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Hydrological response to land cover and management (1935-2014) in a semi-arid mountainous catchment of northern Ethiopia

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List of acronyms

A	Area (km^2)
ANOVA	Analysis Of Variance
AP	Aerial Photographs
C	Correction factor
Cd	Discharge coefficient
CIESIN	Center for International Earth Science Information Network
CSA	Central Statistical Agency of Ethiopia
Cv	Correction factor for water velocity
DEM	Digital Elevation Model
Dg	Density of gully (km km^{-2})
DR	Distance from road
DT	Distance from town
FAO	Food and Agricultural Organization
g	Gravity (m^2 s^{-1})
GCV	Generalized Cross Validation
GE	Google Earth
GIS	Geographic Information System
Gv	Gully with vegetation
Gv-	Gully without vegetation
h	Depth of flow (cm)
IAP	Italian Aerial Photograph
IGC	Infiltration in gully with conservation
IGM	Istituto Geografico Militare
IGNC	Infiltration in gully without conservation
IPCC	Intergovernmental Panel on Climate Change
Irr	Irrigated exclosure
IUSS	International Union of Soil Sciences
L	Gully reach in limestone without check dams and vegetation
LC	Gully reach in limestone with check dam only
LCV	Gully reach in limestone with check dam and vegetation
Le	Lag to end runoff
Li	Lag to runoff initiation
Lp	Lag to peak flow
LSC	Sedimentary rock lithology (with calcium carbonate)

LSNC	Sedimentary rock lithology (non-carbonate)
LSS	Sandstone lithology
L_{tot}	Total gully length (km)
LUC	Land use and land cover
LV	Volcanic rock
MARS	Multivariate Addaptive Regression Spline
MEA	Millennium Ecosystem Assessment
n	Number of observations
NIrr	Non-irrigated exclosure
Q	Discharge ($m^3 s^{-1}$)
Rbb	Runoff from bare and built-up area
RC	Runoff coefficient
Rcrop	Runoff from cropland
Rg	Runoff from grazing land
Rveg	Runoff from vegetation area
S	Gully reach in sandstone without check dams and vegetation
SCV	Gully reach in sandstone with check dams and vegetation
SMS	Soil Moderately Suitable for agriculture
SNS	Soil Not Suitable for agriculture
SRTM	Shuttle Radar Topography Mission
SS	Soil Suitable for agriculture
SSC	Sorenson's Similarity of Coefficient
SWC	Soil and Water Conservation
UNCCD	United Nations Convention to Combat Desertification
UNFCCD	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
UNSO	United Nations Sudano-Sahelian Office
WBISPP	Woody Biomass Inventory and Strategic Planning Project

Publications

A1 - International publications in journals indexed in the ISI web of Science

Etefa Guyassa, Frankl A., Amanuel Zenebe, Poesen J., Nyssen J. 2016. Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. Journal of Hydrology, 545: 299–309

Etefa Guyassa, Frankl, A., Amanuel Zenebe , Lanckriet S., Biadgilgn Demissie , Gebreyohanis Zenebe , Poesen, J., Nyssen, J. Changes in Land use/cover mapped over 80 Years in the Highlands of Northern Ethiopia. Journal of Geographical Sciences. In press

Hendrickx H., Jacob M., Frankl A., **Etefa Guyassa**, Nyssen J. 2015. Quaternary glacial and periglacial processes in the Ethiopian Highlands in relation to the current afro-alpine vegetation. Zeitschrift für Geomorphologie, 59 (1): 37–57.

Jacob M., Frankl A., Hurni H., Lanckriet S., De Ridder M., **Etefa Guyassa**, Beeckman H. and Nyssen, J. 2016. Land cover dynamics in the Simien Mountains (Ethiopia), half a century after establishment of the National Park. Reg Environ Change, 17(3): 777–787.

Jacob M., Frankl A., Hans Beeckman, Gebrekidan Mesfin, Marijn Hendrickx, **Etefa Guyassa**, Nyssen J. 2014. North Ethiopian afro-alpine tree line dynamics and forestcover change since the early 20th century. Land degradation & development, 26 (7): 654–664.

Jacob M., Annys S., Frankl A., Maaike De Ridder, Hans Beeckman, **Etefa Guyassa** & Nyssen J. 2014. Tree line dynamics in the tropical African highlands –identifying drivers and dynamics. Journal of Vegetation Science, 26(1): 9 – 20.

Lannoeye, W., Stal, C., **Guyassa, E**., Zenebe, A., Nyssen, J., Frankl, A. 2016. The use of SfM-photogrammetry to quantify and understand gully degradation at the temporal scale of rainfall events: an example from the Ethiopian drylands. Physical Geography, 36 (7): 430 – 451.

A1 - In review

Etefa Guyassa, Frankl A., Amanuel Zenebe, Poesen J., Nyssen. Mapping 80 years of changes to gully and soil and water conservation densities in Northern Ethiopia. Earth Surface Processes and Landforms. In review.

B- Book chapter

Kumar M., **Etefa Guyassa**, Raj AJ. 2013. Forest ecology. In: Raj A.J. & Lal S.B. (eds.) Forestry: Principle and application. Scientific publisher: ISBN 9788172338107.

Etefa Guyassa and Raj A.J.2013. Plantation forestry. In: Raj A.J. & Lal S.B. (eds.) Forestry: Principle and application. Scientific publisher: ISBN 9788172338107.

C – International conference contributions (as first author)

Etefa Guyassa, Frankl A., Amanuel Zenebe, Poesen J., Nyssen J. 2017. Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. Paper presented at European Geoscience Union (EGU), Vienna, Austria, 23-28 April, Book of Abstracts, 19.

Etefa Guyassa, Frankl A., Amanuel Zenebe, Abebe Damtew, Descheemaeker, K., Motuma Tolere, Poesen J., Nyssen J. 2017. Response of woody plant species diversity and tree growth in exclosure to spate irrigation from gullies. Paper presented at European Conference of Tropical Ecology, Brussels, 6 -10 February 2017. Book of Abstracts.

Etefa Guyassa, Frankl, A., Amanuel Zenebe, Lanckriet, S., Biadgilgn Demissie, Gebreyohanis Zenebe, Poesen, J., Nyssen, J., 2016. Eighty years of land use/cover change in a semi-arid area of Northern Ethiopia. Rehabilitation of steep tropical mountains and its implication on peak discharge and bed load dynamics: the case of western Rift Valley escarpment of Ethiopia. Poster presented at GAPSYM10, Ghent Africa Platform, 8-9 December 2016. Book of Abstracts.

Etefa Guyassa, Frankl, A., Amanuel Zenebe , Lanckriet S., Biadgilgn Demissie , Gebreyohanis Zenebe , Poesen, J. Nyssen, J. 2016. Changes in Land Use and Cover over 80 Years in the Highlands of Northern Ethiopia. Paper presented at Sustainable Land and Water Management (SLMW3), Mekelle, Ethiopia, 28 -30 November, Book of Abstracts.

Etefa Guyassa, Frankl F., Amanuel Zenebe, Lanckriet S., Biadgilgn Demissie, Gebreyohanis Zenebe, Poesen J., and Nyssen J. 2016. A land cover change study in the Highlands of Northern Ethiopia using a flight of aerial photographs dating back to the 1930s. Poster presented at European Geoscience Union (EGU), Vienna, Austria, April 17-22, Book of Abstracts, 18.

Etefa Guyassa, Frankl, A., Amanuel Zenebe, Poesen, J., Nyssen, J., 2015. Effect of check dams in gullies on runoff response in the headwaters of Tekeze. Paper presented at TropiLakes 2015, Bahir Dar, Ethiopia, 23-29 September, Book of Abstracts.

Etefa Guyassa, Frankl A., Amanuel Zenebe, Poesen J., Nyssen J. 2014. Hydrological balance of long-term changes to land cover and management in dryland areas: the case of Northern Ethiopia. Poster presented at Ghent Africa Platform Symposium (GAPSYM8), Ghent, Belgium, 27 November 2014, Book of Abstracts.

C –National conference contributions (as first author)

Etefa Guyassa, Frankl, A., Amanuel Zenebe, Poesen, J., Nyssen, J., 2015. Response of runoff to gully control measurement in northern Ethiopia. Poster presented at 6th Belgian Geography Day, Vrije Universiteit, Brussels, 13 November, Book of Abstracts.

Etefa Guyassa, Frankl A., Amanuel Zenebe, Poesen J., Nyssen J. 2014. Understanding long-term impacts of land use, cover and management on the water balance of dryland areas: the case of Northern Ethiopia. Poster presented at Day of Young Soil Scientist. The Royal Academies of Belgium for Science and the Arts, Brussels Belgium, February 15, Book of Abstracts.

Other publication

Samuale Tesfaye, **Etefa Guyassa**, Raj A J, Emiru Birhane, and Gebeyehu TayeWondim. 2013. Land Use and Land Cover Change, and Woody Vegetation Diversity in Human Driven Landscape of Gilgel Tekeze Catchment, Northern Ethiopia. International Journal of Forestry Research

Etefa Guyassa. Abdela G., Abdlkadir A.2013. Morphology characterization of Cordia africana Lam. populations at six provenances in northern Ethiopia". International Journal of Agricultural Science and Research (IJASR). Vol. 3 Issue 2, 175-186.

Etefa Guyassa and Raj A. J. 2013. Assessment of biodiversity in cropland agroforestry and its role in livelihood development in dryland areas: A case study from Tigray region, Ethiopia. Journal of Agricultural Technology, 9(4): 829-844

Summary

Human use of land combined with population increase, poverty, changing economic conditions and institutional factors have transformed land cover at an unprecedented magnitude on a local to a global scale. Understanding the history of biophysical change of a catchment is very important for the present and future catchment management and for the successful implementation of different operations in the catchment. Hence, this study aims to evaluate the effects of different land use/cover and soil and water conservation practices on the hydrology of the Geba catchment over the last 80 years (1935-2014). The study was carried out in the North Ethiopian highlands, more specifically in the Geba catchment located between 13°16' to 14°15' North and 38°38' to 39°48' East. Historical data on land use/cover, degradation and soil and water conservation were obtained from Italian aerial photographs taken in 1930s-40s, while Google Earth images were used for the 2014 data source. The point count technique was applied to determine the fraction of land use/cover types in 1935-36 and in 2014. The results have demonstrated significant modifications in the fraction and spatial shifts of land use/cover during the last eighty years. Different explanatory factors (topographic, lithologic, climatic and proximate) have influenced the spatial distribution of land use/cover. The density of gullies and soil and water conservation were measured and a higher density was obtained in the present as compared to earlier times. The extent to which the construction of check dams has a significant effect on the runoff characteristics (lag time, peak flow and runoff volume) in gullies was measured, as well as the potential of exclosures to trap the runoff through spate irrigation. Different indices showed that species diversity is increased in irrigated areas as compared to non-irrigated areas. The runoff coefficient and river discharge data were obtained from earlier research (Descheemaeker et al.,2006; Taye et al.,2013; Amanuel et al.,2013) and interpolated based on the actual situations. The development of the conceptual hydrological model based on land use/cover and soil and water conservation is important to predict the catchment runoff discharge in the absence of the river discharge data. There is a significant difference in the runoff generation between 1935-36 and the present with and without SWC and also between the scenario (no SWC) and actual condition (with SWC) in 2004-07. Further implementation and maintenance of SWC particularly on bare land is suggested to control the further land degradation and the increase of soil moisture and ground water.

1 General Introduction

1.1 Problem statement

Land degradation, a decline in land resources quality (MEA, 2005), has been one of the principal global concerns in the past and remains high on the international agenda in the 21st century because of its impacts on the world food security and the quality of the environment (Eswaran et al., 2001). It directly affects the poorest, marginalized and politically weak citizens of the world (Mannava, et al., 2007). The statistics regarding the intensity and effects of land degradation are variable from place to place not only because of its causes but due to the definitions and terminology given and statistics existing on the rates and the extent of degradation (Mannava et al., 2007).

Dryland environments that constitute about 40% of the Earth’s land mass (UNSO, 1997) and are home to more than 38% of the world population (Reynolds et al., 2007) are relatively prone to environmental degradation due to the recurring drought and shortage of moisture which cause low vegetation cover in this region (IPCC, 2014; Reynolds, et al., 2007). Recurrent droughts which often affected the sub-Saharan and East Africa (Nicholson, 1989), combined with poor economies and utilization of scarce resources in an unsustainable manner, have exacerbated the rate and intensity of environmental degradation in a dryland environments (Darkoh, 1998). The Tigray region of northern Ethiopia, which has a semi-arid climate, has experienced extreme land degradation and failure of crop yields due to shortage of moisture and soil fertility (Lanckriet et al., 2015; HTS, 1976; Nyssen et al., 2004a, 2009, 2015). This problem has continued till a large scale soil and water conservation had started during the last quarter of the 20th century, which provided many positive changes (Alemayehu et al., 2009; Descheemaecker et al., 2006; Desta et al., 2005; Haregeweyn et al., 2015; Nyssen et al., 2009, 2014; Vancampenhout et al., 2006).

Human use of land for cultivation, livestock grazing, settlement and timber extraction (Turner et al., 1994) combined with population increase, poverty, changing economic conditions and institutional factors (Lambin et al, 2001), have transformed land at an unprecedented magnitude on a global scale. There is a strong agreement between local, regional and global studies that the expansion of cropland at the expenses of forests/woodlands has become a common phenomenon over the last few decades or centuries, although the scale differs in time and space of changes (Abdelgalil, 2003; Goldewijk, 2001; Ramankutty and Foley, 1999; Taylor et al., 2002). For instance, in dryland areas of Africa, destruction of native forests continued at a significant extent exceeding the reforestation efforts (Abdelgalil, 2003), which results in the climate impact's increase in the region (Taylor et al., 2002).

Most often, surface processes (land use/cover change, gully erosion, surface runoff and implementation of soil and water conservation) have occurred on large spatial and temporal scales in northern Ethiopia (Hurni et al., 2005). However, most existing reports on these processes are limited to small scales with some exceptions (e.g. Frankl et al., 2013; Meire et al., 2013; Nyssen et al., 2009, 2014). Most of the previous studies on land use/cover in the region began from 1960s and were restricted to a small watershed (Alemayehyu et al., 2009; Munro et al., 2008; Teka et al., 2013). Different researchers have reported different LUC changes (increase or decline) in north Ethiopia over the last half century.In recent years, several researchers have documented that shrubland, forest and built-up areas have increased while cropland and bare land declined or kept constant compared to the 1960s-1980s (Alemayehu et al., 2009; Meire et al., 2013; de Muelenaere et al., 2014; Teka, et al., 2013). In contrary other studies indicate a continued deforestation of some parts of north Ethiopa during the last few decades (Jacob et al.,2015, 2017; Munro et al., 2008) However, the status of the current LUC was rarely compared to the condition of LUC 80 years back in time (1930s). The availability of historic data on LUC with a large coverage is useful to understand the current and future environmental changes Moreover, research on the identification of important explanatory factors that determine the occurrence of LUC in the region is limited. In addition, maps of major LUC hardly exist in a large scale catchment (e.g. the scale of this study is ca. 5142 km^2) particularly in the 1930s. A better understanding of the underlying explanatory factors of LUC allow reliable predictions and improve scenarios of future environmental changes (Lambin et al., 2003). A map with a spatial distribution of LUC on a large scale can be used for the prediction and management of the biophysical environment.

Clearance of vegetation and increased pasture and cropland are among the major causes or act as an accelerator of gully erosion (Gabris et al., 2003; Munro et al., 2008; Poesen et al., 2003; Shi and Shao, 2000; Stankoviansky, 2003; Valentine et al., 2005). Catchments affected by gullies become unsuitable for cultivation and grazing and also experience increased loss of water and sediment (Gabaris et al., 2003; Nyssen et al., 2006; Poesen et al., 2003). Despite its important environmental consequences on hydrology particularly in semi-arid mountenous regions the assessment of density of gullies, mapping and identifying hotspot areas are rarely reported (Frankl et al., 2013; Valentine et al., 2005; Gabris et al., 2003; Stankoviansky, 2003). The high risk of gully erosion threatens the semi-arid region due to the current global warming (Valentine, et al., 2005). Recently different conservation measures are initiated to recover or combat the environmental deterioration. International conventions such as the United Nations Convention to Combat Desertification (UNCCD) that provides a global framework and supports the development and implementation of policy or programme to tackle land degradation in dryland regions (UNCCD, 1999). The UN Framework Convention on Climate

Change (UNFCCC) is another international convention that aims at mitigating climate change through enhancement of land use, land use change and forestry as a reservoir of greenhouse gases (UNFCCC, 2006).

In northern Ethiopia, massive soil and water conservation (stone bund on cropland, check dam in gullies, exclosure, hill side terraces, trench water harvesting ponds and reservoirs) have been implemented over the last three decades (Descheemaecker et al., 2006; Frankl et al., 2013; Haregeweyn et al., 2006; Nyssen et al., 2000; 2004b). Despite their extensive implementation and effects on hydrological components (Taye et al., 2013; Vancampenhout et al., 2006), data on the density and spatial distribution of SWC structures are rare in north Ethiopia. Likewise, the density of traditional soil and water conservation (*daget*) technique which were widely used in earlier times (Nyssen et al., 200) is not documented. Data on the densities of gullies and SWC structures are very important to identify the hotspot areas for the present and future conservation activities and also to use the data in hydrological modeling. In north Ethiopia although check dams are widely implemented as a SWC technique to control gully erosion (Nyssen et al., 2004b), the extent to which it affects hydrological processes such as on peak flow discharge, lag time, runoff volume and infiltration has not been quantified. In addition to physical soil and water conservation, exclosure were also extensively implemented in north Ethiopia for the rehabilitation of degraded land although their effectiveness is constrained by the lack of adequate management activities (shortage of water being in the semi-arid region) (Aerts et al., 2002). Neither the spate irrigation with storm runoff on vegetation growth in exclosure nor the effect of exclosure on the water balance is well understood.

The dynamic process of land use/cover change has a direct impact on the different surface processes including land degradation, hydrology (Lambin et al., 2003). The hydrological behavior of the semi-arid mountainous catchment is affected by a number of factors including topography, soils, vegetation, land use, river morphology, geology and climate (Güntner and Bronstert, 2004). Among these factors land use/cover is the most important factor to exert a substantial influence on the local, regional and global hydrological processes (infiltration, runoff, evapotranspiration, streamflow and ground water recharge) (Arnold and Friedel, 2000; Eshleman, 2004; Fohrer, 2001; Kang et al., 2001; Liu et al., 2008; Scanlon et al., 2007). Most often, the runoff is higher in semi-arid than in humid regions due to the sparse vegetation cover or litter and the physical property of dryland soils to form impermeable soils (Matari, 2007), overgrazing of pasture land (Tromble, 1976) and also a high intensity of rainfall (Nyssen et al., 2005) which leave the region prone to flood hazards (Matari, 2007). Although many studies on runoff influenced by land use/cover and soil and water conservation exist in other parts of the world (Dunjo et al., 2004; Kang et al., 2001; Niehoff et al., 2002; Nunes et al., 2011; Huang and Zhang, 2004), only few studies dealing with this topic are available in Ethiopia particularly in northern Ethiopia (HTS, 1976; Descheemaeker et al., 2006; Mwendera and Saleem, 1997; Mwendera et al., 1997; Nyssen et al., 2010; Taye et al., 2013).

Research works in relation to hydrology most often operate at small scales (i.e. plot scale, watershed scale and short time) (Descheemaeker et al., 2006; Nyssen et al., 2010; Taye et al., 2013). Amanuel et al. (2013) have measured the river discharge of the 10 sub-catchment of the Geba basin (large scale with area ca. 5142 km ^{2}) in 2004-07 and determined the runoff coefficients for each catchment. The long term environmental history of northern Ethiopia, which emphasizes land use/cover, management change and land degradation (gully erosion), is explored using terrestrial photographs (Frankl et al., 2011, 2013; Nyssen et al., 2009, 2014, Meire et al., 2013). Despite the availability of aerial photography of the 1930s-1940s which has recently been rediscovered (Nyssen et al., 2016) and the availability of data on a plot scale and the river discharge hydrology, the use of this database for a large scale study of hydrology is lacking. Synthesis of data on the responses of catchment hydrology to different catchment conditions (land use/cover and SWC) over a long time contributes to the hydrogeomorphic studies and for the present and future environmental management in semi-arid mountainous environments. Though more geomorphic processes area operated at large scale as compared to small scale processes, there are few reports on a large scale (Poesen et al., 1996). The understanding on the history of geomorphic processes at a large catchment scale is very useful for the present and future strategic decisions.

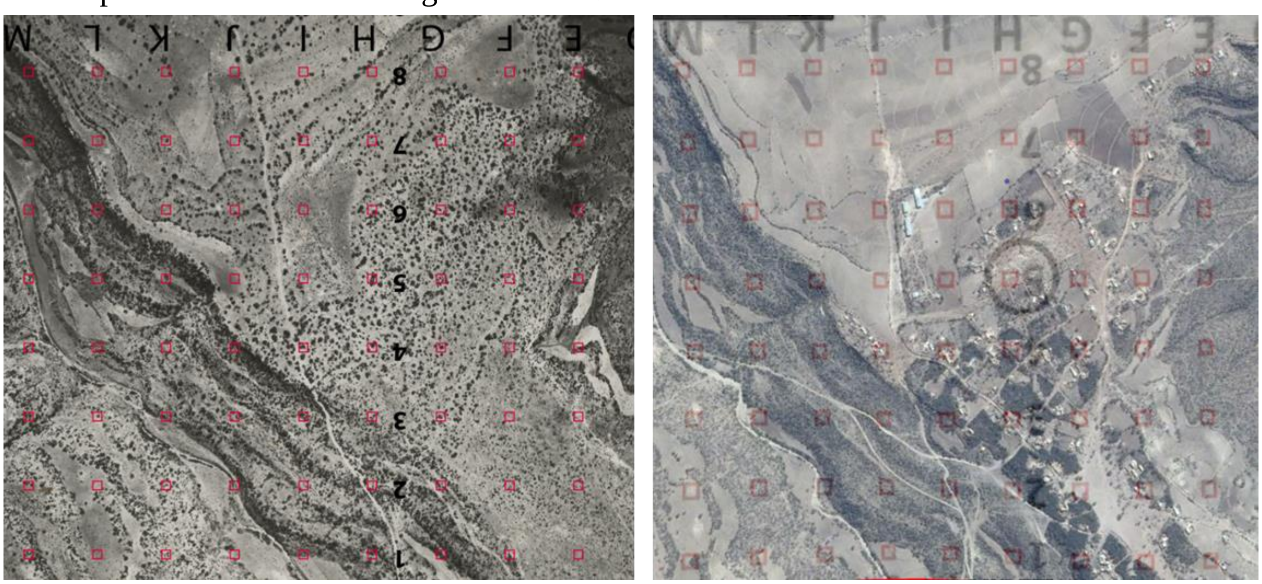

Figure 1.1 Land use/cover pattern: historical time (left) – Italian aerial photograph in January 1935 and present time (right) – Google Earth image (january 2014). Location: 13.790604° N and 39.528663° E (West of Wukro town)

1.2 Definitions

Land use and cover

Land use/cover is classified based on several criteria, depending on the purposes for which the classification is to be used. According to Turner et al. (1993) land cover refers to the attributes of a part of the Earth's land surface and immediate subsurface, including biota, soil, topography, surface and ground water and human structures and land use refer to the purposes for which humans are exploiting the land cover. Gregorio and Jansen (2000) described land covers as the observed (bio) physical cover on the earth’s surface, and land use as the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it. Meyer and Turner (1992) defined land cover as the physical and biota character of the land surface and land use as the human employment of land or land cover. Examples of some land covers include forest, croplands, grasslands, bare land and settlements and examples of land use comprise agriculture, grazing and forestry (Gregorio and Jansen, 2000). Different physical soil and water conservations (stone bund, check dam, terraces and water harvesting reservoirs) are also types of land use and land cover which are being widely observed in northern Ethiopia mainly at the current time.

Land use is a hybrid category with land cover (Meyer and Turner, 1992), hence in most cases land use and land cover are used interchangeably or together (e.g. Asmamaw et al., 2011; Schilling et al., 2008). Since one component is linked to the other type, these concepts are most frequently utilized interchangeably in the study of land use and cover (LUC) (Green et al., 1994) but are separated when one intends to discuss the individual effects of land use or land cover (e.g. Goldewijk and Ramankutty, 2004; Lambin et al., 2001; 2003; Turner et al., 1994). Connecting the two components (i.e. land cover and use), which are the imminent sources of change: the physical environment directly changed by human actions (i.e. changes in human land use immediately result in land cover transformation (Gregorio and Jansen, 2000; Meyer and Turner, 1992). Land use/cover are the most important driving force for the change of catchment hydrology (e.g. runoff and river discharge) and the occurrence of land degradation (e.g. gully erosion) over a long time period. Land use/cover influence hydrology by affecting the different components of hydrology (interception of raindrops, infiltration, evapotranspiration, runoff).

Hydrology

For a good understanding of the scope of this thesis, it is also necessary to mention the definition of hydrology. Hydrology has a wide scope and has provided several definitions. In the Oxford English dictionary, hydrology is defined as "the science which treats water, its properties and laws, its distribution over the earth's surface, etc". Viessman and Lewis (2003) defined it as the earth science that encompasses the occurrence, distribution, movement and properties of the earth's waters. It is also defined as the geoscience that describes and predicts the occurrence and circulation of the earth's fresh water (Dingman, 2015). The rainfall-runoff component of hydrology simulates the physical process by which water is moving from the land surface and through the stream network: interception, infiltration, subsurface and overland flow and channel flows (Dingman, 2015). This is especially important for predicting the streamflow response under the condition other than those for which we have record experience, including extreme flood producing rainfall, major land use change such as deforestation and urbanization and an altered climate change regime. In our study, the scope of hydrology encompasses seasonal precipitation, surface runoff, infiltration and river discharge components and the responses of these components to different site or catchment conditions.

1.3 Objectives and research questions

The main objective of this study is to evaluate the effects of land use/cover and soil and water conservation practices over 80 years (1935-2014) on hydrology in the semi-arid basin of mountainous catchment in Northern Ethiopia. This objective was arised from the research problems of this study discussed in depth in the previous section (see section 1.2). In this section, several research gaps were identified to be focused on among which are the insufficient studies on water balance modelling and on the link between hydrology and catchment characteristics at large spatio-temporal scale. Also based on these research problems a comprehensive research question was formulated as to what level catchment hydrology (mainly runoff coefficient and runoff discharge) is determined by catchment conditions that are subjected to change over long time period? This general question is built from more detail questions which are treated in the main chapters (chapter 2 to 6): How the occurrence and density of land use/cover, SWC and gullies changed over long time period? Are check dams have significant effect on runoff in gullies? Can diversion of runoff amplify the growth of vegetation in exclosure? How modelling of water budget perform with the input of existing databases?

In order to understand the response of catchment hydrology to different land use/cover as well as to different soil and water conservation structures in the past and present times it is necessary to break down the major objective into specific objectives. By dealing with these specific objectives, data on land use/cover and densities of SWC and gully are compiled at the scale of

Geba catchment (ca. 5142 km^2) while data on the effects of check dams on runoff and on the link between runoff and vegetation growth in exclosure are synthesized at selected experimental sites in the Geba basin. Building of these database facilitate to solve the problems and questions of this study. Hence, the specific objectives are formulated as:

- To quantify and map the land use/cover of the Geba catchment (Northern Ethiopia);
- To measure and map the density of soil and water conservation and gully density in the Geba catchment;
- To quantify the runoff response to check dam construction in gully reaches;
- To evaluate the impact of gully runoff diverted to exclosure on vegetation growth and discharge;
- To calibrate and model water budget based on land use/cover and soil and water conservation database and predict budget for 1935-36 and a hypothetical current scenario without SWC.

It is aimed that understanding the response of hydrology to land use/cover change and soil and water conservation (e.g. stone bund, check dam) contribute in the present and future management of land use/cover and soil and water conservation, water harvesting and control of runoff.`

In order to answer the research questions and to achieve the objectives of this study the following actions were necessary they are explained in detail in the subsquent chapters:

- to count the land use/cover, soil and water conservation, gullies on Italian APs and Google Earth images of 2014
- to quantify the runoff discharge from runoff data at the upper and lower section of gully reaches
- to develop the raster data sets containing different variables (topographic, , lithology, soil type, distance to town and road, population density)
- to verify the land use/cover and soil and water conservation through ground control points and Google Earth images
- to measure and to analysze the vegetation growth parameters in exclosures

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1.4 Thesis outline

<table>
<tr><td colspan="2">General introduction</td></tr>
<tr><td>Part 1: Land use, cover and management dynamics
Chapter 2: Changes in land use/cover mapped over 80 Years
Chapter 3: Changes in gully soil and water conservation structure densities in north Ethiopia in over the last 80 years</td><td>Part 2: Impact of conservation measures
Chapter 4: Effects of check dams on runoff characteristics along gully reaches
Chapter 5: From runoff contributor to runoff absorber: spate irrigation on exclosures</td></tr>
<tr><td colspan="2">Part 3: Water balance modeling
Chapter 6: Catchment runoff response as impacted by land use/cover, soil and water conservation</td></tr>
<tr><td colspan="2">Part 4: General discussion and conclusion</td></tr>
</table>

1.5 Study area selection

The study area, the Geba basin, is situated in the Tigray Regional State, North Ethiopian highlands, between $13^{\circ}16'$ to $14^{\circ}15'$ North and $38^{\circ}38'$ to $39^{\circ}48'$ East. The Geba River drains an area of 5142 km^2 with elevations ranging from about 900 m a.s.l. at its outlet in the southwest to 3300 m a.s.l. at its origin in the North. The Geba River is the tributary of the Tekeze River, which joins the Atbara and the Nile River in Sudan.

The study area has been selected for two major reasons. The first reason is the availability of a large dataset in the catchment that can be used for a long term study on land use and cover, land degradation, land management and hydrology. It has 15 weather stations in and around the catchment most of which have an age of more than 30 years even up to 60 years at the Mekelle Airport but with several missing data. Other datasets include the Italian Aerial photographs of the 1930s – 1940s, which recently been discovered by Nyssen et al. (2016), a lithological map (Tesfamichael et al., 2010), the river discharge (Amanuel et al., 2013), a soil map (Tielens, 2012), the plot scale runoff (Descheemaeker et al., 2006; Taye et al., 2013) and many other data on land use, degradation and management (e.g. Frankl et al., 2013; Teka et al., 2013; Alemanyehu et al., 2009; Nyssen et al., 2002, 2006; 2009; 2014). The second reason for the selection of the Geba catchment is due to its representability for the Northern Ethiopian Highlands in terms of its bio-physical characteristics (i.e. climate, geology, soils, topography land use and cover). The Geba catchment is characterized by diversified bio-physical elements. Chapter 2, 3, 5 of this thesis cover the entire catchment while Chapter 4 and 6 refer to the experimental sites around Hagere Selam (Figure 1.2).

The study area will be described in detail in each main chapter of this thesis.

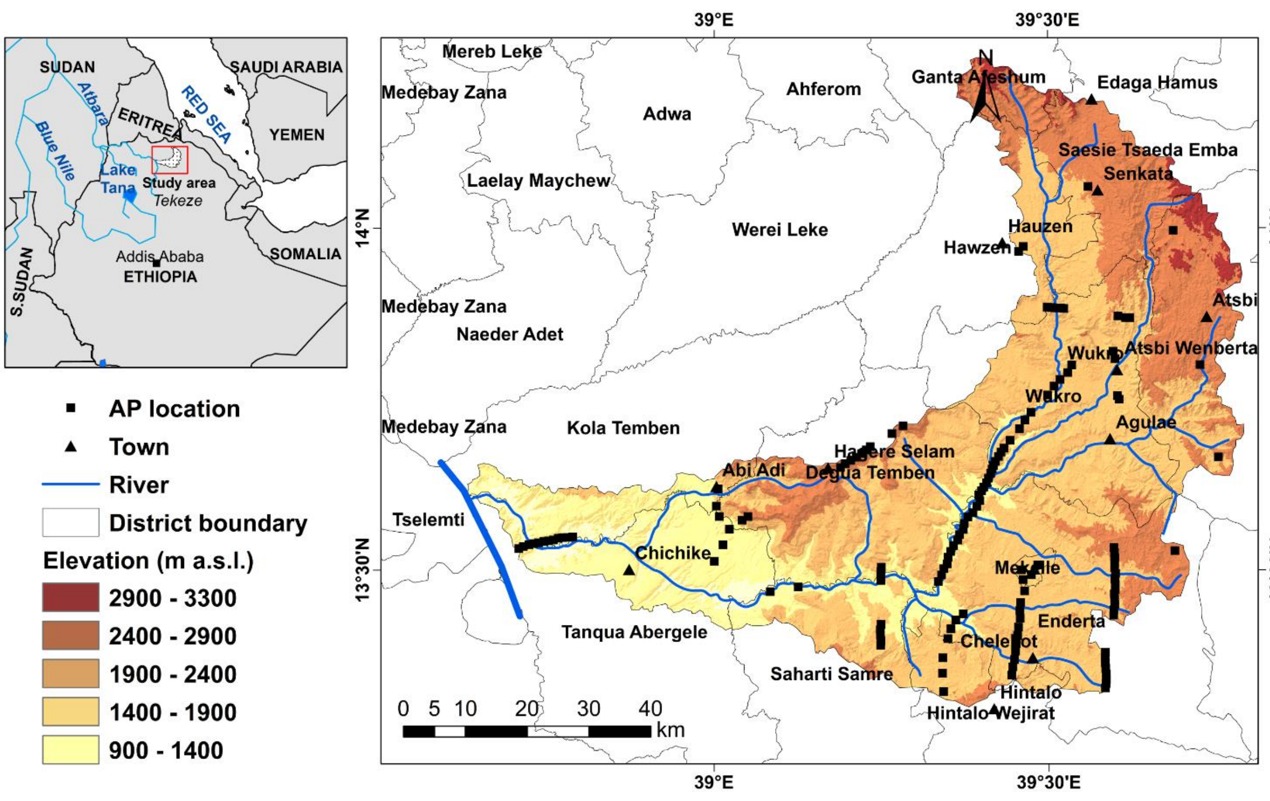


Figure 1.2 Location of the study area

1.6 References

Abdelgalil EA. 2003. Deforestation in the drylands of Africa: Quantitative modelling approach. Environmental, Development and Sustainablity 6: 415-427

Aerts R, November E, Behailu M, Deckers J, Hermy M, Muys B. 2002. Forest rehabilitation: one approach to water conservation in Central Tigray. Ethiopian Journal of Water Science and Technology 6: 34-37.

Alemayehu F, Taha N, Nyssen J, Girma A, Zenebe A, Behailu M, Deckers, Poesen J. 2009. The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). Resour Conserv Recy 53(4): 192-198.

Amanuel Z. 2009. Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, northern Ethiopia. PhD Thesis, KULeuven University, Belgium.

Asmamaw L, Mohammed A, Lulseged T. 2011. LUC dynamics and their effects in the Gerado catchment, northeastern Ethiopia. Int J Environ Stud 68(6): 883-900.

Arnold TL, and Friedel MJ. 2000. "Effects of land use on recharge potential of surficial and shallow bedrock aquifers in the upper Illinois River basin," Rep. No. 2000-4027.

Darkoh MBK. 1998. The nature, cause and consequence of desertification in drylands of Africa. Land degradation and development, 9: 1-20.

Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B, Deckers S. 2006. Runoff on slopes with restoring vegetation: a case study from the Tigray highlands, Ethiopia. Journal of Hydrology, 331(1): 219-241.

Desta G, Nyssen J, Poesen J, Deckers J, Mitiku H, Govers G, Moeyersons J. 2005. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray Highlands, northern Ethiopia. Soil Use and Management, 21: 287-297.

Dingman SL. 2015. Physical Hydrology (3rd ed.). Waveland Press, Inc.

Dunjó G, Pardini G, Gispert M. 2004. The role of land use–land cover on runoff generation and sediment yield at a microplot scale, in a small Mediterranean catchment. Journal of Arid Environments, 57: 239-256.

Eshleman KN. 2004. Hydrological consequences of land use change: a review of the state-ofscience. In Ecosystems and Land Use Change (R. Defries, G. Asner, and S. Houghton, Eds.), pp. 13-29, Geophysical Monograph Series 153, American Geophysical Union, Washington, DC (UMCES Scientific Series No. 3786).

Eswaran H, Lal R, Reich PF. 2001. Land degradation. An overview conference on land degradation and desertification. khon kaen, Thailand: Oxford Press, New Dehli, India

Fohrer N, Haverkamp S, Eckhardt K, Frede HG. 2001. Hydrologic Response to Land Use Changes on the Catchment Scale. Phys. Chem. Earth (B), 26 (7-8): 577-582.

Frankl A, Nyssen J, De Dapper M, Haile M, Billi P, Munro RN, Deckers J, Poesen J. 2011. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology, 129: 238-251.

Frankl A, Poesen J, Haile M, Deckers J, Nyssen J. 2013. Quantifying long-term changes in gully networks and volumes in dryland environments: The case of Northern Ethiopia. Geomorphology, 201: 254-263.

Gabris Gy, Kertesz A, Za´mbo L. 2003. Land use change and gully formation over the last 200 years in a hilly catchment. Catena, 50: 151– 164

Goldewijk KK. 2001. Estimating global land use change over the 1930s 300 years: the HYDE database. Glob. Biogeochem. Cycles, 15(2): 417-433.

Goldewijk KK, Ramankutty N. 2004. Land cover change over the last three centuries due to human activities: the availability of new global data sets. GeoJournal, 61(4): 335-344.

Green K, Kempka D, Lackey L. 1994. Using remote-sensing to detect and monitor land-cover and land-use change. Photogrammetric Engineering and Remote Sensing, 60 (3): 331-337.

Gregorio A, Jansen LJM. 2000. Land cover classification system (LCCS): Classification concepts and user manual. FAO Land and Water Development Division. Rome, Italy.

Güntner A, Bronstert A. 2004. Representation of landscape variability and lateral redistribution processes for large-scale hydrological modeling in semi-arid areas. Journal of Hydrology,. 297; 136–161.

Haregeweyn N, Tsunekawa A, Nyssen J, Poesen J, Tsubo M, Tsegaye Meshesha D, Schu tt B, Adgo E, Tegegne F. 2015. Soil erosion and conservation in Ethiopia: A review. Progress in Physical Geography, 39: 750-774.

Haregeweyn N, Poesen J, Nyssen J, De Wit J, Haile M, Govers G, Deckers S. 2006. Reservoirs in Tigray (Northern Ethiopia): characteristics and sediment deposition problems. Land Degradation & Development, 17: 211-230.

HTS (Hunting Technical Services). 1976. Tigrai Rural Development Study, Annex 2: water resources, Volume 1: hydrology and surface water. Hunting Technical Services Ltd: Hemel Hempstead (G.B.). 213 pp.

Huang M, Zhang L. 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrological Processes, 18: 1885-1898.

Hurni H, Tato K, Zeleke G. 2005. The implications of changes in population, land use, and land management for surface runoff in the upper Nile basin area of Ethiopia. Mountain Research and Development, 25: 147-154.

Jacob M, Frankl A, Beeckman H, Mesfin G, Hendrickx M, Etefa Guyassa, Nyssen J. 2015. North Ethiopian Afro-alpine tree line dynamics and forest cover change since the early 20th century. Land Degradation & Development, 26: 654–664.

Jacob M, Frankl A, Hurni H, Lanckriet S, De Ridder M, Etefa Guyassa, Beeckman H, Nyssen J. 2017. Land cover dynamics in the Simien Mountains (Ethiopia), half a century after establishment of the National Park. Regional Environ Change, 17:777–787.

Kang SZ, Zhang , Song XY, Zhang SH, Liu XZ, Liang YL, Zheng SQ. 2001. Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau of China. Hydrological Processes, 15 (6): 977– 988

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C. 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change, 11(4): 261-269.

Lambin EF, Geist HJ, Lepers E. 2003. Dynamics of land-use and land-cover change in tropical regions. Annu Rev Environ Resour, 28(1): 205-241.

Lanckriet S, Derudder B, Naudts J, Bauer H, Deckers J, Mitiku Haile Nyssen J. 2015. A political ecology perspective of land degradation in the north Ethiopian highlands. Land Degradation and Development, 26: 521–530.

Liu M, Tian H, Chen G, Wei Ren W, Zhang C, Liu J. 2008. Effects of Land-Use and Land-Cover Change on Evapotranspiration and Water Yield in China During 1900-2000. Journal of the American Water Resources Association, 44(5): 1193–1207.

Sivakumar MVK, Ndiang'ui N (Eds). 2007. Climate and Land Degradation. Springer, Verlag Berlin.

Matari E. 2007. Effects of Some Meteorological Parameters on Land Degradation in Tanzania. Sivakumar, M.V.K., Ndiangui N (eds.): Climate and land degradation. p629

Meyer WB, Turner BL. 1992. Human population growth and global land-use/cover change. Annual review of ecology and systematics, 23(1): 39-61.

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and Human Well-being: Desertification Synthesis. World Resources Institute, Washington, DC.

Meire E, Frankl A, De Wulf A, Haile M, Deckers J, Nyssen J. 2013. Land use/cover dynamics in Africa since the nineteenth century: warped terrestrial photographs of North Ethiopia. Regegional Environmental Change, 13(3): 717-737.

Munro RN, Deckers J, Haile M, Grove A, Poesen J, Nyssen J. 2008. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena, 75(1): 55-64.

Mwendera EJ, Saleem MAM. 1997. Infiltration rates, surface runoff, and soil loss as influenced by grazing pressure in the Ethiopian highlands. Soil Use and Management 13 (1), 29–35.

Mwendera EJ, Saleem MAM, Dibabe A. 1997. The effect of livestock grazing on surface runoff and soil erosion from sloping pasture lands in the Ethiopian highlands. Australian Journal of Experimental Agriculture, 37 (4): 421–430.

Nicholson SE, Tucker CJ, Ba MB.1998. Desertification, Drought, and Surface Vegetation: An Example from the West African Sahel. Bulletin of the American Meteorological Society.

Niehoff D, Fritsch U, Bronstert A. 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. Journal of Hydrology, 267: 80-93.

Nunes AN, De Almeida AC, Coelho CO. 2011. Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. Applied Geography, 31: 687-699.

Nyssen J, Haile M, Moeyersons J, Poesen J, Deckers J. 2000. Soil and water conservation in Tigray (Northern Ethiopia): the traditional technique and its integration with introduced techniques. Land Degradation & Development, 11: 199-208.

Nyssen J, Poesen J, Moeyersons J, Luyten E, Veyret-Picot M, Deckers J, Haile M, Govers G. 2002. Impact of road building on gully erosion risk: a case study from the Northern Ethiopian Highlands. Earth Surface Processes and Landforms, 27: 1267-1283.

Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M, Lang A. 2004a. Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. Earth-Sci Rev, 64(3): 273-320.

Nyssen J, Veyret-Picot M, Poesen J, Moeyersons J. Haile M, Deckers J, Govers, G. 2004b. The effectiveness of loose rock check dams for gully control in Tigray, northern Ethiopia. Soil Use and Management, 20, 55-64.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G. 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology, 311(1): 172-187.

Nyssen J, Poesen J, Veyret-Picot M, Moeyersons J, Haile M, Deckers J, Dewit J, Naudts J, Teka K, Govers G. 2006. Assessment of gully erosion rates through interviews and measurements: a case study from northern Ethiopia. Earth Surface Processes and Landforms, 31: 167-185.

Nyssen J, Haile M, Naudts J, Munro N, Poesen J, Moeyersons J, Frankl A, Deckers J, Pankhurst R. 2009. Desertification? Northern Ethiopia re-photographed after 140 years. Science of the Total Environment, 407(8): 2749-2755.

Nyssen J, Clymans W, Descheemaeker K, Poesen J, Vandecasteele I, Vanmaercke M, Zenebe A, Van Camp M, Haile M, Haregeweyn N. 2010. Impact of soil and water conservation measures on catchment hydrological response—a case in north Ethiopia. Hydrological Processes, 24: 1880-1895.

Nyssen J, Frankl A, Mitiku Haile Hurni H, Descheemaeker K, Crummey D, Ritler A, Portner B, Nievergelt B, Moeyersons J, Munro N, Deckers J, Billi P, Poesen J. 2014. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. Scince of the Total Environment, 485–486: 164–179.

