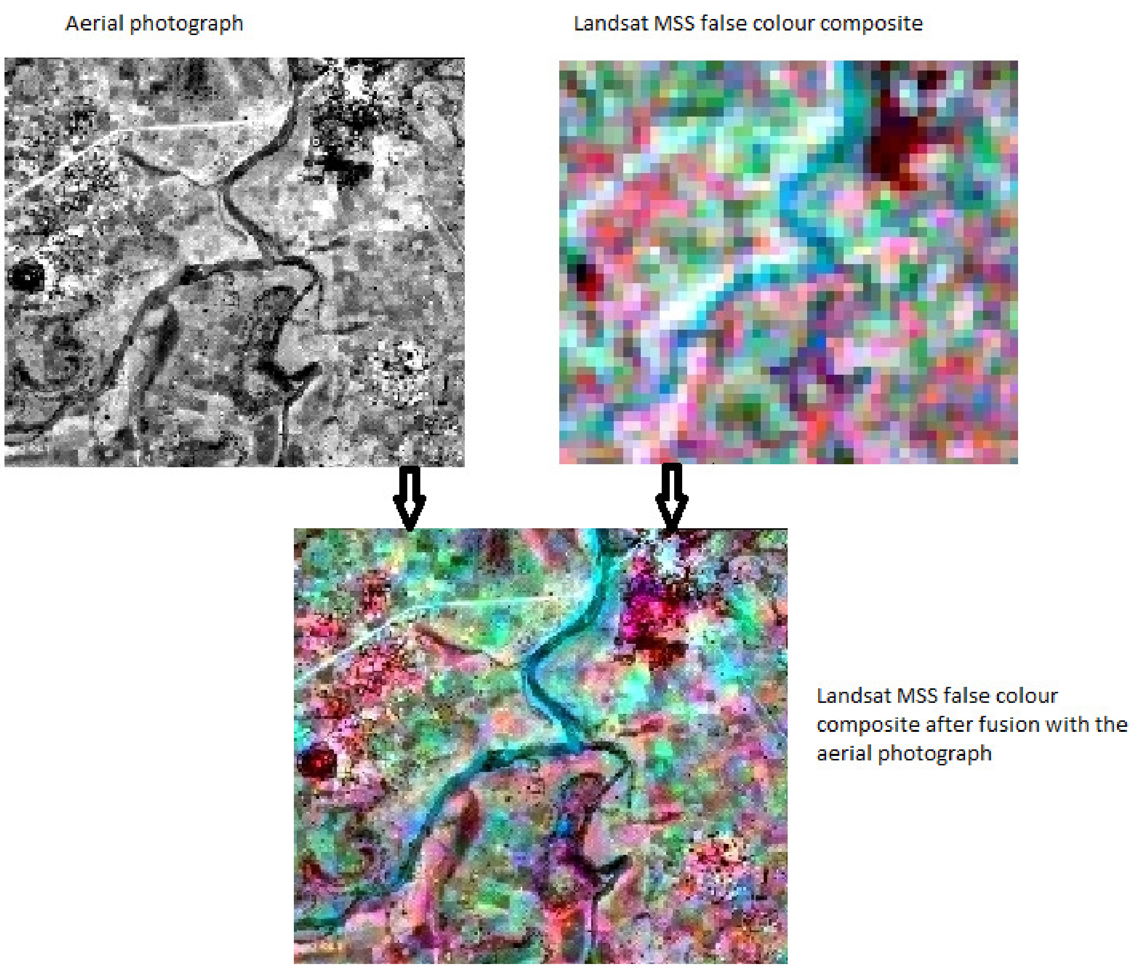

Figure 2-4: 1979 Landsat MSS false color composite of small part of the area around the .outlet of the Koga catchment before and after pansharpening

For the year 1999, a 30 m spatial resolution false color composite of the Landsat ETM was pansharpened by the panchromatic 15 m resolution of band 8. The ground truth data was collected by the same method used for 1957 and 1979 data. Maximum likelihood classifier was used for supervised image classification. A small part of the upper catchment of the study area was cloud covered in the Dec. image. Due to this, the cloud covered areas were masked and replaced by the September 1999 image that was classified with the same techniques as the December image. The 1999 classification has an overall accuracy of 96.5% with a kappa coefficient of 0.94. The data sources, number of ground truth points used and overall accuracy of the land use/cover classifications for all the years considered is summarized in Table 2-2.

Table 2-2: Data sources, number of ground truth points and overall accuracy of the land use/cover classification from 1957-2010

Year	Data Sources	Number of Ground Truth Points	Overall Accuracy	Kappa Coefficient
1957	December 1957 1:50,000 scale aerial photographs, 2011 ASTER DEM	70	-	-
1979	December 1979 Landsat MSS image of 60 m spatial resolution, 1:50,000 scale aerial photographs for January 1982	70	96.17	0.94
1986	December 1986 Landsat TM image of 30 m spatial resolution	70	87.97	0.82
1999	December and September 1999 Landsat ETM image of resolution 30 m with a panchromatic band of 15 m resolution	70	96.50	0.94
2010	August 2010 ASTER visible and near infrared image of 15 m spatial resolution	124	99.48	0.99

Since May 2003, there has been the malfunction of Landsat 7 due to failure of the Scan Line Protector (SLP) on board Landsat 7. For this reason, an image from the Advanced Space borne Thermal Emission and Reflection Radiometer ASTER, which is an imaging instrument onboard Terra (the flagship satellite of NASA's Earth Observing System), was used to generate the land use/cover map for the year 2010.

The HDF4 file format of the ASTER Level 1A product for the year August 2010 was downloaded from NASA'S LP DAAC website. The Level 1A product contains image data with geometric correction coefficients and radiometric calibration coefficients appended but not applied. The radiometric calibration and geometric correction was done by ENVI 4.7 from the HDF4 file. The false color composite was created from the visible and near infrared bands with a ground resolution of 15 m. A mosaic of two ASTER scenes was used as the study area was not completely covered with one scene. Ground truth data was collected through field visit for 124 points. Maximum likelihood classifier was used for supervised image classification. The classification has an overall accuracy of 99.48% with a Kappa coefficient of 0.99. The part of the reservoir that lies within the Koga catchment was separately digitized using the false color composite as a background image and was used to replace that particular area on the classified image to avoid some of the pixels in the classified image.

Finally, the classified images for all the years considered were clipped using the Koga watershed boundary for land use/land cover change analysis.

2.3 Results

The following are the results of land use/cover classification of the Koga catchment for the years 1957, 1979, 1986, 1999 and 2010 (Figure 2-5).

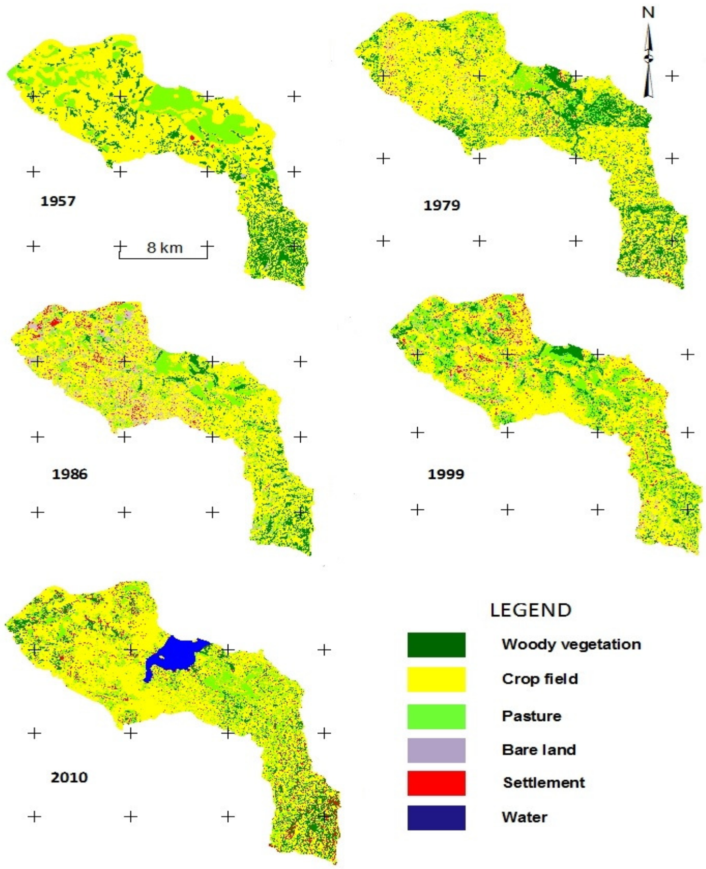

Figure 2-5: Land use/cover map of the Koga catchment

As referred from Table 2-3, there was a 46% loss of woody vegetation cover from the 1950s to 2010. ENVI change detection statistics show that 2,665 ha of the woody vegetation of the 1957 land use/cover was converted to crop fields, 372 ha into settlement, 620 ha in to pasture and 60 ha into water in 2010, which was mainly associated with the loss of natural woody vegetation. In addition, 33 ha of bare land, 1,663 ha of crop fields, 4 ha of settlement, and 418 ha of pasture from 1957 was converted to woody vegetation in 2010, which is attributed to the plantation of eucalyptus trees. Only 895 ha of the woody vegetation of the 1957 land use/cover remained as woody vegetation in 2010. In 1986, it was observed that 48% of the woody vegetation in 1979 was cleared that contributed to the increase in bare lands by five times until the year 1986.The sudden appearance of the water land use/land cover class in the 2010 classification is due to the construction of the Koga reservoir for irrigation of the downstream areas.

Table 2-3: Koga catchment land use/cover classes from 1957-2010 in hectares

	1957 (ha)	1979 (ha)	1986 (ha)	1999 (ha)	2010 (ha)	Change from 1957 to 2010 (ha)
Woody vegetation	5,576	4,587	2,388	2,738	3,012	↓2,563
Pasture	4,221	2,817	3,869	6,232	4,728	↑507
Crop field	16,080	17,521	16,122	15,022	15,683	↓398
Bare land	139	571.7	2,865	1,088	0	↓139
Settlement	36	566	832	984	1,535	↑1,499
Water	0	0	0	0	1,108	↑1,108
Agricultural land (pasture + Crop field)	20,302	20,338	19,991	21,253	20,411	↑109

Since all rural and urban land was under public ownership beginning from 1975, with the possession of rural land plots conditional upon residence in a village, the lack of belongingness of the woody vegetation resources by the individual communities in the transitional time was therefore the reason for much of the deforestation as confirmed by the key informants. Most of the destruction of the natural woody vegetation occurred between the 1970s and 1980s. From 1986, there is a gradual increase in woody vegetation until the year 2010. During field work in the catchment in 2011 and 2012, it was observed that farmers are increasingly planting trees, partly converting their crop fields into eucalyptus vegetation. From the year 1986 to 1999, and from 1999 to 2010, 1,321 and 1,076 ha of crop fields were respectively converted in to woody vegetation (Figure 2-6) where as the amount of woody vegetation that was converted to crop fields was only 809 and 747 ha from 1986 to 1999 and from 1999 to 2010 respectively.

The loss of fertility of the crop land from time to time is making the land unproductive unless plenty of fertilizers are used which sometimes is impossible for the low income farmers due to the unaffordable price of the fertilizers. Farmers in the area have started to consider planting trees especially eucalyptus trees that can be safely harvested at a relatively shorter time than other native woody vegetation types as a good source of income. The farmers believe that this would significantly reduce the labor they incur in farming their crop fields and avoid the cost of fertilizers they would have used for their crops. It is clearly observed and has also been noted by the informants of the area that most of the indigenous vegetation is being dominated by eucalyptus trees since the last 20 years as these species matures in a relatively short period of time, and because it can be sold before maturity as building material. The rational for the increasing interest in planting may include the high market demand and price of tree products and the need to earn more income with less labor. In general, there is an increasing trend in woody vegetation in the catchment since the 1980s. Most of the remaining natural woody vegetation is located around churches and along the Koga River.

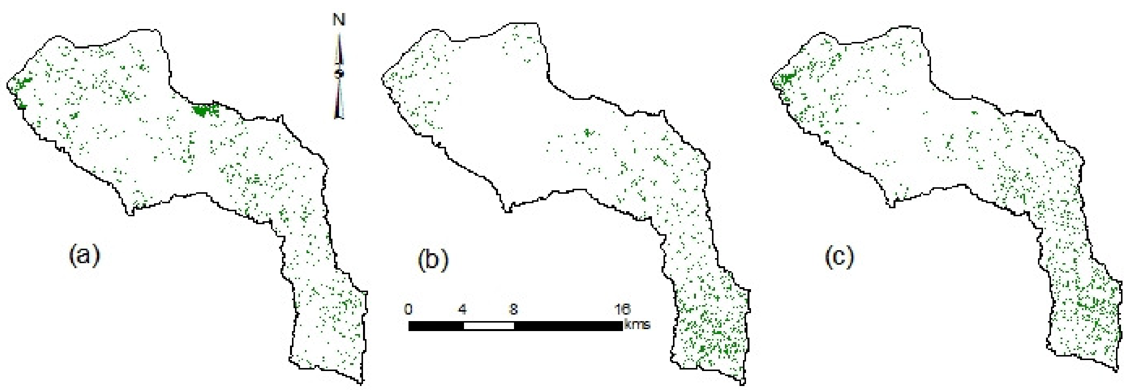

Figure 2-6: Map of crop fields converted to woody vegetation from 1986 to 1999 (a), from 1999 to 2010 (b), from 1986 to 2010 (c)

When the overall area coverage is considered, there is no significant change observed in the number of crop fields in the study catchment but there is a big change in the land holding per household due to increase in population. In 1984, the total population of the Mecha Woreda (district) within which the Koga catchment is located was 156,986 with 151,625 (97%) as the farming population. The number of farming families totaled 33,694 with an average family size of 4.5 persons at that time. According to the 1994 national census data, the total population for this woreda was 244,943 in 49,098 households, out of which 232,696 (95%) were rural dwellers. As of the 2007 census data, the total population of the Mecha woreda is 292,000 out of which 269,404 live in the rural part while 22,677 live in the urban part (CSA, 2007). The population of the woreda in which the catchment resides has increased by 1.5 times from 1984 to 1994 and 1.2 times from 1994 to 2007. The population has increased almost by double since the 1980s. This population has to share the same amount of crop field since the 1960s. Average land holding per household for crop land in 1993 was 2.44 ha (Acers International Ltd., 1995a; Acers International Ltd., 1995b) where as in 2001, the crop land holding per household decreased to 1.64 ha (Gebremedhin et al., 2007). Increasing population in the rural areas was thus absorbed in agriculture through leveling down of holdings, rather than through alternative forms of employment (Gebreselassie, 2006). In 1996, land was given to landless youth and returnee ex-soldiers in Amhara Region by reducing the holding of farmers who were reportedly associated with previous governments (Gebreselassie, 2006) where as in other regions communal grazing lands and wood land was allocated to new claimants. Most parts of the catchment have been continuously used for agricultural production for more than 50 years without significant conservation measures. Farmers are complaining about the fact that the once fertile land has been very much degraded and the productivity of the land is decreasing. Soil studies have showed nutrient deficiencies (Acers International Ltd., 1995c). Farming is practically impossible without use of fertilizers.

The livestock density in Mecha woreda is very high as compared to the national average (Acers International Ltd., 1995c). Koga catchment supports the largest cattle population density in the region (Ethiopian Ministry of Water Resources, 2004). Cattle play an increasingly important role in household budgets and coping strategies during times of drought in the study area (Acers International Ltd., 1995b). As per the 1993 Birr and Koga household survey data, the average livestock holding per household (excluding poultry) in the Koga catchment was 7.17 (Acers International Ltd., 1995c). From 1999–2001, the average livestock holding (excluding poultry) per household in the woreda was 5.36 Tropical livestock Unit (TLU) (Gebremedhin et al., 2007), which is equivalent to 9.3/household. This shows a 30% increase from 1993 to 2001. Mature cattle, donkeys, horses and mules can be considered 1 TLU each while small ruminants like sheep and goats can be taken as 0.2 TLU (Astatke et al., 1986). There has been an increasing trend in livestock in the area with the increasing population. In 2007, the income of the Mecha woreda people generated from livestock was almost half of the income generated from crops (Ethiopian Ministry of Agriculture and Rural Development, 2007). Agriculture is done with draught animals like oxen. Transportation of crops to markets is done with donkeys, horses and mules. These facts reflect that pasture is as equally important to the community as that of crop land. This is the likely reason why there was no significant change in the amount of pasture since the 1950s. In addition to the communal pasture lands, farmers use part of their crop fields to grow fodder for their livestock for the dry season and this same land is used to grow crops the next year.

As referred from Figure 2-7 and Table 2-3, the amount of agricultural area that includes the crop fields and pasture together has remained almost the same throughout all the years. An increase in the number of crop fields is accompanied by a decrease in the pasture land while a decrease in crop fields accompanies an increase in pasture making the total amount of agricultural land almost the same throughout all the years. The relatively lower amount of agricultural area in 2010 compared to that of 1999 is due to the Koga reservoir which has replaced 327 ha of woody vegetation, 363 ha of crop field, 352 ha of pasture, 14 ha of settlement and 37 ha of bare land from the land use/cover of the year 1999. The reservoir area has been at the expense of agricultural land and settlement areas. A number of inhabitants in the lower catchment of the area have been displaced due to the construction of the irrigation dam. Settlements had to be given up and people have escaped from the inundated parts of five kebeles and relocated themselves to either Merawi (closest town outside the catchment) or dry lands in the woreda (Irit and Tesfai, 2011). On the other hand, the irrigation dam has contributed to the conversion of bare lands either to settlement (due to relocation), or to crop fields, pasture and woody vegetation due to the availability of water for irrigation to the lower catchment in the dry season. A relatively higher percentage of the bare lands in 1999 were converted to crop fields in 2010. In 2010, there was practically no bare land in the catchment.

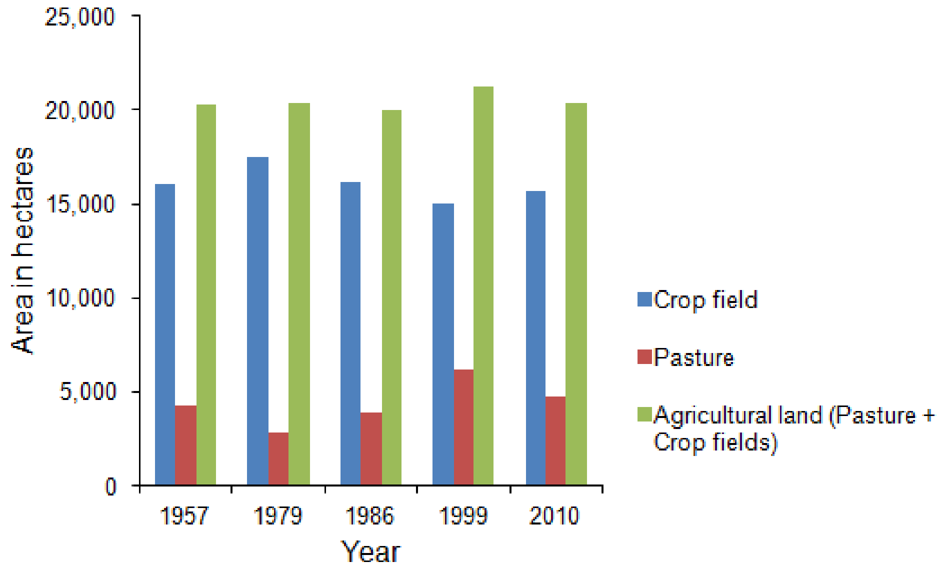

Figure 2-7: Change in Crop fields and Pasture (Agricultural area) in the Koga Catchment from 1957–2010

The increase in population has also been reflected by the increase in the area covered by settlement. The area covered by settlement in the year 2010 is 43 times greater than the settlement area in the 1950s. There has been a continuous increase in the area covered by settlements from 1957 to 2010.

2.4. Discussion

While a few land use/cover change studies used remotely sensed data from sources with a relatively similar scale (Baris et al., 2013; Bolca et al.,2012), differences in the scales of the input data were not taken into consideration by many authors that have used satellite images, mainly Landsat images for land use/land cover studies in different parts of the world like in Tanzania (Msoffe et al., 2011; Nduwamungu et al., 2008), in Uganda (Bernard et al., 2010; Egeru and Majaliwa, 2009); in Ghana (Braimoh, 2004), in

Nepal (Gautam et al., 2003; Rimal, 2005), in Kenya (Campbell et al., 2005; Mundia and Aniya, 2006; Serneels and Lambin, 2001) in Nigeria [Braimoh and Onishi, Fanan et al., 2011; Oyinloye and Kofoniyi, 2011; Oyinloye and Oloukoi, 2012], in Zimbabwe (Kamusoko et al., 2009), in India (Jat et al., 2008; Prakasam, 2010; Prakash and Gupta, 1998), in Turkey (Alphan, 2003; Hepcan et al, 2010; Reis, 2008), in Iran (Reveshty, 2011; Solaimani et al, 2010), and in Bangladesh (Dewan and Yamaguchi, 2009a; Dewan and Yamaguchi, 2009b; Dewan et al., 2012). Similarly, differences in the scales of the remotely sensed input data were not considered in most of the land use/cover studies that have been done in Ethiopia (Zeleke and Hurni, 2001; Alemayehu et al., 2007; Bewket, 2002; Mulugeta, 2011). Though all these studies have contributed a lot to land use/cover change studies, no reconciliation of the differences in scales were made when using different data sources. The image fusion techniques, more specifically pansharpening that was used in this particular study has enabled to bring the different data sources in to relatively similar scale to produce reliable land use/cover maps for comparison of the changes.

The 1979 image was acquired by one of the early generation of Landsat (Landsat 2). The 1986 scenes were acquired by the more advanced second generation of Landsat (Landsat 5) while the 1999 images were acquired from Landsat 7 Enhanced Thematic Mapper (ETM). On the other hand, the 2010 images are from the ASTER sensor. Regardless of the reconciliations for the differences in the scales of the input data, differences in the numbers and spectral ranges of the spectral bands and radiometric differences among images still affect the land use/cover change analysis. Radiometric differences among images are caused by inconsistencies of acquisition conditions such as seasonal changes, sensor variations, atmospheric properties, and sensor target-illumination geometry (Yang, 2000).

Different land use/land cover studies for some parts of Ethiopia indicate that croplands have expanded at the expense of natural vegetation, including forests and shrublands (Zeleke and Hurni, 2001; Alemayehu et al, 2009; Mulugeta, 2011; Fisseha et al., 2011; Kidanu, 2004; Shiferaw, 2011; Tegene, 2002; Tsegaye, 2010) while Tekle and Hedlund

(2000) reported increases in the size of open areas and settlements at the expense of shrublands and forests. Unlike many of the findings in land use/cover studies in Ethiopia, there have been almost no observed changes in the overall amount of area used for agriculture for about the last fifty years with increasing human and livestock population in the Koga catchment resulting in soil degradation due to over exploitation and erosion from the ploughed fields. Changes were observed only in the amount of cultivated land holding per household, which has been decreasing over time. There has been a significant change in the woody vegetation of the Koga catchment since the 1950s although there also has been an increasing trend in the woody vegetation after the 1980s. At the same time, the natural vegetation has increasingly been dominated by eucalyptus trees. This finding coincides with that of Bewket (2002) that indicated a decrease in woodlands and shrubland between 1957 and 1982 and in increase after 1982 in a watershed in the upper Blue Nile basin.

