Modeling hydrological and sediment responses to human activities and climate variability in the Upper Blue Nile basin, Ethiopia

(青ナイル川上流域における人間活動と気候変動に対する水文学的応答および堆積物応答のモデリング)

Mulatu Liyew Berihun

The United Graduate School of Agricultural Sciences

Tottori University, Japan

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Submitted to The United Graduate School of Agricultural Sciences, Tottori University in partial fulfilment of the requirements for the Degree of Doctor of Philosophy in Global Arid Land Science

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2020

DEDICATION

I would like to dedicate this thesis to:

My beloved wife ***Mebrihit Kiros Wolay*** *and daughters* ***Meklit Mulatu and Redeat Mulatu***

My family: Liyew Berihun (father), Atalay Bitaw (mother) and all my sisters and brothers

for their generous love and support

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LIST OF ABBREVIATIONS

AC	*Acacia decurrens*
BL	Bushland
CDT	California Department of Transportation
CI	Conversion Index
CN	Curve Number
CSA	Central Statistical Agency
CV	Coefficients of Variation
DEM	Digital Elevation Model
EP	Eucalyptus plantation
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GD	Gully Density
GL	Grazing land
GIS	Geographic Information Systems
GPS	Global Position System
IPCC	Intergovernmental Panel on Climate Change
HRU	Hydrologic Response Unit
KII	Key Informant Interviews
LULC	Land use/Land Cover
MK	Mann-Kendall
MoWR	Ministry of Water Resources
EMA	Ethiopia Mapping Agency
NMA	National Meteorology Agency

PBIAS	Percent Bias
PET	Potential Evapotranspiration
RC	Runoff coefficient
NSE	Nash-Sutcliffe Efficiency
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
SDV	Standard Deviation
SLM	Sustainable Land Management
SRTM	Shuttle Radar Topography Mission
SSC	Suspended Sediment Concentration
SUFI	Sequential Uncertainty Fitting
SY	Sediment Yield
SWC	Soil and Water Conservation
SWAT	Soil and Water Assessment Tool
TLU	Tropical Livestock Units
UBN	Upper Blue Nile
UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations International Children's Emergency Fund
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Mercator
VC	Vegetation Cover

WEPP	Water Erosion Prediction Project
WHAT	Web-based Hydrograph Analysis Too
WLRC	Water and Land Research Center
WMO	World Meteorological Organization

CHAPTER 1

1. General Introduction

1.1. Background

1.1.1. Overview of land degradation

Land degradation associated to soil erosion is a serious global environmental challenge, globally, about 35.9 Pg yr^{-1} of soil eroded in 2012 (Figure 1-1; Borrelli et al., 2017). As per their prediction, the erosion is more severe in sub-Saharan Africa, South America and Southeast Asia (Figure 1-1). Supportively, the severity is the worst in the East Africa as confirmed in the recent study by Fenta et al., (2020) (Figure 1-2 left). Human activity such as population pressure and poor land management practices and related land use change (expansion of cultivated land) are the primary cause of accelerated soil erosion (Borrelli et al., 2017; Fenta et al., 2020).

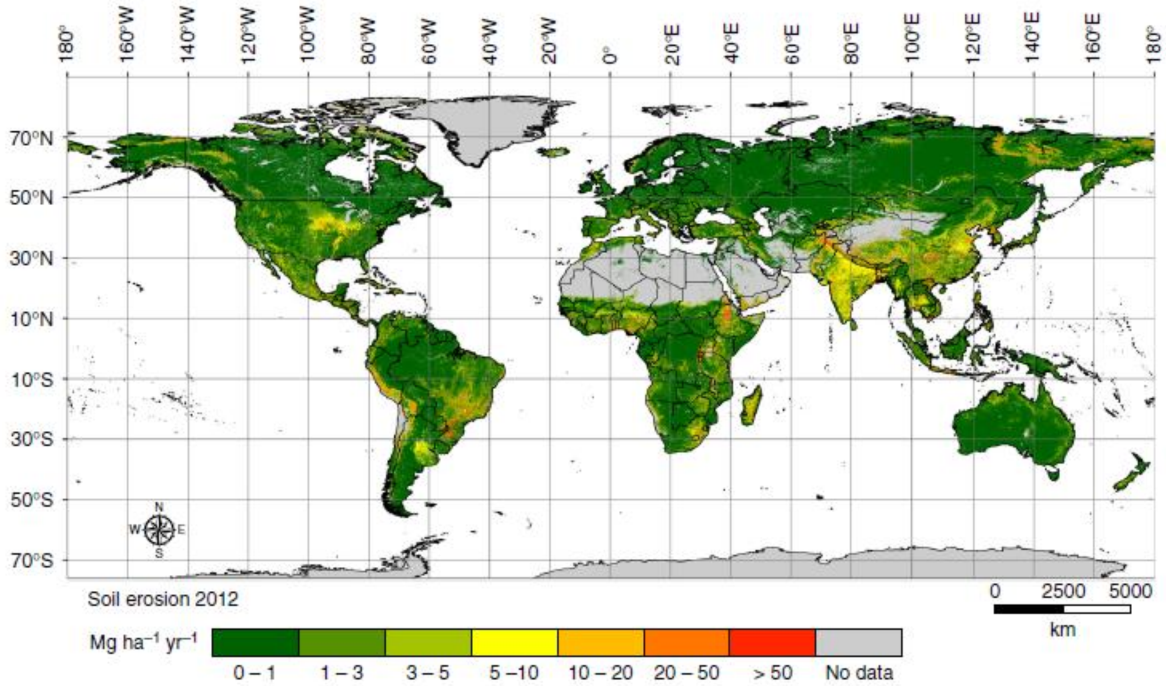

Figure 1-1 Global rates of soil displacement by water erosion (Borrelli et al., 2017).

Several researches showed that soil erosion may increase runoff and soil nutrient loss that deteriorated soil productivity (Haregeweyn et al., 2017, 2013, 2008; Obalum et al., 2012; Vanmaercke et al., 2010) and also it has a substantial implications for nutrient and carbon cycling, land productivity and in turn, worldwide socio-economic conditions.

Particularly, during the past decades the increasing population growth in Ethiopia coupled with a traditional land and water resource management system put enormous pressure on the natural resources. These growing populations posed serious challenges such as land degradation in simultaneously meeting food requirements and water demand in the future mainly due to remarkable conversion of natural vegetation into agricultural land. Consequently, land degradation by water erosion problem has had serious consequences in the country particularly in the Ethiopian highlands (Figure 1-2) where overcultivation and uncontrolled grazing are predominant (Betrie et al., 2011; Bewket and Sterk, 2003; Easton et al., 2010; Fenta et al., 2016; Hurni, 1993; Nyssen et al., 2009; Welde, 2016) including occurrence of persistent food insecurity, economic losses and various environmental hazards such as recurrent drought resulted from climate variability.

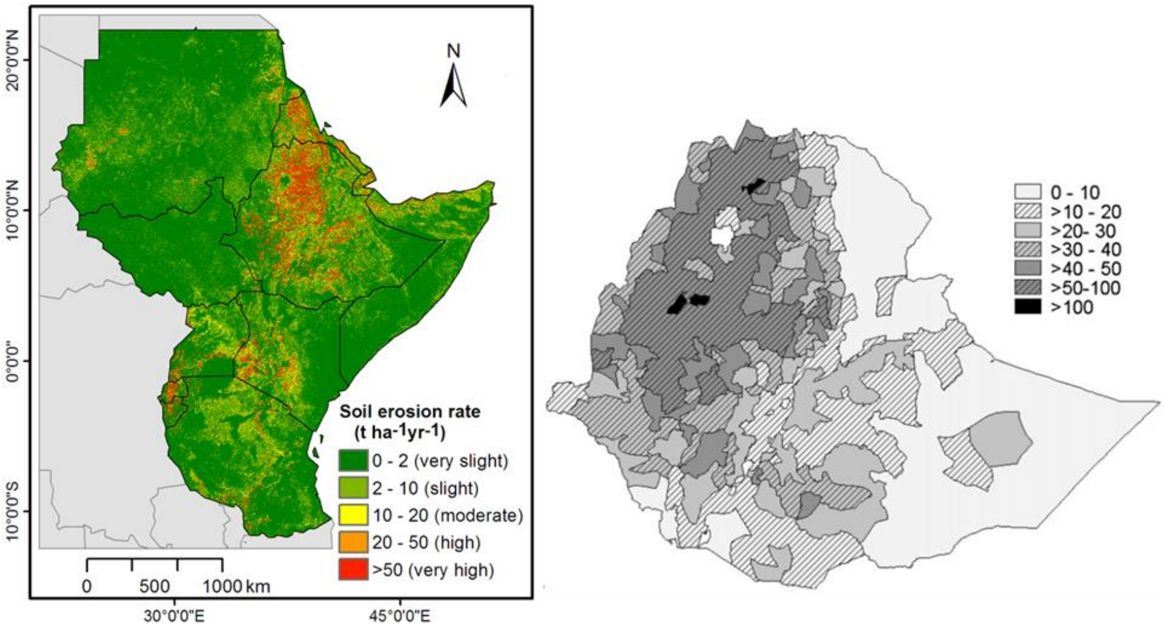

Figure 1-2 Land degradation by water erosion in East Africa (left, Fenta et al., 2020) and Ethiopia highlands (right, Sonneveld et al., 2011).

In addition, annual and seasonal climate change or variability highly aggravates the surface runoff and the soil erosion in the Ethiopia highlands (Gashaw et al., 2018; Mekonnen et al., 2018, Woldesenbet et al., 2018; Worku et al., 2017). In general, therefore, human activities (such as land use/land cover change and poor soil and water conservation practices) and climate variability are the main causes of land degradation by soil erosion in eastern Africa, particularly in Ethiopia highlands.

1.1.2. Land use/land cover change

Land use/land cover (LULC) is a biophysical characteristic which refers to the cover of the surface of the earth, whereas land use is the way in which humans exploit the land cover (Lambin et al., 2003). Besides the definition, LULC change is a major challenge of global environment (Kates and Torrie, 1998). Global scale LULC changes research findings reported that the expansion of cultivated land (Figure 1-3) historically increased mainly at the expense of natural vegetations (e.g., Goldewijk et al., 2011; Goldewijk and Ramankutty, 2004; Ramankutty and Foley, 1999).

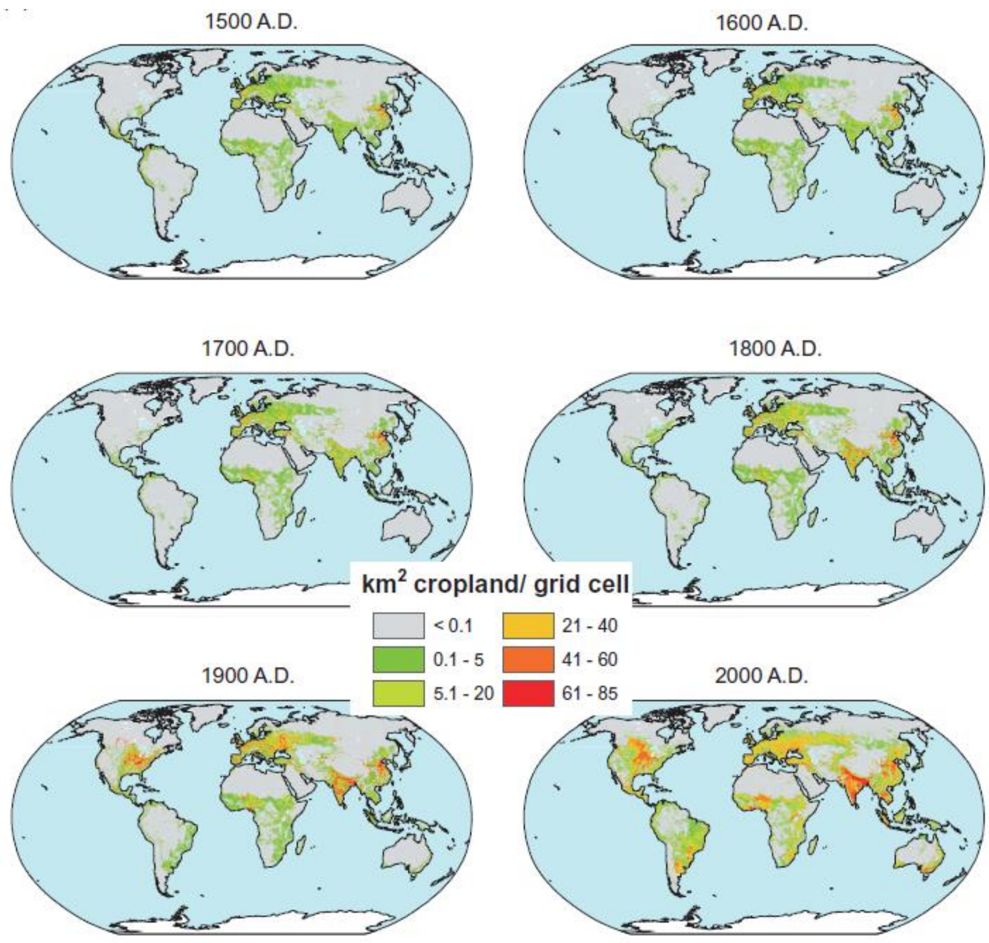

Figure 1-3 Worldwide historical cropland area 1500–2000 (Goldewijk et al., 2011).

However, its change dynamics was not uniform in all parts of the world (Lambin et al., 2003). Although, whatever the change is negative or positive, population pressure, human activities, and economic development have caused LULC changes (Bosch and Hewlett, 1982; Hegazy and Kaloop, 2015). This pressure of human activities processes with faster rate significantly affect the earth system functioning (Lambin et al., 2003). In many areas of developing countries, the rapid increase of population pressure has often led to changes in LULC due to deforestation with the aim of increasing agricultural production demand and for other consumptions (Lørup et al., 1998; Maitima et al., 2009; Rawat and Kumar, 2015).

For different parts of Ethiopia where agricultural activity serves as the backbone of the economy, land cover changes were studied from small scale to large scale (e.g., Bantider et al., 2011; Bewket, 2002; Munro et al., 2008; Gashaw et al., 2017; Gebrehiwot et al., 2014; Minta et al., 2018; Rientjes et al., 2011; Zeleke and Hurni, 2001). Most of these studies have shown that agricultural land has expanded at the expense of natural vegetation, including forests, grazing land and shrub lands through deforestation since a late century. In many parts of Ethiopia highlands, agriculture has gradually expanded from gently sloping land into the steeper slopes of the neighboring mountains (Mengistu, 2008; Minta et al., 2018; Zeleke and Hurni, 2001). On the other hand, some previous studies showed that recently deforestation trend was reduced, and woodland area is improved in some part of the country due to afforestation efforts on degraded hillsides (Bantider et al., 2011; Bewket, 2002; Gashaw, 2014; Lemenih and Kassa, 2014; Munro et al., 2008). Also, according to 2016 LULC map of Ethiopia which was produced by Water and Land Research Center (WLRC; http://www.wlrc-eth.org.), the coverage of woodland had found at the second rank (23%) following shrub/bush LULC (25%; Figure 1-4).

In general, previous research findings shown that there is no uniform trend and magnitude of LULC change in the country. Also, the spatial and temporal LULC change quantification is not enough in the country. This makes it difficult to trace back or predict the known trends, even within a specific region such as the Upper Blue Nile (UBN) basin. This is mainly because of the influence of various human activities (Zeleke and Hurni, 2001) and agro-ecology settings of the watersheds in the basin.

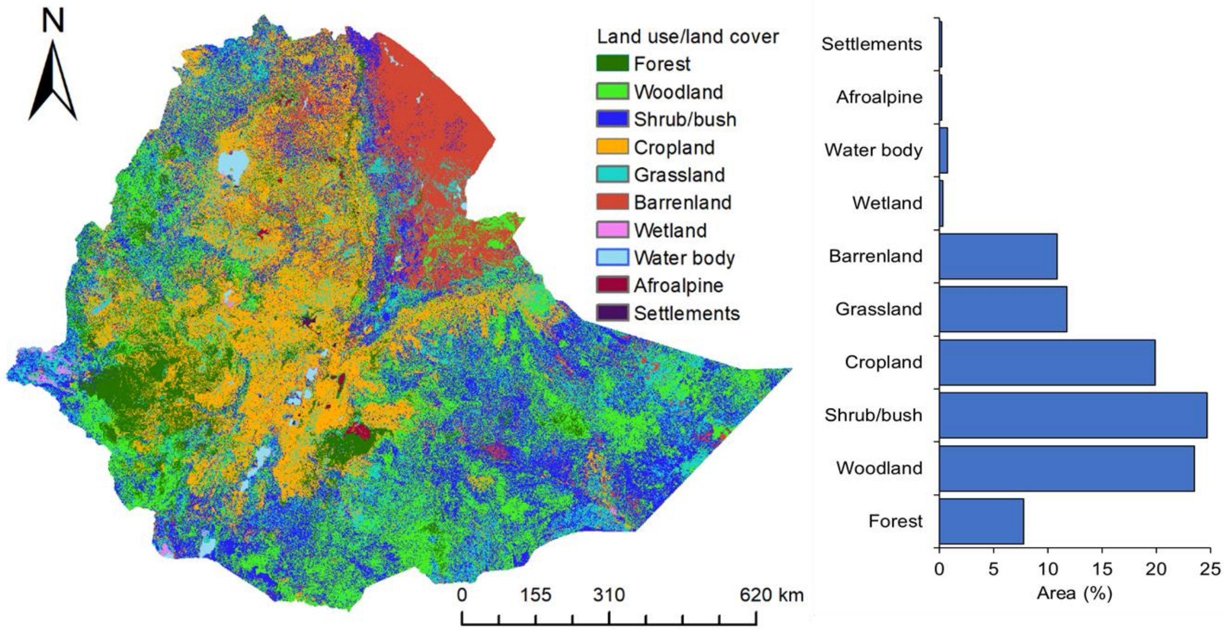

Figure 1-4 LULC map of Ethiopia produced for the year 2016 by WLRC (credit to Kassawmar et al., 2016)

LULC change have great impacts, among others, on agro-biodiversity, soil degradation and sustainability of agricultural production (Lambin et al., 2003). LULC change assessment is an important step in planning sustainable land management that can help to minimize agro-biodiversity losses and land degradation (Kiros, 2008). Investigation of LULC dynamics at contrasting agro-ecologies and varying human activities is therefore crucial in the country in general and in the UBN basin in particular. In view of the research problems described in the proceeding section, this research seeks to investigate the spatial and temporal variability of LULC changes in the watersheds located in different agro-ecological environments of the UBN basin varying with human activities *(see chapter 2)*.

1.1.3. Climate change and variability

Climate is usually defined as the “average weather", or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years (IPCC, 2007). The relevant quantities are most often surface variables such as temperature, precipitation, wind sunshine, wind and humidity. As defined by the World Meteorological Organization, the classical period for averaging these variables is 30 years [*see Appendix 1: Glossary of IPCC (2007)*].

According to Intergovernmental Panel on Climate Change (IPCC) climate change defined as follows: “*Climate change refers to a change of the long-term in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer*” (IPCC, 2007). However, the United Nations Framework Convention on Climate Change (UNFCCC, 2006) defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. The change whether driven by natural internal processes or human forcing such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use by increasing the emission of greenhouse gases and carbon die oxide concentration (IPCC, 2013). This change can lead to changes in the likelihood of the occurrence or strength of extreme weather and climate events such as extreme precipitation events or warm spells (IPCC, 2013).

The global average Earth surface temperature has increased by about 0.6 ^{o}C over the 20th century (Folland, 2001). Supportively, the IPCC (2007) stated that: “*Most of the observed increase in globally-averaged temperatures since the mid-20th century is very likely due to the* *observed increase in anthropogenic greenhouse gases concentrations*". Following Folland (2001), the IPCC (2018) special report on Global warming of 1.5 °C reported that the past two decades have included 2018 warmest years since record-keeping began in 1850 according to World Meteorological Organization (WMO) data (Figure 1-5).

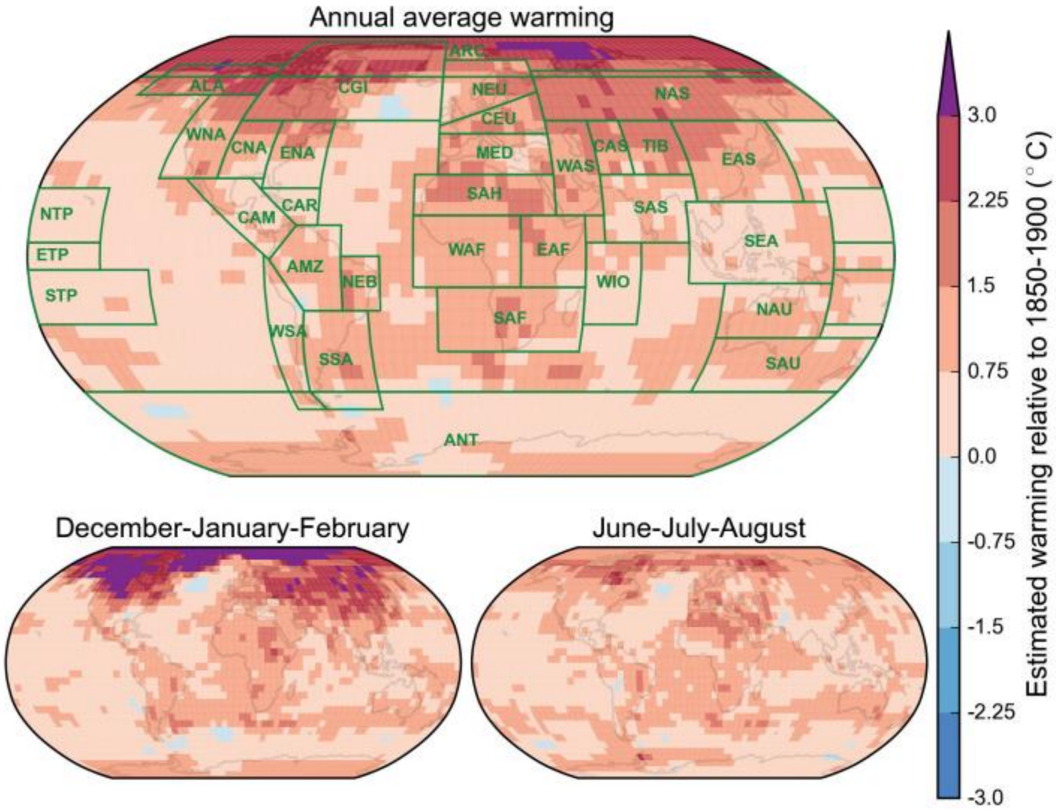

Figure 1-5 Spatial and seasonal pattern of present-day warming: Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January, and February (bottom left) and for June, July, and August (bottom right). For detail description of the region labeled by green boxes and climate model used for this analysis (*see IPCC (2018) special report on Global Warming of 1.5 °C*).

The WMO report on the global climate in 2015-2019 (WMO, 2019) also confirmed that the of global temperature increased by 1.1 ± 0.1 °C since the pre-industrial period (1850–1900), and by 0.20 ± 0.08 °C compared to 2011–2015, which is set to be the warmest five-year period on record. Particularly, continental average temperatures typically show greater variability than the global mean.

Africa is one of the most vulnerable regions in the world to climate change, during the 20th century, the historical climate record for Africa showed a warming of ~0.7 over most of the continent (Desanker, 2002). The warming climate resulted a decrease in precipitation over large portions of the Sahel and an increase in precipitation in east central Africa (Desanker, 2002). Predictions of temperature and precipitation scenarios for Africa indicate future warming across the continent ranging from 0.2°C per decade to more than 0.5°C per decade (Woodfine, 2009). These warming trends and changes in precipitation patterns are expected to increase more rapidly and be followed by a rise in sea level and an increase in the frequency of extreme weather events such as droughts, floods and storms, and severity particularly in the south and east Africa.

Ethiopia is one of the countries located in east Africa continent that challenged by climate change since 1970s and the change is consistent with the change in wider African and global trends (Simane et al., 2017). The country experienced both dry and wet years, the temperature in the country increased by about 0.2°C per decade whereas average annual rainfall remained stable over the last 50 years as mentioned in climate risks and development project reported by Keller (2009). The previous studies by Conway et al. (2011) also reported that mean annual temperature has increased by 1.3°C between 1960 and 2006, an average rate of 0.28°C per decade. However, at local conditions, the spatial and temporal variability of rainfall is high while it does not reflect the large-scale climate trends (Simane et al., 2017). In general, however, it varies based on spatial and temporal analysis of climate change studies (see e.g., Conway, 2011, 2004; Sileshi and Zeleke, 2004). The previous studies in Ethiopian highlands particularly in the UBN basin showed that there have been no significant changes in annual rainfall (e.g. Conway, 2000; Mekonnen et al., 2018). However, the increases in temperature observed in this basin that show an increase in mean annual temperature from 0.028 °C to 1.08 °C between 1980 and 2015 (e.g. Alemayehu and Bewket, 2017; Birara et al., 2018; Mekonnen et al., 2018). Studies with more detailed regional climate models, however, indicate that the sign of the expected precipitation change is uncertain, and the temperature will very likely continue to increase for the next few decades with the rate of change as mentioned above (Keller., 2009).

1.1.4. Hydrological responses to LULC and climate variability

Understanding the impact of historic LULC changes and climate variability on hydrological responses is important to understand the future effects of LULC, and climate change on the water yield at a watershed as well as basin level (Mekonnen et al., 2018; Woldesenbet et al., 2017). The impacts of LULC and climate changes, and land management on hydrological responses have also received a considerable amount of interest in hydrology and integrated indicators of watershed condition. LULC change is among the most important factors contributing to alterations of the land surface across all spatial and temporal scales (Bosch and Hewlett, 1982; Conway, 2000; Legesse et al., 2003). LULC influences hydrological responses by partitioning rainfall between return flow to the atmosphere as evapotranspiration (ET) and flow to aquifers and rivers (Costa et al., 2003; Fang et al., 2013; Woldesenbet et al., 2017; Zhang et al., 2001). However, techniques for the analysis of the impact of LULC change on hydrological responses are not straightforward but rather complex because it is dependent on watershed scale, seasons, climate, and soil conditions (Lambin et al., 2003). Previous studies have shown the impact of LULC change on hydrological responses such as surface runoff, ET (key components in the water balance equation) or both, at various spatial and temporal scales (Bosch and Hewlett, 1982; Fang et al., 2013; Gashaw et al., 2018; Worku et al., 2017; Yin et al., 2017; Zhang et al., 2014). Most these studies conclude that the expansion of agricultural land at the expense of vegetation cover markedly increases the runoff potential in a given watershed (e.g., Bosch and Hewlett, 1982; Dong et al., 2015; Fang et al., 2013; Gashaw et al., 2018; Teklay et al., 2018). However, the conversion of forest cover to other LULC types notably reduces ET (Fang et al., 2013; Li et al., 2017; Yang et al., 2012; Zhang et al., 2001).

Besides to LULC, climate change or variability is one of the most significant factors influencing the changes in runoff and ET (Chen et al., 2006; Dong et al., 2015; Ficklin et al., 2010; Guo et al., 2008; Li et al., 2017; Yang et al., 2017; Zhang et al., 2014). However, the degree to which LULC or climate changes influence variations in runoff and ET varies depending on the characteristics of a watershed or basin and agro-ecological settings of the study sites (e.g, Dong et al., 2015; Mekonnen et al., 2018; Yang et al., 2017).

Modeling the long-term hydrological response to LULC change has been a topic of active research for many research groups worldwide since the development of hydrological models. Previous studies in different parts of the world particularly in developing countries such as Ethiopia (e.g. Mekonnen et al., 2018; Gashaw et al., 2018; Woldesenbet et al., 2018, 2017; Worku et al., 2017) assessed the effect of LULC change and climate variability on hydrological responses. These studies used process-based hydrological models that constitute a single agro-ecological environment and uniform human activities. However, modeling using these spatially distributed processed based hydrological models is a challenge in Ethiopia due to data scarcity. For example, the source region of the UBN basin is one of the basins which is difficult to model due to lack of long-term hydro-meteorological data (Awulachew et al., 2008; Conway, 2000, 1997; Tekleab et al., 2014). As such, further research is needed in the UBN basin to better understand the responses of hydrological processes under LULC and climate change at small watershed scales under different agro-ecological settings (Dile et al., 2018). Moreover, more complex models are not necessarily more useful than simpler models, whose parameters can easily be determined from available data (Haregeweyn et al., 2016; Savenije, 2009). Thus, in this study, simple proportional loss model known as the runoff coefficient model (Geiger et al.,

1987) and ET model (Zhang et al., 2001) were used to analysis long-term hydrological responses such as surface runoff and ET, respectively under LULC change and climate variability *(see chapter 3).*

1.1.5. Soil and water conservation practices in Ethiopia

In Ethiopia, to hamper the alarming consequences of land degradation by soil erosion high priority has been given to soil and water conservation (SWC) practices (Haregeweyn et al., 2015; Hurni et al., 2015). Event though, early field studies to evaluate the effects of SWC practices on runoff and soil erosion back to the nineteenth century, implementation of these practices were largely neglected in Ethiopia before mid of 1970s (Haregeweyn et al., 2015; Osman and Sauerborn, 2001). While after the mid of 1970s, SWC practices institutionally recognized and countrywide implementation efforts were initiated subsequent to the devastating famine of the time (Hurni, 2015, 1993; Osman and Sauerborn, 2001).

Since 2010, SWC practices were implemented mainly through government and non-governmental Sustainable Land Management (SLM) initiatives in food for work community mobilizations at a concerted effort in Northern Ethiopian highlands since 2010 (e.g., Haregeweyn et al., 2015; Nyssen et al., 2010, Osman and Sauerborn, 2001; Molla and Sisheber, 2017; Tamene et al., 2017). Recently, the distribution of existing SWC practices in the Ethiopian highlands were quantified by Hurni et al. (2015) using an expert-based approach and a combination of spatial proxies (land cover, slope and village accessibility) to model the locations where the SWC practices occur (Figure 1-6). Despite all these efforts, most of the previous SWC efforts focused primarily in drought-prone areas and until recently land management had been given little policy attention in the northwestern and southwestern parts of the country, where drought risks are low, and the productivity of soils is relatively high (Haregeweyn et al., 2015). The implemented SWC practices boldly categorized into two: physical measures such as soil/stone bunds, check dams, micro-basins and hillside terraces and biological measures such as exclosures, agro-forestry, afforestation, and tree plantations (Hurni 1993; Osman and Sauerborn, 2001; Haregeweyn et al., 2015; Nyssen et al., 2010, 2007).

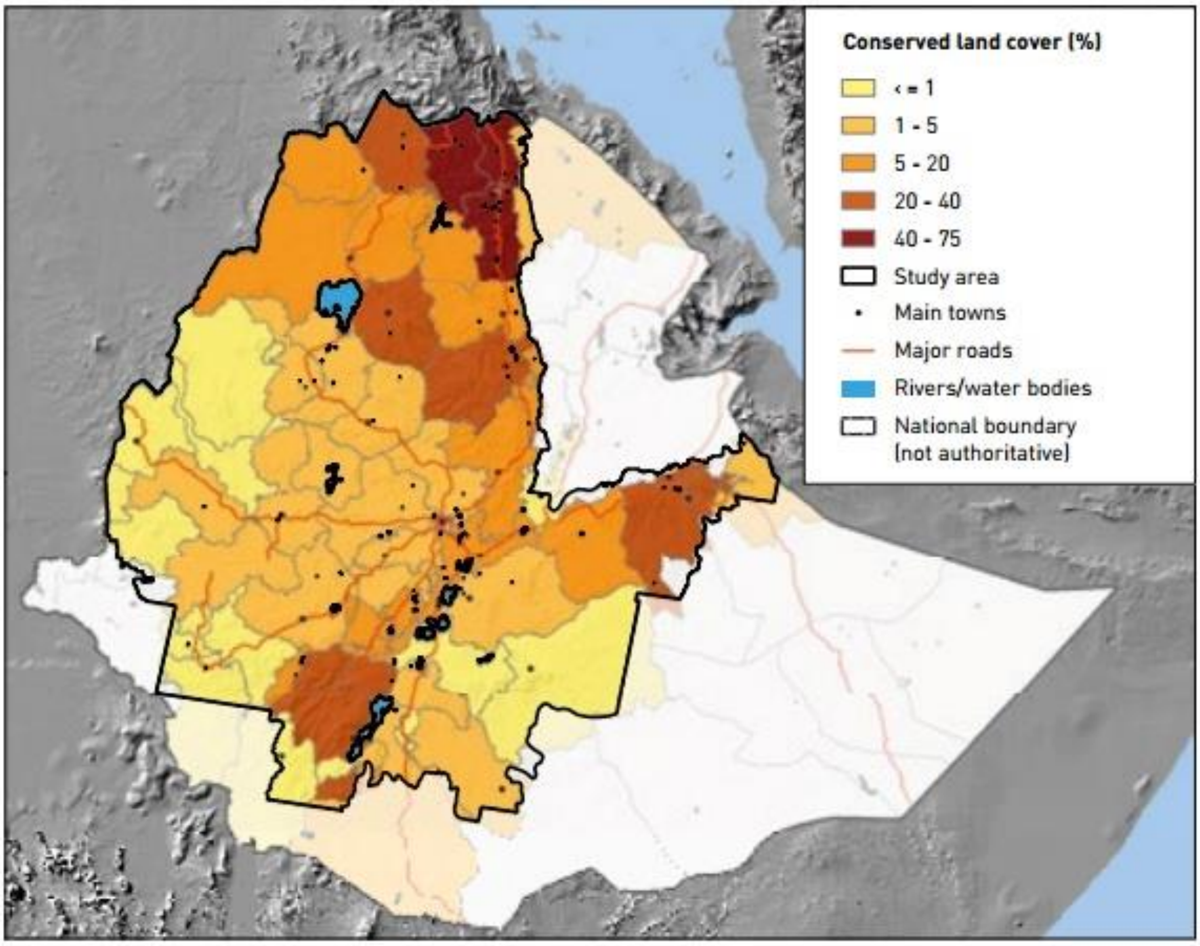

Figure 1-6 The share of the existing conservation structures by land cover classes (Source: Hurni et al. 2015).

The main aim of these SWC practices are to reduce both on-site runoff and soil loss as well as off-site consequences of soil erosion such as siltation of downstream lakes, reservoirs, and river channels aggravating flooding, landslides and degradation of ecosystem services (Haregeweyn et al., 2015; Morgan, 2005). Recent researches also focus on the role of SWC practices in the conservation of various ecosystem functions of the soil and its role in bio-geochemical cycles, including carbon sequestration (e.g., Conley, 2000). However, the role of SWC in reducing soil loss is well recognized (Morgan, 2005), there is still a need to integrate SWC practices effectively into good agricultural and sustainable land management practices.

Moreover, several international scientific projects in different part of the world focus on both quantifying the effectiveness of different SWC practices in reducing runoff and soil loss as well as on their successful implementation (Haregeweyn et al., 2019). Similarly in developing country particularly in Ethiopia, previous studies have attempted to assess the effectiveness of such SWC practices on hydrological and soil erosion processes at experimental plot scale (e.g., Ebabu et al., 2019; Nyssen et al., 2010, 2007; Sultan et al., 2018a, 2017; Taye et al., 2013) and watershed scale (e.g., Arabi et al., 2006; Dagnew et al., 2015; Jemberu et al., 2017; Lemann et al., 2016; Melaku et al., 2018; Molla and Sisheber, 2017). The studies reported that the SWC practices are sufficiently effective in reducing runoff, soil loss and sediment yield (SY) at both plot and watershed scales. However, the short- and long-term impacts on the dynamics of runoff and SY at watershed scale has not been sufficiently evaluated due to fragmented and limited observed data, and lack of robust and harmonized methodology (Haregeweyn et al., 2019, Osman and Sauerborn, 2001).

The ratio of soil loss from a plot with SWC practices and soil loss from reference or control plot with the same characteristics but without SWC practices is the most widely used method to quantify the effectiveness of SWC practices in reducing soil loss (e.g., Ebabu et al., 2019; Nyssen et al., 2010, 2007; Sultan et al., 2018a, 2017; Taye et al., 2013) but these approach is not enough to evaluate the SWC practices at watershed scale. On the other hand, certain biophysical models such as the Universal Soil Loss Equation (USLE) (e.g., Belayneh et al., 2019; Bewket and Teferi, 2009; Fenta et al., 2016; Haregeweyn et al., 2017; Tamene et al., 2017), Water Erosion Prediction Project (WEPP) (e.g., Zeleke, 2001) and Soil and Water Assessment Tool (SWAT) (e.g., Betrie et al., 2011; Lemma et al., 2019; Melaku et al., 2018) have been applied with some degree of success. Among these models, SWAT (Arnold et al., 1998; Srinivasan et al., 1998) demonstrated wider applications in the Ethiopian highlands particularly in the UBN basin since it has the capability to estimate the impacts of SWC practices in reducing runoff and soil erosion (e.g., Betrie et al., 2011; Easton et al., 2010; Melaku et al., 2018; Setegn et al., 2010).

Although few studies reported the effects of SWC practices on runoff and SY responses, the actual impacts of SWC practices based on field measurements have not yet been well modeled especially by employing comprehensive modeling approaches. Thus, this study evaluated the effectiveness of SWC practices on runoff and sediment responses using field measurement and alternative modeling approaches by calibrated SWAT model in one of the study sites of the UBN basin (*see chapter 4*).

1.2. Problem statement

Soil erosion-caused land degradation is a serious global environmental challenge, and this is more severe specifically in the least developed countries like Ethiopia (Borrelli et al., 2017; Fenta et al., 2020). The rate and impact of soil erosion are more visible in the Ethiopian highlands, particularly in the UBN basin that even affects downstream countries like Sudan and Egypt. This is mainly because of unsustainable human activities such as LULC change (due to deforestation, expansion of cultivated land, over-cropping of marginally productive land, and over grazing) and poor SWC practices being driven by population growth and climate variability. These human activities and climate variability are strongly altering the hydrological and sediment responses.

Previous studies reported on the impact of these possible factors–i.e. LULC change, climate variability and SWC practices on hydrological (e.g., Mekonnen et al., 2018; Gashaw et al., 2018; Woldesenbet et al., 2018, 2017; Worku et al., 2017) and soil erosion or sediment responses in Ethiopia highlands (e.g., Betrie et al., 2011; Bewket and Sterk, 2003; Easton et al., 2010; Fenta et al., 2016; Haregeweyn et al., 2017; Hurni, 1993; Nyssen et al., 2009; Welde, 2016). Despite of this facts, most of these studies in Ethiopia focus on single effect of LULC changes (disregarding of climate variability) or climate variability (disregarding of LULC changes) on hydrological responses (e.g., Gashaw et al., 2018; Woldesenbet et al., 2017; Worku et al., 2017). On the other hand, although assessment of the hydrological responses to LULC change and climate variability in different agro-ecological settings is vital, particularly in UBN basin (Dile et al., 2018), previous studies focused on specific watersheds that constitute a single agro-ecological environment. This is profoundly due to fragmented, limited, and lack of observational data such as runoff, sediment, and climate at wider spatial and temporal scales as well as lack of adoptable methodologies to evaluate the impacts. With this constraints, the above mention studies applied process–based hydrological models (SWAT) that needs more meteorological variables beyond rainfall and temperature data which are not commonly found in most watersheds of the UBN basin. Therefore, to fill this research gaps studies focus on single and combined effects of LULC change and climate variability on the hydrological responses of a watershed located in different agro-ecological environments with observed hydro-climatic data using simple empirical models calibrated for the local conditions more paramount importance for integrated watershed management.

Moreover, although previous studies reported the effects of SWC practices on runoff and sediment responses, the actual effects of SWC practices based on field measurements have not yet been well modeled. Most of these previous studies widely conducted at plot scale experimental setups in the Ethiopian highlands (e.g., Ebabu et al., 2019; Nyssen et al., 2010, 2007; Sultan et al., 2018a, 2018b, 2017; Taye et al., 2013). However, plot scale experimental findings on SWC practices implementations cannot be extrapolated to the watershed scale due to uncertainty introduced by lack of spatial representation and processes. On the other hand, the short- and long-term effectiveness of SWC practices in reducing runoff and sediment at the watershed scale has not been sufficiently addressed (Haregeweyn et al., 2015; Osman and Sauerborn, 2001). Furthermore, previous studies rarely reported the separate effects of SWC practices from the effects of existing changes in LULC and climate at the watershed scale.

Thus, besides LULC change and climate variability, evaluation of runoff and sediment responses to SWC practices using field measurement and modeling techniques through SWAT modeling approaches is crucial to devise proper land and water management strategies for sustainable use of natural resources.

1.3. Research objectives

Following the prominent land degradation challenge in the country (Ethiopia) due to unsustainable human activities being driven by population growth and climate variability in the highlands, understanding the hydrological and sediment responses to human activities (LULC change and SWC practices) and climate variability in the UBN basin are so pertinent for devise future land and water management strategies. Therefore, the central objective of this study was to understand the single and combined impact of human activities (LULC changes and SWC practices) and climate variability on the spatiotemporal dynamics of hydrological and sediment responses by integrating field observations, spatial analysis, and modeling approaches. The study was conducted in three drought-prone watersheds located in different agro-ecological environments of the UBN basin. The watersheds include Guder, Aba Gerima and Debatie, which represent highland, midland and lowland agro-ecologies of the basin, respectively. The specific objectives of this study were to: (i) explore and evaluate LULC change, drivers and their possible implications; (ii) examine hydrological responses to LULC change and climate variability and (iii) examine runoff and sediment responses to SWC practices through employing alternative modeling approaches: paired watershed approach (by comparing treated and untreated watersheds) and single watershed approach (only treated watershed through comparing the baseline data–i.e. before and after SWC implementation).

1.4. Description of the study areas

1.4.1. Location, topography and climate

This study was conducted in three representative paired watersheds: Guder (Kasiry and Akusity), Aba Gerima (Kecha and Laguna), and Debatie (Sahi and Bekafa) are geographically located between 10°59′30″–11°1′0″N and 36°54′0″–36°56′0″E, 11°38′0″–11°40′30″N and 37°29′30″–37°31′0″E, and 10°45′30″–10°47′0″N and 36°16′0″–36°18′0″E, respectively in UBN basin of Ethiopia **(**Figure 1-7).

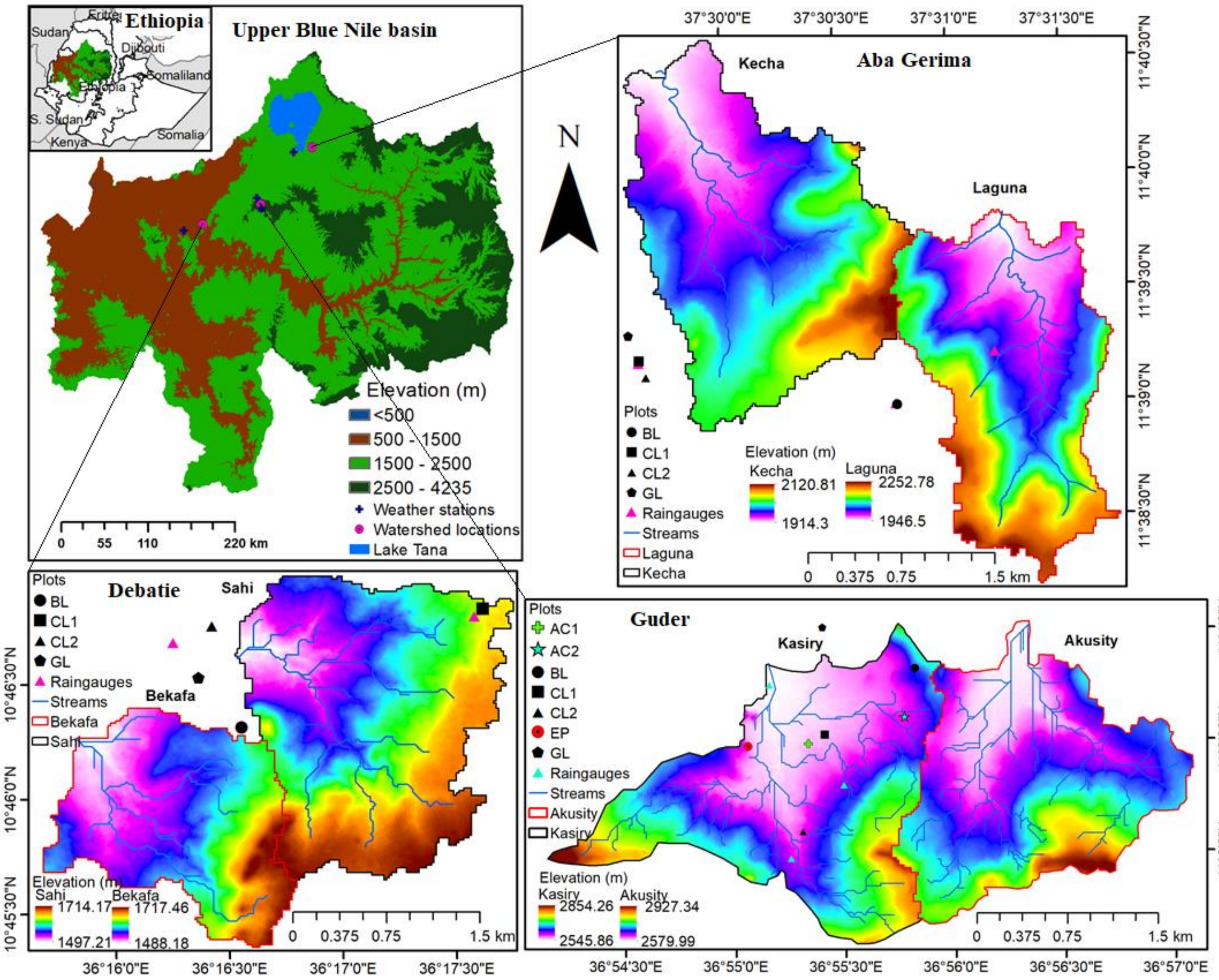

Figure 1-7 Location maps of the study sites in the Upper Blue Nile basin and location of hydro-metrological data monitoring sites such as runoff plot experiments at different land uses such as CL: Cultivated land; GL: grazing land; BL: bushland; AC: *Acacia decurrens*; EP: eucalyptus plantation.

These three sites were also selected to represent three different agro-ecological environments: highlands (Guder), midland (Aba Gerima) and lowland (Debatie), classified on the basis of elevation, precipitation, and cropping systems (Hurni et al., 2016) and they characterized by specific agro-ecological features (Table 1-1, Figure 1-8).

The Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) with a spatial resolution of 30 m (http://earthexplorer.usgs.gov/) were used to delineate the boundaries of the watersheds and to describe the watersheds' topographic characteristics. Thus, the elevations were ranging from 1488 meters above sea level (m.a.s.l) at Debatie to 2927 m.a.s.l. at Guder (Figure 1-7). The slope was also reclassified into five categories: flat (0–3% slope), gentle (3–8% slope), sloping (8–15% slope), steep (15–30% slope) and very steep (>30% slope). The area of the study watersheds predominantly characterized by steep [Guder (40% of area) and Debatie (36.4% of area)] and sloping (Aba Gerima (38.5% of area)) slope categories. The area falls on very steep slope categories of Guder watershed (31% of area) is higher than Debatie (10.8% of area) followed by Aba Gerima (4.2% of area) watershed. On the other hand, the area considered in flat and gentle slope categories (10%, 36% and 21.5% area of Guder, Aba Gerima and Debatie paired watersheds, respectively) are dominantly used for crop production and residences.

In 37 years (1982–2018) of recorded data obtained from the respective nearby meteorological stations (Bahir Dar, Dangila, Enjibara, and Bullen), the mean annual rainfall increased in the order Debatie (lowland) < Aba Gerima (midland) < Guder (highland) (Figure 1-8, Table 1-1). Even though the watersheds have located in different agro-ecological environments, they are characterized by similar rainy (Jun to October) and dry (November to May) seasons. More than 80% of the rainfall concentrated during the rainy seasons (Jun to September, Figure 1-8). In contrast to rainfall, average monthly temperature decreased from lowland to highland in the order Debatie > Aba Gerima > Guder watershed (Figure 1-8).