Nyssen J, Petrie G, Mohamed S, Gebremeskel G, Seghers V, Debever M, Hadgu KM, Stal C, Billi P, Demaeyer P. 2016. Recovery of the aerial photographs of Ethiopia in the 1930s. J Cult Herit, 17: 170-178

Poesen J, Nachtergaele J, Verstraeten G, Valentin C. 2003. Gully erosion and environmental change: importance and research needs. Catena, 50, 91-133.

Ramankutty N, Foley JA. 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Glob Biogeochem Cycles, 13(4): 997-1027.

Reynolds JF, Smith DMS, Lambin EF, Turner, B, Mortimore M, Batterbury SP, Downing TE, Dowlatabadi H, Fernández RJ, Herrick JE. 2007. Global desertification: building a science for dryland development. science, 316(5826): 847-851.

Scanlon BR, Reedy RC, Tachovsky JA. 2007. Semiarid unsaturated zone chloride profiles: Archives of past land use change impacts on water resources in the southern High Plains, United States. Water Resour Res, 43(W06423): 1-13.

Shi H, Shao M. 2000. Soil and water loss from the Loess Plateau in China. Journal of Arid Environments, 45: 9-20.

Schilling KE, Jha MK, Zhang YK, Gassman PW, Wolter CF. 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions, Water Resource Research. An AGU Journal, 44 (7): W00A09, doi:10.1029/2007WR006644.

Stankoviansky M. 2003. Historical evolution of permanent gullies in the Myjava Hill Land, Slovakia. Catena, 51(3-4): 223-239.

Taye G, Poesen J, Wesemael BV, Vanmaercke M, Teka D, Deckers J, Goosse T, Maetens W, Nyssen J, Hallet V. 2013. Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography, 34(3): 236–259

Taylor CM, Stephenne S, Lambin EF, Harding RJ, Essery RLH. 2002. The influence of land use change on climate in the Sahel. American Meteorological Society, 15: 3615 - 3629

Tesfamichael G, De Smedt F, Miruts H, Solomon G, Kassa A, Kurkura K, Abdulwassie H, Bauer H, Nyssen J, Moeyersons J, Deckers J, Mitiku H, Nurhussen T. 2010. Large-scale geological mapping of the Geba basin, northern Ethiopia. Tigray Livelihood Paper No 9, VLIR – Mekelle University IUC Program, 46 pp. ISBN 978-90-8826-134-3

Teka K, Van Rompaey A, Poesen J. 2013. Assessing the role of policies on land use change and agricultural development since 1960s in northern Ethiopia. Land Use Policy, 30(1): 944-951.

Tielens S. 2012. Towards a Soil Map of the Geba Catchment using benchmark soils. Dissertation, K.U. Leuven, Belgium. pp226

Tromble JM. 1976. Semi-arid rangeland treatment and surface runoff. Journal of Range Management, 29: 251-255.

Turner BL, II Moss R.H, Skole DL, (ds). 1993. Relating Land Use and Global Land- Cover Change: A Proposalforan IGBP-HDP Core Project. IGBP Report 24/HDP Report 5, International Geosphere-BiosphereP rogramme,S tockholm.

Turner BL, Meyer, WB, Skole DL. 1994. Global land-use/land-cover change: towards an integrated study. Ambio, 23(1): 91-95.

UNSO. 1997. Aridity zones and dryland populations. An assessment of population levels in the World's drylands. Office to Combat Desertification and Drought (UNSO/UNDP).

UNCCD. 1999. United Nations Convention to Combat Desertification in those countries experiencing serious drought and/or desertification, particularly in Africa. Text with Annexes. Secretariat of the Convention to Combat Desertification. Bonn, Germany.

UNFCCC. 2006. United Nations Framework Convention on Climate Change (UNFCCC). Bonn, Germany.

Viessman W, Lewis GL. 2003. Introduction to Hydrology, 5th Edition

Valentin C, Poesen J, Li Y. 2005. Gully erosion: Impacts, factors and control. Catena, 63: 132-153.

Vancampenhout K, Nyssen J, Gebremichael D, Deckers J, Poesen J, Haile M, Moeyersons J. 2006. Stone bunds for soil conservation in the northern Ethiopian highlands: Impacts on soil fertility and crop yield. Soil and Tillage Research, 90: 1-15.

Part 1
Land use, cover and management dynamics

2 Changes in land use/cover mapped over 80 Years

This chapter is based on

Etefa G, Frankl A, Zenebe A, Lanckriet S, Demissie B, Zenebe G, Poesen J, Nyssen J. 2017. Changes in Land use/cover mapped over 80 Years in the Highlands of Northern Ethiopia. Journal of Geographical Sciences: In press.

Abstract

Despite many studies on land degradation in the Highlands of Northern Ethiopia, quantitative information regarding long-term changes in land use/cover (LUC) is rare. Hence, this study aims to investigate the LUC changes in the Geba catchment (5,142 km^2), Northern Ethiopia, over 80 years (1935 – 2014). We used 134 aerial photographs (APs), which have been taken during the 1930s and compared these afterwards to Google Earth (GE) images (2014) so as to detect changes. Five supplementary locations were included from earlier LUC studies, which were not covered by the 1930s APs. The point-count technique was utilized by overlaying a grid of 18 x 15 points on APs and GE images representing the same area. The occurrence of cropland, forest, grassland, shrubland, bare land, built-up areas and water body was counted to compute their fractions. A multivariate adaptive regression spline (MARS) was applied to identify the explanatory factors of LUC and to create fractional maps of cropland, shrubland and forest. The results indicate significant changes of most types, except for forest and cropland. In the 1930s, shrubland (48%) was dominant, followed by cropland (39%). The fraction of cropland in 2014 (42%) remained approximately the same as in the 1930s, while shrubland significantly dropped to 37%. Forests shrank further shrunk from a meagre 6.3% in the 1930s to 2.3% in 2014. High overall accuracies (93% and 83%) and strong Kappa coefficients (89% and 72%) for point counts and fractional maps respectively indicate the validity of the techniques used for LUC mapping. These distributions are explained by environmental and socio-economic variables.

Key words: Fractional map, Google Earth, land use/cover, Multivariate Adaptive Regression, Italian aerial photographs

2.1 Introduction

Through the past centuries and decades, land use/cover (LUC) has transformed (on different spatial scales) across the world (FAO, 2010; Lambin et al., 2003; Lepers et al., 2005; Maitima et al., 2009), including Ethiopia (Alemayehu et al., 2009; Asmamaw et al., 2011; Byragi and Aregai, 2011; Emiru et al., 2012; Meire et al., 2013; Mengistu et al., 2012; Muelenaere et al., 2014; Tefera, 2011). Developed regions had their strongest land use/cover change during the 19th century, while most of the developing regions experienced the largest transformation at the end of the 20th century (Goldewijk, 2001).

Changes of LUC include both an increase and decrease in the area occupied by a particular land use type on different spatio-temporal scales. On global and regional scales, an increase of the cropland area has been a common phenomenon at the expense of the forest and shrubland area during the last few centuries (Goldewijk, 2001; Goldewijk and Ramankutty, 2004; Ramankutty and Foley, 1999). On local scales, e.g. Northern Ethiopia, an increase of the forest area, a decrease of bare land and the grassland area and an approximately constant cropland area have been reported during the last 2- 3 decades (Alemayehu et al., 2009; Byragi and Aregai, 2011; Meire et al., 2013; Muelenaere et al., 2014; Teka et al., 2013). In Northern Ethiopia, severe land degradation occurred until the large-scale implementation of soil and water conservation (SWC) measures, that started in circa 1991 (Frankl et al., 2011b; Hurni and Wiesmann, 2010; Nyssen et al., 2004a). Forests which once covered large country areas vanished, although there are no reliable data on the original forest cover, about which many speculations exist (Pankhurst, 1995; Woien, 1995).

The explanation of the causes of land use/cover change extends from simple to multiple factors and their complex interactions occur on different spatial and temporal scales (Lambin et al., 2001). The rapid population growth, changing economic conditions and institutional factors, local and global uses are identified as the main factors for the transformation of the earth’s surface on a global scale (Lambin et al., 2003; Lambin et al., 2001; Turner et al., 1994). The agriculture-based economy (Nyssen et al., 2004a), low income (FAO, 2011; Kidane et al., 2010), rapid population growth (CSA, 2008) and recurrent drought occurrences are assumed to be the prominent drivers for the land cover changes in the Tigray region.

Despite the presence of ancient human settlements and agricultural practices in Northern Ethiopia (Bard et al., 2000; Nyssen et al., 2004a), the long-term evolution of change in land use/cover has received a little attention in the region, particularly on a local scale. Although some studies on land use/cover change are available in the region, (e.g. (Alemayehu et al., 2009; Byragi and Aregai, 2011; Muelenaere et al., 2014; Munro et al., 2008a; Teka et al., 2013), they all cover the period from 1965 to 2014 and generally focus on small catchments.

Nyssen et al. (2009b) and Meire et al. (2013) have compared the land use type and environmental changes in the region by using repeated historical terrestrial photographs over 140 years (from 1868 to 2008). Despite the wide application of terrestrial photographs for the study of land use/cover changes, the inaccessibility of remote sites constrains the spatial representation of terrestrial photographs as compared to aerial photography and satellite images.

Earlier reports on land cover, e.g. vegetation cover, are based on subjective descriptions and cause inconclusive reports on the original cover and deforestation rate in Ethiopia (Woien, 1995). In this regard, the shortage of historical datasets on land use/cover is claimed as a problem to measure the long-term environmental changes. Although the 1930s Aerial Photographs (APs), which are the oldest aerial photographs of the region taken during the Italian occupation of Ethiopia (1935 – 1941) (Nyssen et al., 2016a), are available, they have rarely been used to compare the historical land use/cover with the current situation. An exception to that is the local study by Frankl et al. (2015). These Italian aerial photographs are important historical datasets for spatio-temporal analyses of land use, cover and management (Nyssen et al., 2016a). Aerial photographs taken for military purposes during the World War II have been widely used for civilian purposes, such as land use change studies (Zeimetz et al., 1976).

Long-term data are required for reliable land use/cover change assessments and quantifications (Lambin et al., 2003). A good knowledge of historic land use trends with adequate coverage is important so as to understand the current and future developments (Goldewijk, 2001). A better understanding of the distribution of land use/cover allows reliable predictions and improves the scenario of future environmental changes (Lambin et al., 2003). Large-scale land use/cover changes can have substantial biophysical consequences and influence the water balance of a catchment, which in turn determines the economic development activities (e.g. dam construction, ground water use) in the area. Moreover, the map of LUC on the scale of the Geba catchment (ca.5,142 km^2), Northern Ethiopia, particularly in the 1930s, which is very important for the analysis of environmental changes over a long period. The Geba catchment is characterized by diversified bio-physical elements. Hence the study area was selected due to its representativeness for the Northern Ethiopian Highlands in terms of its bio-physical characteristics (i.e. climate, geology, soils, topography and land use/cover). Therefore, this study aims: 1) to quantify the long-term LUC changes of the Geba catchment (5,142 km^2), Northern Ethiopia, by comparing the areal fractions of the different LUC classes on the oldest aerial photographs (1935 – 1936) to the Google Earth images of 2014 2) to analyze the major explanatory factors, which determine the LUC occurrence in the two different periods, and 3) to create fractional maps of the major LUC of the Geba catchment in the 1930s and in 2014.

2.2 Materials and methods

2.2.1 Study area

The study area, the Geba catchment (Figure 2.1), is located in the Tigray region, North Ethiopian highlands, between 13°16' to 14°15' North and 38°38' to 39°48' East. The topography of the catchment was obtained from the DEM-SRTM data with a 30 m x 30 m resolution (USGS, 2016). It covers an area of 5142 km^2 with elevations ranging from about 900 m a.s.l. at its outlet in the southwest to 3300 m a.s.l. near Adigrat in the north. The Geba River is one of the major tributaries of the Tekeze River which finally joins the Atbara River and the Nile in Sudan (Figure 2.1).

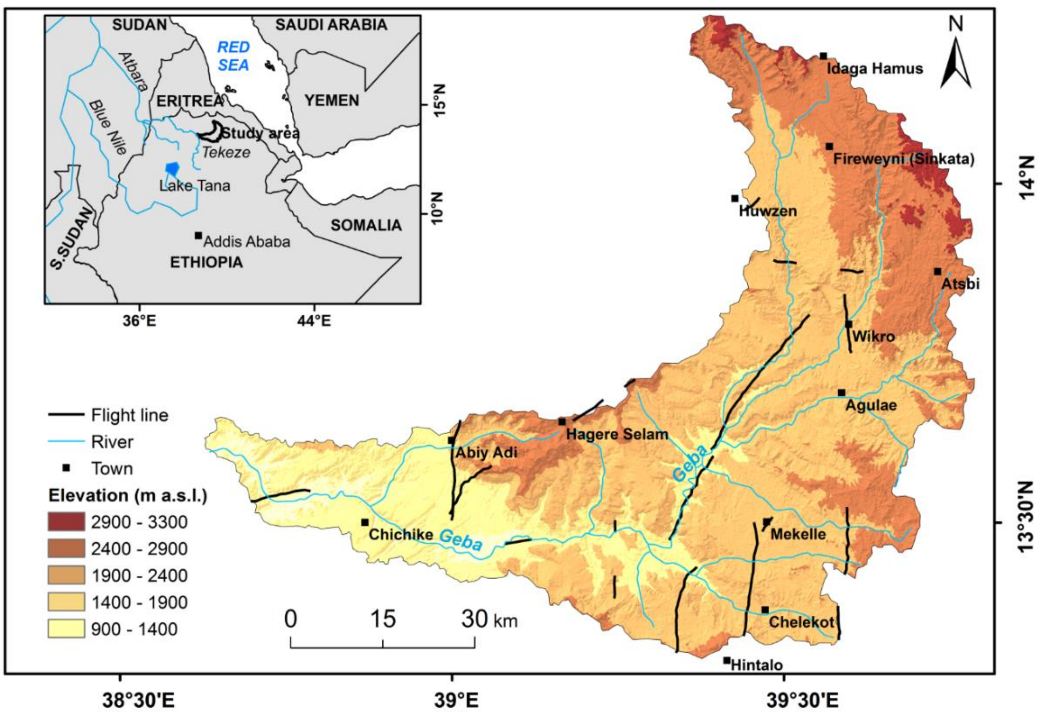


Figure 2.1 Oro-hydrography of the Geba catchment and flight lines of Italian aerial photographs

The Geba catchment is characterized by a diversified geology: precambrian basement, palaeozoic and mesozoic sedimentary rocks, tertiary volcanic rocks and quaternary deposits (Tesfamichael et al., 2010a). Steep volcanic mountains with sharp cliffs and plateaus, deep gorges, rugged terrain and rock outcrops characterize the catchment (Billi, 2015;

Tesfamichael, 2009; Tesfamichael et al., 2010a). The slope gradients of the study area range from 0% to nearly vertical (Figure 2.4B). A larger part of the catchment (55%) is classified as sloping (6% – 15%) and over 30% is steep (>15%) while most of the flat areas are found around Mekelle, Wukro, Sinkata and Atsbi accounting for only about 15% (Tesfamichael, 2009; Tielens, 2012b). Lithologic and topographic relations are very important factors for explaining the soil type distribution (Van de Wauw et al., 2008; Tielens, 2012). The dominant soils of the catchment include Leptosols, Cambisols and Regosols, with the most developed and deepest soil types on gentle slopes (Vertisols, Luvisols, Cambisols) (Nyssen et al., 2008a; Tielens, 2012b). Soil erosion, landslide and deposition processes in the catchment result in the formation of young soils particularly on foot slopes (HTS, 1976b; Nyssen et al., 2008a; Van de Wauw et al., 2008). On steep slopes and plateaus, shallow soils (like Leptosols) and bare rock are found, while more fine-textured soils with alluvial, stagnic or vertic properties are found in the valley bottoms (Tielens, 2012b).

The Geba catchment has a tropical and semi-arid climate with a bi-annual rainfall distribution ("belg" = small rain and "kremt" = main rain season). The main rainy season, which accounts for circa 80% of the annual precipitation is short, restricted to mid-July - early September, but is characterized by intense showers and large drop sizes (Nyssen et al., 2005); (Virgo and Munro, 1978). The rainfall is highly variable with an annual depth between 555 mm and 1200 mm. It is mainly determined by topographical factors such as the slope aspect, general orientation of the valley and slope gradient over longer distances (Nyssen et al., 2005), but lacks a significant correlation to the elevation (Amanuel, 2009b; Gebresamuel et al., 2010a; Nyssen et al., 2005; Taye et al., 2013b; Vanmaercke et al., 2014; Virgo and Munro, 1978). The annual evapotranspiration depth of the Geba catchment exceeds the precipitation depth, except during the rainy season, ranging from 905 mm to 2538 mm (Hadush, 2012).The mean annual maximum average air temperature ranges from 21 to 31 ºC and the mean annual minimum air temperature ranges from 3 to 16 ºC (Araya et al., 2010b) whereas the monthly average varies between 12 and 19 ºC.

The economy of the rural communities (85% of population) depends on agriculture, hence cropland dominates land use followed by bushland and bare land (Amanuel, 2009b; Gebresamuel et al., 2010a; Taye et al., 2013b). Rangeland is mainly found on steep slopes and very degraded due to overgrazing. The study area has lost its native forests a long time ago (Aerts et al., 2016a; Gebru et al., 2009; Nyssen et al., 2004a) and the remnant patches of forests are usually limited to inaccessible areas and around churches (Aerts et al., 2016a; Gebru et al., 2009; HTS, 1976b; Munro et al., 2008a). Over the last century, the Tigray region (including the study area) has faced various man-made and natural problems at different times. The war (by the Italian) in the 1930s in which chemical weapons were used, famines and population displacement due to the drought and civil war (1974 – 1991) (Lanckriet et al., 2015) and the peak land degradation from the 1930s to the second half of 20th century (Nyssen et al., 2014) were among the major shocks which took place in the region. Over the last few decades, massive soil and water conservation activities including afforestation had been organized in Northern Ethiopia in order to reverse the environmental degradation (Descheemaeker et al., 2006a; Frankl et al., 2011b & 2013; Munro et al., 2008a; Nyssen et al., 2008b; Nyssen et al., 2004a; Taye et al., 2013b; Vancampenhout et al., 2006).

2.2.2 Land use/cover analysis by the point counting method

Remote sensing products such as Aerial Photographs (APs) and satellite images have been widely used to assess land use/cover changes and for natural resource inventories in Northern Ethiopia (e.g. (Alemayehu et al., 2009; Teka et al., 2013). Despite its obvious importance for the study of land use, the 1930s photography, which represent the oldest APs of Ethiopia remain underutilized in Ethiopia (Frankl et al., 2015b; Nyssen et al., 2016a), mainly due to their recent rediscovery. The Italian Military Geographical Institute (IGM) took these black and white APs with a scale ranging from 1:11,500 (nearly vertical photograph) to 1:13,000 – 1: 18,000 (oblique photographs) during the Italian occupation of Ethiopia (1930s – 1940s) and the sets were recovered by (Nyssen et al., 2016a). These APs cover large areas of Northern Ethiopia, including parts of the Geba catchment except the eastern and northern part of the catchment.

These Italian APs were taken using multi-cameras, so as to expose four photographs (one vertical, two low oblique and one high oblique simultaneously across the flight line (Frankl et al., 2015b; Nyssen et al., 2016a). Due to the obliqueness of these photographs and small areas covered by the stereo pairs of the vertical photographs, creating orthophotographs from these photographs using the conventional photogrammetry method is difficult to apply on large regions (Frankl et al., 2015b).

Alternatively, the point counting approach allows to extract information easily and to estimate the fractions of land use/cover from the APs as applied by e.g.\(Bellhouse, 1981; Daniels et al., 1968). In this technique, different land covers that occur under the points of a grid superimposed on an area are being identified and counted (Bellhouse, 1981). This technique has been chosen for resource assessment and to examine land cover and use changes (Saebo, 1983; Shockey, 1969; Zeimetz et al., 1976). Hence, we applied this point counting technique on Italian aerial photographs to assess the fraction of LUC in 1935-36, while the land use/cover data in 2014 were obtained from Google Earth imageries captured in the same season (December to February) as the APs. The Google Earth images of the study area for the period from December 2013 to February 2014 are based on Pleiades 1A and Pleiades 1B satellites (2 m resolution) and SPOT 6 satellite (1.5 m and 6 m resolution).

Table 2.1 Variables and their descriptions

Factor	Variable	Description	Source / reference
Land use/cover	Bare land	Land with no vegetation cover, rock outcrop, quarry	WBISPP, 2003
	Built-up area	Land under settlement, roads	
	Cropland	Cultivated land (irrigated and non-irrigated) including open and regularly ploughed with or without shrub or tree line (boundary) and scattered trees, fallow with and without bushes/trees.	
	Forest	Land covered with dense trees or open; woodland; riparian trees, plantation (large scale and woodlot), church forest	
	Grassland	Land covered with grasses used as grazing area	
	Shrubland	Land covered with bushes: open, open with trees, dense, dense with trees, exclosures	
	Water body	Land covered with water: lake, pond, river including dry river bed	
Topography	Alt (m a.s.l.)	Average elevation at different locations	DEM-SRTM 30 m x 30 m resolution
	Slope (%)	Average slope gradient on different locations.	DEM-SRTM 30 m x 30 m and rescaled to 1.5 km x 1.5 km

Soil type	SS	Soils suitable for cultivation, well to perfectly drained, fertile, moderately deep to deep soil. E.g. Vertic Cambisols, Calcaric Vertisols, Vertic Phaeozems	Tielens et al. (2012)
	SMS	Soils moderately suitable for cultivation, shallow to moderately deep, moderate fertility, moderately drained. e.g. Eutric Regosols, Eutric Cambisols, Calcic Luvisols, Calcaric Cambisols	
	SNS	Soils not suitable for cultivation, very shallow, rock outcrop, stony, excessively or poorly drained. e.g. Leptosols, Gleysols	
Lithology	LV	Volcanics (intrusive and extrusive): Trap series; Mekelle dolerite. Contain wide range of minerals, which enhance the growth of trees and crops.	Tesfamichael et al. (2010); Tesfaye and Gebretsadik (1982)
	LSC	Sedimentary rock dominated by calcium carbonate: metalimestone; Antalo limestone; Agula shale. The land has a dry aspect because of karst and high infiltration.	
	LSNC	Sedimentary rocks (non-carbonate): slates, metavolcanics; Edaga Arbi glacials; alluvium. Fine-texture, results in slow infiltration and relatively fertile soils.	
	LSS	Sandstones: metaconglomerate; major intrusive (these are granites); Enticho sandstone; Amba Aradom sandstone; Adigrat sandstone. These rocks have a coarse texture, silica dominated. Sandy weathering materials where water will easily infiltrate; the domination of Si further makes that few minerals are available for vegetation growth.	
Socio-economy	Pop10 (#/km^2)	Population density in 2010	CIESIN, 2016
	DT (km)	Distance to towns in 1930s (DT30 and distance to towns in 2014 (DT14)	
	DR14 (km)	Distance to roads in 2014	

For the assessment of LUC, a point grid with 270 points (18 x 15 points) with a spacing of circa 130 m between the points (Figure 2.2) was superimposed on the scanned vertical and one oblique AP and GE whose area ranges from 2.39 km^2 to 12.36 km^2 with an average area of 4.66 (±1.72) km^2. The size and location of GE is approximately the same to the APs. The grid point density was chosen in order to maximize the probability of recording all major land use/cover classes in the target areas. The size of these points is approximately 30 x 30 m on the ground and they were made transparent (Figure 2.2) to allow visibility of the land use/cover classes under these points so that the land use/cover category can be identified easily. When a mixed land use/cover was encountered in the points the dominant class had been recorded. In total, 134 aerial photographs, which cover about 12% of the study area, taken along 15 flight lines fairly distributed over the study were used (Figure 2.1). To cover the northern and eastern part of the study area where APs do not exist (Figure 2.1), five additional locations were selected where data were available for land use/cover in 1965 for Dergajen, Hadnet and Sinkata (Teka et al., 2015) and for upper Agulae watershed (Alemayehu et al., 2009) and known (permanently forested) places in Dessa' throughout the twentieth century. We assumed that the 1965 interpretation was the best (though not perfect) supplement for the missing Italian APs of that area, while the error of using the 1965' information for the 1930s LUC condition is assumed to be small. Hence, sample locations were well represented by the dominant agro-ecological zones and lithologies of the study area (Figure 2.3).

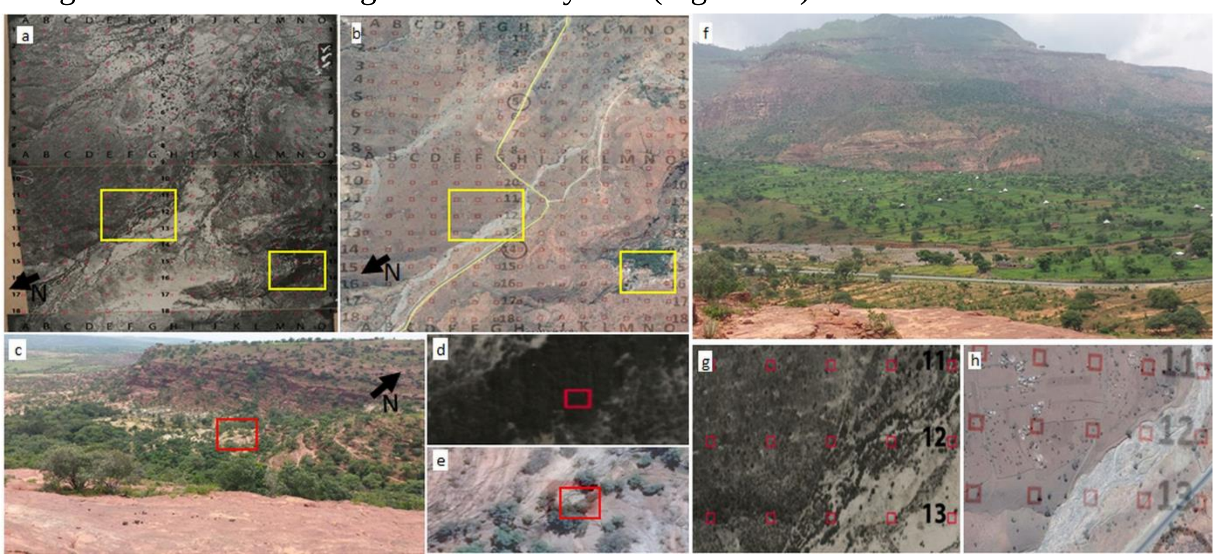
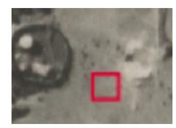
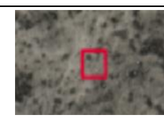
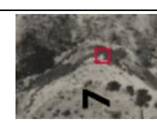


Figure 2.2 An example of a point grid superimposed on: a) aerial photograph of January 3, 1936 with coordinates of the centre of vertical photo 13.561547° N and 39.024014° E (i.e. south of Abiy Adi); b) Google Earth image of January 4, 2014. Significant conversion of land use/cover occurred at this location as shown by: c) terrestrial photo around grid point N16 where land cover changed from dense forest in 1936 (d) to open forest in 2014 (e), and f) terrestrial photo around grid point F12 where land cover changed from open forest in 1936 (g) to cropland with trees in 2014 (h)

Land use/cover categories on APs and GE were counted on the screen by three experts. The experts had to count the different APs and GE in order to do the point counting in a relatively short time. Key were prepared for this counting (Table 2.2) (appendix A1). Important photo interpretation elements such as pattern, shape, association, tone and location of LUC were used to count each LUC (Loelkes et al, 1983).

Table 2.2 Keys used for the classification of LUC during the point counting on AP and GE

Major class	Details class	Description	
	X	Impossible to interpret (clouds, damage to photo, poor scan quality)	
	U	Unsure, Unknown land cover class	
Bare land	B	Bare (bare soil, rock outcrop), mining area	
Cropland	C0	Cropland fallow (scattered small shrubs)	
	C1	Cropland (open, regularly ploughed)	
	C2	Cropland with shrub or tree line (on lynchet or boundary)	
	C3	Cropland with scattered trees	
Forest	F0	Forest – open; woodland	
	F1	Forest – dense	
Grazing land	G	Grassland	
Built-up	H	Habitat (homestead, houses), road	
Shrubland	S0	Shrubland – open	
	S1	Shrubland – open – with trees	
	S2	Shrubland – dense	
	S3	Shrubland – dense – with trees	
Water body	W	Water (lake, river, dry river bed, reservoir)	

Seven common land use/cover classes, forest, shrubland, cropland, grassland, bare lands, water bodies and built-up areas are considered in this study (Table 2.1). All classes were defined before counting (to check for subjectivity errors that can result from the experts who are involved in the counting of land use/cover points). The detail LUC classification has been used as a key to classify these major LUC (Table 2.3).

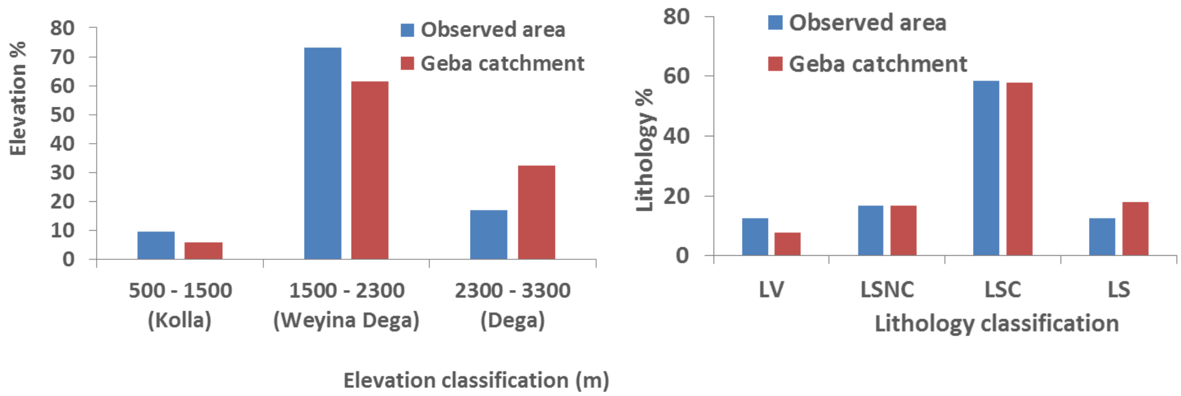


Figure 2.3 Proportion of elevation (classified based traditional agro-ecology) and lithology for the observed and predicted maps. For explanation on variables see Table 2.1.

2.2.3 Explanatory factors for LUC changes

Climatic variations, geomorphic settings and socio-economic effects are among the major explanatory factors of land use/cover occurrences. Northern Ethiopia is characterized by a large climatic and biophysical heterogeneity. Potential environmental factors believed to influence the land use/cover occurrences and changes in the Geba catchment are climate (precipitation, air temperature, evapotranspiration) and topography (elevation, slope), lithology and soil types. Despite the availability of long-term climate data in meteorological stations in and nearby the study area, a further analysis regarding the effects of climate variables on the distribution of LUC is not done in this study as the interpolation of the point meteorological data resulted in large errors due to the strong topographic effects on the rainfall distribution. Other existing databases for spatial rainfall data (e.g. Rainfall Estimate (RFE), from the National Oceanic and Atmospheric Administration Climate Prediction Centre (NOAA-CPC)) was checked if it can be used but the validation of this database using the meteorological stations has resulted in a weak correlation (R^2 = 0.38, n = 15) (Figure A3-1). But climatic variables have a strong correlation with topography (such as elevation and slope) which are used as explanatory factors.

The physical and chemical properties of different lithologies (Hahm et al., 2014) and soil types (Eswaran et al., 2003; IUSS, 2015) play an important role in plant growth, particularly for crop production. A lithological map of a part of the Geba catchment was created by (Tesfaye and Gebrethadik, 1982) and recently for the entire catchment by (Tesfamichael et al., 2010a). In order to analyze the effect of lithology on land use/cover distribution, the detailed classification of the catchment was grouped into four major lithological categories based on their mineral composition and physical properties (Table 2.1). The soil map of the study area produced by (Tielens, 2012b) was used for this study by grouping the soils in to three major classes based on their suitability for crop production or plant growth (Figure 2.4A, Table 2.1). This suitability classification was done using the soil structure, soil drainage and depth characterization of each soil unit (Tielens, 2012b).

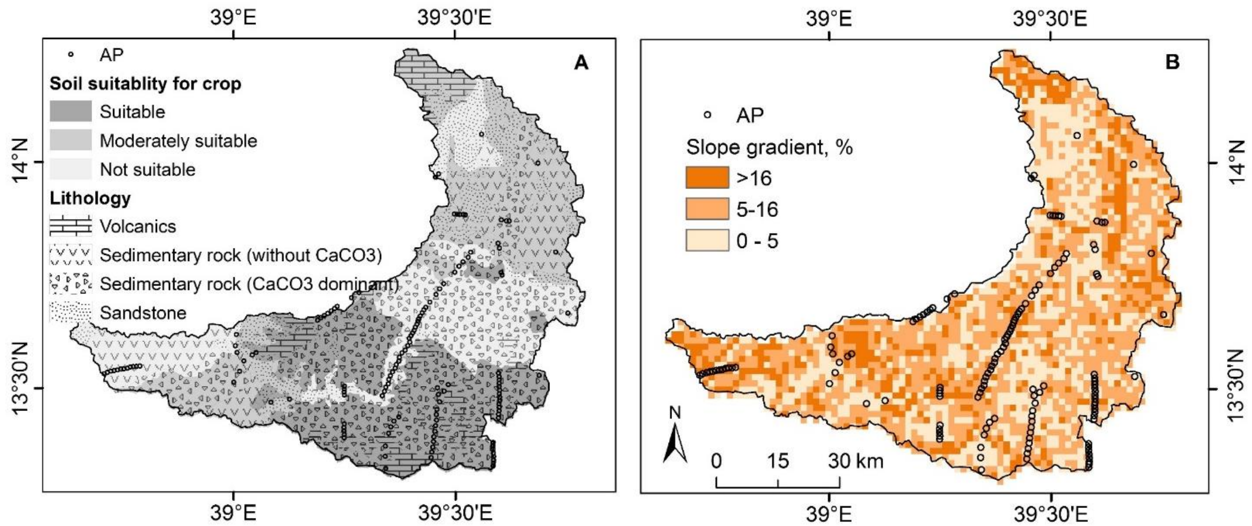


Figure 2.4 Geba catchment showing: A) lithology (extracted from Tesfamichael et al., 2010; Tesfaye and Gebretsadik, 1982) and soil suitability for cultivation (based on Tielens, 2012); B) slope gradient extracted from DEM – SRTM (USGS, 2014). AP: Location of Italian aerial photo.

Socioeconomic variables which anticipate to influence the land use/cover occurrence are mapped for the Geba catchment and are to be used in the land use/cover modelling. Population density, distance to main roads and distance to towns are the variables used to investigate if socio-economic factors are affecting land use/cover occurrences. Town is defined as an urban settlement with different facilities, businesses and social service centres (e.g. shop, market, school, healthcare, church, etc.) and with a size larger than a village. In our case, it also includes the city (e.g. Mekelle city). Road refers to the road for vehicles which was probably built during the Italian invasion in the region (1940s). The population density map for 2014 at 1 km grid was extracted from the Centre for International Earth Science Information Network (CIESIN, 2016). Mapping the distance of cells to main roads and towns in 2014 was based on the Google Earth database (January 10, 2014), while the map of distance to towns in the 1930s was created based on the1930s topographic maps of the study area (IGM, 2012) (Figure 2.5).

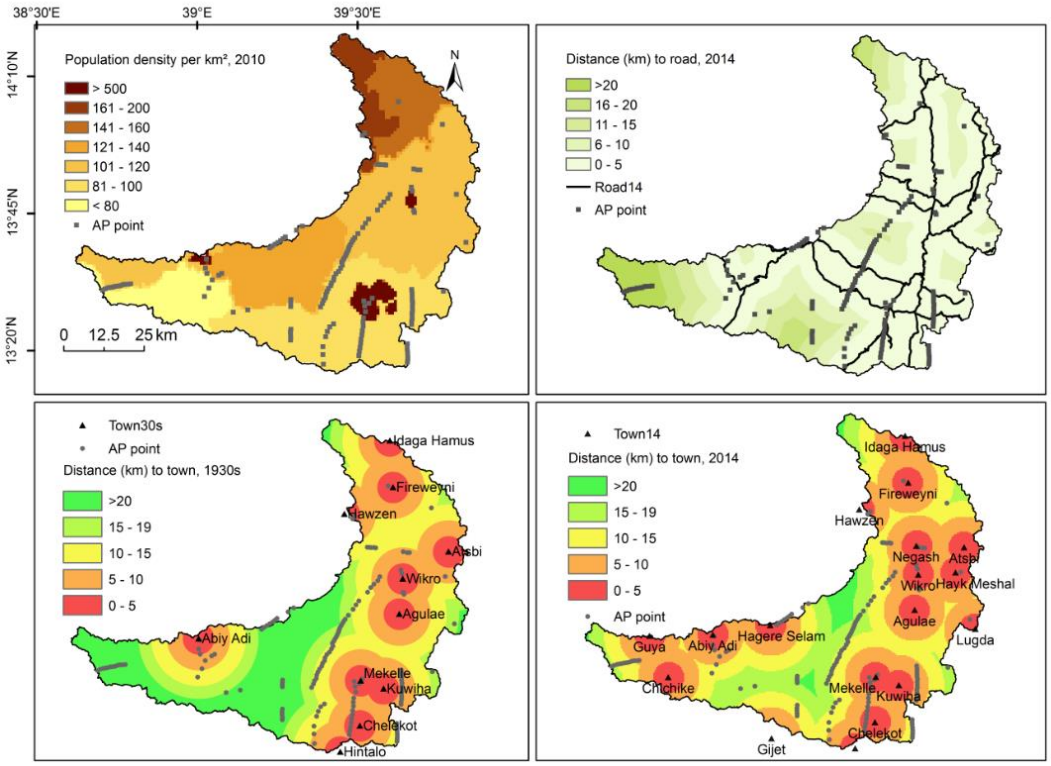


Figure 2.5 Maps of socio-economic variables.

2.2.4 Accuracy assessment of the point counting method and spatial map

An accuracy assessment was necessary so as to evaluate the validity of points counted from APs and GE images. Confusion (error) matrixes (Congalton et al., 1983; Hoffer, 1975) were prepared for the point counting and the fractional mapping accuracy measurements. For the accuracy assessment of the point counting 275 ground control points that correspond to the points counted on APs/GE were randomly selected from 55 APs (i.e. 3 – 7 points per photo) and used for verification of both the1930s and 2014 land use/cover. For the 1930s land use/cover, the verification was done based on the information obtained from old people who have lived in the area and have information on the historical land use/cover (from their parents). For 2014, field observations were made to validate whether the different land use/cover types were correctly identified on the screen. The assessment of accuracy of the fractional maps of the dominant land use/cover of the study area was done using the Google Earth image (Fritz et al., 2009; Bastin et al., 2013; Annys et al., 2016). Using the 2 km x 2 km grid, 233 points have been randomly selected utilizing ArcMap from the map of the Geba catchment. Then the values of the different land use/cover maps of 2014 corresponding to the random points were extracted. Based on these values the dominant LUC at each random point was selected and contrasted the dominant LUC in the corresponding point in the fractional maps. The same random points were overlaid on the 2014 GE image so as to count the classes that were correctly allocated to the map. The dominant LUC in the random point corresponds to a 1.5 x 1.5 km pixel on the fractional map, while the observation on GE was just at a point which can result in the error of disagreement by selecting the non-dominant class. An accuracy check for the historical land use/cover map could not be made as no field database exists.

2.2.5 Data analyses

The fractions of the land use/cover classes, described as the density or weight of land use/cover, were calculated for each scene (AP and GE) as the ratio of the total number of points for each class to the total number of points of all land use/cover counted per AP/GE (Daniels et al., 1968). Points where the land use/cover is unknown or invisible on APs due to the clouds or damage of the photographs were excluded from further analyses and the corresponding points on GE omitted, too. The significance of the differences in the fraction of each land use/cover type between the 1930s and 2014 were tested by using the Mann-Whitney U test ($\alpha = 0.05$), while the significance in the frequency of spatial distribution of LUC across the sample area (scene) was checked by using the Chi-square test ($\alpha = 0.05$). The spatial distribution of LUC refers to the binary description of the LUC occurrence (i.e absence or presence) in the sample scene. A change matrix was prepared between LUC in 1930 and 2014 so as to analyze the transformation of LUC in 2014 as compared to the 1930s (i.e. how different land use/cover replaced each other over a long time period).

Rasters of the selected explanatory factors with a resolution of 1.5 x 1.5 km were used in order to fit approximately to the scale from which the LUC data were obtained from the APs and GE images (ca. 4.66 km^2). This grid size was selected based on the smallest scene (2.4 km^2), so that all observations have at least 1 cell. Average values of different explanatory factors at the location of all scenes were extracted from their spatial maps created for the Geba catchment. After checking the non-linear relation (using multiple linear regression) between land use/cover and the explanatory factors, Multivariate Adaptive Regression Splines (MARS) (Friedman, 1991), a non-parametric regression was used to model the land use/cover classes. It is a stepwise (forward and backward pass) method and a powerful and flexible non-parametric regression for modelling the complex multivariate datasets (Friedman, 1991)widely applied in various disciplines including the LUC change studies (e.g. Quiros et al., 2009; Tayyebi and Pijanowski, 2014). It uses the basis functions as predictors in place of the original data by breaking the data into different regions for fitting. The generalization of the model is checked using the Generalized Cross Validation (GCV) and by its normalized value (GCV R^2) statistics which are also used to avoid over-fitting training data (Friedman and Silverman, 1989). The relative importance of the explanatory variables is ranked using the three criteria method of the MARS model (number of subset, GCV and RSS) which varies for the different land use/covers (Table 2.3).

The MARS equations developed for the different land use/cover types in the 1930s and 2014 needed used to create fractional maps of the land use/covers, using pixel size of 1.5 km x 1.5 km that are approximately the same size as the smallest scene area (2.4 km^2) of the interpreted APs. In a fractional map, for every pixel the fraction (0.00 -1.00) or the percentage (0% - 100%) of a particular land use/cover class is represented (Romanov et al., 2003).

Point count and mapping of LUC were validated by computing the commission errors (measure of the producer's accuracy), the omission error (measure of the user' accuracy) and overall accuracy from the error matrix table (Congalton et al. 1983; Hoffer, 1975). Furthermore, the degree of agreement between the accuracy of the counting and the field observation and between the mapping and Google Earth was measured by computing the Kappa coefficient of agreement from the confusion matrix (Fleiss, 1971; Stehman, 1997). This coefficient is used for the correction of the chance (expected) agreement. The multiple Kappa coefficient, i.e. the Fleiss Kappa coefficient, was applied by taking into account the multiple random points and the different LUC classes used for this precision assessment (Fleiss, 1971). Hence, the Kappa coefficient is calculated from the LUC error matrix as follows:

$$\boldsymbol{Kappa}\ (\boldsymbol{\kappa}) = \frac{\sum_{i}^{i=q} \boldsymbol{Pii} - \sum_{i}^{i=q} \boldsymbol{Pi_{+}} * \boldsymbol{P_{+}i}}{\mathbf{1} - \sum_{i}^{i=q} \boldsymbol{Pi_{+}} * \boldsymbol{P_{+}i}}$$

Where Pii = Nij/N (i.e. proportion of the correctly counted LUC or ratio of diagonal value to the total number of observation); Pi+ = Ni/N (i.e, proportion of the marginal row total); P+i = Mi/N (i.e. proportion of the marginal column total). Statistical analyses were carried out in R 3.3.2 and SPSS ver. 21 software packages while all mapping was done in ArcGIS 10.1.

2.3 Results

2.3.1 Geomorphic settings

Sedimentary rocks with calcium carbonate dominate the study area followed by sedimentary rocks without calcium carbonate such as sandstones (17%), while volcanic rock covers a smaller area (10%) (Figure 2.4A). The soil type of southern and central Geba is categorized as suitable (34%) and the northern and south western part are moderately suitable (35%) while eastern areas are dominantly non-suitable soils (31%) (Figs. 2.4A). The distribution of the soil suitability classes is related to the geology and topography of the catchment (IUSS, 2015; Tielens, 2012b).