Awulachew *et al.* (2008) related deforestation, overgrazing, land degradation and declining agricultural productivity in the upstream part of the Blue Nile basin to high population pressure, lack of alternative livelihood opportunities and the slow pace of rural development. Shiferaw (2011) stated the reasons for changes in land use/cover were natural factors such as drought and climate change as well as human driving factors such as population growth, over intensification of farm sizes (Hurni et al., 2005), and land tenure policies (Reid et al., 2000; Tadesse, 2001). Zeleke *et al.* (2001) indicated an age-old tradition of clearing increasingly steeper land for cultivation and lack of appropriate land use policies, as reasons land use changes threatening soil degradation in North western Ethiopian highlands. In the Koga catchment, the growing human and livestock population is exerting much pressure on the environment resulting in degradation of the land that in turn is reflected by the increasing tendency of the farmers to shift to plantation of eucalyptus trees on their crop farms, and deforestation and degradation of the natural woody vegetation cover as confirmed by the key informants. Overuse of the agricultural land without appropriate conservation measures is facilitating erosion, which is reflected in the sediment laden runoff (Figure 2-3(a)) from the ploughed agricultural fields in the catchment. The Koga irrigation dam has also contributed to the change in land use/cover by replacing 1,042 ha of woody vegetation and agricultural land into water.

5. Conclusions

The land use/cover classification techniques used in this study has enabled to reconcile the differences in the scales of the different data sources for land use/cover change detection instead of the traditionally used land use/cover classifications and comparisons that do not take into consideration the differences in the scales of input images. However, it should be noted that the input data sets are different not only in spatial scales but also in other observation parameters such as the numbers and spectral ranges of the spectral bands and radiometric performances that still would affect the land use/land cover change analysis.

Analysis of the land use/cover shows that changes have occurred in the form of deforestation of the natural woody vegetation cover in the study area. There has been a significant change in the natural woody vegetation of the Koga catchment since the 1950s although there also has been an increasing trend of eucalyptus tree plantations after the 1980s. The deforestation of the indigenous woody vegetation and the relatively increasing trend in eucalyptus plantations may have a negative impact on the water balance of the catchment due to the high consumption of water by eucalyptus trees. While there almost is no change in the amount of area used for agriculture, the long term continuous use the agricultural area by the increasing human and livestock population has resulted in degradation of the land that is increasingly forcing the farmers to convert their farm plots to eucalyptus plantations. There has been a continuous increase in land used for settlement in the catchment with the increasing population.

The observed changes are associated with increasing human and livestock population and partly with changes in policy. The relationship between the local climate change and the land use/cover changes could be an important future research issue.

3. Temporal variation of Suspended Sediment transport in the Koga Catchment, North Western Ethiopia and environmental implications

Abstract

Event sediment transport and yield were studied for 45 events in the upstream part of the 260 km^2 agricultural Koga catchment that drains to an irrigation reservoir. Discharge and turbidity data were collected over a period of more than a year, accompanied by grab sampling. Turbidity was very well correlated with the sediment concentrations from the samples (r=0.99) which allowed us to estimate the temporal patterns of sediment concentrations within events. The hysteresis patterns between discharge and sediment concentrations were analyzed to provide insight into the different sediment sources. Anticlockwise patterns are the dominant hysteresis patterns in the area, suggesting smaller contributions of suspended sediment from the river channels than from the hill slopes and agricultural areas. Complicated types of hysteresis patterns were mostly observed for long events with multiple peaks. For a given discharge, sediment yields in August and September, when the catchment was almost completely covered with vegetation, were much smaller than during the rest of the rainy season. The hysteresis patterns and timing suggest that the sediment availability from the agricultural areas and hill slopes affects sediment yields more strongly than does peak discharge. Two distinct types of sediment rating curves were observed for the season when the agricultural land was covered with vegetation and when it was not, indicating the dominating contribution of land use/cover to sediment yields in the catchment. The rate of suspended sediment transport in the area was estimated as 25.6 t year^{-1} ha^{-1}.

3.1 Introduction

Many countries suffer from land degradation and from associated processes such as gullying, flooding, and sedimentation (Sadeghi et al., 2008). The economic implication of this is more serious in developing countries because of a lack of capacity to cope with it and also to replace lost nutrients (Tamene and Vlek, 2008). Soil erosion in the Ethiopian highlands is a natural phenomenon due to erosive rainfall and steep and undulating topography but is enhanced under agricultural systems that reduce protective soil cover (Guzman et al., 2013). The intensified use of the already stressed resources due to high population growth in Ethiopia makes soil erosion the most serious environmental problem affecting the quality of soil, land, and water resources upon which humans depend for their subsistence (Tamene and Vlek, 2008; Shiferaw and Holden, 1999). The annual rate of soil loss is significantly higher than the annual rate of soil formation rate in the country.

Estimates of sediment yield and its temporal variation are needed for various purposes including design of erosion control structures (Russel et al., 2001), river morphological computations, and evaluation studies of the effects of various land use management practices (Sadeghi et al., 2008; Gao and Pasternack, 2007; Gao and Puckett, 2011). Understanding and quantifying erosion is important in highly erodible catchments that eventually contribute to siltation of downstream reservoirs (Lopez-Tarazon et al., 2009; Guzman et al., 2013; Gao and Puckett, 2011), especially with storms of high rainfall intensity where runoff occurs over highly unconsolidated sediments on agricultural areas (Nyssen et al., 2008). Once sediments reach the reservoirs, siltation becomes a long-term socio-economical problem because it reduces water storage capacity (Lopez-Tarazon et al., 2009).

Sediment supply in a catchment is heterogeneous in time and space depending on climate, land use and a number of landscape characteristics such as slope, topography, soil type, vegetation and drainage conditions (Marttila and Klove, 2010). The investigation of suspended sediment concentration (SSC) discharge relationships of individual events allows inference of the dominant origins and processes contributing to suspended sediment (SS) dynamics of a basin (Lefrancois et al., 2007; Gao and Puckett, 2011; Smith; Dragovich, 2009; Sadeghi et al., 2008). The relationship between discharge and sediment concentration usually presents a hysteretic loop which can be classified according to their symmetry, and their clockwise or anticlockwise hysteresis (Gentile et al., 2010; Jansson M., 2002; Smith and Dragovich, 2009; Lefrancois et al., 2007). Variability in the SSC-discharge relationship has been studied to identify sediment origins on catchments of varying sizes. The features of the hysteresis loops have been attributed to the location of the sediment source in the basin, the river bed, or the river banks (Jansson, 2002; Gao and Puckett, 2011; Smith and Dragovich, 2009). Clockwise loops have often been related to the depletion of available sediments in the catchment or in the stream channel or the successive reduction of the erosive effect of rainfall (Jansson M., 2002; Gao and Josefson, 2012). An anticlockwise hysteresis usually reflects sufficient hillslope sediment supply, delayed in-channel sediment resuspension caused by the late break-up of biofilms, additional sediment sources from channel banks or tributaries, or variable rainfall patterns (Gao and Josefson, 2012). The clockwise hysteresis between SSC and discharge is regarded as a normal condition for most fluvial systems where suspended sediment transport is mainly caused by precipitation-induced flooding (Gao and Puckett, 2011).

In the Ethiopian highlands, sediment delivery depends on discharge, the onset of rainfall, land use and land cover which vary between rainfall seasons (Awulachew et al., 2010). Because of this, sediment rating curves are complex and sediment budgets have rarely been established (Nyssen et al., 2007). While a number of studies have been performed in small catchments (Marttila and Klove, 2010; Eder et al., 2010; Lefrancois et al., 2007; Sadeghi et al., 2008; Smith and Dragovich, 2009; Gao and Pasternack, 2007) much less is known about the sediment dynamics in medium scale catchment (Gao and Josefson, 2012). The aim of this paper is to quantify the temporal variability of sediment yield from a medium sized catchment in the Ethiopian highlands, and identify the dominant (possible) sediment sources and generation mechanisms. This paper also assesses the future environmental implications of sediment delivery in the study area.

3.2 Materials and Methods

3.2.1 The Study Area

3.2.1.1 Location, Climate and Topography

The considered study area is 9838 hectares in size and represents the upstream part of the 260 km^2 Koga catchment (Figure 3-1) in northwestern Ethiopia. The Koga catchment is a typical catchment for the Ethiopian Highlands, 72% of which is used for subsistence agriculture. The Koga River is a tributary of the Gilgel Abbay, which flows northwest into Lake Tana, and lies in the upper part of the Blue Nile (Abbay) watershed.

The climate of the Koga catchment falls within the Woina Dega (cool semi-humid, 1,500 to 2,400 m asl) and Dega zones (cool, above 2,400 m asl). The majority of the catchment area lies within the Woina Dega zone and is characterized by distinct dry and wet seasons. The dry seasons occur between November and April and the wet season between May and October; small rains occur sporadically during April and May. The mean annual rainfall for the catchment is 1550mm (period 2006-2010). The mean daily temperature is 18.25 ℃. The monthly mean maximum temperature varies from 30.0 ℃ in March to 23.7 ℃ in August. The monthly mean minimum temperature varies from 5.4 ℃ in December to 13.1 ℃ in May and June. Whereas the land elevation of the Koga catchment varies from 1,875 m asl at the mouth of the Koga River to 3,215 m asl at its highest point on the watershed divide, the considered study area has its lowest elevation of 2015 m asl at its mouth where it joins the Koga reservoir. The Koga reservoir (Fig. 1) is used for irrigation of the downstream areas. The Koga River flows at a distance of 26 km before it joins the Koga irrigation reservoir and a distance of 49 km before it joins the Gilgel Abbay, which eventually flows into Lake Tana. The Koga catchment is generally elongated with a pronounced narrowing above the Village of Rim where the mean width of the catchment is only 3.8 km. The course of the Koga river is northerly up to the village of Rim and then westerly to Wetet Abbay.

3.2.1.2 Geology and Soils

The regional geology of the Koga catchment comprises extensive flow type, volcanic (extrusive) rocks mainly of the Ashangi Group; these were deposited during the palaeocene-Oligocene-Miocene (Teritiary) stages of geological time. The Ashangi group comprises the older volcanic rocks, which were formed by lava and debris, ejected from fissural volcanic eruptions. The Choke shield volcanic group, deposited during the Miocene and Pliocene, has covered a small area of the Upper Koga catchment in the Eastern part. The Shield volcanic group consists mainly of pyroclastic basalt and is petrographically similar to the Ashangi group. The soil types within the upper part of the Koga catchment we studied are Luvic Phaeozems (Typic Argiustolls), Chromic Cambisols (Fluventic and Typic Ustropepts), Lithic Leptosols (Lithic Ustropepts), Haplic Alisols (Typic Paleustults), Eutric Vertisols (Ustic Tropaquepts) and Eutric Gleysols (Typic Tropaquepts). These soils have clay to clay loam texture with the exception of Eutric Gleysols (Typic Tropaquepts) that has clay to sandy clay loam texture.

3.2.1.3 Population and tillage practices

The total population of the Mecha woreda, within which the Koga catchment is located, is 292,000, of which 269,404 live in the rural part while 22,677 live in the urban part (CSA, 2007). Subsistence rain fed production of cereals comprising teff, maize, barley and millet, as well as pulses, oilseeds and some legumes is dominant in the area while irrigated agriculture takes up a small percentage of the cultivated area of the Koga catchment. Soil tillage is done with oxen-drawn ploughs. There exist some attempts to prevent soil erosion through soil and water conservation structures such as stone stacks along with tree planting (Figure 3-11e), storm water diversion channels, soil bunds (Figure 3-11c), channel and orchard terraces, contour cultivation, etc. though not based on sufficient study as to which of these are most effective in controlling soil erosion in the catchment. Crop cultivation is the main source of income followed by livestock for the poor farmers in the area.

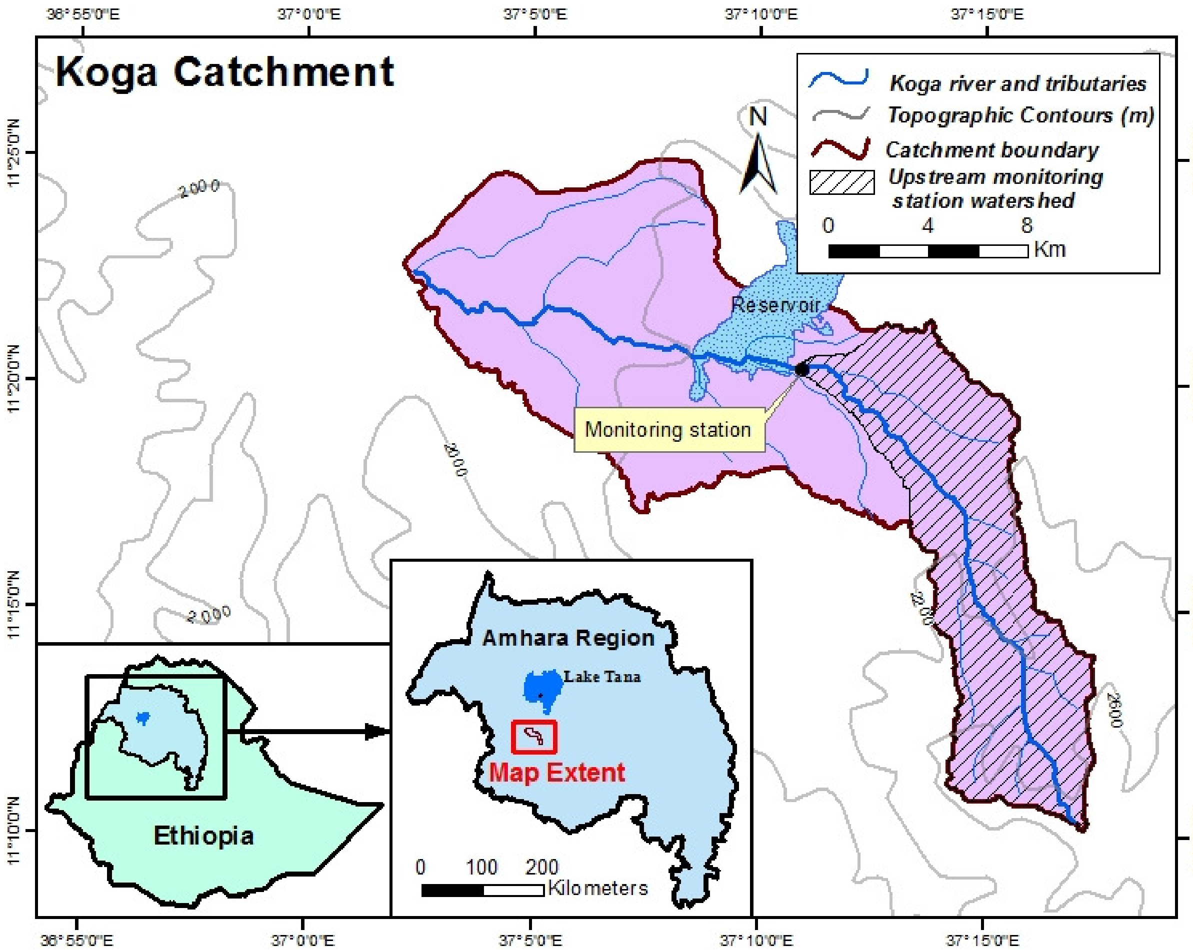

Figure 3-1: Location Map of the Koga Catchment

3.2.2 Methods

3.2.2.1 Event data collection and developing a relationship between turbidity measurements and SSC

A hydrological monitoring station consisting of pressure transducer, DTS-turbidity sensor, axiom data logger and staff gauge have been installed along a relatively stable and relatively steep cross section in the Koga catchment (Fig. 3-1). The station was installed just above the Koga reservoir along the river that serves for irrigation of the downstream areas. The DTS-turbidity sensor was put around the middle of the horizontal cross section and was moved up or down in the different seasons depending on the flow conditions so that it remained, approximately, at the midpoint of the vertical section of the flow. Though it is expected that there is a difference in suspended sediment concentrations both vertically and horizontally along river cross sections, some researchers have indicated that the difference in SSC may be small at low flows (Gao and Josefson, 2012), with an average spatial variation of 9% of the mean of all samples collected along the vertical and horizontal cross-sections at a time (Lopez-Tarazon et al., 2009). Gao et al. (2007) indicated that grab samples at a point of a cross section can be regarded as the averaged sample over the cross section at any time. For high flow conditions, mixing increases which will make the measurements from the turbidity sensors more representative of the whole cross-section although entrainment from the river bed and river bank may lead to layering of the sediment concentrations. Given that most of the sediment comes from the hill slopes (see later in the paper) the latter effect is probably small. Some biases due to the sensor position may still have occurred which would be of interest to analyze in more detail. The DTS-turbidity sensor was factory calibrated and it was able to prevent biofilm growth on the sensor by a wiper that wipes the sensor system every 30 seconds. A rating curve was developed for the cross section using Manning's equation accompanied by several velocity measurements for various water levels (high flows and low flows) using current meter and floating devices. We set up the monitoring station in a relatively stable and steep cross section to minimize sediment deposition along the cross section. Considering the possibility of inundations at the monitoring station, the data logger was placed at considerable height. While there were several events that produced nearly bank full peak flows, none of the events exceeded the bank full discharge at the monitoring station in the study period. This was because of upstream inundations resulting from small weirs across the stream that have been used for irrigation during the dry season by individual upstream farmers. The shapes of the hydrographs suggest, however, that the upstream flows into the flood plains were relatively small. The bank full discharge is $47.6 m^3/s$ at the monitoring station.

Using the Axiom data logger, we were able to have a continuous record of water turbidity expressed in NTU (nephelometric turbidity units) and water level data in meters for one year starting from Oct. 2011 to Oct. 2012. In addition, 257 water grab samples were collected manually with 500 ml plastic bottles from along the mid of the river for 25 events. 4 to 12 samples per event were collected at 10 to 15 minutes intervals. Sample collection was based on convenience for collection either for the rising limb, falling limb or both without preference to any of the rainfall events. The sampling process did not cover the whole duration of an event and was much less than the total duration of any of the 45 events as also seen on Figures 3-3 (a &c), Figure 3-4 (a), and Figure 3-5. Samples were collected either for the rising limbs, peaks, for the falling limbs or combinations of these three for the different events that in turn makes the sampling process representative of the 45 events for creating suspended sediment concentration-turbidity relationship. From the 257 samples collected, 222 were analyzed for suspended sediment concentration at the national and regional water bureaus. The remaining 35 samples were disregarded since leakage of part of the sample occurred before reaching the labs due to a failure to close the bottles tightly.

A relationship between turbidity measurements and suspended sediment concentration was developed based on the SSC values of the collected samples. Out of the 222 samples analyzed for SSC, 179 samples were used for establishing the relationship between turbidity and SSC. The remaining 43 samples were excluded as they were either outliers or had extremely low turbidity readings for events with extremely large SSC values (up to 22000 mg/l). Using the 179 samples, we were able to get a very good correlation coefficient (R^2=0.987) between turbidity values and sample SSC values. Because of the excellent correlations, estimated sediment concentrations for events without samples were also considered reliable. Although texture analysis was not done on the suspended sediment from the water grab samples, previous soil studies in the catchment suggest that 85% of the upper catchment has a soil texture ranging from clay to clay loam (Acers International Limited & Shawel Consult, 1995d). Soil texture analysis made on 12 soil samples we took from the different soil types in the catchment indicated that the upper catchment does have soil texture ranging from heavy clay to loam. This reduces the potential effect coarser suspended sediments would have had on the turbidity-suspended sediment concentration relationship especially during high flows. Turbidity values of some of the events in June exceeded the measurement range of the turbidity sensor and in that case the turbidity sensor recorded only its maximum limit (1797 NTU). For those events, the suspended sediment yield is a little underestimated.

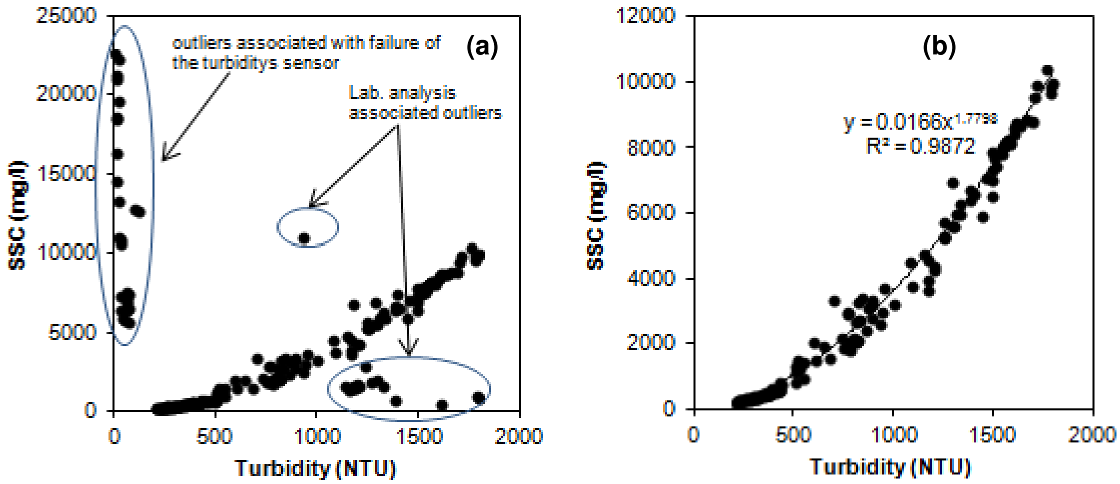

Figure 3-2: SSC-Turbidity relationship before (a) and after (b) removing outliers

3.2.2.2 SSC-discharge hysteresis analysis

Hysteresis patterns of SSC were generated and analyzed for a link to the likely sediment sources and transport processes. Hysteresis analysis was done by the classic visual analysis as it was found to give more reliable information than other methods (Gao and Josefson; 2012).

3.2.2.3 Calculating SSY and examination of the relationship between SSY and Q_{peak}

We summed up the suspended sediment yield (SSY) calculated every ten minutes throughout the event to generate the SSY of each event. To have a good estimate of total sediment yield of each event, we examined whether or not there is a trend in suspended sediment concentration beginning from an hour before the start of the event until the start of the event. If there was a decreasing trend in sediment concentration before the start of the event, the corresponding sediment yields were calculated from the sediment concentrations, and the rate of decrease in the sediment yield was considered when subtracting the amount of sediment before the start of the event from the sediment yield of the event. If there was no trend in the sediment yield before the start of the event, the amount of sediment yield just before the start of the event was subtracted from the event flow. This is believed to increase the accuracy of the estimated event sediment yield. The relationship between SSY and Q_{peak} was then analyzed for each event and for each month to identify the seasonal variation and sediment sources in the study area. In this study, we considered only suspended sediment load that makes the major part of the total sediment load. However, it should be noted that transport of materials like soil aggregates and sand and gravel size materials as a bed load may contribute to the total sediment load. We calculated the SSY for each event to determine the major sediment sources due to the fact that sediment transport in the study area is mainly associated with a few erosive events throughout the hydrological year. The yearly sediment yield was calculated based on the continuous discharge and turbidity values for one hydrological year using the established relationship with sample SSC. For the few missing SSC data for the June events when the turbidity sensor failed, we used the rating curve we developed based on Q_{peak} for calculating the sediment yield for that particular time. This might add some uncertainty to the SSY estimates for these points in time.

The main rainy season in the catchment is June, July and August. The rainfall starts to decrease in September and significantly decreases in October, with little or no rainfall in November. We started data collection in October 2011 when the rainfall was decreasing. The major rainy season started in June 2012 which was a little later than usual. This was the time when the crop fields were ploughed in preparation for cultivation in the major rainy season. The cultivated land and most of the pasture was completely devoid of vegetation in early June. While the pasture land is green by mid-June, crops start to grow towards the end of June, and most of the cultivated crop fields are at an early stage of crop growth and do not turn green until mid-July. From around mid July the cultivated land begins to be covered with vegetation. Around mid August until the end of September, the catchment is almost completely green and covered with vegetation. Crop harvest of most of the crops begins in early October. Part of the cultivated land that is close to the river became swampy from mid July until the end of September and was ploughed and made ready for sowing in early October. These vegetation dynamics were accounted for when interpreting suspended sediment yield.