According to Hurni et al. (2016) local climate zone classification, Guder, Aba Gerima and Debatie sites are belong to Wet Dega (mean annual precipitation of ≥1400 mm), Moist Weyna Dega (mean annual precipitation of 900–1400 mm), and Moist Kolla (mean annual precipitation of 900–1400 mm), agro-ecological environments, respectively (Table 1-1).

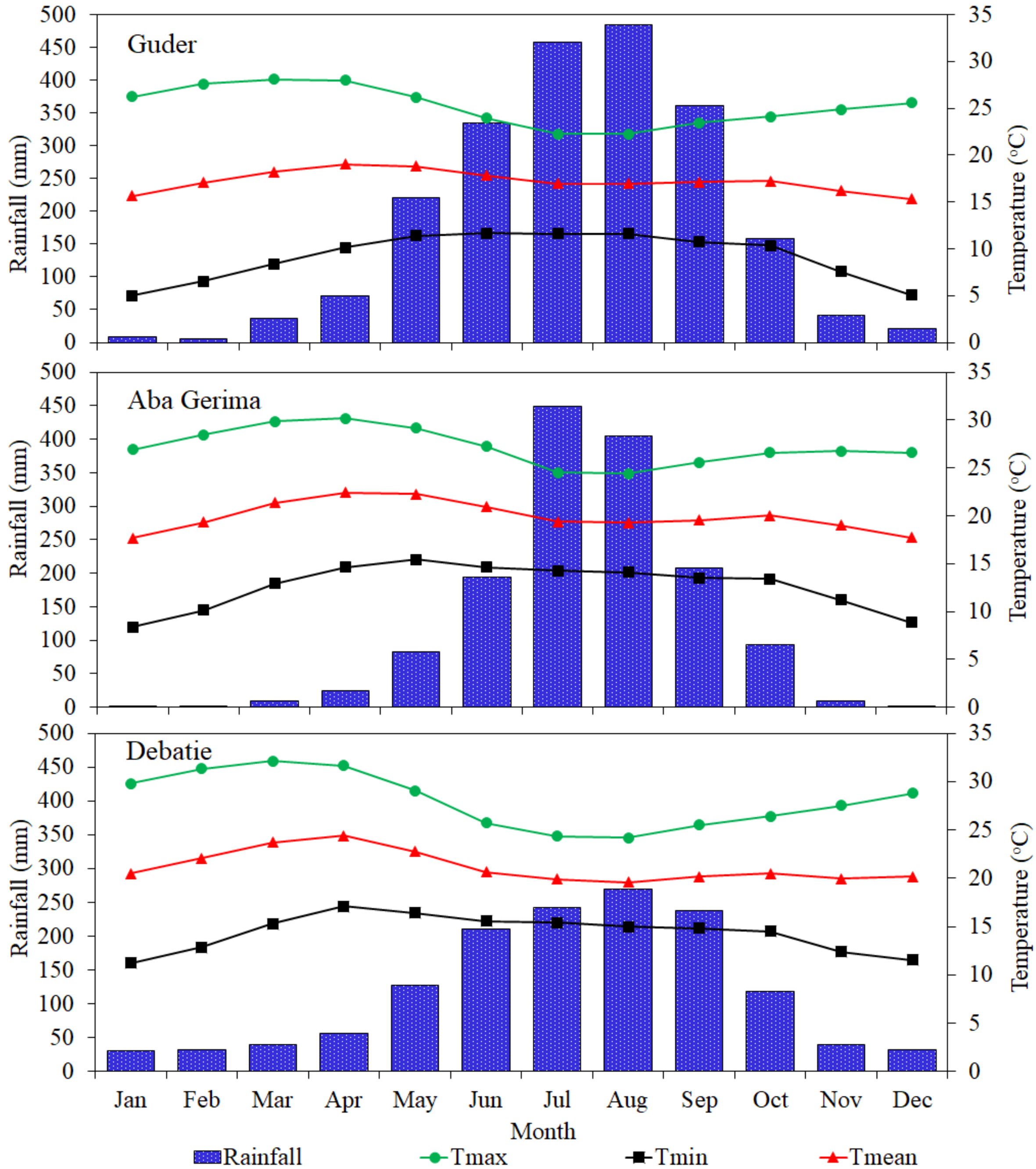

Figure 1-8 Monthly average rainfall and temperature, and monthly minimum and maximum temperatures at Guder, Aba Gerima, and Debatie sites during 1982–2018.

Table 1-1 Main biophysical characteristics of the three study watersheds in the Upper Blue Nile basin.

Characteristics	Guder (highland)	Aba Gerima (midland)	Debatie (lowland)
Elevation (m)	2546–2927	1914–2253	1488–1717
Mean monthly temperature (°C)	15–24	17–31	18–29
Mean annual rainfall (mm)	2495	1343	1022
Rainfall pattern	Unimodal	Unimodal	Unimodal
Agro–ecology zone[a]	Moist subtropical (Wet Dega)	Humid subtropical (Moist Weyna Dega)	Humid tropical (Moist Kolla)
Major soil types	Acrisols, Luvisols	Regosols, Leptosols	Vertisols, Luvisols
Dominant crops	Barley, teff, wheat, and potatoes	Finger millet, teff, maize, and wheat	Finger millet, teff, maize, and groundnut
Dominant livestock	Cattle, sheep, donkeys, and horses	Cattle, sheep, goats, and donkeys	Cattle, sheep, goats, and donkeys
SWC activities	Medium	High	Low

Sources: Ebabu et al. (2019), Sultan et al. (2018) and surveys by the authors. [a]Teff (*Eragrostis tef*), finger millet (*Eleusine coracana*), wheat (*Triticum aestivum*), maize (*Zea mays*), and groundnut (*Arachis hyogaea*); SWC: soil and water conservation.

1.4.2. Major soil types

The dominant soil types in the FAO classification system were identified in the three paired study watersheds (Figure 1-9, Mekonnen, 2018): Acrisols (the soils have been formed from granites and undifferentiated lower complex), Luvisols (well-drained, deep to very deep, usually over soft weathering rocks predominantly clay texture throughout the soil profile), Leptosols (soils are generally young and are limited by their topsoil horizon or directly over altered parent rocks), Regosols (developed on unconsolidated parent materials derived from different types of rocks) and Vertisols (heavy clay throughout the profile and the proportion of clay fraction is mostly greater than 60%). All four soil types occur in the Guder paired watersheds except Regosols, Acrisols and Luvisols more dominant in Kasiry and Akusity watersheds, respectively. In Aba Gerima paired watersheds, Luvisols, Leptosols, and Regosols are the common soil types, whereas only three (Luvisols, Vertisols, and Leptosols) are present in Debatie paired watersheds (Figure 1-9).

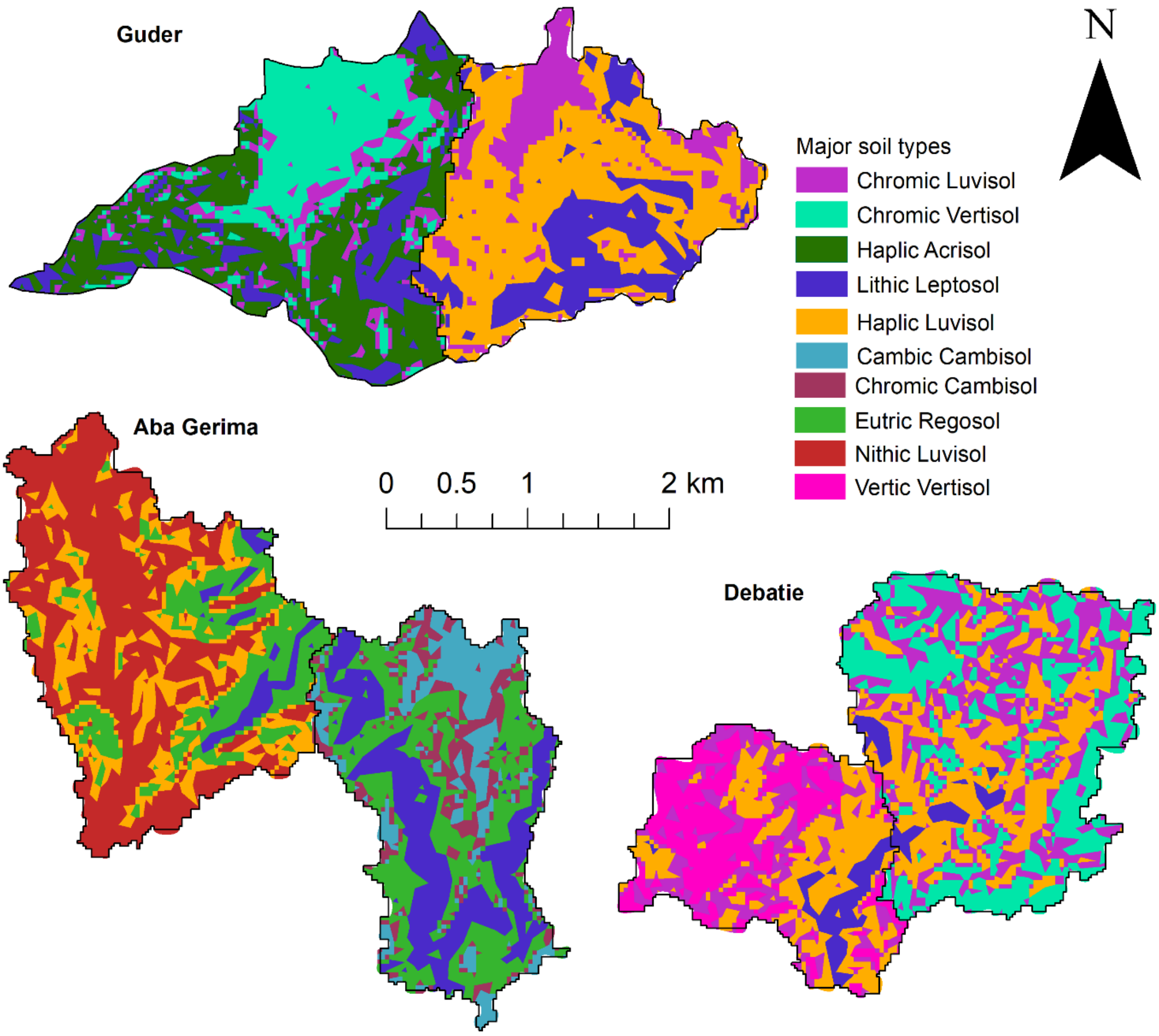

Figure 1-9 Map of soil types in Guder, Aba Gerima and Debatie watersheds (Mekonnen, 2018).

1.4.3. Land use and farming practices

According to Berihun et al. (2019a) comprehensive LULC change study, the paired watersheds experienced different state of degradation resulted from fragmented traditional land use practices over the last three and half decades. bush land cultivated land, forest land, and grazing land are the most common LULC types in all study sites over the last 35 years. After 2005, *Acacia decurrens* and khat (*Catha edulis*) LULC types becomes more popular in Guder and Aba Gerima paired watersheds *(see chapter 2)*, respectively due to its important on income generation aspects for the community found in the sites (Abeje et al., 2019). Among the three sites, grazing lands at Aba Gerima site are frequently and heavily grazed, and are thus, more susceptible to soil erosion when intense rain events occur, particularly untreated Laguna watershed.

In all study sites, the farming system is characterized by a subsistence mixed production system of rain-fed cropping integrated with livestock production (Abeje et al., 2019). In Guder, tef (*Eragrostis tef*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and potato (*Solanum tuberosum*) are the major crops, whereas finger millet (*Eleusine coracana*), maize (*Zea mays*), barley and tef are the major crops at Aba Gerima and Dibatie sites. In addition to these cereal crops, khat (*Catha edulis*) in Aba Gerima, and groundnut (*Arachis hypogaea L.*) and chili pepper (*Capsicum annuum*) in Dibatie are also cultivated as cash crops. Moreover, like cash crops, the predominant exotic tree species: *Acacia decurrens* and *Eucalyptuss* trees in have been planted in Guder site for alternative income generation activities (Nigussie et al., 2017a). Livestock types are more or less similar at the three sites: cattle (*Bos primigenius*), donkey (*Equus africanus*) and sheep (*Ovis aries*) are dominant at all three sites, followed by horse (*Equus caballus*) at Guder, and goat (*Capra hircus*) at the Aba Gerima and Dibatie sites (Table 1-1).

1.4.4. Soil and water conservation practices in the study sites

The paired watersheds were purposively selected aiming to represent treated and untreated watersheds with and without SWC practices respectively. Thus, Kasiry, Kecha and Sahi were considered as treated watersheds whereas Akusity, Laguna and Bekafa were considered as untreated watersheds in Guder, Aba Gerima and Debatie sites, respectively. At present, each watershed has been under governmental or non-governmental SWC programs, sometimes both for the last decades to reduce the on-site and off-site effects of runoff and soil erosion in the UBN basin. The treated Kasiry watershed has been implementing SWC measures since 2008, supported by a Swiss Development Cooperation project. Likewise, the treated Kecha watershed has been part of the National Sustainable Land Management Programme since 2011 (Figure 1-10a), supported by funds obtained from the World Bank food for work initiatives (Berihun et al., 2019b, Ebabu et al., 2019). Unlike treated Kasiry and Kecha watersheds, treated Sahi has not received external support for SWC programs. In fact, however, a few physical SWC structures have been constructed through the regular governmental extension programs or campaign-based community mobilization since 2008.

Figure 1-10 Google earth image showing SWC practices (February 08, 2019) in the treated Kecha watershed (left) and *A. decurrens* plantation (December 16, 2017) in Kasiry watershed (right).

Besides the traditional drainage ditches and field boundaries, soil bund (an embankment of soil accompanied by a ditch on the uphill side), *fanya Juu* (an embankment of soil accompanied by a ditch on the downhill side) for cultivated lands, and trenches (rectangular pits arranged in staggered manner along the contour with the embankment on the downhill side) for non-cultivated lands (e.g., in Kecha watershed, Figure 1-10a) were constructed to reduce overland flow and soil erosion. In addition to construction of the physical barriers, some cheap practices such as planting grasses, conservation tillage and exclosure for restoration are now being recognized to effectively control soil erosion and improve in-situ soil quality properties.

Moreover, small-scale farmers have recently adopted a *taungya* system using *Acacia decurrens* trees to stabilize the soil during and after the growing season (Figure 1-10b). Plantation of this tree is getting expanded since 2005 at the expense of cultivated lands (Berihun et al., 2019a) mainly because of its economic benefits: provides additional income for farmers and others involved at different activities from seedling preparation to charcoal production (Berihun et al., 2019a; Nigussie et al., 2017). The change from cultivated land to this plantation, however, has some trade-offs concerning hydrologic processes: high runoff and low soil loss paradox both at plot and watershed scales (Berihun et al., 2019b; Sultan et al., 2017) due to bare and sealed ground surface created at later stages. In general, this thesis at chapter four try to address the impact of SWC practices on runoff and sediment responses for future possible land management innervation development.

1.5. Organization of the thesis

The thesis organized in five chapters (Figure 1-11). Chapter 1 presents the general introduction, which includes background information, state of the art, the problem statement, research objectives, and description of the study area. Following Chapter 1 the concepts of LULC changes, methods data acquisition, detection and quantification of LULCs and analysis related to change drivers and their implications made at three different agro-ecological settings [Guder (highland), Aba Gerima (midland) and Debatie (lowland)] of the UBN basin are elaborated in Chapter 2 (Figure 1-11). Treated Kasiry, Kecha and Sahi watersheds were considered for chapter three. On the other hand, only Aba Gerima paired watersheds were selected as a result of clear difference in terms of SWC practices implementation between treated Kecha and untreated Laguna watersheds.

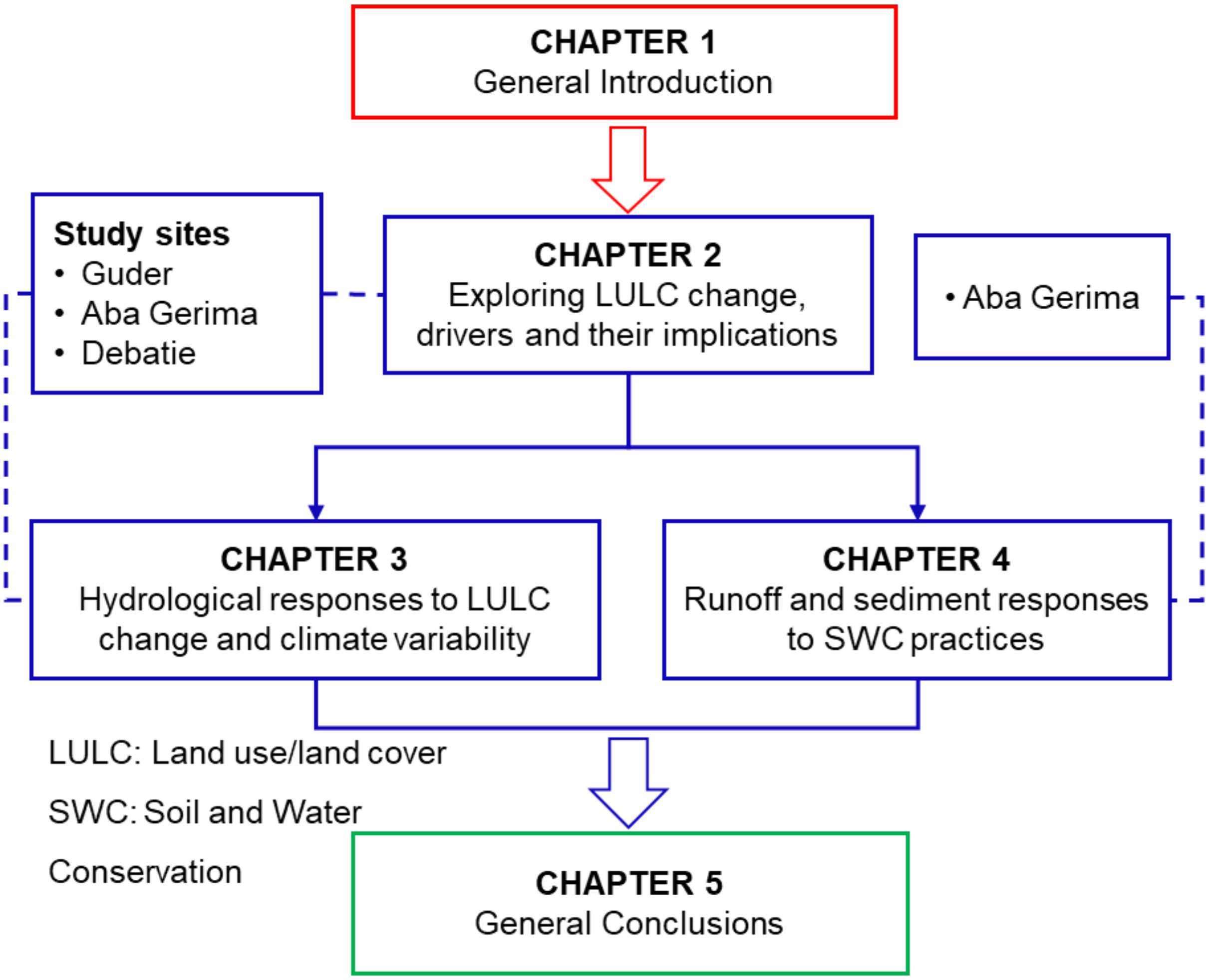

Figure 1-11 Flowchart showing the structure of the thesis.

Chapter 3 describes hydrological responses to change in LULC and climate variability in contrasting agro-ecological environment. In this chapter the single and combined effect of historical LULC change and climate variability on surface and ET were analyzed using watershed based calibrated empirical runoff and ET models. It further discusses on processing and preliminary analysis of input data for the models such as climate trend and runoff coefficient under different LULC types. Chapter 4 deals with quantitative and qualitative analysis of runoff and sediment response to SWC practices at Aba Gerima paired watersheds using two (paired and single watershed) modeling approaches. In this chapter SWAT model was calibrated and validated for treated and untreated watersheds with and without SWC practices, respectively based on field measured data. Also, the separated effect of SWC practices, LULC change and climate variability on surface runoff and sediment yield responses were evaluated. Finally, in Chapter 5, general conclusions and recommendations are provided.

1.6. Overall methodological framework of the study

The method to evaluate the impacts of LULC changes, climate change and land management practices on hydrological response can be achieved through integrating GIS, remote sensing, and hydrological models. Advances in computing have allowed distributed watershed models to perform hydrologic simulation with reasonable resolution at a more detailed level while distributed hydrological model is not always effective due to lack of hydro-mereological data in the watersheds. LULCs delivered by repeated aerial photography and satellite images greatly contribute to planning and management of available resources, especially in the watersheds where other kinds of background data are often lacking. Specifically, LULC information is of critical importance in hydrologic modelling, as it helps determine model variables that account for the volume, timing, and quantity of runoff.

In this study, historical LULC maps (1982-2017) were produced for three sites in different agro-ecology through high resolution aerial photographs and satellite images using GIS on-screen digitizing techniques. The analyzed LULC maps were used as an input for both empirical (runoff and ET models) and physical-based (SWAT) hydrological model to examine the hydrological and sediment responses of the watersheds. Likewise, long-term climate, experimental and watershed streamflow data were used for calibration and validation of these models. In addition, watershed spatial datasets such as DEM, soil and SWC data were used for SWAT model to evaluate the runoff and sediment responses to SWC practices in Aba Gerima watersheds. The methodological framework showing the components and relationships that have been used as a framework for the analysis in this research is indicated in Figure 1-12.

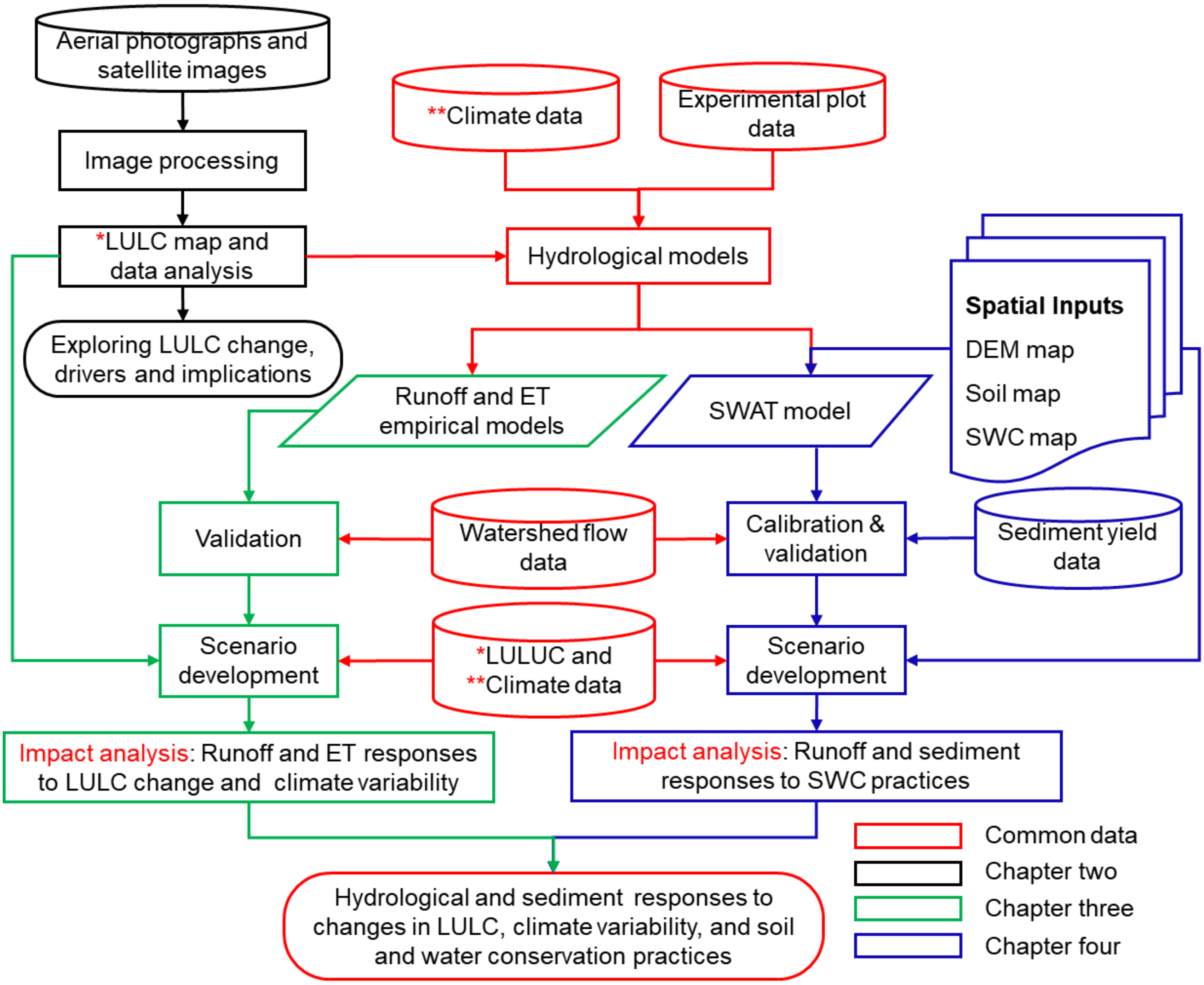

Figure 1-12 Overall methodological framework of the study. LULC, land use/land cover; ET, Evapotranspiration; SWAT, Soil and Water Assessment Tool; DEM, Digital Elevation Model; SWC, Soil and water conservation.

CHAPTER 2

2. Exploring land use/land cover changes, drivers and their implications in contrasting agro-ecological environments of Ethiopia

Part of this chapter is published as:

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2.1 Introduction

Land use/land cover (LULC) change is a major global challenge (Kates and Torrie, 1998). It contributes significantly to earth–atmosphere interactions, forest fragmentation, land degradation, and biodiversity loss (Haregeweyn et al., 2015; Maitima et al., 2009). On a global scale, research findings on LULC changes have clearly shown the expansion of cultivated land at the expense of forest, natural grassland, and savanna (Goldewijk and Ramankutty, 2004; Ramankutty and Foley, 1999). However, LULC change dynamics have not been uniform in all parts of the world because of different driving factors. Population pressure, human activities, and development have influenced LULC changes (Bosch and Hewlett, 1982; Haregeweyn et al., 2015; Meshesha et al., 2014). In many areas of developing countries, rapid population increases have often led to LULC changes caused through deforestation aimed at increasing agricultural production (Maitima et al., 2009; Ramankutty and Foley, 1999) and production of other materials for consumption.

LULC changes are also a major environmental challenge in Ethiopia (Gashaw et al., 2017; Tekle and Hedlund, 2000), where agricultural activity serves as the backbone of the economy. Previous studies have shown notable LULC changes in different parts of the country through deforestation and reforestation activities since the late twentieth century (e.g. Bewket, 2002; Gebrehiwot et al., 2014; Zeleke and Hurni, 2001). In particular, studies focused on the Ethiopian highlands have pointed out that the expansion of cultivated land increased through time at the expense of natural forest (Betru et al., 2019; Dessie and Kleman, 2007; Gashaw et al., 2017; Minta et al., 2018; Tekle and Hedlund, 2000; Zeleke and Hurni, 2001). Some studies, however, have also shown that the deforestation trend has recently been reduced and vegetation cover has improved in some parts of the country because of plantation activities on degraded hillsides (e.g. Bantider et al., 2011; Lemenih and Kassa, 2014; Wondie and Mekuria, 2018). Plantation activities have been implemented as part of community efforts to rehabilitate the environment, and the wood is used as a source of fuel and income generation (Nigussie et al., 2017a; Wondie and Mekuria, 2018).

In general, no uniform trend or magnitude of LULC change has been observed in Ethiopia. This makes it difficult to trace back or predict by using known trends in areas that have not been surveyed, although it is broadly possible to summarize most of the LULC change findings as showing competition between vegetation cover and cultivated land. In particular, the expansion of cultivated land at the expense of vegetation cover has gradually aggravated land degradation (Dessie and Kleman, 2007; Mossie, 2002; Zeleke and Hurni, 2001) in the Upper Blue Nile basin. In contrast, the expansion of vegetation cover as a result of plantation expansion at the expense of cultivated land could alleviate the problems associated with degraded areas. Currently, vegetation cover has surprisingly been increasing within a short period of time as farmers plant exotic tree species such as *Acacia decurrens (A. decurrens)* and *Eucalyptus* in plantations in community woodlots and communal lands in some parts of the Upper Blue Nile basin highlands (Wondie and Mekuria, 2018). In particular, the nitrogen-fixing species *A. decurrens* plays an important role in the provisions of fuelwood and income, soil fertility management, and soil and water conservation (Belete, 2015; Nigussie et al., 2017a; Wondie and Mekuria, 2018). Eucalyptus plantations also offer a possible solution to alleviate the shortage of fuelwood and construction wood in midland and lowland areas of the Upper Blue Nile basin where cultivated land expansion has occurred at the expense of vegetation cover.

Although LULC change is a common phenomenon in Ethiopia, it is difficult to generalize any trends, even within a specific region such as the Upper Blue Nile basin, mainly because of the influence of the various human activities (Zeleke and Hurni, 2001) and agro–ecological setup of the watersheds. Most previous studies (Bewket, 2002; Dessie and Kleman, 2007; Gashaw et al., 2017; Tekle and Hedlund, 2000; Yeshaneh et al., 2013) assessed LULC change in the basin considering only specific watersheds that constitute a single agro-ecological environment and uniform human activity, such as increasing demand for agricultural land. Investigation of LULC dynamics in different agro-ecologies and for a variety of human activities is therefore rare in the country in general and in the Upper Blue Nile basin in particular. Studies of agro-ecological based watershed–specific LULC changes are vital for better land use planning and land resource management to control land degradation. Also, the results of LULC change analyses are important tools for decision-makers, land planners, and local communities to formulate appropriate land management policies and strategies (Desalegn et al., 2014; Kamusoko and Aniya, 2007; Ningal et al., 2008). Therefore, this study aimed to understand the spatio-temporal variability of LULC dynamics and its possible implications in three paired watersheds located in three different agro–ecological environment of the Upper Blue Nile basin: Guder (highland), Aba Gerima (midland), and Debatie (lowland). We also investigated the possible drivers of LULC change in line with agro–ecological–based human activities. Moreover, unlike many previous studies, we used very high resolution remote–sensing data (e.g., Pleiades, IKONOS–2, Quick Bird; 0.5−3.2 m resolution) to assess the LULC changes in a geographic information system (GIS) environment.

2.2 Research methods

2.2.1. Data types, sources and LULC classification

The spatial and temporal dynamics of the different LULC classes were examined by using remote- sensing data (aerial photographs, scale 1: 50,000, and satellite images with a resolution of 0.5–3.2 m) covering 35 years from 1982 to 2016/2017 (Table 2-1). We purchased orthorectified aerial photographs from the Ethiopian Mapping Agency (EMA) and satellite images from AIRBUS defense and space. The images were selected based on data availability, anticipated major changes, and year consistency between the study sites. All satellite images were taken during the dry season under clear cloud cover conditions. Images were collected in four years for Guder and Debatie and three years for Aba Gerima paired watersheds (Table 2-1). Population data for the years 1994 and 2007 at the *kebele* level (the smallest administration unit) for the three paired watersheds were obtained from the Ethiopian Central Statistical Agency (CSA). Population data for 2016 were also obtained from the *kebele* administration office of each site. Furthermore, field observations augmented with Garmin global positioning system data and key informant interviews (agricultural development agents and local elders) were conducted to collect primary data on the current and historical LULC classes of the watersheds.

Table 2-1 Data sources used to produce LULC maps in the Guder, Aba Gerima, and Debatie paired watersheds.

Site	Acquisition date	Resolution/scale	Satellite sensor/photo	Spectral resolution type
Guder	January 1982	1:50,000	Aerial photograph	Panchromatic
	March 2006	3.2×3.2 m	IKONOS–2	Multispectral
	February 2012	1.6×1.6 m	WorldView–2	Multispectral
	January 2017	0.5×0.5 m	Pleiades	Multispectral
Aba Gerima	January 1982	1:50,000	Aerial photograph	Panchromatic
	March 2005	0.6×0.6 m	Quick Bird	Multispectral
	March 2016	1.5×1.5 m	Spot 7	Multispectral
Debatie	February 1982	1:50,000	Aerial photograph	Panchromatic
	April 2006	3.2×3.2 m	IKONOS–2	Multispectral
	January 2012	1.6×1.6 m	WorldView–2	Multispectral
	March 2017	0.5×0.5 m	Pleiades	Multispectral

2.2.2. LULC mapping and classifications

As mentioned above in Table 2-1, we used orthorectified very high-resolution multi-scale satellite images (ranging from 0.5 to 3.2 m). It is worth mentioning that direct use of multi-scale images for LULC mapping may induce uncertainty on the spatial patterns of LULC changes. Thus, before LULC classification, we employed up-scaling (aggregation) approaches using nearest neighbor algorithm (Liang, 2004) so that all images have the same resolution (3.2 m). Such up-scaling procedure helps to minimize potential uncertainty that could result from differences in resolution of the satellite images used for LULC classification (e.g., Roth et al., 2015; Xu et al., 2018). The LULC identification, mapping and classification processes were performed through intensive visual interpretations followed by on-screen digitization technique (Bewket, 2002; Gebrehiwot et al., 2014; Gebrelibanos and Assen, 2015; Haregeweyn et al., 2015) based on the LULC classes presented in Table 2-2. For satellite images, we attempted unsupervised and maximum likelihood supervised classification techniques with sufficient training areas. However, the classification output showed a significant level of errors, and some areas were found to have been misclassified because of substantial spectral similarity among some classes, for example, plantations, bush land and forest land. Supportively, Xu et al. (2018) demonstrated that LULC classes can apparently be interpreted and mapped with reasonable precision from satellite images which have resolutions ranging from 1m to 8m. Moreover, it has been commonly accepted that for very high spatial resolution images (≤ 5m), where pixels are usually smaller than objects, visual interpretation may be more suitable for LULC classification; however, visual interpretation could not be a suitable approach for images with coarse spatial resolution (Estoque et al., 2015). Therefore, we employed visual interpretation on-screen digitization technique using Arc GIS 10.4 software (Long et al., 2007; Meshesha et al., 2014) with support information from key informant interviews and intensive field observation of the area. Although the digitizing process was time consuming and tedious the output was better than that of the automatic classification technique (unsupervised and supervised).

The classification process was done by identifying a minimum of four and a maximum of six LULC classes for each year in each watershed (Table 2-2). Eucalyptus plantation and natural forest were combined into one forest land class in the Aba Gerima and Debatie paired watersheds because of the negligible amount of these areas as compared to the other classes.

Table 2-2 Description of LULC classes used to measure the changes in periods 1982 to 2017 [a].

Code	LULC class	Description
BL	Bushland	Areas covered with small trees, bushes, and shrubs. Scattered large trees can sometimes be found, and grasses are found in some areas.
CL	Cultivated land	Agricultural land, areas of land plowed and/or prepared for growing crops (perennial and annual crops). This includes most flat areas and some steep slopes where various crops are grown either on a rain–fed basis or using irrigation.
KC	Khat cultivation	Areas covered by khat (*Catha edulis)* cultivation.
FL[a]	Forest land	This covers natural forests, church forests which are densely grown and include riverbank trees, and eucalyptus plantations. This also includes areas with scattered natural trees greater than greater than 2 m in height.
GL	Grazing land	Land covered with grasses, land units allocated as sources of animal feed (including privately and communally owned grazing areas with little tree cover), and bare lands.
ST	Settlement	Homesteads, small rural communities, manmade structures, and other areas used for construction, including asphalt roads and tree fences.
PL	Plantations	Areas covered with planted trees, which includes *A. decurrens* plantations and riverine trees.

[a]Eucalyptus plantations are not included in the FL category in the Guder paired watershed where they are included in the plantations cover class. KC and PL classes are only considered in the Aba Gerima and Guder paired watersheds, respectively. In some analyses, bush land, grazing land, forest land, and plantations were grouped into a single "vegetation cover" category.

In the Guder paired watersheds, natural forest, riverine trees, and plantation (uncommon in 1982) were combined into the forest land class for the 1982 LULC classification process because they had the same image tone, which made it difficult to differentiate them. Finally, LULC maps of the respective years were produced for further analysis. Furthermore, the classes were grouped into vegetation cover (including forest, bush, plantation, and grazing lands), cultivated land, and settlement to enable us to analyze the trends of each component in the different agro-ecologies and their future implications. Accuracy assessment through the use of ground control points is important to determine the quality of classified LULC maps from remotely sensed data (Congalton and Green, 2009; Gashaw et al., 2017; Kiage et al., 2007; Meshesha et al., 2014). In this study, this type of accuracy assessment was unnecessary because the image classification was done by using on-screen digitization technique based on very high resolution remote-sensing data (pixel size less than 3.2 m) supported by data from intensive field observations, GPS points and key informant interviews.

2.2.4. LULC change detection analysis

LULC change detection analysis is needed to clarify the extent of changes occurring between periods and helpful to categorize changes occurring in the different LULC classes and make useful decisions (Gashaw et al., 2017; Ningal et al., 2008). Percent changes (Long et al., 2009, 2007; Fenta et al., 2017) of individual LULC classes were computed to describe the extent of change between periods:

$$\text{Percent change (\%)} = \left(\frac{A_2 - A_1}{A_1}\right) \times 100 \qquad (2\text{-}1)$$

where A_1 is the area in year 1 and A_2 is the area in year 2 of a LULC class (ha).

Another technique was used a transition matrix by overlay procedure to describe the extent and the nature of changes observed and the transition between different LULC classes. We calculated the percentage of “conversion loss to” or “conversion gain from” according to Equations (2-2) and (2-3) (Guo et al., 2009; Long et al., 2007) in relation to the total loss or gain in each LULC class between periods. For LULC class i in change matrix A,

$$P_{loss(i),j} = (p_{i,j} - p_{j,i})/(p_{ci} - p_{ri}) \times 100, \qquad i \neq j \qquad (2\text{-}2)$$

$$P_{gain(i),j} = (p_{j,i} - p_{i,j})/(p_{ci} - p_{ri}) \times 100, \qquad i \neq j \qquad (2\text{-}3)$$

where $P_{loss(i),j}$ is the percentage taken by LULC class j in the total “conversion loss” of class row i ; $P_{gain(i),j}$ is the percentage taken by class j in the total “conversion gain” of class row i;

$p_{i,j}$ and $p_{j,i}$ are the individual entries in a given change matrix ; p_{ci} is the column total of class i; and p_{ri} is the row total of for class i.

A LULC conversion index (CI) was calculated according to Equation (2-4) (Minta et al., 2018) to assess the LULC class contributing most to specific LULC classes that expanded:

$$CI = \Delta LC_{i-j}/Mean\Delta LC \quad (2\text{-}4)$$

where CI is land use conversion index, ΔLC_{i-j} is area of LULC class i converted to LULC j between periods 1 and 2 (i.e., the period between the target reference years), and *Mean* ΔLC is mean of areas of all LULC classes converted to LULC class j in period between period 1 and 2. LULC classes contributing most to the expansion of LULC class j have $CI > 1$, whereas those that contribute the least have $CI < 1$.

2.2.5. Exploring drivers of LULC changes

LULC changes are influenced by a variety of driving factors. In Ethiopia, human activity is often mentioned as the major driver of observed LULC changes (e.g. Bewket, 2002; Gashaw et al., 2017; Zeleke and Hurni, 2001). To better understand the effect of human activities on LULC change, we first reclassified the six major land use types into two categories: cultivated land and vegetation cover (including grazing land, bush land, forest land, and plantation). The relationship between changes in these two LULC categories and population number was established for the years 1982, 1994, 2007, and 2016. In addition, we investigated the effect of changes in farming practices, specifically the introduction of *A. decurrens* in Guder and khat (*Catha edulis)* cultivation in Aba Gerima site, on the observed LULC change.

Population data for 1994 and 2007 were obtained from the Ethiopia Census report (CSA, 1994, 2007), and population data for 2016 were collected from the local *kebele* administration offices. However, it was not possible to obtain population data that corresponded to the respective watershed's boundaries because the data were assembled according to different administrative boundaries. As a result, only the *kebele*–level population data whose entire area fell within the studied watersheds were considered. Six *kebeles*, two for each paired watershed, were considered for the study: Asera Ambesna and Endeweha Arets for Guder, Aba Gerima Abune Hara and Gomibat Aba Gerima for Aba Gerima, and Angtok and Debatie town for Aba Gerima. Because there were no *kebele*–level census data available before 1994, the population for 1982 was extrapolated using the following exponential growth rate relationship recommended by the Ethiopian CSA:

$$P_2 = P_1 e^{rt} \tag{2-5}$$

$$r = \frac{1}{n} \ln\left(\frac{P_2}{P_1}\right) \times 100 \tag{2-6}$$

where P_1 is the population at time 1, P_2 is the population at time 2, r is growth rate in percent, and t is the number of years between time 1 and time 2.

In addition, the data on drivers of LULC change was collected from key informant interviews (KIIs) focused on the trend and conversion pattern of LULC dynamics. During the KIIs had identified the major immediate drivers and also provided their future expectation on these drivers.

2.2.6. Evaluating the implications of LULC changes

In this study, the implication of LULC changes on the effect soil erosion, surface runoff response, and socio–economic and environmental were explored. To evaluate the implication of soil erosion, we compared the trend of vegetation cover and cultivated land with gully erosion density, which are often cited as the worst form of soil erosion (Morgan, 2005), have been widely observed at the study watersheds. On the other hand, we followed three steps to evaluate the implication of LULC dynamics on surface runoff response in the study watersheds. First, we calculated the plot seasonal runoff coefficients for the year 2015, 2016 and 2017 by dividing the seasonal runoff measured from 16 experimental runoff plots established at the five main land use classes (Table 2-2) found in the three watersheds by the respective seasonal rainfall. A detailed description of the instrumentation and measurement of each experimental runoff plot can be found in (Sultan et al., 2018). Next, we estimated the average seasonal runoff coefficient of vegetation cover by taking the areal average runoff coefficients of the bush, forest, grazing lands, and plantation LULC classes. Finally, the implication of LULC change on surface runoff was evaluated by analyzing the change in runoff coefficient respect to vegetation cover and cultivated land in the three paired watersheds.

Furthermore, the introduction of *A. decurrens* in Guder and khat cultivation in Aba Gerima sites were evaluated in terms of soci–economic and environmental implication based on observed LULC change, key informant interviews and reviewing relevant studies conducted in our study areas and elsewhere.

2.3. Results and discussion

2.3.1. Extent and trends of LULC changes from 1982 to 2017

Guder (highland) paired watersheds

We prepared LULC maps for 1982, 2012, 2006, and 2017 for Guder paired watersheds (Figure 2-1). In 1982, bush land had the least coverage as compared with the other two sites (Figure 2-1 to 2-4). Also, this LULC type continuously decreased from 15.3% in Kasiry and 16% in Akusity in 1982 to 5.3% in Kasiry and 8.1% in Akusity in 2017 (Figure 2-4). During the 35-year period, the area covered by bushland decreased by about 66% in Kasiry and 50% in Akusity, mainly because of conversion to cultivated and plantation land. Cultivated land was the second most dominant LULC type (following forest land) and covered 23.1% in Kasiry and 24.3% in Akusity in 1982 (Figures 2-1, 2-4). Cultivated land had increased by 99.7% in Kasiry and 107.1% in Akusity in 2006. From 2006 to 2012, the share of cultivated land shrank by 3.3% in Kasiry but increased by 2.4% in Akusity. Between 2012 and 2017, cultivated land decreased by 29.2% in Kasiry and by 34.1% in Akusity (Figure 2-1, Table 2-3). The decrease in cultivated land was a result of growing demand for more area for plantations (mainly *A. decurrens*) and settlements (Figure 2-1). Among the study watersheds, Guder was relatively forest-rich, with 41% coverage (average value of the paired watersheds) in 1982. However, within the study period, the amount progressively decreased to 7.1% in 2017 in Kasiry and to 12.3% in 2017 in Akusity (Figure 2-4). Forest cover decreased by 73.7% in Kasiry and by 67.1% in Akusity from 1982 to 2006 (Table 2-3), and the decreasing trend corresponded with the expansion of land for agricultural use (Table 2-4). Grazing land was the third most dominant LULC type, covering 19.5% in Kasiry and 18.8% in Akusity in 1982. Like forest land and bushland, this LULC type continuously decreased from 1982 to 2017 (Figure 2-4). Compared to the other periods, it notably decreased from 2012 to 2017 by 25.1% in Kasiry and by 11.7% in Akusity, mainly due to the expansion of plantation and cultivated land during this period (Table 2-4).

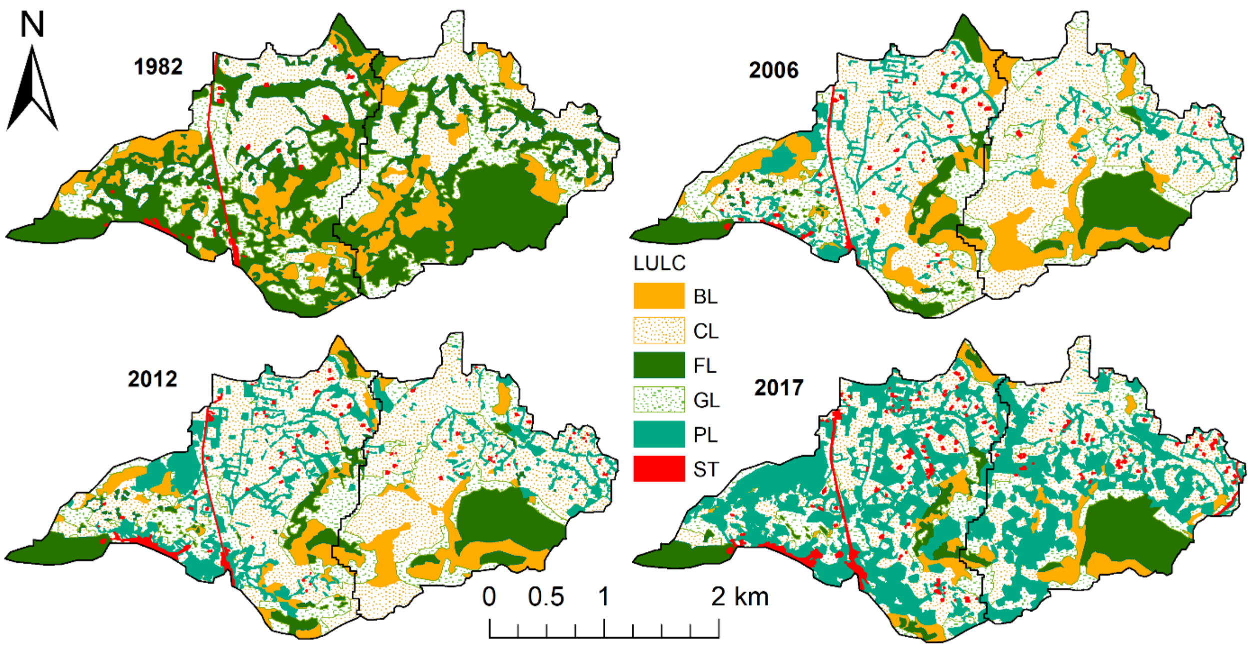

Figure 2-1 LULC maps of Guder paired [Kasiry (left) and Akusity (right)] watersheds (1982, 2006, 2012, and 2017).

Overall, from 1982 to 2017, grazing land declined by 32.2% and 27.3% in Kasiry and Akusity, respectively (Figure 2-4, Table 2-3). Plantation (mostly *A. decurrens*) appeared for the first time in the 2006 image, when it covered 10.9% in Kasiry and 4.6% in Akusity. Unlike forest land, grazing land, and bushland, plantation increased markedly from 2006 to 2012, by 58.8%

and 47.7% in Kasiry and Akusity, respectively (Table 2-3). In 2017, plantation was the dominant LULC type, covering 39.3% and 30.8% in Kasiry and Akusity, respectively (Figure 2-4), after increasing by 127.7% in Kasiry and 354.8% in Akusity between 2012 and 2017 (Table 2-3). Compared to other LULC types, settlements accounted for the least coverage. It accounted for less than 5% in both the Kasiry and Akusity watersheds but persistently increased during the study periods (Figures 2-1, 2-4). The total area of the watersheds covered by settlement increased by 15.4%, 31.2%, and 65.4% in Kasiry and 100%, 66.3%, and 204.5% in Akusity during the three periods, respectively.