2.3.2 Change of land use/cover fraction from the 1930s - 2014

Field observation for the verification of the point counting method has resulted in a high overall accuracy (93%) for the recent LUC, as shown in the error matrix (Table 2.3). The count of shrubland and cropland led to a high accuracy (i.e. a low omission error), 97% and 93% respectively, while the forest count resulted in a low accuracy. The error matrix shows that other land (summation of bare land, housing, waterbody, grassland) was identified with a high accuracy (89%) or low errors. Moreover, the error matrix caused a very strong kappa coefficient ($\kappa = 0.89$) (Table 2.3). The accuracy assessment for the 1930s land use/cover was not possible to do through a field visit but showed a high correspondence (86%) to the result of the interview carried out on the old people concerning the history of land use in ancient times. The interviewed people with an average age of 69 years have explained the historical land use/cover of their area with some important landmarks, which they remember or which is based on what they heard from their parents. For example, the forests and shrubs in which they were cutting trees for different purposes such as to build their house and fence, for firewood and farming implements do not exist or are being degraded now.

Table 2.3 Commission-omission error matrix of LUC point counting and mapping

		Ground control / Google earth					
		Cropland	Shrubland	Forest	Other classes	Sum	Commission Error
LUC count on screen	Cropland	132	1	0	2	135	0.02
	Shrubland	6	88	3	2	99	0.13
	Forest	0	0	6	0	6	0.00
	Other classes	3	2	0	30	35	0.10
	Sum	141	91	9	34	275	
	Omission error	0.06	0.03	0.33	0.12		
	Overall accuracy					0.93	
	Kappa coefficient					0.89	
LUC map	Cropland	106	10	1	6	123	0.16
	Shrubland	12	68	1	1	82	0.21
	Forest	1	1	3	0	5	0.67
	Other classes	4	2	0	17	23	0.35
	Sum	123	81	5	24	233	
	Omission error	0.14	0.16	0.40	0.29		
	Overall accuracy					0.83	
	Kappa coefficient					0.72	

Strength of Kappa coefficient: < 0.00 (poor), 0.00-0.20 (slight), 0.21-0.40 (fair), 0.41-0.60 (moderate), 0.61-0.80 (substantial), 0.81-1.00 (almost perfect) (Landis and Koch, 1977)

The results of the quantitative analysis indicate that shrubland and cropland were the dominant LUC in both the 1930s and 2014. In the 1930s, the percentage of shrubland and cropland covers 48% and 39% respectively, but in 2014 the cropland outstretched to 42%, while the shrubland contracted to 37% (Figure 2.6). All land use/cover categories (except shrubland and forests) have increased over the last 80 years (Figure 2.6). The test of land use/cover fractions using Mann-Whitney U tests showed significant differences between the 1930s and 2014 for all categories except for cropland and forest. This test revealed that the fraction of shrubland decreased significantly in 2014 as compared to the 1930s while the bare land, grazing land, built-up area and water body had increased significantly in 2014 compared with the 1930s. The forest cover has dropped from about 6.3% to 2.3% during the last 80 years.

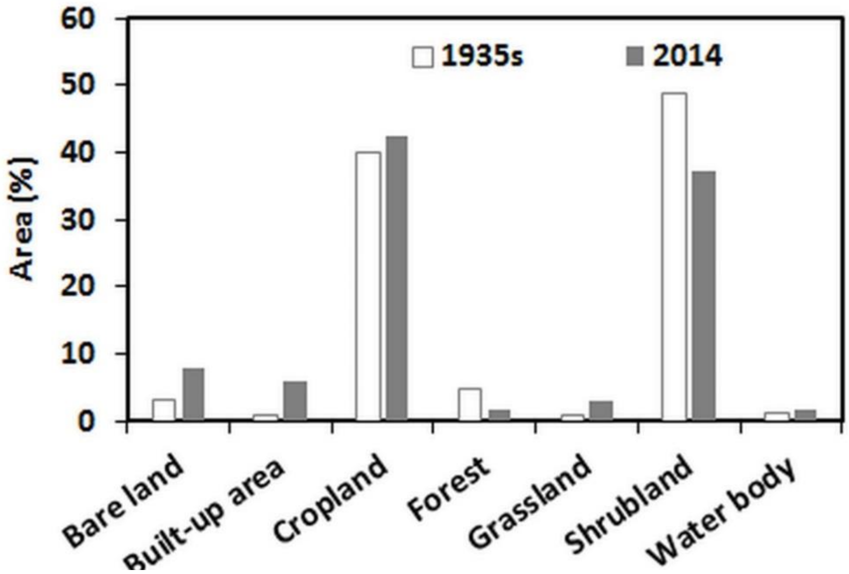


Figure 2.6 Areal percentage of different land use/cover in the 1930s and 2014, n = 34192.

2.3.3 Spatial distribution of land use/cover

In the 1930s, shrubland and cropland were frequently observed (greater than 90%) categories at sample locations while the other categories occurred in less than 45% of the total sample areas. In 2014, all land use/cover classes had been encountered in about 85% of the observation (n = 139), except forest and water body which occurred in 45% and 71%, respectively (Figure 2.7). Land use/cover types have undergone dynamic changes (increase or decrease) over a long time period (Figs. 2.6 – 2.8). Nevertheless, there are cases where constant fractions and patterns of land use/cover were observed over this period. The chi-square test for the frequencies of spatial occurrence across the sample areas reveals significant changes in the location of occurrence of land use/cover except for forests (Table 2.4).

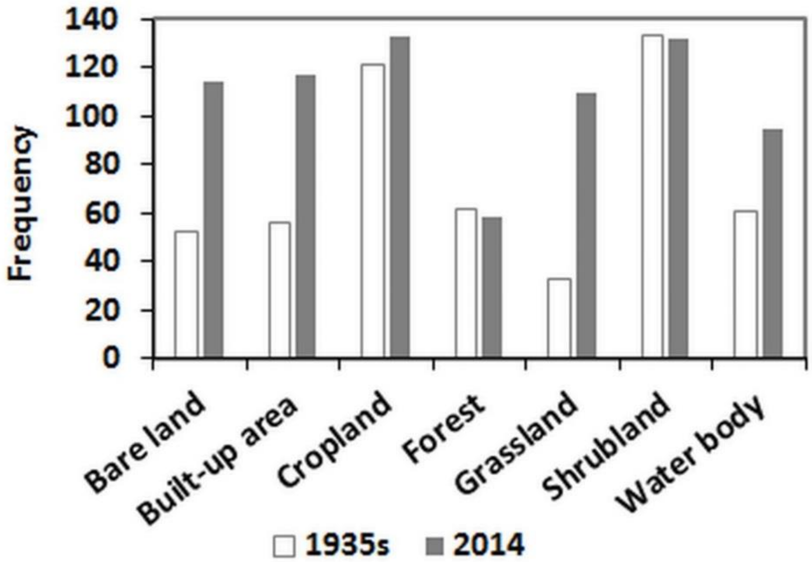


Figure 2.7 Frequency of occurrence (absence or presence) of different land use/cover in the 1930s and 2014 scenes, n = 139

Table 2.4 Frequency and percentage of scene in which land use/cover types have shown different changes between the 1930s and 2014; Chi-square test result. n = 139.

Land use/cover	Increased		Decreased		No change		Sig.
	Frequency	Percent	Frequency	Percent	Frequency	Percent	
Bare land	101	73	23	17	15	11	<0.001
Built-up area	113	81	17	12	9	6	<0.001
Cropland	85	61	52	37	2	1	<0.001
Forest	33	24	53	38	53	38	0.088
Grassland	96	69	14	10	29	21	<0.001
Shrubland	29	21	105	76	5	4	<0.001
Water body	73	53	28	20	38	27	<0.001

Although cropland did not experience significant changes in fraction between two times, it showed however important spatial changes. In other words, some land that was under agriculture in the 1930s, was abandoned in 2014 and new agricultural lands were created by converting other land use/cover. The constant fraction of the cropland over a long period was retained at the expense of other land use/cover mainly by encroaching and/or expanding into shrubland and forests, and abandonment of marginal, exhausted land, as well as the steepest slopes ban administrative decision. This study also shows a significant decline in the spatial distribution of shrubland and the expansion of bare lands, grasslands and built-up areas (Figure 2.7).

The prepared change matrix (based on point counting) revealed a complex transformation of LUC over the last 80 years. It should be noted that this transformation matrix is not free from errors due to the obliqueness of the APs and the non-georeferenced grid points on APs, which have resulted in a few meters' displacement of points on GE as compared to their location on AP. Nevertheless, the matrix showed that all land use/cover have replaced each other although the transformation intensity is variable (Table 2.5). The results indicate that about 67% and 54% of the cropland and shrubland respectively, remained spatially unchanged in 80 years, while only 5% of the forest was recorded at its location in the 1930s. a large portion of cropland has transformed into shrubland, built-up area, bare land and grazing land; shrubland transformed into cropland, bare land, built-up area and grazing land while forest mainly changed into shrubland to cropland in the order of importance. Examples of APs, Google Earth images and terrestrial photographs are given in appendix A2 to demonstrate the changes of LUC over 80 years.

Table 2.5 Land use/ cover transformation matrix from the 1930s to 2014 in the Geba catchment.

1935\2014	Crop land	Shrub land	Forest	Grazing land	Bare land	Built-up	Water body	Total
Cropland	9047	2193	116	434	714	920	168	13592
Shrubland	4195	9151	351	460	1701	680	289	16827
Forest	514	861	84	36	80	123	17	1715
Grazing land	125	95	12	18	21	85	6	362
Bare land	265	410	12	23	226	60	23	1019
Built-up	79	29	4	7	10	117	1	247
Water body	67	177	5	7	75	40	59	430
Total	14292	12916	584	985	2827	2025	563	34192

2.3.4 Explanatory factors affecting the land use/cover

The results of the MARS model have revealed the importance of different factors for the occurrence probability of different land use/cover types in the 1930s and in 2014 (Table 2.7). The models show that all climatic environmental and socio-economic variables considered in this study have significantly affected one or more land use/cover types. However, the pressure of the socio-economic factors (i.e. the population density, distance to town) on land use/cover change have been increasing after the 1930s. For each model, several variables and terms (basis functions) were used to predict the land use/cover occurrences (Table 2.6 & 2.7). The occasion of more than one basis function for a single explanatory factor in a model depicts the nonlinear relations between the explanatory factors and land use/cover categories. The regression models have also illustrated the significant interaction of the explanatory factors on the distribution of land use/cover (Table 2.6). The results also demonstrated different thresholds for different explanatory variables in the 1930s and 2014.

Table 2.6 Equations of three major land use/cover (cropland, shrubland and forest) in the 1930s and 2014 which were developed by the Multivariate Adaptive Regression Spline model. C1930s = cropland in the 1930s, C2014 = cropland in 2014, S1930s = shrubland in the 1930s, S2014 = shrubland in 2014, F1930s = forest in the 1930s and F2014 = forest in 2014. h=hinge function with zero and a constant (*knot*) of a factor. For the detail explanation see Table 2.1.

Land use/cover	1930s	2014
Cropland	C1930s = 0.2232 -0.01063 * h(0, DT30s - 6) +0.02519 * h(0, 17.4 - slope) -0.1589 * h(0, DT30s - 8) * SS +0.09218 * h(0, 6 - DT30s) * SMS +0.04719 * h(0, 7 - slope) * SS -0.00141 * h(0, 2037 - alt) * SS +0.1724 * h(0, DT30s - 6) * SS	C2014 = 0.1196 +0.2177 * SS +0.0008321 * h(0, alt - 1859) +0.02293 * h(0, 16 - slope) -0.000121 * Pd * SS -0.0000118 * Pd * h(0, 16 - slope) +0.0005874 * h(0, 1859 - alt) * SMS -0.0000299 * h(0, alt - 1859) * h(0, slope - 7) -0.0001047 * h(0, alt - 2150) * h(0,16 - slope)
	GCV 0.041 RSS 4.281 GCV R^2 0.53 R^2 0.64	GCV 0.028 RSS 2.78 GRSq 0.63 R^2 0.73
Shrubland	S1930s = 0.6112 +0.1556 * SNS -0.000357 * h(0, alt - 1778) -0.01745 * h(0, 15.4 - slope)	S2014 = 0.6841 -0.2899 * SS -0.1131 * SMS -0.0003771 * h(0, 1778 - alt) -0.0002857 * h(0, alt1 - 1859) -0.02089 * h(0, 14 - slope)
	GCV 0.044 RSS 5.441 GCV R^2 0.38 R^2 0.44	GCV 0.027 RSS 3.16 GCV R2 0.58 R2 0.64

Table 2.6 continued

Land use/cover	1930s	2014
Forest	F1930s= 0.06381 +0.08914 * LSNC -0.0001301 * h(0, 2361 - alt) +0.0001466 * h(0, slope -6) * h(0, alt - 1980) +0.0001778 * h(0, slope - 6) * h(0, - 2053) +0.0001651 * slope * max(0, alt - 2361) * LSC +0.000121 * h(0, slope - 6) * h(0, alt - 1980) * SNS	F2014 = 0.006373 -0.1273 * SS +0.0002263 * h(0, alt - 1830) +0.0003854 * h(0, alt - 2396)* SNS *LSC +0.02682 * h(0, alt - 2396) * LSC +0.000000614 * h(0, 2396 - alt) * h(0, Pd - 81)
	GCV 0.012 RSS 1.276 GCV R^2 0.40 R^2 0.52	GCV 0.002 RSS 0.251 GCV R^2 0.31 R^2 0.47

Among all the considerable variables, the slope gradient, elevation, soil suitability for cropping and proximity to town were significantly influencing the cropland fraction in the 1930s explaining 64% of the probability of its occurrences. The soil type which was the mainly suitable soil for cultivation was the most important factor for the occurrence of a larger fraction of cropland in the 1930s followed by the slope gradient and the distance from town. The nearest was the area to town in 1930. The result shows that in moderately sloping to flat areas (i.e. a slope gradient of less than 16%), the fraction of cropland was positively affected while the fraction was decreasing when the proximity of the area to town decreased except in suitable soil areas (Table 2.6). Similarly, in 2014, the soil type and slope gradient remained the dominant factors for determining the distribution of cropland in which suitable soil and slope gradients of less than 16% were increasing the cropland the fraction. However, the effects of suitable soils and slope gradients were reversed when combined with the population density. The MARS also showed a larger cropland fraction in mid to high elevation areas except at steep slope gradients during both the 1930s and 2014 (Table 2.6). From the MARS model, it is also apparent that the distribution of shrubland was highly dependent on the slope gradient but in reverse direction to the cropland distribution. In flat areas, the fraction of shrubland was negatively affected while in sloping and steep slope areas the coverage had increased in both the 1930s and 2014. Moreover, soil types and elevation were also other dominant explanatory factors for the distribution of shrubland. The result showed that suitable soil for cultivation favoured the occurrence of shrubs while suitable and moderately suitable soils affected the distribution of shrubland negatively. Moreover, the results revealed that when elevation increases over circa1800 m the fraction of shrubland had decreased both in past and present times (Table 2.6).

Table 2.7 Relative importance of variables in the model using three criteria: 1) the number of the subset (the number of the model subset that includes the variables), 2) the RSS (the scaled summed decrease of the residual sum of squares overall the subset) and 3) the Generalized cross validation (GCV). For the explanation on the variables see Table 2.1

	1930s				2014			
	Predictor	Number of subset	GCV	RSS	Predictor	Number of subset	GCV	RSS
Cropland	SS	7	100	100	SS	8	100	100
	DT30s	6	75	77	Pd	7	66	69
	Slope	6	75	77	Slope	6	55	59
	Alt	2	17	26	Alt	5	30	39
	SMS	1	12	18	SMS	2	4	18
	GCV R^2 =0.52		R^2 = 0.64		GCV R^2 =0.63		R^2 = 0.73	
Shrubland	Alt	3	100	100	SS	5	100	100
	Slope	2	54	58	Slope	4	51	55
	SNC	1	28	33	Alt	3	32	38
					SMS	1	13	18
	GCV R^2 = 0.38		R^2 = 0.44		GCV R^2 =0.58		R^2 = 0.64	
Forest	Slope	6	100	100	Alt	6	100	100
	Alt	6	100	100	LSC	6	100	100
	SNS	6	100	100	Pd	6	100	100
	LSC	4	36	49	SS	6	96	97
	LSNC	2	25	34				
	GCV R^2 = 0. 40		R^2 = 0.52		GCV R^2 =0.31		R^2 = 0.47	

During both the 1930s and the 2014 elevation, lithologies, soil suitability and slope gradients showed an important relation to the presence of forests although their explanatory power was weak (R^2 = 0.52 in the 1930s and R^2 = 0.47 in 2014) (Table 2.6). In both the 1930s and 2014, the elevation was the most important factor for the occurrences of forest in which a larger fraction of forest exists in areas with an elevation of over 1900 m. The interaction of elevation and lithology, soil suitability and population density resulted in different fractions of forest. The result also depicted that it was unlikely to find forest in areas with suitable soil for cultivation, while the increase of population density affected the forest occurrence positively, particularly in 2014.

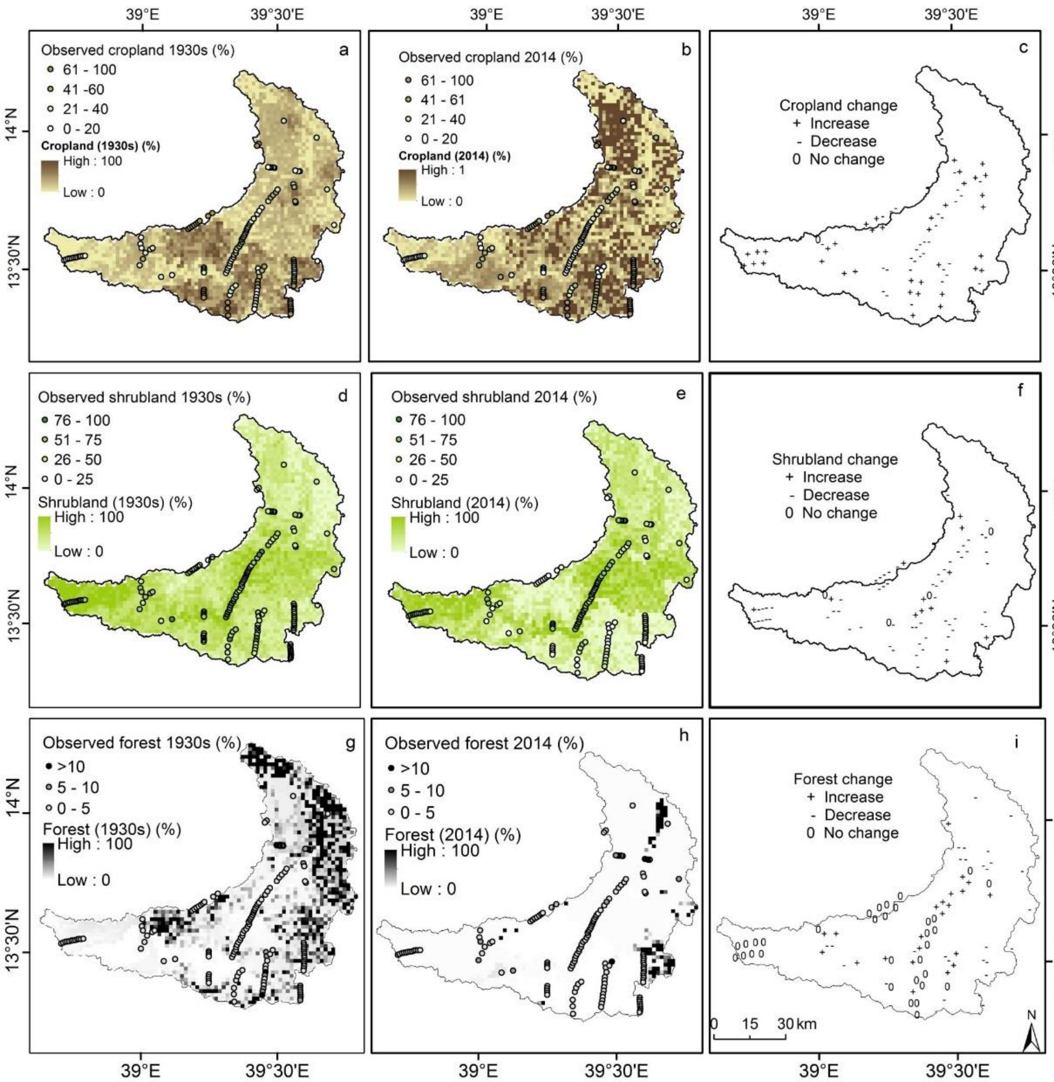


Figure 2.8 The spatial distribution and change of three the dominant land use/cover types of the study area: Cropland (A – C), shrubland (D – F) and forest (G – I). A positive (+) and negative (-) sign in these figures indicates the spatial expansion and the shrinkage of land use/cover types, respectively. Graduated classifications illustrate the percentage occurrence of the land use type in the 1930s and 2014 that also reveal the degree of spatial change within each location. Sd, Sf1, Sf2, Sh, Ss are supplementary data at Dergajen, Dessa forest 1, Dessa forest 2, Hadinet and Sinkata respectively.

The Multivariate regression models developed for different land use/covers in the 1930s and 2014 were used to calculate the raster data for each explanatory factor selected by the models. These raster databases were utilized to calculate fraction maps of three major land use/cover types (i.e. cropland, shrubland and forest), using the MARS equations of the LUC.

Accordingly, at least five spatial raster layers, which represent the explanatory factors, were prepared to create the fractional maps of cropland, shrubland and forest in the 1930s and 2014. Hence, these fractional maps indicated the spatial and temporal distributions and the changes of LUC. The mapping of land use/cover of the Geba catchment (Figure 2.8) was done by 1.5 x 1.5 km grid of the important explanatory factors in each model. As the values of every pixel are not absolute, but percentages of the different land use/cover types, separate maps were produced for the cropland, shrubland and forest. Colour gradients of each LUC have been used to compare the percentages of areal distribution and changes of land use/cover in the study area over the last 80 years. In these maps high gradients (larger percentages) of a different LUC did not occur on the same location, although mixed land use/covers having a smaller percentage on a particular location are observed (Figure 2.8). Given the several limiting factors for the inaccurate mapping of LUC, the validation of the maps of 2014 using 233 random points on GE showed a high accuracy for cropland (86%) and shrubland (84%) and a lower one for the forest map (60%) and other land covers (71%). Overall, the confusion matrix showed a higher overall accuracy for the fractional map (83%) and a very strong Kappa coefficient (72%) (Table 2.3).

2.4 Discussion

2.4.1 Point counting method, APs and GE images

Despite the difficulty of stereo viewing, which allows 3-D viewing, due to the high obliquity and a small area of overlapping vertical photos, the 1930s aerial photography is found to be an important source of historical information. The application of the point counting method, i.e. visualizing and tallying the land use/cover type under grid points was straightforward to identify the different classes, although it required a GIS expert (i.e. who can identify and interpret different LUC classes). Detailed information, individual objects within a 30 x 30 m area on the ground (e.g. tree, residence compound, etc.) can be readily recognized from these historical photographs (Figure 2.2). The scale of the photographs (i.e. medium scale), as it was originally aimed for military missions, has facilitated the view of the photographs in detail. Medium and large scale aerial photography is important as it improves the efficiency of the resource inventory and reduces the ground survey inventories which are expensive and slow (Fensham et al., 2002; Spencer and Hall, 1988) and impossible in case of historical photographs. In addition, zooming the scanned photograph on a computer screen until the target object (land use/cover) is recognized, is also helpful for a detailed examination of the aerial photographs. The high overall accuracy (93%) and a very strong Kappa coefficient agreement (89%) of LUC counting as shown in the error matrix (Table 2.3), validated that counting LUC on Google Earth was done accurately.

A good visualization and a high resolution nature of GE motivates, beside its potential for validation, its direct application in the environmental inventories including land use/cover studies (Frankl et al., 2013b; Fritz et al., 2009; Hu et al., 2013). The medium scale and zooming technique make the photographs comparable to the Google Earth image resolution and viewing, which suggests the appropriateness of the comparison of results from the two sources. (Frankl et al., 2013b) have used a combination of historical aerial photographs and GE images so as to analyze the temporal change of a gully network in Northern Ethiopia. Further, we are aware of only one study that used aerial photographs produced between 1936 and 1941 on a scale of 1: 64,000 for a land use cover change study in Texas and New Mexico, United States (Scanlon et al., 2007).

2.4.2 Land use/cover fraction

Cropland showed a slight increment over the long time period, which can be called stable with regard to its overall fraction in the catchment. Despite the rapid rise of the human population (Nyssen et al., 2009b), whose livelihood largely depends on agriculture (Deressa et al., 2008), the area of cultivated land remained almost constant during a long period. This indicates that suitable land for agriculture had been entirely occupied for many years, probably centuries, in Northern Ethiopia. Similar results have been reported locally in the catchment (that cultivated lands nearly did not expand over tens of years) (Alemayehu et al., 2009; Meire et al., 2013; Teka et al., 2013). Mitiku et al. (2006) documented that limits to lands (suitable for agriculture) are reached in Northern Ethiopia and that food demands for the increasing population could be met through an intensified use of the existing cropland. On the contrary, a significant expansion of cropland occurred in other parts of Ethiopia (e.g. Rembold et al., 2000; Tsegaye et al., 2010; Zeleke and Hurni, 2001), Africa and worldwide (Lambin et al., 2003; MEA, 2005) during the second half of the twentieth century. Dynamic changes (expansion or contraction, rapid or slow) of cropland were reported in the southwest of Ethiopia despite a rapid population growth in the region in the last 50 years (Reid, et al., 2000).On the other hand, the most dominant land cover in the 1930s, namely shrubland, has significantly decreased in fraction over the last eighty years. The decline might not only be visible in the land's percentage under shrub cover but the quality of the shrubland might also have deteriorated compared to history, although it had not been quantified. Field visits demonstrated that in 2014, the shrubs had a low plant density and an open canopy cover. The forest showed a declining trend from its already low percentage in the 1930s (from 6.3% to

2.3%). This small fraction of forest cover in the 1930s indicates that the forest resources had been cleared, even before the 1930s. Despite the strong claims on a dense forest cover in the 1930s in Ethiopia (including our study region), there is no reliable record of forest cover and no precise date and rate of deforestation (Pankhurst, 1995; Woien, 1995). Previous studies in or close to our study area have reported that the forest and shrubland illustrated an increment during the last three to five decades (Alemayehu et al., 2009; Belay et al., 2015; Meire et al., 2013; Muelenaere et al., 2014; Teka et al., 2013). However, our results may not be contradictory to such findings as their study period only extended to 1965 and covered small parts of the study area. The study carried out by Nyssen et al. (2014) in northern Ethiopia concerning environmental conditions over the last 145 years indicates the highly variable land degradation. This study discussed that the woody vegetation cover peak during the end of the 1930s, strongly declined until the large-scale soil and water conservation activities started in the last decade of the 20th century. Hence, our results are in line with those of Nyssen et al. (2014): as compared to the 1930s, the land is still more degraded nowadays in northern Ethiopia. Despite extensive forest rehabilitation practices in Northern Ethiopia, there was an exceptionally ongoing deforestation on the remnant natural forest in the region (Munro et al., 2008a). Recent deforestation has been detected in the Mt. Lib Amba and Simien Mountains, northern Ethiopia (Jacob et al., 2015, 2017). Our results also clarify an increase in bare land, grassland, built-up area and water body, which is in agreement with earlier findings (Alemayehu et al., 2009; Meire et al., 2013; Teka et al., 2013), particularly before the start of the SWC practices. The increase of bare land and built-up area can be explained by vegetation clearance, agricultural and settlement expansions resulted from the rapid growth of population. The increase in water body can be linked to the construction of reservoirs and ponds as part of the massive SWC practices in the Tigray region. The overall decline of vegetation in the last 80 years is also in line with the existence of larger areas where the SWC (including exclosure) has not been fully implemented, for example in the lower parts of the study area, which are relatively remote. Although our study shows the decline of shrubland and forest in present time, there are strong policies, institutions and village bylaws (not to cut trees and graze in exclosures and sacred areas) and community awareness to restore the environment through physical and biological soil and water conservation practices in the Tigray region. In general, this study clearly shows important variations in the proportion of LUC between two time points. Unfortunately, results only correspond to the end points of 80 year time interval (i.e. 1935-36 and 2014) while the condition of LUC in the intermediate times could not be addressed in this study.

2.4.3 Spatial change of LUC

Considerable spatial changes of land use/cover have taken place over the last eighty years. In the 1930s, less heterogeneity of land use in aerial photography (scenes) was observed as compared to the data of 2014. In other words, land use/covers were less fragmented in the 1930s. By 2014, land use/cover classes had encroached upon the land that was under different use/cover during the 1930s. Hence, it is not uncommon to observe a mosaic land use/cover, such as cropland that encroached shrubland, a tree plantation (mainly Eucalyptus) in cropland as patches or in a linear form (Meire et al., 2013), settlement and water body in cropland and so on. However, this study has a limitation of showing the spatio-temporal dynamism of LUC change over the last 80 years in the Geba catchment, due to a lack of intermediate time period data on LUC.

Although cropland did not a show significant change in fraction over a long time (section 2.4.2), an important spatial change was noted that about 33% of the cropland was transformed to a different LUC, mainly to shrubland, built-up area and bare lands (Table 2.5). It is obvious that cropland, which lost its productivity due to an exhaustive cultivation, can no longer used as cropland but is converted to bare land, degraded grazing land or shrubland, unless it is reclaimed. On the other hand, lands that were under shrub, forest and grass in the1930s was converted to cropland in 2014, probably to search fertile soils. This result is consistent with previous studies (e.g. Alemayehu et al., 2009; Zeleke and Hurni, 2001). Hence, while a fraction of cropland had been given away to other LUC classes it was also compensated by taking other LUC, especially shrubland and forest. There are also some areas where bare lands were converted to cropland which shows the critical shortage of suitable lands for cropping leading an agricultural expansion into marginal lands. Shrubland was also affected by an increase of grazing land, which can be explained by the rise in livestock production associated with the population growth. The transformation of forest into shrubland and cropland in 2014 shows that deforestation had continued over the last 80 years. The conversion of bare lands to forest and shrubland can be linked to the plantation forest and the implementation of exclosures over the last few decades. Considerable fraction of built-up area were recorded in 2014 on the locations previously (1930s) covered by cropland, shrubland and forest which can be linked with a to rapid population increase. Other studies also indicate that built-up areas (mainly urban areas) increased at the expense of cropland in Ethiopia during the last few decades (Haregeweyn et al., 2012; Miheretu and Yimer, 2017)..

2.4.4 Explanatory factors of land use/cover distribution and change

Land use/cover change in the Geba catchment is the outcome of a variety of processes. Overall, over the last 80 years, the study area had been hit by two major droughts and several famines. Identifying causative factors have influence land use/cover occurrences/ change significantly, is very essential for the development of a strong land use/cover change model. The common explanation for land use/cover change in earlier research carried out in the north or in other parts of Ethiopia, comprises the socio-economic forces, policies and institutions (Alemayehu et al., 2009; Belay et al., 2015; Byragi and Aregai, 2011; Fisseha et al., 2011; Meire et al., 2013; Muelenaere et al., 2014; Tadesse et al., 2014; Teka et al., 2013). Physical elements are rarely correlated to land use/cover changes (Reid et al., 2000; Tadesse et al., 2014), though they trigger significant changes particularly when the land is under stress (Lambin et al., 2001). The present study demonstrated that consideration of topography, soil type and lithology as potential explanatory factors of land use/cover occurrence, provided a moderate to high model fitting and the validation of results, particularly for cropland and shrubland. This study also illustrates that the land use/cover occurrence is governed by multiple factors. The non-linear relationship nature between land use/cover and explanatory factors are evidently proven through the MARS application in the current study.

The consistent effect of the slope gradient on cropland density throughout a long period explains the importance of the slope for land cultivation. Despite the shortage of suitable cultivation lands in the study area for a long time, steep slope areas remained unsuitable for agriculture. Other reports also indicate that arable lands are frequently observed on level to gentle slope lands (plains, foot slopes and valley floors) (Meire et al., 2013; Teka et al., 2013). But currently, cropland sometimes appears on steep slopes where soil and water conservation (SWC) measures like stone bunds or trenches are executed so as to counter soil erosion. This is in line with a previous study on long-term land use change in the same region (Meire et al., 2013). The current inverse correlation between the population density and the cropland fraction describes the conversion of cropland to built-up (such as housing, roads) areas following a population increase. Ramankutty et al. (2002) explained that the rapid population increase and urbanization resulted in less cropland area per capita. Jacob et al. (2015) have analyzed an increase of the tree line elevation in mountainous areas due to anthropogenic pressure. On the other hand, steep slope lands appear to be reserved for shrub use in the study area, (which is) explained by the extensive conservation measures that had been carried out in degraded areas of the Tigray region during the last two to three decades. Exclosures, as part of SWC, were mostly applied on very steep and degraded slopes, which suffer from a severe soil erosion. Various reports illustrated that sloping and steep areas are often employed for afforestation in Northern Ethiopia (Descheemaeker et al., 2006b). Forests that grew in suitable soils for cropping in the 1930s, had been deforested in 2014. Hence, in 2014, remnants of forests were available in areas where the soils are moderately suitable and non-suitable for cropping, sandstone and sloping, which appear to the fact that afforestation is promoted in less fertile soils. Currently, the forest density has augmented nearby towns which can be linked to the increased awareness of tree growing and management in the Tigray region (de Muelenaere, et al. 2014). Clusters of forests planted along farmland boundaries and in villages are commonly encountered in the region (Meire et al., 2013).

The creation of fractional maps on different land use/cover in the Geba catchment, which use model developed for each class with a set of explanatory elements, resulted in an approximately similar pattern with the observed fractions (Figure 2.8). It is important to possess proportional samples of AP/GE (in different explanatory factors) (Figure 2.3) for the prediction of land use/ cover distribution in the entire catchment. The verification of these maps using Google Earth images (2014) showed the model validity in order to predict the f land use/cover occurrence, particularly for 2014. Overall, 84 % of the land use/cover was correctly allocated to the fractional map of the land use/cover. Cropland and shrubland were more or less predicted accurately, while large errors had been noticed in the the forest prediction. This poor forecast accuracy can be related to the small fraction of forest in each scene which less likely dominants the scene. Moreover, the very strong Kappa coefficient agreement ($\kappa = 72$) confirms the validity of the created fractional maps. In general, this result suggests that the models we developed for the Geba catchment are reliable to foretell the fraction of land use/cover change, while using the important explanatory factors selected in each model (Table 2.7).

2.5 Conclusions

This study demonstrated the usefulness of the analysis of 1930s APs and GE images for the study of land/cover distribution and changes. The results have demonstrated significant modifications in the fraction and spatial shifts of land use/cover during the last eighty years. Despite insignificant changes in the fraction of cropland area, 39% in the 1930s to 42% in 2014, it partially shifted its location at the expense of other land use/cover. The transformation matrix illustrates that 33% of the cropland was given away to different LUC, mainly to shrubland, bare land, and grassland probably due to its decreasing productivity and change to built-up areas, which can be explained by a rapid population growth. Shrubland is the most affected land use/cover over this long time, as it significantly shrank from 48% in the 1930s to 37% in 2014, associated with a shift of cropland and an expansion of the built-up area and grazing land. Forest cover has dropping continuously in the last 80 years, from about 6.3% through an absolute minimum in the 1970s – 1980s to less than 2.3%. in 2014 The increased frequency of occurrence of different land use/cover in observation areas (scenes) shows a more the mixed or fragmented land use/cover system in 2014 compared to to 1930s.

The effects of different forces (environmental and socio-economic variables) on LUC distribution was indicated by non-linear regression analysis. This study also indicates that explanatory factors influence LUC types at different thresholds. Cropland was generally recorded in flat to sloping areas (<16%), while shrubland and forest were often seen on slopes above 5%, although the thresholds change when other important factors exist. The latter (such as elevation, soil suitability, lithology and socio-economic factors) were also very important for influencing the distribution of cropland, shrubland and forest. The unexplained variation in this study could be related to land management activities, other socio-political factors and institutions. Land use/cover distribution and changes are not explained by a single but by multiple factors (Lambin et al., 2001; Serneels and Lambin, 2001). The comparison of the fractional maps with the observed fraction reveals similar patterns in their distribution. The validation of this fractional map on Google Earth demonstrated a high overall accuracy (83%) and a strong Kappa coefficient (72%), which confirm the usefulness of the databases (GE and explanatory factors) and the MARS model in order to create an accurate LUC fractional map of LUC.

Overall, this study provided useful information regarding the condition of LUC in the Geba catchment in the 1930s and 2014, demonstrating larger areal fractions of shrubland and forest and an approximately constant cropland area in the1930s as compared to 2014. This suggests that more efforts of land management (SWC and exclosure) practices need to be implemented particularly in remote areas. Moreover, further investigation on the historical land use/cover of the study area could prove important so as to evaluate the ongoing SWC interventions or to design new land management strategies.

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2.6 Rreferences

Aerts R, Van Overtveld K., November E, Wassie A, Abiyu A, Demissew S, Daye DD, Giday K, Haile M, Tewoldeberhan S .2016. Conservation of the Ethiopian church forests: threats, opportunities and implications for their management. Sciences of The Total Environment, 551: 404–414.

Alemayehu F, Taha N, Nyssen J, Girma A, Zenebe A, Behailu M, Deckers, Poesen J .2009. The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). Resources, Conservation and Recycling, 53(4): 192–198.

Amanuel Z .2009. Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, northern Ethiopia. Dissertation, K.U. Leuven, Belgium.

Annys S, Demissie B, Amanuel Zenebe, Jacob M, Nyssen J .2017. Land cover changes as impacted by spatio-temporal rainfall variability along the Ethiopian Rift Valley escarpment. Reg Environ Change, 17(2): 451–463.

Araya A, Keesstra SD, Stroosnijder L .2010. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia. Agricultural and Forest Meteorology, 150 (7):1057–1064.

Asmamaw L, Mohammed A, Lulseged T .2011. LUC dynamics and their effects in the Gerado catchment, northeastern Ethiopia. International Journal Environtal Studies, 68(6): 883–900.

Bard KA, Coltorti M, DiBlasi MC, Dramis F, Fattovich R .2000. The environmental history of Tigray (Northern Ethiopia) in the Middle and Late Holocene: a preliminary outline. Afr Archaeological Review, 17(2): 65–86.

Bastin L, Buchanan G, Beresford A, Pekel JF, Dubois G .2013. Open resource mapping and services for web-based land-cover validation. Ecol Inform 14:9–16.

Bellhouse D .1981. Area estimation by point-counting techniques. Biometrics 37(2): 303–312.

Biadgilgn Demissie, Frankl A, Mitiku Haile, Nyssen J .2015. Biophysical controlling factors in upper catchments and braided rivers in drylands. Land Degradation and Development, 26: 748–758.

Billi P. 2015. Geomorphological Landscapes of Ethiopia. In: Billi P (ed) Landscapes and Landforms of Ethiopia (pp 3–32). Springer.

CIESIN (Center for International Earth Science Information Network) - Columbia University .2016. Gridded Population of the World, Version 4 (GPWv4): Population Density Adjusted to Match 2015 Revision UN WPP Country Totals. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4HX19NJ. Accessed 20 March 2016.

Congalton R, Oderwald R, Mead R. 1983. Assessing landsat classification accuracy using discrete multivariate analysis statistical techniques. Photogrammetric engineering and Remote Sensing 49 (12):1671 -1678

CSA .2008. Summary and Statistics Report of the 2007 Population and Housing Census. Federal Democratic Republic of Ethiopia Population Census Commission. December 2008, Addis Ababa, Ethiopia.

Daniels RB, Gamble EE, Bartelli LJ, Nelson LA .1968. Application of the Point count method to problems of Soil Microbiology. Soil Science, 106(2): 149–152.

de Muelenaere S, Frankl A, Haile M, Poesen J, Deckers J, Munro N, Veraverbeke S, Nyssen .2014. Historical landscape photographs for calibration of Landsat land use/cover in the Northern Ethiopian highlands. Land Degradation & Development, 25(4): 319–335.

Deressa T, Hassan RM, Alemu T, Yesuf M, Ringler C .2008. Analyzing the determinants of farmers' choice of adaptation methods and perceptions of climate change in the Nile Basin of Ethiopia. IFPRI discussion paper 00798.

Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B, Deckers S. 2006a. Runoff on slopes with restoring vegetation: a case study from the Tigray highlands, Ethiopia. Journal Hydrology, 331(1): 219–241.

Descheemaeker K, Nyssen J, Rossi J, Poesen J, Haile M, Raes D, Muys B, Moeyersons J, Deckers S. 2006b. Sediment deposition and pedogenesis in exclosures in the Tigray Highlands, Ethiopia. Geoderma, 132(3): 291–314.

Eswaran H, Rice T, Ahrens R, Stewart BA. 2003. Soil classification -a Global desk reference. CRC Press, Washington, D.C. 280pp.

FAO. 2010. Global Forest Resources Assessment: Main report. Foresty paper 163, Food and Agricultural Organization (FAO) of the United Nations, Rome, Italy.

FAO. 2011. Food and Agriculture Organization Ethiopia Country Programming Framework: 2012- 2015. Office of the FAO representative in Ethiopia to AU and ECA, Addis Ababa

Fleiss JL. 1971. Measuring nominal scale agreement among many raters. Psychological Bulletin 76: 378-382

Fazzini M, Bisci C, Billi P. 2015. The Climate of Ethiopia. In: Billi, P (ed.). 2015, Landscapes and Landforms of Ethiopia . Physics and Earth Sciences, University of Ferrara, Ferrara, Italy.: pp 65-88.

Fensham R, Fairfax R, Holman J, Whitehead P. 2002. Quantitative assessment of vegetation structural attributes from aerial photography. International Journal of Remote Sensing, 23(11): 2293-2317.

Fisseha G, Gebrekidan H, Kibret K, Yitaferu B, Bedadi B. 2011. Analysis of land use/land cover changes in the Debre-Mewi watershed at the upper catchment of the Blue Nile Basin, North West Ethiopia. J. Biodivers. Environ, Sci, 1: 184-196.

Frankl A, Nyssen J De Dapper M, Haile M, Billi P, Munro RN, Deckers J, Poesen J. 2011. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology, 129(3): 238–25.

Frankl A, Poesen J, Haile M, Deckers J, Nyssen J. 2013a. Quantifying long-term changes in gully networks and volumes in dryland environments: The case of Northern Ethiopia. Geomorphology, 201: 254–263.

Frankl A, Seghers V, Stal C, De Maeyer P, Petrie G, Nyssen J. 2015. Using image-based modelling (SfM–MVS) to produce a 1935 ortho-mosaic of the Ethiopian highlands. International Journal of Digital Earth, 8(5): 421–430.

Frankl, A, Zwertvaegher A, Poesen J, Nyssen J. 2013b. Transferring Google Earth observations to GIS-software: example from gully erosion study. International Journal of Digital Earth, 6(2): 196–201.

Friedman JH. 1991. Multivariate adaptive regression splines. The annals of statistics, 19 (1): 1-67.

Friedman JH, Silverman BW (1989. Flexible parsimonious smoothing and additive modeling. Technometrics, 31(1): 3–21

Fritz S, McCallum I, Schill C, Perger C, Grillmayer R, Achard F, Kraxner F, Obersteiner M. 2009. Geo-Wiki. Org: The use of crowdsourcing to improve global land cover. Remote Sensing, 1(3): 345–354.

Gebresamuel G, Singh BR, Dick O. 2010. Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. Acta Agr Scand BSP, 60(3): 211–226.

Gebru T, Eshetu Z, Huang Y, Woldemariam T, Strong N, Umer M, DiBlasi M, Terwilliger VJ. 2009. Holocene palaeovegetation of the Tigray Plateau in northern Ethiopia from charcoal and stable organic carbon isotopic analyses of gully sediments. Palaeogeography, Palaeoclimatology, Palaeoecology, 282(1): 67–80.

Goldewijk KK .2001. Estimating global land use change over the 1930s 300 years: the HYDE database. Global Biogeochemical Cycles, 15(2): 417–433.

Goldewijk KK, Ramankutty N .2004. Land cover change over the last three centuries due to human activities: the availability of new global data sets. GeoJournal, 61(4): 335–344.