3.3 Results and discussions

3.3.1 SSC-discharge hysteresis analysis

We observed 5 types of hysteresis: anticlockwise (A), clockwise (C), two types of 8 shaped anticlockwise-clockwise-anticlockwise (ACA) and clockwise-anticlockwise-clockwise (CAC), and complicated patterns. While most of the events with single peak discharge and short peak discharge time showed any of the first four hysteresis patterns, events with multiple peak discharges or prolonged single discharge time showed complicated patterns.

While the September events showed all the above-named 5 types of hysteresis (Table 3-1 and Figure 3-6a), the events with clockwise hysteresis showed much larger sediment yields than those with anticlockwise hysteresis and other types of hysteresis for similar peak discharges (Table 3-1). Flow for the event 27-28/9/2012 with a peak flow of 16 m^3/s and clockwise hysteresis had a sediment yield of 89.8 tons while the event 10/9/2012 with the same peak flow and with anticlockwise hysteresis had a sediment yield of only 17.6 tons. The same is true of the event 4-5/9/2012 with a peak flow of 30.27 m^3/s and a clockwise hysteresis (flow duration of 8:50 hrs) as compared with the event of 1/9/2012 that had the same peak flow but anticlockwise hysteresis (flow duration 12:20). This suggests more sediment is generated from the river channels than from other sources in September. This is because crop vegetation cover in September is higher than in the other months of the year and sediment contribution from the agricultural areas is less in this month than in the previous months.

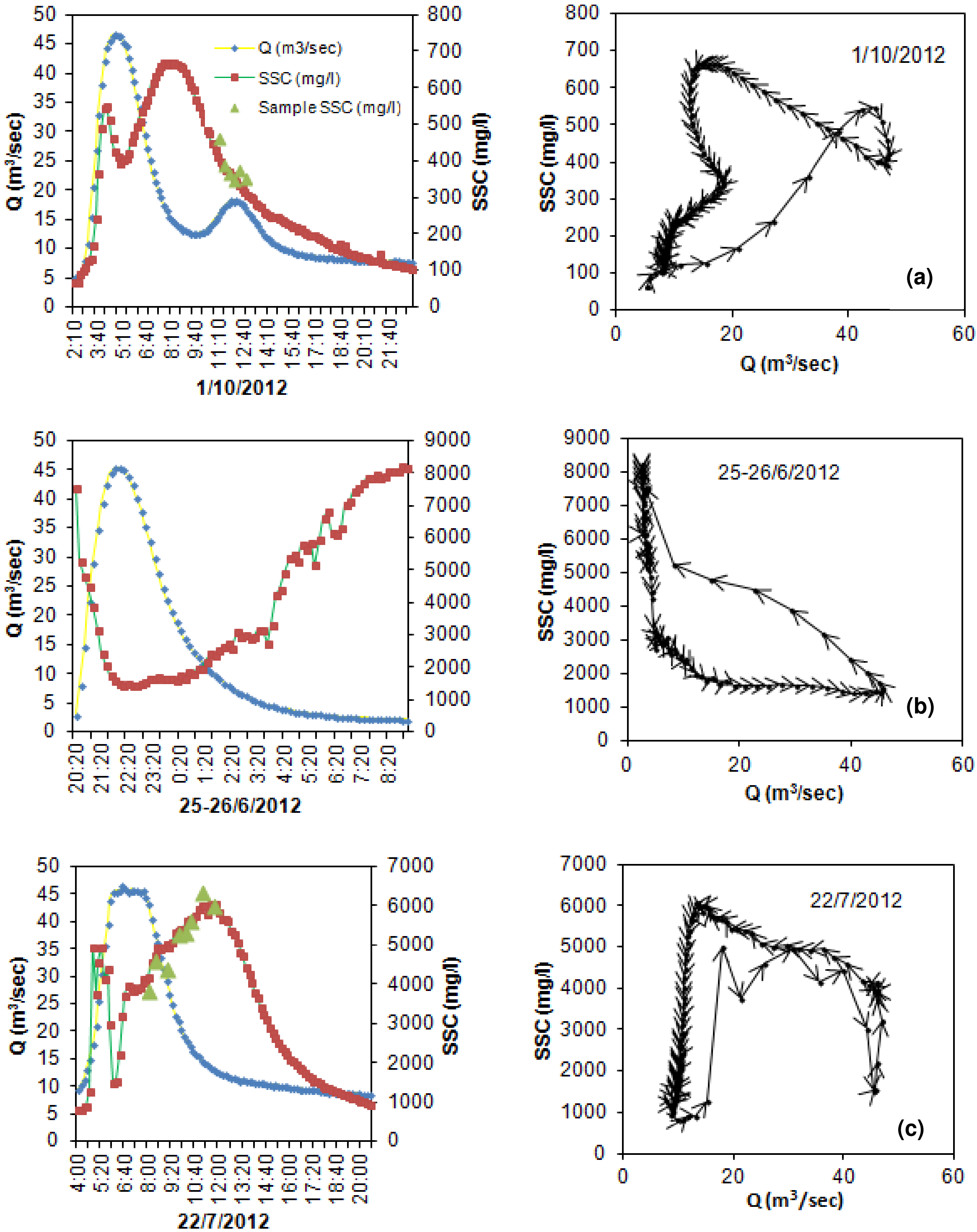

Figure 3-3: SSC-discharge hysteresis loops of (a) ACA; and (b & c) anticlockwise patterns of some of the events

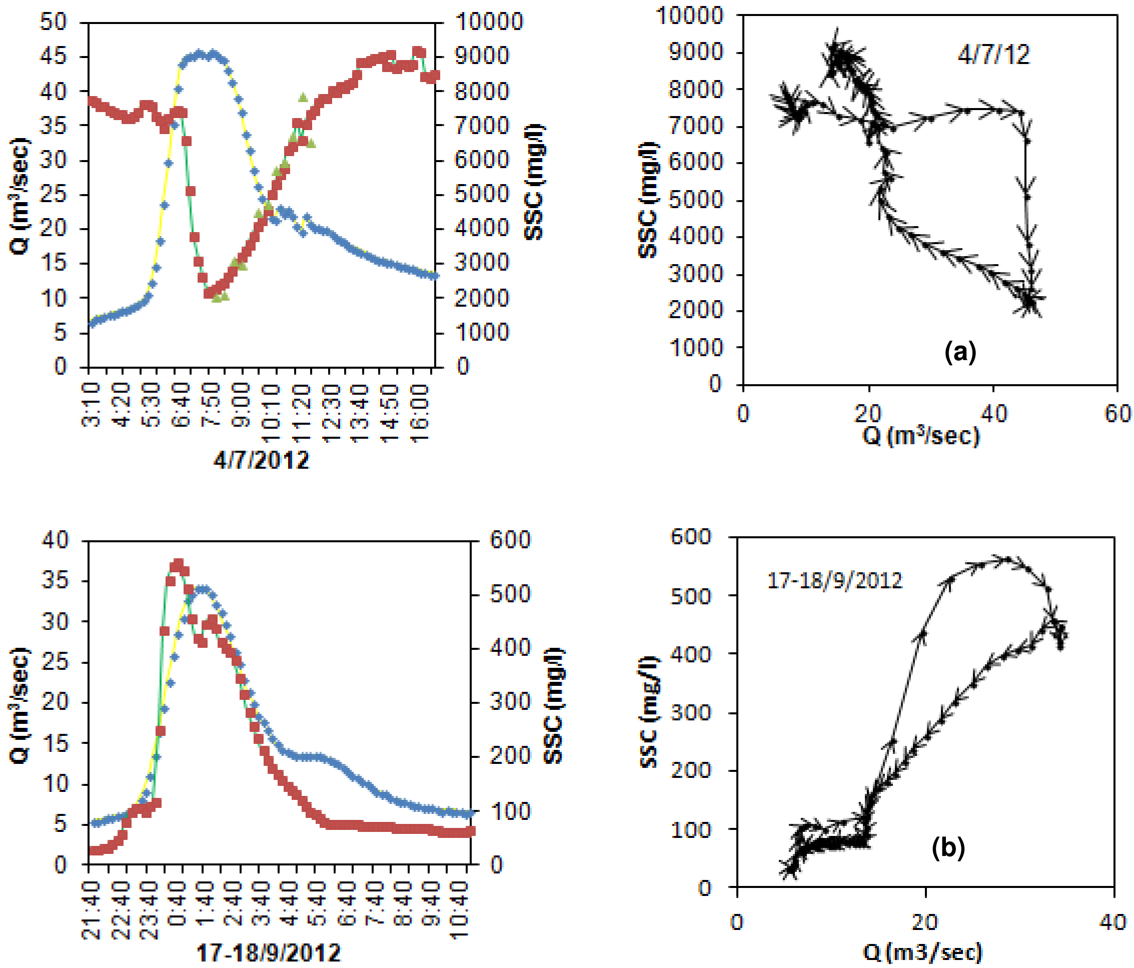

Figure 3-4: SSC-discharge hysteresis loops of (a) CAC and (b) clockwise patterns

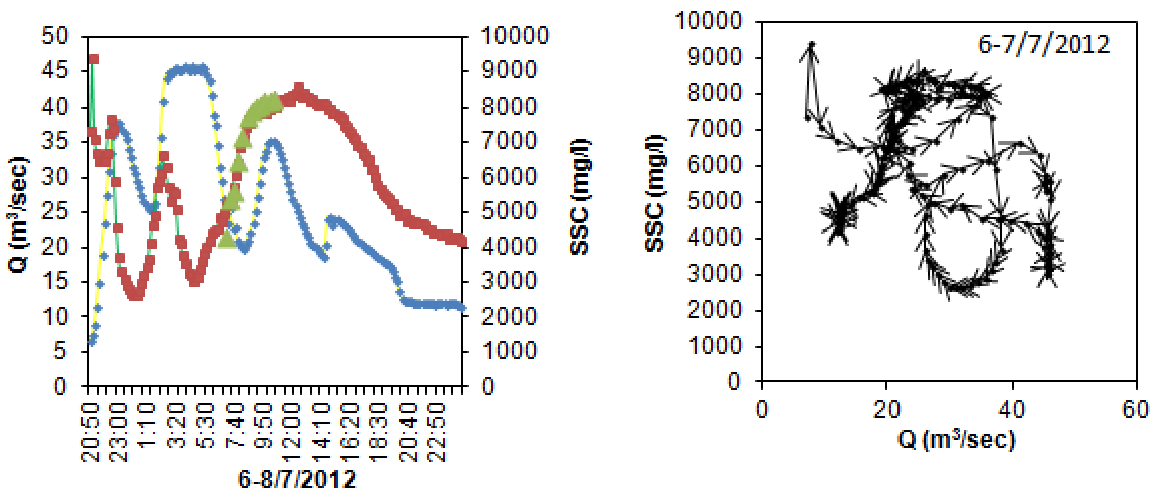

Figure 3-5: SSC-discharge hysteresis loop of a complicated pattern

Sediment yields after mid August are much smaller than sediment yields before mid August for similar peak flows (Table 3-1). Nearly all the August events showed complicated hysteresis patterns except two of them in late August that showed anticlockwise patterns (Figure 3-6a). Anticlockwise hysteresis patterns showed much less sediment yield than those with complicated patterns.

July events mainly showed anticlockwise and complicated patterns but for events with similar peak flows, the ones with complicated hysteresis types showed higher amounts of sediment yield, followed by events with anticlockwise hysteresis patterns. Events with clockwise hysteresis had the lowest amount of sediment yield, indicating channel sources are less important sources than other sources for this month, while at the same time it indicates that complicated environmental conditions are involved in sediment transport. All the four June events showed three types of hysteresis patterns (anticlockwise, clockwise, and complicated). A large event in June with a complicated hysteresis pattern showed much greater sediment yield than an event with similar magnitude but an anticlockwise pattern. The clockwise hysteresis patterns of June and July events tend to be associated with sediment entrainment from deposition of antecedent runoff events, especially when there is a relatively short time gap between successive events that reduces the time of subsurface flows to transport the deposited sediments before the succeeding events. For example, the Q_{peak} time gap between the successive events 27/6/2012 - 27_28/6/2012 and the successive events 1_2/7/2012 - 2_3/7/2012 is 23 and 21 hours respectively, and they resulted in clockwise patterns to follow anticlockwise patterns in the first events. However, this pattern does not seem to be consistent for the consecutive events of 25_26/6/2012 - 27/6/2012 with a Q_{peak} time gap of 30 hours which both showed anticlockwise hysteresis patterns. More work would be needed to shed light on the effect of consecutive events on hysteresis patterns. Regardless of peak flow or duration of flows, all October events and the one November event showed A-C-A hysteresis pattern, except for the small mid October event that showed an anticlockwise hysteresis.

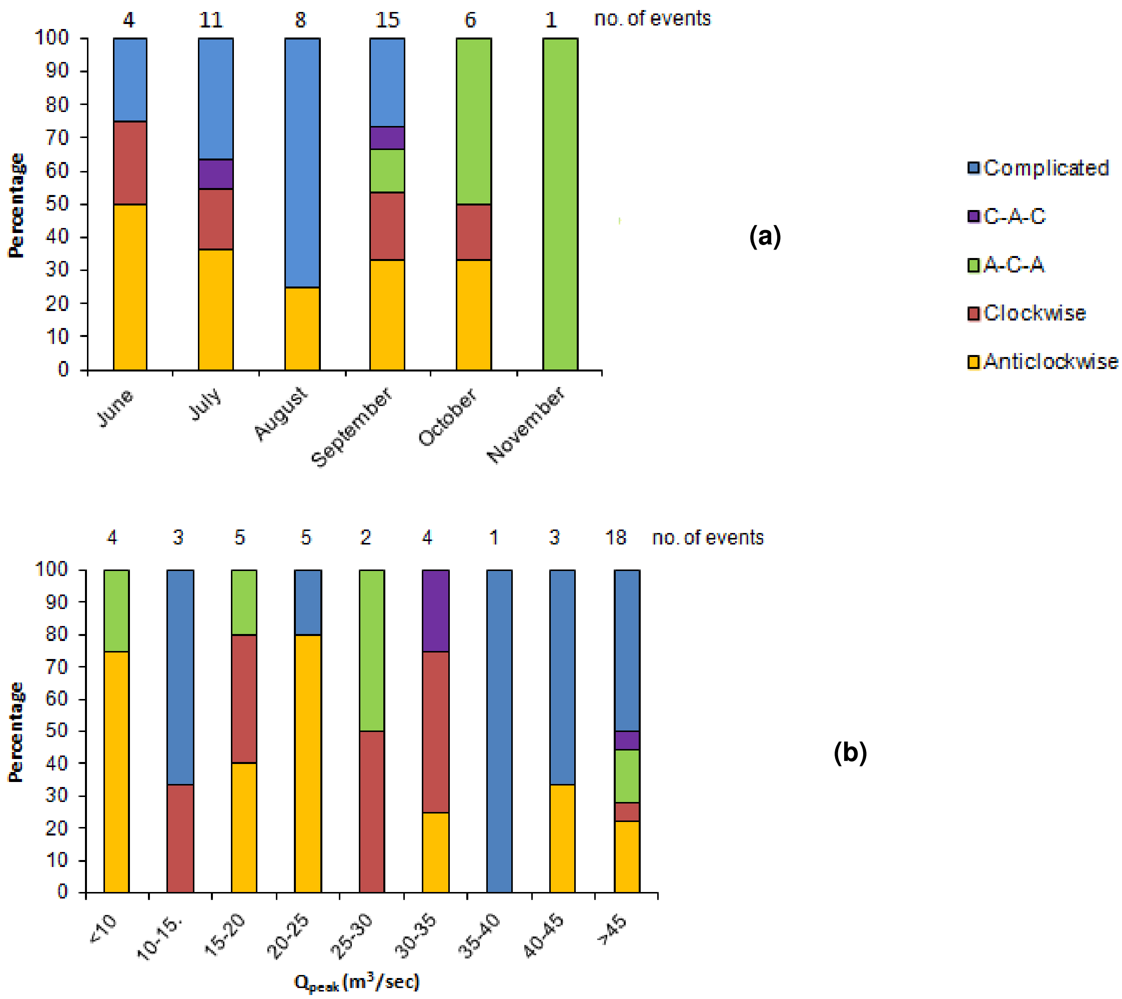

Figure 3-6: Percentage of hysteresis patterns observed for the considered 45 events a) for each month, b) versus peak discharge

Table 3-1: Characteristics of discharge and sediment concentration and hysteresis patterns of the 45 events in the Koga catchment

Date	Qmean (m^3/sec)	Qpeak (m^3/sec)	SSC mean (mg/l)	SSY (tones)	Hysteresis pattern	Duration (hours)
8/10/2011	10.8	15.2	3987	3647	A-C-A	20:20
8_9/10/2011	10.0	16.1	1405	820	A	15:50
1/10/2012	16.23	46.8	322	446	A-C-A	20:40
2/10/2012	13.0	28.3	252	239	A-C-A	19:40

Table 3-1: Cont'd

Date	Qmean (m^3/sec)	Qpeak (m^3/sec)	SSC mean (mg/l)	SSY (tones)	Hysteresis pattern	Duration (hours)
15/10/2011	0.3	0.7	636	7	A	8:20
30_31/10/2011	5.8	17.9	8175	1924	C	10:30
3/11/2011	1.4	3.7	4416	388	A-C-A	16:20
25_26/6/2012	13.8	45.5	4228	1502	A	12:40
27/6/2012	3.7	6.2	4602	468	A	9:10
27_28/6/2012	5.1	13.0	3024	479	C	16:00
30/6/2012	19.6	45.9	3866	3080	Complicated	15:50
1_2/7/2012	10.2	23.7	2785	831	A	8:50
2_3/7/2012	14.1	25.8	3581	1032	C	6:00
3/7/2012	22.0	32.6	7104	8778	C-A-C	15:30
4/7/2012	22.8	45.9	6814	3831	C	13:20
6/7/2012	12.2	22.5	8719	1445	A	9:30
6_7/7/2012	25.8	38.0	5918	9630	Complicated	28:00
8/7/2012	19.5	43.6	5635	5352	A	18:40
14_15/7/2012	32.4	46.5	6420	12146	Complicated	20:30
15_16/7/2012	30.49	45.6	3704	7675	Complicated	24:00
22/7/2012	19.16	46.7	3437	3804	A	16:30
25_26/7/2012	30.02	46.4	1930	6717	Complicated	30:00
6/8/2012	17.52	44.9	792	1231	Complicated	18:40
17_18/8/2012	34.09	44.0	599	848	Complicated	12:40
23-24/8/2012	22	46.7	330	1087	Complicated	30:20
26/8/2012	21.2	46.6	469	511	A	12:40
28/8/2012	22.9	46.0	479	675	Complicated	14:50
31/8/2012	13.5	20.3	214	70	A	7:30
31/8_1/9/2012	25.0	46.7	454	697	Complicated	17:40

Table 3-1: Cont'd

Date	Qmean (m^3/sec)	Qpeak (m^3/sec)	SSC mean (mg/l)	SSY (tones)	Hysteresis pattern	Duration (hours)
1/9/2012	15.5	31.1	258	136	A	12:20
2_3/9/2012	27.4	47.0	452	536	A-C-A	12:00
3_4/9/2012	9.8	10.4	128	28	Complicated	11:40
4_5/9/2012	15.1	30.3	424	194	C	8:50
6/9/2012	22.0	46.3	313	387	A-C-A	11:40
6_7/9/2012	22.6	46.9	412	600	C-A-C	19:00
9_10/9/2012	9.1	21.5	195	98	A	7:50
10/9/2012	11.9	16.3	110	18	A	7:00
12_13/9/2012	7.9	12.4	102	33	Complicated	11:50
16/9/2012	12.5	20.7	247	104	Complicated	10:20
17_18/9/2012	14.8	34.3	178	179	C	13:20
25/9/2012	5.1	8.9	177	29	A	13:10
26/9/2012	14.8	46.7	529	405	Complicated	13:40
26_27/9/2012	23.7	47.4	664	518	A	10:20
27_28/9/2012	10.8	16.0	206	90	C	19:10

3.3.2 SSY and relationship with Q_{peak}

The relationship between suspended sediment and discharge reflects the overall pattern of erosion and suspended sediment delivery operating in the catchment area, shedding light on basin suspended sediment response (Walling and Webb, 1982). In our study area there was a good relationship between the peak flows and sediment concentration for the 15 events in September with a correlation coefficient of 0.88. All the September events, whether high or low, were associated with lower sediment yields than similar events in other months of the rainy season. The hysteresis patterns suggest that the contribution of sediment yield from the river channel is more important than contributions from the agricultural areas and hill slopes for this month. The dominance of channel erosion as a sediment source may explain the good correlation between sediment yield and peak flow in September.

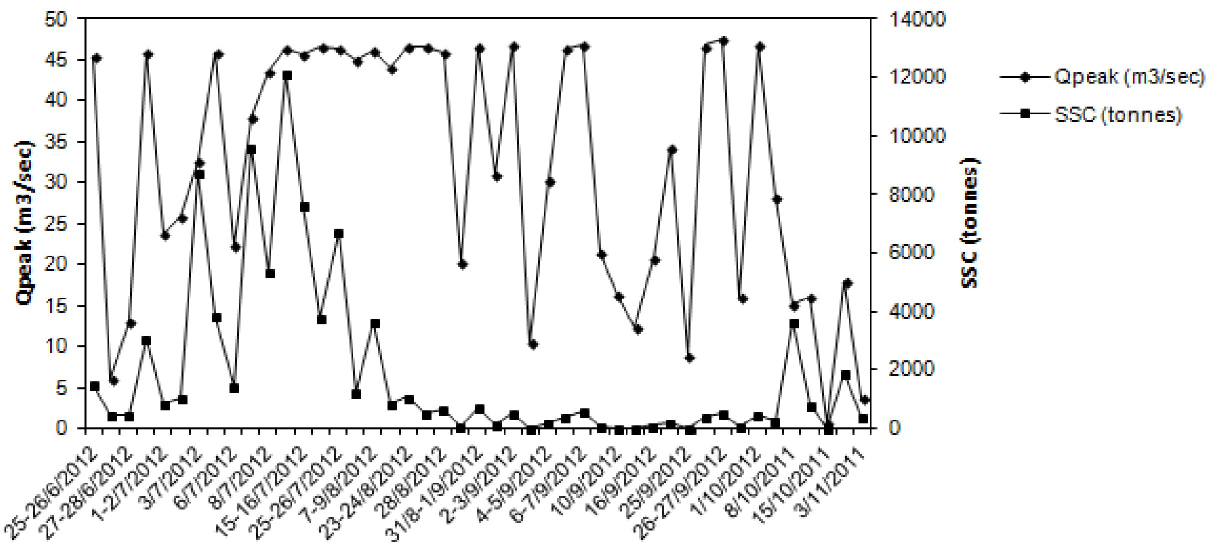

Figure 3-7: SSC and Q_{peak} of the considered events

For the 23 events in the high rainfall months of June, July and August, the correlation coefficients are much smaller (Figure 3-8). The highest yields were not necessarily related to high peak flows. Some of the small events had the highest yields. This is likely related to the dependence of sediment yield on sediment availability from the agricultural areas and hill slopes during this time of the year. Although the number of October and November events is not representative enough to draw firm conclusions about the relationship between sediment yield and peak flows, the few events do suggest that peak flows are not directly correlated with sediment yield.