Aba Gerima (midland) paired watersheds

We prepared LULC maps for the Aba Gerima paired watersheds for 1982, 2005, and 2016 (Figure 2-2). In 1982, bush land was the third dominant LULC class followed by grazing land, covering an area of 27.1%. Bushland covered less area in Kecha than Laguna throughout the study period, covering 22.0% in 1982, 8.5% in 2005, and 5.1% in 2016 in Kecha and 27.1%, 16.9%, and 13.9% in the same years in Laguna (Figures 2-2, 2-4). The area covered by bushland decreased by 76.6% in Kecha and 48.6% in Laguna by 2016 (Table 2-3), mainly due to conversion to cultivated and grazing lands (Table 2-4). The most dominant LULC type was cultivated land during the entire study period (41.7%, 69.8%, and 68.9% in Kecha and 29.1%, 64.7%, and 66.5% in Laguna in 1982, 2005, and 2016, respectively) (Figure 2-4). From 1982 to 2005, cultivated land increased by 67.6% in Kecha and 122.4% in Laguna (Table 2-4). Between 2005 and 2016, however, it decreased by 1.3% in Kecha due to eucalyptus plantation and khat cultivation but increased by 2.9% in Laguna (Table 2-3). Overall, cultivated land increased by 65.5% in Kecha and 128.9% in Laguna between 1982 and 2016. Forest land was the third most dominant LULC type in Kecha (18.7%) and the most dominant in Laguna (32.0%) in 1982 (Figures 2-2, 2-4). From 1982 to 2005, it decreased by 54.9% in Kecha and 59.8% in Laguna. From 2005 to 2016, however, forest land increased by 29.2% in Kecha but decreased by 13.7% in Laguna. Overall, this land cover decreased by 41.7% in Kecha and 65.3% in Laguna over the entire study period (Table 2-3). Grazing land covered 17.6% in Kecha and 11.9% in Laguna in 1982 (Figure 2-4). Like bushland, its cover continuously decreased from 1982 to 2016 (Figures 2-2, 2-4), decreasing from 1982 to 2016 by 40.2% (from 17.5% to 10.5%) and 63.4% (from 11.9% to 4.4%) in Kecha and Laguna, respectively (Figure 2-4, Table 2-3). Khat cultivation appeared in 2005, accounting for less than 1% of cover in Kecha and Laguna (Figure 2-4). It increased from 2005 to 2016 by 408.4% and 585.7% in Kecha and Laguna, respectively, mainly at the expense of cultivated land (Table 2-4). Settlement accounted for the least coverage compared to other LULC types. Between 1982 and 2016, it covered less than 3.5% and 1% in Kecha and Laguna, respectively (Figure 2-4). Similar to the trend with khat cultivation, settlements in the study watersheds increased consistently by more than 100% in each study period.

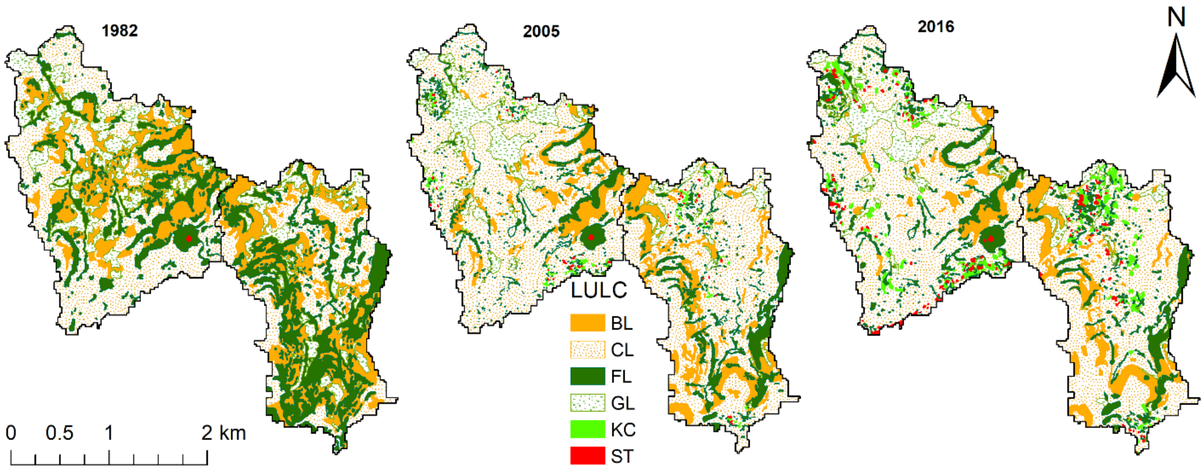

Figure 2-2 LULC maps of Aba Gerima paired [Kecha (right) and Laguna (left)] watersheds (1982, 2005, and 2016).

Debatie (lowland) paired watersheds

Like Guder paired watersheds, we prepared four LULC maps for1982, 2006, 2011 and 2017 for Debatie paired watersheds (Figure 2-3). In 1982, bushland was one of the major LULC types, accounting for 22.9% in Sahi and 36.6% in Bekafa in 1982 (Figure 2-4). A notable change in bushland cover took place between 1982 and 2006 in Sahi (decreased by 18.6%) and between 2006 and 2011 in Bakafa (decreased by more than 28%). Overall, the area covered by bushland decreased by 32.0% in Sahi and 58.7% in Bekafa over the entire period (Table 2-3), mostly due to the expansion of cultivated and grazing lands in the watersheds. As compared to the other two study sites, cultivated land had the least cover in 1982, with only 16.2% in Sahi and 6.2% in Bekafa (Figure 2-4). Between 1982 and 2006, coverage increased by 185.0% and 419.7%, respectively (Table 2-3). Cultivated land coverage continued to increase, but from 2011 to 2017, the increase was only 3.8% in Sahi and 5.3% in Bekafa. In 2017, cultivated land was the dominant LULC type (61.3% in Sahi and 54.0% in Bekafa) (Figure 2-4, Table 2-3). The average forest cover of these paired watersheds was similar to that of Aba Gerima and accounted for 26.4% of the total area of the watersheds in 1982 (Figure 2-4). However, forest cover declined by 47.7% (1982–2006) and 53.8% (2006–2011) in Sahi, and by 27.4% (1982–2006) and 48.9% (2006–2011) in Bekafa (Table 2-3). Between 2011 and 2017, coverage slightly increased (2.5%) in Sahi, but slightly decreased (0.4%) in Bekafa (Table 2-3). Overall, between 1982 and 2017, forest cover markedly declined in both areas (Table 2-3). Grazing land was the most dominant LULC type in Sahi (28.6%) and the second most dominant type in Bekafa (36.4%) in 1982. However, by 2006, it had decreased by 35.8% (from 28.6% to 18.3%) in Sahi and by 24.6% (from 36.4% to 27.4%) in Bekafa (Figure 2-4, Table 2-3). Overall, grazing land decreased by 48.3% in Sahi and by 38.3% in Bekafa between 1982 and 2017 (Table 2-3). Similar to the other watersheds, this class accounted for the least coverage, covering less than 1% in the Sahi and Bekafa watersheds during the entire study period (Figure 2-4). Similar to the trend for cultivated land, settlements increased consistently throughout the study period (Figures 2-3, 2-4 and Table 2-3).

LULC change among paired watersheds showed similar trends (Figure 2-4), whereas the rate of change for each LULC type was remarkably different (Table 2-3). This difference was more pronounced between Kasiry and Akusity at Guder and Kecha and Laguna at Aba Gerima. The Kecha watershed has been receiving SWC measures since 2011, supported by a Swiss Development Cooperation project. Similarly, the Kasiry watershed was part of the National Sustainable Land Management Programme since 2008, supported by funds obtained from the World Bank.

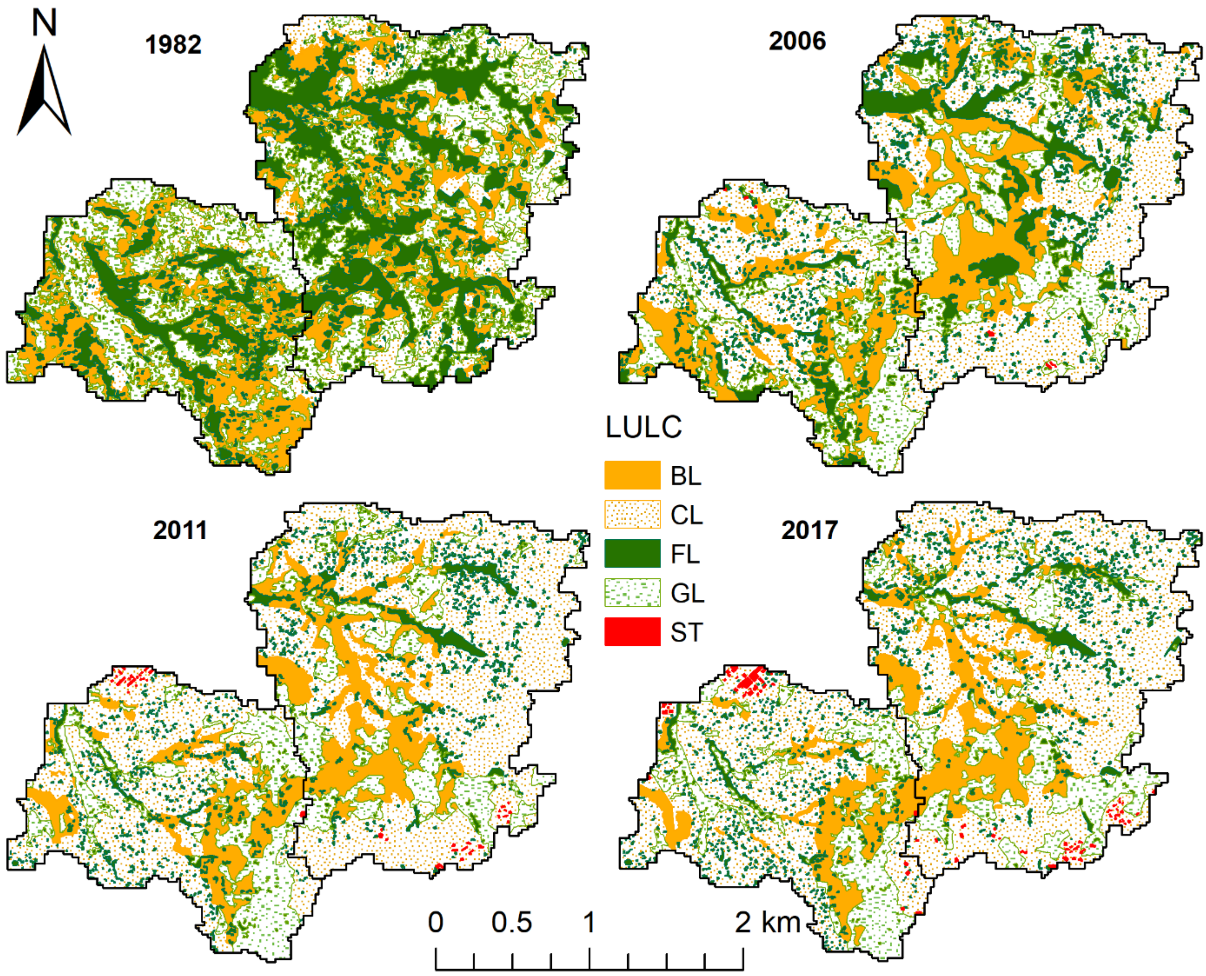

Figure 2-3 LULC maps of Debatie paired [Sahi (right) and Bekafa (left)] watershed (1982, 2006, 2011, and 2017).

In general, by averaging the paired watersheds LULC extent analysis value, in the period from 1982 to 2016/2017, forest land, bushland, and grazing lands respectively decreased by about 76%, 58%, and 30% in Guder; 54%, 63%, and 52% in Aba Gerima; and 69%, 45%, and

43% in Debatie. During the same period, cultivated land increased by approximately 38%, 97%, and 492% in Guder, Aba Gerima, and Debatie, respectively (Figure 2-4, Table 2-3).

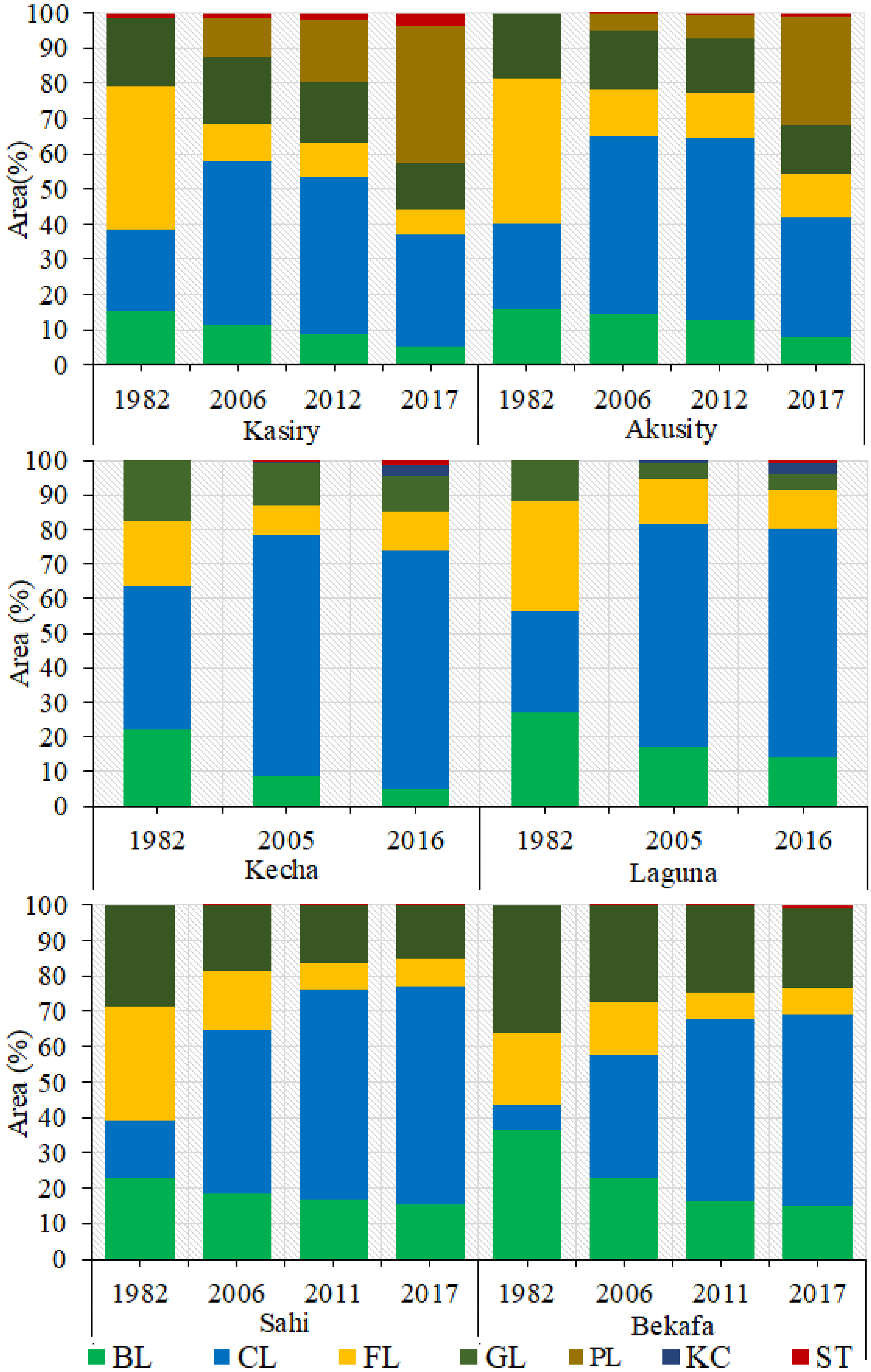

Figure 2-4 Area extent of LULC types in the year 1982, 2005/2006, 2011/2012 and 2016/2017: Guder, Aba Gerima, and Debatie paired watersheds.

Table 2-3 Change (%) in LULC classes in the three paired watersheds from 1982 to 2016/2017.

Site		Change (%)				Change (%)			
		Kasiry				Akusity			
	LULC	1982–2006	2006–2012	2012–2017	1982–2017	1982–2006	2006–2012	2012–2017	1982–2017
Guder (741 km^2)	BL	–24.8	–25.5	–39.0	–65.8	–8.5	–12.4	–37.0	–49.5
	CL	+99.7	–3.3	–29.2	+36.7	+107.1	+2.4	–34.1	+39.6
	FL	–73.7	–9.5	–27.0	–82.6	–67.1	–3.5	–5.5	–70.0
	GL	–2.1	–7.4	–25.1	–32.2	–11.0	–7.5	–11.7	–27.3
	PL	+100.0	+58.8	+127.7	+100.0	+100.0	+47.7	+354.8	+100.0
	ST	+15.4	+31.2	+65.4	+150.4	+100.0	+66.3	+204.5	+100.0
		Kecha				Laguna			
	LULC	1982–2005	2005–2016	1982–2016		1982–2005	2005–2016	1982–2016	
Aba Gerima (759 km^2)	BL	–61.3	–39.5	–76.6		–37.4	–18.0	–48.6	
	CL	+67.6	–1.3	+65.5		+122.4	+2.9	+128.9	
	FL	–54.9	+29.2	–41.7		–59.8	–13.7	–65.3	
	GL	–29.9	–14.8	–40.2		–58.9	–10.9	–63.4	
	KC	+100.0	+408.4	+100.0		+100.0	+585.7	+100.0	
	ST	+175.4	+421.7	+1336.6		+100.0	+368.2	+100.0	
		Sahi				Bekafa			
	LULC	1982–2006	2006–2011	2011–2017	1982–2017	1982–2006	2006–2011	2011–2017	1982–2017
Debatie (645.2 km^2)	BL	–18.6	–9.2	–8.0	–32.0	–37.4	–28.4	–8.1	–58.7
	CL	+185.0	+28.3	+3.8	+279.6	+419.7	+47.0	+5.3	+704.3
	FL	–47.7	–53.8	+2.5	–75.2	–27.4	–48.9	–0.4	–63.0
	GL	–35.8	–12.8	–7.6	–48.3	–24.6	–10.8	–8.3	–38.3
	ST	+100.0	+314.7	+66.1	+100.0	+100.0	+631.4	+225.8	+100.0

LULC: land use/land cover; BL: bushland; CL: cultivated land; FL: forest land; GL: grazing land; PL: plantation; KC: Khat cultivation; and ST: settlement.

In the three paired watersheds, the results showed that substantial portions of the landscapes across the three agro-ecologies experienced different LULC changes. In general, between 1982 and 2017, the area coverage of forest, grazing, and bush lands decreased at all the paired watersheds (Figure 2-4, Table 2-3). In contrast, settlements in all paired watersheds and cultivated land in Aba Gerima and Debatie showed an increasing trend during the entire study period. Plantation coverage dramatically increased in Guder, especially after 2012, mainly at the expense of cultivated, grazing, and bush lands (Figure 2-1). Similarly, in Debatie, there was an extreme expansion of cultivated land at the expense of vegetation cover (bush, forest and grazing lands) as compared to the Guder and Aba Gerima paired watersheds (Figure 2-4).

The results are in good agreement with those of previous studies conducted in the Upper Blue Nile basin and elsewhere (e.g. Betru et al., 2019; Gashaw et al., 2017; Minta et al., 2018; Tekle and Hedlund, 2000; Wondie and Mekuria, 2018), all of which reported that the expansion of cultivated land has increased at the expense of forest, bush, and grazing lands. The observed remarkable expansion of plantation area in the Guder paired watersheds between 2012 and 2017 at the expense of cultivated land also are in agreement with the results of Belete (2015) and Wondie and Mekuria (2018) who reported that, in the Fagita Lekoma District, farmers extensively planted *A. decurrens* in a woodlot agroforestry system and that 50% of cultivated lands had been converted to *A. decurrens* woodlots by 2014. Similarly, the studies in Chemoga watershed of the highland of Ethiopia showed that forest cover through afforestation notably increased between 1982 to 1998 as source of fuel wood and income generation (Bewket, 2002).

2.3.2. Analysis of LULC conversions from 1982 to 2017

A LULC conversion matrix of each watershed between 1982 and 2016/2017 is presented in Table 2-4. Conversions between the individual study periods and conversion indexes (CIs) are provided in the Supplementary Material (Appendix Tables A1–A8). The diagonals in Table 2-4 and Tables A1–A3 show a class's persistence (i.e., the area that remained the same), and the off-diagonal numbers in the matrix represent conversions from one class to the other.

Guder paired watersheds

Between 1982 and 2006, 17.9, 65.9, and 27.2 ha of cultivated land in Kasiry and 29.4, 43.87, and 31.33 ha of cultivated land in Akusity were converted from bushland, forest land, and grazing land, respectively (Table A1). Also, the conversion of forest land to cultivated land occurred at a higher rate than that of the other LULC types (the CI was 3.0 in Kasiry and 1.3 in Akusity) (Table A4). In addition, a considerable portion of forest land in both watersheds was converted to bushland, grazing land, and plantation (Table A1). The gross gain in cultivated land from other LULC types was 60.5% in both watersheds, whereas 21.1% (Kasiry) and 18.3% (Akusity) of cultivated land was converted to bushland, grazing land, and settlement. The most notable LULC transitions between 2006 and 2012 were the conversion of grazing land and plantation to cultivated land (CI ≥ 2.1) in both the Kasiry and Akusity watersheds (Table A4). In contrast, during the same period, 28.7 ha (Kasiry) and 12.1 ha (Akusity) of cultivated land was converted to plantation (Table A4). Also, the CIs (2.9 in Kasiry and 2.4 in Akusity) were higher than those of the other LULC types (Table A5). The gross gains in plantation cover were 70.2% in Kasiry and 81.2% in Akusity from other LULC types. In the period between 2012 and 2017, the conversion of cultivated land to plantation land was significant (CI of 3.1 in Kasiry and 3.8 in Akusity) compared to other LULC types (Table A4). The gross gains of plantation cover from other LULC types were 69.2% and 87.2% in Kasiry and Akusity, respectively. On the other hand, cultivated land gained 24% in Kasiry and 18% in Akusity from other LULC types. Also, a notable amount of bushland (70.9% in Kasiry and 65.2% in Akusity) was converted to other LULC types during these periods. Over the entire period (1982–2017), the major LULC transitions were a marked gain of plantation land (100%) and settlements (85.3%) from bushland, cultivated land, forest land, and grazing land. During the same period, 93.7% (Kasiry) and 91.6% (Akusity) of bushland were converted to cultivated land, grazing land, and plantation land (Table 2-4).

Aba Gerima paired watersheds

In Aba Gerima watershed, the gain in cultivated land was derived from conversions of bushland, forest land, and grazing land between 1982 and 2005 (Table A2). The more pronounced transitions were conversion of bushland to cultivated land in Kecha (CI ≥ 1.5) and conversion of forest to cultivated land in Laguna (CI ≥ 1.4). During the same period, the gain in khat cultivation was mainly derived from cultivated land, with CIs of 3.8 and 2.6 in the Kecha and Laguna watersheds, respectively (Table A7). Large areas of bushland (losses = 80.7%) and forest land (losses = 78.9%) were also converted to other LULC types. In the period between 2005 and 2016, more cultivated land was converted from grazing land and bushland as compared to other LULC types in both watersheds (Table S2). A considerable area of khat cultivation (10.5 ha) was converted from cultivated land (CI = 4.2, Table A7), but the percentage gain and loss in the other LULC types was relatively small in comparison. Over the entire period (1982–2016), sizable amounts of bushland (55.8 ha), forestland (45.7 ha), and grazing land (48.2 ha) were converted to cultivated land in Kecha (Table A2). Similarly, in Laguna, the gain in cultivated land was from bushland (51.5 ha), forest land (65.3 ha) and grazing land (25.6 ha) (Tables 2-4, A6). During the same period, the gain in forest cover as a result of the considerable expansion of eucalyptus plantation was 27.2 ha in Kecha and 21.1 ha in Laguna (Table A2), but the conversion of cultivated land into khat cultivation was higher than other LULC transitions (CI ≥ 2.8) in both watersheds (Table A7).

Debatie paired watersheds

Between 1982 and 2006, the gain in cultivated land was derived dominantly from the conversion of grazing land (60.9 ha in Sahi and 40.1 ha in Bekafa) (Table A3), with a CI of 1.3 in Sahi and 1.6 in Bekafa (Table A8). The conversion of forest land to bushland (33.1 ha), cultivated land (42.7 ha), and grazing land (23.7 ha) was more prominent in Sahi than in Bekafa (bushland, 15.5 ha; cultivated land, 12.1 ha; and grazing land, 11.7 ha). Overall gains were high for cultivated land (74.0% in Sahi and 85.7% in Bekafa), whereas considerable losses occurred in bushland (76.5% in Sahi and 69.2% in Bekafa) (Table A3). As in the previous period, conversion of grazing land to cultivated land from 2006 to 2011 was higher than it was for the other LULC types (CI > 1.5, Table A8). The overall gain in cultivated land from other

LULC types was about 32% in Sahi and 44% in Bekafa (Table A3). Similarly, bushland gained 54.6% in Sahi and 47.4% in Bekafa, mostly from forest and grazing land (Table A3). From 2011 to 2017, cultivated land continued to increase at the expense of grazing land, with a CI of 2.4 in Sahi and 2.1 in Bekafa (Table A8). Overall cultivated land gained about 18% in both the Sahi and Bekafa watersheds (Table A3). Similarly, forest cover gained 49.2% in Sahi and 59.9% in Bekafa from bushland, cultivated land, and grazing land. In addition, a considerable amount of bushland (30.8% in Sahi and 35.5% in Bekafa) was converted to other LULC types (Table A3). Over the entire period (1982–2017), cultivated land increased by about 78% in Sahi, of which about 35% and 40% were derived from the conversion of forest land and grazing land, respectively (Table 2-4). Similarly, in the Bekafa watershed, the gain in the cultivated land was about 90%, mainly derived from the conversion of grazing land (48%) and bushland (33%) (Table 2-4).

Comparatively, the conversion of forest land to cultivated land in Aba Gerima is more prominent than Guder followed by Debatie paired watersheds during the study periods (Table SA–A2). Overall from 1982 to 2016/17, cultivated land gained 44.7 ha, 66.9 ha and 34.4 ha from forest land in Guder, Aba Gerima and Debatie paired watersheds, respectively. On the other hand, small amount of forest land (0.13 ha in Guder and Aba Gerima, and 0.18 ha in Debatie) converted to settlements. Similarly, settlements gain a total of 3.2 ha in Guder, and 1.9 ha in Aba Gerima and Debatie paired watersheds from forest land (Table A1–A2). It important to mentioning that in Guder paired watersheds, forest land was converted to cultivated land and in turn the cultivated land was converted to plantation land mainly as of *A. decurrens* since 2006.

In general, the conversion results indicated that in Guder (highland) paired watersheds from 1982 to 2012, the most prominent LULC transformation was the conversion of forest land and grazing land to cultivated land; while from 2012 to 2017, remarkable expansion of plantation from the conversion of cultivated land and grazing land was dominant (Figure 2-1, Tables 2-4, A1). Similarly, in Aba Gerima (midland) paired watersheds, the conversion of forest land to cultivated land was dominant from 1982 to 2005 while after 2005 the conversion of bushland to cultivated land was more noticeable (Figure 2-2, Tables 2-4, A2). Whereas, in Debatie (lowland) paired watersheds, the transition from grazing land to cultivated land was very pronounced over the entire study period (Figure 2-3, Tables 2-4, A3) as indicated by the higher CI value than other LULC classes (Table A6). The continuous conversion of LULC results reveal that the landscape rehabilitation is prominent on the highland areas due to remarkable expansion of *A. decurrens* plantation starting from 2006. In contrary, lowland areas have presumably experienced landscape degradation as a result of extreme expansion of cultivated land at the expense of vegetation cover (Figure 2-5). Also, the condition of the landscape in the midland areas falls between the highland and lowland landscape processes (Figure 2-5). It is worth noting that the experiences of landscape rehabilitation in the highland areas could be adopted in other study watersheds to minimize unforeseen environmental degradations.

Previous studies conducted in various parts of Ethiopia and elsewhere have reported LULC conversions (e.g. Betru et al., 2019; Dessie and Kleman, 2007; Gashaw et al., 2017; Ju et al., 2018; Kamusoko and Aniya, 2007; Minta et al., 2018; Ningal et al., 2008; Tekle and Hedlund, 2000; Yeshaneh et al., 2013; Zeleke and Hurni, 2001). The results of this study are in good agreement with the findings of previous studies conducted in the Ethiopian highlands. For example, our findings on the conversion of forest cover to cultivated land in the watersheds consistent with those of Tekle and Hedlund (2000), and Zeleke and Hurni (2001), who reported that a tendency towards land being brought under cultivation at the expense of forest cover.

Table 2-4 Transition area matrix[a] (ha) between 1982 and 2016/2017 in the three paired watersheds.

Site	1982–2017 LULC	Kasiry (ha) BL	CL	FL	GL	PL	ST	Total 1982	Loss (ha)	Loss (%)	Akusity (ha) BL	CL	FL	GL	PL	ST	Total 1982	Loss (ha)	Loss (%)
Guder (741 km²)	BL	3.9	15.6	2.1	9.2	29.8	0.5	61.0	57.1	93.7	4.6	16.6	0.1	9.8	23.8	0.1	55.0	50.4	91.6
	CL	0.0	49.3	0.2	1.6	38.1	2.8	92.0	42.6	46.4	0.3	49.3	0.0	3.5	27.3	2.9	83.4	34.1	40.9
	FL	13.6	41.6	23.9	17.5	59.3	2.2	161.6	137.7	85.2	21.2	29.6	42.0	17.0	29.7	0.8	140.3	98.3	70.1
	GL	3.4	17.6	1.9	24.0	27.7	2.8	77.4	53.4	69.0	1.7	21.0	0.1	16.7	25.0	0.2	64.8	48.0	74.2
	ST	0.0	0.0	0.0	0.0	0.0	5.5	5.5	0.0	0.0	–	–	–	–	–	–	–	0.0	0.0
	Total 2017	20.9	125.7	28.1	52.5	156.5	13.8	397.5	294.4	–	27.9	116.5	42.2	47.1	105.9	4.0	343.5	230.9	–
	Gain (ha)	17.0	76.4	4.2	28.5	156.5	11.8	–	294.4	–	23.2	67.2	0.1	30.4	105.9	4.0	–	230.9	–
	Gain (%)	81.5	60.8	14.9	54.3	100.0	85.3	–	–	–	83.4	57.7	0.3	64.5	100.0	100.0	–	–	–

Site	1982–2017 LULC	Kecha (ha) BL	CL	FL	GL	KC	ST	Total 1982	Loss (ha)	Loss (%)	Laguna (ha) BL	CL	FL	GL	KC	ST	Total 1982	Loss (ha)	Loss (%)
Aba Gerima (759 km²)	BL	12.1	55.8	8.8	14.0	1.9	0.5	93.2	81.0	87.0	20.6	51.5	10.6	5.5	1.8	0.5	90.6	70.0	77.3
	CL	1.6	142.7	15.4	5.1	8.2	3.7	176.7	34.0	19.3	3.0	80.2	7.2	0.7	4.9	1.2	97.3	17.1	17.5
	FL	6.2	45.7	18.9	6.7	1.3	0.4	79.2	60.3	76.1	18.6	65.3	17.0	2.8	2.9	0.5	107.1	90.1	84.1
	GL	1.8	48.2	3.0	18.9	2.5	0.4	74.8	55.9	74.8	4.4	25.6	2.3	5.5	1.7	0.3	39.8	34.2	86.2
	ST	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	–	–	–	–	–	–	–	–	–
	Total 2017	21.8	292.4	46.2	44.7	13.9	5.2	424.3	210.5	–	46.5	222.7	37.2	14.6	11.3	2.5	334.7	195.8	–
	Gain (ha)	9.7	149.7	27.3	25.8	13.9	4.9	–	210.5	–	25.9	142.4	20.2	9.1	11.3	2.5	–	195.8	–
	Gain (%)	44.3	51.2	59.1	57.8	100.0	93.0	–	–	–	55.8	64.0	54.2	62.2	100.0	100.0	–	–	–

Site	1982–20016 LULC	Sahi (ha) BL	CL	FL	GL	PL	ST	Total 1982	Loss (ha)	Loss (%)	Bekafa (ha) BL	CL	FL	GL	PL	ST	Total 1982	Loss (ha)	Loss (%)
Debatie (645.2 km²)	BL	18.8	50.3	6.3	15.7	–	0.1	91.2	72.4	79.4	18.5	39.4	5.7	26.6	–	0.2	90.5	71.9	79.5
	CL	1.8	53.1	3.6	5.2	–	0.6	64.3	11.2	17.4	0.1	13.5	0.9	1.5	–	0.6	16.6	3.0	18.3
	FL	29.9	63.9	14.8	20.1	–	0.2	128.9	114.1	88.5	11.3	23.9	6.0	8.9	–	0.1	50.1	44.1	88.0
	GL	11.5	76.9	7.2	17.9	–	0.4	113.8	95.9	84.3	7.4	56.6	5.9	18.4	–	1.4	89.8	71.4	79.5
	ST	–	–	–	–	–	–	–	0.0	0.0	–	–	–	–	–	–	–	0.0	0.0
	Total 2017	62.0	244.2	31.9	58.9	0.0	1.3	398.2	293.6	–	37.3	133.4	18.5	55.4	0.0	2.4	247.0	190.5	–
	Gain (ha)	43.2	191.0	17.1	41.0	0.0	1.3	–	293.6	–	18.8	119.8	12.5	37.0	0.0	2.4	–	190.5	–
	Gain (%)	69.7	78.2	53.6	69.7	0.0	100.0	–	–	–	50.3	89.8	67.7	66.8	0.0	100.0	–	–	–

LULC: land use/land cover; BL: bushland; CL: cultivated land; FL: forest; PL: plantations; GL: grazing land; KC: khat cultivation; ST: settlements. The shaded values along diagonals in the matrix represent the area of each LULC type that was not converted to another type during the time interval. [a]Values in the table are the areas (ha) of the LULC classes in the left column converted to the LULC classes across the top of the table during the time interval specified.

In contrast, a study in China by Ju et al. (2018) reported that the cultivated land showed a decreasing trend since 1987 mainly as a result of the expansion of built-up area (42,822 km^2 (43.8%) at the expense of cultivated land from 1987 to 2010). The conversion of grazing land to cultivated land in the Guder and Debatie watersheds also agrees well with the results of Dessie and Kleman (2007) in the south-central rift valley region of Ethiopia, Minta et al. (2018) in Dendi-Jeldu in the centeral Ethiopia highlands, and Ningal et al. (2008) in Morobe Province of Papua New Guinea. The expansion of plantation cover at the expense of cultivated land and grazing land in Guder agrees with studies conducted by Kamusoko and Aniya (2007) in the Bindura District of Zimbabwe, Yeshaneh et al. (2013) in the Koga watershed (Ethiopia), and Bewket (2002) in the Chemoga watershed of the Upper Blue Nile basin. Similarly, Wondie and Mekuria (2018) reported that forest cover in Fageta Lekoma District (Guder watershed located in this District) showed a substantial increase (mainly through planting of *A. decurrens*) with an annual increasing trend of 5.2% from 2010 to 2015, and Desalegn et al. (2014) reported that the plantation increased by 33.5% at the expense of grazing lands in the Wetabecha Minjaro area of the central Ethiopia highlands between 1975 and 2014 for the purpose of fuel wood and house construction.

2.3.3. Drivers of LULC changes

Population growth

From 1982 to 2016, population grew by 200%, 243%, and 655% in Guder, Aba Gerima, and Debatie, respectively (Figure 2-5), and the average growth rate (estimated based on Equation 2-6) was 2%, 3%, and 5% for the three study sites, respectively. The population showed an increasing trend at the Guder site throughout the entire study period (1982–2016). Compared to prior periods, the growth rate decreased from 2007 to 2016 (Figure 2-5). The increase was consistent and positively correlated with the expansion of cultivated land between 1982 and 2006, while that relationship was reversed after 2006. This change was primarily a result of the increase of vegetation cover at the expense of cultivated land (Figure 2-5), mainly because of farmers' growing interest in allocating more land to plantations (dominantly *A. decurrens*) to remedy a decline in soil fertility and to grow *A. decurrens* for fuelwood and charcoal production (Belete, 2015; Nigussie et al., 2017a; Wondie and Mekuria, 2018). This result confirmed that a population increase does not always correspond to vegetation cover losses; hence, the "more people more trees" assertion proposed in Tanzania by Kabanza et al. (2013) was shown to be valid.

Compared to the other two paired watersheds, the change in population at Aba Gerima was more uniform between the successive study periods (Figure 2-5). Between 1982 and 2005, the expansion of cultivated land at the expense of vegetation cover was strongly linked with the increase in population number. However, the population also increased after 2007 when the cultivated land area did not substantially change (Figure 2-5). Vegetation cover did slightly increase because of increased khat cultivation, due to farmers wanted to increase farm diversification and have an alternative source of income generation (Nigussie et al., 2017a).

Unlike at the Aba Gerima paired watersheds, the rate of population growth increased throughout the entire study period at the Debatie paired watersheds, especially after 1994. This increase is most likely a result of the implementation of a resettlement policy in this area in the mid-1980s during the "Derg" regime (Provisional Military Government of Socialist Ethiopia; Woldemeskel, 1989). The policy resulted in a remarkable expansion of cultivated land and a decline of vegetation cover due to deforestation to meet the increasing demand for agricultural production (Figure 2-5). As a result, the population increase was positively correlated with the expansion of cultivated land and a decrease in vegetation cover, this type of changes aggravates soil erosion in the area as explained in Section 2.3.4 and the analogy of "more people more erosion" reported in Kenya by Ovuka (2000) seems valid here.

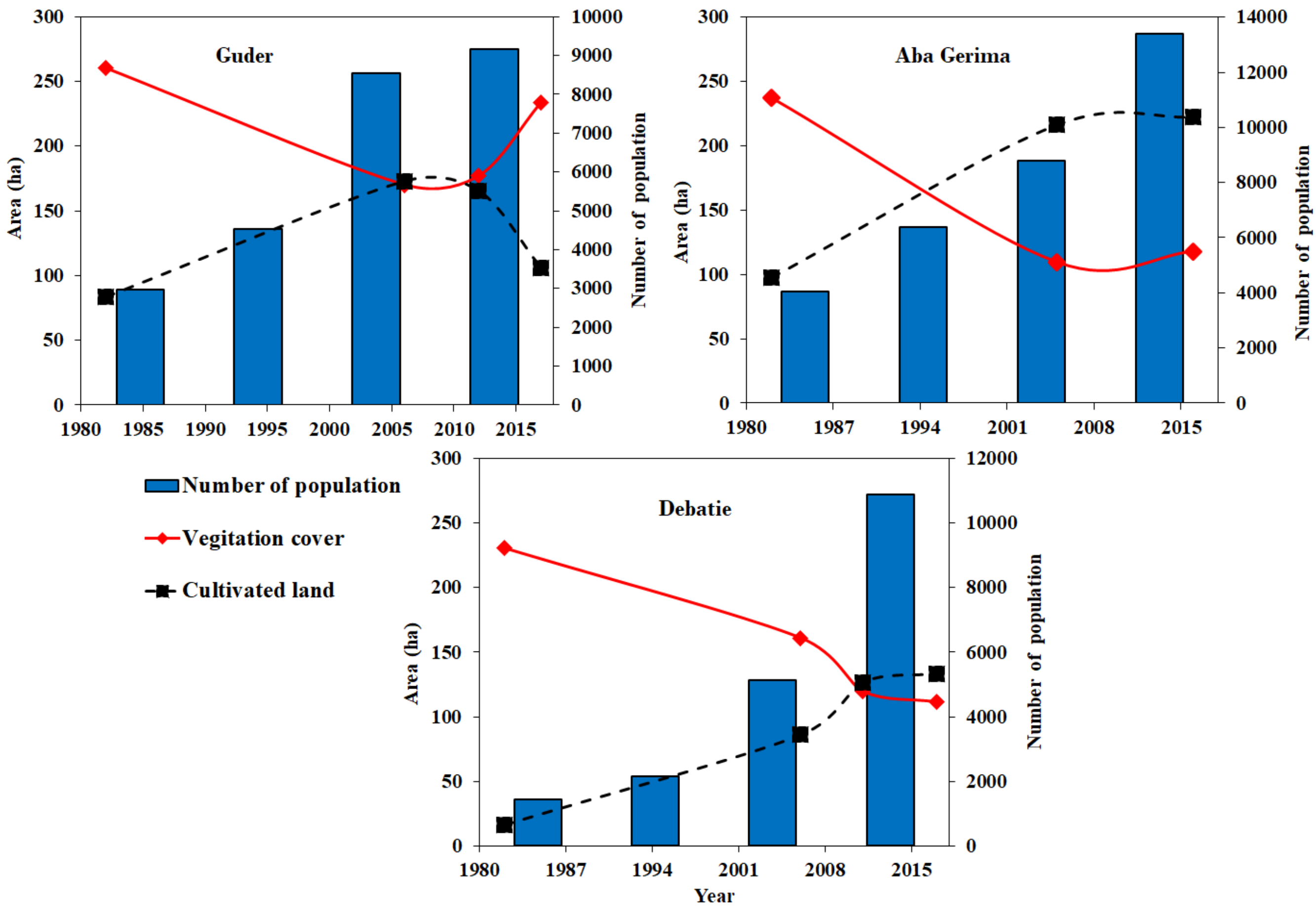

Figure 2-5 Total number population, area of vegetation covers and cultivated land from 1982 to 2016/17 for Guder, Aba Gerima, and Debatie paired watersheds.

In general, population increase appears to be the main driver of LULC changes in the study areas, which were largely expressed through the expansion of cultivated lands at the expense of vegetative cover, particularly in Aba Gerima and Debatie (Figure 2-5). These finding confirmed by the KIIs. The KIIs revealed that the expansion of cultivated land, charcoal, extraction for fuel wood and other wood products such as products for house construction associated with the increase of population number were the major proximate drivers of loss of natural vegetation cover in the study areas. This conclusion is consistent with the findings of Bewket (2002), Gashaw et al. (2017), and Gebrelibanos and Assen (2015), who reported that population growth as the main driving factor for LULC changes. As population increases, the demand for agricultural land, fuelwood, charcoal, and increase of house construction interest, all of which contribute to vegetation losses (Betru et al., 2019; Bewket, 2002; Gebrehiwot et al., 2014; Hurni et al., 2005). Conversely, increased population was positively correlated with vegetation cover (i.e., *A. decurrens* plantation) at the Guder paired watersheds agree with previous studies by Yeshaneh et al. (2013) and Minta et al. (2018), who pointed out that, even in a period of population growth, improved economic gains led to the rapid expansion of eucalyptus plantations into cultivated lands in the Ethiopian highlands. The increased population was also reflected in the increase in the area covered by settlements, which was observed at all study watersheds (Figures 2-1, 2-2, 2-3), and is another potential driver of LULC changes in the study watersheds.

On the other hand, the proximity of the study watersheds to urban areas is apparently result in the increase of population size (Fischer and Heilig, 1997; Jenerette and Wu, 2001) which could in turn contribute to LULC changes. Thus, the proximity of Enjebara town (district center) to Guder watershed, Bahir Dar town (regional center) to Aba Gerima paired watersheds and Debatie town (district center) to Debatie paired watersheds is most likely contribute to the observed LULC changes. This conclusion is also supported by previous studies in Ethiopia and elsewhere indicated that proximity to urban areas is one of the most important drivers of LULC changes (e.g., Fenta et al., 2017; Haregeweyn et al., 2012; Long et al., 2007).

Farming practices

A major shift from traditional annual cropping to more economically attractive tree-based farming practices such as plantations of *A. decurrens* in Guder and *C. edulis* in Aba Gerima was evident, especially after 2006 (Tables A4, A5). Local communities use such practices as alternative sources of income generation as well as to improve environmental conditions. The key informants also stated that due to the reduction of soil fertility and increasing interest of farmers for charcoal production (to increase income generation) in Guder paired watersheds, plantation of *A. decurrens* was considered as the most strategic solution for farmers and youths.

Similarly, the key informants again mentioned that due to high economic return and offers good market opportunities resulted to the expansion of khat cultivation in Aba Gerima paired watersheds.

The *A. decurrens* plantations in Guder represent a new economically competitive type of farm activity that has caused a massive land area to be withdrawn from cultivation and grazing lands (Figure 2-6(b), (c)), particularly after 2006. During this period, the *A. decurrens* plantation area has increased the vegetation cover of the Guder paired watersheds by 34% (Figures 2-1, 2-4). Belete (2015) reported that *A. decurrens* was first introduced into Fagita Lekoma in general and to the Guder watershed in particular in 1990. At that time, a few farmers started planting it at their homesteads and farm boundaries for fuelwood and forage.

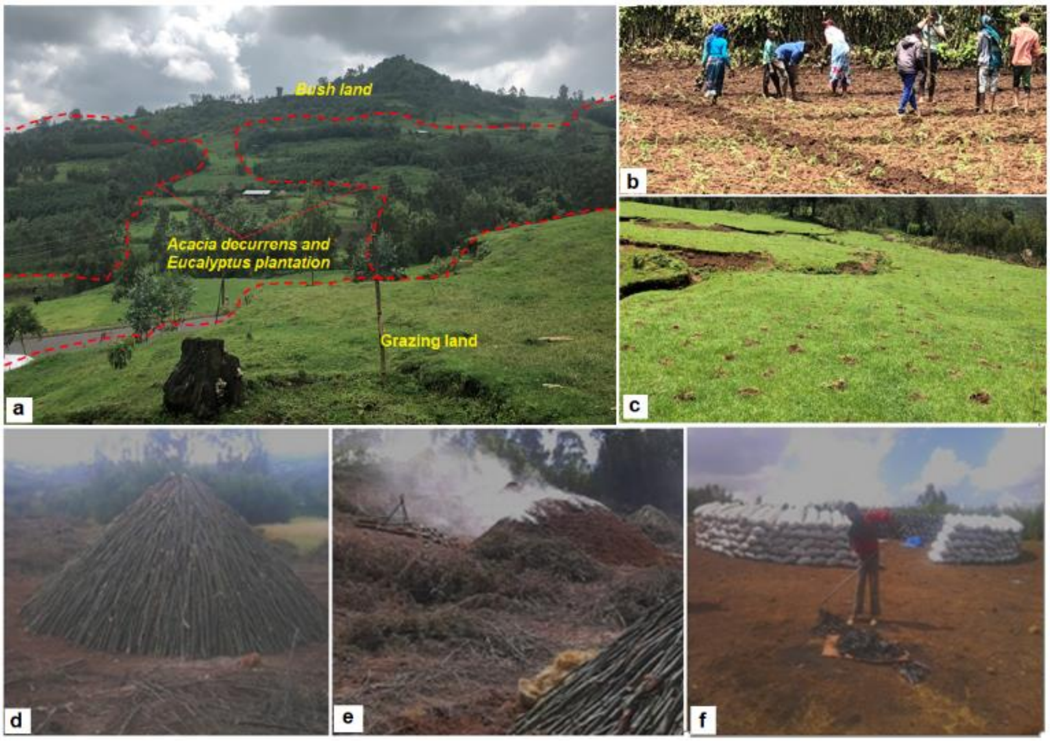

Figure 2-6 Sample photos of LULC classes (a), *A. decurrens* plantation on cultivated land (b) and grazing land (c) and traditional process of producing fuel wood (charcoal) from *acacia decurrens* tree (d, e and f) in Guder site.

In 2002, the Amhara Regional Bureau of Agriculture designed agroforestry packages to implement on farmland, and farmers were advised to plant woodlots on degraded farmlands.