Hadush G. 2012. Modeling of Hydrological Process in the Geba River Basin in the northern Ethiopia. PhD thesis (unpublished), Vrije Universiteit, Brussels, Belgium.

Hahm WJ, Riebe CS, Lukens CE, Araki S. 2014. Bedrock composition regulates mountain ecosystems and landscape evolution. Proceedings of the National Academy of Sciences, 111(9): 3338-3343.

Haregeweyn N, Fikadu G, Tsunekawa A, Tsubo M, Meshesha DT. 2012. The dynamics of urban expansion and its impacts on land use/land cover change and small-scale farmers living near the urban fringe: A case study of Bahir Dar, Ethiopia. Landscape and urban planning, 106(2): 149-157.

Haregeweyn N, Tsunekawa A, Nyssen J, Poesen J, Tsubo M, Meshesha DT, Schutt B, Adgo E, Tegegne F .2015. Soil erosion and conservation in Ethiopia: A review. Progress in Physical Geography, 39(6): 750–774.

Hoffer R. 1975. Natural resource mapping in mountainous terrain by computer analysis of ERTS-1 satellite data. Purdue University. LARS Research Bulletin 919: 124 pp.

HTS .1976. Tigrai Rural Development Study, Annex 1. Land and vegetation resources. Hunting Technical Services Ltd: Hemel Hempstead.

Hu Q, Wu W, Xia T, Yu Q, Yang P, Li Z, Song Q. 2013). Exploring the use of Google Earth imagery and object-based methods in land use/cover mapping. Remote Sensing, 5(11): 6026–6042.

Hurni H, Wiesmann U. 2010. Global change and sustainable development: A synthesis of regional experiences from research partnerships. University of Bern. Switzerland. Perspectives of the Swiss National Centre of Competence in Research (NCCR) North-South, University of Bern,Vol. 5. Bern, Switzerland: Geographica Bernensia.

IGM. Instituto Geografico Militare, Ente Cartografico dello Stato. 2012. www.igmi.org. Accessed 10 January 2016

IUSS. 2015. World reference base for soil resources 2014, Revised 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources reports No. 106. FAO, Rome, Italy.

Jacob M, Frankl A, Beeckman H, Mesfin G, Hendrickx M, Etefa Guyassa, Nyssen J. 2015. North Ethiopian Afro-alpine tree line dynamics and forest cover change since the early 20th century. Land Degradation & Development, 26: 654–664.

Jacob M, Frankl A, Hurni H, Lanckriet S, De Ridder M, Etefa Guyassa, Beeckman H, Nyssen J. 2017. Land cover dynamics in the Simien Mountains (Ethiopia), half a century after establishment of the National Park. Regional Environ Change, 17:777–787.

Kidane G, Dejene A, Malo M. 2010. Agricultural based Livelihood Systems in Drylands in the Context of Climate Change: Inventory of Adaptation Practices and Technologies of Ethiopia. Environment and Natural Resource working paper 38, FAO, Rome.

Lambin EF, Geist HJ, Lepers E. 2003. Dynamics of land-use and land-cover change in tropical regions. Annual Review of Environment and Resources, 28(1): 205–241.

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C. 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change, 11(4): 261–269.

Lanckriet S, Derudder B, Naudts J, Bauer H, Deckers J, Mitiku Haile Nyssen J. 2015. A political ecology perspective of land degradation in the north Ethiopian highlands. Land Degradation & Development, 26: 521–530.

Landis JR, Koch GG. 1977. The measurement of observer agreement for categorical data. Biometrics, 33: 159-174

Lepers E, Lambin EF, Janetos AC, DeFries R, Achard F, Ramankutty N, Scholes RJ. 2005. A synthesis of information on rapid land-cover change for the period 1981–2000. BioScience, 55(2): 115–124.

Maitima JM, Mugatha SM, Reid RS, Gachimbi LN, Majule A, Lyaruu H, Pomery D, Mathai S, Mugisha S. 2009. The linkages between land use change, land degradation and biodiversity across East Africa. LUCID Working Paper No. 42. Nairobi (Kenya): ILRI. http://hdl.handle.net/10568/1934.

Matheron G. 1971. The Theory of Regionalized variables and its applications. Ecole Nationale Superieure des Mines de Paris.

Meire E, Frankl A, De Wulf A, Haile M, Deckers J, Nyssen J. 2013. Land use/cover dynamics in Africa since the nineteenth century: warped terrestrial photographs of North Ethiopia. Regional Environmental Change, 13(3): 717–737.

Mengistu DA, Waktola DK, Woldetsadik M. 2012. Detection and analysis of land-use and land-cover changes in the Midwest escarpment of the Ethiopian Rift Valley. Journal of Land Use Science, 7(3): 239–260.

MEA. 2005. Ecosystem and Human Well-being: Synthesis. Millennium Ecosystem Assessment, 2005. Island Press, Washington DC.

Miheretu BA, Yimer AA. 2018. Land use/land cover changes and their environmental implications in the Gelana sub-watershed of Northern highlands of Ethiopia. Environmental Systems Research, 6(1): 7

Mitiku H, Herweg K, Stillhardt B. 2006. Sustainable land management–A new approach to soil and water conservation in Ethiopia. Mekelle University, Mekelle, Ethiopia, University of Berne, Berne, Switzerland.

Munro RN, Deckers J, Haile M, Grove A, Poesen J, Nyssen J. 2008. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena, 75(1): 55–64.

Nyssen J, Frankl A, Mitiku Haile Hurni H, Descheemaeker K, Crummey D, Ritler A, Portner B, Nievergelt B, Moeyersons J, Munro N,Deckers J, Billi P, Poesen J. 2015. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. Science of The Total Environment, 485: 164–179.

Nyssen J, Haile M, Naudts J, Munro N, Poesen J, Moeyersons J, Frankl A, Deckers J, Pankhurst R. 2009). Desertification? Northern Ethiopia re-photographed after 140 years. Science of The Total Environment, 407(8): 2749–2755.

Nyssen J, Naudts J, De Geyndt K, Haile M, Poesen J, Moeyersons J, Deckers J. 2008a. Soils and land use in the Tigray highlands (Northern Ethiopia). Land Degradation & Development, 19(3): 257–274.

Nyssen J, Petrie G, Mohamed S, Gebremeskel G, Seghers V, Debever M, Hadgu KM, Stal C, Billi P, Demaeyer P. 2016. Recovery of the aerial photographs of Ethiopia in the 1930s. Journal of Culture Heritage, 17: 170–178.

Nyssen J, Poesen J, Descheemaeker K, Haregeweyn N, Haile M, Moeyersons J, Frankl A, Govers G, Munro N, Deckers J. 2008b. Effects of region-wide soil and water conservation in semi-arid areas: the case of northern Ethiopia. Zeitschrift für Geomorphologie 52:291–315.

Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M, Lang A. 2004. Human impact on the environment in the Ethiopian and Eritrean highlandsa state of the art. Earth-Science Review, 64(3): 273–320.

Nyssen J, Poesen J, Moeyersons J, Haile M, Deckers J. 2008c. Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands–towards a sediment budget. Earth Surface Processes and Landforms, 33(5): 695–711.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G. 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology, 311(1): 172–187.

Pankhurst R. 1995. The history of deforestation and afforestation in Ethiopia prior to World War I. Northeast African Studies, 2(1): 119–133

Quiros E, Felicísimo AM, Cuartero A. 2009. Testing multivariate adaptive regression splines (MARS) as a method of land cover classification of TERRA-ASTER satellite images. Sensors, 9(11): 9011–9028.

Ramankutty N, Foley JA. 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biogeochemical Cycles, 13(4): 997–1027.

Ramankutty N, Foley JA, Olejniczak N.J. 2002. People on the Land: Changes in Global Population and Croplands during the 20th Century. Ambio, 31(3): 251- 257.

Reid RS, Kruska RL, Muthui N, Taye A, Wotton S, Wilson, CJ, Mulatu W. 2000. Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of southwestern Ethiopia. Landscape Ecology, 15(4): 339–355.

Romanov P, Tarpley D, Gutman G, Carroll T. 2003. Mapping and monitoring of the snow cover fraction over North America. Journal of geophyscal Research, 108(D16), 8619.

Rembold F, Carnicelli S, Nori M, Ferrari GA. 2000. Use of aerial photographs, Landsat TM imagery and multidisciplinary field survey for land-cover change analysis in the lakes region (Ethiopia). International Journal of Applied Earth Observation and Geoinformation, 2(3-4): 181-189.

Saebo HV. 1983. Land use and environmental statistics obtained by point sampling. Central Bureau of Statistics of Norway. Artikler 144.

Scanlon BR, Reedy RC, Tachovsky JA. 2007. Semiarid unsaturated zone chloride profiles: Archives of past land use change impacts on water resources in the southern High Plains, United States. Water Resoures Research, 43(6): 1–13.

Serneels S, Lambin, EF. 2001. Proximate causes of land-use change in Narok District, Kenya: a spatial statistical model. Agriculture, Ecosystems & Environment, 85(1): 65-81.

Shockey WR. 1969. Point sampling of land use in the Washita Basin, United state department of agriculture, Agricultural research service. Archived documents, 41–149

Spencer RD, Hall R. 1988. Canadian large-scale aerial photographic systems(LSP). Photogrammetric Engineering and Remote Sensing, 54(4): 475-482.

Stehman SV. 1996 Estimating the Kappa Coefficient and its Variance under Stratified Random Sampling. Photogrammetric Engineering & Remote Sensing 62(4): 401-402

Tadesse G, Zavaleta E, Shennan C, FitzSimmons M. 2014. Policy and demographic factors shape deforestation patterns and socio-ecological processes in southwest Ethiopian coffee agroecosystems. Applied Geography, 54: 149–159.

Taye G, Poesen J, Wesemael BV, Vanmaercke M, Teka D, Deckers J, Goosse T, Maetens W, Nyssen J, Hallet V. 2013. Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography, 34(3): 236–259

Tayyebi A, Pijanowski BC. 2014. Modeling multiple land use changes using ANN, CART and MARS: Comparing tradeoffs in goodness of fit and explanatory power of data mining tools. International Journal of Applied Earth Observation and Geoinformation, 28: 102–116.

Teka K, Van Rompaey A, Poesen J. 2013. Assessing the role of policies on land use change and agricultural development since 1960s in northern Ethiopia. Land Use Policy, 30(1): 944–951.

Teka K, Van Rompaey A, Poesen J, Van Bruyssel S, Deckers J, Amare K. 2015. Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? Land Degradation & Development, 26(7): 680–689.

Tesfamichael G. 2009. Regional groundwater flow modelling of the Geba basin, northern Ethipia, PhD thesis, K.U. Leuven, Belgium.

Tesfamichael G, De Smedt F, Miruts H, Solomon G, Kassa A, Kurkura K, Abdulwassie H, Bauer H, Nyssen J, Moeyersons J, Deckers J, Mitiku H, Nurhussen T. 2010. Large-scale geological mapping of the Geba basin, northern Ethiopia. Tigray Livelihood Paper No 9, VLIR – Mekelle University IUC Program, 46 pp.

Tesfaye C, Gebretsadik E. 1982. Hydrogeology of Mekelle Area (ND37 - 11). Ministry of Mines and Energy, Ethiopian Institute of Geological Survey. The Provisional Military Government of Socialist Ethiopia. Memoir No.2, Addi Ababa, Ethiopia.

Tielens S. 2012. Towards a soil map of the Geba catchment using benchmark soils. Dissertation, K.U. Leuven, Belgium.

Tilahun K. 2006. Analysis of rainfall climate and evapo-transpiration in arid and semi-arid regions of Ethiopia using data over the last half a century. J Arid Environ 64(3): 474–487.

Tsegaye D, Moe SR, Vedeld P, Aynekulu E. 2010. Land-use/cover dynamics in NorthernAfar rangelands, Ethiopia. Agriculture, Ecosystems & Environment, 139(1): 174-180.

Turner BL, Meyer WB, Skole DL. 1994. Global land-use/land-cover change: towards an integrated study. Ambio, 23: 91–95.

USGS. 2016. Shuttle Radar Topography Mission (SRTM) (1-arc second) documentation. https://earthexplorer.usgs.gov/. Accessed 29/04/2016.

Van de Wauw J, Baert G, Moeyersons J, Nyssen J, De Geyndt K, Taha N, Zenebe A, Poesen J Deckers J. 2008. Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. Catena, 75(1): 117–127.

Vancampenhout K, Nyssen J, Gebremichael D, Deckers J, Poesen J, Haile M, Moeyersons J. 2006. Stone bunds for soil conservation in the northern Ethiopian highlands: Impacts on soil fertility and crop yield. Soil and Tillage Research, 90(1): 1–15.

Virgo, K. and Munro, R. 1978. Soil and erosion features of the Central Plateau region of Tigrai, Ethiopia. Geoderma, 20(2): 131–157.

Woien H. 1995. Deforestation, information and citations. GeoJournal, 37(4): 501–511.

WBISPP (Woody Biomass Inventory and Strategic Planning Project). 2003. Tigray Regional State: A strategic plan for the sustainable development, conservation, and management of the woody biomass resources. Final report, Mekelle, Ethiopia.

Zeimetz, KA, Dillon E, Hardy EE, Otte RC. 1976. Using Area Point Samples and Airphotos to Estimate Land Use Change. Agricultural Economics Research, 28(2): 65–74

Zeleke G, Hurni. H. 2001. Implications of land use and land cover dynamics for mountain resource degradation in the Northwestern Ethiopian highlands. Mountain Research and Development, 21(2): 184-191.

3 Changes in gully and soil and water conservation structure densities over the last 80 years

This chapter is based on

Etefa G, Frankl A, Zenebe A, Poesen J, Nyssen J. 2017. Changes in gully and soil and water conservation structure densities in North Ethiopia over the last 80 years. Earth Surface Processes and Landforms, In review.

Abstract

Gullies have been a common phenomenon in north Ethiopia for the last centuries. On the other hand, different soil and water conservation (SWC) structures have been implemented since a long time to curb land degradation. However, like for most of the affected areas worldwide, the densities and distribution of gullies and SWC structures, their factors and interrelations were insufficiently assessed. The aims of this study were to develop a technique for mapping the densities of gullies and SWC structures, to explain their spatial distribution and to analyze changes over the last 80 years (1935 – 2014) in the Geba catchment. Aerial photographs (APs) from 1935-36 and Google Earth (GE) images from 2014 were analyzed in this study. Transect lines were established to count gullies and SWC strucrures in order to calculate densities. On average, a gully density of 1.14 km km-2 was measured in 1935-36 of which the larger portion (75%) were vegetated indicating they were not very active. Over 80 years, the density of gullies has significantly increased to 1.59 km km-2 with less vegetation growing in their channel, but 66% of these gullies were treated by check dams. There were ca. 3 km km-2 of indigenous SWC structures (daget or lynchets) in 1935-36 whereas a high density (20 km km-2) of introduced SWC structures (mainly stone bunds and terraces) were observed in 2014. The density of gullies is positively correlated with slope gradient and shrubland and negatively with cropland whereas the density of SWC structures significantly increased with increasing cropland proportion. Gully and SWC structures density maps indicate sensitive areas to gully formation and priority areas for the implementation of soil and water conservation in Geba catchment. The obtained results reveled the feasibility of the methods applied for mapping the density of gullies and SWC structures in northern Ethiopia.

Keywords: check dam, gully density, stone bund, aerial photograph, lynchet

3.1 Introduction

Gully erosion has become a major concern as it plays a key role in causing land degradation particularly in semi-arid regions where vegetation cover is poor (Frankl et al., 2011a; Lesschen et al., 2008; Nyssen et al., 2006; Oostwoud Wijdenes and Bryan, 2001; Patton and Schumm, 1975; Salleh and Mousazadeh, 2011; Shi and Shao, 2000; Valentin et al., 2005). Poesen et al. (2003) defined gully as "erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths". Gully erosion causes land degradation by increasing connectivity in the landscape and transfer runoff and sediments from upland to river channel (Poesen et al., 2003). Gullies are geomorphic features with V- and U-shaped cross-sections that hinder different activities such as ploughing (FAO, 1965; Imeson and Kwaad, 1980). Gullies are formed by concentrated flow erosion and incision, with channel depth ranging between 0.5 m to 30 m (Betts et al., 2003; Poesen et al., 2003).

The northern Ethiopian highlands have experienced land degradation over the last few millennia (Bard et al., 2000). From the 19th century onwards and throughout the 20th century the problem of land degradation has been a common phenomenon in the Tigray region (Nyssen et al., 2014; Nyssen et al., 2009a). The evolution of soil erosion rate due to progressive vegetation clearance in this region even dates back to the Middle Holecene (Bard et al., 2000). Gullies are present in northern Ethiopia at least since the mid-19th century, mainly due to vegetation removal (Frankl et al., 2011a; Nyssen et al., 2006). It is obvious that the removal of fertile soil and dissection of cropland by gully erosion results in the reduction of crop yields (Nyssen et al., 2006). A literature review by Haregeweyn et al. (2015a) shows that gully erosion rates vary from 1.1 t ha^{-1} y^{-1} to 17.6 t ha^{-1} y^{-1} in north Ethiopia.

Site-specific studies in north Ethiopia indicate that the density and volume of gullies have significantly increased until large-scale soil and water conservation (SWC) structure were implemented in the region since the last decades of the 20th century (Frankl et al., 2013a). Studies indicate that the spatial distribution of gullies is influenced by several factors including lithology, soil type, land use/cover and topography (Frankl et al., 2013a; Gutiérrez et al., 2009; Mukai, 2017; Poesen et al., 2003; Salleh and Mousazadeh, 2011). From the late 19th century onwards and until the mid-20th century gullies were relatively stable and the channels mostly covered with vegetation, while in the second half of 20th century gullies became more active and their cross-section increased (Frankl et al., 2011a). The construction of roads in this mountainous region has also contributed to the increase of the density of gullies (Nyssen et al., 2002).

Despite their important effects on the environment and agricultural production, relatively few data are available on gully occurrence in northern Ethiopia (Haregeweyn et al., 2015a), particularly on the density and spatial distribution of gullies at the scale of large catchments such as Geba catchment (5142 km^2). A few site-specific studies were conducted in this catchment to show the change of gully density and explanatory factors for changes from 1965 to 2010 (Frankl et al., 2013a). Moreover, spatial mapping of gullies has received less attention worldwide although such information is very important to understand the distribution of gullies in a catchment and also to use the map for pixel based environmental analysis. The studies by Hughes et al. (2001) and Knight et al. (2007) in Australia are among the few attempts made to map the spatial distribution of gully erosion.

Different types of soil and water conservation SWC practices have been proposed or implemented in different countries to rehabilitate degraded environments and to curb further land degradation (e.g. Chen et al., 2007; Lesschen et al., 2008; Pender and Kerr, 1998; Reij et al., 1996; Sidibé, 2005; Valentin et al., 2005). As the awarness about the socio-economic and environmental impacts of land degradation in north Ethiopia has increased, local communities and the government (particularly Tigray regional government) began the implementation of different physical and biological SWC structures since the last decades of 20th century and this has brought positive results (Desta et al., 2005; Frankl et al., 2013a; Haregeweyn et al., 2015a; Herweg and Ludi, 1999; Nyssen et al., 2009a). The densities of stone bunds in north Ethiopia, specifically in Geba catchment, were estimated at 2.3 to 5.6 km km^{-2} in 2007 (Amanuel, 2009a). Several studies evaluated the effectiveness of SWC practices in the controling runoff and soil loss most often using experimental plots (Descheemaeker et al., 2006a; Etefa et al., 2017; Herweg and Ludi, 1999; Taye et al., 2013a; Vancampenhout et al., 2006). Before the implementation of the introduced SWC structures, indigenous SWC practices (i.e. daget or lynchets) have been also widely practiced by farmers for moisture conservation and to indicate their farm boundary (Nyssen et al., 2000). Despite their extensive implementation, data on the density and spatial distribution of SWC structures are rare. Likewise there is no general accepted technique developed for the measurement and mapping of SWC structures specifically stone bunds in cropland, using very high resolution images (e.g.Google Earth) are limited. Mekuriaw et al. (2017) applied automated linear feature mapping techniques to map SWC structures.

Data on the densities and spatial distribution of gullies and SWC structures (*daget*, stone bund, terraces, check dams) installed over the last 80 years are very important to study the historical and present time environmental conditions. Data on densities and SWC structures are useful to model and map the hydrological condition (runoff) of a catchment over time and space. Moreover, these data can be used as a basis for monitoring the progress of implementation of SWC practices. This study, therefore, aimed: 1) to develop a technique for mapping of gully and SWC densities; 2) to map and measure the density and spatial distribution of gullies and SWC practices (*daget*, stone bund, terraces, check dams), and 3) to analyze changes in the densities of gullies and soil and water conservation structures over the last 80 years (1935-2014).

3.2 Materials and methods

3.2.1 Study area

Geba catchment (Figure 3.1), the study area, is located in the north Ethiopian highlands, between 13°16' to 14°15' N and 38°38' to 39°48' E. The catchment covers an area of 5142 km^2 with an elevation ranging between 900 m a.s.l. and 3300 m a.s.l. The Geba River flows towards the Tekeze River which eventually joins the Atbara River and the Nile in Sudan (Figure 3.1).

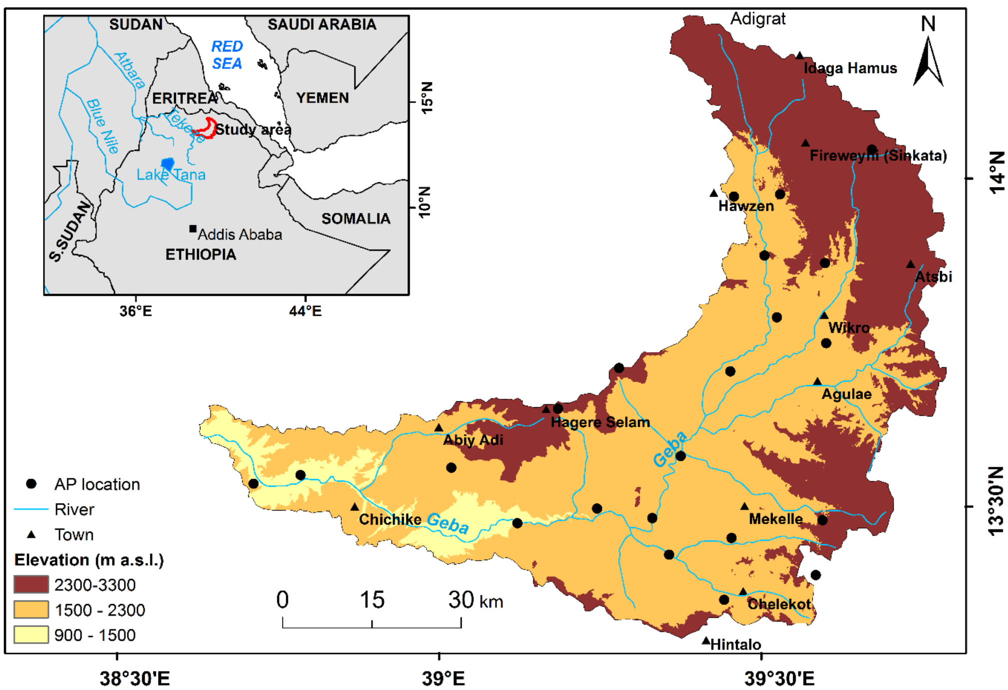

Figure 3.1 Map of study area showing sampled 1935-36 aerial photograph locations (AP location) and traditional agro-ecological zones (i.e. kola = 900 – 1500 m, weyina dega = 1500 – 2300 m and dega = 2300 – 3300 m) of Geba catchment

Steep volcanic mountains with vertical cliffs and plateaus, deep gorges, rugged terrain and rock outcrops characterize the catchment (Billi, 2015; Tesfamichael et al., 2010b). The slope gradients of the study area range from level to nearly vertical and were categorized as flat (<5%), sloping (5% – 15%), and steep gradients (>15%) (Figure 3.2). Sloping and steep gradients comprises respectively about 45% and 21% of the catchment while about 34% of the area is flat. Diversified lithologies and topography (Tesfamichael et al., 2010b) of the catchment are the basis for complex soil type distributions (Tielens, 2012a; Van de Wauw et al., 2008). Cambisols, Leptosols and Regosols are among the dominant soil types the catchment (Nyssen et al., 2008a; Tielens, 2012a; Virgo and Munro, 1978). On steep slopes, shallow soils such as Leptosols and rock outcrops are commonly observed, and Fluvisols dominate in the valley bottoms (Nyssen et al., 2008a; Tielens, 2012a).

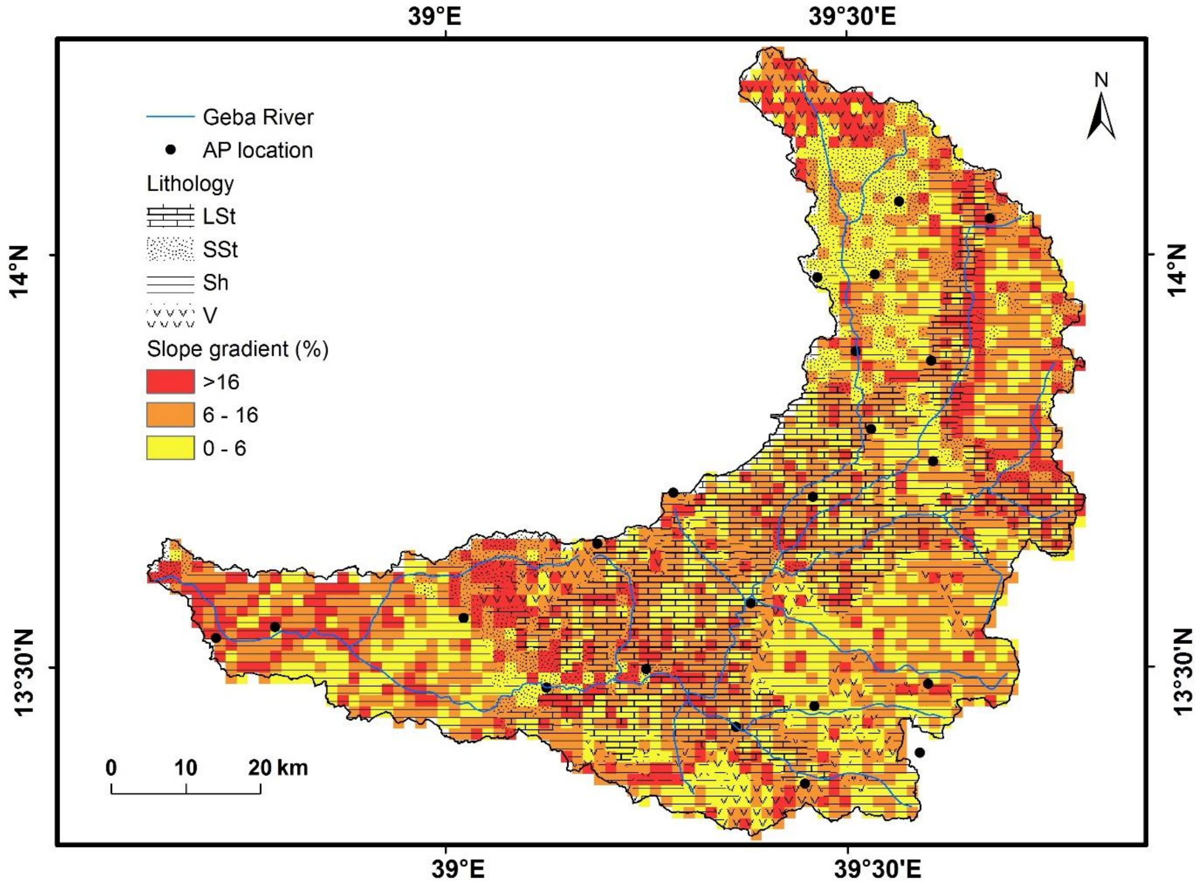

Figure 3.2 Map of slope gradients and lithology of Geba catchment. The slope gradients averaged for 2.25 km^2 were divided into three classes: flat (0% - 5%), sloping (6% - 16%) and steep (>16%) gradient. LSt – limestone; SSt – sandstone; Sh – shale; and V – volcanic lithologies. AP location – aerial photograph location.

The Geba catchment has a tropical and semi-arid climate with a bi-annual rainfall distribution. The main rainy season of the region is from to July to early September and accounts for ca. 80% of the annual precipitation. Short season, intense showers with large drop sizes characterize the rainfall of the catchment (Nyssen et al., 2005; Virgo and Munro, 1978). Mean annual precipitation is ca. 640 mm ranging between 555 mm and 1200 mm. Distribution of rainfall is influenced mainly by topographic variables (slope aspect, orientation of the valley and slope gradient) (Nyssen et al., 2005). Annual evapotranspiration depth of Geba catchment ranges from 905 mm to 2538 mm (Hadush, 2012).The mean annual maximum average air temperature ranges from 21 to 31 ºC and the mean annual minimum air temperature ranges from 3 to 1 ºC (Araya et al., 2010a).

Land use is dominated by cropland followed by shrubland (Amanuel, 2009a; Gebresamuel et al., 2010a). Shrubland and grassland are mainly found on sloping land and on steep slopes while croplands are found on flat and sloping gradients (chapter 2). The study area has lost its native forests a long time ago (Aerts et al., 2016b; Gebru et al., 2009; Nyssen et al., 2004a) and the remnant patches of forests account only for 2.3% which are usually limited to remote areas and around churches (Aerts et al., 2016b; Gebru et al., 2009; HTS, 1976b; Munro et al., 2008b). An indigenous soil and water conservation, structure, i.e. the daget which is on cultivated strip on which grasses and trees are grown, have been practiced by local communities in earlier times which are nowadays replaced by the introduced soil and water conservation structures (Nyssen et al., 2000). Over the last few decades, large-scale physical and biological soil and water conservation structures such as stone bunds, check dams, hillside terraces, as well as exclosures have been implemented in the catchment to reverse land degradation (Descheemaeker et al., 2006a; Herweg and Ludi, 1999; Munro et al., 2008b; Nyssen et al., 2014; Vancampenhout et al., 2006).

3.2.2 Gully and SWC density measurement

For this analysis we used the central part (1:11,500) and low-oblique part (1:13,000 – 1:18,000) of the aerial photographs that the Italian Military Geographical Institute took over the study area in 1935 – 36 (Nyssen et al., 2016b) as well as the corresponding site on Google Earth in 2014. Google Earth images of the study area for the period from December 2013 to February 2014 are based on Pleiades 1A and Pleiades 1B satellites (2 m resolution) and SPOT 6 satellite (1.5 m and 6 m resolution). The analyzed sample areas range from 2.5 km^2 to 8 km^2 with an average of 4.8 km^2 (±1.53). The same location and area were selected on GE that correspond to each APs by using grid points (18 x 15 points) (Figure 3.3) .

To measure the densities of gullies and soil and water conservation structures (*daget*, stone bunds, terraces) in the Geba catchment, 22 APs of sample areas were selected in order to have representative samples of the heterogeneous catchment, which is characterized by diversified topographic settings and agro-ecological zones (Figure 3.1), lithologies and slope gradients (Figure 3.2). The area occupied by APs used as sample scenes was quite small (2%) as compared to the catchment area, this is due to the manual measurement technique which is time intensive but on the other hand the sample sites were fairly distributed over the catchment (Figure 3.1).

The densities of gullies in 1935-36 (November to January) were assessed from APs whereas the densities of gullies in 2014 were obtained from Google Earth images. Likewise, daget systems were assessed from APs of 1935-36 while Google Earth was used for the stone bundes/terraces. Other types of soil and water conservation such as trenches and check dams (which do not concern vast areas in the study catchment) were not taken into account in this measurement. Google Earth has been used in successfully several studies, especially for geomorphological analysis. For example, a gully network study in Northern Ethiopia (Frankl et al., 2013a), mapping of density of scar network (Tesfaalem et al., 2016), mapping of river channel width, landslide and faults (Fisher et al., 2012) are among the studies used Google Earth image database.

Grid points that were used to select areas on GE that corresponding to APs were also used to draw transect lines (along the column or row of the grid points depending on the orientation of the gullies) to count gullies and conservation structures in 1935-36 and in 2014. Accordingly, transect lines were established perpendicular to the gullies at an average distance of 135 m between consecutive transect lines. Similarly, densities of SWC structures were measured using transect lines selected across the structures of SWC at an average distance of ca. 112 m between consecutive transect lines. All gullies (active and stabilized) and SWC structures (*daget* system, stone bunds and terraces) encountered along the transect lines were counted. Active gullies refers to gullies that are not conserved with check dams and without vegetation.Counting of gullies and daget SWC structures were done by visualizing them on screen for both APs and GE images. Gullies and SWC structures were carefully identified from other linear features (e.g.footpath, farm boundery) based on their characterstics such as direction, shape, association, tone and location (Loelkes et al, 1983). With the exception of the main rivers, linear features running along hillside and that compose the drainage network were counted as gully. Thanks to the large scale of Italian aerial photographs and high resolution and terrain display of Google Earth images allowed to readily differentiate gullies and SWC structures from other features. Although drainage directions can be perceived from Italian aerial photography, Google Earth was very important to view the terrain of selected scenes which help to comfortably recoganize drainage and SWC structures directions found in the scenes. In 1935-36, it was common to view vegetation growth along gullies and *daget* system, which was used as supplementary indices for identification of these features. The method used to count the densities of gully and SWC structure aerial photographs neverthless is not perfect, due to different reasons such as problems related to photographs due to damage or scanning quality, similarity of feature characterstics, and local variablity in slope orientation.

Simple linear and power regressions were used to describe the relationship between the densities of gullies and SWC structures and their influencing factors. Slope gradient and lithology are among the factors that predominantly determine the occurrence of gullies particularly in the semi-arid parts of northern Ethiopia (Frankl et al., 2013). Regression models between density of gullies and water conservation and inluencing factors were used to create density maps of gullies and SWC structures in Geba catchment, by creating raster layers of the independent variables in a GIS. Raster layers of explanatory factor and mapping was done at 1.5 km x 1.5 km pixel size that are approximately the same size as the smallest scene area (2.25 km^2) of the interpreted APs.

Accuracy assessments were carried out to verify the validity of density mapping of gullies and SWC structures for the 1935-36 and 2014 changes. For the accuracy assessment of 1935-36 density maps, APs which were not used for mapping were used and the corrersponding areas on Google Earth were used for the accuracy assessment ofthe 2014 density maps. For this purpose 10 additional scenes (Figure 3.8) were randomly selected from different flight lines distributed over Geba catchment to count the densities of gully and SWC in 1935-36 and 2014 using the technique (i.e. transect lines) previously applied in this chapter. The average densities of gully and SWC at the sample area were also extracted from density maps of 1935-36 and 2014 for the accuracy measurement.

3.2.3 Data analysis

Gullies and SWC structures (daget, stone bunds, terraces) (Figure 3.3) counted along transect lines were converted to length (km) and density.(km km^{-2}) The total length of gullies and SWC structures on each AP/GE was calculated as the product of the average number of gullies or SWC structures encountered along the transect lines on the photograph and the length of the AP/GE image perpendicular to the transect lines.

$$L_{tot} = N * l \qquad (1)$$

Where; L_{tot} = total gully or SWC structure length (km) on scene, N = average number of gullies or SWC per transect line on photograph, and l = length (km) of the scene perpendicular to transect lines.

Then the density of gullies and SWC, in km km^{-2}, was calculated as the ratio of total length of gullies or SWC structures per change to the total area of the analyzed change.

$$Dg = L_{tot} / A \qquad (2)$$

Where, Dg = density (km km^{-2}) of gullies or SWC, A = area (km^2) covered by the AP scene.

The proportion of stabilized (vegetated and/or with installed check dams), non-active gullies, was calculated as the density of stabilized gullies divided by the total density. Density of stablized gullies is derived from the total number of gullies with conservation per scene. Generally, the conservation treatment of gullies is done for the entire length or the larger part of a gully. Hence, gullies with at least a large part that is conserved with check dams and / or vegetation were counted as stablized gully. The Mann Whitney U test was used to test if there is a significant difference between the densities of gullies in 1935-36 and 2014. Accuracy measurement for the mapping of gully and SWC structure density was accomplished using linear regression between the measured and predicted densities of gullies and SWC structures of 10 selected scenes. All statistical data analysis were done in R 3.3.2 software while ArcGIS10.1 was used for spatial data processing and mapping.

3.3 Results

3.3.1 Densities and conditions of gullies in 1935-36 and in 2014

The fact that the APs and corresponding GE images were taken in the dry season, was important to readily recognize gullies and SWC structures. During growing season these features are masked by vegetation, particularly it is difficult to identify stone bunds during crop growth as the technique is largely implemented on agricultural land (Mekuriaw et al., 2017; Taye et al., 2013a). The transect line method was very fast and easy to tally gullies and SWC structures manually. Unlike the automated or semi-automated technique for linear feature extraction, the manual method is important to easily visualize and identify features but it is time consuming (Mekuriaw, et al., 2017).

The measurement of gully density in Geba catchment in 1935-36 indicated the existence of already a large density of gullies in the catchment at that time: gullies were observed in all sampled APs except for two. The density of these gullies ranged from 0 to 2.19 km km^{-2} with an average density of 1.14 (±0.52) km km^{-2}. The measurement of gullies from GE for the present time (2014) revealed an increment as compared to the gully density in 1935-36 (Figure 3.3). In 2014, the density of gullies ranged between 0 and 2.82 km km^{-2} with an average value of 1.59 (±0.82) km km^{-2}. The Mann Whitney U test indicates that gully density in 2014 was significantly greater than the density in 1935-36 ($P = 0.047$, $\alpha = 0.05$; $N = 22$ in this and all subsequent statistical analyses of this chapter). The result shows also that the increase of gully density has occurred in all observation areas except in two where no gullies were encountered.

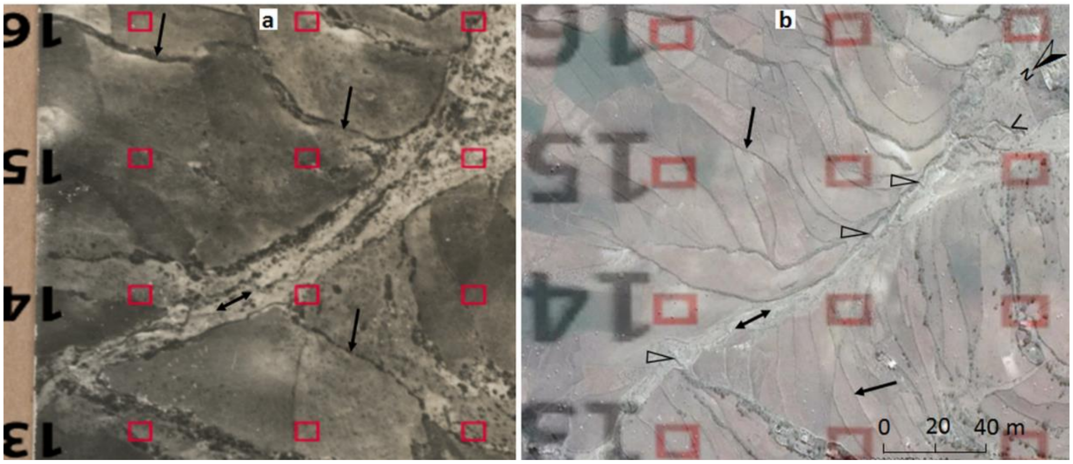

Figure 3.3 Example of soil and water conservation and gullies: a) on aerial photograph (December 02, 1935), b) on Google Earth (January 01, 2014). Gullies and SWC structures are indicated by arrows: Daget system in 1935-36 and 2014 and introduced SWC in 2014 ( ), gullies in 1935-36 and 2014 ( ), new gully in 2014 but not present in 1935-36 ( ) and check dam in gullies in 2014 ( ). Grid points are overlain on the photograph and image for sake of matching imagery as well as to use the points for establishing transect lines. Center of scene at 13°41'7.80"N and 39°14'32.05"E; the land is sloping towards lower left of the scenery. In this scene transects were put along column grid points for gully density and along row grid points for SWC density measurement.

The conditions of gullies, whether they were vegetated or check dams had beenconstructed, or not was also measured: 75% (±23%) in 1935-36 and 66% (±18%) in 2014. The average percentage of gullies in their channel with vegetation was greater in the 1935-36 than in 2014 (for example see Figure 3.4).

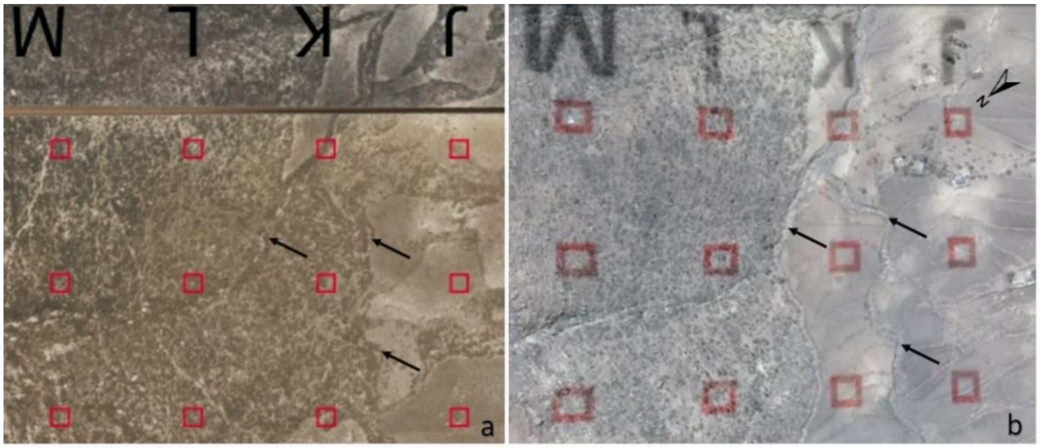

Figure 3.4 Condition of gullies in the 1930s and in 2014: a) on November 2, 1935, the gullies and their catchments were vegetated , b) on January 10, 2014 the gullies were characterized by less vegetation cover in their channels and catchments. Arrows indicate gullies. Center of scene at 13°39'0.58"N and 39°11'42.85"E. The land is sloping towards upper right of the scenery.