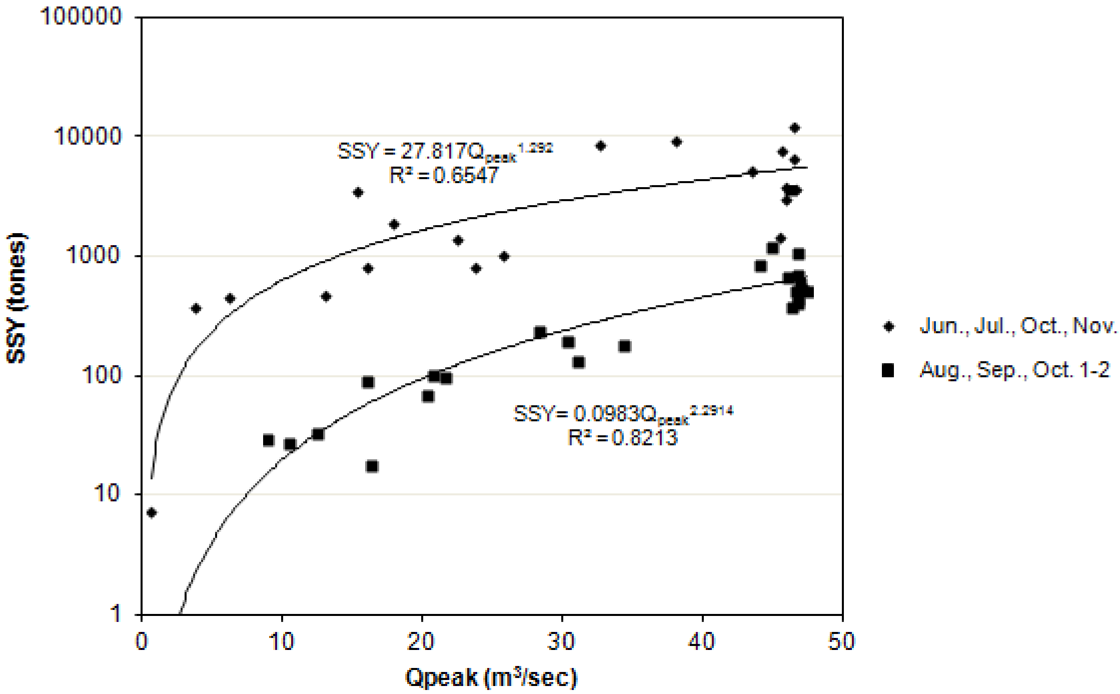

Figure 3-8: Sediment rating curves based on Qpeak

A study in the highlands of Ethiopia (Vanmaercke et al., 2010) suggested that the variations in SSC are mainly due to changes in sediment supply during the rainy season, which is related to the depletion of readily available sediments and the development of a vegetation cover. The modeling study of Easton et al. (2010) indicated that sediment delivery to the main stem of the Blue Nile is dominated by upland landscape erosion in the early part of the crop growing season when tillage occurs and before the soil is moistened and plant cover is established. They also suggested that once plant cover is established in mid August, landscape erosion is negligible and sediment export is dominated by channel processes. Similarly, White et al. (2010) indicated that erosion is controlled by channel factors rather than upland factors after mid-August when erosion controls switch from upland to channel factors. Figure 3-7 indeed indicates that sediment yield in our study area has a decreasing trend from mid July till the end of September regardless of the magnitude of peak discharges. Zegeye et al. (2010) found the greatest rates of erosion early in the planting season but they became negligible in August. In our study, the sediment yield significantly decreased from the end of August until the beginning of October while there were events with similar peak flows as those in June and July. This again suggests the depletion in dominant sediment sources, the ploughed crop fields, that led to a tremendous

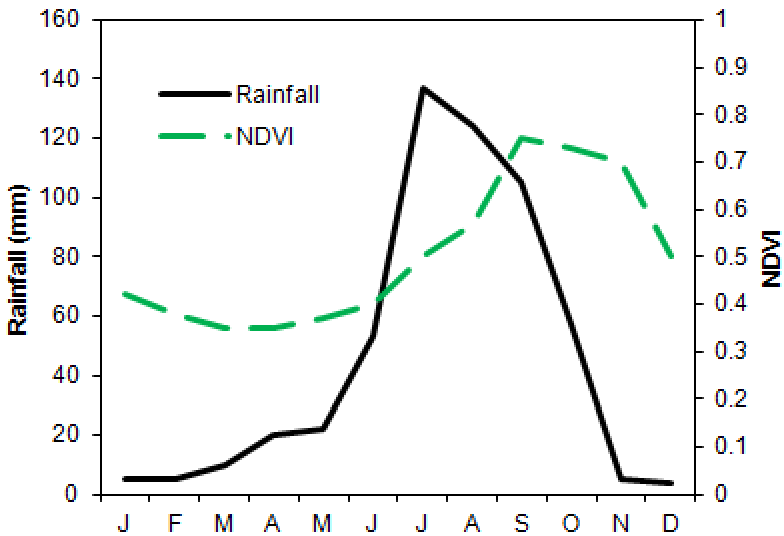

Figure 3-9: Average rainfall and crop NDVI for 1999-2006 for West Gojam zone (Province) of the Amhara region (EC-JRC,2007)

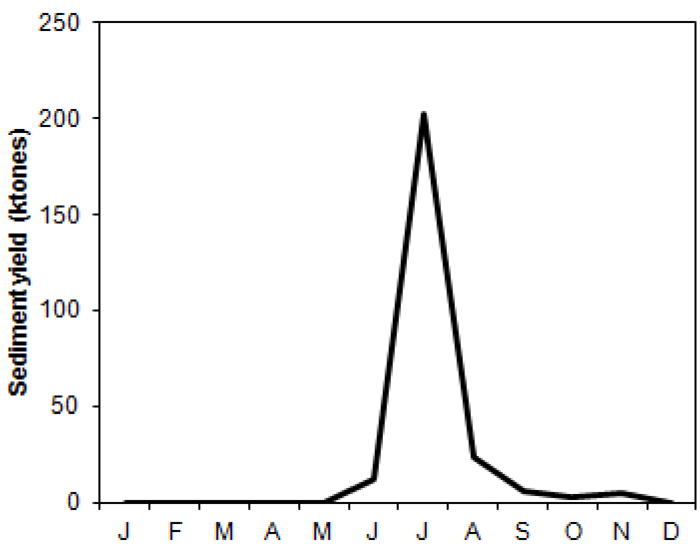

Figure 3-10: Sediment yield calculated for the study area (Oct. 2011-Sept. 2012)

decrease in sediment yield in September, due to the effects of land cover. The decreasing trend of sediment yield after mid August (Figure 3-7) for the same peak flows and the two distinct types of sediment patterns (Figure 3-8) also indicate that erosion rates for the main rainfall season significantly decrease after mid August due to the effects of land use/cover. Figures 3-9 and 3-10 show the seasonal patterns of rainfall and vegetation cover (crop NDVI) of the West Gojam zone which contains the study area of this paper. Crop NDVI (Normalized Difference Vegetation Index), derived from satellite imagery, characterizes the general vegetation dynamics in the area (Vrieling et al. 2011) and is used from crop monitoring. NDVI = 1 indicates the highest amount of green vegetation cover. Figures 3-9 and 3-10 clearly show the decrease in sediment yield with increasing crop vegetation cover while rainfall is still high.

Throughout the world, the relationship between suspended sediment concentration (SSC) and water discharge (Q) during floods tends to be highly variable (Lenzi and Marchi, 2000). Some studies used the seasonal variability of suspended sediment data for generating sediment rating curves (Mossa, 1996) while other studies pointed out the need for a more detailed study at the time scale of individual flood events to improve the knowledge of sediment dynamics (Nadal-Romero et al., 2008). Vanmaercke et al. (2010) found very low correlations of the rating curves even after the data were stratified into three periods in a study conducted in a medium sized catchment in the highlands of Ethiopia. Nadal-Romero et al. (2008) observed high sediment concentrations and a heterogeneous temporal distribution related to seasonal variations in surface runoff production for floods in a 0.45 km^2 humid Mediterranean bad land area in the Central Pyrenees. For our study area, based on the sediment yield of the 45 events and their corresponding peak discharges, Figure 3-8 shows two different sediment rating curves. The first relationship applies to events in August, September and the two October events; the second relationship applies to June, July, October and November. The first relationship shows relatively better correlation (R^2=0.82) than the second one (R^2=0.65). The lower correlation coefficient of the second sediment rating curve is due to the high sediment yield associated with some of the low peak flows due to the abundant availability of loose sediment from the ploughed fields in this period of the year, as also observed from Figures 3-11 a, b and c. The rating curve for August, September and the first two October events is associated with lower sediment yields than the other curve for similar amounts of peak discharges, indicating there was a depletion of sediment from the sediment sources in September and August. These findings suggest that the agricultural fields (the pasture and crop fields) and hill slopes are more important sediment sources than the channels for most of the yearly rainy season.

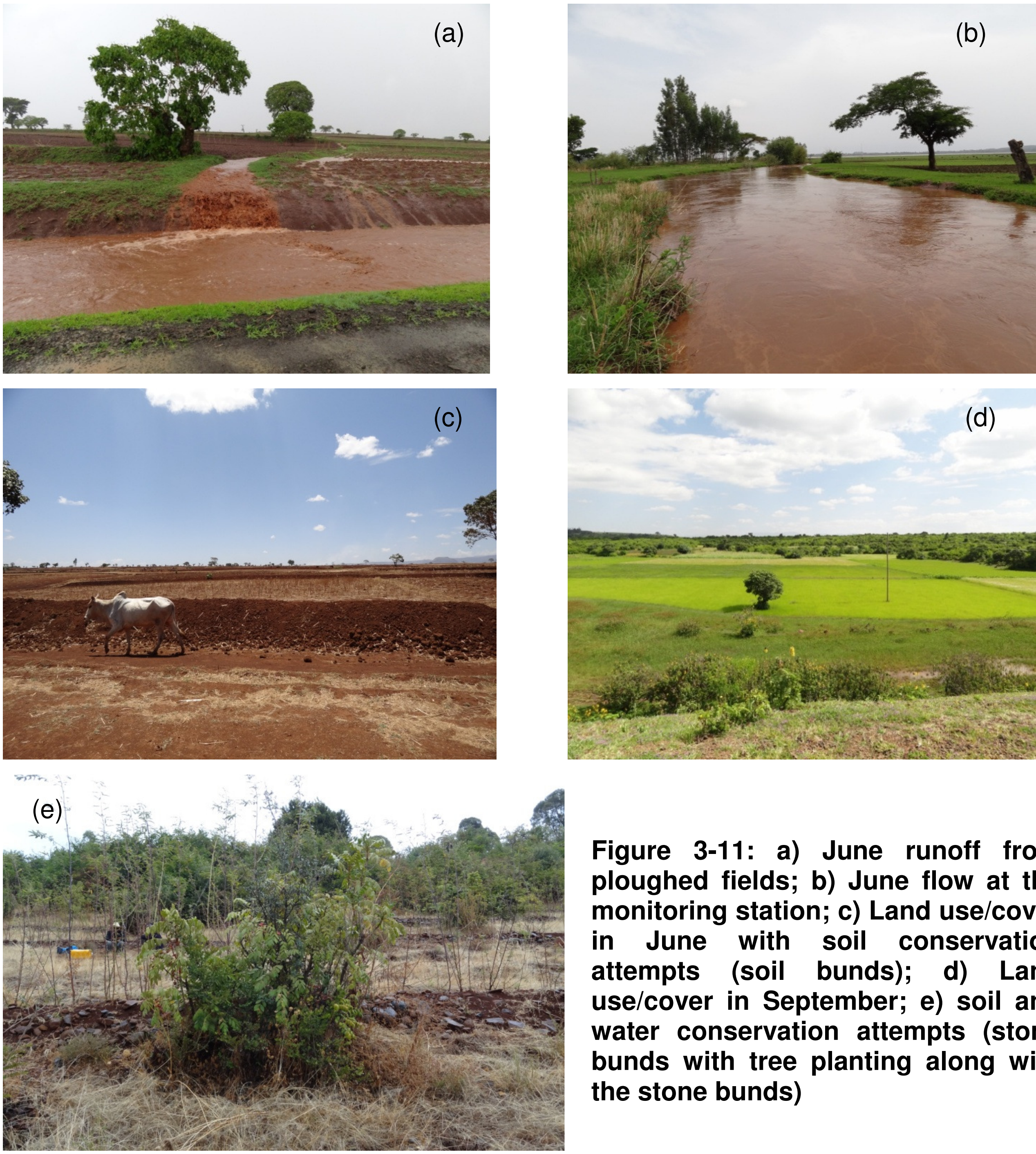

Figure 3-11: a) June runoff from ploughed fields; b) June flow at the monitoring station; c) Land use/cover in June with soil conservation attempts (soil bunds); d) Land use/cover in September; e) soil and water conservation attempts (stone bunds with tree planting along with the stone bunds)

Table 3-2: Soil loss estimates by different studies in Ethiopia

	Study	Soil loss in t ha^{-1} $year^{-1}$	Estimated for	S and W conservation measures
1	Tadesse (2001)	31	Entire highlands	
2	Hurni (1993)	42	Plot based from cultivated fields in the highlands	
3	Nyssen et al (2007)	14.8	199 hectares agriculture dominated catchment in the northern highlands of Ethiopia	yes
4	Ethiopian Highlands Reclamation study (World Bank, 2007)	130	Plot based from Cultivated lands	
5	Ethiopian Highlands Reclamation study (EHRS) (World Bank, 2007)	35	Entire highlands	
6	Vanmaercke et al (2010)	4.97-65.43	513,300 ha (divided into sub-catchments) agriculture dominated catchment in Northern highlands	yes
7	Guzman et al. (2013)	5.2; 24.7; 7.4	477 ha; 113ha, 112ha agriculture dominated catchments in the highlands	yes

Table 3-2 shows soil loss estimated by some studies conducted in Ethiopia. Regardless of the different figures, all the studies indicated the severity of soil erosion in the highlands of Ethiopia. Based on a 2010 land cover/use classification by Yeshaneh et al. (2013), the area upstream of the monitoring station of our study area that drains to the monitoring station consists of 5248 hectares of cultivated land, 1848 hectares of woody vegetation, and 2742 hectares of other land use/cover types, that account for 53%, 19% and about 28% of the land use/cover of the area respectively. Based on the fine temporal resolution (temporal resolution of 10 minutes) continuous discharge and sediment data we recorded at the monitoring station, we calculated a total sediment yield of 252,277 t $year^{-1}$ from the 9838 hectares, which is 25.6 t ha^{-1} $year^{-1}$. This figure is somewhat smaller than the findings of most of the studies conducted in the high lands of Ethiopia, although it is greater than sediment yields from catchments where effective soil and water conservation measures are practiced. This estimate is extremely high from an environmental point of view. The relatively low amount of sediment yield we estimated compared to previous studies could be attributed to various reasons. One possible reason could be our continuous measurement of discharge and sediment data with high temporal resolution, with relatively better technology equipments than previous studies, which we believe has increased the reliability of sediment yield estimation, while there is a possibility of overestimation by previous studies with less regular monitoring. No studies have been performed in the catchment as to the extent the existing soil and water conservation structures have changed the sediment yield of the study area. Although there is a need for an in depth study of the effect of the existing structures and other future additional options on soil erosion in the catchment, the existing structures might have contributed to reducing the sediment yield relative to estimates for the entire highlands of Ethiopia. It has been noted by Yeshaneh et al. (2013) that there is an increasing tendency to eucalyptus tree planting in the catchment in recent years; its impact on sediment yield should be studied along with the conservation measures.

Increased suspended sediment load due to intensive land use has been flagged out as a major concern by a number of studies in catchment and stream management (Martilla and Klove, 2010, Restrepo et al., 2006). Schiettecatte et al. (2008) identified the highest soil losses from crop fields in a 151 km^2 subwatershed in Cuba at times when the soil is tilled and left bare for several weeks. They suggested that conservation measures would be most efficient during those times. If, in our study area, the erosion process continued at the same rate (assuming soil formation is negligible), the top 10 cm of soil will have been eroded in the next 50 years, which will leave the land extremely degraded, making agriculture not practicable at that time. Out of the total yearly sediment yield of 252,277 tons, 91% is transported from early June to mid August, which suggests that soil and water conservation measures need to particularly target this time of the year. This finding is in line with those of McHugh (2006), who indicated that severe erosion in a watershed in the highlands of Ethiopia is associated with a few erratic storms rather than steadily across all seasons. As stated by FAO, about 50% of the highlands of Ethiopia were already “significantly eroded” in the mid-1980s and erosion was causing a decline in land productivity at the rate of 2.2% per year (World Bank, 2007). The total area that drains to the reservoir, including the area downstream from our monitoring station, is 13677 hectares. With a sediment yield of 25.6 t $year^{-1}$ ha^{-1}, it is also worth noting that a total volume of 269000 cubic meters of sediment reaches the Koga irrigation reservoir every year which puts the sustainability of the irrigation dam in question.

3.4 Conclusions

We found anticlockwise hysteresis patterns between discharge and suspended sediment concentration to be dominant in the Koga catchment suggesting that the main sediment sources are the hillslopes and agricultural areas with smaller contributions from the river channels. However, there exist complex hysteresis types where the conclusions are less clear. During the period when the land is completely covered by vegetation, sediment yield associated with clockwise patterns was found to be greater than that associated with anticlockwise and other patterns, suggesting river channels contribute more to sediment yield in such conditions than the other sources. Complicated and other types of hysteresis patterns mostly associated with long events of multiple peaks suggest that a multitude of factors of sediment delivery in the study occur that cannot be inferred from the hysteresis patterns. Sediment availability from the agricultural areas and hill slopes that depends on land use/cover was found to more strongly control the variations in event sedigraphs and rating loops than peak discharge. Suspended sediment yield - peak discharge plots indicated much lower sediment yield for the time after mid of August when the catchment was almost completely covered with vegetation as compared to similar events when the agricultural land was devoid of vegetation. Two distinct types of sediment rating curves based on peak discharges were observed for seasons with and without vegetation cover. Suspended sediment yield in the area is very high (25.6 t ha^{-1} $year^{-1}$) and 91% of the yearly suspended sediment yield is transported from early June to mid August because of the availability of loose sediment from the ploughed fields at this time of the year. If the erosion process continued at the same rate, the top 10 cm of soil will have been eroded in the next 50 years. An amount of 269000 cubic meters of sediment reaches the Koga irrigation reservoir every year. This highlights the urgent need for appropriate soil and water conservation measures.

4. Decadal trends of soil erosion and runoff in the Koga catchment, North Western Ethiopia

Abstract

This study used the physically based distributed AnnAGNPS (Annualized Agricultural Non-point source) model to simulate the decadal trends in soil loss and runoff with changes in land use/cover in the 9838 ha upper part of the 260 sq. km. Koga catchment. The study indicated that soil loss in the study area has increased from 17tons/ha/yr in 1957 to 25tons/ha/yr in 2010 due to a decrease in the amount of woody vegetation cover. We found that, in the past 50 years, high risk erosion areas with soil loss greater than 35 tons/ha/year cover, on the average, 41% of the study area while these same areas contribute, on the average, to 78% of the soil loss from the study area. 21% of the study area has been in the high risk erosion category throughout all the years since 1957. The total amount of soil loss from these areas varied with changes in the amount of woody vegetation cover. In addition to change in woody vegetation cover, other factors such as geomorphology and soil type had effects on the amount of soil erosion from these areas. Whereas most of the high erosion areas were found in the upper part of the catchment, most of high runoff areas were found in the lower part of the catchment indicating the amount of soil erosion is not directly related to runoff volume in the study area. The extent of low runoff areas (runoff less than 500mm/yr) decreased from 1957 to 2010 with the decrease in woody vegetation cover. Crop fields contributed to most of the soil loss in the study area.

4.2 Introduction

Soil erosion has been identified as a major problem in many countries like Ethiopia, degrading land and challenging crop productivity. The destruction of soil through erosion is becoming of particular concern because soil formation is an extremely slow process (Hesbon and Ogalo, 2012). This fact is particularly true for the Ethiopian Highlands where there is a very high rate of erosion when compared to the soil formation rate. In the past, soil and water conservation and rehabilitation efforts and achievements in the highlands of Ethiopia were not encouraging due to the inappropriate methods used in the assessment of erosion processes (Haregeweyn and Yohannes, 2003). Understanding the magnitude of the soil erosion problem is key for tackling the on- and off-site erosion threats that need improved catchment-based erosion control and sediment management strategies (Tamene, 2006)

The impacts of surface runoff and soil erosion in watersheds can be estimated by hydrological models. Watershed models are considered a cost-effective and time-efficient method for assessing pollutant loads and simulating watershed processes and management practices in an effort to address non-point source pollution (Hua et al., 2012). The Annual Agricultural Non-Point Source (AnnAGNPS) model is a useful tool to identify and delineate critical areas with severe erosion and evaluate the response of watershed management practices (Hua et al., 2012). The event-based AGNPS and its continuous version AnnAGNPS have been applied in several countries all over the world. AnnAGNPS can be used to predict runoff, erosion as well as nutrient and chemical transport export from a watershed. The model enables comparative analysis of the different options of best management practices through scenarios of land and water management. AnnAGNPS has been implemented to assess runoff volumes and water quality as well as sediment yield in small to large monitored watersheds (ranging from 0-32 to 2500 km^2) under different environmental conditions (Zema et al., 2010).

Several studies have indicated the influences of gradual and sudden land use/cover changes on soil erosion processes (Martinez-Murillo et al, 2011; Liu A. et al., 2008; Wang et al., 2012; Brath et al., 2002; Ciampalini et al., 2012; Li et al., 2013). While reforestation usually promotes soil stabilization in various ways, land abandonment or intense ploughing can intensify erosion processes (Martinez-Murillo et al, 2011). The objective of this research is to estimate how erosion and runoff have evolved over the past five decades with changes in land use/cover in the upstream part of the Koga catchment.

4.2 Materials and Methods

4.2.1 The Study Area

4.2.1.1 Location, Climate and Topography

The considered study area is 9838 hectares in size and represents the upstream part of the 260 km^2 Koga catchment (Figure 4-1) in northwestern Ethiopia. The Koga catchment is a typical catchment for the Ethiopian Highlands, 72% of which is used for subsistence agriculture. The Koga River is a tributary of the Gilgel Abbay, which flows northwest into Lake Tana, and lies in the upper part of the Blue Nile (Abbay) watershed.

The climate of the Koga catchment falls within the Woina Dega (cool semi-humid, 1,500 to 2,400 m asl) and Dega zones (cool, above 2,400 m asl). The majority of the catchment area lies within the Woina Dega zone and is characterized by distinct dry and wet seasons. The dry seasons occur between November and April and the wet season between May and October; small rain storms occur sporadically during April and May. The average annual rainfall we measured within the years 2011-13 for the catchment is 2500mm. The mean daily temperature is 18.25 ℃. The monthly mean maximum temperature varies from 30.0 ℃ in March to 23.7 ℃ in August. The monthly mean minimum temperature varies from 5.4 ℃ in December to 13.1 ℃ in May and June.

Whereas the land elevation of the Koga catchment varies from 1,875 m asl at the mouth of the Koga River to 3,215 m asl at its highest point on the watershed divide, the considered study area has its lowest elevation of 2,015 m asl at its mouth where it joins the Koga reservoir. The Koga reservoir (Figure 4-1) is used for irrigation of the downstream areas. The Koga River flows a distance of 26 km before it joins the Koga irrigation reservoir and a distance of 49 km before it joins the Gilgel Abbay, which eventually flows into Lake Tana. The Koga catchment is generally elongated with a pronounced narrowing above the Village of Rim where the mean width of the catchment is only 3.8 km. The course of the Koga river is northerly up to the village of Rim and then westerly to Wetet Abbay.