The expansion of *A. decurrens* woodlot plantations began after the introduction of this package. Belete (2015) and Nigussie et al. (2017a) stated that the main driver for *A. decurrens* plantation expansion was its contribution to improving land productivity and income generation in addition to the provision of household fuelwood demands (Figure 2-6(d) – (f)). Farmers appear to have been strongly motivated to expand the area of *A. decurrens* plantation at the Guder paired watersheds, which is reflected in the rapid expansion of plantation area (100%) after 2006 (Table 2-3).

Khat is an exotic perennial crop, usually grows in an altitude range of 1500 to 2500 m above sea level in Ethiopia (Birhane, 2014; Kandari et al., 2014), and 3% of Ethiopian production originates in the Bahir Dar Zuria District in which Aba Gerima is located (Birhane, 2014). Khat cultivation is currently common practice at Aba Gerima, and the annual expansion rate at the watershed has reached as high as approximately 53% (Table 2-3). According to data obtained from the CSA agricultural sample survey conducted in 2009 (CSA, 2009), this rate exceeds the national expansion rate of 16%. Conversion to khat is desirable for both socio-economic and agro-ecological reasons. It has a high economic return and offers good market opportunities for farmers. Lemessa (2001) cited agro-ecological reasons such as lack of enough land for annual crops, soil erosion, weed infestation, and the prevalence of pests as motivating factors for Ethiopian farmers to shift from annual crops to khat cultivation. Feyisa and Aune (2003) reported that farmers expanded khat cultivation in the Haraghe region because of the economic benefits and also the use of its wood for cabinet work, fuelwood, and construction. According to a recent study conducted by Nigussie et al. (2017b) and Hussen (2018), the income gained from khat cultivation in Aba Gerima watershed is greater than the income from cereal crops.

2.3.4. Implications of LULC changes

The three paired watersheds experienced distinct LULC changes, especially after 2005/2006 at the Guder and Aba Gerima paired watersheds. Plantation area (*A. decurrens*) in the Guder paired watersheds expanded by about 400% from 2012 to 2017. Similarly, khat cultivation in the Aba Gerima paired watersheds increased by about 586% from 2005 to 2016. The Debatie paired watersheds had a steadier expansion of cultivated land totaling 704% from 1982 to 2017. These rapid LULC transformations and expansions have hydrological, socio-economic, and environmental consequences, which are discussed below.

Implications for soil erosion

Trends for vegetation cover and cultivated land and gully density over the past 35 years are shown in Figure 2-7. The result shows that the expansion of cultivated land has coincided with a similar increasing trend in gully density, particularly at Debatie and to a lesser extent at Aba Gerima. This is in agreement with previous studies of other areas, reported that gully erosion is accelerated by overgrazing, land use change, and inappropriate agricultural activities (Kakembo and Rowntree, 2003; Valentin et al., 2005). Several studies have documented the effects of gully erosion, such as loss of land as a result of land degradation, damage to infrastructure, providing a major source of sediments at the catchment scale, and increasing watershed sediment connectivity (Daba et al., 2003; Poesen, 2003; Valentin et al., 2005). The continued expansion of cultivated land combined with population growth will accelerate the on- and off-site consequences of gully erosion. The loss of natural vegetation and subsequent conversions to cultivated lands without appropriate conservation measures showed the prevalence of land degradation (Gebrelibanos and Assen, 2015). On the other hand, the relationship between vegetation cover and gully density in Guder watershed will require additional detailed investigation because both showed an increasing trend after 2006 (Figure 2-7).

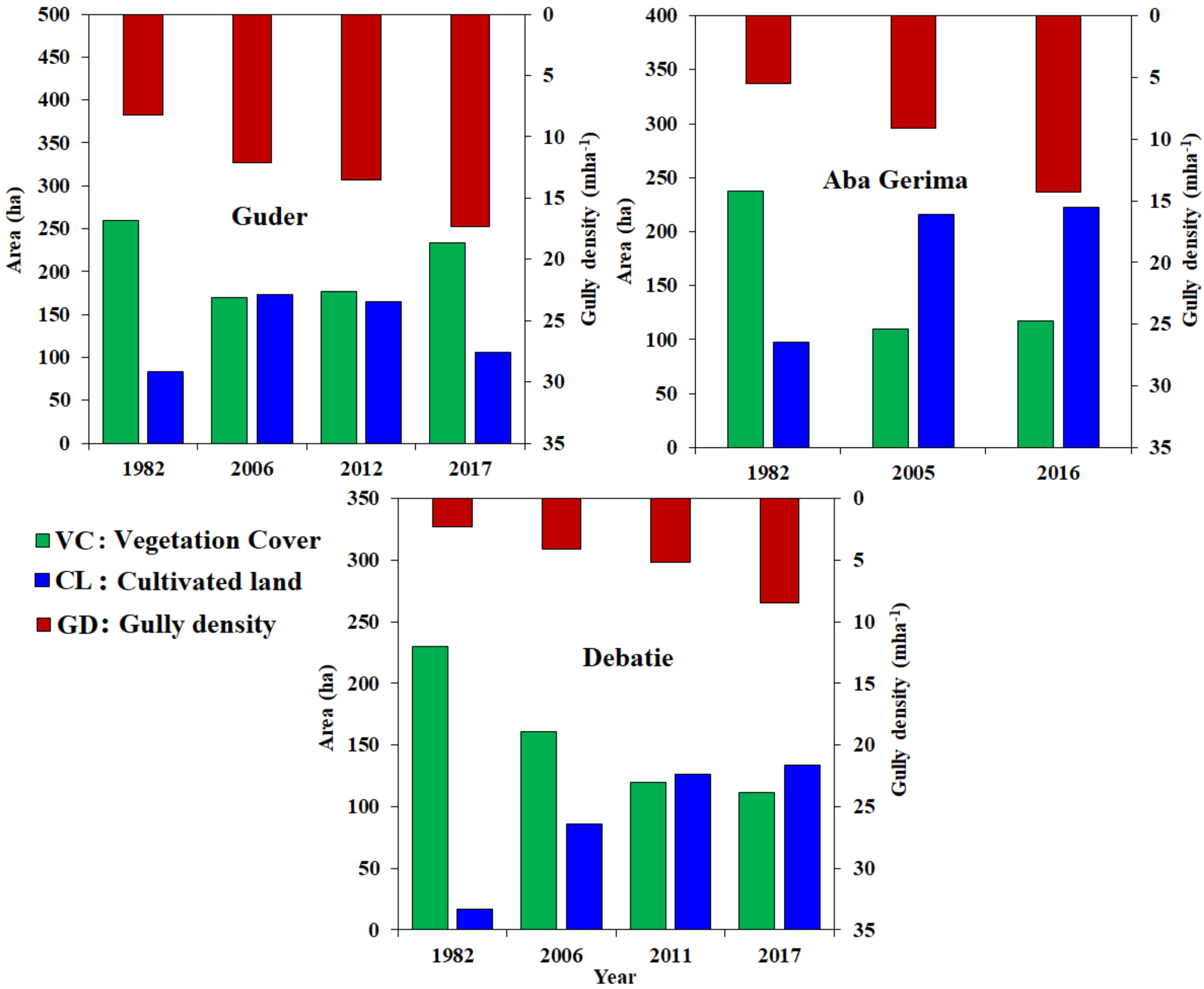

Figure 2-7 LULC change in relation to gully density over the past 35 years at the Guder, Aba Gerima, and Debatie paired watersheds. VC: vegetation cover that includes bushland, forest land, grazing land, plantation, and khat cultivation; CL: cultivated land; and GD: gully density. Gully density was digitized by Yibeltal et al. (2019) from aerial photographs and very high resolution remote-sensing data provided in Table 2-1.

Implications for surface runoff response

The runoff coefficient varied between cultivated land and vegetation cover across the watersheds (Figure 2-8). Thus, cultivated land at the Guder paired watersheds produced the highest seasonal runoff coefficient (30%), followed by Aba Gerima (23%) and Debatie (21%); the value for vegetation cover was lower at each site (25%, 22%, and 15%, respectively).

Cultivated land on average had a 21% higher runoff coefficient, and a higher runoff coefficient can be directly explained by increased surface runoff, which has significant on- and off-site impacts (e.g., depletion of soil moisture and increased soil erosion and sediment deposition in downstream areas).

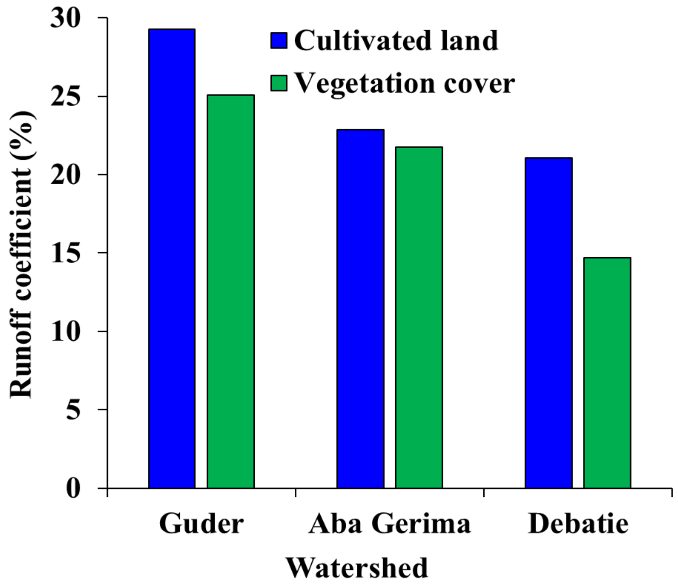

Figure 2-8 Runoff coefficient (runoff depth/rainfall depth) for different LULC types in the three study watersheds for two rainy seasons (June–October 2015 and 2016).

The observed LULC changes at the study watersheds have a notable influence on the surface runoff response. Studies conducted elsewhere in Ethiopia reported that runoff rate variability strongly influenced by LULC class (Haregeweyn et al., 2016; Hurni et al., 2005; Sultan et al., 2017). In general, it is well known that increased surface runoff will aggravate soil erosion, a conclusion supported by a study conducted in the Guder watershed by Ebabu et al. (2018). Sediment material washed away predominantly from cultivated land and hillslopes to low-lying areas, potentially creating problems in downstream areas such as sediment deposition on agricultural and grazing lands. These conditions were clearly observed in some areas at the study watersheds during field visits conducted for this study.

Socio-economic and environmental implications

The major LULC changes observed at the Aba Gerima and Debatie paired watersheds were the remarkable expansion of cultivated land at the expense of forest cover, bush, and grazing land (Tables A2, A3, A5, A6). In contrast, a significant expansion of plantation mainly derived from cultivated land was observed in Guder after 2006. The expansions of *A. decurrens* plantation in Guder and khat cultivation in Aba Gerima are likely to have both positive and negative socio-economic and environmental implications.

According to Belete (2015), farmers gained an average net return of 400% from the sale of *A. decurrens* charcoal, which is higher than the benefit obtained from the sale of annual crops. Also, farmers believed that this activity significantly reduced the amount of labor and the fertilizer costs compared to annual crops. The expansion of *A. decurrens* plantations has also had effects on the physical and chemical properties of the soil (Belete, 2015). For example, the pH value of the soil under *A. decurrens* plantation is 2% lower than the soil under cultivated land. Also, the available phosphorus in cultivated land is 1.25 mg/kg higher than the soil under *A. decurrens* plantation, whereas the total nitrogen of soil under *A. decurrens* plantation is 43.5% higher than that of cultivated land. These results are consistent with those of previous studies conducted in other areas that also reported that LULC change has a significant effect on most physical and chemical properties of soils (Bewket and Sterk, 2002; Lemenih and Kassa, 2014).

The substantial conversion of grazing land to plantation (40% of grazing land converted to plantation between 2006 and 2017; Table 2-4) in Guder has also will have negative consequences on the existing free-grazing feeding system and consequently on the livestock. A similar effect was reported by Desalegn et al. (2014) for the Wetabecha Minjaro area of the Ethiopian highlands; they pointed out that shortage of livestock fodder was a major challenge due to the rapid conversion of grazing land to plantations (increase by 335% from 1975 to 2014).

Khat cultivation in Aba Gerima increased by more than 500% during the entire study period. According to a recent study conducted by Hussen (2018) at the Aba Gerima paired watersheds, khat contributes about 51% of the total annual household income and more than 1.5 times the average income gained from off-farm and non-farm activities. Khat has also been shown to be related to economic crisis for users, families, and the nation because of factors such as family conflict and breakdown, diversion of household and individual income, and loss of work hours (Feyisa and Aune, 2003; Kandari et al., 2014; Mossie, 2002; Wabel, 2011). Moreover, livestock holdings in the Aba Gerima area have decreased from 10 to 6 Tropical Livestock Units (TLUs) since the introduction of khat cultivation in 2005 (Hussen, 2018). Furthermore, waste from khat fields is poisoning lakes, rivers, other water bodies, and the environment at large and ultimately disturbing the ecosystem (UNICEF, 2004). In general, the expansion of khat cultivation at the Aba Gerima paired watersheds needs more attention and detailed investigation in terms of the positive and negative socio-economic and environmental consequences.

2.4. Conclusions

The results of this study revealed that substantial amounts of spatial and temporal LULC change occurred over the past 35 years in the study watersheds located in different agro-ecologies of the Upper Blue Nile basin: Guder (highland), Aba Gerima (midland) and Debatie (lowland) watersheds. In 1982, the dominant LULC classes were forest land in Guder (41%) and Aba Gerima (32%), and bush land in Debatie (36.6%). By 2017, the dominant types were plantation in Guder (33.9%) and cultivated land in Aba Gerima (66.5%) and Debatie (54.0%). Cultivated land showed a remarkable increasing trend in the Aba Gerima and Debatie watersheds from 1982 to 2016/2017 and in Guder watershed between 1982 and 2006, mainly at the expense of forest cover, grazing, and bush lands. In contrast, vegetation covers in the form of plantation increased markedly in the Guder watershed, mainly at the expense of cultivated land, especially from 2012 to 2017. Population growth and changing farming practices (e.g., growing of *A. decurrens* plantation in Guder and khat cultivation in Aba Gerima) were the major drivers of LULC changes. In general, based on the LULC changes in the different agro-ecologies and the varying farming practices in line with population growth, the basin experienced a general trend both towards "more people more trees" and "more people more erosion". The changes have had both positive and negative socio-economic and environmental consequences, and the LULC changes are likely to have more possible implications in terms of land degradation and hydrological responses at the watershed as well as the basin scale. Therefore, a detailed investigation of the implications of LULC changes on land degradation and hydrological responses supported with observational data is required.

CHAPTER 3

3. Hydrological responses to land use/land cover change and climate variability in contrasting agro-ecological environments of the Upper Blue Nile basin, Ethiopia

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3.1. Introduction

Land use/land cover (LULC) change is a major challenge facing the global environment (Kates and Torrie, 1998). In particular, the rapid increase in population pressure in developing countries has pronounced effects on the LULC dynamics mainly through deforestation aimed at increasing agricultural production (Maitima et al., 2009). Ethiopia is one of the developing countries where agriculture is the backbone of the economy, and where agriculture is facing a major environmental challenge from LULC change (Dessie and Kleman, 2007; Minta et al., 2018; Tekle and Hedlund, 2000). Previous studies in different parts of the country, particularly in the Upper Blue Nile (UBN) basin, have shown remarkable LULC dynamics induced by human activities such as deforestation or reforestation (e.g. Bewket, 2002; Gashaw et al., 2017; Gebrehiwot et al., 2014; Tekle and Hedlund, 2000; Zeleke and Hurni, 2001). On the one hand, the basin has largely been experiencing an expansion of agricultural land at the expense of natural vegetation cover (mainly forest) as people search for new land for cultivation and grazing (e.g. Bewket, 2002; Gashaw et al., 2017; Zeleke and Hurni, 2001). On the other hand, some studies show that the rate of deforestation has recently been reduced and the vegetation cover has improved in some parts of the country because of plantation activities on degraded hillsides (e.g., Wondie and Mekuria, 2018).

LULC change is among the most important factors contributing to alterations of the land surface across all spatial and temporal scales (Bosch and Hewlett, 1982; Conway, 2000; Legesse et al., 2003). LULC changes also have a great impact on hydrological processes such as surface runoff, groundwater recharge, infiltration, interception, and evapotranspiration (ET) (Costa et al., 2003; Fang et al., 2013; Gashaw et al., 2018; Guo et al., 2008; Legesse et al., 2003; Woldesenbet et al., 2017; Worku et al., 2017; Zhang et al., 2001). Several previous studies have shown the effects of LULC change on runoff, ET, or both (key components in the water balance equation), at various spatial and temporal scales (Bosch and Hewlett, 1982; Dong et al., 2015; Fang et al., 2013; Gashaw et al., 2018; Li et al., 2017; Worku et al., 2017; Yang et al., 2012; Yin et al., 2017; Zhang et al., 2001; Zhang et al., 2014). Most of these studies agree that the expansion of agricultural land at the expense of vegetation cover markedly increases the runoff potential in a given watershed (Bosch and Hewlett, 1982; Dong et al., 2015; Fang et al., 2013; Gashaw et al., 2018; Teklay et al., 2018; Worku et al., 2017). In contrast to the effect on runoff, the conversion of forest cover to other LULC types notably reduces ET (Fang et al., 2013; Li et al., 2017; Yang et al., 2012; Zhang et al., 2001). In addition to LULC, climate change or variability is one of the most significant factors influencing the changes in runoff and ET (Chen et al., 2006; Dong et al., 2015; Fenta et al., 2017a; Ficklin et al., 2010; Guo et al., 2008; Li et al., 2017; Ma et al., 2009; Mekonnen et al., 2018;Woldesenbet et al., 2018; Yang et al., 2017; Yin et al., 2017; Zhang et al., 2014). However, the degree to which LULC or climate changes influence variations in runoff and ET varies depending on the characteristics of a watershed or basin and agro-ecological settings of the study sites (e.g, Dong et al., 2015; Guo et al., 2008; Li et al., 2017; Ma et al., 2009; Mekonnen et al., 2018; Yang et al., 2017).

The UBN basin is increasingly under human pressure because of a rapidly growing population. This aggravates various human-induced resource degradations, mainly because of increased demand for agricultural land and unplanned LULC changes. Previous studies in different parts of the basin (e.g. Mekonnen et al., 2018; Gashaw et al., 2018; Woldesenbet et al., 2018, 2017; Worku et al., 2017) assessed the effect of LULC change and climate variability on hydrological responses. These studies used process-based hydrological models that constitute a single agro-ecological environment and uniform human activities. As such, further research is needed in the basin to better understand the responses of hydrological processes under LULC and climate change at small watershed scales under different agro-ecologies (Dile et al., 2018).

Process-based hydrological models are not necessarily more useful than those whose parameters can be easily determined from available data (Haregeweyn et al., 2016; Savenije, 2009). It is difficult to undertake detailed process-based hydrological models to analyze hydrological processes in the UBN basin because observed climate and hydrological data in the basin (Awulachew et al., 2008; Conway, 2000, 1997; Tekleab et al., 2014), and in the study watersheds, are limited. Moreover, because as mentioned above surface runoff and ET are key components in the water balance equation and are closely linked with changes in LULC and climate (Bosch and Hewlett, 1982; Costa et al., 2003; Woldesenbet et al., 2018; Yang et al., 2012; Yin et al., 2017; Zhang et al., 2001), it is vital to estimate and evaluate each key component individually under LULC and climate variability to assess the water availability in a given watershed. There have been a number of attempts to estimate these two key components only using existing climate data or the water balance equation. However, estimating ET is a complex process at watershed scale because it is affected by many factors, including rainfall interception, net radiation, turbulent transport, plant available water, and vegetation characteristics (Zhang et al., 2001). These factors can be combined, however, to evaluate the response of ET under vegetation changes by considering their net effects, assuming that ET from land surfaces is controlled by water availability and atmospheric demand (Zhang et al., 2001; Sun et al., 2005). Thus, individually assessing the responses of surface runoff and ET at watershed scale to change in LULC and climate variability using experimentally validated empirical models, is vital for integrated watershed management. Therefore, the main objective of this study was to improve our current understanding of key hydrological responses to historical changes in LULC and climate variability observed over the last 35 years in three different agro-ecological environments in the UBN basin. The specific objectives were (1) to assess LULC change and climate variability of watersheds in different agro-ecological environments, and (2) to analyze the single and combined effects of LULC change and climate variability on surface runoff and ET in those watersheds.

3.2. Materials and methods

3.2.1. Data types and sources

LULC and topography data

Spatial and temporal LULC maps, changes and conversions of LULC for Kasiry (Guder), Kecha (Aba Gerima), and Sahi (Debatie) watersheds for 1982, 2005/06, and 2016/17 were summarized in chapter two (Figure 2-1 to 2-4 and Table 2-1 to 2-4) and considered in this analysis. In addation, the change between three selected periods were described in Figure 3-1. Moreover, we used a Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) with a spatial resolution of 30 m (http://earthexplorer.usgs.gov/) to delineate the boundaries of the watersheds and to describe the watersheds' topographic characteristics.

Temperature, rainfall, streamflow, and runoff data

Daily temperature (maximum and minimum) and rainfall data were obtained from meteorological stations of the National Meteorology Agency (NMA) of Ethiopia, located in Enjibara and Dangila for Kasiry, Bahir Dar for Kecha, and Bullen for Sahi watersheds. To validate the long-term rainfall data from these stations, the daily rainfall data were collected in the three study watersheds during 2015 and 2016 using manual rain gauges. For this validation purpose, the monthly rainfall data of 2015 and 2016 from the stations and study watersheds were aggregated from daily rainfall data. Based on the validation results, the regression equations were developed to estimate long-term rainfall data of the study watersheds. Three "Mini Diver" data loggers (Schlumberger Water Services, The Netherlands) were also installed at the outlets of the three watersheds to monitor streamflow during 2015 and 2016. The base flow was separated by using the WHAT Web-based Hydrograph Analysis Tool (https://engineering.purdue.edu/mapserve/ WHAT/) to obtain surface runoff in the corresponding periods.

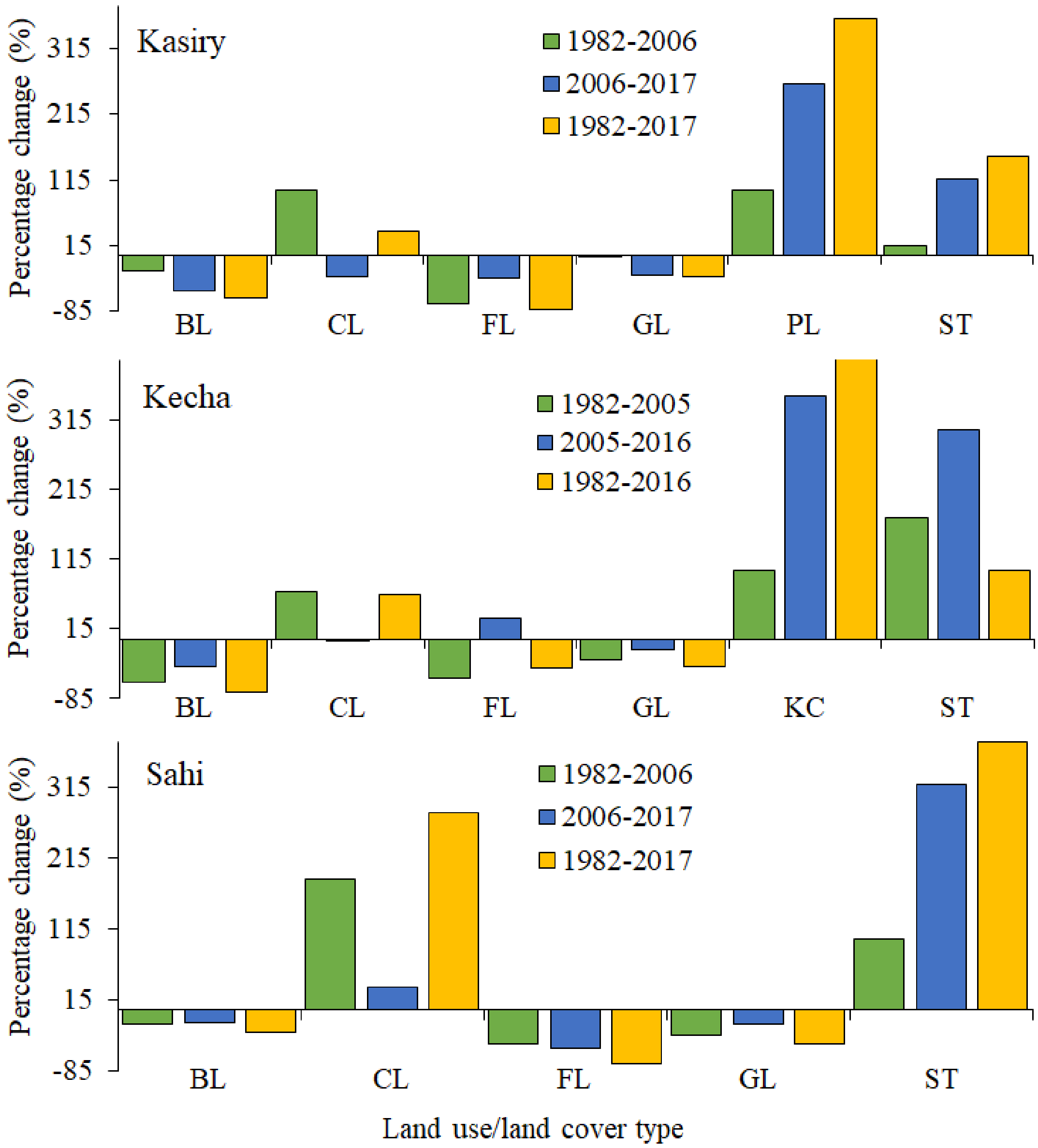

Figure 3-1 Area percentage change of different LULC types in the year 1982, 2005/06, and 2016/2017: Kasiry, Kecha, and Sahi watersheds.

Daily runoff during 2015 and 2016 was also measured from runoff plots with areas of 180 m^2 (30 m long × 6 m wide). We used a total of 15 plots established during 2014/15 (Sultan et al., 2018); seven in Kasiry (Guder), four in Kecha (Aba Gerima), and four in Sahi (Debatie) watersheds selected by considering different slope gradients and land-use types (Figure 1-6): cultivated land in two slope ranges (5% and 15%), grazing land (15% slope), and bushland

(35% slope). In the Kasiry watershed, we used three additional plots: two in *A. decurrens* plantations (on 5% and 25% slopes), and one in a *Eucalyptus* plantation (25% slope). At the lower end of each plot, a trench capable of holding a volume of 9.7 m^3 was excavated; each trench was trapezoidal in cross section and lined with an impermeable geomembrane plastic to allow the collection of surface runoff. A detailed description of the design, dimensions, instrumentation, and measurements of each experimental runoff plot is given by Sultan et al. (2018). Runoff was measured daily during the main rainy season (June to October) in each year; more than 86% of the rainfall in the study watersheds is concentrated in these months (Sultan et al., 2017). Rainfall events outside of the main rainy season are generally characterized by smaller depth and intensity than those occurring during the rainy season. In addition, soils are generally dry and have high infiltration capacity outside of the main rainy season, leading to lower runoff responses (Descheemaeker et al., 2006; Nyssen et al., 2009; Zenebe, 2012).

Surface runoff estimation

Methods and approaches to the estimation of watershed surface runoff range from simple empirical to more complex (conceptual and process-based) rainfall–runoff models. However, more complex models are not necessarily more useful than simpler models, whose parameters can easily be determined from available data (Haregeweyn et al., 2016; Savenije, 2009). As a whole in the UBN basin, it is difficult to apply complex hydrological models because of limited observed data for climatic and hydrological parameters (Awulachew et al., 2008; Conway, 2000, 1997; Dile et al., 2018; Haregeweyn et al., 2015a; Tekleab et al., 2014). Relatively less complex models such as unit hydrograph derived from a spatially distributed velocity field (Maidment et al., 1996) is one of the runoff estimation approaches, however, this model has not been parametrized with the LULC information which is a key input parameter in this study. Thus, we selected a simple proportional loss model known as the runoff coefficient (RC) method (Geiger et al., 1987) to estimate surface runoff in this study. This method is widely used at plot and watershed scales in Ethiopia (e.g. Conway, 2000; Descheemaeker et al., 2006; Haregeweyn et al., 2016, 2012; Nyssen et al., 2010; Taye et al., 2013; Zenebe, 2013). Plot-scale daily and seasonal RC (%) values were calculated by dividing the runoff yield (R, mm) by the corresponding rainfall depth (P, mm) using Equation 3-1.

$$\mathrm{RC}_i = R_p / P \times 100 \tag{3-1}$$

where RC_i is the runoff coefficient calculated for up to six of the land-use types i described in above. P is rainfall depth (mm), and R_p is surface runoff yield (mm), calculated by dividing the runoff volume measured at the collecting trench (after subtracting the direct rainfall falling on the open trench) by the runoff-plot area (6 m × 30 m). Daily runoff coefficients were estimated by observing a total of 257, 199 and 121 daily rainfall–runoff events in 2015 and 2016 in Kasiry, Kecha, and Sahi watersheds, respectively. Similarly, the seasonal RCs for 2015 and 2016 were calculated for each land-use type by dividing the seasonal runoff measured for each land-use type by the respective seasonal rainfall (Equation 3-1). Then the average seasonal RC for each land-use type was calculated from the respective RCs for 2015 and 2016.

The average seasonal RCs for each land-use type were associated with the corresponding watershed LULC types, identified from the LULC maps for 1982, 2005/06 and 2016/17. Because no runoff plots were established in forest or settlements, the RCs for these LULC types were adopted from the literature. Using the average seasonal RC (RC_{av}) and the area for each LULC type, a weighted RC for each watershed was estimated for a specific period using Equation 3-2.

$$\mathrm{RC}_{wt} = \left(\sum_i^n \mathrm{RC}_{av} \times A_{it}\right) / \sum A_{it} \times 100 \tag{3-2}$$

where RC_{wt} is the weighted watershed RC (%) for LULC study period t (1982, 2005/06 or 2016/17) and A_{it} is the area (ha) of LULC type i in period t (1982, 2005/06 or 2016/17). Because of a lack of long-term seasonal and annual surface runoff data, the daily surface runoff for 2015 and 2016 was estimated by multiplying the weighted RC for 2016/17 by the daily rainfall observed in the same year, and then summed these estimates to generate monthly time-steps for the purpose of validation as outlined in Section 3.2.2.

Lastly, we estimated long-term (1982–2016) annual surface runoff for each watershed using the weighted watershed RC (RC_{wt}) and long-term annual rainfall (1982–2016) in Equation 3-3:

$$R_t = \mathrm{RC}_{wt} \times P_t \quad (3\text{-}3)$$

where R_t is the estimated annual surface runoff (mm) and P_t is the long-term annual rainfall (mm) in year t from 1982 to 2016.

3.2.2. Validation of surface runoff model

Long-term observed surface runoff data were not available in the three watersheds (sites) for validation purposes; therefore, we validated the estimated watershed-level daily and monthly surface runoff by using the observed surface runoff measured at the watershed outlets under present-day conditions (2015 and 2016). The performance of the validated empirical model was statistically evaluated by using the coefficient of determination, R^2, of linear regression curves (Moriasi et al., 2007), Nash-Sutcliffe Efficiency (NSE; Saleh et al., 2000), and percent bias (PBIAS; Van Liew et al., 2007). NSE indicates how well the plot of observed versus estimated data fits the 1:1 line; the performance is perfect if NSE = 1. PBIAS measures the average tendency of the estimated data to be larger or smaller than their observed counterparts; the optimal value of PBIAS is 0.0, with low-magnitude values indicating more accurate model estimation. R^2 ranges from 0.0 to 1.0, with higher values indicating better agreement. We estimated these statistical indices by using the following equations:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - O_{avg})(P_i - P_{avg})}{\sum_{i=1}^{n}(O_i - O_{avg})^2 \sum_{i=1}^{n}(P_i - P_{avg})^2}\right]^2 \quad (3\text{-}4)$$

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2}\right] \quad (3\text{-}5)$$

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n}(O_i - P_i)\times 100}{\sum_{i=1}^{n} O_i}\right] \tag{3-6}$$

where O_i is the ith observed value, O_{avg} is the average observed value for the entire study period, P_i is the ith predicted (modeled) value, and P_{avg} is the average of the predicted value over the entire study period.

3.2.3. Trend detection in rainfall and temperature time-series

The analysis of historical trends of climate variables such as temperature and rainfall can help to reveal the effect of climate change or variability on water resources (Chen et al., 2006; Fenta et al., 2017a; Guo et al., 2008; Ma et al., 2009; Woldesenbet et al., 2018; Yin et al., 2017). We analyzed trends in annual rainfall and temperature time-series data using the Mann–Kendall (MK) (Burn, 1994; Westmacott and Burn, 1997) and Pettitt's (Pettitt, 1979) tests. The MK trend and Pettitt's homogeneity tests have been widely applied to detect monotonic and homogeneous trends, respectively, to determine change points in long-term hydro-climatic time-series data (e.g. Chen et al., 2006; Fenta et al., 2017a; Ma et al., 2009; Zhang et al., 2014). These tests were selected because of their robustness with respect to missing and tied values and to non-normality, which are common in hydro-climatic time series; moreover, they have the same power as their parametric counterparts (Kahya and Kalayci, 2004). The MK standard normal Z_c are given as follows:

$$Z_c = \begin{bmatrix} \frac{S-1}{\sqrt{var(S)}}, S > 0 \\ 0, \quad S = 0 \\ \frac{S+1}{\sqrt{var(S)}}, S < 0 \end{bmatrix} \tag{3-7}$$

$$S = \sum_{i=1}^{n-1}\sum_{k=i+1}^{n} sgn(x_k - x_i) \tag{3-8}$$

where var(S) is normal distribution variance, S is the test statistic, x_k and x_i are sequential data values, n is the length of the data series, and $\text{sgn}(x)$ is equal to 1, 0, or –1 when x is greater than, equal to, or less than zero, respectively. The null hypothesis H_0^a (there is no trend) is accepted if $-\text{Z}1 - \alpha/2 \leq \text{Zc} \leq \text{Z}1 - \alpha/2$ at the significance level $\alpha = 0.05$.

According to Pettitt (1979), $x_1, x_2, \ldots\ldots, x_n$ is a series of observed data that has a change point t if $x_1, x_2, \ldots\ldots, x_t$ has a distribution function $F_1(x)$ that is different from the distribution function $F_2(x)$ of the second part of the series, x_{t+1}, $x_{t+2}, \ldots\ldots$, x_T. The non-parametric test statistic $U_{t,T}$ for this test is calculated as follows:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=i+1}^{T} sgn(x_i - x_j) \quad (3\text{-}9)$$

where sgn $(x) = 1$ if $x > 0$, 0 if $x = 0$, and –1 if $x < 0$. The statistic $U_{t,T}$ is considered for $1 \leq t < T$. The test statistic K for the sample series with length n is defined as

$$K_T = \max_{0 \leq t \leq T} \left| U_{t,T} \right| \quad (3\text{-}10)$$

The associated probability (P) used in the test is estimated using the equation of Gao et al. (2010) as follows:

$$P \cong exp\{-6(K_T)^2/(T^3 + T^2)\} \quad (3\text{-}11)$$

when P is smaller than the specific confidence level with significance level α (in this study $\alpha = 0.05$), then the null hypothesis H_0^b assuming the presence of homogeneity trend will be rejected.

3.2.4. Analyzing the effect of LULC change and climate variability on surface runoff

Human activities associated with LULC are the major drivers of changes in the surface runoff response (Bosch and Hewlett, 1982; Costa et al., 2003; Fenta et al., 2017a). We used Eq. 6 to estimate the annual surface runoff for the three watersheds during 1982–2016 according to the LULC classification maps for 1982, 2005/06, and 2016/17, the weighted watershed RCs, and long-term rainfall data (1982–2016). We compared the estimated surface runoff under each LULC scenario by considering the LULC changes within and across the watersheds. To quantify the influence of LULC changes, we evaluated variations in annual surface runoff under the LULC scenarios for 1982, 2005/06 and 2016/17, using the same climate data as the annual rainfall record from 1982 to 2016 in all watersheds. The coefficient of variation (CV) of estimated surface runoff in each watershed was calculated to compare the variation of surface runoff pattern as a result of LULC scenarios. We also estimated the contribution of each LULC type to mean annual surface runoff change from the area contribution and runoff coefficient of each LULC type in the watersheds. In addition, we assessed the effect of climate variability as rainfall change on surface runoff using the methods described in Section 3.2.6.

3.2.5. Analyzing the effect of LULC change and climate variability on actual ET

The amount of actual ET in a given watershed strongly depends on climate variables vegetation covers (Sun et al., 2006, 2005; Yang et al., 2012; Zhang et al., 2001; Zhang et al., 2014) and climate forcing factors such as CO2, aerosols, greenhouse gases, ozone (Ainsworth and Long, 2004; Ficklin et al., 2010; Liu et al.,2016). However, the cumulative or net effects of climate forcing factors can be indirectly reflected in climatic variables such as temperature and precipitation (IPCC, 2013) that are already considered in this study. In particular, long-term change in LULC and related management strategies, along with climate variability are expected to have an effect on watershed ET and hence water yield and groundwater recharge. Therefore, quantifying long-term effects of LULC change on annual ET is extremely important. We used an empirical model which is developed by Zhang et al. (2001) based on data from 250 watersheds worldwide (Equation 3-12) to quantify watershed annual actual ET under long-term LULC change situations.

$$\mathrm{ET}_i = \left(\frac{1+w\frac{\mathrm{PET}}{P}}{1+w\frac{\mathrm{PET}}{P}+\frac{P}{\mathrm{PET}}}\right) \times P \tag{3-12}$$

where ET_i is annual actual evapotranspiration during period i (1982, 2005/06 or 2016/17) for one LULC type with a specific value of w, w is the plant available water coefficient representing the relative difference in the way plants use water for transpiration, P is rainfall depth (mm), and PET is potential evapotranspiration, obtained by using an equation developed by Hargreaves and Samani (1985). For a watershed with mixed LULC types (there are four types based on w values), ET is calculated as follows:

$$\mathrm{ET} = \sum(\mathrm{ET}_i \times R_i) \tag{3-13}$$

where R_i is the proportion of each LULC type. The w parameter was set to 0.5 for grazing and cultivated land, 2.0 for forests and plantations (Zhang et al., 2001), 1.0 for bushland, and 0.0 for settlements (Sun et al., 2005). Khat *(Catha edulis)* (Table S2) cultivation in Kecha watershed was included under the bushland LULC type. The contribution of each LULC type to annual ET was also evaluated based on the relative area extent of each on the 1982, 2005/06 and 2016/17 LULC maps and the plant available water coefficients.

3.2.6. Framework for differentiating effects of LULC change and climate variability

The changes in hydrological responses in a given watershed result from LULC and climate changes, which are assumed to be independent factors (Chen et al., 2006; Guo et al., 2008; Legesse et al., 2003; Ma et al., 2009; Woldesenbet et al., 2018; Yang et al., 2017; Yin et al., 2017; Zhang et al., 2014). Differentiating the effects of LULC change and climate variability involved three steps. First, we divided the study period into two periods that were determined by fixing trend change points in the climate time-series data for 1982–2016. The significance of the change points was tested by using Pettitt's test as described in Section 2.6.1. Next, we developed four scenarios for each watershed based on the two identified climate periods, designated period 1 and period 2 and referring to before and after the change point, respectively, as described in Section 3.4.1. We used the LULC maps for 1982 and 2005/06 to represent LULC conditions during the two periods. The four scenarios are Scenario 1 (SC1), 1982 LULC map and climate data for period 1; Scenario 2 (SC2), 2005/06 LULC map and climate data for period 1; Scenario 3 (SC3), 1982 LULC map and climate data for period 2; and Scenario 4 (SC4), 2005/06 LULC map and climate data for period 2. Finally, after comparing the outputs from these scenarios, we determined the separate effects of LULC change and climate variability on hydrologic responses using Equations 14–16.

$$\Delta H_L = \frac{1}{2} \times (\Delta H_{L1} + \Delta H_{L2}) \tag{3-14}$$

where ΔH_L is the change in hydrological responses due to the separate effect of LULC change and ΔH_{L1} and ΔH_{L2} are the changes in hydrological responses calculated as the difference between the outputs of SC2 and SC1 in period 1, and SC4 and SC3 in period 2, respectively. We applied a similar approach to quantify the separate effect of climate variability on hydrological responses using the following equation:

$$\Delta H_C = \frac{1}{2} \times (\Delta H_{C1} + \Delta H_{C2}) \quad (3\text{-}15)$$

where ΔH_C is the change in hydrological responses due to the separate effect of climate variability and ΔH_{C1} and ΔH_{C2} are the changes in hydrological responses calculated as the difference between outputs of SC3 and SC1 under LULC of 1982 and SC4 and SC2 under LULC of 2005/06, respectively. Finally, the total changes in hydrological responses (ΔH_{LC}) were calculated as the sum of the two effects (Equation 16), or, alternatively, estimated from the difference between SC4 and SC1:

$$\Delta H_{LC} = \Delta H_L + \Delta H_C \quad (3\text{-}16)$$

Previous studies have applied similar approaches using hydrological model simulations to evaluate the separate effects of LULC change and climate variability on hydrological responses (e.g. Fang et al., 2013; Mekonnen et al., 2018; Guo et al., 2008; Ma et al., 2009; Woldesenbet et al., 2018; Yang et al., 2017; Yin et al., 2017). Note that in our study, we replaced the general representation of hydrological responses (ΔH) with the specific hydrological component under consideration; for example, we use ΔET for the change in actual ET and ΔR for the change in surface runoff.

3.3. Results and discussion

3.3.1. Surface runoff and runoff coefficient variability at plot scale

Surface runoff

In the 16 runoff plots in the three agro-ecological watersheds, the seasonal cumulative runoff depth in the rainy seasons of 2015 and 2016 ranged from 252 to 635 mm in Kasiry, from 219 to 454 mm in Kecha, and from 133 to 274 mm in Sahi (Table 3-1). The highest runoff was 635 mm in the grazing land (GL) plot on a steep slope (15%) in Kasiry, and the lowest was 133 mm in the bushland (BL) plot on a steeper slope (35%) in Sahi, both in the 2015 rainy season. The cumulative runoff across the watersheds generally decreased from highland to lowland watersheds: Kasiry (highland) > Kecha (midland) > Sahi (lowland). This trend is similar to the trend in cumulative rainfall amounts among the watersheds (Table 3-1). The ranges of the runoff values during both rainy seasons are comparable to the plot-scale range in other studies in the UBN basin (seasonal runoff 180–302 mm; Alemayehu et al., 2013; Amare et al., 2014; Descheemaeker et al., 2006; Ebabu et al., 2018; Sultan et al., 2018). In the same basin, Haregeweyn et al. (2016) found that runoff variability at basin-scale ranged from 105 mm for silvipastoral land to 1601 mm for water bodies and was strongly controlled by the LULC type.

The differences in runoff among watersheds were due partly to variations in rainfall. A previous study conducted in our study watersheds (Sultan et al., 2018) showed that rainfall is linearly related to, and profoundly affects, the amount of runoff. Elsewhere, studies also have shown that rainfall had a greater impact on surface runoff compared to change in other climate variables such as CO2 and temperature (Ficklin et al.,2010).The highest seasonal runoff for grazing land in Kasiry watershed is explained by the frequent use of grazing land in this watershed by livestock that trampled the soil causing soil penetration resistance to be highest (ranging from 1990 to 2210 kPa) among the land-use types (Sultan et al., 2018). In addition, surface runoff was higher on steep slopes than on flat slopes; for example, the runoff for cultivated land (15% slope) is higher than for cultivated land (5% slope) in all watersheds. This likely related to a reduction in initial abstraction, a decrease in infiltration, or a reduction of the recession time of overland flow on steeper slopes.

Table 3-1 Measured seasonal cumulative surface runoff depth (R_{cum}, mm), seasonal cumulative rainfall depth ($P_{C,}$ mm), seasonal runoff coefficient (RC, %), and seasonal average runoff coefficient ($RC_{av,}$ %) for different land use types in three watersheds during the 2015 and 2016 rainy seasons.

Watershed	Land use	Rainy season 2015 (Jun– Oct)			Rainy season 2016 (Jun– Oct)			
		P_C	R_{cum}	RC	P_C	R_{cum}	RC	RC_{av} (%)
	(slope%)	mm	mm	%	mm	mm	%	± SD
Kasiry	CL (5%)	1567.6	339.3	21.6	1502.1	344.5	22.9	22.3 ± 0.9
	CL (15%)		444.0	28.3		501.6	33.4	30.9 ± 3.6
	GL (15%)		635.3	40.5		537.2	35.8	38.2 ± 3.3
	BL (35%)		370.6	23.6		369.5	24.6	24.1 ± 0.7
	AC (5%)		469.0	29.9		353.5	23.5	26.7 ± 4.5
	AC (25%)		512.7	32.7		391.1	26.0	29.4 ± 4.7
	EP (25%)		339.4	21.7		251.8	16.8	19.2 ± 3.5
Kecha	CL (5%)	1360.7	218.8	16.1	1397.7	307.7	22.0	19.1 ± 4.2
	CL (15%)		393.8	28.9		340.1	24.3	26.6 ± 3.3
	GL (15%)		453.7	33.4		414.2	29.6	31.5 ± 2.7
	BL (35%)		281.1	20.7		339.9	24.3	22.5 ± 2.5
Sahi	CL (5%)	881.2	186.5	21.2	1272.4	251.2	19.7	20.5 ± 1.1
	CL (15%)		229.2	26.0		221.3	17.4	21.7 ± 6.1
	GL (15%)		136.2	15.4		273.5	21.5	18.5 ± 4.3
	BL (35%)		133.2	15.1		206.8	16.3	15.7 ± 0.8

$P_{C:}$ seasonal cumulative rainfall; R_{cum}: seasonal cumulative runoff; SD: standard deviation from the seasonal mean. Approximately 257, 199, and 121 daily runoff events were evaluated for Kasiry, Kecha, and Sahi watersheds, respectively.

Runoff coefficient

The seasonal annual RC varied across and within the watersheds in 2015 and 2016 (Table 3-2). The average RC ranged from 19% to 38% in Kasiry, from 19% to 32% in Kecha, and from 15.7% to 21.7% in Sahi. Also, grazing land exhibited higher RCs in Kasiry (38.2%) and Kecha (31.5%) watersheds, whereas cultivated land had a higher value (21.7%) in the Sahi watershed.

Similarly, there were higher RCs in cultivated land on steeper slopes (15%) compared to cultivated land located on gentle slopes in all watersheds. The literature RC values for the UBN basin and elsewhere in Ethiopia typically lie in the same range, varying from 10% to 40% (e.g Descheemaeker et al., 2006; Sultan et al., 2018, 2017; Zenebe, 2012). On the other hand, our findings on RC and slope relationships contradict with a study conducted in northern Ethiopia by Taye et al. (2013), who explained the relationship between RC and slope by conducting soil particle analysis: RC increased with decreasing slope because of an increase in the coarse-particle content of the soil, because a coarse texture promotes infiltration.

Table 3-2 Seasonal and area-weighted average annual runoff coefficients (RCs, %) for the current and past LULC types found in the three study watersheds.

LULC type	Seasonal average RC (%) adopted from plot results				Data source/method
	Period	Kasiry	Kecha	Sahi	
Bushland	2015 and 2016	24.1	22.5	15.7	Plot
Cultivated land		26.6	22.8	21.1	Plot
Forest		10.0	10.0	10.0	Geiger et al. (1987)
Grazing land		38.1	31.5	18.5	Plot
Plantation		28.0[a]	22.7[b]		Plot
Settlements		60.0	60.0	60.0	CDT[c] (2006)
Area-weighted RC (%) at watershed level					
Weighted runoff coefficient (RC_{wt})	1982	21.9	20.9	15.6	Equation 5
	2005/06	26.8	22.3	17.6	
	2016/17	27.7	22.5	19.2	

[a]Runoff coefficient for Acacia decurrens and eucalyptus plantations. [b]Runoff coefficient for khat cultivation estimated by taking the average of bushland and cultivated land runoff coefficients. [c]California Department of Transportation.