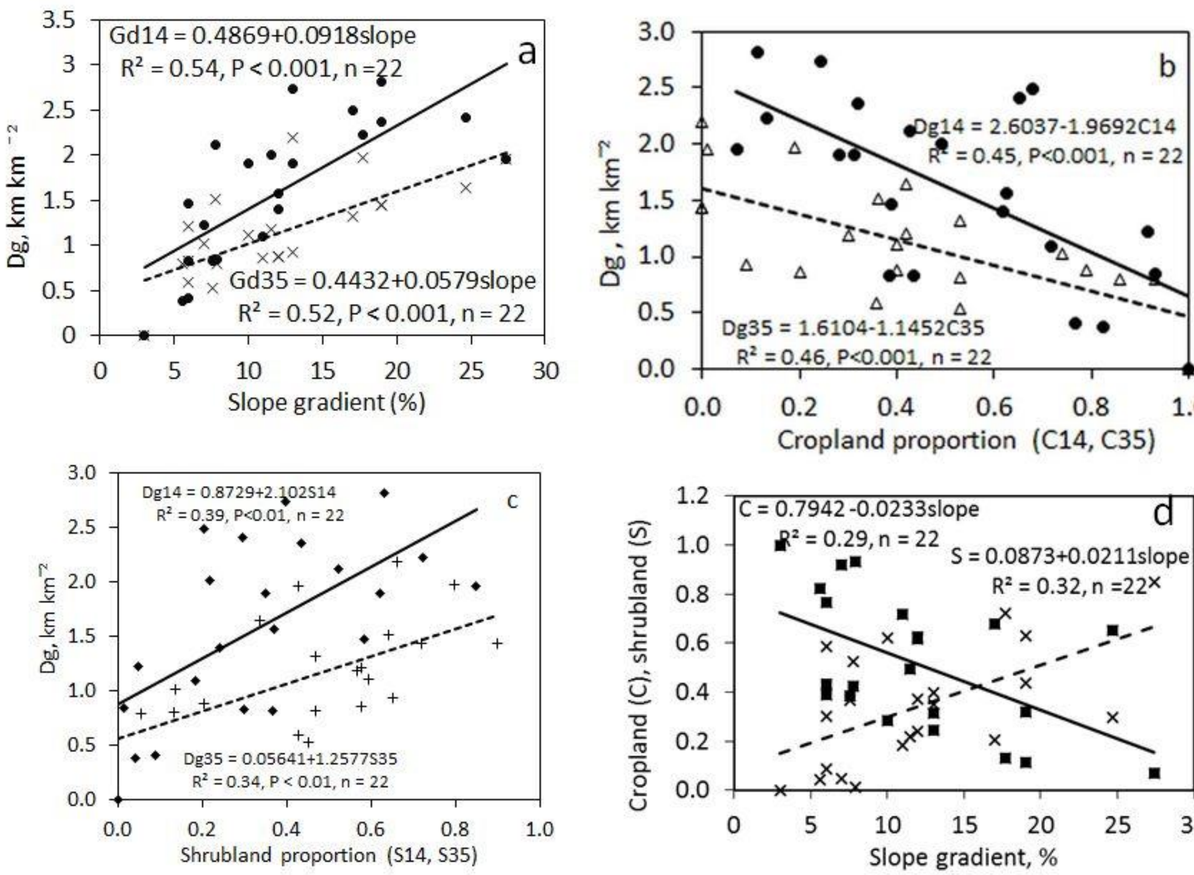

Figure 3.5 Relationship between gully density and: a) slope gradient, b) cropland proportions in 2014 (C14) and in 1935-36 (C35) and c) shrubland proportions

in 2014 (S14) and in 1935-36 (S35); Dg – Density of gullies, Dg14- in 2014, Dg35- in 1935-36 as well as d) collinearity between slope gradient and land use proportions

The density and distribution of gullies could also be related to different factors including slope gradient, land use, lithology, rainfall, elevation and soil type. Simple linear regression indicates gully density increased with slope gradient both in 1935-36 ($R^2 = 0.52$, $P < 0.001$) and 2014 ($R^2 = 0.54$, $P < 0.001$) (Figure 3.5a). An analysis of simple linear regression relationships between gully density and land use indicates a strong association between gullies and cropland and shrubland (Figure 3.5b and Figure 3.5c): gully densities significantly decreased with increasing cropland proportion both in 1935-36 ($R^2 = 0.46$, $P < 0.001$) and 2014 ($R^2 = 0.45$, $P < 0.001$) while inverse relationships were observed between gully density and shrubland proportion during both the 1935-36 ($R^2 = 0.34$, $P < 0.01$) and 2014 ($R^2 = 0.39$, $P < 0.01$). However, in the multiple regression analysis only slope gradient was significantly associated with the density of gullies in both 1935-36 and 2014 which is related to multicollinearity between land use and slope gradient (Figure 3.5d). Regressions did not show significant relationships between gully densities and soil type, lithologies and climatic factors.

3.3.2 Density of SWC (stone bund and terraces)

The density of dagets (Figure 3.3a) was assessed from APs to analyze soil and water conservation practices in the 1935-35. The maximum density of SWC measured on the APs was 10 km km^{-2} and the mean density was 3 (±3) km km^{-2}. No conservation practices were observed on about 20% of the APs. In 2014 different SWC introduced since about two decades were widely implemented in the study area (Figure 3.3b). These practices were encountered in all observation areas with a density ranging from 4 km km^{-2} to 42 km km^{-2} and an average density of 20 km km^{-2}. The spatial distribution of both indigenous and introduced SWC was related to different potential influencing factors. Simple linear and power regression illustrate that the distribution of the SWC was significantly associated with share of cropland (Figure 3.6): in 1935-36 ($R^2 = 0.78$, $P < 0.001$) and in 2014 ($R^2 = 0.45$, $P = 0.015$). By contrast, the densities significantly decreased with proportion of shrubland both in the 1935-36 ($R^2 = 0.61$, $P < 0.001$) and 2014 ($R^2 = 0.41$, $P < 0.01$). The distribution of the densities of SWC in 1935-36 and in 2014 was also inversely correlated with slope gradient both in the 1935-36 ($R^2 = 0.25$, $P = 0.019$) and 2014 (R2 = 0.12, P = 0.11).

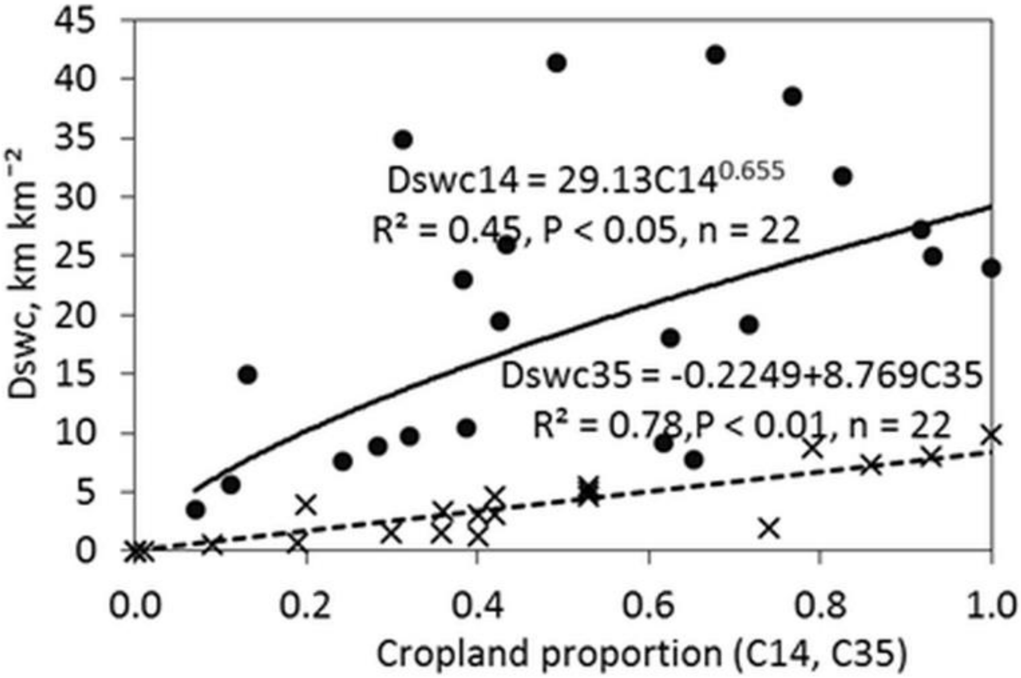

Figure 3.6 Density of conservation structures as influenced by cropland proportion in 2014 (C14) and in 1935-36 (C35). Dswc – density of soil and water conservation, Dswc14 – in 2014, and Dswc35 – in 1935-36.

3.3.3 Mapping of the density of gullies and SWC practices

The density of gullies in 1935-36 and in 2014 was mapped (Figure 3.8) based on the linear relationship models established between gullies and slope gradient (Figure 3.5a). These maps illustrate the hotspot areas of gully erosion in Geba catchment over the last 80 years. The maps of SWC densities (Figure 3.9) created based on the simple linear regression (1935-36) and power relationship (2014) with cropland density in the respective year (Figure 3.6) demonstrate the history of land management in the larger part of the study area over a long period.

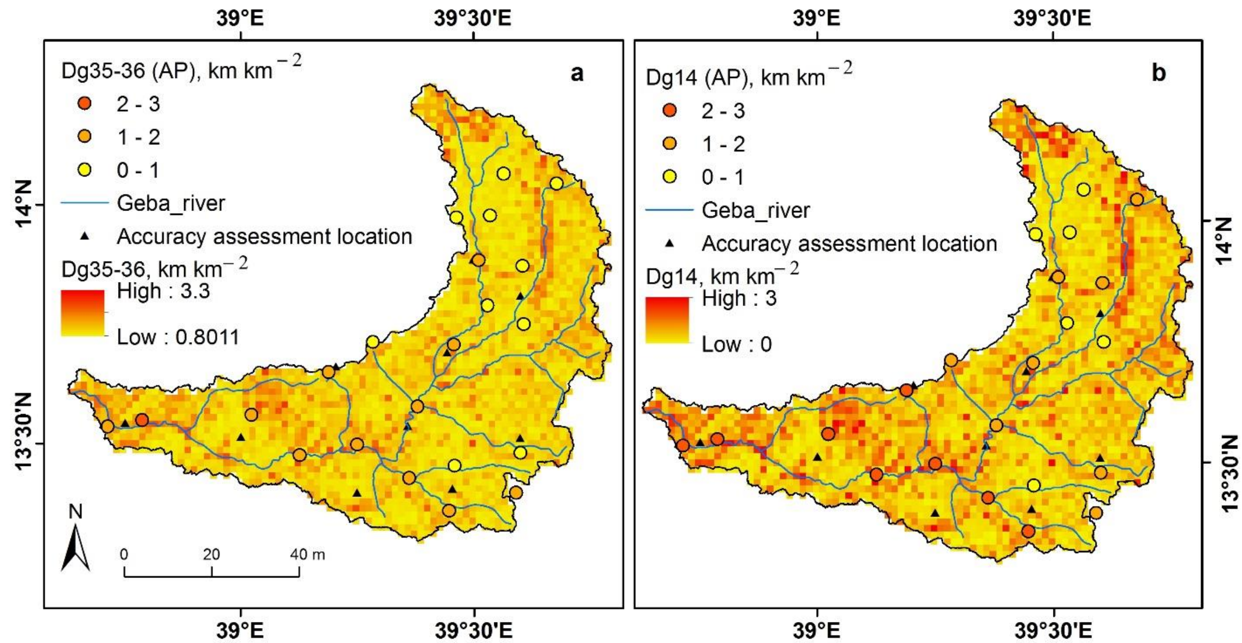

Figure 3.7 Maps of predicted gully density created based on the relationship between measured gully densities and slope gradient. Dg35-36 = gully density in 1935-1936; Dg14 = gully density in 2014; AP = density measured on aerial photograph

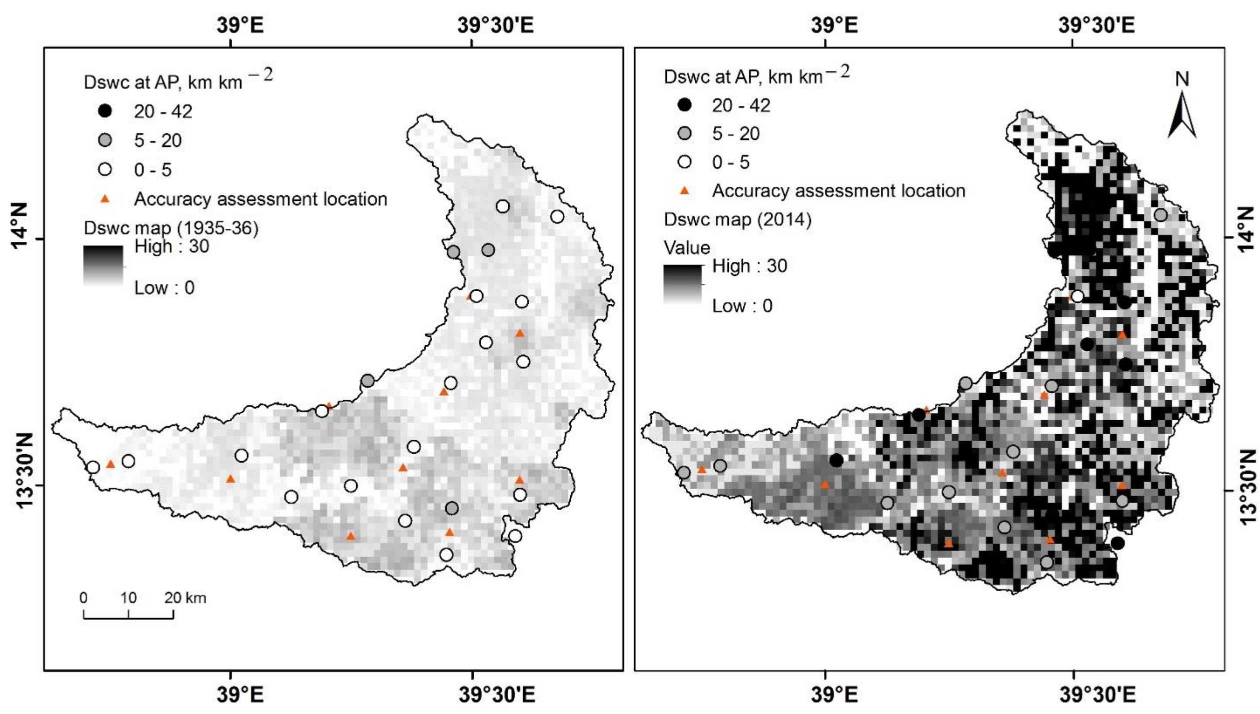

Figure 3.8 Maps of predicted density of soil and water conservation (Dswc) in Geba catchment in. 1935 – 36 and 2014 Dswc at AP – measured density (km km^{-2}) on sample aerial photographs.

Accuracy assessment of density mapping of gullies using regression between the predicted and measured densities (n =10).resulted in strong agreement: R^2 =0.76 (in 1935-36) and R^2 = 0.80 (in 2014). Likewise, regression between the predicted and measured densities of SWC show strong agreement in both 1935-36 (R^2 = 0.73) and 2014 (R^2 = 0.88) (Figure 3.7). In addition, the average ratios of predicted to observed densities of gullies and SWC were computed: ratios of gully densities were 1.28 (±0.70) in 1935-36 and 0.84 (±0.19) in 2014 while ratios of SWC densities were 0.98 (±0.08) in 1935-36 and 0.90 (±0.12) in 2014. The independent t- test did not show significant difference when gully density ratio in 1935-36 and SWC density ratio in 1935-36 are compared to 1 (assuming perfect prediction) while significnt differences were observed between 1 and the actual ratio of gully densities ($P < 0.05$, n = 10) and SWC densities in 2014 ($P < 0.05$, n = 10).

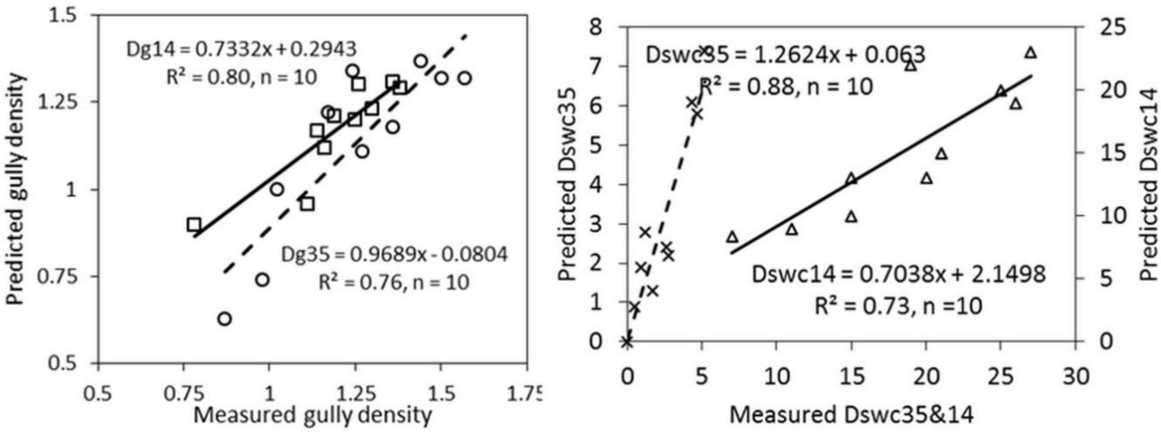

Figure 3.9 Accuracy assessment of density mapping (km km^{-2}) in 1935-36 and 2014; Dg35 = gully density in 1935-36, Dg14=gully density in 2014, Dswc35 = SWC density in 1935-36 and Dswc14=SWC density inn 2014

3.4 Discussion

3.4.1 Densities of gullies

The occurrence of 1.14 km km^{-2} of gully density in Geba catchment in the 1935-36 evidences that land degradation had already occurred in the catchment before 80 years. This finding is in line with the result of Frankl et al. (2011a) that larger gullies were present in the northern Ethiopia during late 19th and early 20th century. Although the exact time period of incipient gullying is not known, Bard et al. (2000) documented that soil erosion began in northern

Ethiopia in the middle Holocene. The longer history of human settlement and population growth in the regions and dependence on agriculture (Bard et al., 2000; Nyssen et al., 2009a) could have been one of the major reasons for the occurrence of gullies. Reports indicate that a large part of the land mass of Ethiopia (including its northern part) was once covered with dense forest which was then progressively deforested many years ago mainly due to human activities (Bard et al., 2000). Nyssen et al. (2009a) also discussed that the condition of vegetation in the last quarter of 19th century was better than in the 20th century. Hence, the progressive deforestation in the historical times could have resulted in serious soil erosion and formation of gullies in the study area. Nevertheless, in 1935-36 most gullies (75%) were vegetated in their channel (

Figure 3.4). These non-active but large number of gullies in 1935-36 indicate the long history of occurrences of gullies through processes mainly related to annual rainfall fluctuations (Bard et al., 2000). This result is in line with Frankl et al. (2013a) that gullies in the late 19th century were less active and vegetated. The density of gullies was also related to slope gradient, in agreement with previous studies (Frankl et al., 2013a). Due to rapid time of concentration, infiltration decreases while surface runoff volume and velocity increases in areas where the slope gradient is steepest which results in gully erosion particularly in semi-arid areas (Huang et al., 2013; Ribolzi et al., 2011). The increases of gully density with slope gradient could be also related to the large shear forces at steepest slope gradient particularly in semi-arid regions which is one of the important factors of soil detachment and erosion (Assouline and Ben-Hur, 2006; Torri and Poesen, 2014)

In 2014 the density of gullies had significantly increased as compared to the density in 1935-36. High soil erosion rates have often been reported in northern Ethiopia which resulted in gully formation especially before the implementation of soil and water conservation practices in the region (e.g. Haregeweyn et al., 2015a; Virgo and Munro, 1978). The density of gullies in the study area in 2014 has a stronger correlation with slope gradient than in 1935-36 (Figure 3.5a). This is in line with the increased clearance of vegetation in the catchment over the last 80 years which led to larger runoff coefficient particularly on sloping and steep terrain and possibly a clear water effect in line with larger areas with outcropping bedrock. Brancaccio et al. (1997) explain the rapid gully expansion in the study area by the increased erosional power of storm runoff. Such clear water effect is enhanced by lower sediment load (Frankl et al., 2015a), “associated with the advanced phase of soil erosion on the hillslopes where bedrock is outcropping” (Brancaccio et al., 1997), as also evidenced by.(Nyssen et al., 2006). Several studies reported significant land use/cover changes in the Geba catchment until the large scale soil and water conservation practices have been implemented in the Tigray region, northern Ethiopia (e.g. de Mûelenaere et al., 2014; Munro et al., 2008b; Nyssen et al., 2014). About 66% of gullies in 2014 were not active in line with the wider implementation of check dams in the last few decades. However, unlike in the 1935-36 gullies were rarely vegetated along their channel in 2014. Construction of roads, which was began after 1936 during Italian occupation in Ethiopia, might have contributed to the increment of gully density in the study area over the last 80 years as explained by Nyssen et al. (2002). The lower gully density occurrence on flat areas can be related to the fact that flat areas are mainly used for cropland (Figure 3.5d), with higher infiltration rates induced by tillage practices and vegetation cover in cropland during rainy season which decrease the volume and velocity of runoff (Taye et al., 2013a). Conversely, the positive linear relationship between gully density and shrubland could be attributed to the increased velocity and energy of runoff in shrubland areas which are most often located in steep slope gradient in the study area (Figure 3.5d) and characterized by low vegetation cover and over grazed (Descheemaeker et al., 2006a; Taye et al., 2013a). Hence, the strong link between slope gradient and gully density is not only the result of runoff energy but also of related to land use and land management: on level lands, croplands and SWC is prevalent.

3.4.2 Soil and water conservation

The presence daget system in 1935-36 with the average density of about 3 km km^{-2} confirms the long history of indigenous of soil and water conservation practices by local community (Nyssen et al., 2000) which describe the awareness of local communities about its role in SWC. Nyssen et al. (2000) also measured 22.7 m ha^{-1} of daget present at one site of our study area, Hagere Selam, in 1974-1994 which is less than the density in the 1935-36 due to their removal by farmers to increase the size of farmland most likely after the 1984-85 famine. This traditional SWC was largely associated with cropland ($R^2 = 0.78$) as the main objective of the practice was to increase crop production by conserving fertile soils and moisture. Similar observation was also reported by (Nyssen et al., 2000) that the density of daget was much higher on cropland than other land use/cover. The practice of daget ca. 50 years ago in southern Tigray, is also reported by Lanckriet et al. (2015). Such indigenous SWC practices have been practiced by local communities over a long period of time in different countries (e.g. Engdawork and Bork, 2014; Reij et al., 1996). According to the review of Reij et al. (1996) some indigenous SWC practices failed, some were sustained and some were used as basis for the development of the new SWC technologies which are widely practiced nowadays.

In northern Ethiopia, over the last three decades the indigenous practices were either removed for scale of using the fertile soil accumulated in it or replaced by the introduced SWC (Nyssen et al., 2000). In 2014, a higher density of SWC (stone bund and terraces) was measured as compared to the traditional SWC. On average, 20 km km^{-2} of stone bunds and terraces were present in 2014 which is about six times of the earlier density of daget. This confirms the large-scale implementation of SWC practices in different land uses including cropland, grazing land, bare land and degraded shrubland although the density of stone bunds is higher in cropland (Taye et al., 2013a). The effectiveness of the introduced SWC, which are widely implemented in Tigray region, in the control of soil erosion, reduction of sediment transport and runoff has been well documented (Descheemaeker et al., 2006a; Desta et al., 2005; Nyssen et al., 2007; Vancampenhout et al., 2006).

3.4.3 Mapping of gullies and SWC

The simple linear and power regression models developed, based on the measured data of gullies and SWC, were successfully used for mapping the density of gullies and SWC at Geba catchment level (Figure 3.8 and Figure 3.9). In all cases, the developed maps show similar patterns with the measured densities at sample locations. These maps contain the density of gully and SWC at any pixel, hence continuous data on gully and SWC are available at the catchment level at 1935-36 and 2014.

Several experiences also exist on the mapping of a variable including gullies and SWC, based on model developed, spatial interpolation of sample measurement and secondary data (reports) and automated or semi-automated extraction from images (e.g. Amanuel, 2009a; Hughes et al., 2001; Knight et al., 2007; Mekuriaw et al., 2017) (Table 3.1). These authors mapped density of gullies and SWC using different data sources, method and resolution which have determined the accuracy of the mapping (Table 3.1). In contrast to these earlier studies, the accuracy of the maps of gullies and SWC that we developed are higher: 77% in 1935-36 and 73% in 2014 for the map of gully density and 89% in 1935-36 and 87% in 2014 for the map of SWC density. Hence, these accuracies confirm that the method we have applied for mapping is feasible to map the density of gullies and SWC.

Table 3.1 Mapping methods applied for gullies and SWC density over wider areas

Feature modeled	**Data base/method**	**Area covered**	**Resolution**	**Reference**	**Accuracy**
SWC density	Tigray BoANR report	5133 km^2	Scale of district	Amanuel, 2009	Depend on quality of official reports
SWC (individual structures)	Google Earth, automated mapping	28 scenes (1 km x 1 km each)	1 m	Mekuriaw et al., 2016	80%
Gully density	AP and report, regression tree model	1.7×10^6 km^2	Continental scale, Australia	Hughes et al., 2001	-
Gully density	Satellite image (Aster)	600 km^2	250 m	Knight et al., 2007	Low, 50%
SWC and gully	AP/GE, regression model	5142 km^2	1:11, 500 to 1:18,000 (AP), 1 m (GE)	The present study	87% (SWC) and 73% (gully)

In line with its strong conditions to slope gradients in both years, he gully density map of 2014 demonstrates that areas where gullies started before 80 years remained as hotspot areas of gully erosion in 2014 while showing progressive expansion over the entire study area which is related to land use/cover changes and weak land management over the last 80 years (de Mûelenaere et al., 2014; Lanckriet et al., 2015; Nyssen et al., 2014). The SWC map of 2014 demonstrate higher practices of SWC over the study area at present time which is in line with several reports on the large-scale implementation of SWC practices in the last two to three decades (e.g. Amanuel, 2009a; Descheemaeker et al., 2006a; Haregeweyn et al., 2015a; Nyssen et al., 2014). Our SWC density map in 2014 (Figure 3.9) fits to the overall pattern, with some exceptions, of the map created by Amanuel (2009a), using 2005 – 2007 data obtained from Tigray Bureau of Agriculture and Natural Resources, although resolution is totally different and values mapped are less. These differences could be linked to quality of data, scale of interpolation and time period. Areas which were given priority, i.e. cropland, for soil and water conservation practices over the study area in 1935-36 and 2014 are also revealed by these maps. Moreover, the study identified areas where urgent implementation of SWC is needed in the catchment.

3.5 Conclusion

Land degradation due to gully formation mainly by water erosion was a common phenomenon in northern Ethiopia for the last several decades or even more than a century. Gullies were recorded in 91% of observation areas (APs with average area of 4.8 km^2) in the study area illustrating that the catchment has experienced gully formation over long time. On average, 1.14 km km^{-2} gully density was measured in 1935-36. The larger portion (75%) of these gullies were less active (vegetated) which can be explained by the presence of high vegetation cover upstream of the gullies which can control runoff velocity and depth. Our results indicate that the density of gullies has significantly increased to 1.59 km km^{-2} over the last 80 years. Beside density, the condition of gully channels in 2014 was different from 1935-36 as in the present time gullies are active, probably due to removal of vegetation from the gullies and from their catchment. But thanks to the construction of check dams in gullies in recent decades about 66% of gullies had become stabilized by 2014 (Figure 3.3b) which significant effect in controlling runoff. Our study also indicated that the spatial distribution of gullies in both 1935-36 and 2014 was determined by slope gradient.

The result of this study also indicated the long history of soil and water conservation in northern Ethiopia. The assessment of SWC practices in 1935-36 depicted that there was about 3 km km^{-2} of indigenous practices (daget or lynchets) in the study area which indicates community awareness on soil and water conservation to maintain soil productivity. As a spontaneous measure, this practice was strongly associated to the proportion of cropland (R^2 = 0.78). In 2014, the introduced SWC practices that had been widely implemented over the last three decades were recorded in all observation areas with high density (20 km km^{-2}). Unlike daget, the introduced SWC practices were implemented in areas with various land use/cover such as cropland, grazing land, bare land and degraded shrubland.

Models developed based on the spatial data of gullies, SWC and explanatory factors were successfully used for mapping the density of gullies and SWC at Geba catchment. The developed maps show similar patterns with the measured densities at sample locations. The high accuracy mapping in this study confirms the feasibility of the method applied for mapping the density of gullies and SWC. The maps show hotspot areas of gully occurrences over the Geba catchment in 1935-36 and priority areas forcurrent soil and water conservation. Hence, these density maps of gully and SWC can be used as a tool for control of soil erosion (i.e. gully expansions) and for further implementation of the soil and water conservation activities which are underway in northern Ethiopia.

3.6 References

Aerts R, Van Overtveld K, November E, Wassie A, Abiyu A, Demissew S, Daye DD, Giday K, Haile M, TewoldeBerhan S, Teketay D, Teklehaimanot Z, Binggeli P, Deckers J, Friis I, Gratzer G, Hermy M, Heyn M, Honnay O, Paris M, Sterck F J, Muys B, Bongers F, Healey J R. 2016. Conservation of the Ethiopian church forests: Threats, opportunities and implications for their management. Science and the Total Environment, 551-552: 404-14.

Amanuel Z. 2009. Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, northern Ethiopia. PhD Thesis, KULeuven University, Belgium.

Araya A, Keesstra S, Stroosnijder L. 2010. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia. Agricultural and Forest Meteorology, 150: 1057-1064.

Assouline S. Ben-Hur M. 2006. Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. Catena, 66(3): 211-220.

Bard KA, Coltorti M, DiBlasi M C, Dramis F, Fattovich R. 2000. The environmental history of Tigray (Northern Ethiopia) in the Middle and Late Holocene: a preliminary outline. African Archaeological Review, 17: 65-86.

Bastin L, Buchanan G, Beresford A, Pekel JF, Dubois G. 2013. Open-source mapping and services for Web-based land-cover validation. Ecological Informatics, 14: 9-16.

Betts HD, Trustrum NA, Rose RCD. 2003. Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. Earth Surface Processes and Landforms, 28: 1043-1058.

Billi P. 2015. Geomorphological Landscapes of Ethiopia. In: Billi,P (Ed.), Landscapes and Landforms of Ethiopia. University of Ferrara, Ferrara, Italy. pp. 3 - 32.

Brancaccio L, Calderoni G, Coltorti M, Dramis F. 1997. Phases of soil erosion during the Holocene in the highlands of Western Tigray (Northern Ethiopia): a preliminary report. In: Bard, K. (Ed.), The environmental history and human ecology of Northern Ethiopia in the Late Holocene. Istituto Universitario Orientale, Napoli, pp. 30– 48.

Chen L, Wei W, Fu B, Lü Y. 2007. Soil and water conservation on the Loess Plateau in China: review and perspective. Progress in Physical Geography, 31: 389-403.

de Mûelenaere S, Frankl A, Mitiku H, Poesen J, Deckers J, Munro N, Veraverbeke S, Nyssen J. 2014. Historical landscape photographs for calibration of Landsat land use/cover in the Northern Ethiopian highlands. Land Degradation & Development, 25: 319-335.

Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B, Deckers S. 2006. Runoff on slopes with restoring vegetation: A case study from the Tigray Highlands, Ethiopia. Journal of Hydrology, 331: 219-241.

Desta G, Nyssen J, Poesen J, Deckers J, Mitiku H, Govers G, Moeyersons J. 2005. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray Highlands, northern Ethiopia. Soil Use and Management, 21: 287-297.

Engdawork A, Bork HR. 2014. Long-term indigenous soil conservation technology in the Chencha area, southern Ethiopia: origin, characteristics, and sustainability. Ambio, 43: 932-42.

Etefa G, Frankl A, Zenebe A, Poesen J, Nyssen J. 2017. Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. Journal of Hydrology, 545: 299-309.

Fisher BG, Amos CB, Bookhagen B, Burbank DW, Godard V. 2012. Channel widths, landslides, faults, and beyond: The new world order of high-spatial resolution Google Earth imagery in the study of earth surface processes. Geological Society of America, Special Papers, 492: 1-22.

FAO. 1965. Soil erosion by water. Some measures for its control on cultivated lands. Food and Agriculture Organization, Rome. Bulletin No. 81.

Frankl A, Nyssen J, De Dapper M, Haile M, Billi P, Munro RN, Deckers J, Poesen J. 2011. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology, 129: 238-251.

Frankl A, Poesen J, Haile M, Deckers J, Nyssen J. 2013. Quantifying long-term changes in gully networks and volumes in dryland environments: The case of Northern Ethiopia. Geomorphology, 201: 254-263.

Frankl A, Poesen J, Moeyersons J, Nyssen J. 2015. Gully development in the Tigray highlands. In: Billi, P. (ed.), Landscapes and Landforms of Ethiopia. Dordrecht, Springer: 191-200.

Gebresamuel G, Singh BR, Dick O. 2010. Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. Acta Agriculturae Scandinavica Section B–Soil and Plant Science, 60: 211-226.

Gebru T, Eshetu Z, Huang Y, Woldemariam T, Strong N, Umer M, DiBlasi M, Terwilliger VJ. 2009. Holocene palaeovegetation of the Tigray Plateau in northern Ethiopia from charcoal and stable organic carbon isotopic analyses of gully sediments. Palaeogeography, Palaeoclimatology, Palaeoecology, 282: 67-80.

Gutiérrez ÁG, Schnabel S, Contador FL. 2009. Gully erosion, land use and topographical thresholds during the last 60 years in a small rangeland catchment in SW Spain. Land Degradation & Development, 20: 535-550.

Hadush G. 2012. Modeling of hydrological process in the Geba River Basin in the northern Ethiopia. PhD thesis (unpublished), Vrij University, Brussels, Belgium.

Haregeweyn N, Tsunekawa A, Nyssen J, Poesen J, Tsubo M, Tsegaye Meshesha D, Schu tt B, Adgo E, Tegegne F. 2015. Soil erosion and conservation in Ethiopia: A review. Progress in Physical Geography, 39: 750-774.

Herweg K, Ludi E. 1999. The performance of selected soil and water conservation measures—case studies from Ethiopia and Eritrea. Catena, 36: 99-114.

HTS. 1976. Tigrai Rural Development Study, Annex 1. Land and vegetation resources. Hunting Technical Services Ltd: Hemel Hempstead (G.B.).

Huang J, Wu P, Zhao X. 2013. Effects of rainfall intensity, underlying surface and slope gradient on soil infiltration under simulated rainfall experiments. Catena, 104: 93-102.

Hughes AO, Prosser IP, Stevenson J, Scott A, Lu H, Gallant J, Moran CJ. 2001. Gully erosion mapping for the national land and water resources audit. CSIRO land and water, Canberra, technical report, 26: 01-20.

Imeson AC, Kwaad FJ. 1980. Gully types and gully prediction. Geografisch Tijdschrift, XIV(5), 430-41.

Knight J, Spencer J, Brooks A, Phinn S. 2007. Large-area, high-resolution remote sensing based mapping of alluvial gully erosion in Australia's tropical rivers. In: "Proceedings of the 5th Australian Stream Management Conference", pp. 199-204. Charles Sturt University.

Lanckriet S, Derudder B, Naudts J, Bauer H, Deckers J, Haile M, Nyssen J. 2015. A political ecology perspective of land degradation in the North Ethiopian Highlands. Land Degradation & Development, 26: 521-530.

Lesschen JP, Cammeraat LH, Nieman T. 2008. Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. Earth Surface Processes and Landforms, 33: 1574-1584.

Loelkes GL, Howard GE, Schwertz EL, Lampert PD, Miller SW. 1983. Land Use/Land Cover and Environmental Photointerpretatlon Keys. U.S. Geological Survey Bulletin 1600

Mekuriaw A, Heinimann A, Zeleke G, Hurni H, Hurni K. 2017. An automated method for mapping physical soil and water conservation structures on cultivated land using GIS and remote sensing techniques. Journal of Geographical Sciences, 27: 79-94.

Mukai S. 2017. Gully erosion rates and analysis of determining factors: A case study from the Semi-arid Main Ethiopian Rift Valley. Land Degradation & Development, 28: 602-615.

Munro RN, Deckers J, Haile M, Grove AT, Poesen J, Nyssen J. 2008. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena, 75: 55-64.

Nyssen J, Haile M, Moeyersons J, Poesen J, Deckers J. 2000. Soil and water conservation in Tigray (Northern Ethiopia): the traditional technique and its integration with introduced techniques. Land Degradation & Development, 11: 199-208.

Nyssen J, Poesen J, Moeyersons J, Luyten E, Veyret-Picot M, Deckers J, Haile M, Govers G. 2002. Impact of road building on gully erosion risk: a case study from the Northern Ethiopian Highlands. Earth Surface Processes and Landforms, 27: 1267-1283.

Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M, Lang A. 2004. Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. Earth-Science Reviews, 64: 273-320.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G. 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology, 311: 172-187.

Nyssen J, Poesen J, Veyret-Picot M, Moeyersons J, Haile M, Deckers J, Dewit J, Naudts J, Teka K, Govers G. 2006. Assessment of gully erosion rates through interviews and measurements: a case study from northern Ethiopia. Earth Surface Processes and Landforms, 31: 167-185.

Nyssen J, Poesen J, Gebremichael D, Vancampenhout K, D'aes M, Yihdego G, Govers G, Leirs H, Moeyersons J, Naudts J, Haregeweyn N, Haile M, Deckers J. 2007. Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. Soil and Tillage Research, 94: 151-163.

Nyssen J, Naudts J, De Geyndt K, Haile M, Poesen J, Moeyersons J, Deckers J. 2008. Soils and land use in the Tigray highlands (Northern Ethiopia). Land Degradation & Development, 19: 257-274

Nyssen J, Haile M, Naudts J, Munro N, Poesen J, Moeyersons J, Frankl A, Deckers J, Pankhurst R. 2009. Desertification? Northern Ethiopia re-photographed after 140 years. Science of Total Environment, 407: 2749-55.

Nyssen J, Frankl A, Haile M, Hurni H, Descheemaeker K, Crummey D, Ritler A, Portner B, Nievergelt B, Moeyersons J, Munro N, Deckers J, Billi P, Poesen J. 2014. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. Science of the Total Environment, 485-486: 164-79.

Nyssen J, Petrie G, Mohamed S, Gebremeskel G, Seghers V, Debever M, Hadgu KM, Stal C, Billi P, Demaeyer P, Haile M, Frankl A. 2016. Recovery of the aerial photographs of Ethiopia in the 1930s. Journal of Cultural Heritage, 17: 170-178.

Oostwoud Wijdenes DJ, Bryan R. 2001. Gully-head erosion processes on a semi-arid valley floor in Kenya: a case study into temporal variation and sediment budgeting. Earth Surface Processes and Landforms, 26: 911-933.

Pankhurst R. 1995. The history of deforestation and afforestation in Ethiopia prior to World War I. Northeast African Studies, 2: 119-133.

Patton PC, Schumm SA. 1975. Gully erosion, Northwestern Colorado: a threshold phenomenon. Geology, 3: 88-90.

Pender JL, Kerr JM. 1998. Determinants of farmers' indigenous soil and water conservation investments in semi -arid India. Agricultural Economics, 19: 113-125.

Poesen J, Nachtergaele J, Verstraeten G, Valentin C. 2003. Gully erosion and environmental change: importance and research needs. Catena, 50: 91-133.

Reij C, Scoones I, Toulmin C. 1996. Sustaining the soil: Indigenous soil and water conservation in Africa. Earthscan Publications, Ltd., London.

Ribolzi O, Patin J, Bresson LM, Latsachack K, Mouche E, Sengtaheuanghoung O, Silvera N, Thiébaux JP, Valentin C. 2011. Impact of slope gradient on soil surface features and infiltration on steep slopes in northern Laos. Geomorphology, 127(1): 53-63.

Salleh KO, Mousazadeh F. 2011. Gully erosion in semiarid regions. Procedia - Social and Behavioral Sciences, 19: 655-661.

Shi H, Shao M. 2000. Soil and water loss from the Loess Plateau in China. Journal of Arid Environments, 45: 9-20.

Sidibé A. 2005. Farm-level adoption of soil and water conservation techniques in northern Burkina Faso. Agricultural Water Management, 71: 211-224.

Taye G, Poesen J, Van Wesemael B, Vanmaercke M, Teka D, Deckers J, Goosse T, Maetens W, Nyssen J, Hallet V, Haregeweyn N. 2013. Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography, 34: 236-259.

Tesfaalem A, Frankl A, Haile M, Nyssen J. 2016. Catchment Rehabilitation and Hydro-geomorphic Characteristics of Mountain Streams in the Western Rift Valley Escarpment of Northern Ethiopia. Land Degradation & Development, 27: 26-34.

Tesfamichael G, De Smedt F, Miruts H, Solomon G, Kassa A, Kurkura K, Abdulwassie H, Nyssen J, Bauer H, Moeyersons J, Deckers J, Mitiku H, Nurhussen T. 2010. Large-Scale Geological mapping of the Geba basin, northern Ethiopia. Tigray Livelihood Paper, No. 9: pp. 46.
Tielens S. 2012. Towards a soil map of the Geba catchment using benchmark soils. PhD. Thesis, KU Leuven University, Belgium.
Torri D, Poesen J. 2014. A review of topographic threshold conditions for gully head development in different environments. Earth-Science Reviews, 130: 73-85.
Valentin C, Poesen J, Li Y. 2005. Gully erosion: Impacts, factors and control. Catena, 63: 132-153.
Van de Wauw J, Baert G, Moeyersons J, Nyssen J, De Geyndt K, Taha N, Zenebe A, Poesen J, Deckers J. 2008. Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. Catena, 75: 117-127.
Vancampenhout K, Nyssen J, Gebremichael D, Deckers J, Poesen J, Haile M, Moeyersons J. 2006. Stone bunds for soil conservation in the northern Ethiopian highlands: Impacts on soil fertility and crop yield. Soil and Tillage Research, 90: 1-15.
Virgo K, Munro R. 1978. Soil and erosion features of the Central Plateau region of Tigrai, Ethiopia. Geoderma, 20: 131-157.

4 Effects of check dams on runoff characteristics along gully reaches

This chapter is modified from:

Etefa G, Frankl A, Zenebe A, Poesen J, Nyssen J. 2017. Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. Journal of Hydrology 545: 299-309

Abstract

In the Highlands of Northern Ethiopia soil and water conservation (SWC) practices, including construction of check dams in gullies, have been widely implemented for the last three decades. Despite this, the effect of check dams on runoff response is not well understood as compared to those of other SWC practices. Hence, this study examines the effects of check dams on runoff response in gully channels. V-notch weirs were installed to measure a wide range of discharges at the upper and lower sections of five gully reaches: two channel cut in sandstone (a gully with check dams and vegetation (SCV) and an untreated gully (S)) and three cut in limestone (an untreated gully (L), a gully with check dams and no vegetation (LC) and a gully with check dams and vegetation (LCV)). Automatic sensors were installed to monitor runoff depth (76 events in all reaches) during two rainy seasons (29/08/14 - 17/09/14 and 24/7/15 – 14/09/15). Runoff characteristics at the lower section of every gully reach were calculated at 50 m, normalized length of gully reaches. In the sandstone area, the results show longer lag times of runoff to reach the lower section of the channel reach in the treated gully (SCV) compared to the untreated gully: difference in lag time equals 51% for runoff initiation, 61% for peak runoff and 44% for runoff end. An increase of hydraulic roughness by check dams and water transmission losses in deposited sediments are responsible for the delay of runoff. In the limestone area, different time lags were recorded in different gully reaches regardless of the treatment effects (lag to runoff initiation, lag to peak flow and lag to runoff end were larger at LC, L and LCV, respectively). The reduction of peak runoff between the upper and lower gully sections was larger in the gullies with check dam and vegetation (8% – 17%) than in gullies without treatment (5% – 6%). Reduction of runoff volume between these 2 gully sections was also larger in treated gullies than in untreated gullies: i.e. 18%, 9% and 8% in SCV, LCV and LC, respectively while it was only 4% in S and 6% in L. This study shows that the implementation of check dams combined with vegetation reduced peak flow discharge and runoff volume as large sections of runoff infiltrated in the sediments deposited behind the check dams. As gully check dams are implemented in a large areas of the North Ethiopia Highlands, this contributes to groundwater recharge and increased river baseflows.

Keywords: Gully control, lag time, Northern Ethiopia, peak runoff discharge, runoff volume, Tekeze basin

4.1 Introduction

Soil and water conservation (SWC) practices affect the water balance of a catchment by altering the major hydrological components. Hillslope runoff, base flow and stream flow are influenced through the implementation of different SWC practices e.g. terraces, check dams, afforestation (Haregeweyn et al., 2015b; Huang and Zhang, 2004; Zhang et al., 2014). In the Tigray region of north Ethiopia, extensive SWC structures have been installed during the last three decades. Dry masonry stone bunds on hillslopes and check dams in gullies resulted in enhanced infiltration and spring discharge and reduced soil erosion rates (Nyssen et al., 2010; Nyssen et al., 2008b; Nyssen et al., 2008c) while gullies are stabilized following check dam construction (Frankl et al., 2013a). A significant decrease of runoff production was reported after installing exclosures on degraded land (Descheemaeker et al., 2006a) and implementation of stone bunds with trenches on cultivated land and rangeland (Taye et al., 2013b).

A check dam is a structure constructed of stone or other material placed across the flow channel to be used as a barrier for soil and water losses. It is a common SWC technique used in areas where gully development is a problem (Frankl et al., 2011a & 2013; Huang et al., 2012; Nyssen et al., 2004b). It is widely implemented in China (Xiang-zhou et al., 2004), Ethiopia (Nyssen et al., 2004b), Italy (Bombino et al., 2009; Lenzi and Comiti, 2003), US (Diaz-Ramirez, 2014), Spain (Romero-Diaz et al., 2007) and Iran (Hassanli et al., 2009).