4.2.1.2 Geology and Soils

The regional geology of the Koga catchment comprises extensive flow type, volcanic (extrusive) rocks mainly of the Ashangi Group; these were deposited during the palaeocene-Oligocene-Miocene (Tertiary) stages of geological time. The Ashangi group comprises older volcanic rocks, which were formed by lava and debris, ejected from fissural volcanic eruptions. The Choke shield volcanic group, deposited during the Miocene and Pliocene, has covered a small area of the Upper Koga catchment in the Eastern part. The Shield volcanic group consists mainly of pyroclastic basalt and is petrographically similar to the Ashangi group. The soil types within the upper part of the Koga catchment we studied are Luvic Phaeozems (Typic Argiustolls), Chromic Cambisols (Fluventic and Typic Ustropepts), Lithic Leptosols (Lithic Ustropepts), Haplic Alisols (Typic Paleustults), Eutric Vertisols (Ustic Tropaquepts) and Eutric Gleysols (Typic Tropaquepts). These soils have clay to clay loam texture with the exception of Eutric Gleysols (Typic Tropaquepts) which has clay to sandy clay loam texture.

4.2.1.3 Population and tillage practices

The total population of the Mecha woreda, within which the Koga catchment is located, is 292,000, of which 269,404 live in the rural part while 22,677 live in the urban part (CSA, 2007). Subsistence rain fed production of cereals comprising teff, maize, barley and millet, as well as pulses, oilseeds and some legumes is dominant in the area, while irrigated agriculture takes up a small percentage of the cultivated area of the Koga catchment. Soil tillage is done with oxen-drawn ploughs. There exist some attempts to prevent soil erosion through soil and water conservation structures such as stone stacks along with tree planting, storm water diversion channels, soil bunds, channel and orchard terraces, contour cultivation, etc., though these have not been studied sufficiently to determine which methods are most effective in controlling soil erosion in the catchment. Crop cultivation is the main source of income followed by livestock for the poor farmers in the area.

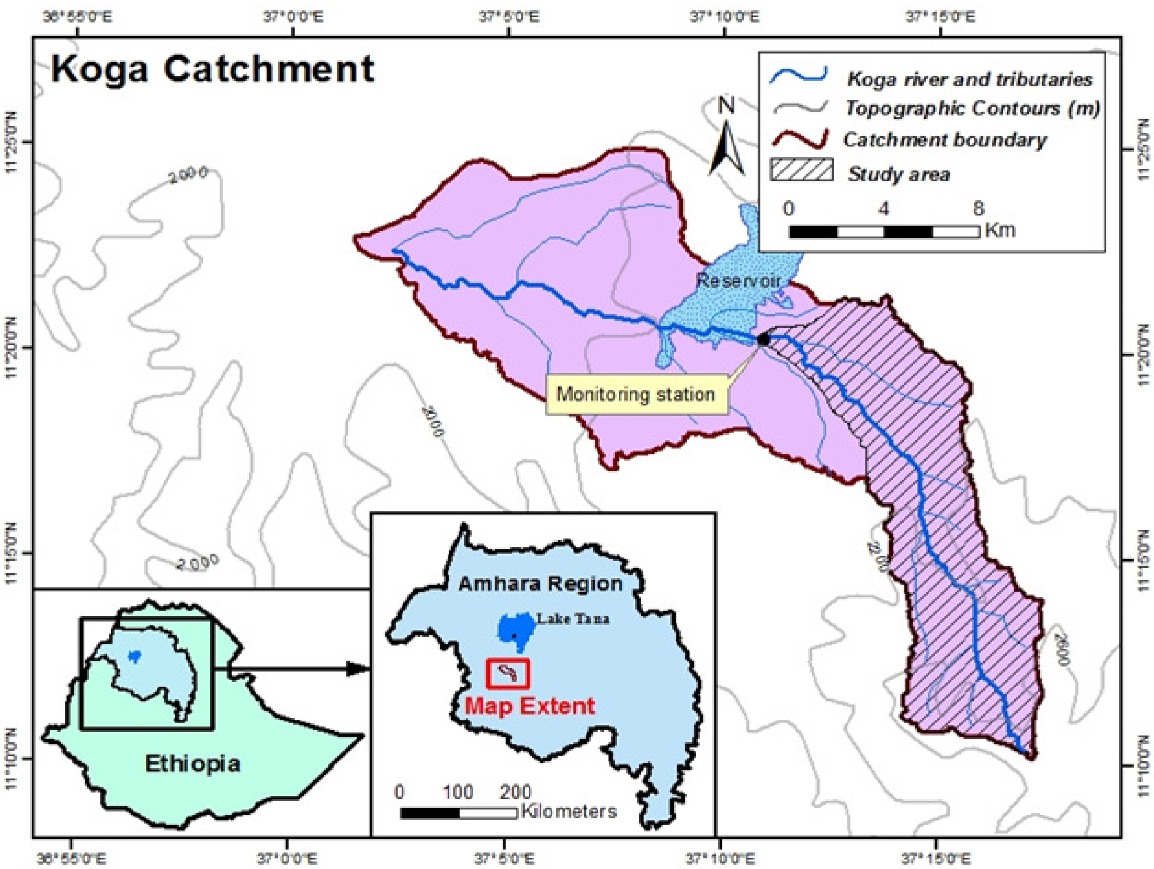

Figure 4-1: Location Map of the Koga Catchment (Yeshaneh et al. 2013b)

4.2.2 Methods

4.2.2.1 Discharge, suspended sediment, and rainfall data collection

A hydrological monitoring station consisting of a pressure transducer, Digital Turbidity Sensor (DTS), axiom data logger and staff gauge has been installed along a relatively stable and relatively steep cross section in the Koga catchment (Figure 4-1). The station was installed just above the Koga reservoir. We used the rating curve and turbidity-suspended sediment concentration relationships developed by Yeshaneh et al. (2013) to estimate daily discharge and suspended sediment concentration for the time period starting from Sept. 2011 to Sept. 2013. These measured suspended sediment and runoff data were used for calibrating and validating the AnnAGNPS model. We measured rainfall for the two years we used in calibrating and validating the model at a station in our study area using a tipping bucket rain gauge installed around the same location with a data logger that recorded rainfall every 10 minutes.

4.2.2.2 AnnAGNPS – the model and how it works

AnnAGNPS (Annual Agricultural Non-point Source) model is a spatially distributed physically based model developed for simulating sediment, runoff, nutrient and pesticide from agricultural watersheds (Theurer and Cronshey, 1998). The AnnAGNPS model (Bingner and Theurer, 2001b) is a continuous version of the event based Agricultural Non-Point Source (AGNPS) model (Young et al., 1989, 1994). Although the AnnAGNPS pollutant loading model was initially created for agricultural watershed applications, it can be quite helpful for various sedimentation management applications and studies. When compared with AGNPS, AnnAGNPS enables continuous simulation for better representation of the processes involved in transport and deposition of the generated sheet and rill erosion (Baginska et al., 2003)

AnnAGNPS has a GIS interface (ArcView 3.1 for this study) by which the watershed is divided into cells based on the Digital Elevation Models (DEMs), land use, and soil type. Each cell contains a constant slope, length, elevation, management field, and soil type value. The cells are linked together to form streams (reaches) and are then used to simulate the movement of water, sediment and various chemicals. In this particular study we used ASTER DEM with a resolution of 15 meters and documented soil type data by Acers and Shawel Consult (1995e). For the land use input, we used the 2010 land use map generated from satellite data by Yeshaneh et al. (2013a). The AnnAGNPS-GIS interface determines the size of each cell by its Critical Source Area (CSA) minimum Source Channel Length (MSCL) (Shrestha et al., 2006) defined by the user based on a variety of different soils, land use, and topography information. The MSCL represents the minimum reach length in meters that connects a set of cells with the same runoff route (usually a stream or tributary within the watershed). In this study, we used a CSA of 20 ha and 210 m as the MSCL value to divide the study area into 543 cells, as it was found to produce a very similar total sediment yield to a setup with a larger number of cells, but with the advantage of being computationally less demanding. Using lesser CSA and MSCL values didn't appear to improve the outputs.

The cell and reach data produced using the AnnAGNPS-GIS interface is then used as input to the AnnAGNPS input editor, together with daily climate data, crop & crop growth data, management field data, management schedule and crop management operation data, non-crop data, runoff curve number (CN), simulation period, soil, watershed, and the output options data fields for the simulation of runoff and sediment within our watershed.

The daily climate data included daily rainfall, daily minimum and maximum temperature, dew point temperature and evapo-transpiration data for the model simulation years. The rainfall data from the station at the Koga reservoir were used. The1981-2010 average monthly maximum and minimum temperatures from a station (in a town) towards the outlet of the Koga catchment, was input to the model on a daily basis. The monthly maximum and minimum temperatures were repeated for each day within a month. The 1966-1995 average monthly evapo-transpiration data (from piche evaporimeter) and wind speed for the town of Bahirdar located 35 kms away from the Koga catchment was used on daily basis for our study area after some adjustment of the evapo-transpiration data for the temperature differences.

Out of the four management field IDs (woody vegetation, crop field, pasture and settlement), crop field was schedule for management operations. Tillage, new crop growth and harvest operations were scheduled at the end of May, mid of June, and end of September respectively. Residue cover on the surface after tillage was initially estimated. In addition, crop parameter inputs such as the amounts of crop residues for having various levels of surface cover were estimated. For the non-crop management fields, the annual root mass, annual cover ratio, annual rainfall height, and surface cover residue factors were estimated. All the estimated parameters were adjusted manually during calibration where needed. The non-crop and crop data inputs are summarized in Table 4-1 and Table 4-2. Beginning of simulation period was set as 28/09/2011 and end of simulation period as 30/09/2013. About 98% of the yearly runoff and associated sediment loss occurs within the months between June and September each year as indicated by Yeshaneh et al (2013b).

Table 4-1: Non-crop data inputs

Non-crop ID	**Annual root mass (kg/ha)**	**Annual cover ratio (ratio of ground covered by canopy to total ground area)**	**Annual rainfall height (m)**	**Surface cover residue (%)**
Woody vegetation	6500	0.9	6	87
Pasture	2600	0.7	1	78

Table 4-2: Crop data inputs

	Type of input	Amount
1	Yield units harvested (Quintals/ha)	13
2	Residue mass to crop mass ratio	0.1
3	Crop residue for 30% surface cover (kg/ha)	1800
4	Crop residue for 60% surface cover (kg/ha)	4600
5	Crop residue for 90% surface cover (kg/ha)	9800
6	Yield unit mass (kg/Quintal)	100
7	**Growth stage** Initial growth stage time ratio Development growth stage time ratio Mature stage time ratio Senescence	 0.2 0.3 0.4 1.0
8	**Root mass (kg/ha)** 1st 30 days from planting remaining days until harvest	 9000 23000

Table 4-2: Cont'd

	Type of input	Amount
9	**Canopy cover (%)**	
	1st 30 days from planting	40
	remaining days until harvest	98
10	**Rainfall height (m)**	
	1st 30 days from planting	0.5
	remaining days until harvest	2

The runoff curve number was used as in Table 4-3. We used the Manning's n as in Table 4-4 for each management schedule of management field data. The Manning's n was initially based on Chow (1959) but was then modified during calibration. Crop fields were assumed to have their highest Manning's roughness from mid-August to the end of September each year as the crop fields are completely covered with vegetation at that time of the year (Yeshaneh et. al., 2013b)

Table 4-3: Runoff Curve numbers used in the model for different hydrologic soil groups

(Initially based on USDA-NRCS Conservation Engineering Division Technical Release 55 (USDA, 1986)

	CN_A	CN_B	CN_C	CN_D
Crop field : Aug. 15-Sept. 30	44	65	78	84
Crop field: Oct. 1-30	83	88	90	98
Crop field: Nov. 1- June 30	78	84	89	96
Crop field: July 1- Aug. 14	80	87	91	94
Pasture	40	57	70	76
Woody vegetation	48	53	60	65
Settlement	52	65	77	82
Bare area	52	65	77	82

Table 4-4: Manning's n used for each management schedule of management field data

	Manning's n ($s.m^{1/3}$)
Crop field : Aug. 15-Sept. 30	0.07
Crop field: Oct. 1-30	0.033
Crop field: Nov. 1- June 30	0.02
Crop field: July 1- Aug. 14	0.038
Pasture	0.04
Woody vegetation	0.099
Settlement	0.01
Bare area	0.01

The runoff, erosion, sediment yield, and other chemical substances attributable to each cell and reach are calculated with daily precipitation values over a continuous time period by the AnnAGNPS input editor. The overall simulation within the watershed is for all cells, linked together, to establish a cumulative runoff value containing the hill slope sediment yield and any nutrient in the stream as a result of a storm event on the watershed, which travels to the outlet of the watershed (Massey, 2008)

The SCS curve number technique is used within AnnAGNPS to determine the surface runoff from a field. The AnnAGNPS model uses the related soil retention value and soil moisture adjustment for each CN entered by the user and creates algorithms to calculate the runoff generated for the cells within the watershed (Shrestha et al., 2006). Next, the peak flow of runoff within each cell reach is broken up into three categories (overland, concentrated, and channel flow) to better estimate the Time of concentration (Tc) within the AnnAGNPS model through the NRCS TR-55 graphical peak discharge method (Theurer & Crohshey, 1998).

The model uses the Revised Universal Soil Loss Equation (RUSLE) based on land cover, soil, management practices, topography, and precipitation values for each cell to calculate the daily sheet and rill erosion. The AnnAGNPS input editor required soil data for each layer of each soil type. Soil data used for the model is summarized as in Table

4-5. The soil data we got from Acers International Ltd. and Shawel Consult International (1995e) was complemented by field infiltration tests we did at 12 sites in the study area and laboratory analysis for texture and organic matter of the soil samples taken from these sites. Soil saturated conductivity was adjusted during calibration. Estimating of soil field capacity and wilting point depended on Saxson and Rawls (2006) estimation of these parameters through soil texture. The RUSLE K factor was estimated for the different soil types based on Wischmeier and Smith (1978) soil erodibility nomograph. The RUSLE Slope length and steepness factors were within the cell data produced by the AnnAGNPS-ArcView interface; the RUSCLE C factor is calculated by AnnAGNPS based on crop and non-crop data input parameters. The P factor was set to 1, due to the very limited amount of soil and protective structures when compared to each of the cell sizes used in the watershed. The rainfall erosivity factor (R) was estimated from the isoerodent map of Ethiopia by Krauer (1988) but was then calibrated within the allowable range based on model sediment output. The rainfall factor was a major input for the simulation period data in addition to the simulation begin and end dates.

Table 4-5: Soil input data

Soil ID	Hydrologic Soil Group	Clay ratio	Silt ratio	Sand ratio	Saturated Conductivity (mm/hr)	Field Capacity	Wilting Point	Bulk density (g/cm3)
Pd/g	D	0.64	0.21	0.15	4.8	0.36	0.22	1.05
Upb	D	0.73	0.17	0.10	4.0	0.41	0.22	1.13
UpA	D	0.84	0.13	0.03	4.0	0.41	0.22	1.13
Pd/gb	D	0.64	0.21	0.15	4.8	0.36	0.22	1.05
Pd/gd	D	0.64	0.21	0.15	4.8	0.36	0.22	1.05
UpC	D	0.84	0.13	0.03	4.0	0.41	0.22	1.13
Md	C	0.53	0.27	0.20	12.3	0.30	0.25	1.03
Pf/t	C	0.42	0.28	0.30	6.3	0.38	0.22	1.04

After (the rill and inter-rill erosion) sediment erosion has been estimated for each cell by RUSLE, the model uses the Hydro-geomorphic Universal Soil Loss Equation (HUSLE) to calculate the sediment load from each cell to a stream reach after deposition from runoff. Because RUSLE does not assume any deposition from sheet and rill erosion, the AnnAGNPS model uses HUSLE to create a delivery ratio to determine the amount of deposition occurring from erosion and sediment yield for five separate soil particle sizes (clay, silt, sand, small and large aggregates) based on each particle's mass fall velocity (Bingner et al., 2003) and finally outputs the sediment loads from each cell.

Runoff and sediment that are calculated by AnnAGNPS are finally routed from each cell through a channel network to the outlet of the watershed (Hua et al., 2012). We calibrated the model first by the yearly sediment and runoff data and then with selected daily data of the first one year period (2011/12). It was then validated with the daily sediment and runoff data of the second year (2013).

4.2.2.3 Simulation of AnnAGNPS model for changes in land use

After calibrating and validating AnnAGNPS using the land use data of 2010, the model was then used to simulate for changes in land use using land use data generated from satellite imagery by Yeshaneh et al. (2013a). The land use data for the years 1957, 1978, 1986, and 1999 were used in the AnnAGNPS-GIS interface to produce different cell and reach data for each year as inputs to the AnnAGNPS input editor when simulating the land use related changes in runoff and soil loss over the past 50 years. In estimating the decadal changes in erosion and runoff, it should be noted that the one and only factor that was considered variable throughout the last 50 years is the land use factor. All the other factors were assumed to remain constant.

4.3 Results and discussions

4.3.1 Model calibration and validation

Several studies in different parts of the world ranging from small to medium watersheds indicated that AnnAGNPS and its event based predecessor AGNPS predicted runoff and sediment well (Shamshad et al., 2007 (Malaysia); Mohammed et al., 2004 & Haregeweyn and Yohannes, 2003 (Ethiopia); Bagniska et al., 2003 (Australia); Zema et al., 2010 (Belgium); Yuan et al., 2001 (Mississippi, USA); Polyakov et al., 2007

(Hawaii, USA); Sarangi et al., 2007 (S. Lucia Island, British West Indies); Licciardello et al., 2007 (Sicily, Italy). Like the many successful studies using AnnAGNPS, the model performed satisfactorily in our study area.

We first calibrated the model using measured annual runoff and sediment data for the year 2011/12. Calibration results created a good fit between the modeled and measured annual runoff and sediment data. While we measured 1300mm of annual runoff and 26 tones/ha of annual sediment yield at our monitoring station, the model produced an average annual sediment yield of 25 tons/ha and 1276mm of runoff. We then calibrated the model using measured daily runoff and sediment data of 43 days in the same year (Figure 4-2). We selected the days for calibration based on the relative reliability of the measured runoff and sediment data on those days compared to other days. For example, for some of the days, the turbidity values were beyond the measurement range of the turbidity sensor, which resulted in under estimation of sediment. Such days were not used during calibration. At the same time, we took care to select enough days both in high and low rainfall periods. The SCS curve number (CN) is the most important factor for accurate prediction of runoff (Grunwald and Norton, 2000; Bosch et al., 1998 in Shamshad et al. 2007). Therefore, selection of an accurate CN was essential for better performance of the model. In the calibration process, we modified the initial Curve Numbers that were adopted from USDA-NRCS conservation engineering division Technical Release 55 (TR-55) (USDA, 1986) until we got a good fit between the modeled and observed runoff. Model calibration resulted in a correlation coefficient of 0.6 (Figure 4-2a) between daily measured and modeled runoff with a Nash-Sutcliffe model efficiency coefficient of 0.5. Model sediment has been calibrated by changing the most sensitive factors such as Manning's roughness coefficients and cover factors such as surface cover residue, annual root mass and annual cover ratio. After calibration, we got a correlation coefficient of 0.87 (Figure 4-2b) between the modeled and measured daily values with the Nash-Sutcliffe model coefficient of 0.87. We found the model sensitive to Manning's roughness coefficient, surface cover residue and annual non-crop root mass in decreasing order in predicting sediment yield. The measured data in Figures 4-2, 4-3 & 4-4 is from our hydrological monitoring station on Figure 4-1.

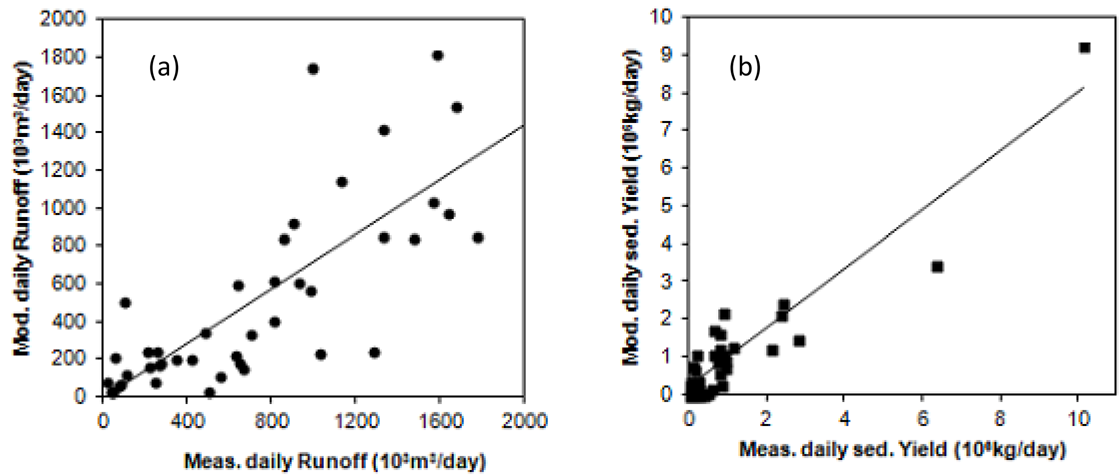

Figure 4-2: Model calibration results on daily runoff (a) and sediment yield (b) for selected days in the time period 5/10/2011 to 8/10/2012

Model validation on 15 days daily data in 2013 resulted in a correlation coefficient of 0.65 (Figure 4-3a) between the measured and modeled daily runoff volume with a Nash-Sutcliffe model coefficient of 0.56. The correlation coefficient between measured and modeled sediment yield during the validation period was 0.88 (Figure 4-3b), with a Nash-Sutcliffe model coefficient of 0.81.

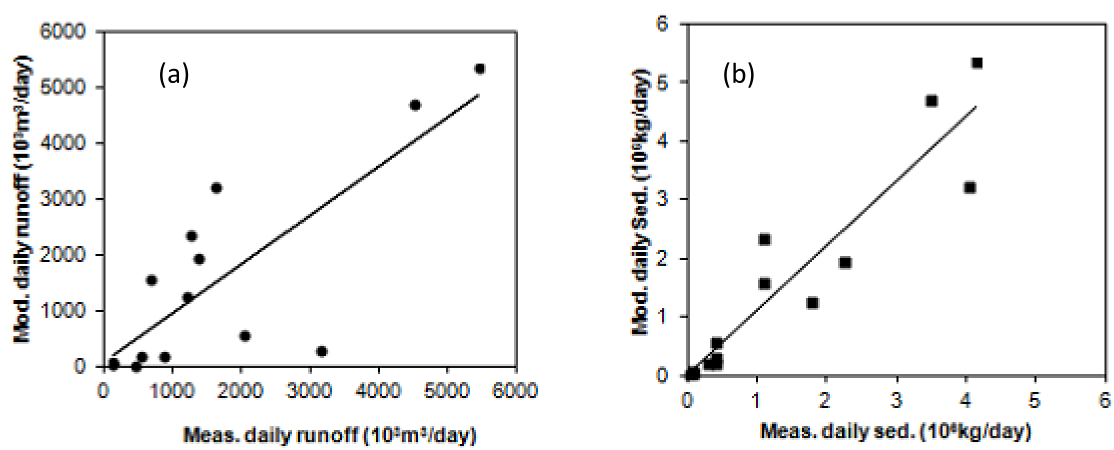

Figure 4-3: Model validation results on daily runoff (a) and sediment (b) for the year 2013 for selected days in the time period 19/6/2013 to 29/9/2013

After model validation, monthly measured and modeled runoff volumes had a correlation coefficient of 0.87(Figure 4-4a) with a Nash-Sutcliffe model efficiency of

0.87.When monthly sediment model outputs were compared with measured values, we got a correlation coefficient of 0.69 (Figure 4-4b) with a Nash-Sutcliffe model efficiency of 0.67. Both the daily and monthly model outputs indicated that the model has performed satisfactorily in predicting runoff and sediment in our study catchment.