The seasonal average RC from the plot experiments and weighted RC of each watershed were determined for three 1-year periods (1982, 2005/06, 2016/17; Table 3-2). The weighted RC increased from 1982 to 2016/17 in Kasiry and Sahi watersheds, whereas in Kecha the values in 2005 and 2016 were comparable. This difference might be due to less conversion of LULC types between the respective study periods. On the other hand, the weighted RC in the watersheds decreased in the order Kasiry (from 21.9% to 27.7%) > Kecha (from 20.9 to 22.5%) > Sahi (from 15.6 to 19.2%), following the runoff volume and rainfall pattern shown in Table 3-2.

3.3.2. Validation of rainfall and surface runoff

The monthly rainfall data validation results showed that data from nearby stations have a good agreement with the study watersheds (Figure 3-2). The value of coefficient of determination (R^2) varies from 0.78 in Sahi to 0.91 in Kasiry watershed. Across the watersheds, the relationship is better in Kasiry (Kasiry with Enjibara), followed by Kecha (Kecha and Bahir Dar) and Sahi (Sahi with Bullen) watershed (Figure 3-2). Thus, the regression equations mentioned in the figure (Figure 3-2) were adopted to the study watersheds to estimate long-term rainfall data from nearby stations.

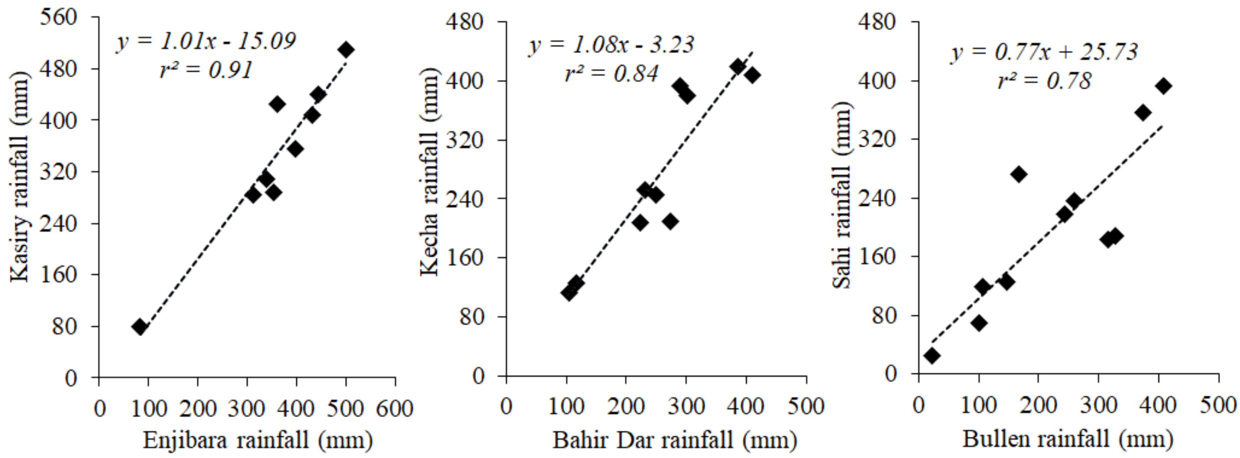

Figure 3-2 Monthly rainfall relationship of nearby stations (Enjibara, Bahir Dar and Bullen) and study watersheds (Kasiry (Guder), Kecha (Aba Gerima) and Sahi (Debatie)) based on seasonal rainfall data of 2015 and 2016 (Jun-November)

The computed and observed runoff were compared at daily and monthly time-steps (Figure 3-3). Pairs of observed and computed values are close to a line of perfect agreement. The performance indicators NSE and R^2 varied over the same range of values: from 0.7 to 0.8 for the daily comparison and from 0.7 to 0.9 for the monthly (Table 3-3). These results indicate that the model performance ranged from "good" to "very good" in terms of the general rating systems of Moriasi et al. (2007) and Saleh et al. (2000). Similarly, PBIAS values ranged from 11% to 14% at daily time-steps and from 3% to 9% at monthly time-steps. These values fall under "good" and "very good" performance ratings for daily and monthly time-steps, respectively (Van Liew et al., 2007).

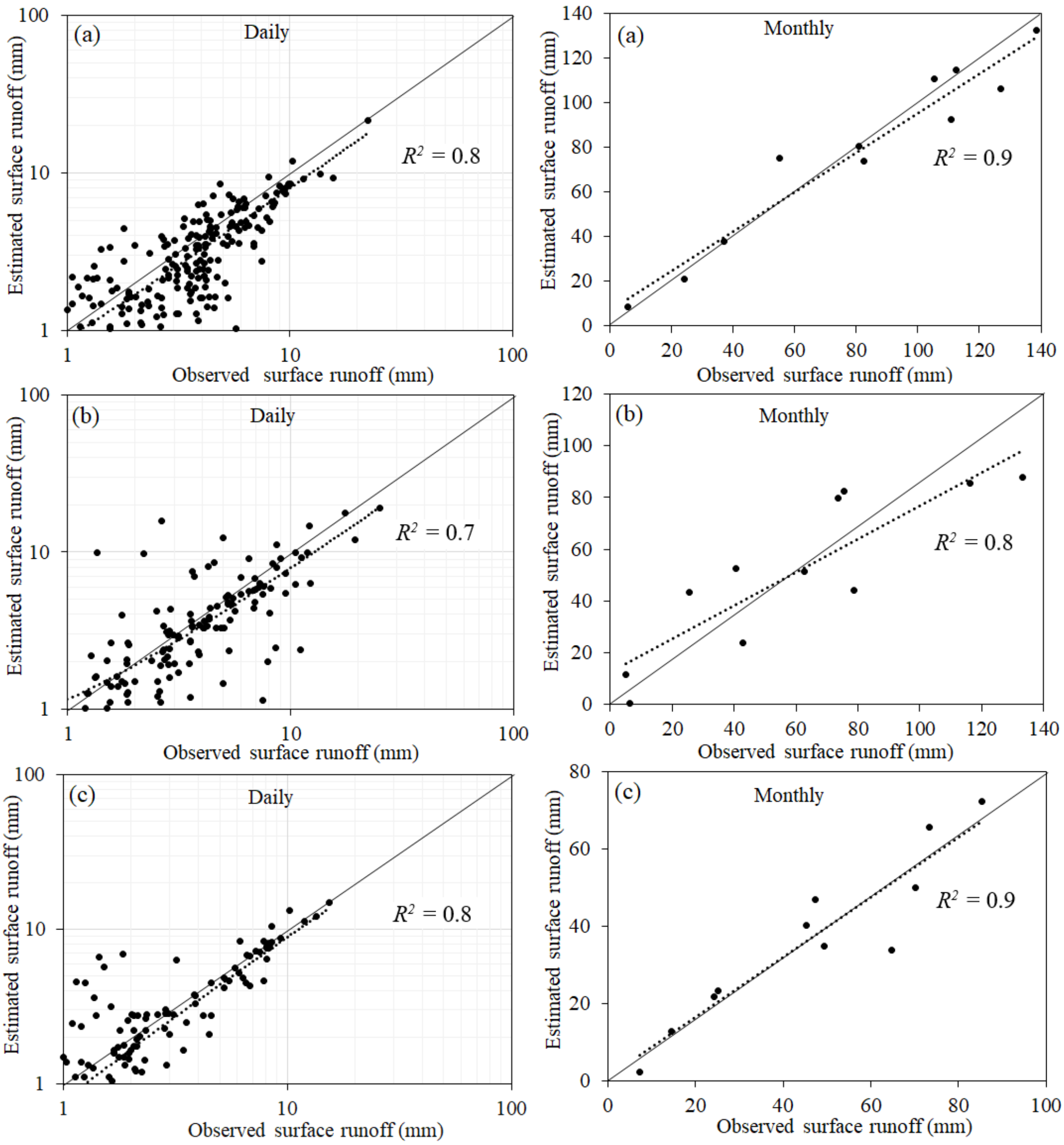

Figure 3-3 Estimated vs. observed daily (left) and monthly (right) surface runoff in Kasiry (a), Kecha (b), and Sahi (c) watersheds. Solid line is the line of perfect fit. Dotted lines indicate a linear relationship between observed and estimated surface runoff.

Generally, across the watersheds, the model performed better in Kasiry watershed, followed by Sahi and then Kecha watershed, especially at monthly time-steps. These results suggest that the model is more efficient at coarser time-steps, with the implication that the model can simulate surface runoff at least at a “good” level for rainfall events in the three watersheds at annual time-steps.

Table 3-3 Summary of statistical criteria for examining the model accuracy in three watersheds.

Criteria	Kasiry		Kecha		Sahi	
	Daily	Monthly	Daily	Monthly	Daily	Monthly
NSE	0.7	0.9	0.7	0.7	0.7	0.7
R^2	0.8	0.9	0.7	0.8	0.8	0.9
PBIAS	10.3	3.0	13.7	8.8	11.1	6.9

NSE: Nash-Sutcliff Efficiency; R^2: coefficient of determination; PBIAS: Percentage bias.

3.3.3. Trends in annual rainfall and temperature time-series

The MK time-series test for monotonic trends and Pettitt’s test for homogeneous trends were applied to annual rainfall and mean annual temperature data between 1982 and 2016 (Table 3-4, Figure 3-4). The results of the MK tests show no significant long-term monotonic trend in annual rainfall, with Z_c of 1.3, 0.9, and 0.4, for Kasiry, Kecha, and Sahi watersheds, respectively (Table 3-4, Figure 3-4). Similarly, Pettitt’s test showed strong homogeneity in annual rainfall in the three watersheds, indicating that annual rainfall did not change significantly over the study period (Table 3-4, Figure 3-4). Therefore, the null hypotheses H_0^a and H_0^b for the two tests for annual rainfall in the three watersheds were accepted.

Previous studies have also confirmed that there have been no significant changes in annual rainfall in either the UBN basin in particular (e.g. Conway, 2000; Mekonnen et al., 2018) or in Ethiopia in general (e.g. Fenta et al., 2017b).

Table 3-4 Monotonic trend (Mann-Kendall) test and significant change (Pettitt's homogeneity) test for two climate variables (annual rainfall and mean annual temperature time series) for 1982–2016 in three watersheds.

Climate variable	Watershed	Mann-Kendall test			Pettitt's test		
		Z_c	*P*	H_0[a]	*K*	*P*	H_0[b]
Rainfall	Kasiry	1.30	0.20	A	134.00	0.20	A
	Kecha	0.90	0.30	A	108.00	0.60	A
	Sahi	0.40	0.90	A	68.00	0.40	A
Temperature	Kasiry	3.92	<0.0001	R	272.00	<0.0001	R
	Kecha	2.07	0.04	R	172.00	0.03	R
	Sahi	4.55	<0.0001	R	258.00	<0.0001	R

H_0^a is the null hypothesis that there is no monotonic trend in the time series for annual rainfall or mean temperature; H_0^b is the null hypothesis that there is no significant change in the time series data for annual rainfall or mean temperature (the data are homogeneous). The null hypotheses are accepted (A) or rejected (R) at significance level $\alpha = 0.05$.

In contrast, there were significant long-term monotonic and non-homogeneous trends in mean annual temperature ($P < 0.05$) in all watersheds, and the Z_c values of 3.92 in Kasiry, 2.07 in Kecha and 4.55 in Sahi confirmed that there were significant changes in annual temperature over the study period (Table 3-4). The mean annual temperature increased by 0.04 °C per year in Kasiry watershed, 0.02 °C per year in Kecha, and 0.03 °C per year in Sahi from 1982 to 2016. Such increases in temperature could result in a change in ET, and a change in soil moisture and runoff. The increases in temperature observed in our study watersheds agree with the results of other studies in the UBN basin and elsewhere in Ethiopia that show an increase in mean annual temperature from 0.028 °C to 1.08 °C between 1980 and 2015 (e.g. Alemayehu and Bewket, 2017; Birara et al., 2018; Mekonnen et al., 2018).

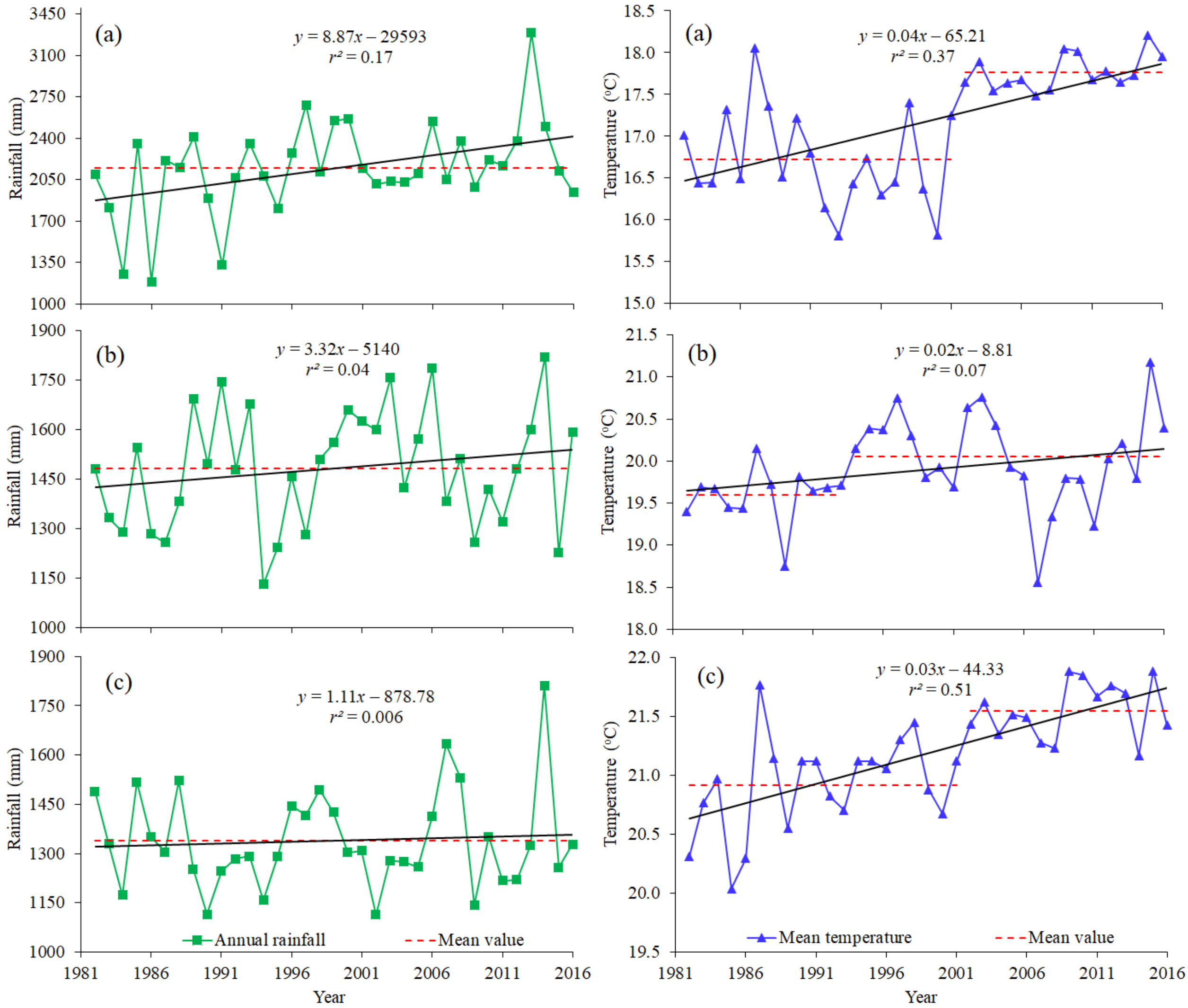

Figure 3-4 Trends and changes in annual rainfall (left) and mean annual temperature (right) in the Kasiry (a), Kecha (b), and Sahi (c) watersheds from 1982 to 2016. The dotted lines indicate the Pettitt test homogeneity trend result at a significance level $\alpha = 0.05$, and also showed mean value of annual rainfall (right), and temperature before and after change point (left).

Unlike for annual rainfall, the Pettitt's test applied to mean annual temperature showed a change point in 2001 for Kasiry and Sahi, and in 1993 for Kecha (Figure 3-4, right panels). On the basis of these change points, the long-term time-series climatic data were divided into two periods: period 1 (1982–2001 for Kasiry and Sahi, 1982–1993 for Kecha) and period 2 (2002–2016 for Kasiry and Sahi, 1994–2016 for Kecha). We did not try to separate the effects of

LULC change and climate (as rainfall variability) on the estimated surface runoff change because there was no significant trend in annual rainfall in any of the study watersheds. Hence, any change in annual surface runoff during the study period (1982–2016) attributed to the effects of LULC change. In contrast, the significant increases in temperature, and the changes in LULC before and after the change points, might have altered the actual ET. Therefore, we analyzed the change in the actual ET due to the isolated effects of LULC change (ΔH_L as ΔET_L) and climate variability (ΔH_C as ΔET_C) was analyzed by comparing periods 1 and 2. The climate data (annual rainfall and temperature) and related statistics for periods 1 and 2 in all watersheds are summarized in Table 3-5.

Table 3-5 Annual rainfall and annual mean temperature data for the study watersheds. Period 1 is 1982–2001 and period 2 is 2002–2016 for Kasiry and Sahi watersheds. Period 1 is 1982–1993 and period 2 is 1994–2016 for Kecha watershed.

Parameter	Rainfall (mm)					
	Kasiry		Kecha		Sahi	
Period	1	2	1	2	1	2
Length of record (years)	20	15	12	23	20	15
Mean	2061.5	2305.8	1474.6	1497.7	1321.3	1374.4
Maximum	2679.0	3288.4	1756.8	1819.7	1522.4	1811.1
Minimum	1186.4	1942.1	1131.1	1227.2	1113.2	1143.3
Standard deviation	391.7	365.0	176.7	189.0	121.9	194.7
Coefficient of variation	0.2	0.2	0.1	0.1	0.1	0.1
	Temperature (°C)					
Period	1	2	1	2	1	2
Length of record	20	15	12	23	20	15
Mean	16.7	17.8	19.6	20.1	20.9	21.6
Maximum	18.1	18.2	20.2	21.2	21.8	21.9
Minimum	15.8	17.5	18.8	18.6	20.0	21.2
Standard deviation	0.6	0.2	0.3	0.6	0.4	0.2
Coefficient of variation	0.0	0.0	0.0	0.0	0.0	0.0

3.3.4. Response of annual surface runoff to LULC change

Long-term (1982–2016) estimated annual surface runoff patterns varied across the three watersheds under different LULC scenarios (Figure 3-5). In Sahi, the annual estimated surface runoff pattern showed the clearest variation among LULC scenarios (CV = 0.18) followed by Kasiry (CV = 0.12). In these watersheds, the variation in annual surface runoff between LULC scenarios from 1982 and 2006 (CV of 0.15 in Sahi and 0.09 in Kasiry) is relatively higher than that between 2006 and 2017 (CV of 0.05 in Sahi and 0.03 in Kasiry) (Figure 3-5a, c). The CV of rainfall across the watersheds remains almost the same, ranging from 0.11 in Kasiry to 0.13 in Sahi. This result indicates that the variation in annual surface runoff derived mainly from the expansion of cultivated land, by 99.7% and 185% in Kasiry and Sahi, respectively (Figure 3-1). In Kecha, however, there is less variation between all LULC scenarios (CV from 0.003 to 0.024) (Figure 3-5), because of the lower conversion of LULC types between study periods compared to the other two watersheds.

The estimated mean annual surface runoff increased between the 1982 and the 2005/06 LULC scenarios from 475.8 to 588.2 mm (23.6% increase) in Kasiry, from 325.0 to 339.3 mm (4.4%) in Kecha, and from 207.8 to 237.6 mm (14.3%) in Sahi (Table 3-6). Similarly, between the 2005/06 and 2016/17 LULC scenarios, the mean annual surface runoff increased to 612.4 mm (4.1% higher) in Kasiry and to 255.7 mm (7.6%) in Sahi. In Kecha, however, mean annual surface runoff during this period decreased slightly to 337.9 mm (0.4%; Table 3-6). The increases in mean annual surface runoff likely result from a lower rate of water loss through ET, and to continuous deterioration of soil structural qualities by tillage with the expansion of cultivated land at the expense of natural vegetation between 1982 and 2016/17.

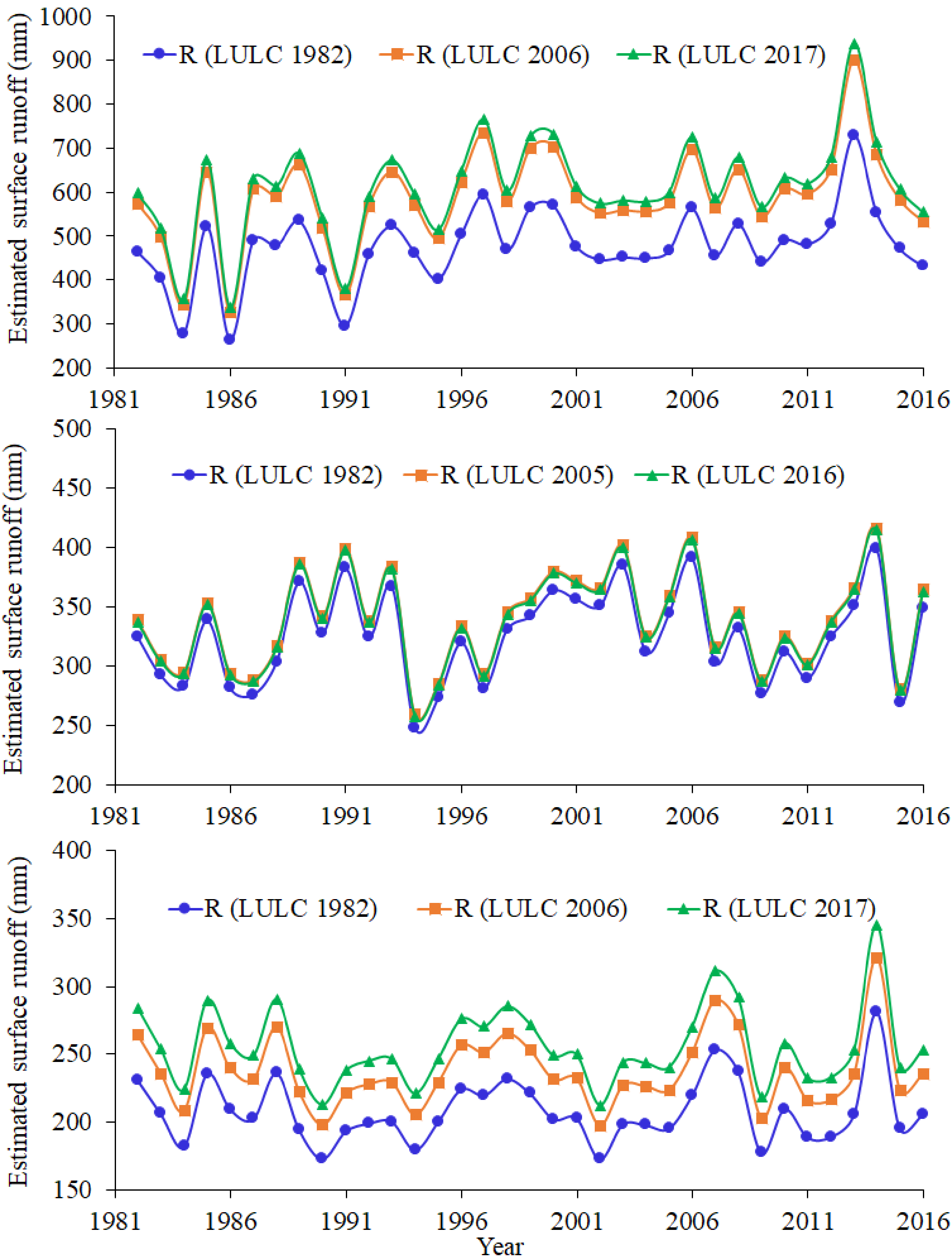

Figure 3-5 Long-term patterns in estimated annual surface runoff under different LULC scenarios (1982, 2005/06, and 2016/17) in Kasiry (a), Kecha (b), and Sahi (c) watersheds for the period from 1982 to 2016.

Table 3-6 Mean annual surface runoff changes in three watersheds estimated under different LULC scenarios (1982, 2005/06 and 2016/17) with the same annual rainfall data from 1982 to 2016.

Watersheds	LULC scenario	Runoff (mm)	Mean annual rainfall (mm)	Change in annual runoff (ΔR)					
				1982–20005/06		20005/06–2016/17		1982–2016/17	
				mm	%	mm	%	mm	%
Kasiry	1982	475.8	2145.3	112.4	+23.6	24.2	+4.1	136.6	+28.7
	2006	588.2							
	2017	612.4							
Kecha	1982	325.0	1482.5	14.3	+4.4	–1.4	–0.4	12.9	+4.0
	2005	339.3							
	2016	337.9							
Sahi	1982	207.8	1339.5	29.8	+14.3	18.1	+7.6	47.9	+23.1
	2006	237.6							
	2017	255.7							

Comparatively speaking, the change in mean annual surface runoff between 1982 and 2005/06 (from 4.4% to 23.6%) is higher than that between 2005/06 and 2016/17 (from –0.4% to 7.6%) across the watersheds (Table 3-6). This resulted from the dramatic expansion of cultivated land between 1982 and 2005/06 compared to the period between 2005/06 and 2016/17 in all watersheds (Figures 2-4, 3-1).

The change in each LULC type over the study period makes a separate contribution to the mean annual surface runoff in the watersheds. From 1982 to 2006, the contribution of cultivated land to the mean annual surface runoff increased from 28% to 45% in Kasiry (Figure 3-6a), resulting from the expansion of cultivated land by 99.7% at the expense of other LULC types. However, the decrease in forest by 73.7%, bushland by 24.8%, and grazing land by 24.8% reduced their collective contribution to annual surface runoff from 68% to 41% and then to 25% in 1982, 2006, and 2017, respectively (Figures 3-1, 3-6a). In contrast, the expansion of plantation by 261.6%, mainly at the expense of cultivated land (Figure 3-1), resulted in an increase in surface runoff from 11% to 39% between 2006 and 2016 in Kasiry. In Kecha, cultivated land was the highest contributor to changes in mean annual surface runoff from 1982 (43%) to 2016 (69%) (Figure 3-6b). Similarly, during this period the contribution from bushland, forest, and grazing land decreased from 23% to 5%, from 9% to 5%, and from 25% to 15%, respectively, as a result of a continuous reduction in their respective areas. In Sahi, grazing land was the highest contributor to mean annual surface runoff in 1982, followed by bushland, with a combined contribution of more than half (57%) of the mean annual surface runoff (Figure 3-6c). The contribution of grazing land and bushland decreased from 19% to 14% and from 16% to 13% between 2006 and 2017, respectively, because of conversion to cultivated land. The share of cultivated land in 2006 (46% of area) and 2017 (61.3%) (Figure 3-1) also contributed 55% and 68%, respectively, to mean annual surface runoff (Figure 3-6c). The overall contribution of forest to mean annual surface runoff decreased by a factor of five from 1982 to 2017 (from 21% to 4%).

In general, across the three watersheds the contribution of cultivated land to annual surface runoff increased from 1982 to 2016/17 because of the increase in agricultural demand. In Kasiry in 2017 a large portion of the contribution of cultivated land was taken over by plantation (39%) (Figure 3-6a). Even though the expansion rate of settlement area (18% per year on average) was higher than those of other LULC types, the contribution of settlements to surface runoff was relatively minor in the three watersheds, ranging from only 1% to 7% (Figures 3-1, 3-6).

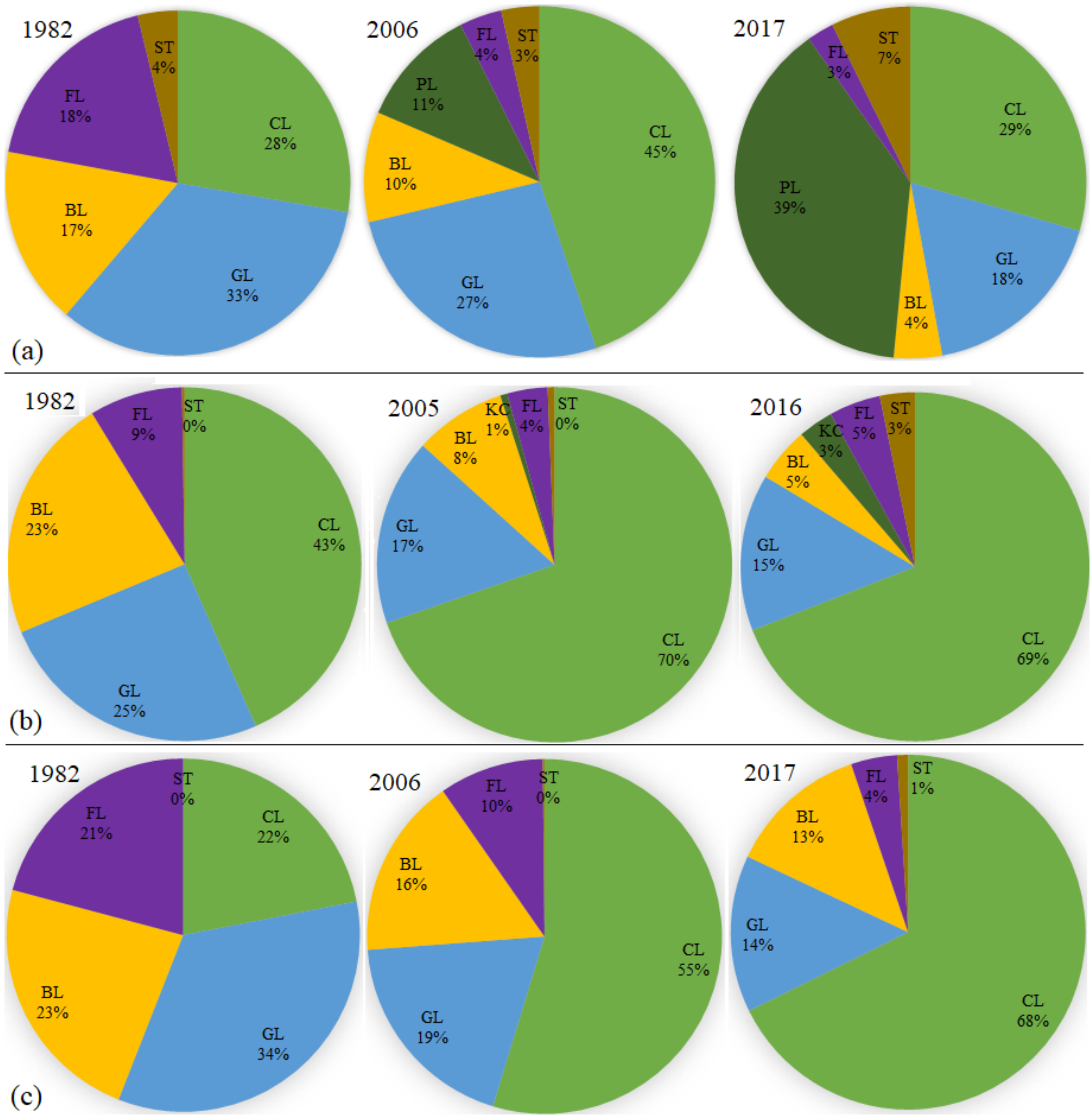

Figure 3-6 Percentage contribution of LULC types to mean estimated annual surface runoff (1982–2016) under different LULC scenarios in Kasiry (a), Kecha (b), and Sahi (c) watersheds.

The increase in surface runoff resulting from the expansion of cultivated land, at the expense of natural vegetation, because of the increased agricultural demand, agrees well with other studies in the UBN basin in Ethiopia and elsewhere (e.g. Dong et al., 2015; Gashaw et al., 2018; Legesse et al., 2003; Ma et al., 2009; Teklay et al., 2018; Worku et al., 2017). For instance, the mean annual surface runoff increased by between 158 and 313 mm during 1984–

2015 in the UBN basin because of the increase of cultivated land at the expense of forest, barren land, bushland, and grassland (Gashaw et al., 2018; Teklay et al., 2018; Worku et al., 2017). Elsewhere, studies have reported that human-induced reduction of natural vegetation cover due to the expansion of cultivated land has resulted in increases in surface runoff because of the decrease in vegetation cover, which intercepts and reduces water loss through ET (Ma et al., 2009; Bosch and Hewlett, 1982; Costa et al., 2003; Fang et al., 2013; Zhang et al., 2014). Similarly, the expansion of plantations increased the surface runoff in Kasiry watershed because of reduced water interception due to the cleared ground surface and the absence of understory vegetation beneath the *A. decurrens* trees (Sultan et al., 2017). This agrees with the findings of Cheng (1999), who reported that surface runoff increased from 9% to 25% as a result of the expansion of artificial forests through reforestation activity. As a general conclusion, the spatial and temporal conversion of LULC types had both negative and positive influences on surface runoff responses in the three watersheds. Moreover, a substantial LULC conversion in the form of expanded cultivated land and plantations and reduced natural vegetation, mainly forest, has resulted in increased annual surface runoff in the study watersheds.

3.3.5. Response of actual ET to LULC change and climate variability

As for surface runoff, the annual ET under different LULC scenarios (1982, 2005/06 and 2016/17) and the same climate data (temperature and rainfall) was estimated from 1982 to 2016. In relative terms, the estimated ET in the three watersheds was higher using the 1982 LULC scenario than with the 2005/06 and 2016/17 scenarios (Figure 3-7). In Kecha, there was slight variation in annual ET (CV = 0.02) between 2005 and 2016 LULC scenarios because there was less conversion between LULC types (Figure 3-7b, Table A4). The estimated mean annual ET decreased by 78.6 mm (6.2%), 40.1 mm (3.9%), and 33.1 mm (3.3%) in Kasiry, Kecha, and Sahi, respectively, between the 1982 and 2005/06 LULC scenarios (Figure 3-7, Table 3-7).

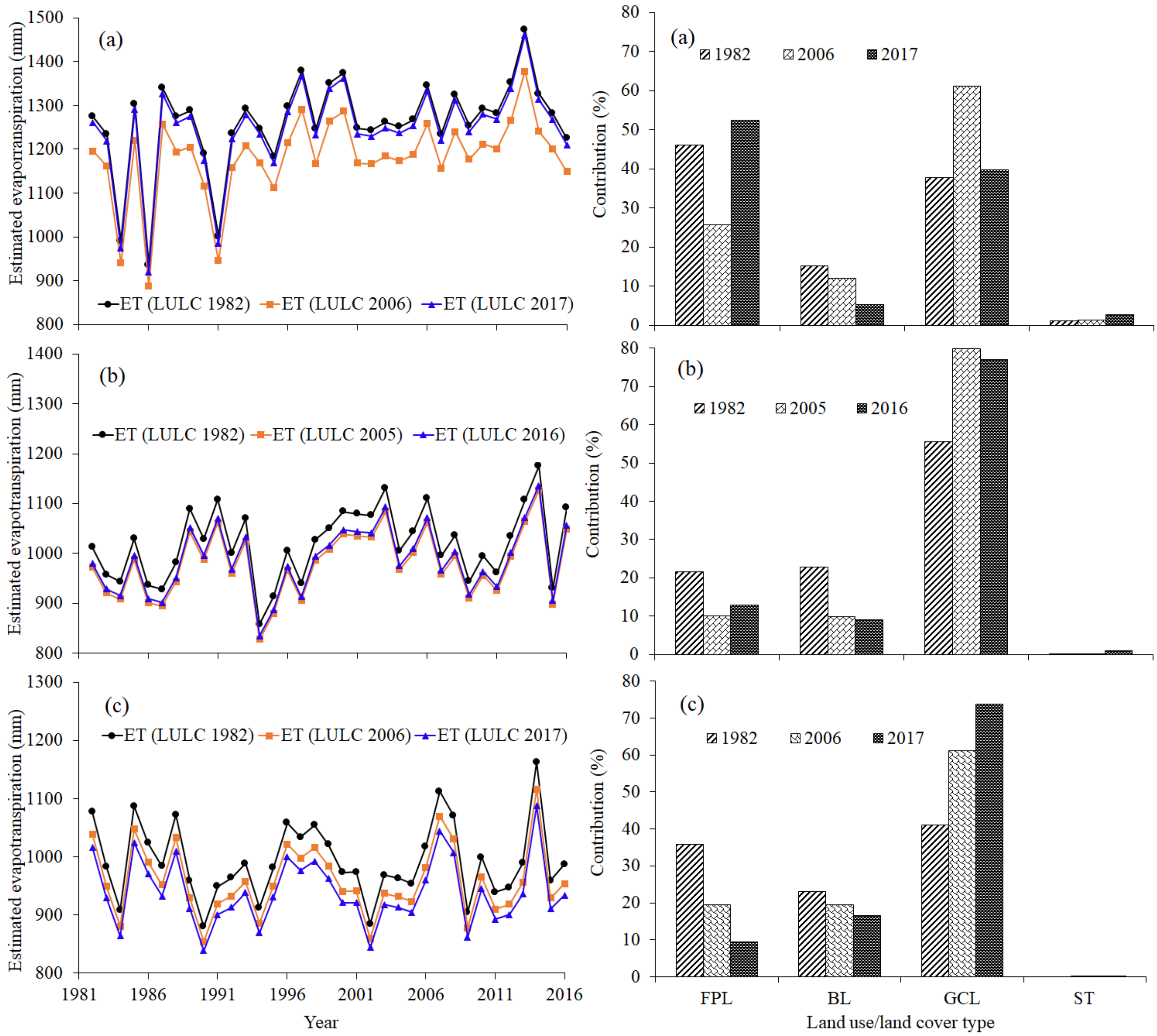

Figure 3-7 Trend in estimated annual actual evapotranspiration (ET, left), and percentage contribution of LULC types to estimated mean annual ET (1982–2016) (right) under different LULC scenarios in Kasiry (a), Kecha (b), and Sahi (c) watersheds. FPL: forest and plantation land; BL: bushland; GCL: grazing and cultivated land; ST: settlements.

This decrease was mainly caused by conversion of natural vegetation cover such as forest, bush, and grazing lands to cultivated land between 1982 and 2005/06 (Tables A3–A5), resulting in less water lost through interception by vegetation. In contrast, the mean annual ET increased by 64.7 mm (5.5%) and 8 mm (0.8%) in Kasiry and Kecha, respectively, between 2005/06 to 2016/17 as a result of the expansion of plantation through reforestation activity, mainly at the expense of grazing and cultivated lands. However, during this period in Sahi, the continuous increase of cultivated land relative to other LULC types resulted in the decrease of mean annual ET by 20.2 mm (2.1%) (Table 3-7, Figure 3-1). In general, the decrease in mean annual ET between 1982 and 2005/06 was greater than the offsetting increases between 2005/06 and 2016/17, so that the overall mean annual ET decrease ranged from 1% in Kasiry to 5% in Sahi (Figure 3-7, Table 3-7). The relatively low reduction of mean annual ET in Kasiry resulted from less conversion of vegetation cover (mainly forest and plantation) between 1982 and 2017.

The cultivated and grazing land LULC types were the major contributors to the change in annual ET under all LULC change scenarios, accounting for 56–80% and 41–74% in Kecha and Sahi, respectively (Figure 3-7b, c). However, in Kasiry, except in 2006, the forest and plantation lands were the dominant contributors in all LULC scenarios; their contributions ranged from 46% to 52% (Figure 3-7a). The contribution of bushland to annual ET decreased from the 1982 to the 2016/17 LULC scenarios: from 15% to 5% in Kasiry, from 23% to 9% in Kecha, and from 23% to 17% in Sahi. Similarly, except in Kasiry in 2017, in all LULC scenarios the contribution of forest and plantation lands decreased considerably from 1982 to 2016/17 (Figure 3-7a). It is worth mentioning that the increases in cultivated and grazing lands due to the conversion from forest, plantation land, and bushland, negatively influenced the annual ET in all watersheds whereas the expansion of forest and plantation land had a positive influence on annual ET (Figure 3-7).

Table 3-7 Mean annual actual ET changes in three watersheds under different LULC scenarios (1982, 2005/06 and 2016/17) with the same annual rainfall data from 1982 to 2016.

Watershed	LULC scenario	ET (mm)	Change in annual actual ET (ΔET)					
			1982–20005/06		20005/06–2016/17		1982–2016/17	
			mm	%	mm	%	mm	%
Kasiry	1982	1260.4						
	2006	1181.8	–78.6	–6.2	+64.7	+5.5	–13.9	–1.1
	2017	1246.5						
Kecha	1982	1019.4						
	2005	979.3	–40.1	–3.9	+8.0	+0.8	–32.2	–3.2
	2016	987.3						
Sahi	1982	1012.9						
	2006	979.8	–33.1	–3.3	–20.2	–2.1	–53.3	–5.3
	2017	959.6						

Overall, our results indicate that the conversion of cultivated and grazing lands to forest as plantation through reforestation had more effect than the conversion of vegetation cover (as forest and plantation) to cultivated and grazing lands on the increase of annual ET. The decline of annual ET in the watersheds as a result of LULC change (mainly the expansion cultivated land with the reduction of natural vegetation) is in agreement with other findings in the UBN basin in Ethiopia (e.g. Gashaw et al., 2018; Woldesenbet et al., 2017). Elsewhere, studies have shown that actual ET is generally greater for forest than for non-forest (cultivated and grazing lands) LULC types, which is attributed to the reduction in soil moisture in non-forest LULC types due to the loss of vegetation cover (Fang et al., 2013; Li et al., 2017; Ma et al., 2009; Woldesenbet et al., 2018; Yang et al., 2017; Yang et al., 2012; Zhang et al., 2001). Moreover, because of a highly developed root system and higher leaf area index, forests have a much higher transpiration than other vegetation types, leading to a higher annual ET value (Yang et al., 2012).

3.3.6. Separated effects of LULC change and climate variability on actual ET

The combined and separate effects of LULC and climate variability on actual ET were analyzed (Table 3-8). In the three watersheds, there was a remarkable reduction of mean annual ET as a result of LULC change from 1982 to 2016: a decrease of 79.0 mm (57.9%) in Kasiry, 39.1 mm (66.4%) in Kecha, and 33.1 mm (59.4%) in Sahi. This could be attributed to a shortage of soil moisture as a result of the expansion of cultivated land at the expense of natural vegetation cover. In contrast, climate variability had a positive effect on the annual ET response; mean annual ET increased by 57.4 mm (42.1%), 19.8 mm (33.6%), and 22.6 mm (40.6%) in Kasiry, Kecha, and Sahi, respectively (Table 3-8). The variation of mean annual ET resulting from climate variability might be due mainly to the significant increases in annual temperature during the study period across the watersheds (Figure 3-4). The offsetting effect of LULC change on climate variability resulted in an overall decrease of annual ET by 21.6 mm (15.8%), 19.3 mm (32.8%), and 10.5 mm (18.8%) in Kasiry, Kecha, and Sahi, respectively, over the study period (1982–2016). This probably resulted from the continuous expansion of cultivated land (+99.7% in Kasiry, +67.6% in Kecha, and +185.0% in Sahi from 1982 to 2005/06) at the expense of natural vegetation (Figure 3-1). Both LULC change and climate variability had a higher influence on annual ET in Kasiry than in the other watersheds because of the expansion of plantations there after 2006 and the increase of annual temperature between periods was slightly greater compared to other watersheds (Fig 3-4, Table 3-5). In general, then, the differing effects of the two factors among the three watersheds reflect the spatial heterogeneity of LULC change and climate variability.

The decline and increase of annual ET as a result of LULC change and climate variability, respectively, in the study watersheds are in agreement with the findings of other studies in the UBN basin in Ethiopia (e.g. Gashaw et al., 2018; Woldesenbet et al., 2017) and elsewhere (e.g. Li et al., 2017; Yang et al., 2017; Yang et al., 2012). For instance, Gashaw et al. (2018) stated that LULC change in the Andassa watershed of the UBN basin, predominantly the conversion from vegetative to non-vegetative cover, has resulted in the reduction of annual ET. Also, the dominant effects of LULC change found in our study watersheds are consistent with the study by Yang et al. (2012), who found that LULC change has a more pronounced effect than climate change on mean annual ET in Shalamun River (China) watersheds.

Table 3-8 Changes in estimated mean annual actual evapotranspiration (ET) under separate and combined effects of LULC change and climate variability.

Watersheds	Scenario	LULC	Climate data	ET (mm)	Factor	ET change	
						mm	%
Kasiry	SC1	1982	1982–2001	1234.7			
	SC2	2006	1982–2001	1158.3	ΔET_L	–79.0	–57.9
	SC3	1982	2002–2016	1294.6	ΔET_C	+57.4	+42.1
	SC4	2006	2002–2016	1213.1	ΔET_{LC}	–21.6	100.0
Kecha	SC1	1982	1982–1993	1007.0			
	SC2	2005	1982–1993	967.0	ΔET_L	–39.1	–66.4
	SC3	1982	1994–2016	1025.9	ΔET_C	+19.8	+33.6
	SC4	2005	1994–2016	987.7	ΔET_{LC}	–19.3	100.0
Sahi	SC1	1982	1982–2001	991.7			
	SC2	2006	1982–2001	958.7	ΔET_L	–33.1	–59.4
	SC3	1982	2002–2016	1014.4	ΔET_C	+22.6	+40.6
	SC4	2006	2002–2016	981.2	ΔET_{LC}	–10.5	100.0

LULC: Land use/land cover; SC1–SC4: scenario numbers 1 to 4 (please see text); ET: evapotranspiration. For ET change, the change due to changes in LULC (ΔET_L) = average of [(SC2 – SC1) + (SC4 – SC3)]; the change due to climate variability (ΔET_C) = average of [(SC3 – SC1) + (SC4 – SC2)]; the total change (ΔET_{LC}) = (SC4 – SC1). Percent (%) ΔET_L = $\Delta ET_L/\Delta ET_{LC} \times 100$ and $\Delta ET_C = \Delta ET_C/\Delta ET_{LC} \times 100$. The negative sign is not considered when calculating the percentage contribution of each factor to the total change.

The opposite was found by Woldesenbet et al. (2017) in Ethiopia, and by Li et al. (2017) and Yang et al. (2017) in China, who reported that climate variability had a greater effect than LULC change on annual ET response. It is worth mentioning that our study captured a reduction in annual ET caused by LULC change that was relatively larger in magnitude than the offsetting increase caused by climate variability, indicating that the LULC change played a dominant role affecting annual ET.

3.4. Conclusions

This study investigated annual surface runoff and ET responses from 1982 to 2016 under LULC change (comparing 1982, 2005/06, and 2016/17) and climate variability scenarios in Kasiry (highland), Kecha (midland), and Sahi (lowland) watersheds in the Upper Blue Nile basin in Ethiopia. The LULC change results revealed that from 1982 to 2016/17, the natural vegetation cover (forest, bushland, and grazing lands) decreased by about 32–83% in Kasiry, 40–77% in Kecha, and 32%–75% in Sahi. During the same period, cultivated land cover increased by approximately 37%, 66%, and 280% in the three respective watersheds. In contrast, between 2006 and 2017, plantation land increased by 262% in the Kasiry watershed, mainly at the expense of cultivated and grazing lands. Long-term annual rainfall variability was insignificant at all three sites. On the other hand, long-term mean annual temperature showed significant ($P < 0.05$) variation across the three watersheds, with the mean annual temperature increasing by 0.04 °C in Kasiry, 0.02 °C in Kecha, and 0.03 °C in Sahi from 1982 to 2016.

LULC change and climate variability caused different hydrological responses across the watersheds. LULC change positively influenced the annual surface runoff in all three watersheds. Because there was no significant trend in annual rainfall, this climate factor did not significantly affect the estimated surface runoff change. LULC change, and climate variability in terms of temperature, had negative and positive effects, respectively, on the changes in annual ET. However, even though climate variability increased ET, from 33.6% in Kecha to 42.1% in Kasiry, LULC change resulting in a reduction of natural vegetation had an offsetting effect that led to an overall decrease in ET, from a 15.8% reduction in Kasiry to 32.8% in the Kecha watershed over the 35 years. In general, our results indicate that the role of LULC change is more dominant than that of climate variability in the annual surface runoff and ET responses. These effects are mainly attribute to LULC conversion and temperature variation across the watersheds during the study period.