A catchment affected by gullies experience many environmental problems among which are soil loss, siltation of rivers, reduction of baseflow, larger but short-lived stream flow, etc (Costa et al., 2007; Poesen et al., 2003). Several studies indicated the effectiveness of check dams in slowing down water and sediment movement along gully and stream channels (e.g. Castillo et al., 2007; Hassanli et al., 2009; Nyssen et al., 2004b; Polyakov et al., 2014; Remaître et al., 2008; Xiang-zhou et al., 2004; Xu et al., 2013). Nyssen et al. (2010) evaluated the impact of check dam constructed in degraded catchments on runoff abstraction and concluded that this intervention resulted in the rise of the ground water table, emergence and expansion of cropped fields in stabilized gullies and prolonged crop-growing periods. Despite its extensive practices and environmental importance, particularly in arid and semi-arid regions, its effect on runoff characteristics is poorly understood in Ethiopia as compared to other SWC techniques such as exclosures or stone bunds (Descheemaeker et al., 2006a; Nyssen et al., 2010; Taye et al., 2013b; Vancampenhout et al., 2006). In north Ethiopia where check dams are widely implemented as a SWC technique to control gully erosion (Nyssen et al., 2004b), the extent to which it affects hydrological processes such as on peak flow, lag time, runoff volume and infiltration has not been quantified. The runoff responses in gullies to check dam construction depend on lithology and vegetation characteristics in the gully. Check dams may also impact the transfer of runoff from uplands to lower areas and hence also the runoff connectivity in the landscape. We hypothesise that check dams have a significant effect on runoff characteristics in gullies. To evaluate the impact of check dam construction in gullies on runoff, it is important to compare the runoff response of gullies with and without check dams. The objectives of this study are to quantify the time delay of runoff at lower sections of gully reaches due to check dam construction in different lithologies and to quantify the peak flow and runoff volume reduction due to check dams constructed in gully reaches.

4.2 Materials and methods

4.2.1 Study area

The study area (Figure 4.1) is located in the Dogu'a Tembien district (Hagere Selam), Geba catchement, Tigray region, north Ethiopian highlands, ca. 45 km west of Mekelle, capital of the region. Geographically it is located at 13°40' N, 39°14' E, at elevations around 2430 m a.s.l. Specifically, five gully reaches, were chosen as experimental sites in order to represent the two dominant lithologies of the study area (Figure 4.1and Figure 4.2). Two gully reaches in sandstone were selected: One gully with check dams and vegetation (SCV) and one untreated gully (S). Three gully reaches in limestone were chosen: an untreated gully (L), a gully with check dams but without vegetation (LC) and a gully with check dams and vegetation (LCV) (Table 4.1). The study area was selected as it is one of the more degraded areas in the region but extensive SWC measures have also been implemented including check dam construction for gully erosion control.

The study area is characterized by a short but intense rainy season restricted to mid-July to early September (Nyssen et al., 2005). Annual average precipitation ranges from 550 to 900 mm (Gebresamuel et al., 2010b; Nyssen et al., 2005; Taye et al., 2013b). The precipitation is also characterized by intense showers (Virgo and Munro, 1978) and large drop sizes (Nyssen et al., 2005). Considerable interannual variability of rainfall and severe soil moisture deficit characterize the region. The average monthly air temperature varies between 12 and 19 °C.

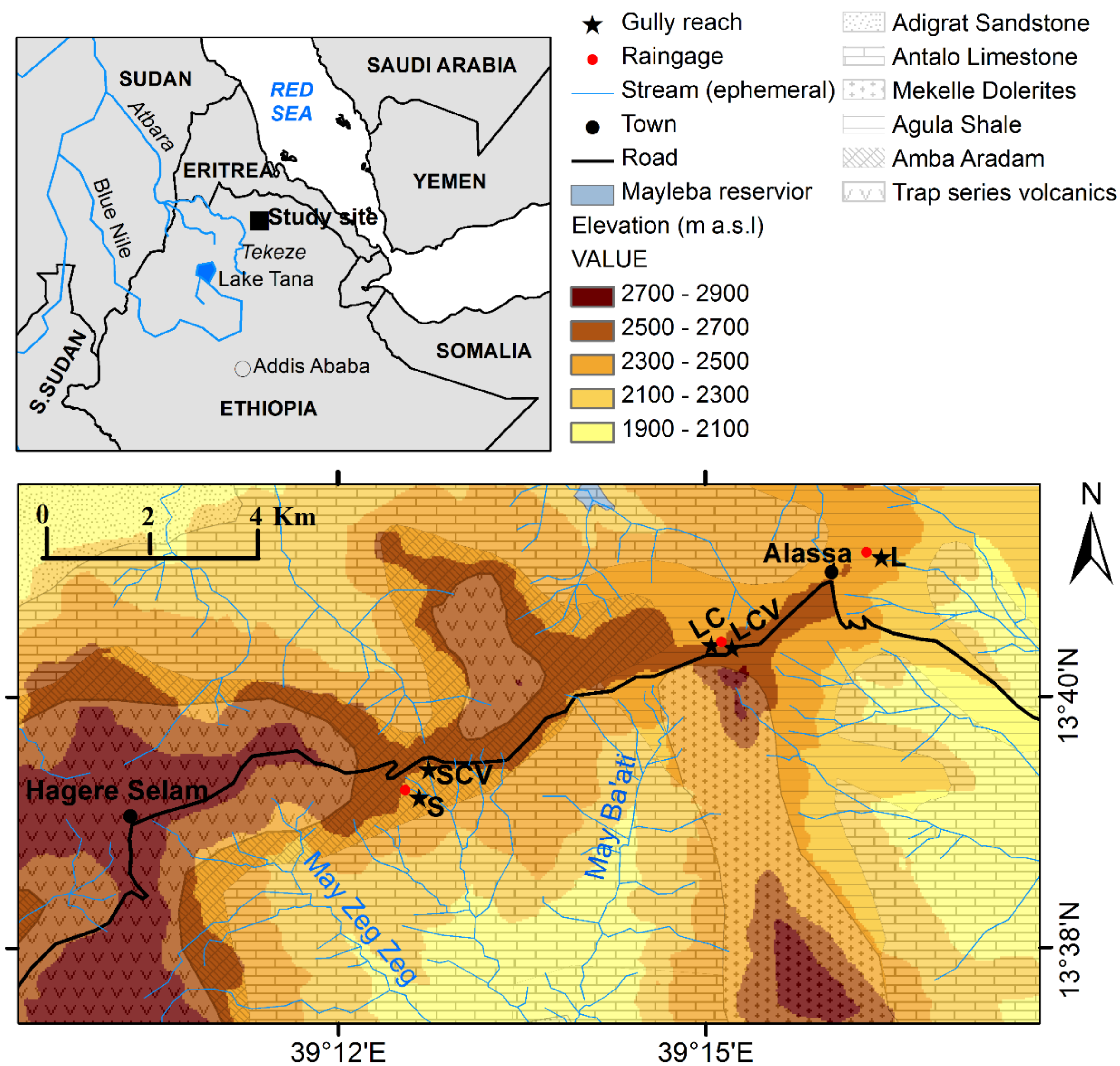

Figure 4.1 Study area with locations of the five gully reaches (S, SCV, L, LC and LCV) in two lithologies (Amba Aradam Sandstone and Agula shale Limestone). Source of Geological map: Tesfaye and Gebretsadik (1982). S = gully reach in sandstone without check dam and vegetation; SCV = gully reach in sandstone with check dams and vegetation; L = gully reach in limestone without check dam and vegetation; LC = gully reach in limestone with check dams but without vegetation; and LCV = gully in limestone with check dams and vegetation

The soils of the study area are young due to active erosion and deposition process (HTS, 1976a; Nyssen et al., 2008c; Van de Wauw et al., 2008). At the studied gully sites on sandstone and limestone Cambisols and Regosols dominate (Van de Wauw et al., 2008). The channel bed and walls (especially at the lower part) of S gully are very stony and show very little soil profile development while gully channels with check dams are filled with 1 – 2 m thick coarse sediments, resulted in sandstone alluvio-colluvial fill in SCV and mixture of limestone and sandstone fill in LCV and LC. Both sides (walls) of the channel of treated gullies with check dams are characterized by shrub and grass vegetation. However the vegetation in the LC gully channel bed was completely cleared in order to contrast it with the vegetated LCV gully.

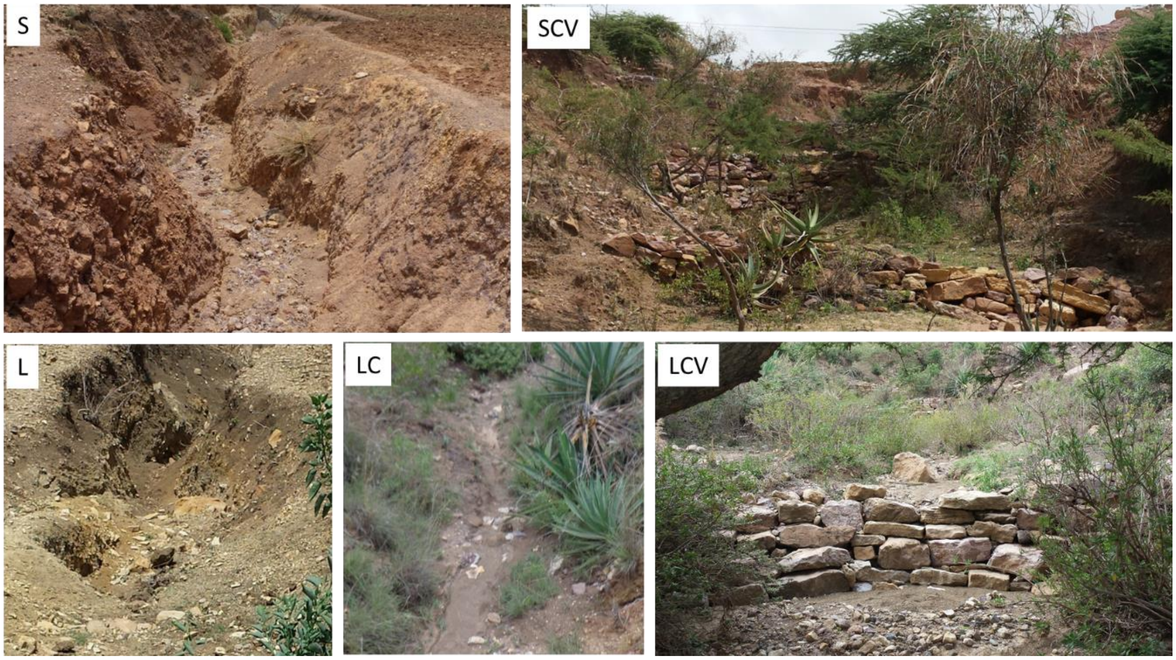

Figure 4.2 Selected gully reaches with and without check dams and vegetation along the channels. For information of S, SCV, L, LC and LCV see Figure 4.1. Google Earth photos corresponding to these gully reaches are given in appendix A4

The livelihood of the people of the study area mainly depends on agriculture, hence land use is dominated by cropland followed by grazing land, shrubland and bare land (Gebresamuel et al., 2010b; Taye et al., 2013b). Rangelands are mainly found on steep slopes and are overgrazed by livestock so that these lands have a low vegetation cover. The study area has lost its native forests a long time ago (Gebru et al., 2009; Nyssen et al., 2004b) and the remnant patches of forests are usually limited to inaccessible areas and around churches (Gebru et al., 2009; HTS, 1976a; Munro et al., 2008a). Land use patterns have resulted in severe soil erosion and gully formation in the area (e.g. Frankl et al., 2011a & 2013; Munro et al., 2008a; Nyssen et al., 2004b). Over the last three decades, extensive land management activities have been made to reverse environmental degradation (Descheemaeker et al., 2006a; Munro et al., 2008a; Nyssen et al., 2004b; Taye et al., 2013b). The establishment of stone bunds on farmland (Nyssen et al., 2008c; Taye et al., 2013b; Vancampenhout et al., 2006) and the construction of check dams in gullies (Frankl et al., 2011a; Frankl et al., 2013a; Nyssen et al., 2004b) have resulted in significant positive effects on environmental restoration. At present, forests are re-appearing following rehabilitation of marginal lands or exclosures (areas set aside for restoration of vegetation) implemented in the region (Aerts et al., 2006; Descheemaeker et al., 2006a; Munro et al., 2008a).

4.2.2 Installation of measuring set up

The selected gully reaches were delimited based on the possibility to divert side runoff between the upper and lower sections of the gully, which depends on the shape of gully banks (Figure 4.3). Diversion canals were constructed on both sides of the gullies so that external inflow runoff could not enter the targeted gully reaches (Figure 4.3). The average channel slope between the two gully sections ranged from 4.6% to 5.8% (Table 4.1).The height of check dams across all gully reaches ranges from 0.5 m to 1.8 m constructed with stone bund all of which are filled with sediments.

Disturbed and undisturbed samples were collected from each gully bed, between the upper and lower V-notches to determine organic matter content, dry bulk density and texture. Two composite sediment samples (one closer to the upper section and the other closer to the lower section) from each gully reach were taken from 50 cm deep pits and two core samples of undisturbed channel bed materialUndisturbed samples were collected using Kopecky rings with a volume of 100 cm^3 for dry bulk density measurment and composite soil samples collected from pits were used for texture and organic matter content determination. . Vegetation cover in the gully reaches was estimated visually while slope gradients was measured by using a clinometer. The average channel width of the gullies was calculated from the measurement of widths at every 10 m along the gully. The runoff contributing area (up-stream of gully reaches) varies from 4.5 to 15 ha (calculated from Google Earth) and are characterized by different land use/cover (LUC) including cropland, grassland, built-up area and vegetation and soil and water conservation structures. Cropland is the dominant LUC in all catchments except LC catchment which is dominated by shrubland (exclosure). Characteristics of the gully reaches at the study sites are summarized in Table 4.1.

Table 4.1 Study site characteristics between the upper and lower V-notches in the selected gully reaches. NA = not available, LUC = land use/cover. For information of S, SCV, L, LC and LCV see Figure 4.1.

Gully reach	Up-stream area, ha	Number of check dams	Vegetation cover in the channel	Channel width (m)	Gully reach length (m)	Channel area (m^2)	Gully reach area (m^2)	Average channel Slope gradient ($m\ m^{-1}$)	Check dam age (year)	Channel bed material/ sediment		
										Organic matter content (%)	Texture	Bulk density ($g\ cm^{-3}$)
S	15	0	0	2.28	78	178	618	0.046	NA	0.14	sandy clay	1.62
SCV	6.5	7	40%	3.63	95	345	1248	0.048	14	1.54	sandy clay loam	1.49
L	4.5	0	0	1.45	56	81	364	0.058	NA	2.06	clay	1.4
LC	6	4	0	1.54	66	102	757	0.055	7	1.56	sandy clay loam	1.61
LCV	11	7	35%	3.36	80	269	1268	0.051	7	1.8	sandy clay loam	1.56

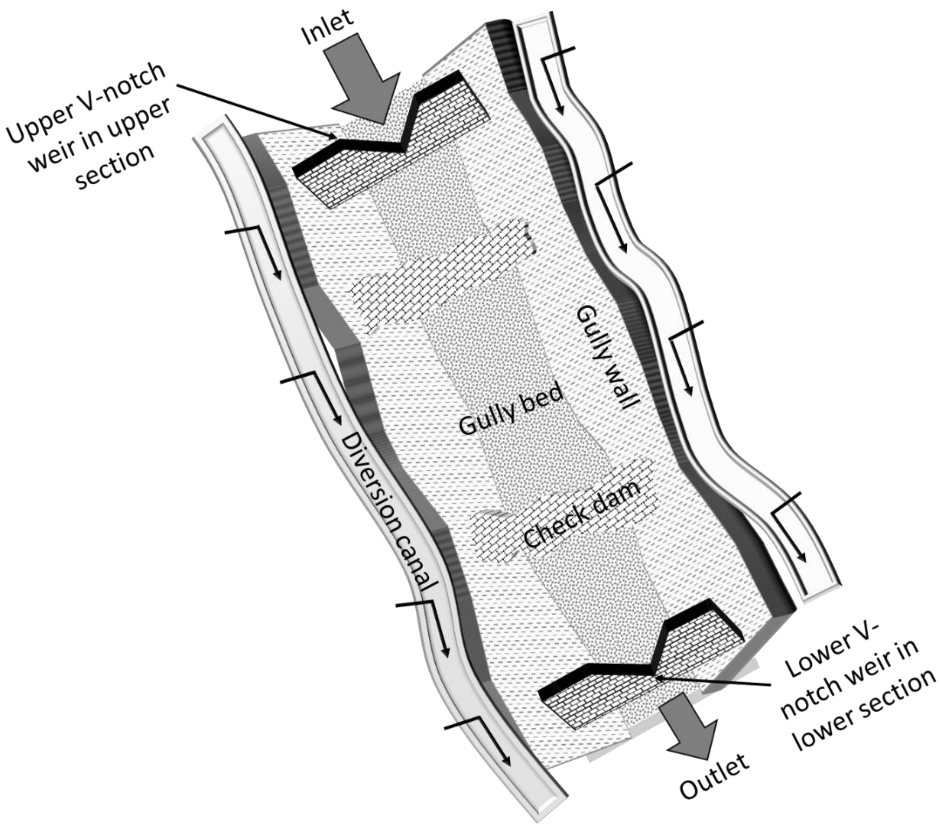

Figure 4.3 Schematic representation of V-notch installation at the upper and lower section of gully reach. The gully length is not at scale for sake of clarity

To monitor runoff, 90^{o} V-notched weirs (Bos, 1989; Hudson, 1993) were installed at the upper and lower sections of gully reaches (Figure 4.4). The V-notch weir has an overflow edge in the form of an isosceles triangle capable of measuring a wide range of discharge (Bos, 1989; Hudson, 1993). The study sites are characterized by high runoff and sediment transport capacities (Haregeweyn et al., 2005). As a fully or partially contracted V-notch (Bos, 1989; Hudson, 1993) is sensitive to sedimentation, the modified 90-degree triangular V-notch (van den Elsen et al., 2003) was adopted. This modified V-notch has 2 cm height below the V-notch opening, 100 cm height opening and 2 m length across the flow channel. The wall of the V-notch (50 cm thick and 50 cm foundation) was constructed with stone and cement to avoid the risk of collapse. Canals were constructed between the upper and lower gully sections to divert side external inflow (Figure 4.3) and construction of side walls was also necessary to control bypass of water (Figure 4.4).

Figure 4.4 V-notch, diversion canal, side wall, sensor and runoff in gully reach in sands stone (S).

Monitoring of runoff depth was done by installing e+ WATER 100L sensors (Figure 4.4) which combine a data logger at the base to measure the water pressure and atmospheric pressure sensor above the water surface. This sensor measures a 0 – 100 cm water column with 5 mm accuracy and 1 mm resolution. The runoff measurements were done from 29 August - 17 September in 2014 and from 24 July – 14 September in 2015.

Automatic tipping bucket and manual rain gages were installed at three locations: Adi Kolakol close to S and SCV, Adigoshu station nearby LCV and LC and Alassa station close to L gully (Figure 4.1).

4.2.3 Runoff discharge equation

Several equations for flow discharge calculation are available from the flow depth produced by 90-degree V-notch weirs (Bos, 1989; Hudson, 1993). As the V-notch used for the present study is modified in order to fit the local conditions, the modified discharge calculation equation (van den Elsen et al., 2003) was adopted to describe the runoff depth as open channel rate (Q):

$$Q = C \left(\sqrt{\frac{g}{2}}\right) h_c^{\frac{5}{2}} \tan\left(\frac{\theta}{2}\right) \tag{1}$$

Where Q = discharge (m^3/s), C = correction factor, g = 9.8 (m/s^2); h_c= depth of flow (m) and θ= angle of V-notch (°).

C combines C_d and Cv coefficients. C_d is a correction factor, also called discharge coefficient, to be applied to correct for effects such as viscosity, turbulence and a non-uniform flow distribution (Bos, 1989). Applying this correction factor is important as high suspended sediment concentrations in the study area causes higher flow viscosities. While it is also affected by the type of weir the coefficient Cd ranges from 0.93 to 1.02 (Bos, 1989). Cv is a correction factor for water velocity upstream of the V-notch. In line with earlier studies (van den Elsen et al., 2003), 0.9 is assumed as correction factor (C) and the value was also checked as it is accurate by comparing discharge obtained by the equation and discharge from direct measurement of velocity multiplied by cross-sectional area of the stream (van den Elsen et al., 2003).

The discharges obtained from equation 1 were used to calculate the total runoff event volume.

The relative reduction of peak flow discharge at the lower section of the gullies was calculated as (eq. 2):

$$\% \text{ reduction in peak discharge} = \frac{\Delta Q_p}{Q_{pu}} \; x \; 100 \qquad (2)$$

Where, ΔQ_P is the difference between upper peak flow discharge (Q_{pu}) and lower peak flow discharge (Q_{lu}).

The relative reduction of runoff volume between the upper and lower sections of gully reaches was calculated as (eq. 3):

$$\% \text{ reduction in volume} = \frac{\Delta V}{V_{upper}} x100 \qquad (3)$$

Where, ΔV is the runoff volume difference between the upper (V_{upper}) and lower (V_{lower}) section of the gullies.

4.2.4 Data analysis

The hydrographs were constructed for each runoff event at the upper and lower cross-sections of all gully reaches. Different lag times (lag to initiation, lag to peak and lag to end) of runoff to reach the lower V-notches were computed and compared among gully reaches. The proportion of average difference between upper and lower peak discharges, flow time and runoff volume are important parameters to compare the effects of gully characteristics on runoff. Simple linear regressions were performed to correlate event peak flow discharges to event maximum rainfall depth per 5 min, peak flow discharge reduction to maximum event rainfall depth and intensity, event volume of runoff to rainfall to draw conclusions on the relationship between rainfall parameters and runoff in gully conditions. All runoff values at the lower section of all gully reaches are linearly standardized to a length of 50 m of gully reach for analysis, which is approximately the same size with the smallest gully reach (L, 56 m). The non-parametric Kruskal–Wallis test was used to check if lag times, reduction of peak flow discharges and reduction of runoff volume in gully reaches are significantly different. Student's t-test was used to check the significance of differences in peak flow discharges and runoff volume within gully reaches and also to compare mean differences of lag times, peak flow discharge and runoff volume reduction in gully channels within and between lithologies. All statistical analyses were performed using SPSS version 20.0.0

4.3 Results

4.3.1 Rainfall

Daily rainfall data is available for three stations (Figure 4.5). The total rainfall depths recorded from 29 August - 17 September in 2014 and from 24 July – 14 September in 2015 at Adi Kolakol station (SCV and S), at Adigoshu station (LCV and LC) and at Alassa station (L) are 393.6, 348.4 and 272.3 mm, respectively. Event rainfall intensity and maximum rainfall depth per 5 min data are available over the measurement period for Adi Kolakol station while for the other two stations the data are available only in the second year. All daily rainfall depths over the monitoring period (in 2014 and 2015) and the rainfall depth that correspond to the individual runoff events considered for analyses are indicated in Figure 4.5.

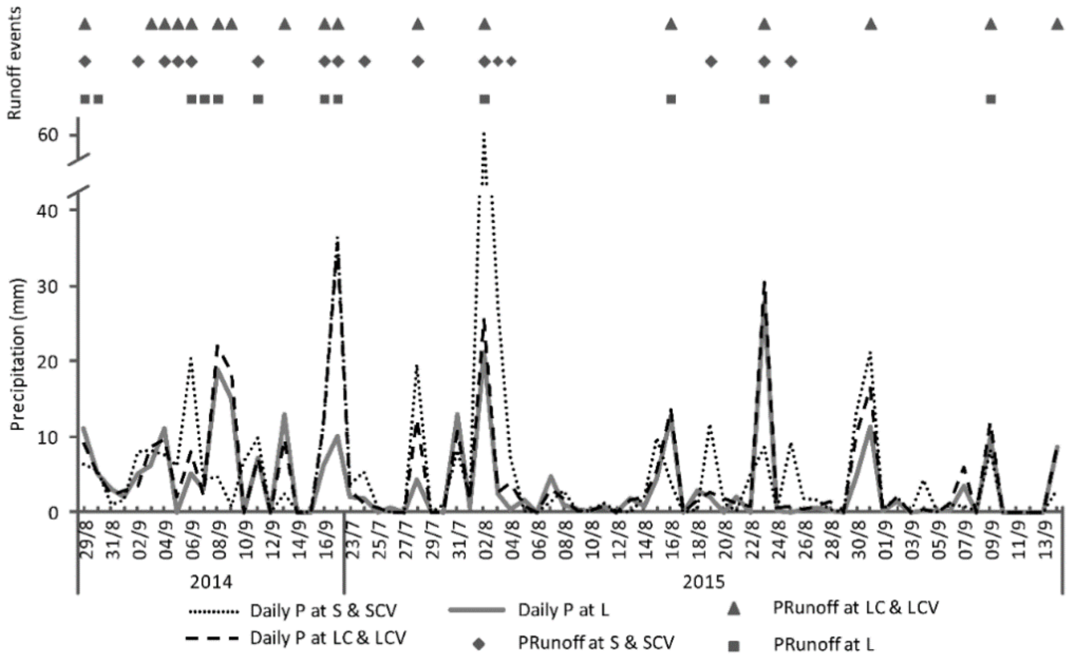

Figure 4.5 Daily rainfall (P) at three sites over the measurement period (29 August - 17 September in 2014 and from 24 July – 14 September in 2015); and PRunoff – rainfall depth corresponding to the individual runoff events analyzed (i.e. the markers indicate the rainfall for the runoff events used at each site). For information of S, SCV, L, LC and LCV see Figure 4.1.

Most storms with less than 5 mm did not create runoff. Some runoff data were cancelled from further analysis due to inflow of side runoff following accidental collapses of the runoff diversion canal or due to blocking of sensors by sediments. Figure 4.6 shows rainfall characteristics at the study sites, all are means over the monitoring period. The mean and duration of storm are larger in LCV and smaller in L while the intensity and peak are larger in Adi Kolakol and smaller at L.

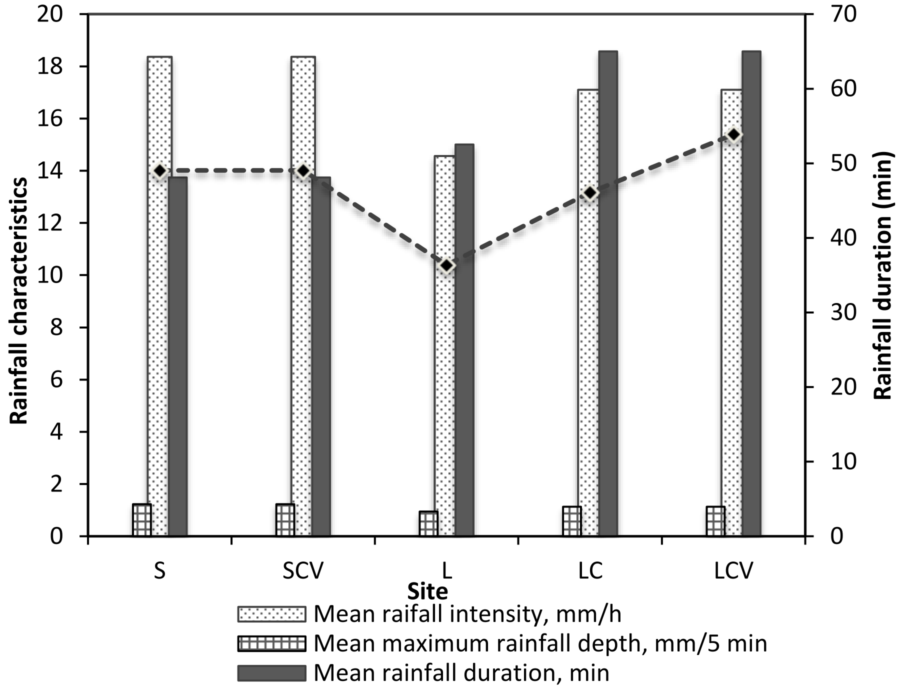

Figure 4.6 Rainfall characteristics (mean rainfall intensity, mean maximum rainfall depth per 5 min recording interval, and mean rainfall depth) and rainfall duration measured at three rain gauge stations (Adi Kolakol for S and SCV, Adigoshu for LC and LCV and Alassa for L gully) corresponding to the analyzed runoff events. All means were calculated from rainfall events measurement. For information of S, SCV, L, LC and LCV see Figure 4.1.

4.3.2 Runoff hydrographs at upper and lower section of gully reaches

Runoff hydrographs were produced at the upper and lower section of all gully reaches. In total, 76 runoff events were recorded in the five gully reaches. The results show that all hydrographs at the upper and lower stations within each gully have the same shape but are different in time, peak discharge and runoff volume. The hydrographs allow to compare the time elapsed for runoff to reach the lower station with reference to the upper station. The hydrographs show variable lag time to runoff initiation, lag to peak and lag to end of runoff between the inlet and outlet of the gully reaches. Gullies with check dams and vegetation show larger differences in lag times between the upper and lower sections of the gullies (Figure 4.7). The runoff hydrographs also show that the time of the rising limbs are very short while falling limbs are longer in untreated gullies.

Differences in the peak flow discharge were also observed from each hydrographs. Among the whole set of hydrographs the lowest reduction of peak flow discharge between the upper and lower sections was 0.7% at S while the highest loss of peak flow discharge was recorded at SCV (52.2%).

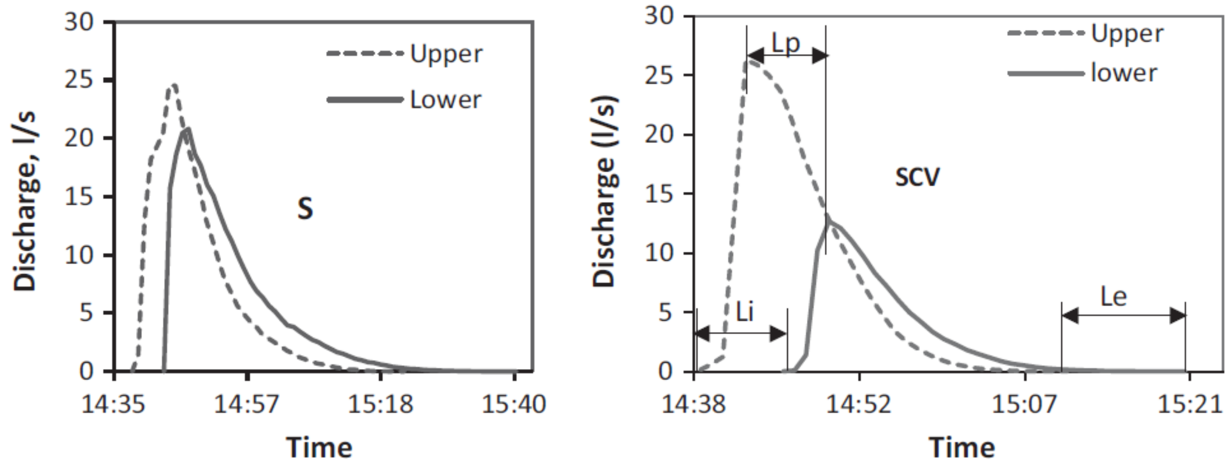

Figure 4.7 Example of runoff hydrograph in gullies without check dam and vegetation (S) and with check dams and vegetation (SCV) in the same lithology during the same rainfall event (02 Sep 2015) and approximately the same runoff discharges at the upper section of the gully reaches. Different lag times (Li - lag to runoff initiation, Lp – lag to peak flow and Le – lag to end runoff) are also indicated

4.3.3 Lag time

Lag time, is defined as the delay time of runoff initiation, peak and end at a lower monitoring station of a gully in reference to runoff at the upper monitoring station of the same gully reach. These lag times are useful runoff characteristics to evaluate the effects of check dams on the delay of runoff along gully reaches.

Comparison of lag to runoff initiation at the lower gully reach section shows that runoff was delayed by, 3.59 (±3.64) min, in L followed by SCV, while the lowest mean lag time (1.69 ±1.26 min) was recorded at S (Table 4.2). In SCV the time to runoff initiation at lower section is significantly different as compared to the lag time in S and LC. Neither lithology alone nor the interaction effect of treatment (check dam and vegetation) and lithology was found significant on the lag time of runoff initiation.

Testing for the differences in lag time to peak flow discharge at the lower section of the gully reaches showed that the lag time to peak discharge was significantly delayed in SCV (3.07 ±2.57 min) as compared to all gullies in limestone and sandstone lithologies, but for the other treatments this lag time was not significantly different (Table 4.2). Considering individual runoff events, the lag time to peak flow discharge ranges from 0.24 min at L gully reach to 9.26 min at SCV gully reach.

Table 4.2 Average lag time between upper and lower gully reach sections at different times (runoff initiation, peak, and end) on runoff hydrographs, after standardizing all values to 50 m gully reach length. n = number of runoff events. For information of S, SCV, L, LC and LCV see Figure 4.1.

Gully reach	Lag time (min)			
	Initiation of runoff	Peak runoff	End of runoff	
	Average (stdev)	Average (stdev)	Average (stdev)	n
S	1.69 a (±1.26)	1.20 a (±0.82)	4.98 a (±2.88)	17
SCV	3.46 b (±2.43)	3.07 b (±2.57)	8.83 b (±4.16)	17
L	3.59 ab (±3.64)	1.92 a (±1.98)	6.19 ab (±2.97)	15
LC	1.77 a (±1.83)	1.29 a (±0.69)	6.73 ab (±3.58)	15
LCV	2.10 ab (±1.39)	1.24 a (±0.79)	9.59 b (±2.75)	12

Average lag times within a column which have no common letter are significantly different at significance level 0.05.

The time differences that the flows ceased at the upper and lower sections were also computed and comparisons were made between the five gully reaches. The results show that the lag time to stop runoff ranges from 0.04 at LC to 18.27 min at SCV. Kruskal–Wallis test indicated that the installation of check dams combined with vegetation in gullies has a significant effect on increasing the time elapsed by runoff to stop at the lower sections of gullies. Pairwise mean comparison revealed that lag time to cease runoff at lower section of gully reaches were significantly higher in SCV (8.83 ±4.16 min) and LCV (9.59 ±2.75 min) than in S (4.98 ±2.88 min) (Table 4.2). Moreover, the lag time in LCV was significantly greater than in LC and L within the limestone lithology. The results also show that check dams affect lag times independently of lithology.

4.3.4 Peak flow discharge

Event peak flow discharges were correlated to event maximum rainfall depth per 5 min (Figure 4.8a) and the relation shows a strong exponential relationship for both upper and lower sites (R^2 = 0.55). Kruskal-Wallis tests were carried out to check whether there are significant differences in peak flow discharges between the upper and lower gully reach sections. The test did not show any significant difference for all gully reaches. The average peak flow discharges at upper and lower sections of each gully reach were computed over the measurement period to analyse the decrease of peak flow along gully reaches (Table 4.3). As external inflowing runoff was diverted and the rainfall on the gully itself was considered negligible, one may expect the peak flow discharge at the upper section to be larger than at the lower section of gully reach.

Table 4.3 Summary of different runoff parameters of the study sites at upper and lower sections for the studied gully reaches. n = number of runoff events. For information of S, SCV, L, LC and LCV see Figure 4.1.

Gully Reach	n	Total rainfall (mm)	Peak flow discharge (l/s)			Flow rate (l/s)		Runoff volume (m^3)		
			Upper gully reach section	Lower gully reach section	Peak flow Discharge reduction (%)	Upper section	Lower section	Upper gully reach section	Lower gully reach section	Volume reduction (%)
			Average (stdev)	Average (stdev)	Average (stdev)	Average (stdev)	Average (stdev)	Average (stdev)	Average (stdev)	Average (stdev)
S	17	252	296 (±371)	288 (±367)	5 a (±4)	62 (±82)	57 (77±)	542 (±1019)	527 (±1004)	4 a (±2)
SCV	17	252	250 (±369)	236 (±308)	17 b (±16)	49 (50±)	34 (36±)	233 (±357)	218 (±340)	18 c (±16)
L	12	125	67 (±101)	64 (±95)	5 a (±3)	13 (18±)	12 (17±)	81 (±128)	78 (±123)	6 ab (±3)
LC	15	198	35 (±42)	33 (±40)	8 b (±3)	7 (8±)	6 (6±)	27 (±36)	25 (±34)	8 bc (±4)
LCV	15	231	252 (±281)	232 (±256)	10 b (±5)	37 (33±)	30 (36±)	301 (±300)	275 (±274)	9 bc (±4)

Average of peak flow reductions were calculated from each event reduction, not directly from the mean peak flows of upper and lower gully sections. Peak flow discharge reduction and volume differences in the columns which have no common letter are significantly different at 0.05

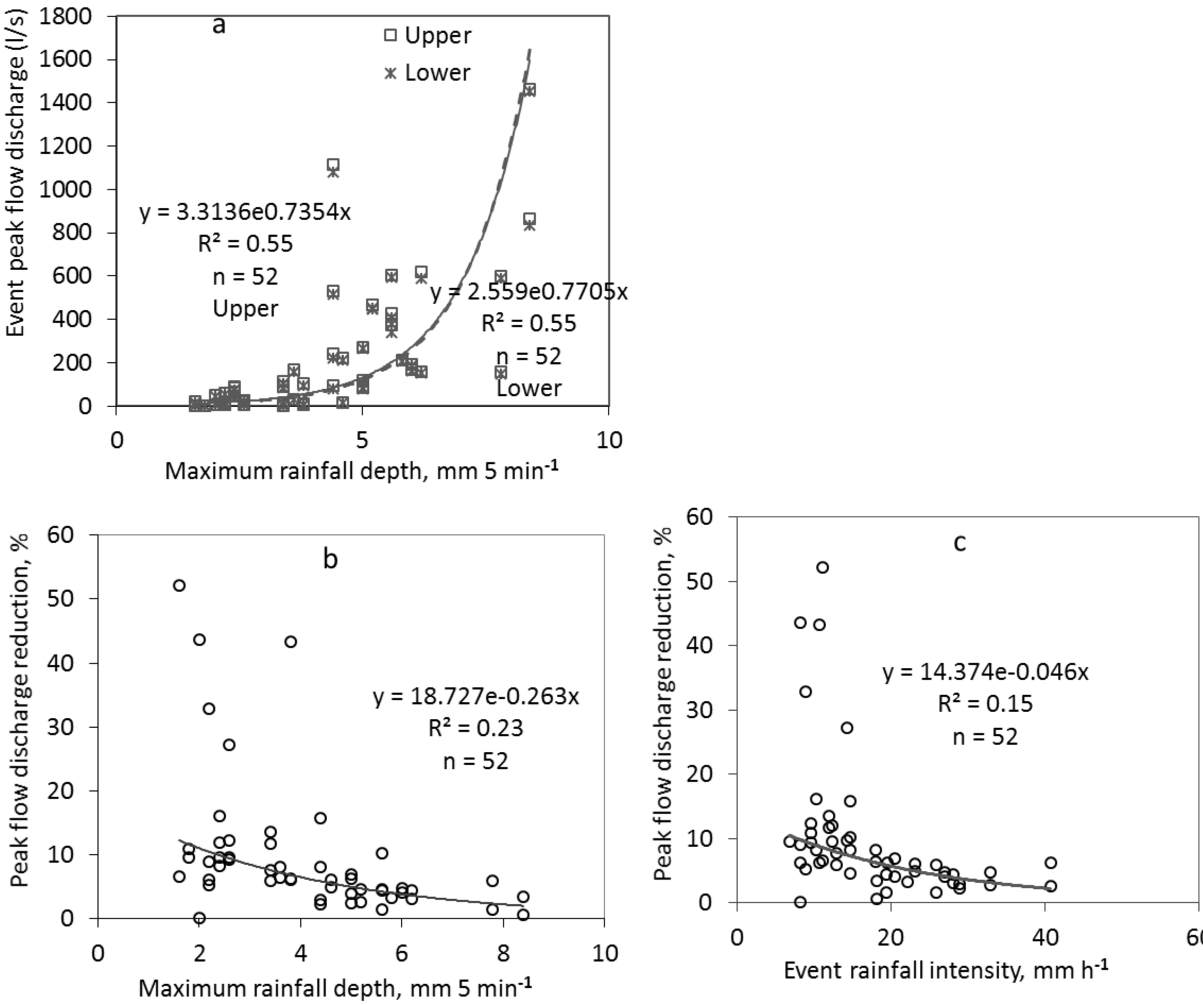

Figure 4.8 Relationships between (a) peak flow discharge – maximum rainfall depth per 5 min at upper section (Upper) and lower section (Lower) of gully reaches; (b) peak flow discharge reduction – maximum rainfall depth per 5 min; and (c) peak flow discharge reduction – rainfall intensity over all gully reaches. Data points in all curves are event based over the five gully reaches. n = 52 is number of events for which rainfall intensity was measured.

The reductions of peak flow discharges between the upper and lower sections were stronger in the gullies with check dams (8% – 17%) than in gullies without check dams (5% – 6%) (Table 4.3).

The non-parametric Kruskal–Wallis test showed important differences in the reduction of peak flow discharge between gully reaches. Gullies with treatments (check dams, vegetation) have significantly reduced peak flow discharges relative to untreated gullies with the highest reduction reaching 52.2% at SCV gully (Table 4.3). Treated gullies do not vary significantly from each other as was also found between untreated gullies. Within each gully reach, peak flow reduction is correlated to event rainfall depth and intensity in which inverse relationships were found, however coefficients of determination are small in both curves (Figure 4.8b & c).

4.3.5 Runoff volume

The relationships between event rainfall and runoff volume were analysed at all sites by simple linear regression (Table 4.4). Positive and significant linear relations were observed between event runoff volume and rainfall for the upper and lower sections of all gully reaches except in L gully. Across all gully reaches, linear regression between rainfall and runoff volume at upper section of gully reaches showed that rainfall explained about 55% of runoff volume generation (Figure 4.9). The dependence of runoff volume on rainfall, especially where significant relations were observed, ranges from 0.63 at LC to 0.89 at S gully (Table 4.4). Hence, in our study area, with typically short but intense storms, rainfall is an important explanatory factor for prediction of runoff volume in gullies with different characteristics.

Table 4.4 Event rainfall – storm runoff volume relation; with indication of R^2 of the regression function described by slope and significance level (0.05). Upper = upper gully section, Lower = lower gully section. For information of S, SCV, L, LC and LCV see Figure 4.1.

Site	Station	Slope	R^2	n
S	Upper	69.2	0.89*	17
	Lower	68	0.88*	17
SC	Upper	22	0.73*	17
	Lower	20.9	0.72*	17
L	Upper	10.6	0.29	12
	Lower	10.1	0.28	12
LC	Upper	3.7	0.64*	15
	Lower	3.6	0.63*	15
LCV	Upper	26.5	0.62*	15
	Lower	24.6	0.64*	15

*Indicates significant relationship between daily rainfall and storm runoff volume.

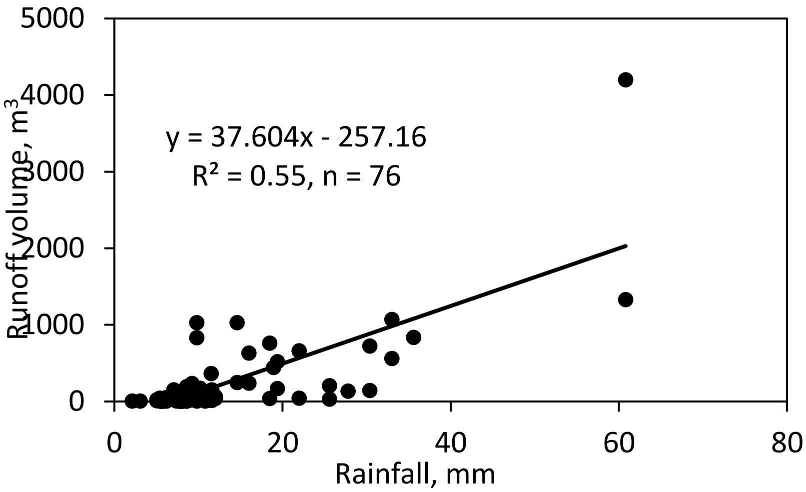

Figure 4.9 The relationship between event rainfall and runoff volume at the upper section of gully reaches.