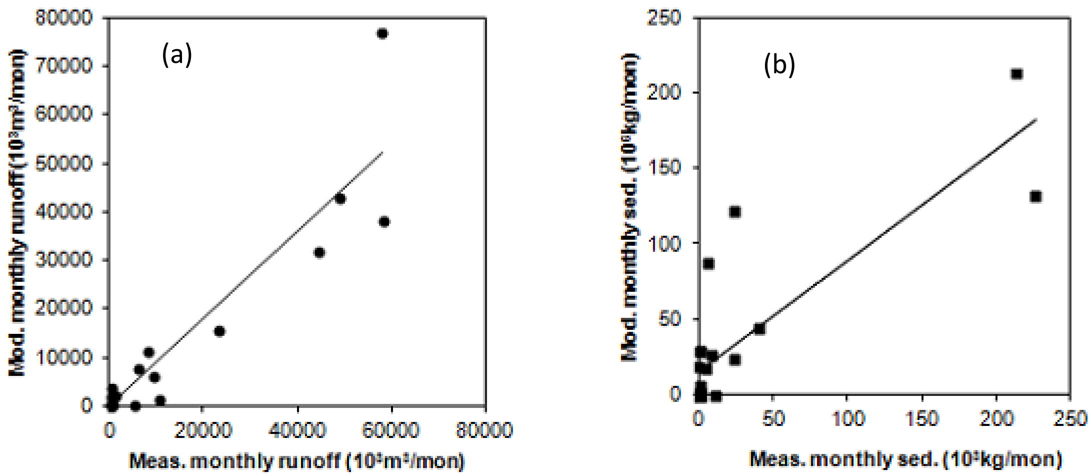

Figure 4-4: Model validation results on monthly and measured runoff (a) and sediment (b) data throughout the two years simulation period

This study confirmed the reliability of AnnAGNPS in predicting daily, monthly and annual sediment and runoff data in our medium scale study catchment in the highlands of Ethiopia.

Sediment yield by daily storm events has hysteresis effects as indicated by Yeshaneh et al. (2013b) on the same study area, Guzman et al. (2013) in a study in the highlands of Ethiopia, and by several other studies in different parts of the world. Hence sediment data based on a few samples from event runoff might not be representative of the daily sediment yield which in turn makes it difficult to compare with modeled sediment data. The fact that we had both sediment and runoff data from continuous measurements of runoff and sediment data, has enabled us to have a relatively reliable measured data on sediment and runoff to compare it with the modeled data at various time scales. While overall results are good, availability of only a single rain gauge in our study area likely plays a role in model performances. A larger number of rain gauges would likely result in better efficiencies. The tipping bucket rain gauge was put close to the discharge measuring station for safety reasons. We sometimes observed high runoff values at the discharge measuring station due to rainfall from the upper part of the catchment, while no rainfall was recorded at our rain gauge. This led to very little or no modeled runoff and sediment values while the measured values were high.

4.3.2 Model simulation for changes in land use/cover

Having predicted both sediment and runoff data using the land use/cover data of 2010, we created the yearly soil loss map for this same year. The model was then run using land use data for the years 1957, 1979, 1986, and 1999 for estimating the spatio-temporal variability of soil loss and runoff with changes in land use in our study area while all the other factors were assumed constant.

4.3.2.1 Soil loss

Figure 4-5 shows the soil loss maps obtained for the time slices since the 1950s. As can be seen on Figure 4-5, most of the erosion occurs in the upper (southern) part of the study area while it is relatively lower in the lower (northern) part. Changes in the patterns of erosion are observed with the changes in land use from 1957 to 2010. In the upper catchment, relatively higher amount of low erosion risk areas are observed in 1957 and 2010 than in the other years. This due to the relatively higher amount of woody vegetation in these years than in the other years as can also be seen on Table 4-9 later in this document.

Soil loss greater than 35 tons/ha/year is considered as high erosion (Drezewiecki et al., 2013; Stone and Hilborn, 2012; Kumar and Kushwaha, 2013). Table 4-6 details the areas in hectares with soil loss greater than 35tons/ha/yr for the years 1957, 1979, 1986, 1999 and 2010 and the percentage contribution of these areas to the total yearly soil loss. While the area coverage of the high erosion risk areas is 41% on the average, these areas contribute 78% of the soil loss from the catchment on the average. These

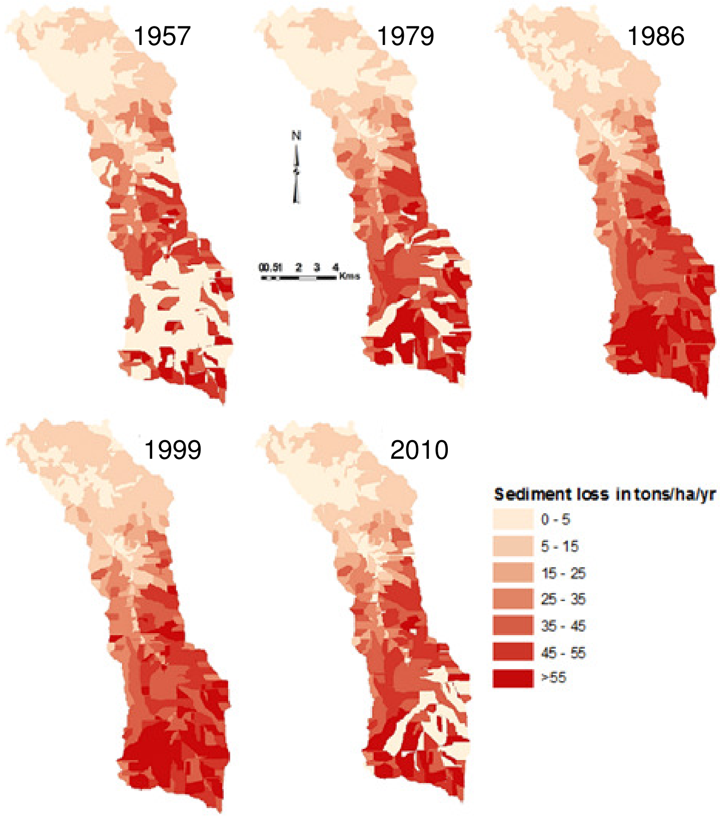

Figure 4-5: Yearly soil loss maps for the past 50 years in the study area

high risk erosion areas are found in the hilly upper part of our study area (Figure 4-5) with relatively higher soil erodibility factor and not in the lower part of the catchment where the land is relatively flatter and with relatively lower soil erodibility factor than the upper part of the study area.

Out of the total high erosion risk areas in each of the years considered, 2065 ha high risk area is common for all the years from 1957 to 2010. This indicates that these areas have been at the same high erosion risk for all the past 50 years. Figure 4-6b shows these areas.

Table 4-6: Areas (in hectares) with soil loss >35 tons/ha and their percentage contribution to the annual soil loss

Year	Area (ha) with soil loss >35 tons/ha/year	% of the high soil loss areas	Soil loss from high risk areas (10^3 tones)	% contribution of high risk areas to total yearly soil loss
1957	2678	27	129	73
1979	4179	42	208	81
1986	4747	48	261	80
1999	4758	48	235	76
2010	3987	40	198	79

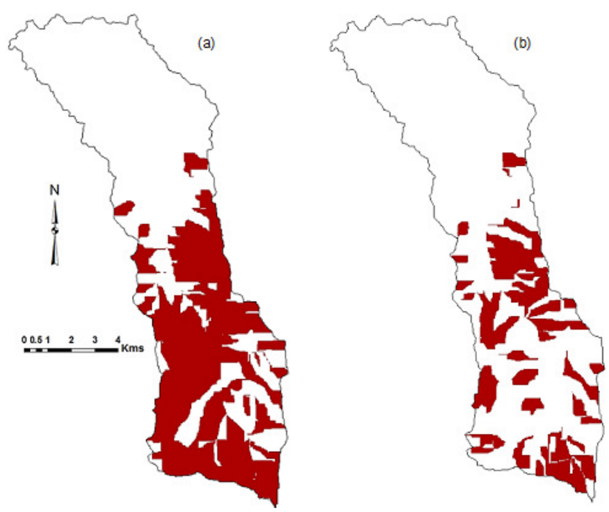

Figure 4-6: Areas with soil loss >35 tons/ha/year (a) in 2010, (b) throughout all the years from 1957 to 2010

Table 4-7 shows that crop fields and woody vegetation are the major land use of the all time high erosion risk areas. As can be seen from Table 4-8, the total amount of soil loss from these all time high erosion risk areas slightly increases from 1957 to 1986 due to a decrease in the woody vegetation cover but then decreases from 1986 to 1999 due to a decrease in the amount of land used as crop fields. This finding is in line with Ciampalini et al. (2012) who found that the change in land use patterns in the 1970s resulted in an increase in soil erosion in the Northern parts of Ethiopia. Li et al. (2013) and Cotler and Ortega-Larrocea (2006) analyzed the impacts of land use conversions

Table 4-7: Land use/cover changes from 1957-2010 on all time high risk erosion areas in Figure 4-6b

Year	Woody vegetation (ha)	Pasture (ha)	Bare land (ha)	Settlement (ha)	Crop field (ha)	% of Woody veg.
1957	704	59	42	0	1240	34
1979	495	142	63	7	1328	24
1986	387	204	86	8	1369	19
1999	260	353	86	52	1291	13
2010	443	248	0	197	1156	22

Table 4-8: Soil loss (tons) from the all time high risk erosion areas in Figure 4-6b

Year	Total yearly soil loss (tons) from the all time high erosion-risk areas	Total yearly soil loss at the outlet of the study area (tons)	Contribution of the all years high risk areas (%)
1957	100657	176817	57
1979	101106	257087	39
1986	129801	326956	40
1999	110166	311054	35
2010	101908	251875	40

on soil loss in a Chinese and a Mexican catchment respectively, and they found that conversion of forest to other land use types induced substantial soil loss, while transition from other land use types to forest reduced soil loss. In our study area, from 1999 to 2010, the sediment loss decreased due to an increase in the woody vegetation cover. It has been indicated by Yeshaneh et al. (2013a) that there is an increasing tendency to eucalyptus tree plantation in the area at the expense of crop fields. While land use change played a role in the changes in the total amount of sediment loss from these areas, one clearly observes that these areas remained in the high risk erosion category throughout the past 50 years. This in turn indicates that other factors such as slope and soil contributed significantly to soil erosion from these particular areas, as also indicated later in this document. Tamene et al (2006) indicated terrain form, gully erosion, surface lithology and land cover as the most important factors in producing sediment yield in the highlands of Northern Ethiopia. Table 4-5 also shows the high percentage contribution of sediment loss from the all time high risk erosion areas, though they cover only 21% of the total study area.

Figure 4-7: Some parts of high risk erosion areas in the upstream part of the study area

When the entire study area is considered, crop fields are the dominant land use/cover types. Model outputs show that more than 80% of the yearly sediment load in the study area comes from the crop fields throughout the past 50 years. Through analysis sediment hysteresis patterns, Yeshaneh et al. (2013b) had indicated in a previous study that most of the yearly sediment at the outlet of the study area comes from the crop fields and hill slopes rather than the river channels. The dominant crop types cultivated in the study area are teff, barley, maize, millet, niger seed, flux, beans and lentils.

Table 4-9: Land use/cover change in the study area

Year	Woody vegetation (ha)	Pasture (ha)	Bare land (ha)	Settlement (ha)	Crop field (ha)
1957	2,786	1,616	125	7	5,341
1979	3,000	910	213	127	5,618
1986	1,727	1,378	327	106	6,427
1999	1,178	2,234	282	264	5,909
2010	1,864	2,002	0	736	5,276

In general, whereas most of the high risk soil erosion areas remained similar from 1957 to 2010, the average amount of soil loss per hectare per year fluctuated between 17.6 in 1957 to 32.7 in 1986; the other values remained in between. The relatively low amount of soil loss per hectare in 1957 is associated with the relatively higher amount of forest cover in this year than in all the other years. When we compare the yearly soil loss in the 1950's with the land use changes since then, we observe that the amount of soil loss per year increases from the 1950 to the 1980s with the decrease in the amount of woody vegetation and increase in the area used for agriculture (crop fields and pasture). The decrease in the yearly soil loss from the 1980s to the 1990s is due to the decrease in the area used as crop fields which are the main sediment sources. The decrease in soil loss still continues from the 1990s to 2010 due to an increase in woody vegetation cover at the expense of agricultural areas (the crop fields and pasture). It has been indicated earlier that farmers in the area are converting parts of their crop fields to eucalyptus tree plantations due to the better income they get from the eucalyptus plantations due to the reduction of labour compared to crop cultivation (Yeshaneh et al 2013a).

It has been indicated by several researchers that erosion is a critical problem in the Blue Nile basin that limits agricultural productivity and leads to sedimentation of dams in downstream areas (Easton et al. 2010; Awlachew et al., 2010). Our study has confirmed these facts and points to the need for simulating various soil and water conservation measures that help indicate the appropriate practices to be implemented on those areas to reduce the soil loss in the catchment.

4. 3.2.2 Runoff

Figure 4-8 shows the runoff maps obtained for the time slices since the 1950s. When we consider the annual runoffs, as Table 4-10 shows, there is an increase in the yearly amount of runoff from 1957 to 1986 while there is almost no change in the amount of runoff from 1986 to 1999, and there is a decrease in 3.3% decrease in runoff from 1999 to 2010. This is due to a decrease in the amount of woody vegetation with the increase in the other land use types in the years from 1957 to 1999 and an increase in the amount of woody vegetation from 1999 onwards. As seen from Figure 4-8 and Table 4-10, the amount of areas with a yearly runoff of less than 500 mm, continuously decreases from 1957 to 1999 but then increases from 1999 to 2010. The decrease in

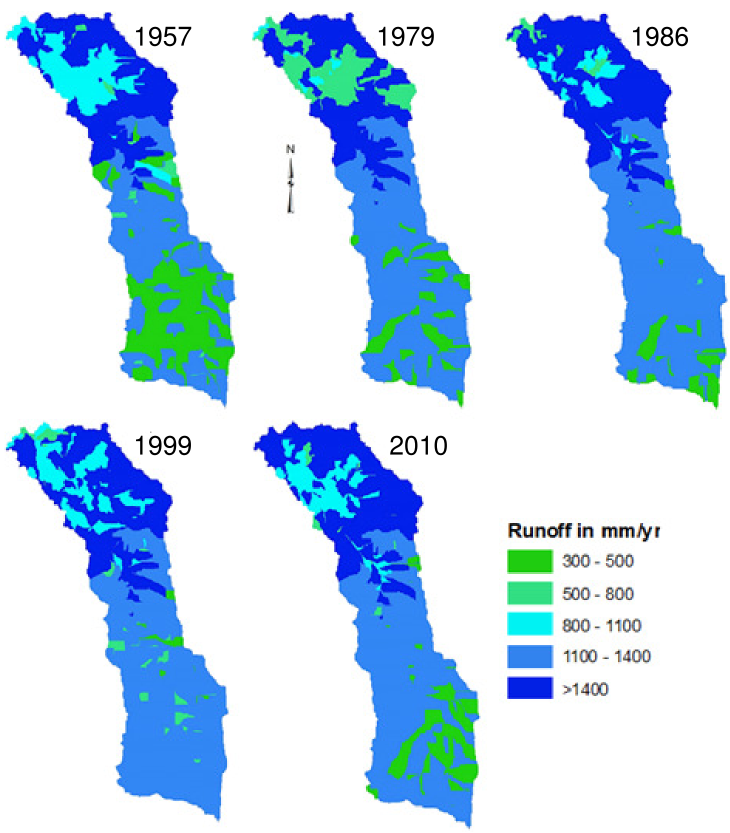

Figure 4-8 : Annual runoff maps of the study area from 1957-2010

the low runoff areas from 1957 to 1999 is due to the decrease in the amount of woody vegetation cover and with the increase in the other land use types within this time. On the other hand the increase in the low runoff areas from 1999 to 2010 is due to the increase in the woody vegetation within this time period. When we consider the amount of areas with yearly runoff greater than 1400mm, there is a slight increase from 1957 to 1986 but a slight decrease since then.

Table 4-10: Runoff volume from the study area for the years 1957-2010

Year	Yearly runoff (m^3)	Percentage increase	Areas (in ha) with runoff <500mm/year	Areas (in ha) with runoff >1400mm/year
1957	110949037		2414	2599
1979	119878857	8% increase	926	2624
1986	130597607	9% increase	642	3241
1999	130621823	0.02% increase	104	2825
2010	126278144	3.3% decrease	1034	3031

Runoff maps on Figure 4-8 indicate that all the areas with yearly runoff >1400mm fall in the lower part of the studied catchment, while almost all the areas with yearly runoff <500 mm fall in the upper part of the catchment. As referred from Table 4-11, while the areas with more than 1400mm runoff contribute about 40% of the total yearly runoff from the whole study area, these same areas contribute only about 10% of the total sediment loss from the whole catchment. Whereas most of the areas with high runoff are in the downstream part of the study area, the areas with high erosion are found in the upper part of the catchment where the runoff is relatively lower. This suggests that the soil erosion in the area is not directly related to the amount of runoff in the area but to other factors. As seen in Table 4-6, while the percentage of woody vegetation from the all time high erosion risk areas ranges from 13% in 1999 to 34% in 1957, the percentage of woody vegetation from the high runoff areas ranges from 8% in 1999 to

Table 4-11: Land use of areas with runoff greater than 1400 mm/year

	1957	1979	1986	1999	2010
Woody vegetation (ha)	239	488	332	216	310
Crop fields (ha)	2060	1797	2431	1913	1838
Pasture (ha)	297	286	402	542	767
Bare area (ha)	0	34	70	41	0
Settlement (ha)	3	19	6	113	116
Sum (ha)	2599	2624	3241	2825	3031
Runoff (m^3) x 10^6	44	44	55	47	51
% contribution to total runoff in the study area	40	37	42	36	41
Total sediment (tons)	22032	22290	24836	22415	25234
% contribution to total sediment in the study area	12	9	8	7	10
% of woody vegetation	9	19	10	8	10

19% in 1979. This fact suggests that the amount of woody vegetation in the area has more effect on the amount of runoff than on the amount of soil loss. Whereas high risk erosion in the study area occurs in the areas where there is a relatively higher percentage of woody vegetation cover than in the areas with high runoff, the high runoff areas lie in the lower part of the catchment. This in turn indicates that while woody vegetation cover affects both the amount of runoff and erosion in the study area, it has more effect on the amount of runoff than the amount of erosion. Of course, other local factors, such as runoff connectivity (Western et al., 1998, 2001) may additionally affect runoff generation and erosion processes.

4.4 Conclusions

Model simulation results suggest that changes in woody vegetation cover and crop fields over the past 50 years resulted in significant changes in sediment yield. While the increase in woody vegetation cover contributed to a decrease in soil loss, the increase in crop fields had the opposite effect. Soil loss increased from the 1950s to the 1980s due to a decrease in the woody vegetation cover and increase in the area used for crop cultivation. From the 1980s to 2010, there is a decrease in the yearly soil loss due to an increase in the woody vegetation cover and decrease in the area of crop fields attributed to eucalyptus tree plantations.

This study identified the areas that contributed more than 35 percent of the soil loss each year throughout the past 50 years. These cover 21% of the study area. These areas have been under the same high risk soil erosion for all those years which implies a need for immediate attention. Crop fields were found to contribute to most of the sediment loss in the catchment which suggests the most attention needs to be paid to the crop fields when formulating soil and water conservation measures.

The study has identified that while high erosion areas are found in the upper part of the study areas where the landscape is hilly, high runoff areas occur in the lower part of the catchment where the landscape is relatively flatter indicating soil erosion in the area is not only associated with runoff but with other factors. While the amount of woody vegetation plays a role both in runoff and erosion processes, we have found that it has more influence on the amount of runoff than on soil loss. The amount of soil loss in the study area is area is more affected by geomorphologic and soil factors than by the amount of woody vegetation. We also have found that the amount of low runoff area decreased from 1957 to 2010 with the decrease in woody vegetation covers.

Water and soil conservation measures are needed to reduce runoff and soil erosion in the study area.

5. Effects of conservation measures on soil loss in the Koga catchment, Northwestern Ethiopia

Abstract

This study was performed in the 9838 ha upper part of the 260 km² Koga catchment, Northwestern Ethiopia. We used the distributed AnnAGNPS (Annualized Agricultural Non-point source) model for simulating the effectiveness of alternative soil and water conservation measures. The study indicates that contour farming accompanied by terraces on the high erosion risk (soil loss>35 $ton.ha^{-1}yr^{-1}$) areas reduces soil loss from the study area by 39% while this measure does not reduce runoff. Reforestation of the high erosion risk areas resulted in a 64% reduction in soil loss and a 22% reduction in runoff. Combinations of reforestation, contour farming and terracing applied to areas with different levels of erosion risk resulted in a reduction of soil loss by up to 88% and runoff by up to 22% from the study area. Mulch till of all the crop fields reduced soil loss by 20% while it had almost no effect on runoff.

5.1 INTRODUCTION

Land degradation is a major threat to sustainable development in Ethiopia and will need tremendous efforts and resources for mitigation (Tadesse G., 2001). Land degradation is mainly caused by soil erosion (Dubale, 2001; Shiferaw and Holden, 1999) and has become one of the major constraints in agricultural production in the highlands of Ethiopia (Mazengia et al., 2007). Land degradation has both on site and off site impacts. While loss of productivity and shortfalls in both food and cash crops are the immediate impacts, siltation of downstream reservoirs resulting in loss of their storage capacity may also occur (Mishara and Rai, 2013). Globally, water erosion is the most important cause of soil degradation (Scherr, 1999). Sheet and rill water erosion are the most important present-day geomorphic processes throughout Ethiopia (Nyssen et al., 2004).

Due to erosion, farmlands in many parts of the highlands of Ethiopia have shallow soil depths and poor fertility (Shiferaw and Holden, 1999).

Conservation practices are designed to reduce losses of soil, nutrients, pesticides, and other biological and chemical materials from agricultural lands, conserve natural resources, and enhance the quality of agro-ecosystems. Without conservation of natural resources, environmental problems such as accelerated erosion could negatively impact society and threaten national security (Delgado et al., 2011). The government of Ethiopia and non-governmental organizations recognized land degradation as a major environmental and socio-economic problem and initiated the design and implementation of conservation strategies since the 1970s, though most of the efforts were ineffective (Dubale 2001; Tesfaye et al. 2014). Since that time, soil conservation efforts have focused on construction of physical soil and water conservation measures in cultivated fields and reforestation of hillsides to rehabilitate degraded environments and stop further degradation (Bewket, 2007).

Much research has been done in Ethiopia about the extent and causes of soil erosion, and control rates (Tefera and Sterk, 2010; Tegene, 2000; Zeleke, 2000; Nyssen et al., 2000; Mohammed et al., 2004; Haregeweyn and Yohannes, 2003; Hurni, 1988; Nyssen et al., 2009) indicating the need for soil and water conservation. Some of these studies were performed on areas where soil and water conservation measures have already been practiced. Since intensive farming can potentially impact soil and water quality, parallel increases in new soil and water conservation practices and technology will be needed to help sustain and maintain agricultural systems (Berry et al., 2003). Many of the studies in Ethiopia focused on the factors that affected the adoption and sustainability of soil and water conservation measures and farmers' perception of the already adopted conservation measures (Tefera and Sterk, 2010; Shiferaw and Holden, 1999; Amsalu and Graaf , 2007; Daba, 2003; Herweg, 1993; Bewket, 2007; Moges and Holden, 2007; Gebremedhin and Swinton, 2003, Tesfaye et al., 2014; Mazengia et al. 2007; Bewket, 2007; and Asrat et al., 2004). A few others such as Descheemaeker et al. (2006), Herweg and Ludi (1999), and Nyssen et al., (2007) studied the biophysical performance of one or more of the already implemented measures. However, studies based on quantification of the relative contribution and importance of the different types of conservation measures in Ethiopia are either very limited or non-existent.