Our results suggest that LULC change and climate variability can modify surface runoff and ET in the UBN basin, and that runoff and ET are important hydrological components subject to change with LULC and climate variation. As the changes in LULC and climate variability in the basin continue to increase, further significant change can be expected in the hydrological components. Thus, further investigations of the hydrological responses under future LULC and climate variability scenarios, including other weather parameters besides rainfall and temperature, are important for devising future sustainable land and water management strategies.

CHAPTER 4

4. Evaluating runoff and sediment responses to soil and water conservation practices by employing alternative modeling approaches

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4.1. Introduction

Soil erosion is a serious global environmental challenge (Borrelli et al., 2017), and the severity is the worst in sub-Saharan Africa owing to population pressure and poor land management practices (Fenta et al., 2020; Vanmaercke et al., 2014). Soil erosion may increase runoff and soil nutrient loss, which leads to deteriorated soil productivity (Haregeweyn et al., 2008, 2013, 2017; Obalum et al., 2012; Vanmaercke et al., 2010). Land degradation associated with soil erosion is common in areas such as the highlands of Ethiopia, where overcultivation and uncontrolled grazing are predominant (Betrie et al., 2011; Bewket and Sterk, 2003; Easton et al., 2010; Fenta et al., 2016; Gessesse et al., 2015; Haregeweyn et al., 2006, 2008, 2013, 2015, 2017; Hurni, 1993; Lemma et al., 2019; Melaku et al., 2018; Nyssen et al., 2009; Welde, 2016; Worku et al., 2017). Besides depleting the fertile soils, soil erosion in the Upper Blue Nile basin of Ethiopia has been causing siltation of downstream lakes, reservoirs, and river channels, thus aggravating flooding, landslides, and degradation of ecosystem services (e.g., Betrie et al., 2011; Easton et al., 2010; Lemma et al., 2018).

To mitigate the alarming consequences of soil erosion, soil and water conservation (SWC) practices have been implemented across much of Ethiopia since the mid-1970s (Haregeweyn et al., 2015, 2019; Herweg and Ludi, 1999; Nyssen et al., 2008; Osman and Sauerborn, 2001) and with concerted effort in the northern Ethiopian highlands since 2010 (e.g., Dagnew et al., 2015; Ebabu et al., 2019; Haregeweyn et al., 2016; Melaku et al., 2018; Molla and Sisheber, 2017; Nyssen et al., 2007, 2010; Sultan et al., 2018a; Tamene et al., 2017), mainly through government and non-governmental sustainable land management initiatives in food-for-work community mobilizations. Numerous studies have attempted to assess the effectiveness of these SWC practices on hydrological and soil erosion processes at the experimental plot scale (e.g., Ebabu et al., 2019; Kebede et al., 2020a; Nyssen et al., 2007, 2010; Sultan et al., 2017, 2018a, 2018b; Taye et al., 2013) and watershed scale (e.g., Arabi et al., 2006; Dagnew et al., 2015; Jemberu et al., 2017; Khelifa et al., 2017; Lemann et al., 2016; Melaku et al., 2018; Molla and Sisheber, 2017; Sultan et al., 2018b) in different agro-ecological regions of Ethiopia. The studies reported that SWC practices may have a significant effect in reducing runoff, soil loss, and sediment yield (SY) at both plot and watershed scales. However, the short- and long-term impacts of SWC practices on the dynamics of runoff and SY at the watershed scale have not been sufficiently evaluated due to fragmented and limited observational data and a lack of robust and harmonized methodology (Haregeweyn et al., 2015, 2019; Nyssen et al., 2008, 2009; Osman and Sauerborn, 2001).

A lack of hydro-meteorological data has been the main constraint for accurate flow and sediment modeling in the Ethiopian watersheds. This, in turn, has made it difficult to apply biophysical models to evaluate the impacts of SWC practices on runoff and SY at a watershed scale. However, biophysical models such as the Universal Soil Loss Equation (e.g., Belayneh et al., 2019; Bewket and Teferi, 2009; Fenta et al., 2016; Haregeweyn et al., 2017; Molla and Sisheber, 2017; Tamene et al., 2017), Water Erosion Prediction Project (e.g., Zeleke, 2001), and Soil and Water Assessment Tool (SWAT) (e.g., Betrie et al., 2011; Lemann et al., 2016; Lemma et al., 2019; Melaku et al., 2018; Welde, 2016) have been applied with some degree of success. Of these models, SWAT (Arnold et al., 1998; Srinivasan et al., 1998) demonstrated wider applicability in the Ethiopian highlands because it can be used to estimate biophysical impacts such as implementation of SWC practices, land use/land cover (LULC) change, and climate variability (e.g., Betrie et al., 2011; Dile et al., 2013, 2016a, 2016b; Easton et al., 2010; Mekonnen et al., 2018; Setegn et al., 2009, 2010; Woldesenbet et al., 2017, 2018; Worku et al., 2017). Furthermore, SWAT allows estimation of the integrated impacts of plausible changes in biophysical factors such as LULC and climate under different alternative SWC scenarios (Arnold et al., 2012; Gassman et al., 2007; Neitsch et al., 2011) for land management interventions. Although a few of the above studies reported the effects of SWC practices on runoff and SY, the actual effects of SWC practices based on field measurements have not yet been well modeled, particularly with regard to alternative approaches.

In this study, we evaluated the impacts of SWC practices on runoff and SY using field measurement and modeling techniques with (1) a paired watershed approach (Hewlett, 1971) that compared watersheds with and without SWC practices (e.g., Ebabu et al., 2018; King et al., 2008; Melaku et al., 2018; Sultan et al., 2018b), and (2) a single watershed approach that compared data before and after the implementation of SWC practices (e.g., Abouabdillah et al., 2014; Betrie et al., 2011; Dagnew et al., 2015; Khelifa et al., 2017; Lemann et al., 2016; Lemma et al., 2019; Molla and Sisheber, 2017). Although the two approaches have been applied for other purposes with some merits and limitations, they were not widely used in the scientific literature to study the impact of SWC practices on flow and SY. Moreover, unlike other studies, we estimated the actual impacts of SWC practices while isolating the impacts of LULC change and climate variability.

Although evaluating the effectiveness of SWC practices is vital, mapping and characterizing soil erosion hotspots is equally important in implementing such interventions such that priority is given to areas where soil erosion is the major threat to sustained agriculture (Belayneh et al., 2019; Bewket and Teferi, 2009; Gessesse et al., 2015; Lemma et al., 2019; Welde, 2016). The SWAT model has been used to estimate the potential impacts of various SWC options on runoff and sediment and to map erosion hotspot areas (Abouabdillah et al., 2014; Arnold et al., 1998, 2010). Therefore, in this study we evaluated the impact of SWC practices on flow and SY in paired drought-prone SWC-treated Kecha and untreated Laguna watersheds in the Upper Blue Nile basin using a calibrated SWAT model. The model was calibrated and validated based on established experimental plots with observed hydro-meteorological and SWC data, which allowed us to characterize and prioritize soil erosion hotspot areas for future land management interventions. The identification of such hotspots will help in applying a targeted response, directing resources to areas of high risk rather than spreading them equally across the landscape (Boardman, 1995; Haregeweyn et al., 2013).

4.2. Materials and methods

4.2.1 Flow and sediment yield (SY) measurements

Flow and SY were determined using the data collected at the outlet of Aba Geima (Kecha and Laguna) paired watersheds (Figure 1-6) where staff gauges and an automatic pressure transducer (TD-Diver) were installed. Graduated staff gauges (locally manufactured) were mounted at the side of the stream bed together with a depth-integrated sediment sampler. The TD-Diver (van Essen Instruments, Delft, the Netherlands) was covered with a 50 cm × 50 cm sheet metal box and placed at the bottom of the staff gauges.

The river flow depth was measured three times per day (at 07:00, 13:00, and 18:00) using the graduated staff gauge and at 10-min intervals using an automatic TD-Diver during four rainy seasons (June to mid-November from 2015 to 2018). The automated flow depth records were corrected using linear regression equations developed from manually and automatically measured flow depths. Flow velocities were measured at multiple depths using both the universal current meter and floating methods (Ebabu et al., 2018; Lemma et al., 2018; Zenebe, 2012). Thereafter, the corresponding discharge was estimated using the velocity–area method (i.e., by multiplying the flow velocity by river cross-sectional area) and used to develop the stage-discharge relationships (rating curves) for each watershed. Once the rating curves were developed, the corrected continuous flow depths were used to determine the corresponding instantaneous discharge (flow).

Like the manual flow depth measurements, depth-integrated suspended sediment concentration (SSC, g L^{-1}) was measured from samples collected three times per day at 07:00, 13:00, and 18:00 and during peak rainfall and runoff events. All the collected SSC samples were filtered using Whatman filter paper, oven-dried at 105°C for 24 h, and weighed on a digital balance with a precision of 0.001g. The measured SSCs were used to establish discharge–sediment rating curves using power functions and thereafter the equation were applied to estimate SSCs for the automatically recorded continuous discharge (Q) series (Asselman, 2000; Ebabu et al., 2018; Guzman et al., 2013; Vanmaercke et al., 2010).

The soil erosion pattern in the watersheds was highly dependent on the land-cover dynamics (Ebabu et al., 2019; Yibeltal et al., 2019a). During the early phase of the rainy season, the land does not have plant cover and it is also plowed, which makes it highly susceptible to erosion. As the season progresses, however, plant cover increases, and the soil becomes less exposed to soil erosion. Some studies indicated that the relationship between Q and SSC is often subject to uncertainties due to differing temporal scales (Alexandrov et al., 2007; Asselman, 2000; Moliere et al., 2004); thus, relying on one Q–SSC rating curve for the whole season may lead to unreliable estimation of SY at the watershed scale. To address this limitation and account for soil erosion dynamics, three rating curves (Table 4-1) that represent different time periods were developed for each rainy season. The Q–SSC analysis periods were thus divided into three runoff and sediment supply regimes for precise Q–SSC analysis: (1) low runoff, but high sediment supply (from 1 July to mid-August); (2) high runoff, but low sediment supply (from mid-August to 30 September); and (3) low runoff and low sediment supply (after 1 October). Studies in other watersheds have followed a similar approach to develop a Q–SSC rating curve (Ebabu et al., 2018; Guzman et al., 2013; Liu et al., 2008; Vanmaercke et al., 2010).

The continuous sub-daily SSC data estimated by the Q–SSC rating curve were used to calculate the daily SY by using Equation 4-1:

$$SY = \sum_{n=1}^{n}[(Q_i \times SSC_i \times 600)]/1000 \, , \qquad (4\text{-}1)$$

where SY is the daily sediment yield (t day^{-1}), n is the number of observations per day at 10-min intervals; Q_i is equivalent discharge (m^3 s^{-1}) for observation i, and SSC_i is the suspended sediment concentration (g L^{-1}) for observation *i*. Seasonal SY and area-specific SY (t ha^{-1}) were also calculated by summing the daily values and dividing the total *SY* by the area of the corresponding watershed, respectively.

Table 4-1 Parameters of the discharge–sediment rating curves measured at Kecha and Laguna monitoring stations.

Season	Period	Kecha				Laguna			
		n	*a*	*b*	R^2	*n*	*a*	*b*	R^2
2015	All	248	1.60	1.20	0.46	286	1.70	0.87	0.68
	P_1	74	2.78	1.21	0.77	84	3.13	0.93	0.80
	P_2	80	1.05	1.01	0.68	90	1.05	0.79	0.80
	P_3	94	0.10	0.43	0.15	112	0.58	0.70	0.18
2016	All	328	0.84	0.89	0.45	335	1.26	0.98	0.37
	P_1	139	2.54	1.47	0.68	145	4.36	1.22	0.60
	P_2	70	1.21	1.34	0.45	80	1.48	1.43	0.32
	P_3	119	1.10	1.19	0.09	110	0.11	0.48	0.07
2017	All	295	1.09	0.81	0.31	278	0.67	0.61	0.37
	P_1	98	3.67	1.35	0.53	142	3.06	1.84	0.58
	P_2	82	1.84	1.07	0.44	61	0.98	0.90	0.47
	P_3	115	1.62	0.57	0.20	75	0.05	0.45	0.01
2018	All	348	1.40	1.34	0.41	439	0.35	0.55	0.33
	P_1	137	1.62	1.62	0.94	150	0.95	1.14	0.79
	P_2	101	1.43	1.58	0.79	126	0.70	1.20	0.55
	P_3	110	0.13	0.28	0.01	163	0.03	0.21	0.07

P_1 (1 June to 15 August), P_2 (16 Agust to 30 September), P_3 (1 October to mid-ovember), *n* is the number of samples in each sample period, *a* and *b* are regression coefficients for the power function $SSC = aQ^b$.

4.2.2. Soil and Water Assessment Tool (SWAT) Model

SWAT is an open-source-code, semi-distributed watershed hydrological model (Arnold et al., 1998; Srinivasan et al., 1998). The model was developed in the early 1990s by the U.S. Department of Agriculture's Agricultural Research Service and has been continuously modified and upgraded (Arnold et al., 2012). SWAT is widely used to predict and analyze the responses of hydrological processes such as flow and SY to changes in LULC, climate, and land management practices in small to large complex watersheds (Arnold et al., 2012; Gassman et al., 2007; Neitsch et al., 2011).

SWAT requires input data such as climate, topography, LULC, and soil properties to simulate physical processes (Gassman et al., 2007). In SWAT, a watershed is divided into multiple sub-basin, which are further subdivided into hydrologic response units (HRUs) that are unique combinations of LULC, soil, and slope. The model estimates biophysical processes at the sub-basin and HRU levels (Arnold et al., 2010; Neitsch et al., 2011). Several of the biophysical processes, such as surface runoff and SY, are calculated at the HRU level, and then the estimates are aggregated at the sub-basin level. Flow, SY, and nutrients, are routed to the stream channels.

Different hydrological components are estimated in SWAT based on the water balance equation at the soil layer (Neitsch et al., 2011). We used the Soil Conservation Service's (SCS, 1972) curve number method to estimate daily surface runoff and the flows were routed into channels using the Muskingum routing techniques. SWAT has the option of using the Penman–Monteith, Priestley–Taylor, or Hargreaves method to estimate potential evapotranspiration. We used the Penman–Monteith method based on recommendations in the literature and the availability of rainfall, temperature, solar radiation, relative humidity, and wind speed data and because this is the method most commonly used in the Upper Blue Nile basin (e.g., Betrie et al., 2011; Mekonnen et al., 2018; Woldesenbet et al., 2018). The Modified Universal Soil Loss Equation was used to estimate SY. There is a detailed description of the model equations in the SWAT theoretical documentation (Neitsch et al., 2011).

4.2.3. Model input data and setup

The SWAT model requires spatially explicit datasets for topography, LULC, soil properties, and daily weather. We used a 30-m-resolution Digital Elevation Model from the Shuttle Radar Topographic Mission (http://earthexplorer.usgs.gov/) to delineate the watersheds (Figure 4-1), create channel networks, and to generate topographic information such as overland slope and slope length.

The LULC data were adapted from LULC maps of 2005 (Kecha) and 2016 (Kecha and Laguna) presented in Figure 2-2 (Berihun et al., 2019a, 2019b) ; the maps have five LULC classes. For this chapter, the LULC data for each watershed is summarized in Table 4-2 from Figure 2-4. The soil map (Figure 4-1c) with its physical and chemical properties for both watersheds (Table 4-3) was adapted from a soil survey carried out by the Amhara Design and Supervision Work Enterprise (Mekonnen, 2018). The soil samples have two to four soil layers over a depth range of 0–150 cm (Table 4-3).

Table 4-2 Land use/land cover (LULC) classes and their areas of coverage (ha, %) in the Kecha and Laguna watersheds

LULC class	SWAT code	Kecha				Laguna	
		2005		2016		2016	
		ha	%	ha	%	ha	%
Bush land	RNGE	36.54	9.38	22.30	5.72	47.56	13.95
Cultivated land	AGRL	268.63	68.96	272.86	70.01	228.85	67.09
Khat cultivation	RNGB	1.64	0.42	40.97	10.51	36.93	10.83
Forest land	FRST	32.81	8.42	42.10	10.80	16.57	4.86
Grazing land	PAST	49.94	12.82	11.55	2.96	11.17	3.27

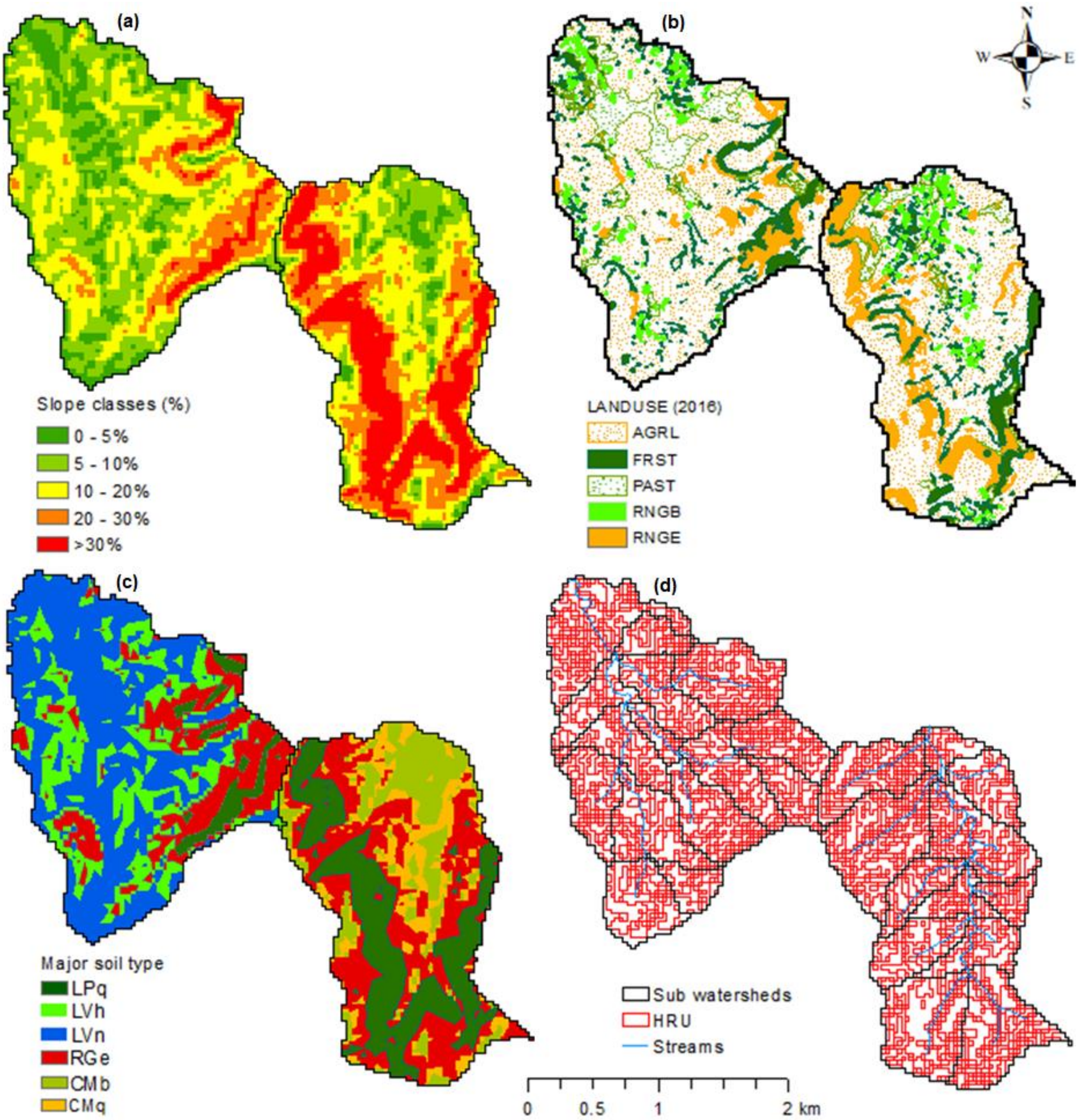

Figure 4-1 Maps of slope classes (a), land use/land cover classes (b), major soil types (c), and sub-watersheds and hydrologic response units (HRUs) (d) of both study watersheds. Abbreviations of land uses, and soil types are described in Tables 4-2 and 4-3, respectively.

Daily rainfall, maximum and minimum temperatures, solar radiation, relative humidity, and wind speed for the period 2000–2018 were collected from the Bahir Dar meteorology station, which is about 15 km far from the two watersheds. In addition, rainfall data from 2015 to 2018 were collected locally from three rain gauges mounted in the watersheds and used to validate the long-term rainfall data collected from the Bahir Dar meteorology station.

Table 4-3 Properties of the major soil types and their area coverage in the Kecha and Laguna watersheds

Watershed	Major soil type	SWAT code	No. of layers	Depth (mm)	Sand (%)	Silt (%)	Clay (%)	Area (%)
Kecha	Lithic Leptosols	LPq	2	0 – 50	49.00	33.00	18.00	4.41
	Haplic Luvisols	LVh	3	0 – 135	20.11	23.44	56.22	24.49
	Nithic Luvisols	LVn	2	0 – 150	9.00	20.00	71.00	50.52
	Eutric Regosols	RGe	3	0 – 90	26.00	25.00	49.00	20.58
Laguna	Cambic Cambisols	CMb	3	0 – 142	7.00	22.67	70.33	19.50
	Chromic Cambisols	CMq	3	0 – 150	9.00	40.33	50.67	15.27
	Lithic Leptosols	LPq	2	0 – 50	9.00	54.00	37.00	28.54
	Eutric Regosols	RGe	3	0 – 115	26.00	26.67	47.33	36.70

Table 4-4 Slope classes and their area coverage (ha, %) in the Kecha and Laguna watersheds

Slope class	Kecha		Laguna	
	ha	%	ha	%
0–5%	59.25	15.23	19.57	5.74
5–10%	136.91	35.18	51.56	15.12
10–20%	133.16	34.22	97.00	28.44
20–30%	43.30	11.13	74.89	21.96
>30%	16.54	4.25	98.03	28.74
Total	389.16	100.00	341.04	100.00

Outliers and missing values of the daily rainfall data from the meteorological station were corrected based on the field-collected rainfall data (Berihun et al., 2019b). A weather generator prepared using the long-term daily climate data was used to complete missing daily weather data except rainfall (Schuol and Abbaspour, 2007).

A separate SWAT project was set up for each watershed (Kecha and Laguna). Models were simulated for the period 2000 to 2018 using 15 years of model warm-up. The watershed delineation for both watersheds was conducted using a threshold area of 11.8 ha, which provided 15 and 12 sub-basins in the Kecha and Laguna watersheds, respectively (Figure 4-

1d). HRUs were created (Figure 4-1d) based on land use, soil, and five slope classes: flat (0–5%), gentle (5–10%), sloping (10–20%), steep (20–30%) and very steep (>30%) (Figure 4-1a, Table 4-4). These slope classes were the basis for the SWC implementation in the watershed. The analysis delineated 276 and 280 HRUs in the Kecha and Laguna watersheds, respectively.

4.2.4 Parameterization to capture the effect of SWC practices

SWC practices affect the hydrological responses mainly by influencing surface runoff and infiltration processes. The impacts on surface runoff were captured by fine-tuning the curve number values (Bieger et al., 2015; Bonta, 1997; Khelifa et al., 2017). We estimated the curve numbers using the CN method of the Soil Conservation Service (SCS, 1972) at different slope ranges, LULC types (cultivated, grazing and bush lands) and SWC practices based on measured rainfall and runoff data from the experimental runoff plots (Table 4-5). Detailed description of the experimental runoff plots were given by Ebabu et al. (2019) and Sultan et al. (2018a). The computational procedure is expressed as follows:

$$Q_i = \frac{(P_i - \lambda S)^2}{P + (1-\lambda)S} \qquad P > \lambda S, \tag{4-2}$$

where Q_i is runoff depth (mm) at event i, P_i is rainfall depth (mm) at event i, S is maximum potential retention (mm), and λ is the initial abstraction ratio (the ratio of initial abstraction to maximum potential retention), which is a non-dimensional value ranging between 0 and 1. Often, λ is assumed to be 0.2. Theoretically, the value of S varies in the range of $0 \leq S \leq \infty$, which is expressed in terms of Equation 3 (Hawkins, 1993):

$$S = 5\left[P_i + 2Q_i - (4{Q_i}^2 + 5PQ_i)^{1/2}\right] \tag{4-3}$$

Once the S value is determined, the CN2 value for each rainfall event can be determined using Equation 4-4:

$$CN2 = \frac{25400}{254 + S} \tag{4-4}$$

Table 4-5 Curve number (CN2) values for different land uses and management practices in the study watersheds calculated based on the daily data from experimental runoff plots

Land use	Slope (%)	Soil texture	Management practices tested	Number of runoff events	Curve number (CN2)					
					Max	Min	Mean	Median	SDV	CN2* (SDV)
Cultivated land	5	Clay loam	Control	163.00	99.97	69.33	84.65	93.84	± 6.06	84.65 (± 6.06)
			Soil bund	75.00	99.83	46.87	73.35	88.92	± 11.06	73.90 (± 11.00)
			Fanyu juu	76.00	99.97	48.93	74.45	89.20	± 10.82	
			Soil bund with grass	74.00	99.82	47.99	73.91	88.99	± 11.10	
Cultivated land	15	Sandy loam	Control	133.00	99.81	64.36	82.09	91.52	± 7.44	82.09 (± 7.44)
			Soil bund	85.00	99.94	49.26	74.60	88.74	± 10.88	74.53 (± 11.12)
			Fanyu juu	84.00	99.14	49.46	74.30	87.52	± 11.40	
			Soil bund with grass	84.00	99.17	50.17	74.67	87.97	± 11.08	
Grazing land	15	Clay loam	Control	157.00	99.97	69.26	84.62	94.43	± 5.49	84.62 (± 5.49)
			Exclosure	73.00	99.10	61.71	80.41	93.06	± 9.03	79.96 (± 9.49)
			Exclosure with trench	78.00	99.51	59.52	79.52	91.18	± 9.95	
Bushland	35	Loam	Control	162.00	99.81	70.49	85.15	92.63	± 6.41	85.15 (± 6.41)
			Exclosure	98.00	99.96	46.63	73.29	90.54	± 9.42	72.73 (± 9.93)
			Exclosure with trench	102.00	99.87	44.48	72.18	88.24	± 10.43	

CN: Curve number value considered in calibration process; SDV:* standard deviation

The mean of the CN values for each LULC types and SWC practices in the experimental plots were estimated using Equations 4-2 to 4-4 and implemented in the SWAT model (Table 4-5). The mean CN2 values estimated from the control plots were used in the untreated watershed. Whereas the mean CN2 values from the treated plots were used in the treated watershed. The CN values were further calibrated based on the lower and the upper limit of CN2 values (standard deviations) of land use types (Table 4-5) using the SWAT–CUP model (Abaspour et al., 2004).

Besides the traditional drainage ditches and field boundaries that exist in both watersheds, soil and stone bunds and *fanya juu* (terraces) have been constructed in the treated Kecha watershed to reduce overland flow and soil erosion since 2011. High-resolution satellite and Google Earth images recorded in 2016 together with an intensive field survey were used to digitize the existing SWC structures (Lemann et al., 2016; Melaku et al., 2018) (Figure 4-2). The digitized SWC structures were overlaid with sub-watersheds, and the density of SWC structures in each sub-watershed was calculated by dividing the total length of SWC bunds and terraces by the sub-watershed area (Table 4-6). The percentage distributions of SWC structures within the LULC classes in each sub-watershed were also calculated (Table 4-6). During model calibration, salient features of these SWC structures were considered in the SWAT model; for simplicity, all were considered as bunds. Therefore, the effect of bunds on SY in the treated watershed was captured in the SWAT model by adjusting the parameters of support practices (USLE_P), slope length (SLSUBBSN), and HRU slope steepness (HRU_SLP) (Khelifa et al., 2017; Lemann et al., 2016; Melaku et al., 2018). The values for parameter USLE_P were adjusted according to the SY trap efficiencies suggested in previous studies of the two watersheds of this study (Ebabu et al., 2019; Kebede et al., 2020b) and elsewhere in the northern Ethiopian highlands (Nyssen et al., 2007, 2009, 2010; Taye et al., 2013, Table 4-6).

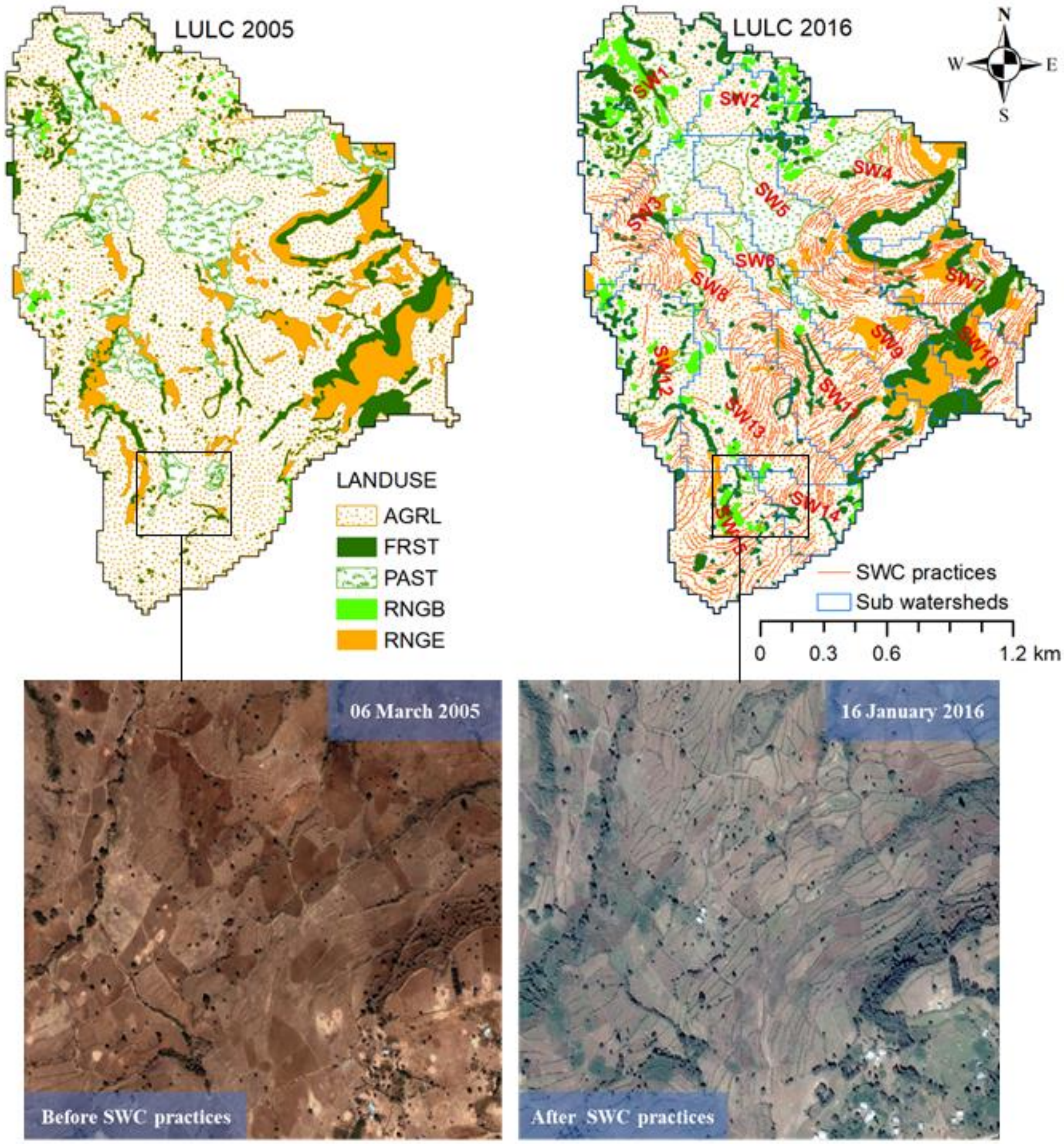

Figure 4-2 Land use/land cover (LULC) classes of 2005 and 2016 (top maps) and distribution of soil and water conservation (SWC) practices in the Kecha watershed. The Google Earth images at the bottom show the difference in SWC practices for the marked areas between the two years (2005 and 2016). Abbreviations of land uses are described in Table 4-1.

Table 4-6 Distribution and area coverage of soil and water conservation (SWC) practices in different land use/land cover (LULC) types of the Kecha sub-watersheds

Sub watershed	SWC length (m)	Area (ha)	Density (m ha^{-1})	Area percentage by LULC (%)			
				AGRL	PAST	RNGB	RNGE
*Density less than 200 m/ha (*trap efficiency 20%, P = 0.8)*							
1	2530.39	51.37	49.26	88.04	11.96	–	–
4	6121.77	40.36	151.68	88.39	3.24	8.38	–
5	3381.17	25.03	135.11	84.16	–	–	15.84
6	822.72	8.84	93.03	88.47	–	–	11.53
12	2926.36	26.72	109.52	91.33	–	8.67	–
Sub total	15782.41	152.32	103.62				
*Density between 200 and 400 m/ha (*trap efficiency 40%, P = 0.6)*							
3	5265.12	19.29	272.99	77.94	22.06	–	–
8	8114.48	24.37	333.01	88.39	4.76	1.35	5.49
9	8035.60	28.79	279.12	92.77	–	–	7.23
11	11785.10	32.27	365.21	95.44	–	–	4.56
13	11176.80	33.40	334.65	95.44	–	0.88	3.67
14	3988.75	12.79	311.74	97.00	3.00	–	–
15	8262.42	30.39	271.90	94.02	–	4.38	1.61
Sub total	56628.27	181.29	312.36				
Density *greater than 400 m/ha (*trap efficiency 60%, P = 0.4)*							
7	11078.15	25.12	441.02	72.266	10.41	–	17.33
10	7191.58	17.78	404.45	82.332	–	–	17.67
Sub total	18269.72	42.90	425.86				

**Trap efficiencies were adopted from Ebabu et al. (2019), Kebede et al. (2020b), Nyssen et al. (2007, 2009, 2010), and Taye et al. (2013).*

4.2.5. Model calibration and validation

Parameters related to flow and SY were identified based on studies conducted in the Ethiopian highlands and similar agro-ecological regions (Betrie et al., 2011; Dile et al., 2016b; Easton et al., 2010; Khelifa et al., 2017; Lemann et al., 2016; Lemma et al., 2019; Mango et al., 2011; Melaku et al., 2018; Setegn et al., 2009, 2010; Worku et al., 2017; Yesuf et al., 2015). Accordingly, 18 flow and SY related parameters (Tables 4-7, 4-8) were selected for calibration.

Table 4-7 Calibrated model parameters, their description, parameter range and fitted values based on observed flow for the Kecha and Laguna watersheds.

Name	Description	Range	Kecha	Laguna
CN2.mgt*	Initial SCS runoff curve number for moisture condition II	35 – 98	62 – 70	74 – 89
GWQMN.gw	Threshold depth of water in shallow aquifer required for return flow to occur (mm H_2O)	0 – 5000	1450	1646.5
GW_REVAP.gw	Groundwater "revap" coefficient	0 – 0.2	0.19	0.12
REVAMN.gw	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H_2O)	0 – 500	375	460
RCHRG_DP.gw	Deep aquifer percolation factor	0 – 1.0	0.20	0.35
SOL_AWC.sol	Available water capacity of the soil layer (mm H_2O/mm soil)	–0.25 to 0.25	0.14	0.10
GW_DELAY.gw	Groundwater delay time (days)	0 – 500	254	350
ESCO.sbn	Soil evaporation compensation factor	0.01 – 1.0	0.55	0.15
ALPHA_BF.gw	Baseflow alpha factor (l/days)	0.1 – 1.0	0.25	0.75
CH_K2.rte	Channel effective hydraulic conductivity (mm/h)	–0.025 to ∞	124.9	132.8

**CN2 values were adjusted based on estimated CN2 from experimental plots (Table 2)*

The selected parameters were first fine-tuned manually (Arnold et al., 2012; Brouziyne et al., 2017; Feyereisen et al., 2007; Lenhart et al., 2002; Santhi et al., 2001) and then calibrated using the Sequential Uncertainty Fitting (SUFI–2) program in the SWAT–CUP (Abbaspour, 2015).

Table 4-8 Calibrated model parameters, their description, parameter range and fitted values based on observed sediment yield (SY) for the Kecha and Laguna watersheds.

Name	Description	Range	Kecha	Laguna
USLE_P.mgt*	USLE support practice factor	0.0 – 1.0	0.40 – 0.80	0.8 – 1.0
SLSUBBSN.bsn	Average slope length	10 – 150	49.4 – 62.9	66.5
HRU_SLP.hru	Average slope steepness	0.0 – 1.0	0.15	0.25
USLE_K.sol	Soil erodibility factor	0 – 0.65	0.2	0.17
SPEXP.bsn	Exponent parameter for calculation sediment re–entrained in channel sediment routing	1.0 – 1.5	1.11	1.21
SPCON.bsn	Linear parameter for calculation sediment re–entrained in channel sediment routing	0.0001 – 0.01	0.005	0.008
CH_COV1.rte	Channel erodibility factor	–0.05 to 0.6	0.37	0.2
CH_COV2.rte	Channel cover factor	–0.001 to 1.0	0.29	0.45

**USLE_P and SLSUBBSN factors were adjusted based on the density of soil and water conservation (SWC) structures <200 m ha^{-1} (sub-watersheds 1, 4, 5, 6, and 12); SWC 200–400 m ha^{-1} (sub-watersheds 3, 8, 9, 11, 13, 14, and 15), and SWC >400 m ha^{-1} (sub-watersheds 7 and 10) (Table 4-3).*

Flow-related parameters were calibrated first followed by SY-related parameters, as recommended by Arnold et al. (2012) and Santhi et al. (2001). Daily runoff and SY data collected in the watersheds from 2015 to 2017 were used for model calibration. As noted above, the CN2 values were adjusted in the SWAT–CUP based on lower and upper limit values (standard deviations) calculated from the experimental plots (Table 4-5). The USLE_P and SLSUBBSN parameters of the treated Kecha watershed were not changed for the SY calibration because they were predefined using the existing condition of SWC practices in the watershed (Table 4-6).

Graphical and statistical model evaluation techniques were applied to determine how well the simulation results replicated the observed data. The statistical evaluations were calculated using the coefficient of determination of the linear regression curve (R^2; Moriasi et al., 2007), Nash–Sutcliffe efficiency (*NSE*; Nash and Sutcliffe, 1970), and percent bias (*PBIAS*; Gupta et al., 1999), as recommended in the literature (Moriasi et al., 2007; Santhi et al., 2001; Van Liew et al., 2007):

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\left[\sum_{i=1}^{n}(O_i - \bar{O})^2\right]^{0.5}\left[\sum_{i=1}^{n}(P_i - \bar{P})^2\right]^{0.5}}\right\}^2, \quad (4\text{-}5)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right], \quad (4\text{-}6)$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} * 100\right], \quad (4\text{-}7)$$

where O_i is the i^{th} observed value, $\bar{O}$ is the average observed value for the entire study period, P_i is the i^{th} predicted (modeled) value and $\bar{P}$ is the average of the predicted value over the entire study period.

The calibrated model was validated using independent daily flow and SY data for the period of 2018 at the outlets of the watersheds.

4.2.6. Framework to separate the effects of SWC practices on flow and SY responses

The impacts of SWC practices and LULC changes on runoff and soil loss have been widely studied at plot-scale experimental setups in the Ethiopian highlands (e.g., Ebabu et al., 2019; Nyssen et al., 2007, 2010; Sultan et al., 2017, 2018a, 2018b; Taye et al., 2013). Likewise, the impacts of LULC changes and climate variability on flow and SY are widely reported (Fenta et al., 2017; Gessesse et al., 2015; Lu et al., 2013; Mekonnen et al., 2018; Tang et al., 2011; Wang et al., 2007; Welde, 2016; Woldesenbet et al., 2018; Worku et al., 2017; Yang and Lu, 2018; Yang et al., 2017; Zhao et al., 2018). However, plot-scale findings on the implementation of SWC practices cannot be extrapolated to the watershed scale due to uncertainty in the spatial representation and processes that occur at the watershed scale. On the other hand, the short- and long-term effectiveness of SWC practices on runoff and SY at the watershed scale has not been sufficiently addressed (Haregeweyn et al., 2015; Lemann et al., 2016; Melaku et al., 2018; Osman and Sauerborn, 2001). Moreover, to our knowledge, no previous study has separated the effects of SWC practices from those of pre-existing changes in LULC and climate at the watershed scale. Therefore, to separate the effects of these other factors at watershed scale we used (1) a paired watershed approach comparing a watershed (Kecha) with SWC practices implemented to a watershed (Laguna) without them (Ebabu et al., 2018; Jemberu et al., 2017; Melaku et al., 2018; Sultan et al., 2018b) and (2) a single watershed (Kecha) approach comparing data before and after the implementation of SWC practices (Dagnew et al., 2015; Khelifa et al., 2017; Lemann et al., 2016).

Paired watershed approach

The paired watershed approach (Hewlett, 1971) has been the predominant method for detecting the effects of forest management on hydrology (Bosch and Hewlett, 1982). This approach establishes statistical relationships for catchment outlet responses between paired watersheds (Zégre et al., 2010). Although the suitability of this approach has been validated for future assessments of the impacts of SWC practices on hydrology responses (King et al., 2008), it has been rarely found in the body of scientific literature. In our application of this approach, we evaluated the effects of SWC practices by direct comparison of hydrological responses measured at the outlets of treated and untreated watersheds. However, these analyses were based on data from only the watershed outlets, which is not sufficient to evaluate the effectiveness of SWC practices at a spatial scale in the watershed. Thus, after flow and SY calibration, we used spatial modeling results to evaluate the effects of SWC practices throughout the paired watersheds as well as at their outlets. This approach, however, has limitations with regard to quantifying the separate effects of SWC practices on runoff and SY owing to the differences in LULC extent, total watershed area, and topography for the treated and untreated watersheds. It is also difficult to quantify the separate effects of LULC change and climate variability on runoff and SY with this approach. Nonetheless, it might be the best approach for watersheds for which there is little information about historical hydro-climatic variables and SWC practices.

Single watershed approach

We investigated the effectiveness of SWC practices in the treated Kecha watershed by comparing flow and SY before and after their implementation. To achieve this, we systematically transferred flow- and SY-related parameters (Cho et al., 2013; Dile et al., 2016b; Lemann et al., 2016) from the untreated Laguna watershed to the treated Kecha watershed to emulate untreated conditions in the Kecha watershed. Generally, we followed three steps to differentiate the single effects of SWC practices, LULC change, and climate variability in the Kecha watershed. The watershed has been part of the National Sustainable Land Management Program since 2011, so first the simulation was divided into two periods: 2000–2010 (period 1) and 2011–2018 (period 2), representing before and after the implementation of SWC practices (Figure 4-2). This resulted in five model simulations with two LULC scenarios, two climate periods (2000–2010 and 2011–2018) with and without any SWC implementation, and a simulation with 2016 LULC and with SWC practices for the period 2011–2018:

- Scenario 1: 2005 LULC map and climate data for period 1 without SWC practices;
- Scenario 2: 2016 LULC map and climate data for period 1 without SWC practices;
- Scenario 3: 2005 LULC map and climate data for period 2 without SWC practices;
- Scenario 4: 2016 LULC map and climate data for period 2 without SWC practices;

- Scenario 5: 2016 LULC map, climate data for period 2 with SWC practices.

After simulation of Scenarios 1 to 4 (without SWC practices), the separate effects of LULC change, climate variability, and SWC practices on runoff and SY were estimated using Equations 4-8 to 4-11. The separate impact of the LULC change was estimated considering the difference in simulated variables for the two LULC mapping periods (2005 and 2016) and averaged over the time periods 2000–2010 and 2011–2018 (Equation 4-8). The separate impact of climate variability was assessed by estimating the difference in the simulated variables for the two climate periods (2000–2010 and 2011–2018) and averaged over the LULC types (Equation 4-9). The separate impact of the SWC practices was estimated by calculating the difference in the simulated variables for cases with and without SWC for the 2016 LULC and the period when the interventions were implemented (2011–2018) (Equation 4-10).

$$\Delta LULC = \frac{1}{2} \times [(SC2 - SC1) + (SC4 - SC3)], \quad (4\text{-}8)$$

$$\Delta CL = \frac{1}{2} \times [(SC3 - SC1) + (SC4 - SC2)], \quad (4\text{-}9)$$

$$\Delta SWC = SC5 - SC4, \quad (4\text{-}10)$$

$$Total\, \Delta = \Delta SWC + \Delta LULC + \Delta CL, \quad (4\text{-}11)$$

where *SC1*, *SC2*, *SC3*, *SC4*, and *SC5* refer to the five scenarios; $\Delta LULC$, ΔCL, and ΔSWC are the changes in hydrological processes (flow, runoff, or SY) due to the separate effect of LULC change, climate variability, and SWC practices, respectively; and total Δ is the total change as a result of combined effects of LULC, climate variability, and SWC practices. Previous studies have applied similar approaches to evaluate the separate effects of change in LULC and climate on hydrological responses (e.g., Berihun et al., 2019b; Mekonnen et al., 2018; Woldesenbet et al., 2018; Yang et al., 2017).

4.2.7. Identifying soil erosion hotspot areas for future land management interventions

Soil erosion risk mapping to identify areas where sediment generation by soil erosion is the major threat to sustained agricultural production (erosion hotspots) is crucial for prioritizing areas for future conservation intervention (Betrie et al., 2011; Bewket and Teferi, 2009; Bieger et al., 2015; Gessesse et al., 2015; Welde, 2016). We mapped sub-watersheds and HRUs prone to soil erosion in the Kecha and Laguna watersheds based on the average seasonal SY (Betrie et al., 2011; Bewket and Teferi, 2009; Bieger et al., 2015; Gessesse et al., 2015; Welde, 2016). Our erosion risk analysis was focused on the 2015–2018 period because it provided reliable field data to validate our findings. Sub-watersheds were prioritized and erosion severity was classified based on Tamene (2005; cited by Gessesse et al., 2015), which was adapted from the 1984 Food and Agriculture Organization/United Nations Development Programme's prioritization of risk of soil removal and erosion on the basis of annual rate of erosion that they applied to the Ethiopian highlands. Accordingly, the soil erosion rate was divided into five severity classes: very high (>50 t ha^{-1} yr^{-1}), high (30–50 t ha^{-1} yr^{-1}), medium (15–30 t ha^{-1} yr^{-1}), low (5–15 t ha^{-1} yr^{-1}), and very low (0–5 t ha^{-1} yr^{-1}). The contribution to soil erosion of each LULC class was also estimated for the different slope ranges of the watersheds.

4.3. Results and discussion

4.3.1. Flow calibration and validation

Flow and sediment sensitive parameters were calibrated and validated at daily and monthly time-steps for the paired watersheds (see Tables 4-7 to 4-9; Figures 4-3, 4-4). The observed mean daily flow was 0.22 m^3 sec^{-1}, which was similar to the simulated flow during the calibration (0.22 m^3 sec^{-1}) and validation (0.21 m^3 sec^{-1}) periods for the Kecha watershed (Table 4-9).