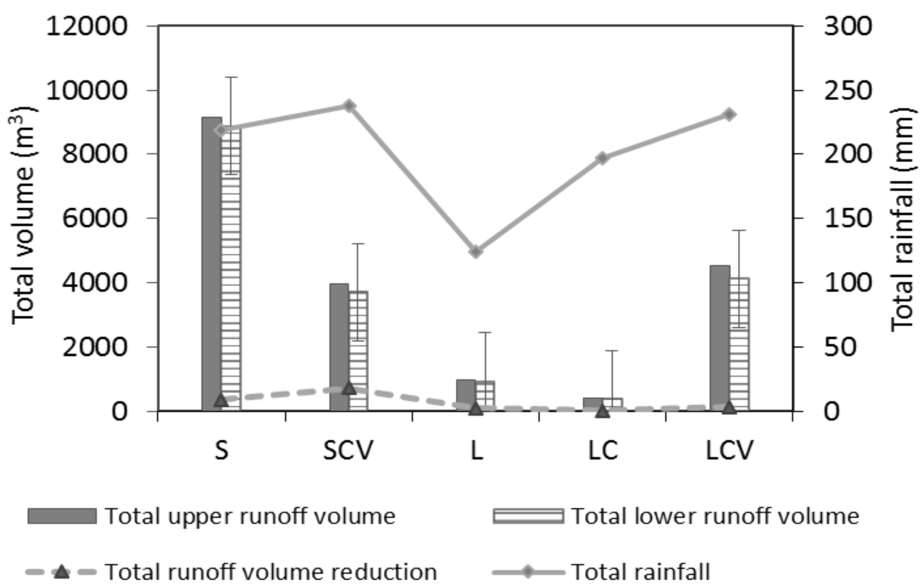

Figure 4.10 Total runoff volume at the upper and lower sections of the gully reaches, total volume reduction at each gully and total rainfall over the measurement period at the five gullies. For information of S, SCV, L, LC and LCV see Figure 4.1.

The results show greater volume of discharge at upper section than the lower section of gullies, but no significant differences were found within each gully. Across lithologies, event volume reductions show a wide range of decrease of discharge volume, 0.4% at S to 52% reduction at SCV (Figure 4.11). Differences in the fall of runoff volume at lower section of gully reaches across lithologies were tested for their significance by using non-parametric Kruskal-Wallis test. The result revealed SCV significantly reduced runoff volume as compared to gullies without any treatment, S and L (Table 4.3). Significantly less reduction was also found at S when compared to LC and LCV. Gullies with similar characteristics do not have important variations when compared with each another. The reduction of runoff of volume is correlated to different rainfall characteristics such as rainfall depth and rainfall intensity. Figure 4.10 shows the total volume of discharge and total reduction in cubic meter and total rainfall during the entire measurement period at each site. During this period (n = 76 runoff events across reaches) the total volume of discharges reduced in all gullies was 942 m^3 out of which 69% was at gullies under treatment with check dam and vegetation.

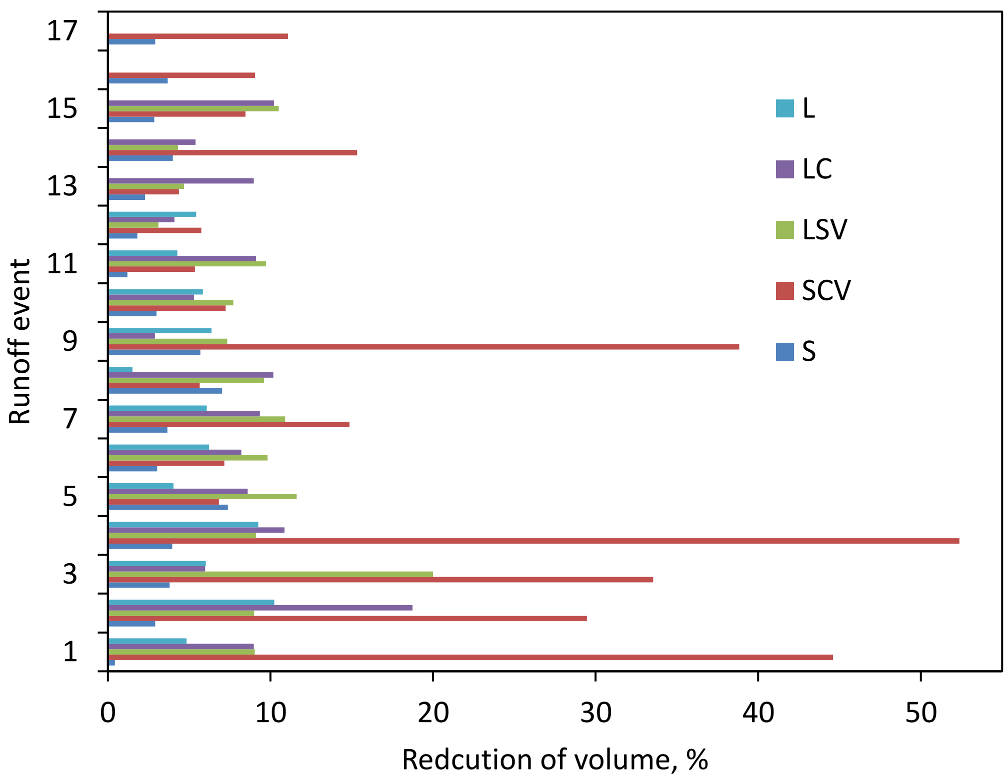

Figure 4.11 Event runoff volume reduction in five gully reaches. For information of S, SCV, L, LC and LCV see Figure 4.1.

4.4 Discussion

4.4.1 Runoff hydrographs for different gullies

Adjusting the water depth sensor to fine measuring intervals (one min), provided reliable data particularly for short duration flows that occurred in this study (about 50% of runoff events lasted only for less than 1 hour). Hydrographs were constructed for each runoff event which allowed to analyze the runoff response to different gully conditions. Hence, by analyzing the shape of the hydrographs one can observe the differences between runoff hydrographs (lag time, duration, peak and volume) at the upper and lower sections of each gully reach and between different gullies. No significant differences in lag time, decrease in peak flow discharge and runoff volume were detected between sandstone and limestone lithologies.

4.4.2 Lag to begin runoff at lower section of gully reach

The results of this study reveal that there is a delay in runoff initiation at the lower section of all gullies during every runoff event. It is not surprising to observe the delay of discharges between the upper and lower sections of gully reaches, as the source of runoff at the lower is only via the upper V-notch. The result to be analysed are the duration of delay of runoff to reach the lower section of the gully reaches. The longer delay at SCV (3.46 $\pm$2.43 min) as compared to S (1.69 $\pm$1.26 min) (Table 4.2) could be associated to the presence of check dams, sediment deposition, vegetation and low bulk density in the former gully channel (Table 4.1, Figure 4.12). Surface roughness, resulting from check dams and vegetation, claimed to slow down runoff by increasing time of concentration and infiltration (e.g. Deasy et al., 2014; Helming et al., 1998). It was reported that soil bulk density is positively correlated with runoff production (e.g. Calvo-Cases et al., 2003; Descheemaeker et al., 2006a), thus affecting runoff discharge and velocity positively.

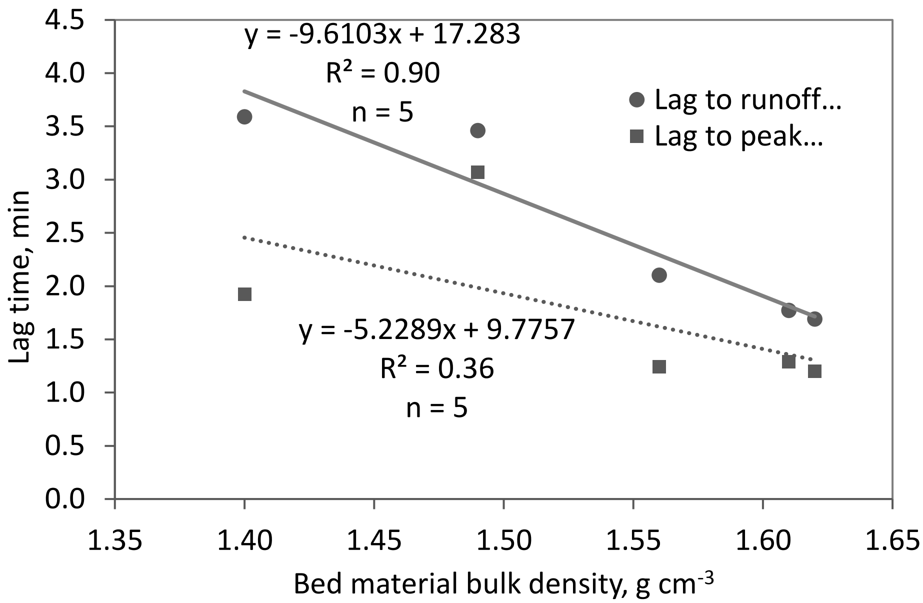

Figure 4.12 The relationship between soil bulk density and two lag times (lag to runoff initiation and lag to peak).

Despite the presence of check dams and vegetation in LCV and check dams in LC the delay of runoff to reach lower section of the gully reaches were shorter than in the L gully which lacks check dams and vegetation (Table 4.2). This may be explained by the higher rainfall intensities in the LCV and LC that leads to rapid soil saturation and increases the velocity of surface runoff (Brouwer et al., 1985). When rainfall intensity is the same for gullies with and without check dams and vegetation in the same lithology the check dams and vegetation increase lag to runoff initiation at lower section of the gully reach (Figure 4.7). The negative correlation between rainfall intensity and lag time (Figure 4.13) indicates that the smaller the intensity the longer the lag time of runoff to reach the lower gully sections. Besides rainfall intensity, smaller bed material bulk density (Table 4.1and Figure 4.12) (Li et al., 2009) and dry conditions of the clay soil (Bouma and Dekker, 1978; Römkens and Prasad, 2006) in L may be hold responsible for the longer delay of runoff by increasing initial infiltration rate. Moreover, the delay of runoff to reach the lower section of gully reaches can be related to the depth of runoff at upper section of the reaches (Figure 4.14). The depth of runoff at the upper section of gully reaches depends on runoff contributing catchment characteristics (area, land use, SWC etc) as well as the amount of rainfall in the catchment.

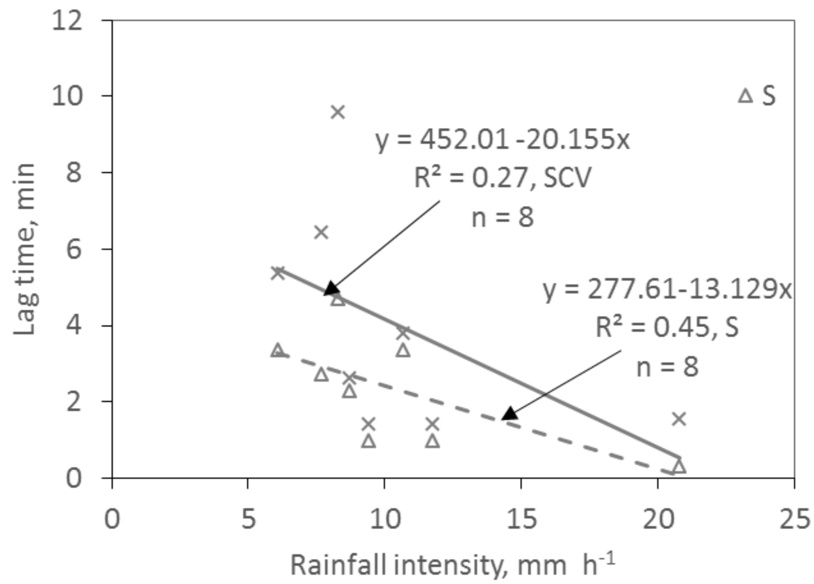

Figure 4.13 Lag time to runoff initiation vs intensity of rainfall in gullies at sandstone lithology without (S) and with check dams and vegetation cover (SCV).

4.4.3 Lag time to peak runoff at lower section

In the gully with check dams and vegetation cover in the sandstone lithology (SCV), runoff takes 2.6 times longer to peak as compared to the one without treatment (Table 4.2). This is related to the presence of check dams, vegetation and sediment accumulation which reduce the runoff speed by increasing channel bed roughness, as described by several authors (Amare et al., 2014; Borst and De Haas, 2006; Deasy et al., 2014; Descheemaeker et al., 2006a; Hood et al., 2007; Namadi et al., 2014). The short lag time to peak can be also attributed to the higher flow rate at the upper section of S gully reach (62 (±82) l s^{-1}) as compared to SCV (Table 4.3). In limestone lithology, the longer lag times to peak were recorded in the gully without management intervention (Table 4.2). This can be attributed to the small rainfall depth (Figure 4.5, Figure 4.6 and Figure 4.10), clay texture and low bulk density of bed material at L (Table 4.1 and Figure 4.12) gully reach which contribute to an increase of infiltration mainly at the beginning of rainfall (Bouma and Dekker, 1978; Li et al., 2009; Römkens and Prasad, 2006) thereby delaying the time to peak flow at the lower section of the gully reach. Cracking of soil was also noticed in the L gully reach without management interventions, which can also increase infiltration rate particularly at the beginning of runoff generation. In addition, the smaller depth of runoff at L particularly compared to LCV can be claimed for the longer lag time to peak at the lower section of L gully reach (Table 4.3, Figure 4.14).

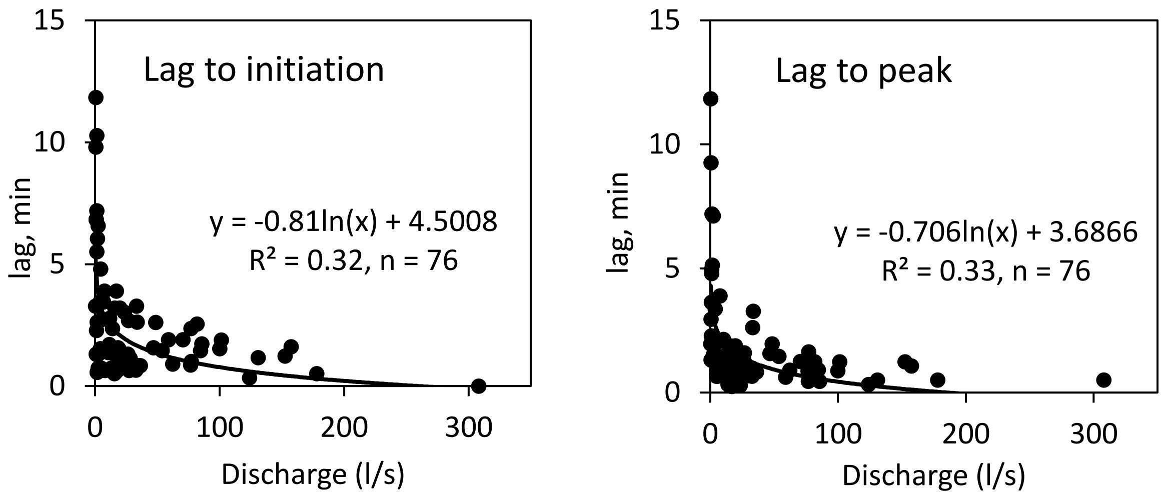

Figure 4.14 Relationship between discharge and lag times (lag to initiation of runoff and lag to peak).

4.4.4 Lag time to end runoff at lower section

During some rain events termination of runoff discharge was found to be faster at the lower section than at the upper section of gully reaches that can be explained by low rainfall intensity, short rainfall duration and dry soil conditions. Polyakov et al. (2014) reported that after installation of soil and water conservation structures, small rainfall failed to produce runoff that reached the watershed outlet. The authors added that check dams are more likely to reduce hydrologic connectivity between uplands, channel network and outlet during small runoff events than during large runoff events. On average, the time of interruption of runoff discharges was delayed at the lower section of all gully reaches which can be attributed to the temporary storage of water in the channel bed between the two sections. The longer flow time at lower sections is larger in gullies with check dam and vegetation cover (Table 4.2), probably enhanced by sediment built-up behind check dams and presence of vegetation. This is in agreement with the finding of Hood et al. (2007) that gully channel management interventions with check dams and vegetation increase lag to peak mainly for small and short storms duration and dry soil conditions.

4.4.5 Peak flow discharge

In all gullies, peak flow discharges are smaller at the lower sections (Table 4.3). This is due to runoff loss as infiltration between the inlet and outlet of the gully reaches. The reduction is larger in gullies with check dams and vegetation (8% - 17%) than in gullies without any treatment (5% - 6%) (Table 4.3). The larger reduction in gullies with check dams and vegetation can be attributed to the sediments deposited behind the check dams and to the presence of vegetation in the channel that reduce runoff velocity and increase infiltration. Earlier studies have also documented the decreasing response of peak flow discharge to check dams and vegetation (Hood et al., 2007; Huang and Zhang, 2004; Namadi et al., 2014; Potter, 1991).

4.4.6 Runoff volume

The reason for the reduction of runoff volume at the lower sections (Table 4.3 and Figure 4.10) is explained by infiltration of runoff between the upper and lower sections. This reduction varies for different runoff events within each gully reach which can be explained by soil moisture content and rainfall intensity (Descheemaeker et al., 2006a; Molina et al., 2009). The amount of runoff volume at the upper catchment has a positive relationship with the reduction of runoff volume at lower section of gully reaches (Figure 4.15). This describes that low runoff depth generated from a catchment leads to lower runoff reduction as compared to larger runoff produced by the catchment. Comparisons of runoff volume reduction between different gully reaches have depicted that significant proportion of discharge volume was abstracted in the gullies treated with check dams and vegetation (8 -18%) (Table 4.3 & Figure 4.10). This is explained by the sediments trapped and vegetation growth as a result of check dam construction in the gullies. Several studies demonstrated the marked effects of physical and biological soil and water conservation on runoff volume reduction by increasing infiltration rates (e.g. Amare et al., 2014; Borst and De Haas, 2006; Hood et al., 2007; Huang et al., 2012; Huang and Zhang, 2004; Lacombe et al., 2008; Molina et al., 2009; Nyssen et al., 2010; Potter, 1991; Taye et al., 2013b; Xu, 2005; Xu et al., 2013; Zhang et al., 2014), eventually resulting in the rise of groundwater levels (e.g. Alderwish, 2010; Huang et al., 2012; Parimala Renganayaki and Elango, 2013). The positive effects of check dams on the abstraction of runoff were also deduced indirectly from reclaiming of gully segments by farmers and increased crop yields after construction of check dams (Nyssen et al., 2010; Xiang-zhou et al., 2004). Moreover, the effects of gully treatments on catchment water balance in Northern Ethiopia is noteworthy as gully density in the region is very high (on average 2.52 km km^{-2}) (Frankl et al., 2013a) and a large fraction of these have been treated by SWC measures. Hence, the result of this study indicates that implementation of check dams in gullies will have a considerable effect on catchment hydrology by increasing infiltration which then improves groundwater recharge and base flows.

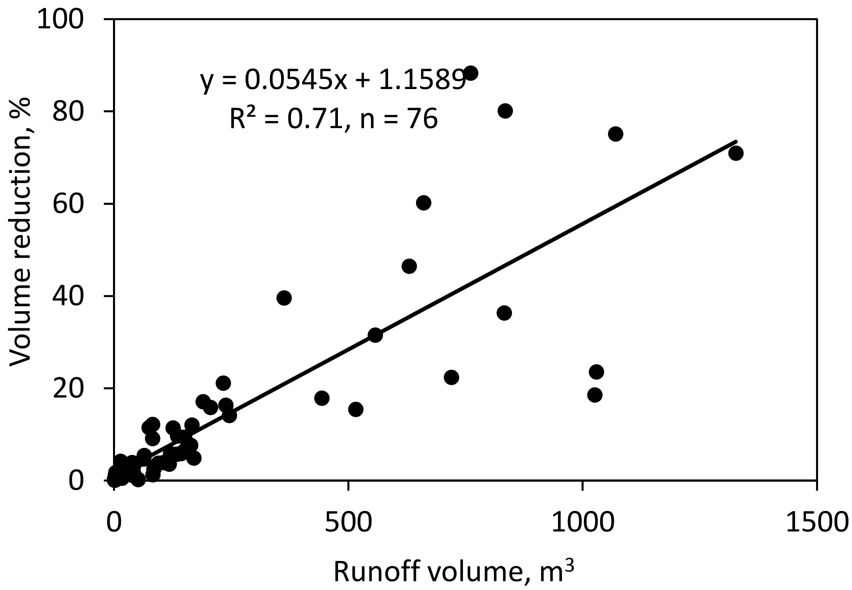

Figure 4.15 Relationship between runoff volume at upper section of gully reaches and runoff reduction at lower section.

4.5 Conclusions

In North Ethiopia, the implementation of check dams in gullies over the last three decades has contributed to environmental amelioration. Besides soil loss reduction and favouring vegetation growth, check dams also influence hydrological properties in gullies and at watershed scale. The present study has confirmed the hydrological effects of check dams after analyzing lag times, peak flow reduction and volume reduction of runoff along gully reaches.

Given different natural variability in gully reaches, variations in different discharge parameters were found within and among gully reaches with and without management interventions in two dominant lithologies (sandstone and limestone). In sandstone lithology, gully treatment with check dam and vegetation increase lag times (lag to initiation, lag to peak and lag to end of runoff) as compared to untreated gully (S), which demonstrates the significant effects of check dams and the consequent sediment deposition and vegetation growth. But in limestone lithology lag time to runoff initiation and to peak were larger in untreated gully (L) than in treated gullies (LC and LSC) which can be attributed to different rainfall intensity and soil physical properties. . This indicates that lag times are not only affected by management interventions but also by soil physical properties of the channel bed and rainfall intensity. Hence, it is difficult to draw general conclusion on the effect of gully treatment on runoff lag times at the lower sections of gully reaches in limestone areas.

Check dams, sediment deposition in the channel and vegetation growth are responsible for the significant variations in the peak flow reduction between gully sections with and without intervention. Generally, this reduction is larger in treated gullies (8% - 17%) than in gullies without treatment (5% - 6%). An increase of channel bed roughness resulting from gully treatment reduces peak flow discharge at lower sections of gully reaches by reducing runoff velocity and increasing infiltration.

Whether gullies are treated or not, runoff volume decreases at lower sections of gullies if side runoff is diverted. Installing check dams increases the magnitude of runoff volume reduction. In the present study, runoff volumes were significantly reduced in gullies with check dams and vegetation (8% – 18%) as compared to the untreated gullies (4% – 6%) within and across lithologies. We conclude that gully management with check dams and the subsequent sediment build up and vegetation growth results in a significant reduction of runoff in gullies by increasing infiltration. This eventually may leads to recharge of groundwater and improves base flows to streams and reservoirs during the dry season. While our study have demonstrated important effects of check dams on runoff characteristics in gully reaches, uncertainty should be also expected due to some uncontrolled limitations during the experiment. For example, it was not easy to find gully reaches with and without conservation but similar in other characteristics (size, slope, lithology, contributing area, etc.). It is expensive and technically not feasible to replicate the experimental sites in different conditions. Hence, in future studies we suggest comparison of the same gully reach before and after intervention as this could help to control the limitations of comparing the hydrology of different gully reaches with and without intervention. However, this approach may not help to report the effects of stabilized gullies (filled with sediment and vegetation growth) in short time (2-3 years) unless the study is carried out over long time period which can help to compare the effects of check dams of different age Hence, further investigation is very important to verify the effects of check dam construction in gullies on runoff characteristics at the outlet of catchments and on river baseflows.

Acknowledgment

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4.6 References

Aerts R, Maes W, November E, Negussie A, Hermy M, Muys B. 2006. Restoring dry Afromontane forest using bird and nurse plant effects: direct sowing of Olea europaea ssp. cuspidata seeds. Forest Ecology and Management, 230(1): 23-31.

Alderwish AM. 2010. Induced recharge at new dam sites—Sana'a Basin, Yemen. Arabian Journal of Geosciences, 3(3): 283-293.

Amare T, Zegeye AD, Yitaferu B, Steenhuis TS, Hurni H, Zeleke G. 2014. Combined effect of soil bund with biological soil and water conservation measures in the northwestern Ethiopian highlands. Ecohydrology & Hydrobiology, 14(3): 192-199.

Bombino G, Gurnell A, Tamburino V, Zema D, Zimbone S. 2009. Adjustments in channel form, sediment calibre and vegetation around check-dams in the headwater reaches of mountain torrents, Calabria, Italy. Earth Surface Processes and Landforms, 34(7): 1011-1021.

Borst L, De Haas S. 2006. Hydrology of sand storage dams: A case study in the Kiindu catchment, Kitui District, Kenya. VU University Amsterdam, Amsterdam, The Netherlands.

Bos MG. 1989. Discharge measurement structures. Discharge measurement structures.

Bouma J, Dekker L.W. 1978. A case study on infiltration into dry clay soil I. Morphological observations. Geoderma, 20(1): 27-40.

Brouwer C, Goffeau A, Heibloem M. 1985. Irrigation Water Management: Training Manual No. 1-Introduction to Irrigation. Food and Agriculture Organization of the United Nations, Rome, Italy.

Calvo-Cases A, Boix-Fayos C, Imeson A. 2003. Runoff generation, sediment movement and soil water behaviour on calcareous (limestone) slopes of some Mediterranean environments in southeast Spain. Geomorphology, 50(1): 269-291.

Castillo V, Mosch W, García C.C, Barberá G, Cano JN, López-Bermúdez F. 2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). Catena, 70(3): 416-427.

Costa FM, Bacellar LAP. 2007. Analysis of the influence of gully erosion in the flow pattern of catchment streams, Southeastern Brazil. Catena, 69(3): 230-238

Deasy C, Titman A, Quinton J.N. 2014. Measurement of flood peak effects as a result of soil and land management, with focus on experimental issues and scale. Journal of environmental management, 132: 304-312.

Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B, Deckers S. 2006. Runoff on slopes with restoring vegetation: a case study from the Tigray highlands, Ethiopia. Journal of Hydrology, 331(1): 219-241.

Diaz-Ramirez J. 2014. Porous Check Dams on Flow Routing and Sediment Transport in Agricultural ditches: A Case Study in the Mississippi Delta.

Frankl A, Nyssen J, De Dapper M, Haile M, Billi P, Munro R.N, Deckers J, Poesen J, 2011. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology, 129(3): 238-251.

Frankl A, Poesen J, Haile M, Deckers J, Nyssen J, 2013. Quantifying long-term changes in gully networks and volumes in dryland environments: The case of Northern Ethiopia. Geomorphology, 201: 254-263.

Gebresamuel G, Singh BR, Dick Ø. 2010. Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. Acta Agriculturae Scandinavica Section B–Soil and Plant Science, 60(3): 211-226.

Gebru T, Eshetu Z, Huang Y, Woldemariam T, Strong N, Umer M, DiBlasi M, Terwilliger VJ. 2009. Holocene palaeovegetation of the Tigray Plateau in northern Ethiopia from charcoal and stable organic carbon isotopic analyses of gully sediments. Palaeogeography, Palaeoclimatology, Palaeoecology, 282(1): 67-80.

Haregeweyn N, Poesen J, Nyssen J, Verstraeten G, De Vente J, Govers G, Deckers S, Moeyersons J. 2005. Specific sediment yield in Tigray-Northern Ethiopia: assessment and semi-quantitative modelling. Geomorphology, 69(1): 315-331.

Haregeweyn N, Tsunekawa A, Tsubo M, Meshesha D, Adgo E, Poesen J, Schütt B. 2015. Analyzing the hydrologic effects of region-wide land and water development interventions: a case study of the Upper Blue Nile basin. Regional Environmental Change: 1-16.

Hassanli AM, Nameghi AE, Beecham S. 2009. Evaluation of the effect of porous check dam location on fine sediment retention (a case study). Environmental monitoring and assessment, 152(1-4): 319-326.

Helming K, Römkens M, Prasad S. 1998. Surface roughness related processes of runoff and soil loss: a flume study. Soil Science Society of America Journal, 62(1): 243-250.

Hood MJ, Clausen JC, Warner GS. 2007. Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development1. JAWRA Journal of the American Water Resources Association, 43(4): 1036-1046.

HTS. 1976. Tigrai Rural Development Study (TRDS). Hunting Technical Services Ltd,Hunting Techinical services, Borehamwood.

Huang J, Hinokidani O, Yasuda H, Ojha CS, Kajikawa Y, Li S. 2012. Effects of the check dam system on water redistribution in the Chinese Loess Plateau. Journal of Hydrologic Engineering, 18(8): 929-940.

Huang M, Zhang L. 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrological Processes, 18(10): 1885-1898.

Hudson N. 1993. Field measurement of soil erosion and runoff, 68. Food & Agriculture Org.

Lacombe G, Cappelaere B, Leduc C. 2008. Hydrological impact of water and soil conservation works in the Merguellil catchment of central Tunisia. Journal of Hydrology, 359(3): 210-224.

Lenzi MA, Comiti F. 2003. Local scouring and morphological adjustments in steep channels with check-dam sequences. Geomorphology, 55(1): 97-109.

Li Z, Wu P, Feng H, Zhao X, Huang J, Zhuang W. 2009. Simulated experiment on effect of soil bulk density on soil infiltration capacity. Transactions of the Chinese Society of Agricultural Engineering, 25(6): 40-45.

Molina A, Govers G, Putte A, Poesen J, Vanacker V. 2009. Assessing the reduction of the hydrological connectivity of gully systems through vegetation restoration: field experiments and numerical modelling. Hydrology and Earth System Sciences, 13(10): 1823-1836.

Munro RN, Deckers J, Haile M, Grove A, Poesen J, Nyssen J. 2008. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena, 75(1): 55-64.

Namadi PH, Saghafian B, Rostami M. 2014. The numerical investigation of the effect of subsequent check dams on flood peaks and the time of concentration using the MIKE 11 modeling system (Case study: Golabdareh catchment, Iran), River Flow 2014. CRC Press, pp. 1745-1750.

Nyssen J, Clymans W, Descheemaeker K, Poesen J, Vandecasteele I, Vanmaercke M, Zenebe A, Van Camp M, Haile M, Haregeweyn N. 2010. Impact of soil and water conservation measures on catchment hydrological response—a case in north Ethiopia. Hydrological Processes, (24): 1880-1895.

Nyssen J, Poesen J, Descheemaeker K, Haregeweyn N, Haile M, Moeyersons J, Frankl A, Govers G, Munro N, Deckers J. 2008a. Effects of region-wide soil and water conservation in semi-arid areas: the case of northern Ethiopia. Zeitschrift für Geomorphologie, 52(3): 291-315.

Nyssen J, Poesen J, Moeyersons J, Haile M, Deckers J. 2008b. Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands-towards a sediment budget. Earth surface processes and landforms, 33(5): 695-711.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G. 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology, 311(1): 172-187.

Nyssen J, Veyret-Picot M, Poesen J, Moeyersons J, Haile M, Deckers J, Govers G. 2004. The effectiveness of loose rock check dams for gully control in Tigray, northern Ethiopia. Soil Use and Management, 20(1): 55-64.

Parimala Renganayaki S, Elango L. 2013. A review on managed aquifer recharge by check dams: a case study near Chennai, India. Int. J. Res. Eng. Technol, 2: 416-423.

Poesen J, Nachtergaele J, Verstraeten G, Valentin C. 2003. Gully erosion and environmental change: importance and research needs. Catena, 50: 91-133.

Polyakov V, Nichols M, McClaran M, Nearing M. 2014. Effect of check dams on runoff, sediment yield, and retention on small semiarid watersheds. Journal of Soil and Water Conservation, 69(5): 414-421.

Potter KW. 1991. Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. Water Resources Research(27): 845-855.

Remaître A, Van Asch TW, Malet J-P, Maquaire O. 2008. Influence of check dams on debris-flow run-out intensity. Natural Hazards and Earth System Science, 8(6): 1403-1416.

Romero-Diaz A, Alonso-Sarriá F, Martínez-Lloris M. 2007. Erosion rates obtained from check-dam sedimentation (SE Spain). A multi-method comparison. Catena, 71(1): 172-178.

Römkens M, Prasad S. 2006. Rain Infiltration into swelling/shrinking/cracking soils. Agricultural water management, 86(1): 196-205.

Taye G, Poesen J, Wesemael BV, Vanmaercke M, Teka D, Deckers J, Goosse T, Maetens W, Nyssen J, Hallet V. 2013. Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography, 34(3): 236-259.

Van de Wauw J, Baert G, Moeyersons J, Nyssen J, De Geyndt K, Taha N, Zenebe A, Poesen J, Deckers J. 2008. Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. Catena, 75(1): 117-127.

van den Elsen E, Hessel R, Liu B, Trouwborst KO, Stolte J, Ritsema CJ, Blijenberg H. 2003. Discharge and sediment measurements at the outlet of a watershed on the Loess plateau of China. Catena, 54(1): 147-160.

Vancampenhout K, Nyssen J, Gebremichael D, Deckers J, Poesen J, Haile M, Moeyersons J. 2006. Stone bunds for soil conservation in the northern Ethiopian highlands: Impacts on soil fertility and crop yield. Soil and Tillage Research, 90(1): 1-15.

Virgo K, Munro R. 1978. Soil and erosion features of the Central Plateau region of Tigrai, Ethiopia. Geoderma, 20(2): 131-157.

Xiang-zhou X, Hong-wu Z, Ouyang Z. 2004. Development of check-dam systems in gullies on the Loess Plateau, China. Environmental Science & Policy, 7(2): 79-86.

Xu J. 2005. Temporal variation of river flow renewability in the middle Yellow River and the influencing factors. Hydrological Processes, 19(9): 1871-1882.

Xu Y, Fu B, He C. 2013. Assessing the hydrological effect of the check dams in the Loess Plateau, China, by model simulations.

Zhang L, Podlasly C, Ren Y, Feger KH, Wang Y, Schwärzel K. 2014. Separating the effects of changes in land management and climatic conditions on long-term streamflow trends analyzed for a small catchment in the Loess Plateau region, NW China. Hydrological Processes, 28(3): 1284-1293.

5 From runoff contributor to runoff absorber: spate irrigation on exclosures

This chapter is based on:

Etefa G, Jacob M, Descheemaeker K, Poesen J, Frankl A, Deckers J, Nyssen J. 2017. From runoff contributor to runoff absorber: spate irrigation on exclosures in Tigray (N Ethiopia). In preparation.

Abstract

Exclosures have been widely implemented in north Ethiopia in the last few decades for rehabilitation of degraded areas. Despite many years of establishment, the effectiveness of exclosures is constrained by lack of adequate management such as supplementing additional water to the short and erratic rain. There is no knowledge on the response of vegetation to such additional water application. This study is aimed to evaluate the effects of such spate irrigation on species diversity, stocking and ring width growth of trees in exclosures. Two exclosures (May Ba'ati and Adi Kolakol), Dogu'a Temben district were used for this study. Each exclosure was divided in two blocks (irrigated and control) to allow comparison of vegetation growth. May Ba'ati was irrigated in 2005 while Adi Kolakol was irrigated from 2012 to 2016 but monitored by the researchers from 2014 to 2016. The amount of irrigation water applied is in the same order of magnitude as the direct rainfall on the site. Several species diversity indices and mean tree ring width growth were used to compare the irrigated and non-irrigated areas. The results show that trees in the irrigated exclosure have larger species richness, Shannon Weaver diversity index, tree density, abundance, evenness and basal area than in the control area. In years with a short rainy season, the changes of these indices were negative in the control area, whereas most indices remained positive in the irrigated area. Moreover, tree ring width growth analysis exhibits the role of additional water to vegetation growth. The findings indicate tha diverting runoff to exclosures results in 15% to 22% increase in ring width as compared to non-irrigated trees. In addition, there is strong abstraction of storm runoff in gullies.

Keywords: tree ring, plant density, growth indices, gully

5.1 Introduction

Exclosures, or areas set aside from human and livestock interference to restore natural resources and ecological restoration, have been widely implemented in north Ethiopia which has brought important environmental as well as socio-economic improvements (Mitiku and Kindeya, 2001; Aerts *et al*., 2002; Descheemaeker *et al*., 2006; Mekuria and Aynekulu, 2011). Several studies have evaluated that the implementation of exclosures in the degraded areas has resulted in the increase of biodiversity and biomass as compared to adjacent open areas mainly degraded communal lands (Mekuria and Yami, 2013; Emiru et al., 2007, Mengistu et al., 2005). Despite the large scale deforestation of native forest in Northern Ethiopia, that markedly challenges natural regeneration of native tree species, exclosures are a dependable option for restoration of woody vegetation including major native tree species e.g. *Olea europea* (Aynekulu et al., 2009, Emiru et al., 2007, Mengistu et al., 2005). Continuous plant community, higher tree abundance, density and basal area have been recorded in exclosures following favorable conditions created for succession of plants.

The age of exclosures in Northern Ethiopia varies from a few years to circa three decades (Descheemaeker et al., 2006), now four decades. Despite the long time of their establishment, the effectiveness of exclosures is constrained by lack of adequate management activities (Aerts et al., 2002). Enrichment planting and construction of terraces in such exclosures are the common management activities practiced (Aerts et al., 2002). Shortage of rainfall (Nyssen et al., 2005) and occurrence of recurrent drought that characterize dryland regions (Beltrando and Camberlin, 1993) can be also another prominent factor to hamper the growth of forest. Despite this fact, management activities with respect to supplementing rainfall through watering or irrigating exclosures is not practiced in the study area, except under very specific conditions (e.g. watering of seedlings during enrichment planting). Experiment on the effect of irrigation on the physiological changes of trees (e.g. radial growth or ring growth) and survival show a sustained increase in growth illustrating the importance of water as limiting factor of growth (Aerts et al., 2002; Timofeeva et al., 2017).

In areas with high climate variability and severe environmental degradation (e.g. loss of soil), irrigation is an important alternative to increase seedling regeneration, survival and growth (Messina and Duncan, 1993). Aerts et al. (2006) also show that enrichment planting and natural regeneration in years with sufficient rainfall resulted in enhanced survival of seedlings while mortality of seedlings was very high in years with poor rains.

So far, the effect of exclosures on vegetation growth has been evaluated by comparing with the adjacent open communal land. However, the evaluation of performance of exclosures under different management practices is lacking. For instance, taking inspiration from spate irrigation that is traditionally practiced on croplands with water originating from the Rift Valley escarpment in Ethiopia and nearby Eritrea (Mehari et al., 2008, 2011; Gebrehiwot et al., 2015; Zegeye et al., 2014; Hailemariam et al., 2017), or on forests in outflow plains in countries like Iran (Kowsar et al., 2008), we conceived experiments of diverting stormwater runoff from gullies to exclosures, high up in the catchments. This management technique, hereafter “spate irrigation”, aims to supplement the rain directly falling on the exclosure. The objectives of this study are 1) to evaluate the effect of spate irrigation on species diversity and stocking in irrigated exclosures; 2) to measure the response of tree rings of dominant tree species to spate irrigation in the exclosure; 3) to verify whether exclosures could be used not only to stop producing uncontrolled runoff, but also to absorb additional runoff generated on upslope areas.

5.2 Materials and methods

5.2.1 Study site

The study area (Figure 5.1) is located in the Dogu’a Tembien district, Tigray region, north Ethiopian highlands, ca. 45 km west of Mekelle, capital of the region, specifically in the Geba catchment. Geographically it is located at 13°40' N, 39°14' E at elevations around 2400 m a.s.l. Two exclosures (May Ba’ati and Adi Kolakol) were intentionally selected based on presence of storm water runoff diversion practices to the exclosures (Figure 5.1). Co-author K. Descheemaeker has irrigated the May Ba’ati exclosure in 2005 during the rainy season (July to September). Soil and Water Conservation measures (e.g. trench construction) were also implemented in the exclosures.

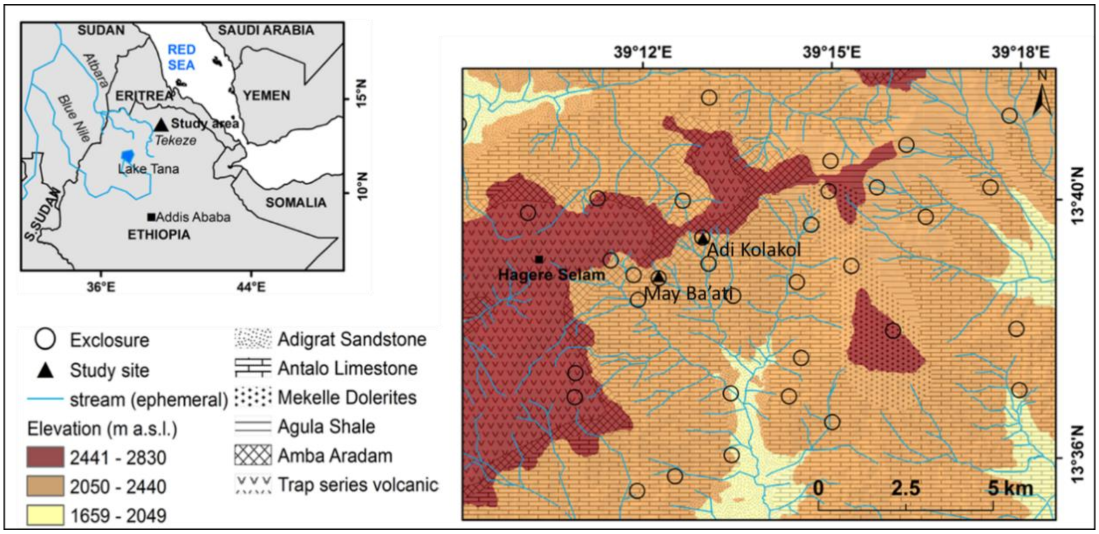


Figure 5.1 Location map with the study sites and surrounding exclosures as well as gullies and ephemeral rivers

The study area is characterized by a short but intense rainy season restricted to mid-July to early September (Nyssen et al., 2005). Annual average precipitation ranges from 550 to 900 mm (Gebresamuel et al., 2010b; Nyssen et al., 2005; Taye et al., 2013b). The precipitation is also characterized by intense showering (Virgo and Munro, 1978) and large drop sizes (Nyssen et al., 2005). Considerable interannual variability of rainfall and severe soil moisture deficit characterize the region. The average monthly air temperature varies between 12 and 19 °C.

The soils of the study area are young due to active erosion and deposition process (HTS, 1976a; Nyssen et al., 2008c; Van de Wauw et al., 2008). Antalo limestone is the dominant lithology in the exclosures (Descheemaeker et al., 2006). The soils are very shallow. Vegetation, particularly shrubland was existing at such sites some 80 years ago (Etefa et al., 2017). It became degraded through time, partly converted into cropland but was exclosed from humans and animals 15 – 30 years ago; forest re-appeared following the last three decades extensive land management activities (Descheemaeker et al., 2006a; Munro et al., 2008a; Nyssen et al., 2004b; Taye et al., 2013b). The dominant species in such areas include *Acacia etbaica*, *Euclea schimperi*, *Dodonaea angustifolia*, and *Maytenus arbutifolia*. Cropland cover is the dominant land use followed by shrubland in the surrounding area (chapter 2). Native forests are restricted to less accessible areas and around churches (Gebru et al., 2009; HTS, 1976a; Munro et al., 2008a).