AnnAGNPS is a hydrological model that has been designed for evaluating the response of a watershed to soil and water conservation measures. AnnAGNPS has been used to simulate the amount of erosion runoff in many parts of the world (Hua et al., 2012; Baginska et al., 2003; Shrestha et al., 2006; Yuan et al., 2001; Polyakov et al., 2007; Sarangi et al., 2007; Licciardello et al., 2007) including Ethiopia (Haregeweyn and Yohannes, 2003; Mohammed et al., 2004). On the other hand, research using the model for simulation of soil and water conservation practices is limited and the ones that exist such as (Yuan et al., 2008) are limited to conditions in the USA. The model can be used for modeling different soil and water conservation measures using data from short-term monitoring, which is cost effective when compared to best management programmes based on long term monitoring (Yuan et al., 2008). The objective of this study is thus to apply the AnnAGNPS model to simulate selected soil and water conservation measures for identifying best management practices in the upstream part of the Koga catchment. The Koga catchment has high rates of erosion compared to the rates of soil formation. Furthermore, the prevention of siltation of the Koga reservoir is an important issue.

5.2 Materials and Methods

5.2.1 The Study Area

5.2.1.1 Location, Climate and Topography

The study area is 9838 hectares in size and represents the upstream part of the 260 km^2 Koga catchment (Figure 5-1) in northwestern Ethiopia. The Koga catchment is a typical catchment for the Ethiopian Highlands, 72% of which is used for subsistence agriculture. The Koga River is a tributary of the Gilgel Abbay, which flows northwest into Lake Tana, and lies in the upper part of the Blue Nile (Abbay) watershed.

The climate of the Koga catchment falls within the Woina Dega (cool semi-humid, 1,500 to 2,400 m asl) and Dega zones (cool, above 2,400 m asl). The majority of the catchment area lies within the Woina Dega zone and is characterized by distinct dry and wet seasons. The dry season occurs between November and April and the wet season between May and October; small rain storms occur sporadically during April and May. The average annual rainfall we measured within the years 2010-13 for the catchment is 2500mm/yr. The mean daily temperature is 18.3 ℃.

Elevations of the Koga catchment range from 1875 m asl at the catchment outlet to 3215 m asl at its highest point. The study area drains into the Koga irrigation reservoir at 2015 m asl. The Koga reservoir (Figure 5-1) is used for irrigation of the downstream areas. The Koga River flows over a distance of 26 km before it drains into the Koga irrigation reservoir and has a total length of 49 km.

5.2.1.2 Soils

The soil types within the upper part of the Koga catchment we studied are Luvic Phaeozems (Typic Argiustolls), Chromic Cambisols (Fluventic and Typic Ustropepts), Lithic Leptosols (Lithic Ustropepts), Haplic Alisols (Typic Paleustults), Eutric Vertisols (Ustic Tropaquepts) and Eutric Gleysols (Typic Tropaquepts). These soils have clay to clay loam texture with the exception of Eutric Gleysols (Typic Tropaquepts) which has clay to sandy clay loam texture.

4.2.1.3 Agricultural practices

Subsistence rain fed production of cereals comprising teff, maize, barley and millet, as well as pulses, oilseeds and some legumes is dominant in the area, while irrigated agriculture takes up a small percentage of the cultivated area of the Koga catchment. Soil tillage is done with oxen-drawn ploughs. There exist some attempts to prevent soil erosion through soil and water conservation structures such as stone stacks along with tree planting, storm water diversion channels, soil bunds, channel and orchard terraces, contour cultivation, etc., though these have not been extensively used nor studied sufficiently to determine which methods are most effective in controlling soil erosion in the catchment. Crop cultivation is the main source of income followed by livestock for the poor farmers in the area.

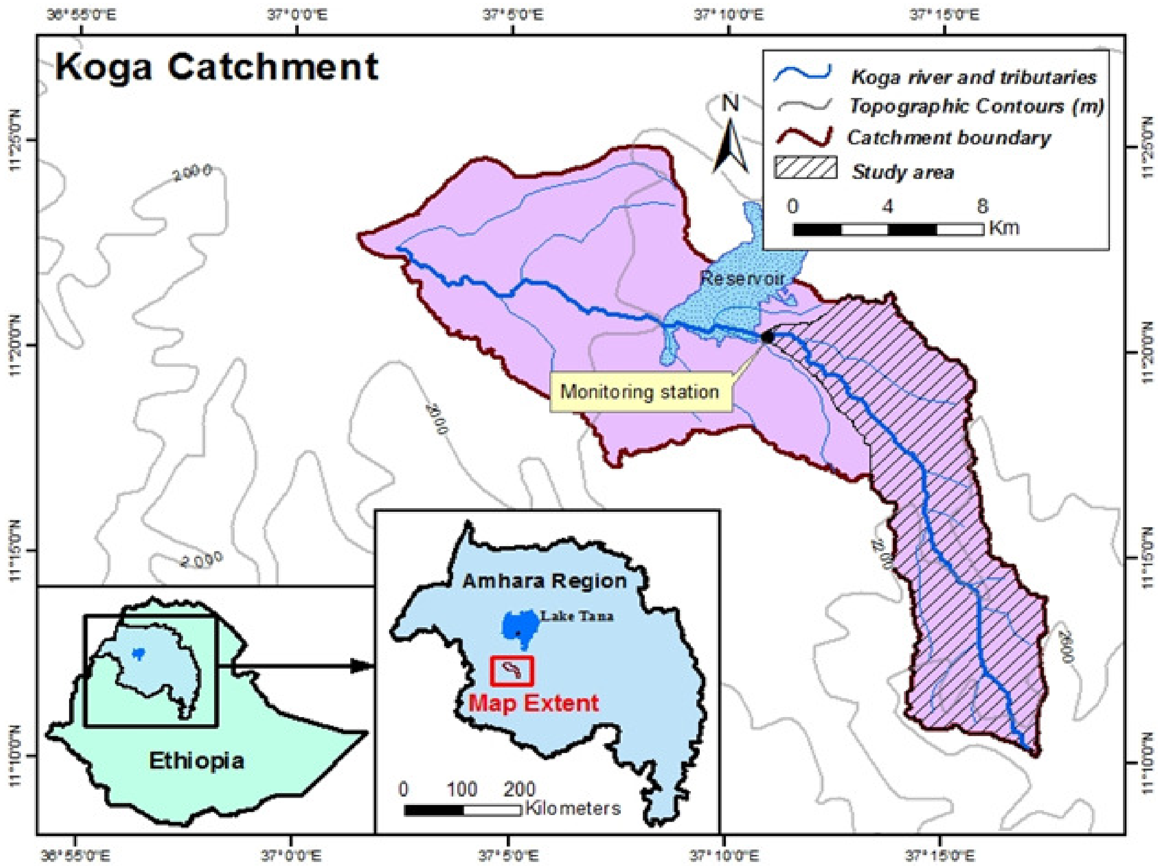

Figure 5-1: Location Map of the Koga Catchment (Yeshaneh et al., 2013b)

5.2.2 Methods

The AnnAGNPS model was used for simulation of selected soil and water conservation methods.

5.2.2.1 AnnAGNPS model description

The AnnAGNPS (Annual Agricultural Non-point Source) model is a spatially distributed model developed for simulating sediment, runoff, nutrient and pesticide loss from agricultural watersheds and for simulating various soil and water conservation measures that enable formulation of best management practices. AnnAGNPS enables continuous simulation of the processes involved in transport and deposition associated with sheet and rill erosion (Baginska et al., 2003)

AnnAGNPS has a GIS interface by which the watershed is divided into cells based on the Digital Elevation Model (DEM), land use, and soil type. The cells are linked together to form streams (reaches) and are then used to simulate the movement of water, sediment and various chemicals. The AnnAGNPS-GIS interface determines the size of each cell by its Critical Source Area (CSA) minimum Source Channel Length (MSCL) (Shrestha et al., 2006) defined by the user based on a variety of different soils, land use, and topography information. The MSCL represents the minimum reach length in meters that connects a set of cells with the same runoff route (usually a stream or tributary within the watershed). Our study area was divided into 543 cells by Yeshaneh et al. (2014, submitted) using a CSA of 20 ha and a MSCL of 210 m.

The cell and reach data produced using the AnnAGNPS-GIS interface was then used as input to the AnnAGNPS input editor, together with daily climate data, crop and crop growth data, management field data, management schedule and crop management operation data, non-crop data, runoff curve number (CN), simulation period, soil, watershed, and the output options data fields for the simulation of runoff and sediment within our watershed. The daily climate data included daily rainfall data, daily minimum and maximum temperature, dew point temperature and potential and actual evapo-transpiration data for the two years considered for simulation. Out of the four management field IDs (woody vegetation, crop field, pasture and settlement), crop field was scheduled for management operations. Tillage, new crop growth and harvest operations were scheduled at the end of May, middle of June, and end of September respectively. Residue cover on the surface after tillage was initially estimated. In addition, crop parameter inputs such as the amounts of crop residues for having various levels of surface cover were estimated (Table 4-2). For the non-crop management fields, the annual root mass, annual cover ratio, annual rainfall height, and surface cover residue factors were estimated (Table 4-1). All the estimated parameters were adjusted manually by Yeshaneh et al. (2014, submitted) during calibration where needed. The USDA-NRCS Conservation Engineering Division Technical Release 55 runoff curve number that was used for the model was modified during calibration (Table 4-3). Yeshaneh et al. (2014, submitted), used Manning's n initially based on Chow (1959) which was slightly modified during calibration (Table 4-4). Crop fields were assumed to have their highest Manning's roughness from mid-August to the end of September each year as the crop fields are completely covered with vegetation at that time of the year (Yeshaneh et. al., 2013b). Soil input data was used as summarized in Table 4-5.

The SCS curve number technique is used within AnnAGNPS to determine the surface runoff from a field. The AnnAGNPS model uses the related soil retention value and soil moisture adjustment for each CN entered by the user and creates algorithms to calculate the runoff generated for the cells within the watershed (Shrestha et al., 2006).

The model uses the Revised Universal Soil Loss Equation (RUSLE) based on land cover, soil, management practices, topography, and precipitation values for each cell and to calculate the daily sheet and rill erosion. The RUSLE K factor was input for the different soil types. Slope length is part of the cell data produced by the AnnAGNPS-GIS interface; the RUSCLE C factor is calculated by AnnAGNPS based on non-crop and crop input parameters. When running the model Yeshaneh et al. (2014, submitted) set the P factor as 1, due to the very limited amount of soil and water protective structures when compared to each of the AnnAGNPS cell sizes in the watershed. Yeshaneh et al. (2014, submitted) estimated the rainfall erosivity factor (R) from the isoerodent map of Ethiopia by Krauer (1988) followed by calibration within the allowable range based on model sediment output.

Runoff and sediment that are calculated by AnnAGNPS are finally routed from each cell through a channel network to the outlet of the watershed (Hua et al., 2012). Yeshaneh et al. (2014, submitted) first calibrated the model with yearly runoff and sediment data of one year period (2011/12) and then with the daily data of the same year. The model was then validated with the daily runoff and sediment data of the second year (2013). Calibration and validation results showed good correlation coefficients between modeled and measured values and good Nash-Sutcliffe efficiency coefficients.

The calibrated and validated model was then used in this paper for simulating the different soil and water conservation measures. Maps of current soil loss and runoff, current high risk erosion areas, and all-time high erosion risk areas throughout the past 50 years were simulated for different management scenarios. High risk erosion areas are areas with soil loss greater than 35tons.ha^{-1}yr^{-1}.

5.2.2.2 AnnAGNPS simulations for different soil and water conservation measures

As our study area drains to the Koga irrigation reservoir, which is affected by siltation, reduction of sediment is much more important than reduction of runoff. Reduction of soil erosion contributes towards reducing siltation of the reservoir and reducing further on site land degradation. Therefore, the scenarios of this paper mainly focus on reducing soil loss rather than on reducing runoff.

The scenarios for the AnnAGNPS model simulations together with the model outputs are put in Table 5-1 in the results and discussion section. The scenarios are combinations of one or more of the following soil and water conservation techniques.

a) Reforestation: Reforestation consists of planting trees on land that had different land use/cover. Reforestation is considered a soil conservation practice as tree cover may be effective in reducing the kinetic energy of rainfall at the soil surface in addition to soil cohesion by tree roots (Hengsdijk et al., 2005). Trees may thus reduce soil loss from slopes. Trees increase water infiltration rates into the soil and reduce surface runoff. How reforestation was implemented in the AnnAGNPS model is stated later in this section.
b) Contour farming: Contour farming involves ploughing, planting and weeding along the contour, i.e., across the slope rather than up and down. Contour farming is usually combined with other measures to enhance its effectiveness. Contour farming was implemented in the AnnAGNPS model by defining a separate contour input data for AnnAGNPS input editor. The contour input data

has defined contour Id to be applied on each land use type of the management field data input, and with defined height of the contour ridges, furrow slope, and code indicating condition of soil cover. In this research we defined only a single contour Id to be applied to the crop fields only.

c) Terracing: Terracing refers to building a mechanical structure of a channel and a bank or a single terrace wall, such as an earthen ridge or a stone wall across the slope. Terraces reduce the slope length and the amount of surface runoff which passes over the area down slope from an individual terrace, encouraging it to infiltrate, evaporate or be diverted towards a predetermined and protected safe outlet at a controlled velocity (Dorren and Rey, 2004; USEPA Office of Water, 2000). Terraces may intercept and conduct surface runoff at a non-erosive velocity to stable outlets, and thus reduce the soil erosion rate and production of sediment within the terrace interval and trap the sediment content in the runoff water (USEPA Office of Water, 2000).

Terraces can be formed from stone/soil bunds associated with ongoing erosion processes (Hengsdijk et al., 2005; Herweg and Ludi, 1999). Bunds consist of elevated structures made from soil and/or stones and ditches, which are uphill and/or downhill of the slope (Herweg and Ludi, 1999). They are constructed at regular intervals parallel to slopes for reducing runoff and the associated soil erosion (Hengsdijk et al., 2005). With continuing soil erosion, soil is deposited uphill of the dam which will result in the buildup of terraces. Both soil (or stone) bunds and Fanya Juu type terraces are the main soil and water conservation techniques introduced on cultivated land in the highlands of Ethiopia. Though soil (or stone) bunds are not supported for simulation by the AnnAGNPS model, simulation for terraces can considered as an indirect simulation for bunds, as bunds form terraces with continued erosion processes. Terraces were implemented within AnnAGNPS directly by inputting values for the terrace horizontal distance and terrace grade fields for selected management field Ids in the management field data input of AnnAGNPS input editor. These fields were left blank before simulation for terraces.

d) Mulches: Mulches are soil erosion control mechanisms used alone or in conjunction with other soil and water conservation practices. To mulch means to apply non-erosive material over bare soil or seeded areas in order to protect the soil from direct effects of rainfall, slow surface flows, reduce erosion and provide a favourable environment for revegetation (Shanks et al. 1998). Straw is the most common mulch used on slopes that have been seeded and are subject to erosion. Mulches may also increase rain water infiltration (Erenstein, 2002).

Two factors were involved when selecting the soil and water conservation scenarios for simulation with AnnAGNPS. The first factor considered is whether or not AnnAGNPS supports the simulation of the selected soil and water conservation technique. While some of the conservation methods on crop fields like terracing and contouring were directly applied in the model, some others like reforesting parts of the study area were indirectly applied in the model by converting the particular cells from other land use types to woody vegetation in the cell input data. When we applied one or a combination of two or more conservation measures for the crop field cells with a specific amount of sediment load, those particular cells were given a different crop field Id (while keeping all the other crop data input parameters the same) in the cell data and then the selected conservation measures are applied to this crop field Id. Mulch till conservation practice was also indirectly applied by increasing the percentage of canopy cover in the first 30 days after planting from the original 40% when no conservation measures were applied to 60% for mulch till conservation practice in the crop input data of the AnnAGNPS input editor. The amount of root mass and rainfall height were kept unchanged. Other soil and water conservation practices such as grassed waterways were not simulated, as such types of soil and water conservation techniques were not directly or indirectly supported in the AnnAGNPS model.

The second factor considered when formulating the soil and water conservation scenarios was towards increasing the number of options for the decision makers involved in implementing the proposed methods, considering both cost and social acceptance related challenges that may be encountered during soil and water conservation attempts. For example, instead of applying conservation measures on all the high erosion risk areas (soil loss >35tons/ha/year), one may prefer to implement the conservation measures only on those areas with soil loss >45 tons/ha/year if budget couldn't allow to do the former even though the benefits of the former are much greater than the later. As Herweg and Ludi (1999) indicated, in Ethiopia, successful soil and water conservation is connected with, among others, the economic viability, social acceptance and ecological soundness of the proposed soil and water conservation measures. Initial high investment cost and initial negative returns are some of the reasons indicated for problems of adoption of soil and water conservation measures by smallholder farmers in a similar environment in Tanzania (Tenge et al., 2005). While applying soil and water conservation to all the agricultural areas in our study area is the most effective measure in reducing erosion and runoff as clearly seen on Figure 5-3(j-n) and in Table 5-1 scenarios j-n, the remaining scenarios on Table 5-1 other than scenario p targeting selected parts of the study area may offer more realistic options in practice in terms of cost and/or social acceptance.

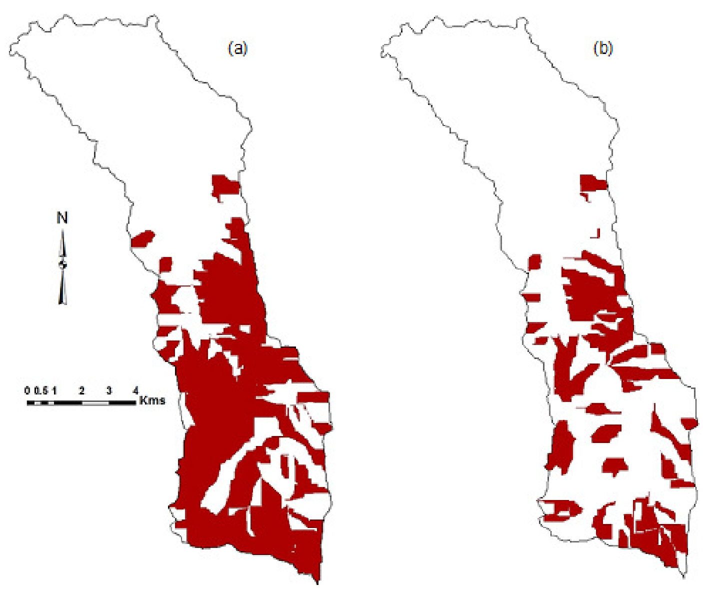

Figure 5-2: Current high erosion risk areas which are affected by soil loss >35 ton.ha^{-1}yr^{-1} (a) and all time high erosion risk areas which are affected by soil loss >35 ton.ha^{-1}yr^{-1} for the past 50 years (b) (from Yeshaneh et al., 2014, submitted).

5.3 Results and Discussion

Simulation of the scenarios in Table 5-1 produced the following results.

Table 5-1: Simulation results of the proposed soil and water conservation scenarios

	Scenarios	Targeted area size (ha)	Runoff at the outlet of the study area (mm)	Sediment load at the outlet of the study area (tons.ha-^{1}yr^{-1})	Runoff reduction as compared to present day conditions (%)	Sediment reduction as compared to present day conditions (%)
a	Without soil and water conservation measures	9838	1274	25	0	0
b	Reforestation of the all time high erosion risk areas	2065	1096	16	14	36
c	Reforestation of the current high erosion risk areas	3987	997	9	22	64
d	Reforestation of the areas with sediment loss > 45 ton.ha^{-1}yr^{-1}	2375	1072	12	16	52
e	Reforestation of the areas with sediment loss >55 ton. ton.ha^{-1}yr^{-1}	947	1191	19	6	24
f	Contouring farming and terraces applied to the current high erosion risk areas	3987	1266	15	0.6	40
g	Reforestation of the all time high erosion risk areas accompanied by contour farming and terracing of the remaining current high erosion risk areas	3987	1098	11	14.5	56
h	Reforestation of the areas with soil loss >45 ton.ha^{-1}yr^{-1} to woody vegetation accompanied by contouring farming and terracing of the remaining current high erosion risk areas	3987	1071	9	16	64
i	Reforestation of the areas with soil loss >55 ton.ha^{-1}yr^{-1} accompanied by contour farming and terracing of the remaining current high erosion risk areas	3987	1191	12	6	52
j	Reforestation of the all time high erosion risk areas accompanied by contour farming and terracing of the remaining crop fields	5300	1096	5	14	80
k	Reforestation of current high erosion risk areas to woody vegetation and contour farming and terracing the remaining crop fields	5300	997	3	22	88
l	Reforestation of the areas with soil loss >45 ton.ha^{-1}yr^{-1} accompanied by contour farming and terracing of the remaining crop fields	5300	1071	4	16	84
m	Reforestation of the areas with soil loss >55 ton.ha^{-1}yr^{-1} accompanied by contour farming and terracing of the remaining crop fields	5300	1191	6	6.5	76
n	Contouring farming and terracing of all crop fields	5300	1266	8	0.6	66
o	Contouring farming and terracing of the all time high erosion risk areas	2065	1266	19	0.6	25
p	Mulch till of all the crop fields	5300	1266	20	0	20

Note:All time high erosion risk areas are the areas with soil loss >35 ton.ha^{-1}yr^{-1} throughout the past 50 years (Fig. 4-2b). Current high erosion risk areas are the ones that are currently undergoing a soil loss >35ton.ha^{-1}yr^{-1} (Fig. 4-2a) .The terraces we used are gradient terraces with a horizontal distance of up to 150m.