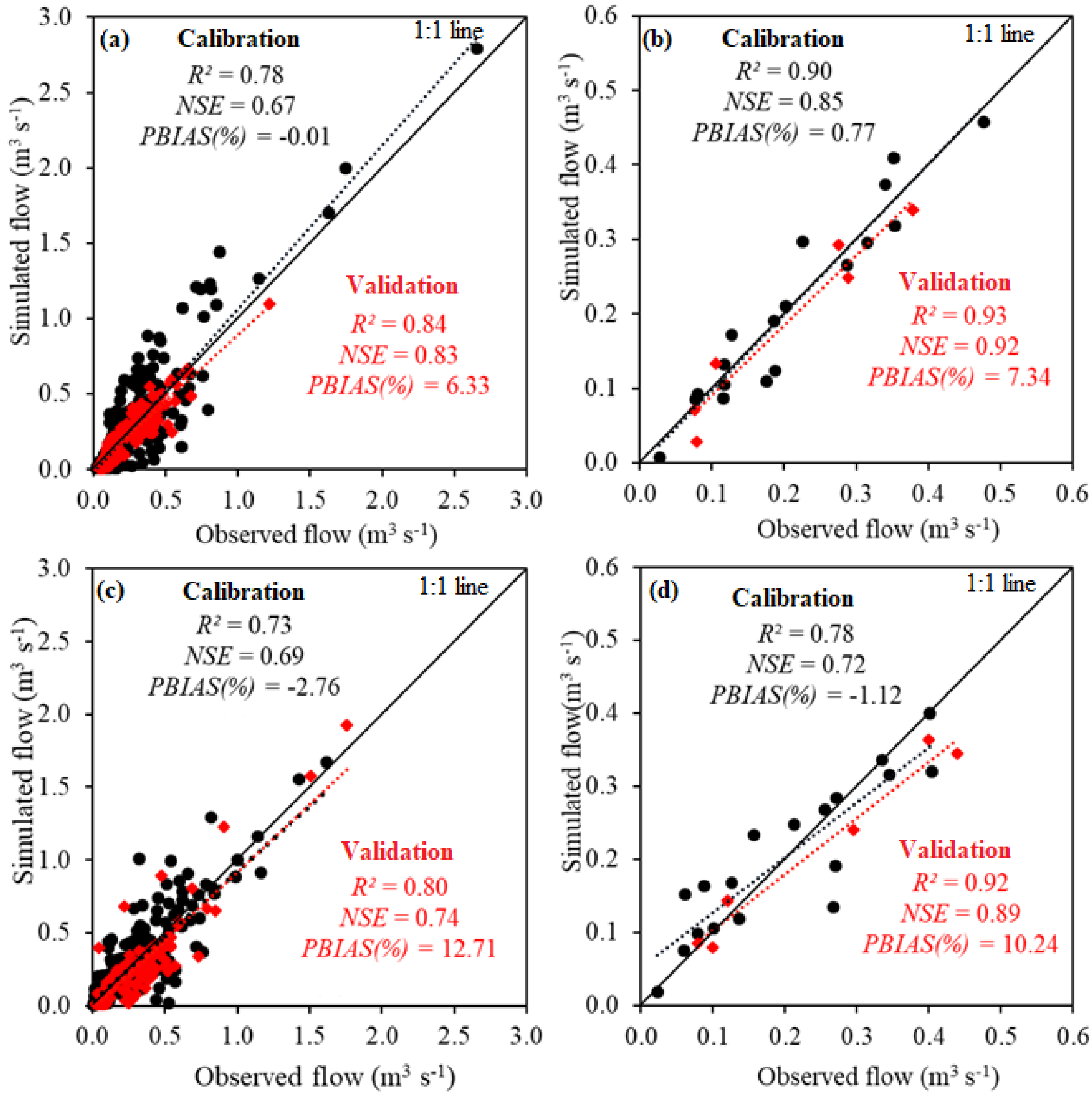

Figure 4-3 Goodness-of-fit of observed and simulated mean daily (a, c) and monthly (b, d) streamflow during the calibration and validation periods for the Kecha (a, b) and Laguna (c, d) watersheds.

The observed mean monthly flow was 0.21 m^3 sec^{-1} for the calibration period and 0.20 m^3 sec^{-1} for the validation period in the Kecha watershed, and the simulated values were 0.21 and 0.19 m^3 sec^{-1}, respectively (Table 4-9). According to the guidelines of Moriasi et al. (2007), model performance was very good with R^2, *NSE*, and *PBIAS* values for daily flow of 0.78, 0.67, and –0.01% for the calibration period and 0.84, 0.83, and 6.33% for the validation period, respectively, in the Kecha watershed (Figure 4-3a). Likewise, the model performance of the monthly simulations was also very good, according to the R^2, *NSE,* and *PBIAS* values (Figure 4-3b).

Table 4-9 Mean daily and monthly streamflow (m^3 sec^{-1}) and sediment yield (SY, t ha^{-1}) of the Kecha and Laguna watersheds for calibration (Cal.) and validation (Val.) periods

Kecha		Daily		Monthly	
		Observed	Simulated	Observed	Simulated
Flow	Cal.	0.22	0.22	0.21	0.21
	Val.	0.22	0.21	0.20	0.19
SY	Cal.	0.20	0.19	5.40	5.04
	Val.	0.15	0.14	4.05	3.71
Laguna					
Flow	Cal.	0.21	0.22	0.20	0.20
	Val.	0.26	0.23	0.24	0.21
SY	Cal.	0.41	0.45	11.16	12.22
	Val.	0.44	0.49	11.80	12.95

The observed and simulated mean daily flow rates for the Laguna watershed were 0.21 and 0.22 m^3 sec^{-1} for the calibration period and 0.26 and 0.23 m^3 sec^{-1}, respectively, for the validation period (Table 4-9). The observed and simulated mean monthly flow rates for the calibration period were both 0.20 m^3 sec^{-1} and for the validation period they were 0.24 and 0.21 m^3 sec^{-1}, respectively (Table 4-9). Model performance was very good, with R^2, *NSE,* and *PBIAS* values of 0.73, 0.69, and –2.76% for daily flow simulations in the calibration period and 0.80, 0.74, and 12.71% in the validation period, respectively (Figure 4-3c). For the monthly simulation, the values of R^2, *NSE*, and *PBIAS* improved to 0.78, 0.72, and –1.12% for the calibration period and 0.92, 0.89, and 10.24% for the validation period (Figure 4-3d).

In both watersheds, the model performance indicators (R^2 and *NSE*) varied over the same range of values: from 0.67 to 0.84 for daily and 0.70 to 0.9 for monthly comparisons (Figure 4-3).

According to the criteria of Moriasi et al. (2007) and Saleh et al. (2000), the model performance ranged from good to very good. Similarly, *PBIAS* values ranged from –2.76% to 0.77% for calibration and 6.33% to 12.71% for validation at daily and monthly time-steps (Figure 4-3), reflecting good and very good performance ratings for daily and monthly time-steps, respectively (Van Liew et al., 2007). Reasonable agreement between observed and simulated flow rates can be seen in the daily and monthly hydrographs for the Kecha and Laguna watersheds (Figure 4-4). However, the simulations slightly overestimated the observed flow rate during calibration and underestimated it during the validation period in both watersheds (Table 4-9, Figure 4-4). Based on goodness-of-fit and graphical evaluations, we conclude that the model can be used to predict flow rates in both watersheds for further analysis. In fact, our calibration and validation results for model flow were better than those reported in similar studies conducted in the Upper Blue Nile basin (e.g., Betrie et al., 2011; Dile et al., 2016b; Lemann et al., 2016; Lemma et al., 2019; Melaku et al., 2018; Setegn et al., 2010; Worku et al., 2017; Yesuf et al., 2015).

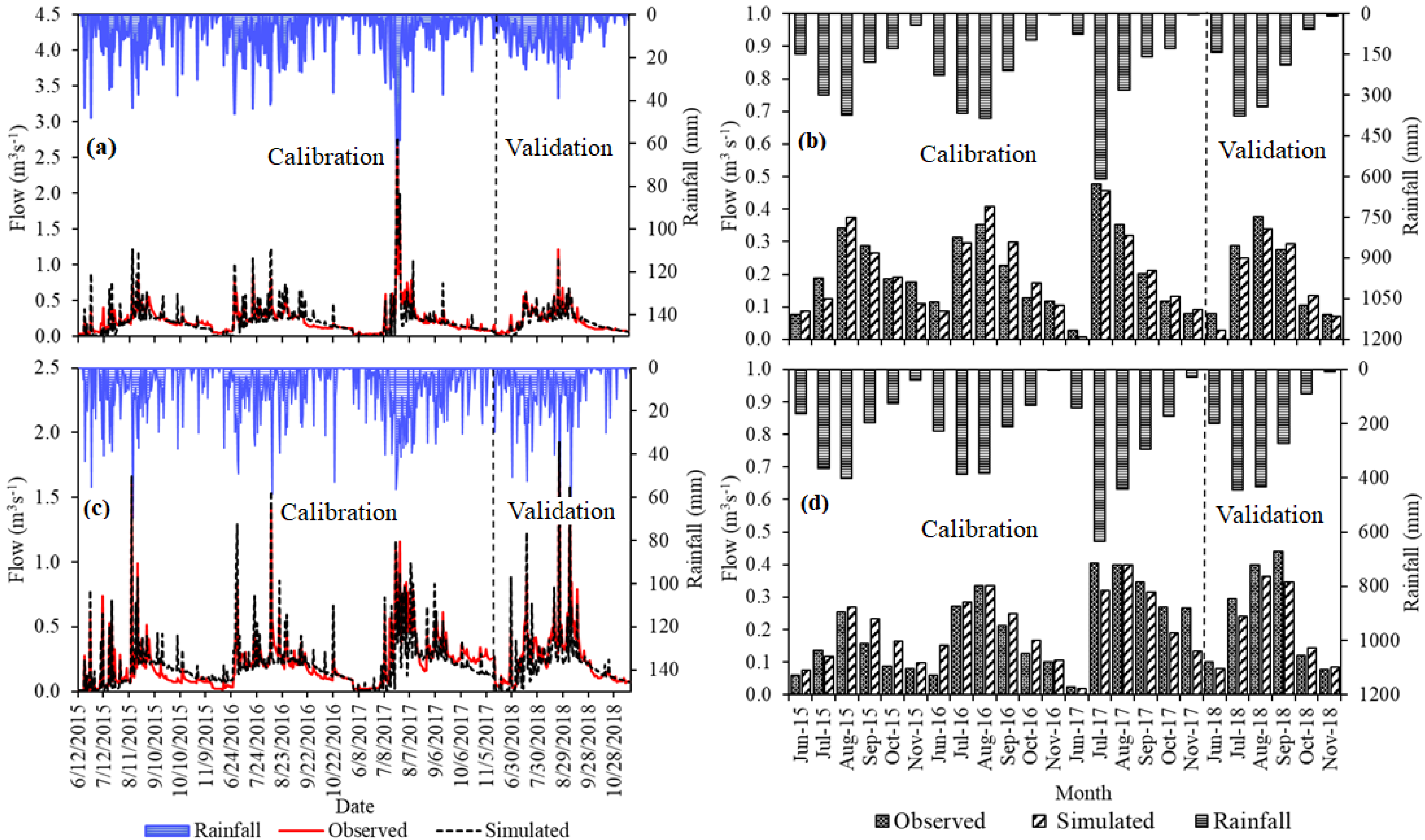

Figure 4-4 Observed and simulated daily (a, c) and monthly (b, d) streamflow and observed rainfall during the calibration and validation periods at the Kecha (a, b) and Laguna (c, d) watersheds.

4.3.2. Sediment calibration and validation

Daily and monthly SY were calibrated using data measured at the outlets of both watersheds (Table 4-9, Figures 4-5, 4-6).

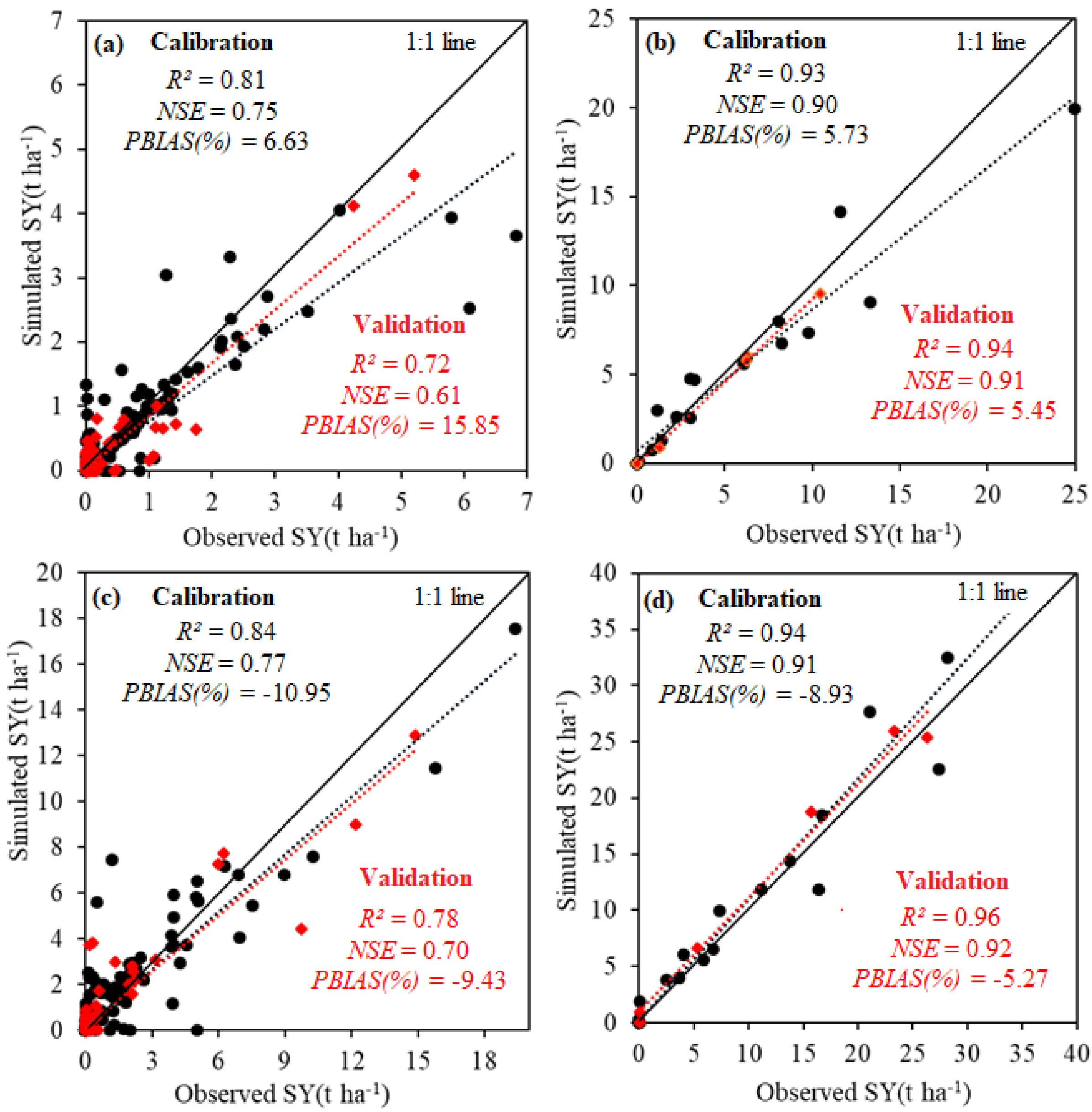

Figure 4-5 Goodness-of-fit of simulated and observed daily (a, c) and monthly (b, d) sediment yield (SY) during the calibration and validation periods for the Kecha (a, b) and Laguna (c, d) watersheds.

The observed average SY at the outlet of the Kecha watershed was 0.20 and 5.40 t ha^{-1} at daily and monthly time-steps for the calibration period and 0.15 and 4.05 t ha^{-1} for the validation period, respectively (Table 4-9). In both periods, the simulated SY was less than the observed SY. According to Moriasi et al. (2007), the SY simulations provided very good performance with R^2, *NSE*, and *PBIAS* values of 0.81, 0.75, and 6.63%, respectively, for daily and 0.93, 0.90, and 5.73% for monthly time-steps during the calibration period (Figure 4-5a, b). Likewise, during the validation period, the evaluation indices were very good (Figure 4-5a, b).

The average observed SY during the calibration and validation periods were similar at daily (ca. 0.4 t ha^{-1}) and monthly (ca. 11 t ha^{-1}) time-steps, whereas the simulated values were slightly higher (Table 4-9). Goodness-of-fit statistical indices showed very good performance with R^2, *NSE*, and *PBIAS* values of 0.84, 0.77, and –10.95% for daily simulations and 0.94, 0.91, and –8.93% for monthly simulations during the calibration period, respectively (Figure 4-5c, d). Likewise, model performance was very good for daily and monthly simulations during the validation period (Figure 4-5c, d).

As was the case for flow simulations, the SY simulation performance was similar in both watersheds with the R^2 and *NSE* values varying between 0.60 and 0.84 at daily and between 0.90 and 0.94 at monthly time-steps, respectively. The goodness-of-fit indices showed that the SY simulation performance was good to very good based on the recommendations of Moriasi et al. (2007) and Saleh et al. (2000). Despite SY model underestimation (*PBIAS* from 5.45% to 15.85%) in the Kecha watershed and overestimation (*PBIAS* from –5.27% to –10.95%) in the Laguna watershed (Figure 4-5, Table 4-9), comparison of daily and monthly observed SY with simulated SY showed very good agreement (Figure 4-6). However, the efficiency results may be reduced to a certain degree without consideration of the peak flow events in the watersheds.

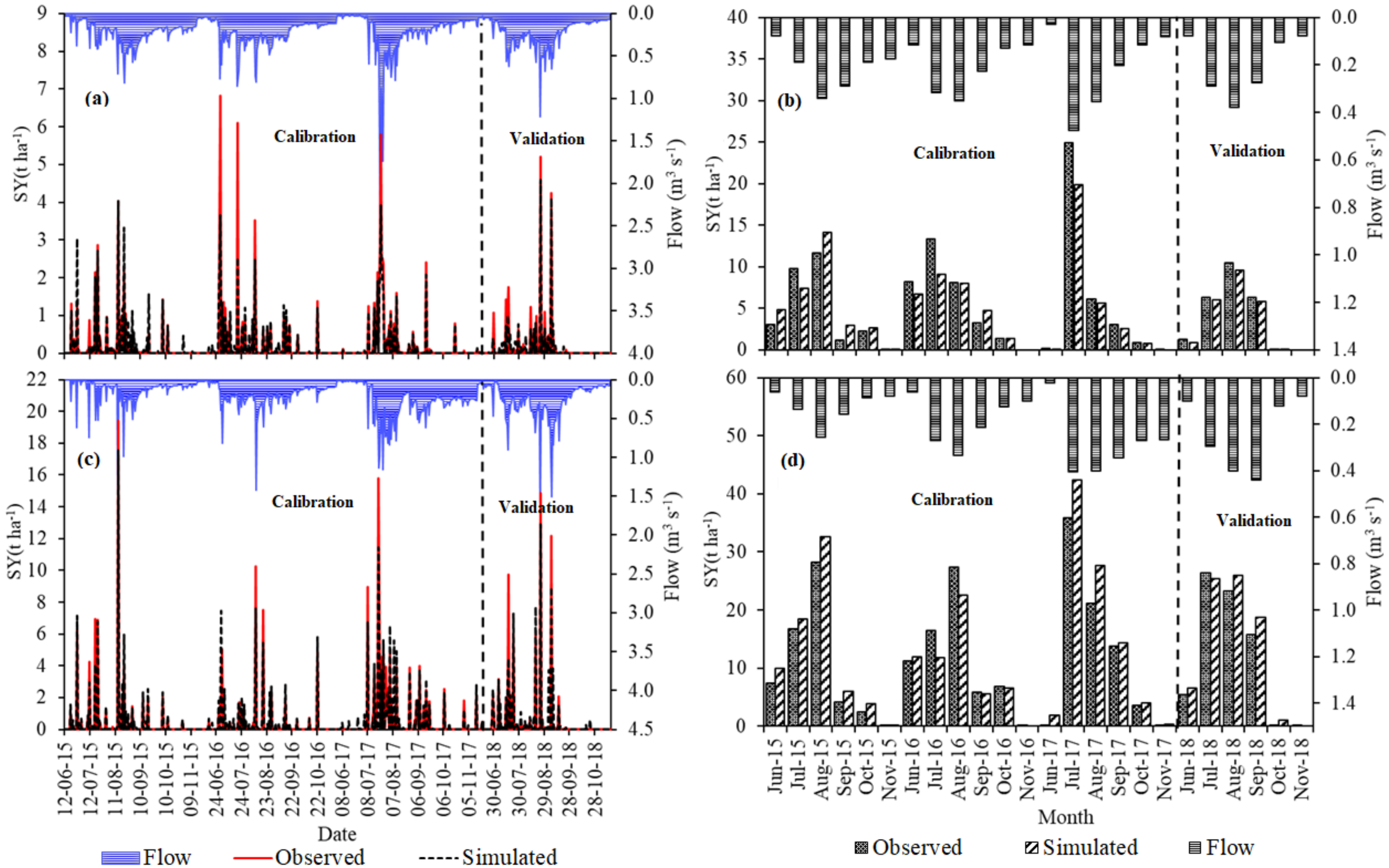

Figure 4-6 Observed and simulated daily (a, c) and monthly (b, d) sediment yield (SY) and observed flow during the calibration and validation periods at the Kecha (a, b) and Laguna (c, d) watersheds.

However, there was SY overestimation and underestimation of peaks in the Laguna watershed, especially during the calibration period (Figure 4-6). This is likely attributable to active gully erosion during peak rainfall events in both watersheds (Yibeltal et al., 2019a). The presence of active gullies can cause slope collapse and thereby increase sediment delivery (Yibeltal et al., 2019b). More than 50% of the seasonal SY in both watersheds (24 to 49 t ha^{-1} in the Kecha watershed and 58 to 70 t ha^{-1} in the Laguna watershed) was generated from only three to five daily rainfall events. This study achieved better model sediment calibration and validation results compared to previous studies in the Ethiopian highlands (e.g., Dile et al., 2016b; Easton et al., 2010; Lemann et al., 2016; Lemma et al., 2019; Melaku et al., 2018; Setegn et al., 2010; Worku et al., 2017; Yesuf et al., 2015). This might be attributable to the use of three different sediment rating curves (Table 4-1), which allowed us to better capture seasonal sediment dynamics, instead of the use of a single rating curve for the whole season (e.g., see Lemma et al., 2019; Melaku et al., 2018; Sultan et al., 2018b).

4.3.3. Seasonal flow and sediment responses in paired watersheds

Seasonal observed and simulated flow and SY at the outlets of the Kecha and Laguna watersheds varied considerably (Figure 4-7, Table 4-10). The observed seasonal flows ranged from 774 to 826 mm and simulated flows were 722 to 889 mm, respectively, for the Kecha watershed (Figure 4-7a) and between 554 and 1210 mm, and 682 to 1014mm, for the Laguna watershed (Figure 4-7a).

The seasonal observed and simulated SY varied at the outlets (Figure 4-7b) and sub-watersheds of the Kecha and Laguna watersheds (Table 4-10). The seasonal observed and simulated SY were similar in both watersheds, although SY of the Laguna watershed was twice that of the Kecha watershed. The seasonal observed SY ranged between 24 and 39 t ha^{-1} in the Kecha watershed, whereas the simulated SY varied from 22 to 32 t ha^{-1}. In the Laguna watershed, the seasonal observed SY varied from 59 to 74 t ha^{-1} and simulated values ranged from 58 to 91 t ha^{-1}, respectively (Figure 4-7b). Also, the spatial simulation results at the sub-watershed level provided SY estimates from 13 to 72 t ha^{-1} in the Kecha watershed and from 44 to 95 t ha^{-1} in the Laguna watershed, respectively (Table 4-10).

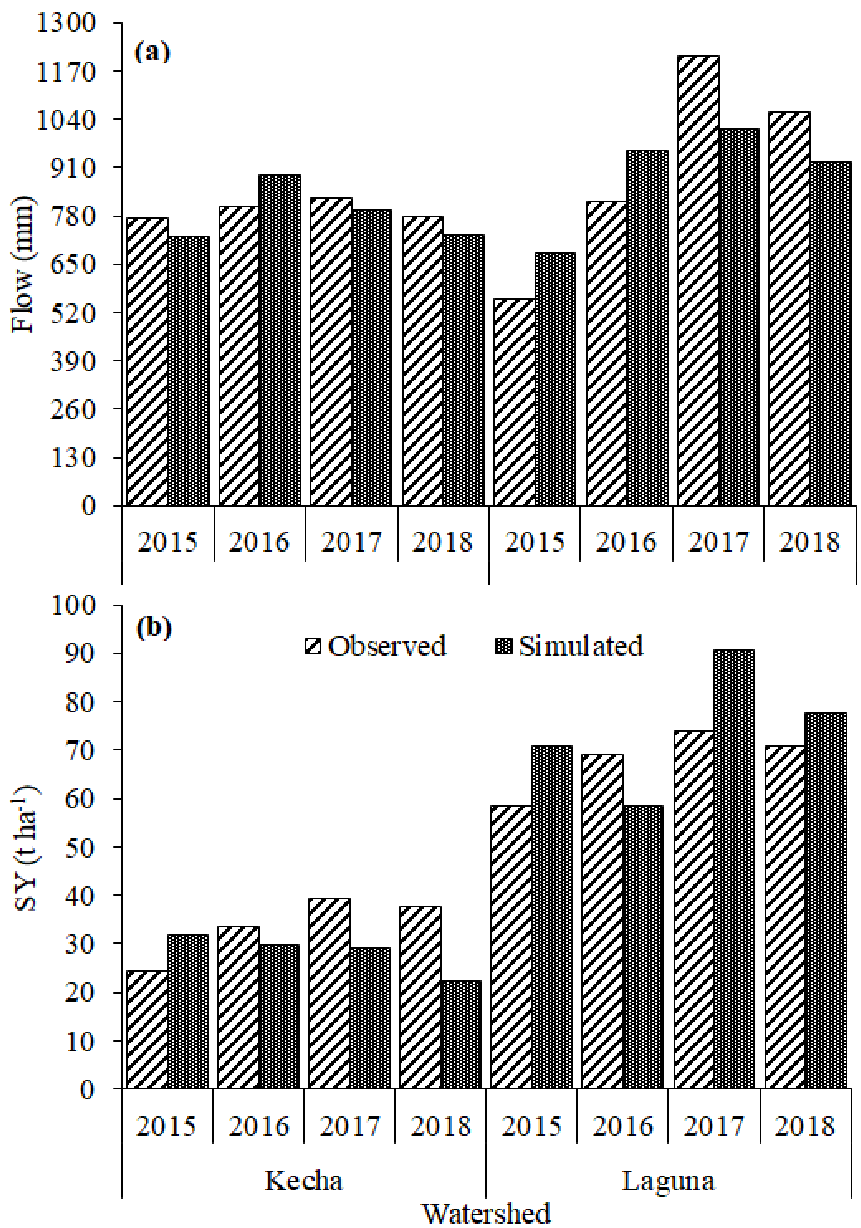

Figure 4-7 Observed and simulated (a) seasonal flow and (b) sediment yield (SY) from the Kecha and Laguna watersheds from 2015 to 2018.

Table 4-10 Total and mean seasonal sediment yield (SY) and priority level of sub-watersheds in the Kecha and Laguna watersheds

	Kecha					Laguna				
Sub watershed	Area (ha)	SY (t ha^{-1})	Total SY (tones)	Total SY (%)	Severity class	Area (ha)	SY (t ha^{-1})	Total SY (tones)	Total SY (%)	Severity class
SW1	51.37	18.50	950.09	8.05	Medium	11.67	44.07	514.17	1.98	High
SW2	13.27	26.35	349.54	2.96	Medium	21.83	68.26	1489.97	5.73	Very high
SW3	19.29	13.06	251.81	2.13	Low	33.77	47.71	1611.43	6.2	High
SW4	40.36	71.6	2889.63	24.5	Very high	54.57	78.27	4271.07	16.43	Very high
SW5	25.03	44.96	1125.03	9.54	High	38.57	87.68	3382.02	13.01	Very high
SW6	8.84	23.49	207.73	1.76	Medium	18.82	69.72	1311.95	5.05	Very high
SW7	25.12	18.56	466.24	3.95	Medium	13.74	79.64	1093.94	4.21	Very high
SW8	24.37	18.26	444.88	3.77	Medium	11.2	81.74	915.14	3.52	Very high
SW9	28.79	19.78	569.53	4.83	Medium	25.68	92.9	2386.13	9.18	Very high
SW10	17.78	15.86	281.93	2.39	Medium	20.51	70.8	1452.11	5.58	Very high
SW11	32.27	30.93	998.24	8.46	High	45.63	95.01	4335.06	16.67	Very high
SW12	26.72	65.39	1747.08	14.81	Very high	45.06	71.84	3237.33	12.45	Very high
SW13	33.4	23.68	790.81	6.7	Medium					
SW14	12.79	25.21	322.57	2.73	Medium					
SW15	30.39	13.17	400.14	3.39	Low					
Total	389.78	428.78	11795.25	100.00		341.04	887.66	26000.31	100.00	

The seasonal average observed and simulated SY in the Kecha watershed (Figure 4-7b) were about the same order of the magnitude (4.0–26.0 t ha^{-1}) as those reported by similar studies in the Ethiopian highlands (e.g., Addis et al., 2016; Haregeweyn et al., 2008; Setegn et al., 2010; Vanmaercke et al., 2010; Yesuf et al., 2015). Although simulated SY at the outlet of the Laguna watershed was higher (59–91 t ha^{-1}, Figure 4-7b), it was comparable to estimates (30–60 t ha^{-1}) in the Lake Tana basin (Setegn et al., 2010) and Upper Blue Nile basin (84 t ha^{-1}) (Easton et al., 2010). Some previous studies in paired watersheds (with and without SWC practices) in the Upper Blue Nile basin (Ebabu et al., 2018; Melaku et al., 2018) reported inconsistent results, some of which agree well with the results presented here. For example, the estimated SY from the Kecha watershed was in agreement with that reported from the treated Gumara-Maksegnit watershed in the Upper Blue Nile basin (33.5 t ha^{-1}; Melaku et al., 2018), whereas the estimated SY from the untreated Gumara-Maksegnit watershed (44.8 t ha^{-1}; Melaku et al., 2018) was slightly lower than our results for the Laguna watershed (59–91 t ha^{-1}; Figure 4-7b). Ebabu et al. (2018) reported a SY of 27.2 t ha^{-1} for a watershed treated with SWC practices in the humid highland region of the Upper Blue Nile basin, which was lower than our estimates for the Kecha watershed (39.26 t ha^{-1}). However, the estimated SY from their untreated case study watershed (71.2 t ha^{-1}) was in the same order of magnitude as our simulated SY in the Laguna watershed. The spatial simulations of SY at the sub-watershed level in the Kecha and Laguna watersheds, which ranged from 13.17 to 95.01 t ha^{-1} (Table 4-10), was generally comparable to estimates from previous studies in Ethiopia (0.4 to 125 t ha^{-1}; Bewket and Sterk, 2003; Bewket and Teferi, 2009; Gessesse et al., 2015; Tamene et al., 2017; Tibebe and Bewket, 2011; Welde, 2016). However, other studies reported far greater SY values of 130 to 170 t ha^{-1} (e.g., Herweg and Stillhardt 1999, cited in Bewket and Teferi, 2009). Overall, the SY values simulated in this study, both at the watershed outlets and spatially across the watershed, were consistent with observed data and with the large body of estimates in the literature.

4.3.4. Effect of SWC practices on flow and sediment responses

Paired watershed approach

Based on observed data and simulated results, the average seasonal flow of the treated Kecha watershed was about 14% less than the estimates for the untreated Laguna watershed (Figure 4-7). Similarly, the observed surface runoff, which was separated from total flow according to the method described by Arnold et al. (1994), and simulated surface runoff of the treated Kecha watershed were lower by about 28% and 36%, respectively, than the corresponding estimates of the untreated Laguna watershed. The contribution of surface runoff to total flow was about 44% in the Kecha watershed and 53% in the Laguna watershed. These results suggest that the Kecha watershed had a higher baseflow contribution to total flow, which could be attributed to enhanced recharge due to the SWC practices such as diversion ditches and bunds in the watershed (Dagnew et al., 2015). The reduction in surface runoff and increase in baseflow due to SWC practices was also reported in other watersheds in the Upper Blue Nile basin (e.g., Melaku et al., 2018; Sultan et al., 2018b). For example, based on a paired watersheds approach in a tropical humid highland watershed of Ethiopia, Sultan et al. (2018b) reported that SWC practices reduced runoff by 34%, although changes in other watershed characteristics such as LULC, slope, and configuration of the watershed may have masked the effect to some extent. Melaku et al. (2018) also reported that the flow in a treated watershed was reduced by about 33% as compared to the untreated watershed in an experimental study at the Gumara-Maksegnit site in the Upper Blue Nile basin.

SWC treatment reduced the observed SY by about 51% and simulated SY by about 62% (the values were normalized by watershed area) in the Kecha watershed (Figure 4-2). The reduction in

SY may be related to the decrease in runoff volume and sediment trapping by the diversion ditches of the bunds. The average spatiotemporal SY in the treated Kecha watershed was reduced by about 68% compared to the same estimate in the untreated Laguna watershed. Other studies reported even higher reductions in SY due to SWC treatment. For example, Ebabu et al. (2018) reported more than 100% SY reductions due to implementation of SWC practices in the Guder paired watershed of the Upper Blue Nile basin. Lemann et al. (2016) also indicated that SWC practices reduced SY in the Gerda and Minchet watersheds in the northwestern Ethiopian highlands by more than 100% (i.e., from 37 to 17 t ha^{-1}). The relative difference between our findings and those of other studies (Ebabu et al., 2018; Lemann et al., 2016; Melaku et al., 2018) may be attributed to differences in topography, climate, the nature and implementation of SWC practices, and the robustness of the methodology used to evaluate the impacts of SWC practices.

In a paired watersheds approach, it is challenging to definitively separate the effects of SWC practices from changes in LULC and climate due to several factors. Some of the outstanding factors include (i) Slightly higher coverage of steep and very steep slope areas in the Laguna watershed (Figure 4-1a, Table 4-3), which may facilitate a more rapid runoff response, leading to concentrated flows that increase erosion at lower positions on the slopes and drainage channels. (ii) Difference in LULC area coverage, particularly in forest and grazing land uses (Table 4-2). (iii) Differences in catchment area and drainage density (Figure 4-1). A high drainage density indicates a well-developed channel system, which encourages rapid flow of surface runoff and thereby SY from the hill slopes. (iv) Differences in soil characteristics (e.g., soil type, depth), which are very important in water infiltration and runoff generation (Neitsch et al., 2011). (v) Difference in elevation (Figure 1-6), which may cause differences in flow and SY (Bosch and Hewlett, 1982; Zégre et al., 2010). Because of these factors, estimating the separate effects of SWC practices using a paired watershed approach has higher uncertainty than the analysis of a single watershed before and after implementation of SWC practices.

Single watershed approach

In the single watershed approach, we studied the combined and separate effects of SWC practices and LULC, as well as the effect of climate variability, on flow and SY in the Kecha watershed before and after implementation of SWC practices (Tables 4-11, 4-12). Implementation of SWC practices caused reductions in surface runoff and SY by about 40% and 43%, respectively, but increased the total flow by about 21% (Table 4-11). Changes in LULC caused less absolute change in total flow, surface runoff, and SY compared to SWC practices and climate variability (Table 4-11). However, whereas SWC practices and climate variability tended to decrease these hydrological variables except total flow, LULC change caused increases, which is related to the expansion of cultivated land during the study period (Table 4-2; Berihun et al., 2019b). Climate variability had a considerable negative effect on total flow, surface runoff, and SY (Table 4-11). The decrease in surface runoff is most likely a response to higher evapotranspiration and a decrease in rainfall (Berihun et al., 2019b). On the other hand, the decrease in surface runoff due to climate variability reduced SY in the watershed (Figure 4-7), which was also observed by Ebabu et al. (2019) in agro-ecological experimental plots in the Upper Blue Nile basin. The highest contribution of SWC implementation was to the total changes of total flow, surface runoff, and SY (followed by climate variability), accounting for about 65–78% change in these parameters (Table 4-12).

Although the approach we used is different, the SWC-related reductions of SY we identified in the Kecha watershed are within the ranges of other estimates that have been reported for the Ethiopian highlands and similar agro-ecological regions.

Table 4-11 Changes in mean seasonal (June to mid-November) streamflow (Q), surface runoff (SR), and sediment yield (SY) for separate and combined effects of LULC change, climate variability (CL), and soil and water conservation (SWC) practices

Seasonal simulation value of Q, SR and SY					ΔLULC		ΔCL		ΔSWC		Total Δ	
Scenarios	LULC	Climate	SWC	Q (mm)	mm	%	mm	%	mm	%	mm	%
SC1	2005	2000–2010	Without	779.83								
SC2	2016	2000–2010	Without	789.59	9.75	+1.25	–72.63	–9.31				
SC3	2005	2011–2018	Without	707.20					152.24	+21.28	87.81	+13.13
SC4	2016	2011–2018	Without	715.40	8.20	+1.16	–74.18	–9.40				
SC5	2016	2011–2018	With	867.64								
				Average	*8.98*	*+1.21*	*–73.41*	*–9.35*	*152.24*	*+21.28*	*87.81*	*+13.14*
	LULC	Climate	SWC	SR (mm)	mm	%	mm	%	mm	%	mm	%
SC1	2005	2000–2010	Without	630.64								
SC2	2016	2000–2010	Without	674.10	43.46	+6.89	–60.33	–9.57				
SC3	2005	2011–2018	Without	570.31					–246.44	–40.40	–267.06	–43.01
SC4	2016	2011–2018	Without	610.02	39.71	+6.96	–64.08	–9.51				
SC5	2016	2011–2018	With	363.58								
				Average	*41.59*	*+6.93*	*–62.20*	*–9.54*	*–246.44*	*–40.40*	*–267.06*	*–43.01*
	LULC	Climate	SWC	SY ($t\ ha^{-1}$)	$t\ ha^{-1}$	%	$t\ ha^{-1}$	%	$t\ ha^{-1}$	%	$t\ ha^{-1}$	%
SC1	2005	2000–2010	Without	79.38								
SC2	2016	2000–2010	Without	84.83	5.45	+6.87	–4.58	–5.77				
SC3	2005	2011–2018	Without	74.80					–34.85	–43.30	–33.75	–41.52
SC4	2016	2011–2018	Without	80.48	5.68	+7.59	–4.36	–5.14				
SC5	2016	2011–2018	With	45.63								
				Average	*5.57*	*+7.23*	*–4.47*	*–5.45*	*–34.85*	*–43.30*	*–33.75*	*–41.52*

Table 4-12 Contributions (%) of soil and water conservation (SWC) practices, land use/land cover (LULC) change, and climate variability (CL) for the change in mean total flow, surface runoff, and sediment yield through the single watershed approach in the Kecha watershed

Factors	Total flow		Surface runoff		Sediment yield	
	mm	%	mm	%	t ha^{-1}	%
LULC	8.98	3.83	41.59	11.87	5.57	12.41
CL	–73.41	31.29	–62.20	17.76	–4.47	9.96
LULC and CL	–64.43	35.11	–20.61	29.63	1.10	22.37
SWC	152.44	64.89	–246.44	+70.37	–34.85	77.63
Total Δ	87.81	100.00	–267.06	100.00	–33.75	100.00

**Absolute values were considered to calculate the contribution of each factor*

For example, Betrie et al. (2011) and Molla and Sisheber (2017) reported that SY decreased by 9–76% after implementation of SWC practices. Plot-level experiments conducted in contrasting agro-ecologic watersheds of the Upper Blue Nile basin also showed that SWC practices caused a reduction of SY by 11–68% (Ebabu et al., 2019). Gebremicheal et al. (2005) and Herweg and Ludi (1999) reported a 72–100% reduction in SY in watersheds in Ethiopia and Eritrea after construction of stone bunds. Similar impacts of SWC practices were also reported in other regions of the world. For example, Abouabdillah et al. (2014) and Khelifa et al. (2017) in Tunisia and Wang et al. (2007) in China reported that SWC practices such as bench terraces and stone bunds decreased SY by 4–86% in their respective study watersheds.

Although SWC practices have had major effects on flow, surface runoff, and SY, LULC change and climate variability also play important roles in shaping biophysical processes in watersheds. Substantial conversion of LULC—mainly through expansion of cultivated land at the expense of natural vegetation (grazing and bush lands)—caused an increase in total flow and surface runoff in watersheds in the highlands of Ethiopia (e.g., Berihun et al., 2019b). On the other hand, seasonal climate variability—mainly an increase in temperature—caused a decrease in flow, surface runoff, and SY in some watersheds in the highlands of Ethiopia (e.g., Fenta et al., 2017; Gessesse et al., 2015; Woldesenbet et al., 2018; Worku et al., 2017). The present study estimated a 7% increase in surface runoff at the Kecha watershed as a result of LULC change (Table 4-11), which is consistent with a previous study by Berihun et al. (2019b). Likewise, Worku et al. (2017) reported that a change in LULC (particularly expansion of cultivated land and settlement areas) between 2010 and 2014 increased the surface runoff of the Beressa watershed of the Upper Blue Nile basin by 4.5–7.5%. Mekonnen et al. (2018) also reported that the annual surface runoff in the Upper Blue Nile basin increased by 9.9% from 1973 to 1995 due to a reduction of forest coverage by 5.1% and an increase of cultivated land by 4.6%, and Gessesse et al. (2015) reported substantial increases (>14%) in surface runoff due to changes in LULC in the Ethiopian highlands. Elsewhere, a study in the Miyun reservoir watershed in China also showed that a LULC change caused a 6.6% change in flow for the period 1999 to 2005 (Tang et al., 2011). Other studies showed decreases in surface runoff as a result of LULC change, especially in cases where expansion of forest, grazing, and shrub lands occur at the expense of cultivated and barren lands (Mango et al., 2011; Yang and Lu, 2018; Yang et al., 2017).

The expansion of cultivated land in the study watersheds (Table 4-2; Berihun et al., 2019b) also increased SY by 7.23% for the years 2005 and 2016. Several studies also reported that an expansion in cultivated land caused higher SY as compared to expansion in other LULC classes, such as forest, grazing, and bush lands (e.g., Betrie et al., 2011; Bieger et al., 2015; Gessesse et al., 2015; Welde, 2016). However, most of these studies in Ethiopia reported higher SY increases (37.0–137.5%) due to expansion of agricultural land (Gessesse et al., 2015; Worku et al., 2017; Yang and Lu, 2018). The difference in these estimates may reflect differences in the extent of the LULC change, climate of the study areas, and other watershed characteristics such topography and soil type.

As was the case in our study watersheds, decreasing total flow, surface runoff, and SY due to climate variability were also reported in previous studies (e.g., Fenta et al., 2017; Lu et al., 2013; Mango et al., 2011; Wang et al., 2007; Zhao et al., 2018). For instance, Berihun et al. (2019b) reported a decrease in total flow mainly attributed to an increase in evapotranspiration in the Upper Blue Nile basin. Elsewhere, Mango et al. (2011) reported a 3% reduction of annual rainfall in Kenya caused a decrease in total flow by 25%. The integrated effects of LULC and climate change in the Kecha watershed also caused a 3% decrease in surface runoff (Table 4-9), which was consistent with findings by Yang et al. (2017) in the Heihe River basin in China. Our SY findings were similar to results reported in China, where SY was reduced by 5.0–10.5% on the Northern Loess Plateau (Zhao et al., 2018) and by 4–61% in semi-arid climates (Lu et al., 2013) because of climate variability.

While addressing the limitations of a paired watershed approach, this study separated the effects of SWC practices from those of changes in LULC and climate. Our estimates were strengthened by applying multiple approaches to estimate the separate effects of SWC practices on changes in surface runoff and SY, which were reductions of about 14–40% and 43–68%, respectively. Our results also showed that the SWC practices played a more dominant role in reducing runoff and SY than LULC changes and climate variability.

4.3.5. Prioritization of soil erosion hotspots for future land management interventions

Soil erosion conditions in the sub-watersheds of the Kecha and Laguna watersheds were characterized and prioritized for future intervention according to the average seasonal simulated

SY for the period 2015–2018. In the Kecha watershed, more than half of the total SY (56.56%) was generated from 4 of the 15 sub-watersheds, which represented 32% of the watershed area (Table 4-13, Figure 4-8). For the high and very high soil erosion severity classes (seasonal SY >30 t ha^{-1}), SY ranged from 30.93 to 71.6 t ha^{-1}, with an average 53.22 t ha^{-1} (Tables 4-10, 4-13).

Table 4-13 Soil erosion severity classes, area coverage, seasonal sediment yield (SY) and priority levels for soil and water conservation (SWC) implementation in the Kecha and Laguna watersheds

Watershed	Severity class* (t ha^{-1} yr^{-1})	No. SW	Area (ha)	Area (%)	Mean SY (t ha^{-1})	Total SY (tones)	Total SY (%)	Priority level
Kecha	Very high (>50)	2	67.08	17.21	68.49	4594.37	38.39	I
	High (30 – 50)	2	57.30	14.70	37.94	2174.06	18.17	II
	Medium (15 – 30)	9	215.73	55.35	21.08	4546.58	37.99	III
	Low (5 – 15)	2	49.67	12.74	13.11	651.33	5.44	IV
	Total	15	389.78	100.00		11966.33	100.00	
Laguna	Very high (>50)	10	295.60	86.68	79.59	23526.03	91.86	I
	High (30 – 50)	2	45.44	13.32	45.89	2085.40	8.14	II
	Total	12	341.04	100.00		25611.43	100.00	

**SW: sub-watershed; Severity classes were adopted from Haregeweyn et al. (2015) and Tamene (2005; cited in Gessesse et al. 2015) (adopted from the 1984 Food and Agriculture Organization/United Nations Development Programme's*

In the medium soil erosion severity class (15–30 t ha^{-1}), 38% of the total SY was generated from 55.35% of the total catchment area in the Kecha watershed (Table 4-11, Figure 4-8). Areas in the low soil erosion severity class represented only 12.74% of the entire area of the Kecha watershed and contributed 5.44% to the total SY (Tables 4-10, 4-13).

In the Laguna watershed, only two soil erosion severity classes were identified. The very high and high soil erosion severity classes covered 86.68% and 13.32% of the catchment area, respectively (Table 4-11). SY generated from the very high severity class accounted for about 92% of the total generated SY, in which seasonal SY ranged from 68.26 to 95.01 t ha^{-1} (Tables 4-10, 4-13).

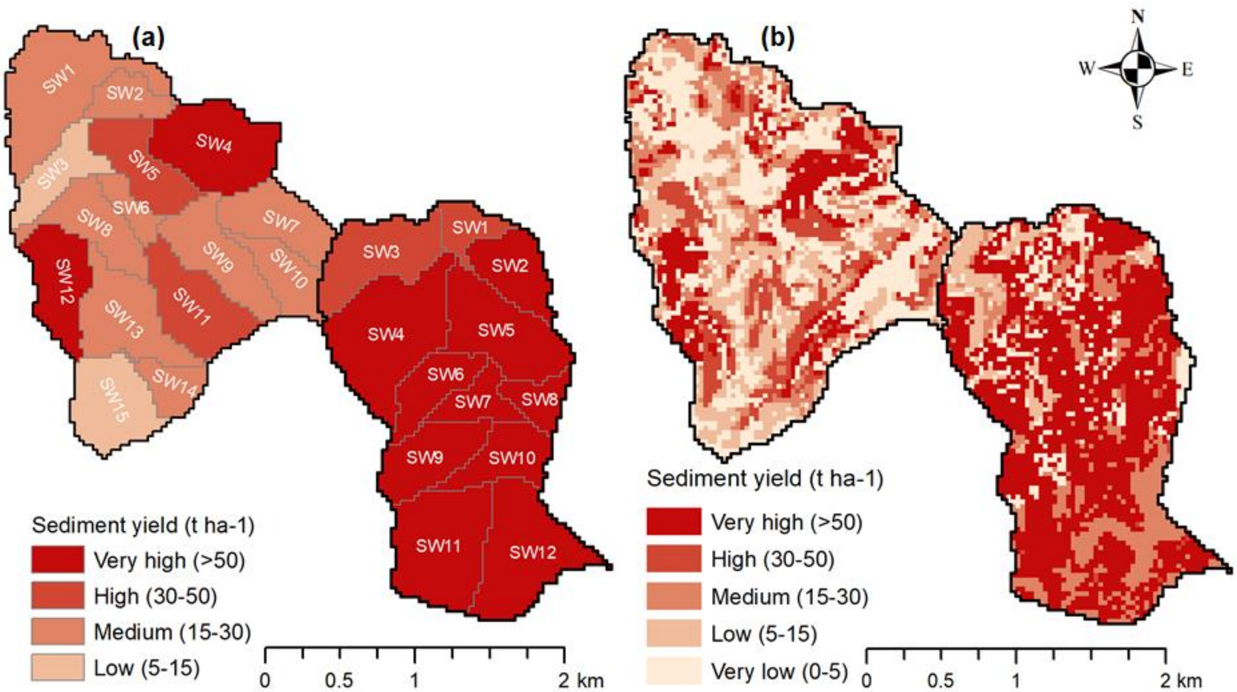

Figure 4-8 Soil erosion hotspot areas characterized based on average seasonal simulated sediment yield. Identifications of soil and water conservation priority locations was based on results at the (a) sub-watershed (SW) and (b) hydrologic response unit level. The analysis was conducted using 2016 land use/land cover data.