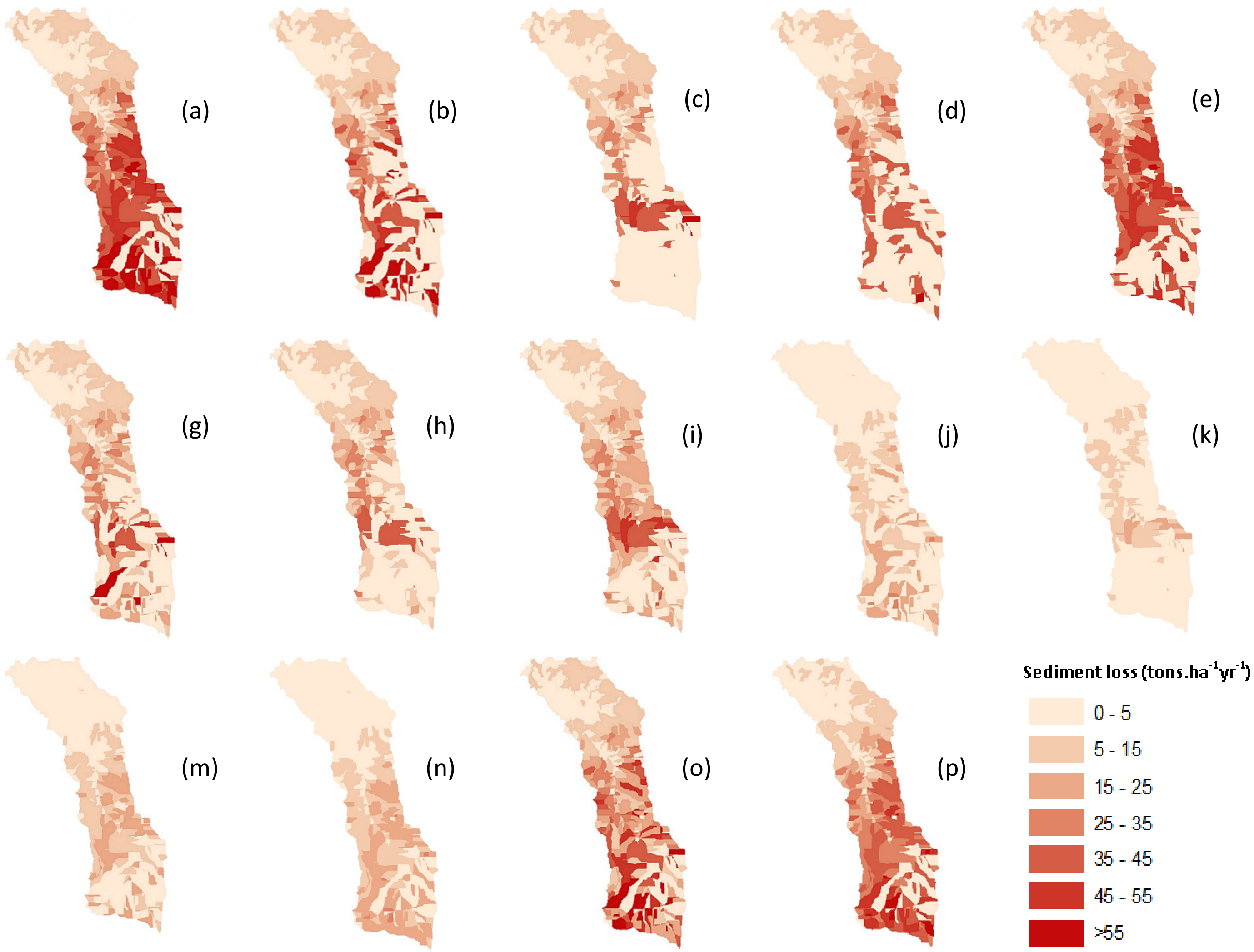

Figure 5-3: Soil loss for the scenarios in Table 5-1 as compared to present day conditions.

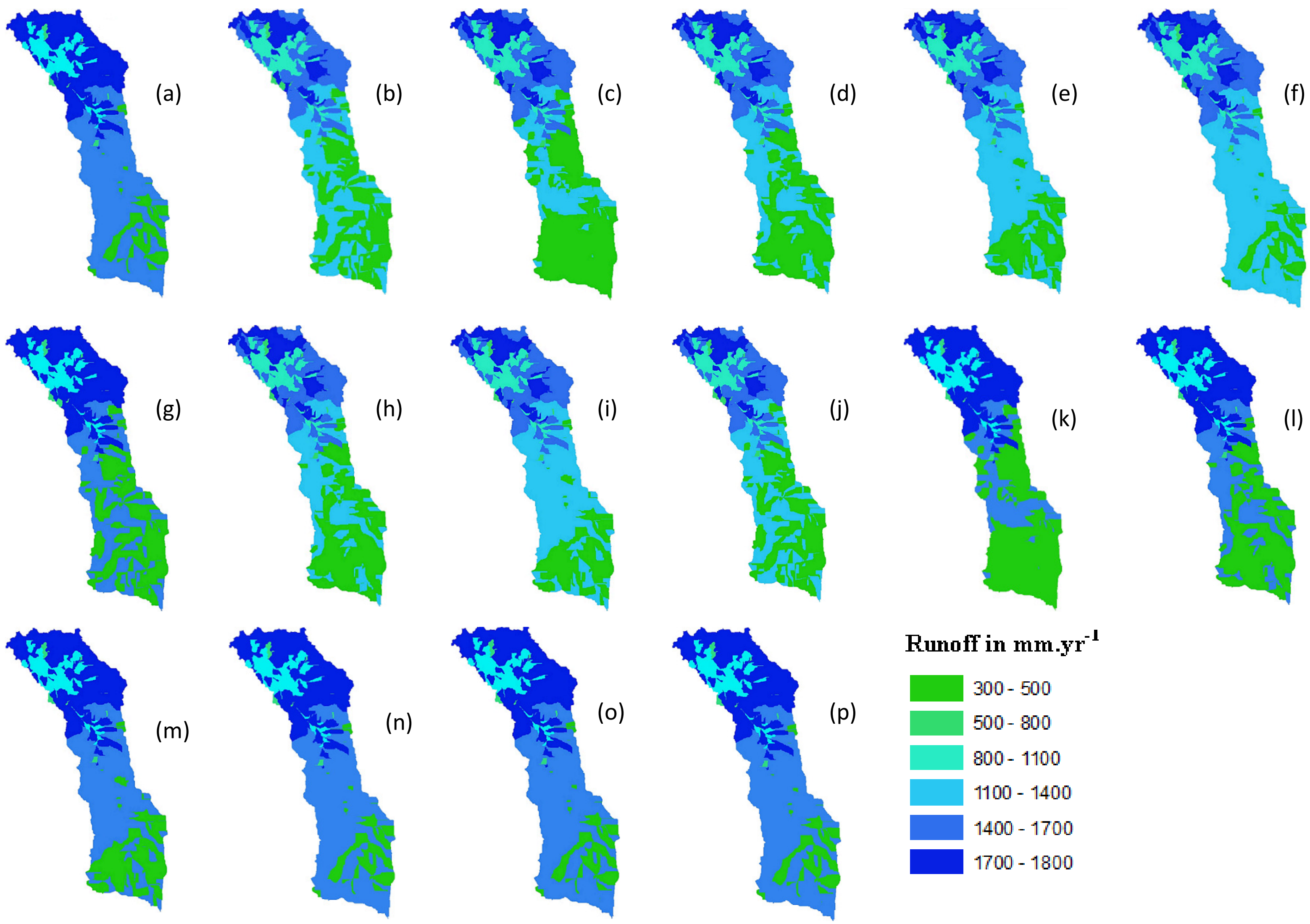

Figure 5-4: Runoff for the scenarios in Table 5-1 as compared to present day conditions.

Table 5-1 indicates that the conservation scenarios can reduce runoff by up to 22%. However, soil loss from our study area can be reduced by up to 88%. This is because the high erosion areas are found in the upper southern part of the catchment while the high runoff areas are found in the lower northern part of the catchment, and the scenarios focused on reducing soil erosion.

When we compare the effects of reforestation with the effects of combined contour–terrace farming on soil loss and runoff from similar areas, reforestation (scenarios b and c) works better than the combined contour-terrace farming (scenarios f and o) both in terms of reducing soil loss and runoff. On the other hand, in an area where poor farmers' only income is generated from their small scale farms, enforcing a decision of reforestation of the farmers' crop fields without their will could be a difficult task. This measure is possible only if the farmers themselves found reforesting their crop lands more benefiting than crop farming which is a likely trend happening in the area. It has been indicated by Yeshaneh et al. (2013a) in a study in the same area that some farmers in the area are converting their farm lands to eucalyptus tree plantation due to a better incomes while incurring less labour than crop farming. Figure 5-5 shows partly reforested crop fields. The findings of our study can be used as a guide for the farmers that have the intention of reforestation to determine which parts of their land to reforest and which ones to keep for crop farming.

Figure 5-5: Parts of crop fields reforested with Eucalyptus trees by farmers in the study area

Hengsdijk et al. (2005) using a hydrological erosion model (LISEM), found a decrease in soil loss of only 12% with 43% due reforestation in a study watershed in the northern highlands of Ethiopia. On the other hand, other studies such as Descheemaeker et al. (2005) indicated that reforestation greatly reduces soil loss from steep slopes in the northern highlands of Ethiopia. Rey (2003) found that forest vegetation cover in the French Southern Alps plays a role in reducing soil loss by fighting erosion and trapping eroded sediments. As seen on Table 1 scenarios b, c, d, e and Figure 3 b, c, d, e, model results in our study area showed the greater effectiveness of reforestation by far amount in reducing soil loss than was found by Hengsdijk et al. (2005) and were consistent with the findings of Descheemaker et al. (2006) and Rey (2003) that showed the tremendous contribution of reforestation in reducing soil loss. The differences may be due to the relatively different climate conditions and different model assumptions. This study suggests that the more reforestations occur in the high erosion risk areas, the greater will be the reduction in soil loss. The scenarios c, d and e, targeting the high erosion risk areas at different levels (areas with soil loss >35 $ton.ha^{-1}yr^{-1}$, >45$ton.ha^{-1}yr^{-1}$, >55$ton.ha^{-1}yr^{-1}$) with the corresponding soil loss reduction after reforestation, will enable decision makers to choose the options which allow them to act as per their budget and the existing conditions in terms of social acceptance.

Studies in different parts of the world have shown that reforestation reduces surface runoff (Mapa, 1995; Huang et al., 2010) and soil erosion (Lacy 2000; Woo et al., 1997) significantly. Harden and Mathews (2002) found through experimental research that soil erosion by sediment detachment decreases over time following reforestation in a basin in southeastern USA that underwent reforestation following extreme degradation. Modeling results in our study area show that reforestation of the high erosion risk areas (which have relatively low runoff) reduces the runoff by up to 22%, but this effect is much less than its effect on reducing soil loss. If the reforestation were to occur on the high runoff areas (>1400$mmyr^{-1}$) at the northern lower part of the catchment, the runoff would have been more significantly reduced. When the model was simulated after reforestation of the high runoff areas (not included in the scenarios in Table 5-1 that were based mainly on reducing soil loss), runoff at the outlet of our study area was reduced by 27% while the runoff from these areas was reduced by 66%. The reduction in soil loss from the study area was only 10% when reforesting the high runoff areas. Our model simulation results indicated that reforestation can reduce both runoff and soil loss (scenarios b, c, d and e) while contour-terracing is effective in reducing only soil loss (scenarios f, n, and o) in our study area conditions. The greater the amount of agricultural area to be converted to woody vegetation in our study area, the greater is the reduction in soil loss and runoff as seen from Table 5-1.

In our study, combined contour-terracing of the current high erosion risk areas (scenario f on Table 5-1) that cover 41% of the study area, reduces soil loss by 40% (Figure 3(f)), while it has almost no effect in reducing runoff (Figure 5-4(f)). If contour-terracing is applied on all crop fields that cover 54% of the study area, soil loss from our study area will be reduced by 66% while it brings almost no effect in reducing runoff. Contour-terracing of the all time high erosion risk areas would rescue these areas from further degradation (Figure 5-3(o)) even though the effect on runoff is negligible. As seen from Table 5-1 and Figure 5-4 (f, n, o) contour farming and terracing appear to have almost no effect in reducing the runoff from the study area. When we used level terraces during model simulation, there was almost no reduction in soil loss nor in runoff. Because of this, we used gradient terraces for simulating the effects of terraces. Our finding showed the effectiveness of terraces in reducing soil loss which is consistent with the findings of studies in the highlands of Ethiopia. Gebremichael et al. (2005) indicated the effectiveness of stone bunds in reducing soil erosion from crop fields in the Tigray highlands of Northern Ethiopia. Nyssen et al. (2007), based on quantitative measurement of average sediment accumulation rates from field parcels with stone/soil bunds, indicated that bunds resulted in decreased soil loss (by 68%) and increased crop yields in the Tigray highlands. Herweg and Ludi (1999) also indicated that Fanya Juu terraces and soil/stone bunds produced a considerable reduction in soil loss in the highlands of Ethiopia and for Kenyan conditions (Hessel and Tenge, 2008). On the other hand, studies in the highlands of Ethiopia have shown that farmers do not like the fact that stone/soil bunds (that would finally lead to formation of terraces) take part of their farm land that they would otherwise use for farming for their immediate benefit (Amsalu and Graaf, 2007; Tegene, 1992). Also, bunds may create suitable environments for infestation by rodents (Amsalu and Graaf, 2007). These difficulties may challenge decision makers in implementing this conservation measure besides cost related challenges.

Our model simulation results indicate that application of mulches to crop fields in the first 30 days of planting (scenario p) decreases the soil loss by 20% while it almost has no effect in reducing the amount of runoff. As the effect of this method alone is not as good as the effects of most of the other scenarios, combining this method with one or more of the other scenarios can enhance the desired results. Crop residue is the most available material that can be used as mulch, but the farmers use straw as fodder for their livestock for the dry season and crop residues of some of the crop types as fuel, so mulching may compete with other uses. Sherr (1999) indicated that in developing countries poverty is one of the reasons exacerbating soil degradation when poor people can meet subsistence food, feed, and fuel needs only through overexploitation of the natural vegetation and consumption of organic residues from farming and livestock that would have helped replenish the soil if not removed. Because of this, forcing poor farmers to implement this measure may itself be a challenge for the decision makers and require side measures to mitigate poverty.

Table 5-2 summarizes studies in different parts of the world that show the impact of terracing and reforestation on soil loss and runoff. If, for example, we consider only the cells with soil loss >35tons.ha^{-1}yr^{-1} in our study area (scenario c and f) for comparison with the studies in Table 5-2, combined contour farming and terracing reduces soil loss by 50% and runoff by 0.4% from these cells, while reforestation contributes to 81% reduction in soil loss and 54% reduction in runoff from these cells. The figures on Table 1 for scenarios f and c show the percentage contribution of soil loss and runoff reduction to the whole study area when contour farming, terracing and reforestation is applied on areas with soil loss >35tons.ha^{-1}yr^{-1}. Our findings stated above are consistent with most of the studies listed in Table 5-2, although our model was not calibrated against data after implementation of the soil and water conservation measures. In addition, in this paper AnnAGNPS model was calibrated against both yearly and daily measured soil loss and runoff data and validated with daily measurements resulting in good model efficiency, which adds credibility to the simulation results for soil and water conservation measures.

Table 5-2: Studies on the effects of selected soil and water conservation measures in some parts of the world

	Reference	Location	Method	Type of conservation measure	Reduction of runoff after conservation (%)	Reduction of Soil loss after conservation (%)
1	Hessel and Tenge (2008)	Kenya, agricultural catchment,	Modelling	Terraces and grass strips	28	60
2	Herweg and Ludi (1999)	Ethiopian highlands; three small watershed with secure high rainfall and high erosion rates	Field measurement	Terraces	2;33; and 50	63%, 68% and 81%
				Bunds	5; 32; and 40	41%; 66%; and 63%
3	Nyssen et al. (2007)	Northern Ethiopia	Field measurement	Stone bunds	Not estimated	68
4	Zhang et al. (2010)	China	Field measurement	Reforestation	Not estimated	50 in the first three years of reforestation, 90 the following two years
5	Huang et al., (2010)	China	Field measurement	Reforestation of farmlands	25.5-61.8	93.9 -96-2
6	Wudomski (2011)	Poland	Modelling	Terraces on bare soil	15	51.7
7	Zhang and Li (2014)	China	Indirect way of field measurement	Terraces on crop fields	Not estimated	16
8	Our current study	Northwestern Ethiopia, areas with soil loss >35tons.ha^{-1}.yr^{-1}	Modelling	Combined contour farming and terraces	0.4	50
				Reforestation	54	81

Our study has indicated the relative effectiveness of possible soil and water conservation scenarios in terms of runoff and erosion. Further studies are needed to assess the socio-economic feasibility of these measures. Simulation of other soil and water conservation measures that were not supported with AnnAGNPS, such as grassed waterways, may also be of interest.

5.4 Conclusions

Our study has indicated that contour farming combined with gradient terracing when applied on the current high erosion risk areas (soil loss>35tons.ha^{-1}yr^{-1}) that cover 41% of the study area may reduce soil loss by 39%, while hardly changing runoff from the study area. Reforestation of these areas reduces soil loss by 64% and runoff by 22%, suggesting the relatively better effects of reforestation in reducing both soil loss and runoff when applied on the high erosion risk areas. If reforestation were applied on the high runoff areas (>1400mmyr^{-1}) which are the relatively low soil loss areas, runoff would decrease by 27% while soil loss only by 10%. The greater the size of high erosion areas reforested, the greater is the reduction in soil loss. The same is true of runoff. On the other hand, contour farming combined with terracing brings a big reduction in soil loss with almost no reduction in runoff.

The reforestation of high erosion risk areas accompanied by combined contour-terrace farming of the remaining crop fields may reduce soil loss by up to 88% and runoff by 22%. The other scenarios based on a combination of these two measures on areas with different levels of soil loss had effects below these figures. Taking into consideration the fact that our study area drains into a reservoir that serves for irrigation of the downstream areas, the scenarios we formulated based mainly on reducing soil loss may be considered as an advantage in reducing soil loss without reducing the runoff needed for the reservoir.

Applying mulches to all the crop fields on the first 30 days from planting may reduce soil loss by 20% while it almost has no effects in reducing runoff. This method should be combined with the other methods mentioned above for better results.

6. Summary of the Findings and Conclusions

The objective of this thesis was to assess environmental changes related to erosion that have occurred over the last few decades in the Koga catchment located in Northwestern Ethiopia, and to identify land management options. A number of different techniques were used for the study.

In chapter 2, we used satellite images and aerial photographs to generate land use/cover for the Koga catchment in the last 5 decades. The remotely sensed data inputs used were reconciled for the scale differences and were brought to a relatively better spatial scale for improved image interpretation. The image inputs were supported by ground truth data achieved through a field survey and interviews with elders that have an in depth knowledge of the land use/cover changes in the study area. Results indicated that the spatial scale reconciled images enabled good comparison of land use/cover changes generated from different data sources, when compared to the traditionally used land use/cover change analysis that don't take the scale factor into consideration. The land use/cover change analyses suggested that there is a tremendous change in the woody vegetation cover of the study area from the 1950s to 2010 and an increase in the area used for settlement within this period. Increases in the human and livestock populations and changes in land use policy were found to be the causes for the land use/cover changes.

In chapter 3, an attempt was made to quantify the temporal variability of sediment yield within a hydrological year in the study area, to identify the main sediment sources and to assess future environmental implications of sediment loss from the study area. Based on discharge and turbidity data for 45 events from a hydrological monitoring station situated in the upstream part of the Koga catchment that was accompanied by water grab samples that were later analyzed for suspended sediment concentration, we were able to develop a relationship between turbidity and suspended sediment concentration values. This relationship was then used to estimate sediment yield for the considered events. The amount of sediment yield estimated this way combined with sediment-discharge hysteresis analysis enable us to observe the temporal variation of sediment transport within a hydrological year and the dominant sediment sources in the study area. Hysteresis analysis indicated that the main sediment sources are the hill slopes and agricultural areas with a smaller contribution from the river channels. 91% of the yearly suspended sediment yield is transported from early June to mid August due to the availability of loose sediment from the ploughed fields at that time of the year when the land has very little or no vegetation cover. During the rest of the main rainy season, after mid August until early October, when the agricultural areas are completely covered with vegetation, the sediment yield from agricultural areas is very low. The study also indicated that if erosion continued at the current rate, a significant depth of the soil will be gone in the coming few decades.

In chapter 4, an attempt was made to estimate how erosion and runoff have evolved over the past 5 decades with changes in land use/cover in the 9838 ha upper part of the 260 sq. km. Koga catchment. The multi parameter spatially distributed AnnAGNPS (Annual Agricultural Non-point Source) model was used to simulate the spatio-temporal changes in runoff and soil loss for changes in land use in the study area. The model predicted runoff and sediment loss well after calibration and validation with measured runoff and sediment data for two years. Model simulation for changes in land use, keeping all other variables constant, enabled us to generate runoff and soil loss maps for the past five decades. We then delineated the current high erosion risk areas as well as the areas that stayed in the high erosion risk (soil loss>35 ton.ha^{-1}yr^{-1}) category throughout the past 5 decades. Model results indicated a significant increase of sediment loss from 17tons/ha/yr in 1957 to 25tons/ha/yr in 2010, associated mainly with a decrease in the amount of woody vegetation cover within this period of time. In addition to the amount of woody vegetation cover, other factors such as geomorphology and soil type were found to have effects on the amount of soil loss from the study area. Simulation results showed that high runoff (>1400mmyr^{-1}) areas are located in the lower part of the study area while high erosion areas are found in the upper part, suggesting the amount of soil erosion is not directly related to runoff volume in the study area. The study showed a decrease in the amount of low runoff (runoff less than 500mm/yr) areas from 1957 to 2010 with the decrease in woody vegetation.

In chapter 5, selected soil and water conservation measures were simulated for the 9838 ha upper part of the 260 km^2 Koga catchment with the AnnAGNPS model, with the intention of determining the best conservation measures. Simulation results suggest that a combination of reforestation, contour farming and terracing, when applied on areas with different levels of erosion risk, result in a reduction of soil loss by up to 88% and runoff by up to 22% from the study area. When contour farming accompanied by terraces is applied to the current high erosion risk areas, soil loss was reduced by 39% from our study area while this measure gives almost no effect in reducing runoff. Reforestation of these same areas results in a 64% reduction in soil loss and 22% reduction in runoff. Applying mulches to all the crop fields for the first 30 days from planting can reduce soil loss by 20%, while it has almost no effect in reducing runoff. The study indicated that reforestation has effects in reducing both runoff and soil loss, while combined contour-terrace farming has an effect only in reducing soil loss.

7. Citations

Chapters 2 & 3 are published in journals and can be cited as follows.

Yeshaneh E., Wagner W., Exner-Kittridge M., Legesse D., and Blöschl G., 2013, Identifying Land Use/Cover Dynamics in the Koga Catchment, Ethiopia from Multi-Scale Data, and Implications for Enviromnental Change, ISPRS International Journal of Geo-Information, 2(2), 302-323.

Yeshaneh E., Eder A., and Blöschl G., 2013, Temporal variation of suspended sediment transport in the Koga catchment, North Western Ethiopia and environmental implications, Hydrological Processes, DOI: 10.1002/hyp. 10090

Chapters 4 and 5 are submitted to the Journal of Land Degradation and Development and can be cited as follows.

Yeshaneh E., Salinas J.L., Blöschl G., 2015, Decadal trends of soil loss and runoff in the Koga catchment, Northwestern Ethiopia, Land Degradation and Development, accepted

Yeshaneh E., Eder A., Blöschl G., 2014, Effects of conservation measures on soil loss in the Koga catchment, Northwestern Ethiopia, Land Degradation and Development, submitted

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9. Appendices

Appendix A: Confusion matrix – 1979 image classification before pansharpening. Overall Accuracy = 75.88%, Kappa Coefficient = 0.67

Class	Ground Truth (Percent)					
	Woody Vegetation	Pasture	Settlement	Crop Field	Bare Area	Total
Woody vegetation	92.7	0.7	0	0.3	0	22.0
Pasture	1.8	73.7	0	32.6	5.8	37.4
Settlement	0	0	93.6	1.3	14.4	2.7
Crop field	0.2	19.3	2.1	61.5	3.3	25.6
Bare area	0.2	6.3	4.3	4.3	76.5	12.4
Total	100	100	100	100	100	100

Appendix B: Confusion matrix—1979 image classification after pansharpening.

Overall Accuracy = 96.17%, Kappa Coefficient = 0.94

Class	Ground Truth (Pixels)					
	Woody Vegetation	Pasture	Settlement	Crop Field	Bare Area	Total
Woody vegetation	99.6	0	0	0.3	0	18.8
Pasture	0	96.6	0	5.6	0	45.6
Settlement	0	0	91.2	0	32.4	0.2
Crop field	0.4	3.4	2.2	94.1	0	35.3
Bare area	0	0	6.6	0.0	67.6	0.2
Total	100	100	100	100	100	100