The spatial scale of soil erosion in the Laguna watershed was far greater than that of the Kecha watershed (Figure 4-8). The entire Laguna watershed is under the severe soil erosion condition, in which the soil erosion rate is much higher than the soil formation rate (22 t ha^{-1}, Hurni, 1993).

The higher soil erosion rate in the Laguna watershed is due to lack of SWC treatment and the very steep slope classes there (Table 4-4).

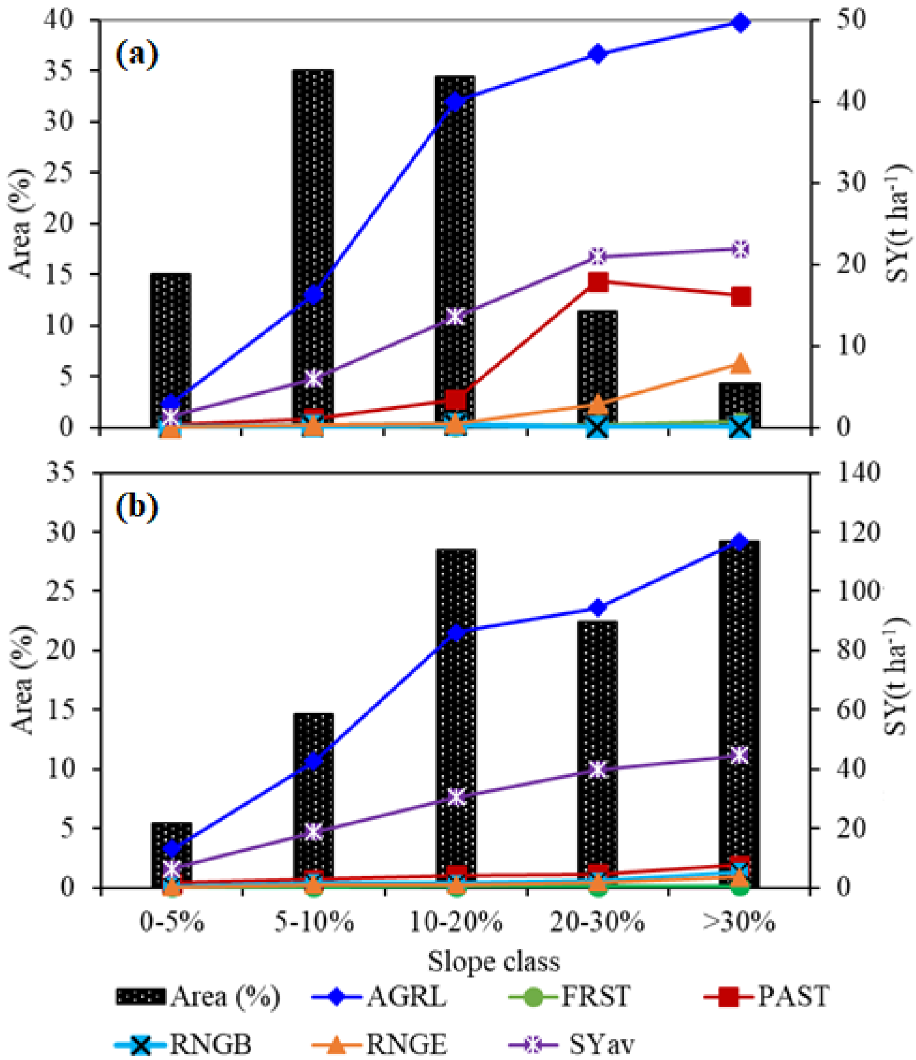

Figure 4-9 Average seasonal sediment yield (SY) estimated at the hydrologic response unit level for different land use/land cover and slope classes in the Kecha (a) and Laguna (b) watersheds. Note the different SY scale in the two panels.

Areas having slopes >10% were characterized by an average seasonal SY of about 18 t ha^{-1} in the Kecha watershed and 38.28 t ha^{-1} in the Laguna watershed, where the erosion was more pronounced in cultivated LULC classes (Figure 4-9). More SY was observed at the bottom of slopes in the Laguna watershed, which may be a response to flow energy dissipation and deposition in flat areas (Betrie et al., 2011). Areas in the high and very high soil erosion severity classes were found to have high active gully densities in the paired watersheds, and the severity was highest in the untreated Laguna watershed (Yibeltal et al., 2019a).

The SY generated from each HRU is mapped in Figure 4-8b, and the contribution of each LULC class is presented in Figure 4-9. The soil erosion severity classes in both watersheds ranged from very low (0–5 t ha^{-1}) to very high (>50 t ha^{-1}). Most of the Kecha watershed was categorized in the very low and low severity classes, covering about 56% of the catchment area (Table 4-14). In the Laguna watershed, however, about 61% of the catchment area was in the very high severity classes, compared with only 15% of the Kecha catchment area. In both watersheds, generated SY (t ha^{-1}) increased as slope increased, and SY was highest in cultivated land (cf., Betrie et al., 2011) followed by grazing land (Figure 4-9). Soil erosion was highest in the cultivated land due to plowing and animal pressure. The average SY generated from the cultivated land in the Laguna watershed was twice that of the Kecha watershed. Similarly, Kidane et al. (2019) reported that the majority of the soil erosion in the Guder watershed (West Shewa Zone) of the Upper Blue Nile basin occurred in cultivated land. The rate of soil loss (31 t ha^{-1}) from cultivated land in the Kecha watershed was in agreement with those in control plots of cultivated land studied by Ebabu et al. (2019) in the same watershed. However, the rate of soil loss from the cultivated LULC class in the Laguna watershed (71 t ha^{-1}) was higher than the 42 t ha^{-1} estimated by Hurni (1993) for Ethiopian highlands.

Soil erosion is a threat to agricultural production in the study area, and integrated SWC practices are needed to abate its serious agro-ecological consequences. The spatial estimates of soil erosion within the watersheds will help to prioritize the implementation of feasible SWC practices in areas with high erosion risk. Areas in the very high, high, and medium soil erosion severity classes should receive priority (in that order) for implementation of SWC practices (Table 4-13). Because cultivated land and slopes greater than 10% were found to be in very high and high soil erosion severity classes, these areas should be given immediate priority in implementing SWC practices to reduce runoff and soil erosion in the watersheds.

Table 4-14 Area contribution of each soil erosion severity class based on sediment yield results generated at the hydrologic response unit level

Soil erosion severity classes (t ha^{-1})	Kecha		Laguna	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Very low (0–5)	135.85	34.85	35.57	10.43
Low (5–15)	82.51	21.17	24.37	7.15
Medium (15–30)	56.54	14.51	70.49	20.67
High (30–50)	55.88	14.34	3.29	0.97
Very high (>50)	58.99	15.13	207.32	60.79
Total	389.78	100.00	341.04	100.00

4.4. Conclusions

We evaluated the impact of SWC practices on surface runoff and SY by applying paired and single watershed approaches using the SWAT model in the Upper Blue Nile basin of Ethiopia. During the calibration processes, flow and sediment model input parameters such as CN2, USLE_P, and SLSUBBSN were adjusted based on measured data from treated and untreated watersheds. Evaluation of the calibration and validation periods using observed data in the paired watersheds showed very good model performance during the study periods. The model slightly overestimated simulated flow compared to measured values during the calibration period and underestimated it during the validation period in watersheds with and without SWC. Although the model underestimated SY in the Kecha watershed and overestimated it in the Laguna watershed, overall there was a good agreement between observed and simulated SY.

This study enabled us to differentiate the impact of SWC practices from changes of LULC and climate variability by using the paired and single watersheds approaches. Results from the paired watershed approach revealed that SWC practices reduced the surface runoff in the treated watershed by about 28–36% and SY by about 51–68% compared to the untreated watershed. The single watershed approach also showed that implementation of SWC practices reduced surface runoff by about 40% and SY by about 43%. Thus, SWC practices may reduce surface runoff and SY by about 28–40% and 43–68%, respectively. SWC practices had major effects on total flow, surface runoff, and SY and accounted for about 65–78% of the total change, which was nearly double the combined effects of LULC change and climate variability. LULC change—mainly expansion of cultivated land at the expense of natural vegetation cover—caused an increase in total flow, surface runoff, and SY in the Kecha watershed, whereas seasonal climate variability reduced these hydrological components. Our soil erosion severity analysis showed that the untreated Laguna watershed was exposed to serious soil erosion (86% of the area had an annual soil erosion rate of >50 t ha^{-1}), which indicates that there is a need to immediately implement SWC practices across most of the catchment. In general, our findings suggest that SWC practices are central to overcoming the serious challenges associated with land degradation in the Ethiopian highlands and in regions with similar environmental settings.

CHAPTER 5

5. General Conclusions and Recommendations

5.1. Conclusions

In this study, we analyzed the hydrological and sediment responses to LULC, climate variability and soil water conservation (SWC) practices in three different agro-ecologies–drought-prone paired watersheds [Guder (highland), Aba Gerima (midland), and Debatie (lowland)] of the Upper Blue Nile basin. The runoff and sediment yield (SY) responses to SWC practices were conducted only in Aba Gerima paired watersheds due to the presence of clear variation in terms of SWC practices implementation between Kecha and Laguna watersheds.

The LULC results revealed that substantial amounts of spatial and temporal LULC change occurred over the past 35 years in the three study watersheds. Cultivated land showed a remarkable increasing trend in the Debatie and Aba Gerima paired watersheds from 1982 to 2016/2017 and in Guder watersheds between 1982 and 2006, mainly at the expense of natural vegetation such as forest cover, grazing land, and bushland. In contrast, vegetation covers in the form of plantation increased markedly in the Guder watersheds, mainly at the expense of cultivated land, especially from 2012 to 2017. Population growth and changing farming practices (e.g., growing *A. decurrens* in Guder and khat in Aba Gerima) were the major drivers of LULC changes. In general, based on the LULC changes in the different agro-ecologies and the varying farming practices in line with population growth, the basin experienced a general trend both towards “more people more trees” and “more people more erosion”. The changes have had both positive and negative socio-economic and environmental consequences, and the LULC changes are likely to have more possible implications in terms of land degradation and hydrological responses at the watershed as well as the basin scale.

The hydrologic responses such as surface runoff and ET (1982 – 2016) to historical LULC change (1982–2016/17) and climate variability were evaluated in Guder (Kasiry, highland), Aba

Gerima (Kecha, midland), and Debatie (Sahi, lowland) watersheds. Besides LULC change, the long-term mean annual temperature showed significant ($P < 0.05$) variation across the three watersheds, with the mean annual temperature increasing by 0.04 °C in Kasiry, 0.02 °C in Kecha, and 0.03 °C in Sahi from 1982 to 2016. Results revealed that LULC change positively influenced the annual surface runoff in all three watersheds. Because there was no significant trend in annual rainfall, this climate factor, thus, did not significantly affect the estimated surface runoff change. LULC change, and climate variability in terms of temperature, had negative and positive effects, respectively, on the changes in annual ET. However, even though climate variability increased ET, from 33.6% in Kecha to 42.1% in Kasiry, LULC change resulting in a reduction of natural vegetation had an offsetting effect that led to an overall decrease in ET, from a 15.8% reduction in Kasiry to 32.8% in the Kecha watershed over the 35 years. In general, the role of LULC change is more dominant than that of climate variability in the annual surface runoff and ET responses. These effects are mainly attribute to LULC conversion and temperature variation across the watersheds during the study period.

Moreover, we evaluated the impact of SWC practices on surface runoff and SY by employing paired and single watershed approaches using the SWAT model in Aba Gerima paired (Kecha and Laguna) watersheds. Results from the paired watershed approach revealed that SWC practices reduced the surface runoff in the treated watershed by about 28–36% and SY by about 51–68% compared to the untreated watershed. The single watershed approach also showed that implementation of SWC practices reduced surface runoff by about 40% and SY by about 43%. Thus, in general, SWC practices may reduce surface runoff and SY by about 28–40% and 43–68%, respectively. SWC practices had major effects on total flow, surface runoff, and SY and accounted for about 65–78% of the total change, which was nearly double the combined effects of LULC change and climate variability. LULC change—mainly expansion of cultivated land at the expense of natural vegetation cover—caused an increase in total flow, surface runoff, and SY in the Kecha watershed, whereas seasonal climate variability reduced these hydrological components. Our soil erosion severity analysis showed that the untreated Laguna watershed was exposed to serious soil erosion (86% of the area had an annual soil erosion rate of >50 t ha^{-1}), which indicates that there is a need to immediately implement SWC practices across most of the catchment areas. Our findings suggest that SWC practices are central to overcoming the serious challenges associated with land and water resource degradation in the Ethiopian highlands and in regions with similar environmental settings.

5.2. Recommendations

Although analyzing the impact of human activities such as LULC change and SWC practices on hydrological and sediment responses in different agro-ecological environments is so important for devise future land and water management strategies, little attention is given to future implication of these changes in the hydrological and sediment processes along with future climate change scenarios in the Ethiopian highlands particularly in the Upper Blue Nile basin. Thus, further investigations of the hydrological responses under future LULC and climate change scenarios, including other weather parameters besides rainfall and temperature, are important for devising future sustainable land and water management strategies.

Moreover, besides to our findings, runoff and sediment could have different responses to the various types of SWC practices when the SWC practices will be implemented on different agro-ecological environments and future climate change scenarios. Therefore, future researches should consider alternative land management intervention, and future LULC and climate change scenarios to evaluate the impact of SWC practices on runoff and sediment responses.

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SUMMARY

Soil erosion-caused land degradation is a serious global environmental challenge, and this is more severe specifically in the least developed countries like Ethiopia. The rate and impact of soil erosion are more visible in the Ethiopian highlands, particularly in the Upper Blue Nile basin that even affects downstream countries like Sudan and Egypt. This is mainly because of unsustainable human activities such as land use/land cover (LULC) change and poor soil and water conservation (SWC) practices being driven by population growth and climate variability. On the other hand, there are few cases of afforestation practices that have been implemented through the initiative of the local community. These human activities and climate variability are strongly influencing the hydrological and sediment responses.

Previous studies on hydrological and sediment responses mainly focus on plot-scale while the few watershed-scales studies rarely addressed the separate or combined effects of three factors such as LULC changes, climate variability, or SWC practices under contrasting environments. The watershed-scale studies either focused on specific sites that constitute a single agro-ecological environment or specific factor. This is profoundly due to fragmented, limited, and lack of observational data such as runoff, sediment, and climate at wider spatial and temporal scales as well as lack of adoptable methodologies to evaluate the impacts. Therefore, the central objective of this study was to understand the single and combined impact of human activities (LULC changes and SWC practices) and climate variability on the spatiotemporal dynamics of hydrological and sediment responses by integrating field observations, spatial analysis, and modeling approaches. The study was conducted in three drought-prone watersheds located in different agro-ecological environments of the Upper Blue Nile basin: Guder (highland), Aba Gerima (midland), and Debatie (lowland). The study

addressed the following three specific objectives: (i) explore and evaluate LULC change, drivers and their possible implications; (ii) examine hydrological responses to LULC change and climate variability and (iii) examine runoff and sediment responses to SWC practices through employing alternative modeling approaches. These case studies are presented from Chapters 2–4 of this thesis, which comprises a total of five chapters, including the introduction and the general conclusions and recommendations, as summarized below:

The first Chapter presents the Introductory section. It provides an overview of land degradation, LULC change, climate variability, SWC practices, and their influences on hydrological and sediment responses. In the end, it presents the aims of this study and the overall structure of the thesis.

The second Chapter discusses the change in LULC, drivers, and their implications in the three sites. The changes in LULC were analyzed by integrating field observations, very high-resolution remote sensing data [0.5–3.2m], and geographic information systems. The study revealed that, from 1982 to 2016/17, forest land, bushland, and grazing lands respectively decreased by about 76%, 58%, and 30% in Guder; 54%, 63%, and 52% in Aba Gerima; and 69%, 45%, and 43% in Debatie. During the same period, cultivated land increased by approximately 38%, 97%, and 492% in Guder, Aba Gerima, and Debatie, respectively. In contrast, between 2012 and 2017, plantation cover increased by 241% in the Guder watersheds, mainly at the expense of cultivated land, which decreased by 32% for the same period. Population growth and associated changes in the farming practices were the major driving forces for the observed LULC changes in the three watersheds. The traditionally deleterious impacts of human activities on the environment have been recently reversed at an unprecedented rate, particularly at Guder and to a lesser extent at Aba Gerima, following the shift from the traditional annual cropping to more economically attractive tree-based farming practices such as Acacia decurrens plantation in Guder and khat (*Catha edulis*) cultivation in Aba Gerima. The continued expansion of cultivated land combined with population growth is directly linked with the increase of gully erosion and runoff potential in the study watersheds particularly, in Aba Gerima and Debatie watersheds. The loss of natural vegetation and subsequent conversions to cultivated lands showed the prevalence of land degradation in the three watersheds.

The third Chapter examines the separate and combined effects of LULC change and climate variability on hydrological (annual surface runoff and evapotranspiration) responses after validating the empirical models in the three study watersheds. The observed LULC changes over the study period (1982–2016) resulted in runoff increases ranging from 4% in Kecha to 28.7% in Kasiry. Climate variability in terms of annual rainfall had no significant effect on estimated runoff. In contrast, evapotranspiration was affected by both LULC change and climate variability. Though climate variability increased evapotranspiration from 33.6% in Kecha to 42.1% in Kasiry, the LULC change related to the reduction in natural vegetation had an offsetting effect, which led to overall decreases in evapotranspiration ranging from 15.8% in Kasiry to 32.8% in Kecha. Overall, the hydrological responses in the watersheds are largely controlled by how the land is being used and managed, which either mitigates or exacerbates the effects of climate variability.

The fourth Chapter evaluates the separate and combined effects of SWC practices, LULC, and climate variability on runoff and sediment yield responses using two approaches in Aba Gerima paired watersheds. In the first (paired watershed) approach, we compared the treated (Kecha) and untreated (Laguna) watersheds. In the second approach, we compared data before (baseline) and after (2011) the implementation of SWC practices for the Kecha watershed. The

SWAT model was adopted for both treated and untreated watershed conditions. Evaluations using the paired watershed approach revealed that the SWC practices reduced the runoff in the treated (Kecha) watershed by about 28–36% and sediment yield by about 51–68% as compared to the untreated (Laguna) watershed. Similarly, compared with the baseline data (before 2011) in Kecha watershed, the SWC practices alone reduced the runoff and sediment yield by about 40% and 43%, respectively, which is accounting for about 65–78% of the total changes brought by LULC change, climate variability and SWC practices. This signifies a greater effect of SWC on sediment yield than on runoff. Moreover, compared to runoff, the effect of SWC is more important in sediment reduction by about 23–32%.

The fifth Chapter presents the general conclusions and recommendations based on the key findings obtained from Chapters 2–4. Overall, an unprecedented natural vegetation degradation has been observed mainly driven by population growth, however, this has been reversed since recent years in the highland site following the shift in farming practices through the introduction of the fast-growing Acacia decurrens plantation for the rehabilitation of degraded area as well as to improve income through the sale of charcoal. This unprecedented LULC change has brought positive consequences on the hydrological and sediment responses in all sites. Climate variability had also positive and negative consequences on the evapotranspiration and sediment responses, respectively. However, the implementation of SWC practices has effectively counteracted the effects of LULC change and climate variability. Moreover, the single effect of SWC practices had considerably a higher impact on the response of sediment than surface runoff. Furthermore, this study provided an important methodological basis for evaluating the effect of SWC practices by showing the pros and cons of two different alternative modeling approaches. The findings of this study, therefore, provides useful information to devise future land and water management strategies for sustainable use of watershed resources. Future research should consider future LULC and climate change scenarios combined with land management scenarios to evaluate future hydrological and sediment responses to mitigate land degradation in the Upper Blue Nile basin and beyond.

学位論文概要

土壌侵食による土地の劣化は深刻な地球環境問題であり、これは特にエチオピアのような後発開発途上国でより深刻である。土壌侵食の速度と影響は、エチオピアの高地、特にスーダンやエジプトなどの下流国にさえ影響を与える青ナイル川上流域でより顕著である。これは主に、土地利用/土地被覆（LULC）の変化などの持続不可能な人間の活動と、人口増加と気候変動によって引き起こされている不十分な土壌・水保全策の導入によるものである。一方、地域社会の主導で実施された植林事例は少ない。これらの人間の活動と気候変動は、水文と堆積物の反応に強く影響している。

水文および堆積物応答に関するこれまでの研究は、主にプロットスケールで行われているが、いくつかの流域スケールの研究では、LULC 変化、気候変動、または対照的な環境下での土壌・水保全策などの 3 つの要因の個別または組み合わせの影響はほとんど扱われていない。流域規模の研究は、単一の農業生態学的環境または特定の要因を構成する特定の場所に焦点を当てたものである。これは、より広い空間的および時間的スケールでの流出、堆積物、気候などの観測データの断片化、制限、欠如、および影響を評価するための採用可能な方法論の欠如が原因である。そこで、本研究ではその主たる目的を、フィールド観測、空間分析、およびモデリングアプローチを統合することにより、人間活動（LULC の変更と土壌・水保全策の導入）と気候変動が水文および堆積物応答の時空間動態に及ぼす単一および複合の影響を理解することとしたる。調査は、青ナイル川上流域の異なる農業生態学的環境にある干ばつが発生しやすい 3 つの流域、Guder（高地）、Aba Gerima（中地）、および Debatie（低地）で行った。本研究の具体的な目的は以下の３点である。①LULC の変化ならびにその要因と影響を探索・評価し、②LULC 変化と気候変動に対する水文学的応答を明らかにし、③代替モデリングアプローチを使用して、土壌・水保全策に対する流出と堆積物の応答を明らかにする。これらの事例研究は、この論文の 2〜4 章を構成する。本研究は、概要、一般的な結論、推奨事項などを含め、合計 5 つの章で構成される。

第 1 章は本研究のイントロダクションである。土地の劣化、LULC の変化、気候変動、土壌・水保全策の実施、および水文学的および堆積物応答に対するそれらの影響の概要を述べる。最後に、この研究の目的と論文の全体的な構造を示す。

第 2 章は、LULC の変化、駆動要因、および 3 つの研究対象流域におけるそれらの影響について説明する。 LULC の変化は、フィールド観測、超高解像度（0.5〜3.2m）のリモートセンシングデータ、および地理情報システムを統合することによって分析した。解析の結果、1982 年から 2016/17 年にかけて、森林地、低木地、および放牧地がそれぞれ Guder で約 76%、58%、および 30%減少したことが明らかになった。Aba Gerima では 54%、63%、52%、Debatie では 69%、45%、43%である。同じ時期に、耕地は Guder、Aba Gerima、Detabie でそれぞれ約 38%、97%、492%増加した。対照的に、2012 年から 2017 年の期間についてみると、Guder 流域では耕作地が 32%減り、植林地が 241%増加した。人口増加とそれに関連する農業慣行の変化が、3 つの流域で観察された LULC 変化の主な駆動要因であった。環境への人間の活動の伝統的に有害な影響は、近年、前例のない速度で逆転している。すなわち伝統的な単年性の作物栽培からより経済的に魅力的な栽培システムへと変化しており、たとえば Guder では *Acacia decurrens* の植林が拡大し、また Aba Gerima ではチャット（*Catha edulis*）の栽培が拡大している。人口増加と組み合わされた耕作地の継続的な拡大は、特に Aba Gerima 流域と Debatie 流域における調査流域のガリー侵食と流出の可能性の増加に直接関連していた。自然植生の喪失とその後の耕作地への転換により、3 つの流域における土地劣化の拡大が示された。

第 3 章では、3 つの調査流域での経験的モデルを検証した後、LULC の変化と気候変動が水文学的応答（年間の表面流出量と蒸発散量）に与える個別の複合的な影響を評価した。調査期間（1982〜2016 年）で観測された LULC の変化により、Kecha 小流域の 4%から Kasiry 小流域の 28.7%の範囲で流出量が増加した。年間降水量に関する気候変動は、推定流出量に大きな影響を与えなかった。対照的に、蒸発散量は LULC の変化と気候変動の両方の影響を受けた。気候変動

により、蒸発散量が Kecha で 33.6%、Kasiry で 42.1%増加したが、自然植生の減少に関連する LULC の変更により相殺効果があり、Kasiry で 15.8%、Kecha で 32.8%蒸発散量が減少した。全体として、流域の水文応答は、土地の使用方法と管理方法によって主に制御され、気候変動の影響を緩和または悪化させていた。

第4章では、Aba Gerima の対照流域で2つのアプローチを使用して、土壌・水保全策の導入、LULC、および気候変動性が流出と土砂生産量に与える影響を個別に評価した。最初のアプローチ（対照流域法）では、土壌・水保全策を導入した小流域（Kecha）と導入していない小流域（Laguna）を比較した。 第 2 のアプローチでは、Kecha 小流域の土壌・水保全策の導入前（ベースライン）と導入後（2011 年）のデータを比較した。 SWAT モデルを用いて、導入あり・なしの両条件で推定を行った。対照流域法を使用した評価では、土壌・水保全策の実施により、導入無し小流域（Laguna）と比較して、導入あり小流域（Kecha）では流出量が約 28～36%、堆積物生産量が約 51～68%減少したことが明らかになった。同様に、Kecha 流域のベースラインデータ（2011 年以前）と比較すると、土壌・水保全策の実施だけで、流出量と土砂量はそれぞれ約 40%と 43%減少した。これは、 LULC 変化、気候変動、および土壌・水保全策の実施によってもたらされた全変化量の 65～78%を説明している。これは、流出よりも堆積物収量に対する土壌・水保全策の影響が大きいことを示している。さらに、流出と比較して、堆積物の削減において土壌・水保全策の効果は約 23～32%と大きく、これがより重要である。

第 5 章では、第 2 章から第 4 章で得られた結果に基づいて、一般的な結論と推奨事項を示した。概して、前例のない自然植生の劣化は主に人口増加によって引き起こされていることが観察されているが、これは近年の高地サイトで、早急に成長する *Acacia decurrens* 植林の導入による農業慣行の移行に伴い、農地の回復により逆転している劣化した地域だけでなく、木炭の販売を通じて収入を改善している。この前例のない LULC の変更は、すべての流域の水文および堆積物応答にプラスの影響をもたらした。気候変動はまた、蒸発散量と堆積物応答にそれぞれ正と負の影響

を及ぼした。ただし、土壌・水保全策の導入は LULC の変化と気候変動の影響を効果的に打ち消した。さらに、土壌・水保全策の単一の影響は、表面流出よりも堆積物の応答にかなり高い影響を与えた。さらに、本研究は、2 つの異なる代替モデリングアプローチの長所と短所を示すことにより、土壌・水保全策の効果を評価するための重要な方法論的基礎を提供した。これらの結果を通じて、本研究は、流域資源の持続可能な利用のための将来の土地および水管理戦略を考案するための有用な情報を提供した。今後の研究では、将来の LULC および気候変動シナリオと土地管理シナリオを組み合わせて、青ナイル川上流域およびそれ以降の土地の劣化を緩和するための将来の水文および堆積物応答を評価する必要がある。

LIST OF PUBLICATIONS

1. Berihun, M.L., Tsunekawa, A., Haregeweyn, N., Meshesha, D.T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A.A., Sultan, D. and Yibeltal, M., 2019. Exploring land use/land cover changes, drivers and their implications in contrasting agro-ecological environments of Ethiopia. Land Use Policy 87: 104052. (DOI: 10.1016/j.landusepol.2019.104052; online)
   [This publication has covered Chapter 2 of the thesis]
2. Berihun, M.L., Tsunekawa, A., Haregeweyn, N., Meshesha, D.T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A.A., Sultan, D., Yibeltal, M. and Ebabu, K., 2019. Hydrological responses to land use/land cover change and climate variability in contrasting agro-ecological environments of the Upper Blue Nile basin, Ethiopia. Science of the Total Environment 689: 347–365. (DOI: 10.1016/j.scitotenv.2019.06.338; online)
   [This publication has covered Chapter 3 of the thesis]

APPENDIXES

Table A1. Transition area matrix (ha) between 1982–2006, 2006–2012, and 2012–2017 in Guder paired watersheds

1982–2006	Kasiry (ha)						Total	Loss	Loss	Akusity (ha)							Loss	Loss
LULC	BL	CL	FL	GL	PL	ST	1982	(ha)	(%)	BL	CL	FL	GL	PL	ST	Total	(ha)	(%)
BL	17.23	17.90	3.80	14.89	7.20	0.00	61.02	43.79	71.76	10.19	29.39	3.69	10.38	1.36	0.00	55.02	44.82	81.47
CL	2.16	72.61	1.16	3.41	11.88	0.76	91.97	19.36	21.05	0.66	68.14	0.05	4.37	9.61	0.58	83.42	15.28	18.31
FL	20.19	65.96	33.49	27.40	14.54	0.00	161.58	128.09	79.27	37.29	43.87	41.31	16.19	1.56	0.13	140.34	99.03	70.57
GL	6.29	27.20	4.10	30.09	9.66	0.10	77.44	47.35	61.14	2.21	31.33	1.19	26.69	3.24	0.08	64.75	38.06	58.77
ST	0.00	0.00	0.00	0.00	0.00	5.53	5.53	0.00	0.00	-	-	-	-	-	-	-	-	-
Total 2006	45.88	183.67	42.54	75.79	43.27	6.38	397.54	-	-	50.36	172.73	46.23	57.63	15.77	0.80	343.52	-	-
Gain (ha)	28.65	111.06	9.05	45.70	43.27	6.38	-	-	-	40.17	104.59	4.93	30.94	15.77	0.80	-	-	-
Gain (%)	62.44	60.47	21.27	60.30	100.00	100.00	-	-	-	79.76	60.55	10.65	53.68	100.00	100.00	-	-	-
2006–2012						Kasiry (ha)	Total	Loss	Loss							Akusity (ha)	Loss	Loss
LULC	BL	CL	FL	GL	PL	ST	2006	(ha)	(%)	BL	CL	FL	GL	PL	ST	Total	(ha)	(%)
BL	16.82	6.89	3.22	10.32	8.62	0.00	45.88	29.05	63.33	26.55	6.49	3.72	10.79	2.80	0.00	50.36	23.81	47.27
CL	2.49	136.75	3.93	8.52	28.75	0.04	183.67	43.72	23.80	3.62	146.96	0.57	8.41	12.04	0.41	172.73	25.05	14.50
FL	7.76	2.74	24.33	7.14	0.43	0.14	42.54	18.22	42.82	10.22	0.54	33.66	1.59	0.23	0.00	46.23	12.57	27.20
GL	5.46	14.27	4.48	40.24	10.44	0.90	75.79	35.55	46.90	3.54	12.19	6.57	31.45	3.84	0.04	57.63	26.18	45.43
PL	1.65	16.96	0.16	3.14	19.46	0.91	43.27	22.81	52.72	0.18	10.01	0.10	1.09	4.27	0.13	15.77	11.51	72.95
ST	0.00	0.00	0.00	0.00	0.00	6.38	6.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.80	0.00	0.00
Total 2012	34.18	177.61	38.49	70.17	68.72	8.37	397.54	-	-	44.12	176.83	44.62	53.33	23.30	1.33	343.52	-	-
Gain (ha)	17.36	40.86	11.78	29.12	48.24	1.99	-	-	-	17.56	29.23	10.96	21.88	18.91	0.53	-	-	-
Gain (%)	50.78	23.01	30.61	41.50	70.19	23.77	-	-	-	39.81	16.53	24.56	41.03	81.14	39.74	-	-	-
2012–2017						Kasiry LULC (ha)	Total	Loss	Loss							Akusity (ha)	Loss	Loss
LULC	BL	CL	FL	GL	PL	ST	2012	(ha)	(%)	BL	CL	FL	GL	PL	ST	Total	(ha)	(%)
BL	9.95	2.18	2.99	4.53	14.38	0.16	34.18	24.23	70.90	15.36	4.54	10.83	4.95	8.44	0.00	44.12	28.76	65.19
CL	0.35	93.74	0.77	8.43	69.05	2.38	177.61	80.99	45.60	1.54	94.62	0.00	7.38	70.04	2.22	176.83	81.19	45.91
FL	5.56	3.92	21.90	2.74	3.85	0.53	38.50	16.60	43.13	5.12	0.31	31.17	6.29	1.72	0.00	44.62	13.45	30.15
GL	4.84	9.78	2.30	30.89	20.98	1.25	70.17	39.15	55.79	4.97	8.69	0.13	27.34	12.13	0.07	53.33	25.99	48.73
PL	0.17	14.30	0.01	5.30	46.02	1.15	68.72	20.94	30.47	0.82	7.45	0.03	1.06	13.46	0.44	23.30	9.80	42.05
ST	0.00	0.00	0.00	0.00	0.00	8.37	8.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.33	1.33	0.00	0.00
Total 2017	20.86	125.73	28.11	52.53	156.47	13.84	397.54	-	-	27.81	116.46	42.15	47.09	105.92	4.05	343.52	-	-
Gain (ha)	10.92	30.18	6.07	21.01	108.26	5.47	-	-	-	12.45	20.99	10.98	19.68	92.34	2.72	-	-	-
Gain (%)	52.33	24.01	21.60	39.99	69.19	39.54	-	-	-	44.77	18.03	26.06	41.80	87.18	67.06	-	-	-

Table A2. Transition area matrix (ha) between 1982–2005 and 2005–2016 in Aba Gerima paired watersheds

1982–2005 LULC	Kecha LULC 2005 (ha) BL	CL	KC	FL	GL	ST	Total 1982	Loss (ha)	Loss (%)	Laguna LULC 2005 (ha) BL	CL	KC	FL	GL	ST	Total 1982	Loss (ha)	Loss (%)
BL	17.99	51.73	0.24	8.00	15.13	0.09	93.18	75.19	80.70	24.43	46.95	0.31	12.75	6.03	0.08	90.55	66.12	73.02
CL	3.32	155.35	2.06	8.78	6.78	0.46	176.75	21.40	12.11	4.55	85.20	1.07	5.17	0.99	0.31	97.29	12.09	12.43
FL	10.92	44.16	0.25	16.70	7.15	0.06	79.24	62.53	78.92	22.13	59.34	0.19	22.67	2.69	0.08	107.09	84.42	78.83
GL	3.87	45.05	0.19	2.26	23.38	0.03	74.77	51.40	68.74	5.61	24.92	0.06	2.46	6.63	0.07	39.75	33.12	83.32
ST	0.00	0.00	0.00	0.00	0.00	0.37	0.37	0.00	0.00	-	-	-	-	-	-	-	-	-
Total 2005	36.09	296.29	2.74	35.74	52.44	1.00	424.30	-	-	56.71	216.40	1.64	43.05	16.34	0.54	334.68	-	-
Gain (ha)	18.11	140.94	2.74	19.04	45.28	0.64	-	-	-	32.28	131.21	1.64	20.37	13.66	0.54	-	-	-
Gain (%)	50.17	47.57	100.00	53.27	86.36	63.66	-	-	-	56.92	60.63	100.00	47.33	83.55	100.00	-	-	-

2005–2016 LULC	Kecha LULC 2016 (ha) BL	CL	KC	FL	GL	ST	Total 2005	Loss (ha)	Loss (%)	Laguna LULC 2016 (ha) BL	CL	KC	FL	GL	ST	Total 2005	Loss (ha)	Loss (%)
BL	18.29	11.79	0.06	3.23	2.70	0.02	36.09	17.80	49.33	36.80	14.68	0.75	2.25	2.17	0.06	56.71	19.91	35.11
CL	0.99	260.23	10.53	12.98	7.63	3.92	296.29	36.06	12.17	2.07	196.00	8.74	6.87	1.05	1.66	216.40	20.40	9.43
KC	0.00	0.44	1.69	0.49	0.04	0.07	2.74	1.05	38.21	0.00	0.32	1.01	0.20	0.01	0.10	1.64	0.63	38.58
FL	1.72	4.98	0.21	27.97	0.65	0.22	35.74	7.77	21.74	7.18	7.54	0.36	27.40	0.53	0.05	43.05	15.65	36.35
GL	0.83	14.99	1.27	1.52	33.68	0.15	52.44	18.76	35.78	0.47	4.13	0.39	0.44	10.80	0.11	16.34	5.54	33.89
ST	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.54	0.00	0.00
Total 2016	21.82	292.43	13.92	46.20	44.69	5.24	424.30	-	-	46.52	222.67	11.25	37.16	14.56	2.51	334.68	-	-
Gain (ha)	3.53	32.20	12.09	18.22	11.01	4.24	-	-	-	9.72	26.66	10.24	9.76	3.76	1.98	-	-	-
Gain (%)	16.20	11.01	86.82	39.45	24.65	80.92	-	-	-	20.89	11.97	91.04	26.27	25.81	78.64	-	-	-

LULC, land use/land cover; BL, bushland; CL, cultivated land; FL, forest land; GL, grazing land; KC, khat cultivation; ST, settlement.

Table A3. Transition area matrix (ha) between 1982–2006, 2006–2011, and 2011–2017 in Debatie paired watersheds

1982–2006	Sahi (ha)					Total	Loss	Loss	Bekafa (ha)					Total	Loss	Loss
LULC	BL	CL	FL	GL	ST	1982	(ha)	(%)	BL	CL	FL	GL	ST	1982	(ha)	(%)
BL	21.50	32.08	18.10	19.57	0.00	91.21	69.75	76.47	27.92	21.70	12.90	27.95	0.00	90.48	62.55	69.14
CL	3.29	47.66	6.88	6.36	0.07	64.32	16.60	25.81	0.24	12.31	1.27	2.76	0.00	16.58	4.27	25.76
FL	33.05	42.67	29.44	23.75	0.00	128.89	99.46	77.17	15.52	12.13	10.74	11.74	0.00	50.12	39.39	78.58
GL	16.44	60.88	12.98	23.38	0.11	113.79	90.41	79.45	12.98	40.04	11.46	25.22	0.09	89.80	64.57	71.91
Total 2006	74.28	183.28	67.40	73.06	0.18	398.20	-	-	56.66	86.18	36.37	67.68	0.09	246.98	-	-
Gain (ha)	52.77	135.62	37.96	49.31	0.18	-	-	-	28.74	73.87	25.63	55.94	0.09	-	-	-
Gain (%)	71.05	74.00	56.33	67.49	100.00	-	-	-	50.72	85.71	70.47	82.65	100.00	-	-	-
2006–2011	Sahi (ha)					Total	Loss	Loss	Bekafa (ha)					Total	Loss	Loss
LULC	BL	CL	FL	GL	ST	2006	(ha)	(%)	BL	CL	FL	GL	ST	2006	(ha)	(%)
BL	30.58	25.47	4.76	13.46	0.00	74.28	43.70	58.83	21.37	18.99	3.99	12.32	0.00	56.66	35.30	62.29
CL	3.50	160.44	3.07	15.93	0.34	183.28	22.84	12.46	3.30	70.80	4.40	7.23	0.46	86.18	15.38	17.85
FL	20.84	21.48	21.60	3.28	0.18	67.40	45.79	67.94	8.27	15.94	6.75	5.33	0.08	36.37	29.61	81.43
GL	12.49	27.79	1.70	31.03	0.06	73.06	42.03	57.53	7.67	20.98	3.46	35.48	0.11	67.68	32.21	47.59
ST	0.00	0.00	0.00	0.00	0.18	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.09	0.00	0.00
Total 2011	67.42	235.18	31.13	63.70	0.76	398.20	-	-	40.60	126.70	18.60	60.36	0.73	246.98	-	-
Gain (ha)	36.84	74.74	9.53	32.67	0.58	-	-	-	19.23	55.90	11.85	24.88	0.64	-	-	-
Gain (%)	54.64	31.78	30.60	51.29	75.88	-	-	-	47.37	44.12	63.69	41.22	87.36	-	-	-
2011–2017	Sahi (ha)					Total	Loss	Loss	Bekafa (ha)					Total	Loss	Loss
LULC	BL	CL	FL	GL	ST	2011	(ha)	(%)	BL	CL	FL	GL	ST	2011	(ha)	(%)
BL	46.64	7.42	3.99	9.36	0.00	67.42	20.78	30.82	26.17	5.37	2.43	6.52	0.10	40.60	14.43	35.54
CL	4.85	203.03	9.75	17.10	0.46	235.18	32.15	13.67	2.21	109.02	6.63	7.35	1.48	126.70	17.67	13.95
FL	3.61	9.19	16.21	2.13	0.00	31.13	14.92	47.93	2.89	6.28	7.42	2.00	0.01	18.60	11.18	60.10
GL	6.91	24.51	1.97	30.27	0.05	63.70	33.43	52.48	6.06	12.70	2.04	39.51	0.05	60.36	20.85	34.54
ST	0.00	0.00	0.00	0.00	0.76	0.76	0.00	0.00	0.00	0.00	0.00	0.00	0.73	0.73	0.00	0.00
Total 2017	62.0	244.15	31.92	58.86	1.27	398.20	-	-	37.33	133.37	18.53	55.37	2.38	246.98	-	-
Gain (ha)	15.36	41.12	15.70	28.59	0.50	-	-	-	11.16	24.35	11.11	15.87	1.65	-	-	-
Gain (%)	24.78	16.84	49.21	48.57	39.71	-	-	-	29.89	18.26	59.94	28.65	69.25	-	-	-

LULC, land use/land cover; BL, bushland; CL, cultivated land; FL, forest land; GL, grazing land; ST, settlement.

Table A4. Area converted and LULC conversion indexes for cultivated land in the periods 1982–2006, 2006–2012, and 2012–2017 in Guder watersheds

Source	Kasiry			Akusity		
	1982–2006	2006–2012	2012–2017	1982–2006	2006–2012	2012–2017
Area converted (ha)						
Bushland	17.9	6.9	2.2	29.4	6.5	4.5
Forest land	66.0	2.7	3.9	43.9	0.5	0.3
Grass land	27.2	14.3	9.8	31.3	12.2	8.7
Plantation land	0.0	17.0	14.3	0.0	10.0	7.5
Settlement	0.0	0.0	0.0	0.0	0.0	0.0
Mean	22.2	8.2	6.4	34.9	5.8	4.4
Conversion index						
Bushland	0.8	0.8	0.3	0.8	1.1	1.0
Forest land	3.0	0.3	0.6	1.3	0.1	0.1
Grass land	1.2	1.7	1.5	0.9	2.1	2.0
Plantation land	0.0	2.1	2.2	0.0	1.7	1.7
Settlement	0.0	0.0	0.0	0.0	0.0	0.0

Table A5. Area converted and LULC conversion indexes to khat cultivation land in the periods 1982–2006, 2006–2012, and 2012–2017 in Guder paired watersheds

Source	Kasiry			Akusity		
	1982–2006	2006–2012	2012–2017	1982–2006	2006–2012	2012–2017
Area converted (ha)						
Bushland	7.2	8.6	14.4	1.4	2.8	8.4
Cultivated land	11.9	28.7	69.1	9.6	12.0	70.0
Forest land	14.5	0.4	3.9	1.6	0.2	1.7
Grass land	9.7	10.4	21.0	3.2	3.8	12.1
Settlement	0.0	0.0	0.0	0.0	0.0	0.0
Mean	8.7	9.8	22.1	3.9	3.8	18.5
Conversion index						
Bushland	0.8	0.9	0.7	0.3	0.7	0.5
Cultivated land	1.4	2.9	3.1	2.4	3.2	3.8
Forest land	1.7	0.0	0.2	0.4	0.1	0.1
Grass land	1.1	1.1	0.9	0.8	1.0	0.7
Settlement	0.0	0.0	0.0	0.0	0.0	0.0

Table A6. Area converted and LULC conversion indexes to cultivated land in the periods 1982–2005 and 2005–2016 in Aba Gerima paired watersheds

Source	Kecha		Laguna	
	1982–2005	2005–2016	1982–2005	2005–2016
Area converted (ha)				
Bushland	51.7	11.8	46.9	14.7
Forest land	44.2	0.4	59.3	0.3
Grass land	45.0	5.0	24.9	7.5
Chat plantation land	0.0	15.0	0.0	4.1
Settlement	0.0	0.0	0.0	0.0
Mean	35.2	6.4	43.7	5.3
Conversion index				
Bushland	1.5	1.8	1.1	2.8
Forest land	1.3	0.1	1.4	0.1
Grass land	1.3	0.8	0.6	1.4
Chat plantation land	0.0	2.3	0.0	0.8
Settlement	0.0	0.0	0.0	0.0

Table A7. Area converted and LULC conversion indexes to khat plantation land in the periods 1982–2005 and 2005–2016 in Aba Gerima paired watersheds

Source	Kecha		Laguna	
	1982–2005	2005–2016	1982–2005	2005–2016
Area converted (ha)				
Bushland	0.2	0.1	0.3	0.7
Cultivated land	2.1	10.5	1.1	8.7
Forest land	0.2	1.7	0.2	1.0
Grass land	0.2	0.2	0.1	0.4
Settlement	0.0	0.1	0.0	0.0
Mean	0.5	2.5	0.4	2.2
Conversion index				
Bushland	0.4	0.0	0.8	0.3
Cultivated land	3.8	4.2	2.6	4.0
Forest land	0.4	0.7	0.5	0.5
Grass land	0.4	0.1	0.2	0.2
Settlement	0.0	0.1	0.0	0.0

Table A8. Area converted and LULC conversion indexes to cultivated land in the periods 1982–2006, 2006–2011, and 2011–2017 in Debatie watersheds

Source	Sahi			Bekafa		
	1982–2006	2006–2011	2011–2017	1982–2006	2006–2011	2011–2017
Area converted (ha)						
Bush land	32.1	25.5	7.4	21.7	19.0	5.4
Forest land	42.7	21.5	9.2	12.1	15.9	6.3
Grass land	60.9	27.8	24.5	40.0	21.0	12.7
Settlement	0.0	0.0	0.0	0.0	0.0	0.0
Mean	45.2	18.7	10.3	24.6	14.0	6.1
Conversion index						
Bush land	0.7	1.4	0.7	0.9	1.4	0.9
Forest land	0.9	1.1	0.9	0.5	1.1	1.0
Grass land	1.3	1.5	2.4	1.6	1.5	2.1
Settlement	0.0	0.0	0.0	0.0	0.0	0.0

Table A9: Annual rainfall and annual mean temperature data for the study watersheds. Period 1 is 1982–2001 and period 2 is 2002–2016 for Kasiry and Sahi watersheds. Period 1 is 1982–1993 and period 2 is 1994–2016 for Kecha watershed.

Parameter	Rainfall (mm)					
	Kasiry		Kecha		Sahi	
Period	1	2	1	2	1	2
Length of record (years)	20	15	12	23	20	15
Mean	2061.5	2305.8	1474.6	1497.7	1321.3	1374.4
Maximum	2679.0	3288.4	1756.8	1819.7	1522.4	1811.1
Minimum	1186.4	1942.1	1131.1	1227.2	1113.2	1143.3
Standard deviation	391.7	365.0	176.7	189.0	121.9	194.7
Coefficient of variation	0.2	0.2	0.1	0.1	0.1	0.1
	Temperature (°C)					
Period	1	2	1	2	1	2
Length of record	20	15	12	23	20	15
Mean	16.7	17.8	19.6	20.1	20.9	21.6
Maximum	18.1	18.2	20.2	21.2	21.8	21.9
Minimum	15.8	17.5	18.8	18.6	20.0	21.2
Standard deviation	0.6	0.2	0.3	0.6	0.4	0.2
Coefficient of variation	0.0	0.0	0.0	0.0	0.0	0.0