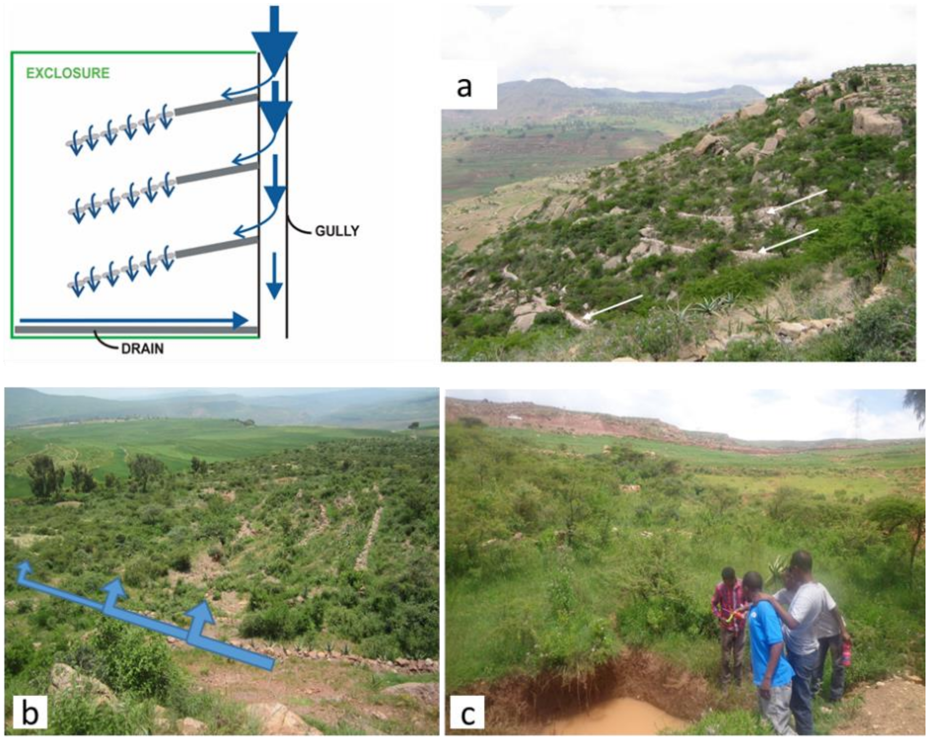


Figure 5.2 Schematic concept of the gully diversion experiment and view of the experimental site with arrows indicating the canals: a) May Ba'ati (Descheemaeker et al., 2009), b) Adi Kolakol, c) Excess runoff collection pit for ground water recharge at Adi Kolakol

5.2.2 Experimental setup

Each of the two exclosures (Adi Kolakol and May Ba'ati) was divided into two blocks; one irrigated by runoff and the other non-irrigated. The source of irrigation water was from stormwater runoff diverted from an adjacent gully into the exclosures (Figure 5.2) to irrigate the exclosures when stormwater runoff occurred. For the Adi Kolakol exclosure, diversion was started in 2012, but monitoring was done from 2014 to 2016 and in May Ba'ati the exclosure was irrigated in 2005. The diversion from the gully to the regenerating forest was done at different locations to enhance even water distribution over the exclosures. Stone bunds constructed in the exclosures for the purpose of soil and water conservation were used as diversion canals, and sometimes reshaped to better allow the flow. The exclosure which was used as control was not supplemented by any runoff other than the direct rainfall. Except for the spate irrigation management all other management activities (e.g. soil and water conservation, enrichment planting, guarding) were the same for both the irrigated and non-irrigated exclosures. Both exclosures are also characterized by the same lithology, and very similar physical and chemical properties of soil, slope gradient and original vegetation type (Table 5.1).

Table 5.1 Biophysical characteristic of the experimental sites

Variables	Adi Kolakol		May Ba'ati	
	Irrigated	Control	Irrigated	Control
Slope gradient **(%)**	9	11	18	23
Soil type	Regosols	regosols	Calcisol	Calcisol
Soil texture	Sandy loam	Sandy loam	Sandy	Sandy
SOM (%)	NA	NA	4.6	4.6
Lithology	Sandstone	Sandstone	Limestone	Limestone
Age of exclosure (year)	20	20	25	25

At May Ba'ati, the gully water was diverted into pair of the exclosure by three diversion structures (Figure 5.2 and 5.3). Canals led the water about 50 to 100 m into the area and stone walls allowed the water to seep through gradually and spread out over the exclosure (Figure 5.2). At the bottom of the exclosure, a cut-off drain served to evacuate the excess water back into the gully (Figure 5.2). The irrigated experimental site is defined as the area comprised between the upper canal and the drain (Figure 5.3) (Descheemaeker et al., 2009).

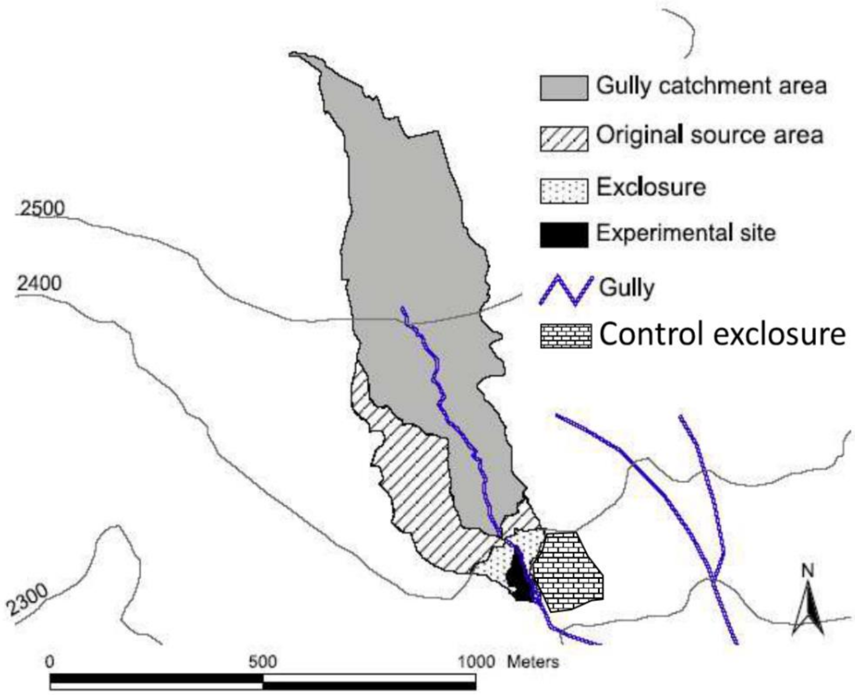


Figure 5.3 Location of May Ba'ati site (Descheemaeker et al., 2009)

5.2.3 Data collection

Monitoring of woody species diversity, density and basal area was done along parallel transect lines for three years (2014 to 2016) in the Adi Kolakol exclosure. The distance between consecutive transect lines was 20 m. Woody species encompasses tree, shrub and liana plant forms. Along these transects, we established permanent quadrats of 5 m x 5 m for monitoring mature trees or shrubs and saplings. Accordingly, 18 plots were established in the 8 ha of irrigated and 13 in the 5 ha of unirrigated exclosure. Within these quadrats data on type of woody plant species, height, diameter at 0.5 m height for mature trees (basal diameter) and diameter at ground surface (collar diameter) for saplings were measured during the monitoring period. Height and diameter were measured using graduated stick and diameter tape. In the centre of each 25 m^2 a quadrat of 3 m x 3 m was established to monitor seedling regeneration. Individual plants were categorized to different stages (mature, sapling and seedling) based on their height and diameter size. Plants whose height is greater than 1.5 m and diameter above 2 cm were categorized as mature, with height from 0.5 to 1.5 m and 0.5 – 2 cm as sapling, otherwise as seedling. Ground cover (grasses) and herbs were not included in this study. Nomenclature was done based on Flora of Ethiopia and Eritrea (Edwards et al., 2000).

To evaluate the response of tree ring increment to spate irrigation, *Acacia etbaica* ring width growth was analyzed as it is the dominant tree species in the exclosures. Stem disc samples from 26 mature trees (diameter > 5 cm), at least one tree from each transect were randomly selected from the two sites (Adi Kolakol and May Ba'ati). The discs were oven dried and transverse sections were sanded using sand paper with grit size ranging from 90 to 400. To improve visibility of the rings, fine wood dusts were removed using compressed air.

Tree ring width was measured in Wood Science laboratory of Wondo Genet College of Forestry using LINTAB™ 5 device that comprises of Leica stereomicroscope and a table connected to a distance-measuring device and a personal computer. Before measuring the ring width, marking of ring growth boundary for all discs was done along three radii using this microscope.

5.3 Data analysis

The different vegetation growth parameters of the Adi Kolakol exclosure were analysed over a three years (2014 – 2016) period. Woody species composition, abundance, relative abundance, frequency and relative frequency in both irrigated and non-irrigated exclosure were derived from the total number of species and individuals encountered in 18 plots in irrigated and in 13 plots in non-irrigated exclosures. Density of woody plants per ha was determined based on the abundance of species observed in the quadrats. The regeneration status and survival of seedlings under different management over the monitoring period were compared by constructing histograms of diameter class distributions. The woody species diversity in both irrigated and control exclosures was estimated using conventional diversity indices: Shannon-Weaver diversity index, Shannon evenness and species richness (Shannon and Weaver, 1962; Kent and Coker, 1992). The similarity between the irrigated and non-irrigated exclosures was analysed using Sørenson's Similarity Coefficient (SSC) (Kent and Coker, 1992).

Shannon Weaver formula (H) = $-\sum_{i=1}^{s}(Pi)(lnPi)$ (1)

Where, s = number of species; Pi = proportion of species i in the community.

Evenness or equitability of species was calculated as the ratio of observed species diversity to the maximum possible number of species in the exclosure (Pielou, 1966). Equitability assumes a value between 0 and 1 with 1 being complete evenness. It is calculated as:

Evenness (J) = H/ Hmax = H/ln S. (2)

Where H is Shannon diversity, S is the number of species in the exclosure

Similarity indices measure the degree to which the species composition of different systems is alike. The Sørensen similarity coefficient is applied to qualitative data and is widely used because it gives more weight to the species that are common to the samples rather than to those occur only in either sample. The Sørensen coefficient of similarity (Ss) is given by the formula:

$$Ss = 2a/(2a+b+c) \quad (3)$$

Where Ss = Sørensen similarity coefficient, a = number of species common to both samples, b = number of species in block 1 only, c = number of species in block 2 only. The coefficient is multiplied by 100 to give a percentage.

The cross-sectional area of all trees whose diameter was measured and total basal area of trees in each exclosure were computed and compared between irrigated and non-irrigated and between different years of the monitoring period.

Cross-dating of tree rings was done until the start of irrigation (i.e. until 2004 for May Ba'ati and until 2012 for Adi Kolakol exclosure) to remove non-climatic variance of tree ring width series. Mean tree ring width curve per sample was produced after pairwise cross-dating of ring width series of multiple radii of the individuals. Extreme wide and narrow rings were used to visually cross-date rings, which helps to correct missing or false ring and provide maximum resemblance between the curves (Gebrekirstos et al., 2008). Mean tree ring width (2005 for May Ba'ati and 2012-16 for Adi Kolakol) was used to compare the effect of irrigation on annual tree ring growth.

5.4 Results

5.4.1 Woody species composition

When entering the exclosures, an overall larger tree stand appeared in May Ba'ati (Figure 5.4a), one year after the irrigation took place. At Adi Kolakol, vegetation is more lush in the irrigated area particularly at beginning and end of the rainy season (Figure 5.4b) and even during the short rains in the spring (Figure 5.5) while vegetation is relatively sparse in the non-irrigated exclosure at Adi Kolakol site (Figure 5.4 d). Even after one decade of the experiment in May Ba'ati, a much lower vegetation cover was observed in the unirrigated exclosure in 2016 (Figure 5.4 c). This overall 'feeling' of positive impact of runoff diversion on vegetation growth has been quantified.

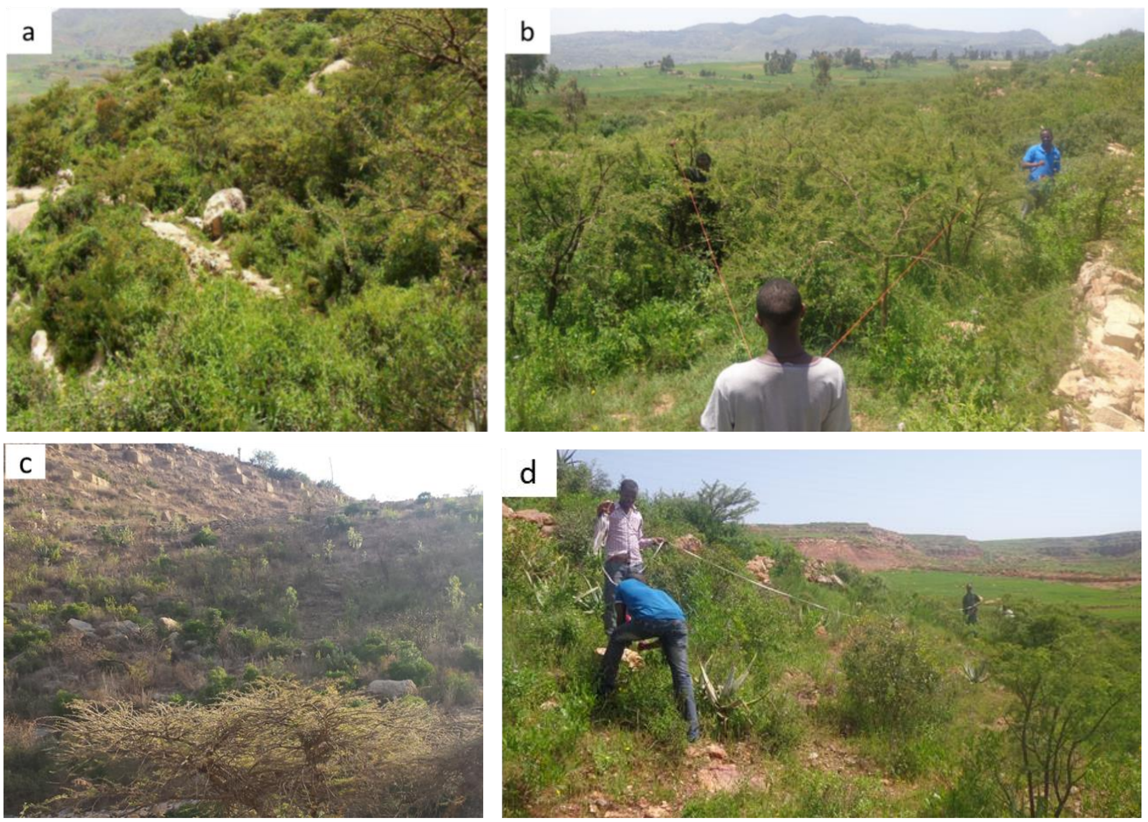


Figure 5.4 The studied exclosures: a) lush vegetation at May Ba'ati in 2006, one year after the experiment (Descheemaeker et al., 2009), b) Adi Kolakol (irrigated

exclosure), its monitoring on September 26, 2014, and control exclosures at: c) May Ba'ati (October, 2016) and d) Adi Kolakol site September 26, 2014.

Figure 5.5 Visual evidence of benefits of spate irrigation on woody vegetation growth in the Adi Kalkwal upland catchment during the short spring rains (16 April 2016): at left in the non-irrigated area and at right in the irrigated area, a few hundred metres apart, from top to bottom: *Becium grandiflorum, Dodonaea angustifolia, Aloe sp., Acacia etbaica*.

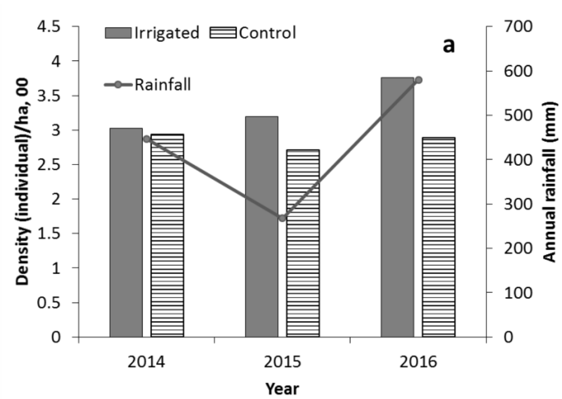
In the irrigated exclosure, 19 to 20 woody species representing 15 families were identified while in the controlled area 16 – 18 species and also representing 15 families were recorded during the study period (Table 5.2). Among these woody species only two species (*Eucalyptus camaldulensis and Acacia saligna*) were exotic while all the others were indigenous plants. In 2014, among the encountered species, 97% were found in both irrigated and non-irrigated and one species, *Acacia abyssinica,* was recorded in irrigated area. In 2015 and 2016 the similarity between two exclosures decreased to 91% and 92% respectively while *Acacia abyssinica, Eucalyptus camaldulensis, Otostegia fruticosa and Psiadia punctulata* were recorded only in the irrigated area. Most families comprised only one species except Fabaceae, Celestraceae and Laminaceae which contained 2 – 3 species. In total, these families constituted 33% – 36% and 43% – 45% of the total species at the irrigated and non-irrigated sites, respectively. Fabaceae is the dominant family followed by Celestraceae and Laminaceae in both areas. More than 90% of the plants recorded are shrubs or shrub/tree life form and one species was climber (Table 5.3). The Shannon-Weaver diversity index and equitability or evenness index results also show variation of species diversity over time and between irrigated and non-irrigated exclosures (Table 5.2).

Table 5.2 Species diversity indices in Adi Kolakol exclosure

	2014		2015		2016	
	Irrigated	Control	Irrigated	Control	Irrigated	Control
Species richness	19	18	19	16	20	17
Density/ha	3022	2933	3200	2711	3756	2889
Shannon-Weaver diversity index (H')	2.4	2.31	2.38	1.94	2.53	2.09
Evenness	0.82	1.84	0.81	1.61	0.84	1.70
Basal area	1.61	1.17	1.93	1.35	2.44	1.56
Sørensen similarity coefficient	97%		91%		92%	

In terms of species abundance, *Acacia etbaica* was the dominant species during the experimental period in both exclosures. This species accounted 23 – 26% at irrigated and 28 –

33% at non-irrigated area followed by *Euclea schimperi and Dodonaea angustifolia*. The relative abundance of *Acacia etbaica, E. schimperi and D. angustifolia* has increased while other species particularly *Acacia saligna* and *Vernonia bipontini* was decreased in the non-irrigated area in 2015 when rainfall was less (Table 5.3). Two species namely (*E. camaldulensis* and *O. fruticosa* observed in 2014 were not encountered in 2015. In the irrigated area, the abundance of most species remained unchanged except for exotic species (*E. camaldulensis* and *A. saligna*) which decreased in the dry year. The relative abundance of some species such as *D. angustifolia, L. abyssinica* and *P. punctulata* has increased during the drought year. In the subsequent year 2016, when there was normal rainfall, the abundance of all species including those decreased or missed in the previous year increased again in both the irrigated and non-irrigated areas (Table 5.3). The result also showed a decline in the density of woody species per ha in 2015 as compared to 2014 in non-irrigated area but an increase in the irrigated exclosure (Figure 5.6). In the subsequent high rainfall year, the density has increased both in the area supplemented by runoff and in the non-irrigated area, but the increase in the irrigated area was about three times that of the non-irrigated area, particularly in the density of plants with diameter class less than 0.5 cm (i.e. seedlings) (Figure 5.6 b). However, the density of plants with diameter class 0.5 to 2 cm was decreased in the irrigated block while it was increased in the non-irrigated exclosure as compared to 2015 (Figure 5.6 b).



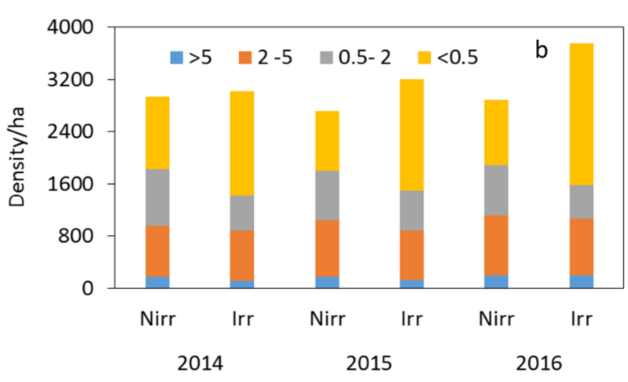


Figure 5.6 Further detail on density of woody species, a) overall density and interannual rainfall variability and b) per diameter class in irrigated (Irr) and non irrigated (Nirr) exclosures at Adi Kolakol. Four diameter classes: >5 cm, 2-5 cm, 0.5-2 cm and < 0.5 cm

Table 5.3 Abundance and density of recorded species in irrigated and non-irrigated areas at Adi Kolakol

Non irrigated exclosure	Family	Life form	2014		2015		2016	
			Abundance /0.045 ha	**Density/ha**	**Abundance /0.045 ha**	**Density /ha**	**Abundance /0.045 ha**	**Density/ha**
Acacia etbaica	*Mimosaceae*	Tree	38	844	40	889	43	956
Euclea schimperi	*Ebenaceae*	Shrub	23	511	26	578	22	489
Dodonaea angustifolia	*Sapindaceae*	Shrub	20	444	22	489	22	489
Maytenus arbutifolia	*Celastraceae*	Shrub	7	156	5	111	5	89
Becium grandiflorum	*Lamiaceae*	Shrub	6	133	5	111	4	111
Clerodendrum myricoides	*Verbenaceae*	Shrub	5	111	4	89	5	133
Hibiscus micranthus	*Malvaceae*	Shrub	5	111	4	89	6	111
Jasminum abyssinicum	*Oleaceae*	Climber	5	111	5	111	5	111
Acacia saligna	*Fabaceae*	Shrub/tree	4	89	1	22	5	67
Vernonia bipontini Vatke	*Asteraceae*	Shrub	4	89	1	44	3	111
Leucas abyssinica	*Lamiaceae*	Shrub	3	67	1	44	1	44
Carissa edulis	*Apocynaceae*	Shrub	2	44	2	44	2	44
Eucalyptus camaldulensis	*Myrtaceae*	Tree	2	44	-	22	1	44
Maytenus senegalensis	*Celastraceae*	Shrub/tree	2	44	2	22	2	22
Osyris quadripartita	*Santalaceae*	Tree	2	44	2	22	2	22
Rhus natalensis	*Anacardiaceae*	Shrub	2	44	1	22	1	22
Asparagus racemosus	*Asparagaceae*	Shrub	1	22	1		1	22
Otostegia fruticosa	*Lamiaceae*	Shrub	1	22	-		-	0
Number of species			**18**		**16**		**17**	
Total			**132**	**2933**	**122**	**2711**	**130**	**2889**

Irrigated exclosure	Family	2014		2015		2016	
		Abundance/0.045 ha	Density/ha	Abundance/0.045 ha	Density/ha	Abundance/0.045 ha	Density/ha
Acacia etbaica	*Mimosaceae*	36	800	37	822	39	867
Euclea schimperi	*Ebenaceae*	25	556	26	578	30	667
Dodonaea angustifolia	*Sapindaceae*	17	378	21	467	23	511
Maytenus arbutifolia	*Celastraceae*	12	267	13	289	15	333
Leucas abyssinica	*Lamiaceae*	3	67	5	111	7	156
Becium grandiflorum	*Lamiaceae*	3	67	3	67	4	89
Jasminum abyssinicum	*Oleaceae*	4	89	4	89	6	133
Eucalyptus camaldulensis	*Myrtaceae*	4	89	3	67	4	89
Rhus natalensis	*Anacardiaceae*	5	111	5	111	5	111
Acacia saligna	*Fabaceae*	4	89	2	44	7	156
Asparagus racemosus	*Asparagaceae*	2	44	3	67	4	89
Clerodendrum myricoides	*Verbenaceae*	4	89	4	89	2	44
Hibiscus micranthus	*Malvaceae*	3	67	3	67	4	89
Carissa edulis	*Apocynaceae*	3	67	3	67	4	89
Maytenus senegalensis	*Celastraceae*	3	67	3	67	3	67
Vernonia bipontini	*Asteraceae*	2	44	2	44	3	67
Acacia abyssinica	Fabaceae	2	44	2	44	3	67
Osyris quadripartita	*Santalaceae*	1	22	1	22	2	44
Otostegia fruticosa	*Lamiaceae*	3	67	4	89	3	67
Psiadia punctulata	*Asteraceae*	-	-	-	-	1	22
Number of species			**19**		**19**		**20**
Total		**136**	**3022**	**144**	**3200**	**169**	**3756**

5.4.2 Effect of spate irrigation on tree ring growth

We compared ring width growth of trees grown under the normal condition (control) and application of spate irrigation to supplement direct rainfall in the exclosures. The history of annual ring widths of sample trees before the intervention (irrigation) was analyzed for each exclosure at two sites.

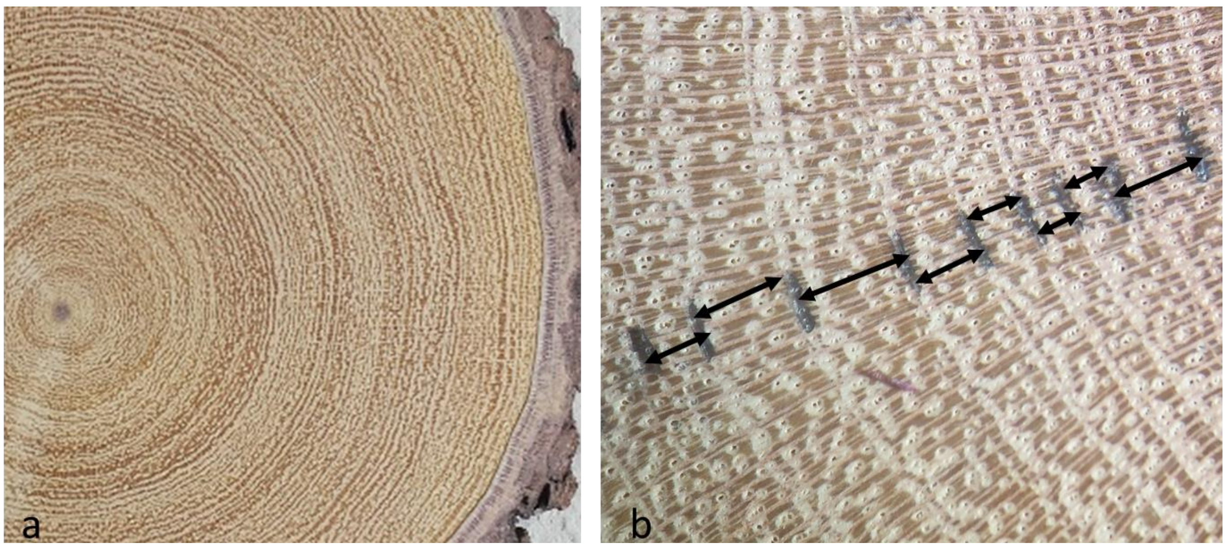


Figure 5.7 a) Example of sample disc cross-section of *Acacia etbaica* tree, and b) its ring width variability in different years. The sample belongs to the May Ba'ati site.

The result shows that all sampled *A. etbaica* trees form distinct tree ring boundaries (Figure 5.7) although variability in mean ring width in each exclosures and sites were measured. The variability in annual mean ring width of sample trees per exclosure indicates that there was no exclosure in which trees were always growing better than trees in the other exclosure until the time of intervention (i.e. 2004 in May Ba'ati and 2013 in Adi Kolakol sites) (Figure 5.8). But as of the irrigation year the overall ring width growth of trees in the irrigated area was enhanced as compared to the non-irrigated area both in the May Ba'ati and Adi Kolakol sites. The relationship between tree ring width growth and direct rainfall is illustrated in which strong correlations were observed between ring width and rainfall in both Adi Kolako and May Ba'ati site (Figure 5.9). During the intervention period (2012-2016) in Adi Kolakol, ring width of individual trees with means of 1.58 (±0.60) mm in the irrigated and 1.38 (±0.61) mm in the control exclosure (Table 5.4). Likewise, in May Ba'ati variable ring width growth was measured between individual trees after irrigation. with means of 1.82 (±0.84) mm in the irrigated and 1.58 (± 0.71) mm in the non-irrigated block (Table 5.4).As of the year of irrigation, tree rings are wider in the irrigated exclosure, an effect that lasts for about 6 years after applying irrigation at May Ba'ati site. Noteworthy, comparisons of the average ring width in the control exclosures before and after intervention show larger ring width before intervention in both sites: Adi Kolakul site: 1.67 (±0.26) mm (before) and 1.50 (±0.64) mm (after); May Ba'ti site: 1.41 (±0.20) mm (before) and 1.40 (±0.43) mm (after).

Table 5.4 Summary of ring width growth (mm) of *Acacia etbaica* in Adi Kolakol (2012 -2016) and May Ba'ati (2005) sites

	Irrigated				Non-irrigated			
Site	Min	Max	Average	n	Min	Max	Average	n
Adi Kolakol	0.46	2.36	1.58 (0.60)	8	0.52	1.73	1.38 (0.61)	6
May Ba'ati	0.87	3.2	1.82 (0.84)	6	0.68	2.55	1.58 (0.71)	7

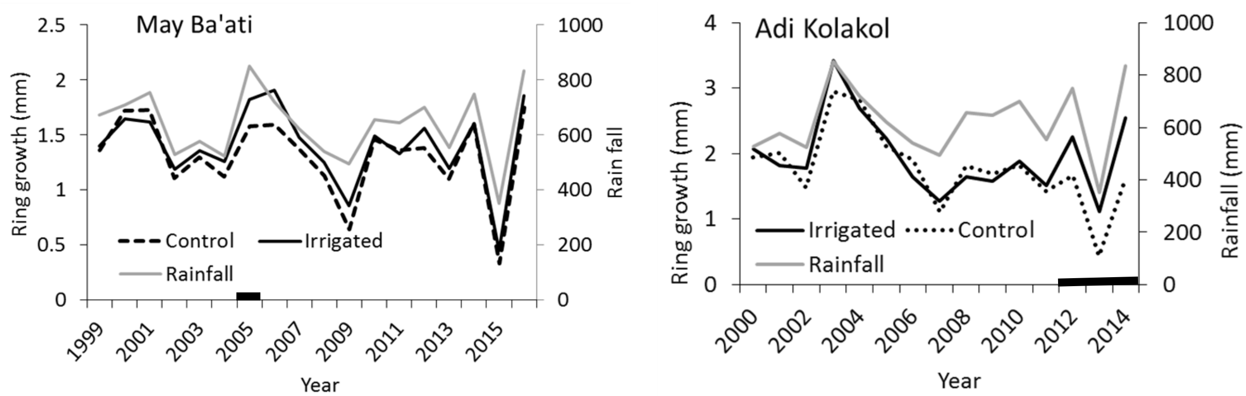


Figure 5.8 Ring width growth of *A. etbaica* at May Ba'ati and Adi Kolakol sites. Each line represents the average of 6-8 stem disks. Period of irrigation is indicated with a thick bar on the horizontal axis.

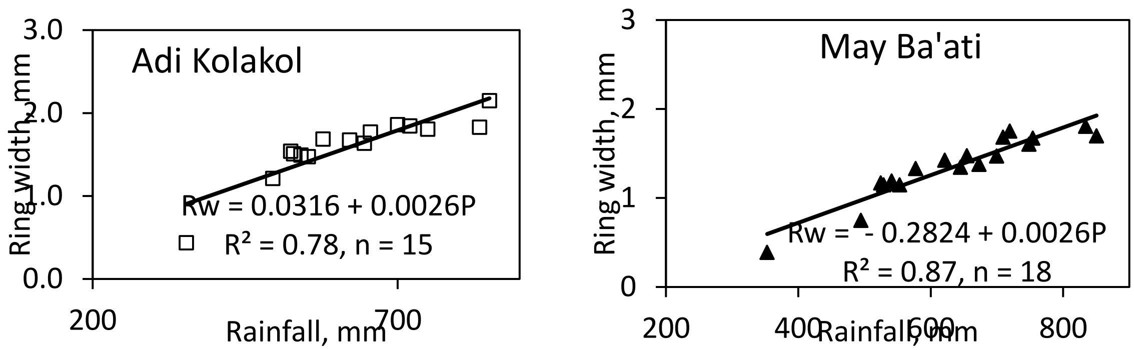


Figure 5.9 Relationship between average tree ring width growth of both irrigated and control exclosures and rainfall in Adi Kolakol (2000-2016) and May Ba'ati (1998-2016) sites. Rw = ring width, P = rainfall

5.4.3 Impacts on the water balance

In May Ba'ati, assuming that a runoff coefficient of 45 % for the gully catchment is applicable throughout the year, it was calculated (Descheemaeker et al., 2009) that 79 10^3 m^3 water was exported through the gully in 2005. The volume runoff diverted in to the exclosure at the inlet canals and of the outflow of excess runoff in the cut-off drain were measured using v-notches in the canals. The gully diversion tapped some of the gully runoff, which resulted in 1117 mm or 4.7 10^3 m^3 additional infiltration in the exclosure. The gully diversion was thus responsible for the alternative allocation of 6% of the total water yield of the upper catchment. The additional infiltration resulted in 262 mm or 1.1 10^3 m^3 additional evapotranspiration and 851 mm or 3.6 10^3 m^3 additional deep percolation (Descheemaeker et al., 2009).

In Adi Kolakol, the exclosure is located closer to the main water divide, hence the adjacent gully drains a smaller discharge from 21 ha of drainage area and about half of the runoff water could be allocated to the spate irrigated exclosure (8 ha). During the experimental period, the annual rainfall that the exclosure has received ranged from 353 to 834 mm or 2824 to 6672 m^3 per year. By assuming 45% runoff coefficient, a total annual runoff volume of 3707 to 8757 m^3 $year^{-1}$ drained from the contributing area has supplemented the irrigated exclosure, resulting in 463-1094 mm yr^{-1} additional water application.

5.5 Discussion

5.5.1 Species diversity, composition and density

Species diversity indices show that there is variability in species diversity between irrigated and non-irrigated exclosures. In terms of species richness virtually equal number and type of species were recorded in both irrigated and control exclosures (Table 5.2). This is not surprising due to the fact that the management history, climate and topography are alike in both exclosures. There is high probability that the seeds come from the same source for both exclosures. It would be also very early to see the effect of irrigation on species richness after three years of experimentation only. The larger Shannon diversity in the irrigated area than in the control area is related to the increase in the abundance of individual species. Gully water diverted in to the exclosure could has likely contributed to the survival of seedlings which increased abundance. The magnitude of increase or decrease of species diversity is variable between irrigated and non-irrigated exclosures and within exclosures in different years. In 2015, when there was shortage of rainfall as compared to 2014, decrease in species richness, Shannon diversity index, equitability index and tree density was greater in the control plot whereas the change was negligible or there was even an increase in the intervened area. During this year density of trees per ha was decreased in the control area by about 7.5% from 2933 individuals in 2014 to 2711 individuals in 2015 probably linked to high mortality of seedlings and even saplings because of lack of sufficient water (Table 5.2, Figure 5.6 a and b). In contrary, during the same year, in the spate irrigated area, tree density has increased by 5% from 3022 individuals to 3200 individuals. The small changes in the density of mature plants and remarkable change in seedling density (Figure 5.6 b) can be explained by the slow change in diameter classes due to slow growth of plants although many seedlings are regenerated in the rainy season mainly when there is high rainfall. This clearly indicates the advantage of spate irrigation to exclosures in supplementing direct rainwater especially in the dry season. The decrease of density of saplings in 2016 in the irrigated area could be due to the lack of new saplings when some of the old ones changed to higher diameter class (greater than 2 cm). The survival of plants (mainly seedlings) by gully water diversion during insufficient rain indicates that the technique is very useful for resilience to short rain or drought. The effect of spate irrigation on vegetation in exclosures was also perceived when short rains came during the dry season particularly on plant phenology: plants in the area with spate irrigation were bearing leafs and flowers while plants in the control area were relatively dormant (Figure 5.10).

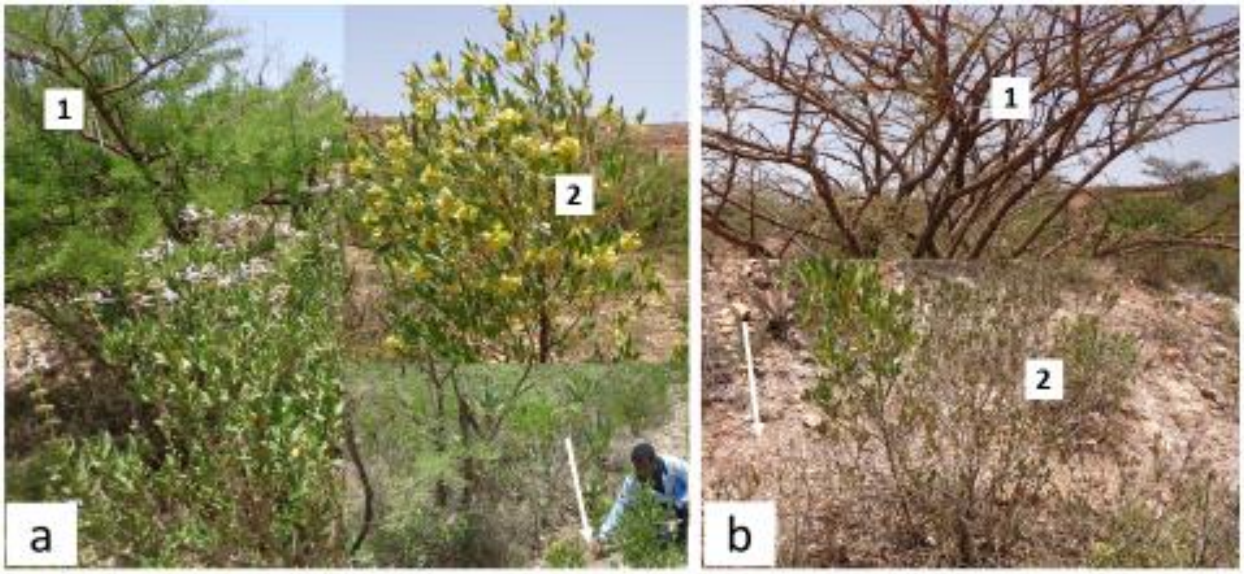


Figure 5.10 Effect of short rain during dry season (16 April 2016) on phenology of plants: a) irrigated area, b) control or non-irrigated exclosure; 1) *A. etbaica* tree with leaf in irrigated and without leaves in non-irrigated, 2) *D. angustifolia* plant with flower in irrigated but dormant in control. The soil was wet (indicated by arrow) in the irrigated exclosure while it was dry in the non-irrigated after few days of raining in the dry season.

5.5.2 Ring width growth

The results of our experiments show that the application of spate irrigation to exclosures has brought a positive effect on ring width growth of *A. etbaica* tree. When compared to the years before intervention, the mean ring width of trees under irrigation was found to be larger by 15% (May Ba'ati) and by 22% (Adi Kolakol) than the mean ring width in the control exclosure. The result also shows that in May Ba'ti the growth of ring width in the irrigated area continued in the subsequent years, even increased in 2006 as compared to the control area and it took some eight years for the rate to ring growth to stabilize at the same level as that for the non-irrigated area. The straightforward explanation for the increment of ring width growth is the additional rain water input diverted from the gully. Another reason for the increased ring width of trees under irrigated area could be the sediments and nutrients brought by the runoff and deported in the exclosure. However, the comparison of growth ring within the irrigated exclosure, before and after spate irrigation, showed larger growth before intervention in both sites. This can be explained by the fact that plants grow faster during their early age as compared to their late age. The rainfall differences before and after irrigation (e.g. drought in 2015) might have also contributed to the larger growth of rings before the spate irrigation.

5.5.3 Hydrological impacts

The impact of spate irrigation on exclosures leads not only to a boost for woody biomass and biodiversity, but also to an important abstraction of runoff; particularly during the peak rainy season when there is excess water in Geba catchment, that cannot be used for crop irrigation, spate irrigation on woody vegetation can be an important buffer for peak discharges and if largely applied, it can reduce floods in the downstream areas. Our experiments show that on average, exclosures on slopes with gradients up to 20 % can absorb 778 mm of spate irrigation water depth annually, in addition to the rainfall. A rough calculation shows that if exclosures in 1% of the area of Geba catchment (51.42 km^2 out of 5142 km^2) are treated with spate irrigation, a total volume of 39.9 10^6 m^3 runoff water could be abstracted annually, which is 9.88% of the average annual storm runoff volume of 403.84 10^6 m^3 at Geba outlet (Chapter 6). Technically, it is also important to stress that the spate irrigation was only installed more than a decade after the establishment of the exclosures, and that physical runoff interception structures were present, so that the existing vegetation could resist well against additional floods onto the area.

5.6 Conclusion

The impact of diverting runoff on vegetation growth in exclosures has been evaluated based on the analysis of different vegetation growth indices. The magnitude of increase or decrease of species diversity is variable between irrigated and non-irrigated exclosures and within exclosures in different years. Different indices showed that species diversity is increased in irrigated areas as compared to non-irrigated areas in the Adi Kolakol site. Overall 16-18 and 18-19 species were recorded in control and irrigated area, respectively, during the experimental period (2014-2016). Water diverted into the exclosure could subsidize the soil moisture what lead to increased survival of seedlings as compared to the control area. The survival of plants (mainly seedlings) by gully water diversion during years with insufficient precipitation could encourage the implementation of gully water diversion so that the exclosure would be more resilience to short rain or drought. Spate irrigation positively affects vegetation growth even during the occurrence of small rainfall in the dry season. Plant phenology variation between trees in control and irrigated area can be also an excellent indicator of the effect of extra water on vegetation growth in exclosures. Furthermore, tree ring width growth analysis exhibits the role of additional water to vegetation growth: diverting runoff into exclosures results in 15%

to 22% increase in ring width as compared to non-irrigated trees. Besides increased biomass and biodiversity, the spate irrigation leads also to strong abstraction of runoff that protects downstream areas from flooding, and gullies from expanding. In contrast to farm crops, spate irrigation on woody vegetation is less demanding in terms of regularity and volumes of available storm runoff. In addition to the promotion of forestry in washout areas of existing spate irrigation systems (Van Steenbergen et al., 2011), we suggest to apply spate irrigation on exclosures in the uppermost parts of the catchments, wherever the topography allows diverting runoff from gullies into exclosures.

5.7 References

Aerts R, November E, Behailu M, Deckers J, Hermy M, Muys B. 2002. Forest rehabilitation: one approach to water conservation in Central Tigray. Ethiopian Journal of Water Science and Technology 6: 34-37.

Aerts R, Van Overtveld K, Mitiku H, Hermy M, Deckers J, Muys B. 2006. Species composition and diversity of small Afromontane forest fragments in northern Ethiopia. Plant Ecol. 187:127-142.

Aynekulu E, Denich M, Tsegaye D. 2009. Regeneration Response of *Juniperus procera* and *Olea europaea* subsp cuspidata to Exclosure in a Dry Afromontane Forest in Northern Ethiopia. Mountain Research and Development, 29(2):143-152

Beltrando G, Camberlin C. 1993. Interannual variability of rainfall in the eastern horn of Africa and indicators of atmospheric circulation. International Journal of Climatology, 13(5): 533–546

Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B, Deckers S. 2006. Runoff on slopes with restoring vegetation: a case study from the Tigray highlands, Ethiopia. J Hydrol 331(1): 219-241.

Descheemaeker K, Nyssen J, Poesen J, Raes D , Terryn L, Mitiku Haile, Muys B, De Baets S, Deckers J. 2009. Water harvesting and sediment trapping in exclosures: a gully diversion experiment in the Tigray Highlands, Ethiopia. Geophysical Research Abstracts, EGU General Assembly 2009, EGU2009-1626, Vol. 11.

Edwards S, Mesfin T, Sebsebe D, Hedberg I. 2000. Flora of Ethiopia and Eritrea, vol. 2. Part 1. The National Herbarium. Addis Abeba University/Department of Systematic Botany, Uppsala University, Addis Ababa/Uppsala, 532 pp.

Emiru B, Demel T, Barklund P. 2007. Enclosures to enhance woody species diversity in the dry lands of eastern Tigray, Ethiopia. East African Journal of Sciences. 1 (2): 136-147.

Gebrekirstos A, Mitlöhner R, Teketay D, Worbes M. 2008. Climate–growth relationships of the dominant tree species from semi-arid savanna woodland in Ethiopia. Trees 22, 631-641.

Gebresamuel G, Singh BR, Dick, Ø. 2010. Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. Acta Agriculturae Scandinavica Section B–Soil and Plant Science 60, 211-226.

Gebrehiwot KA, Haile AM, De Fraiture CM, Chukalla AD, Tesfalem GE. 2015. Optimizing Flood and Sediment Management of Spate Irrigation in Aba'ala Plains. Water Resources Management 29: 833-847.

Gebru T, Eshetu Z, Huang Y, Woldemariam T, Strong N, Umer M, DiBlasi M, Terwilliger VJ. 2009. Holocene palaeovegetation of the Tigray Plateau in northern Ethiopia from charcoal and stable organic carbon isotopic analyses of gully sediments. Palaeogeography, Palaeoclimatology, Palaeoecology 282, 67-80.

Hailemariam Meaza, Frankl A, Poesen J, Amanuel Zenebe, Deckers J, Vaneetvelde V, Nyssen J. 2017. Opportunities and challenges of natural resources for rural development in marginal grabens – a state of the art with implications for the rift valley system in Ethiopia. Journal of Arid Environments, in press.

HTS. 1976. Tigrai Rural Development Study (TRDS). Hunting Technical Services Ltd., Borehamwood, UK.

Kent M and Coker P. 1992. Vegetation Description and Analysis: A practical approach. John Wiley & Sons, Chichester, pp. 363.

Kowsar A, Mortazavi M, Niazi AM. 1996. Eight-year performance of Eucalyptus camaldulensis in water spreaders in a sandy desert. Desertification Control Bulletin (UNEP) 29: 35-41.

Mehari A, Schultz B, Depeweg H, Laat PD. 2008. Modelling soil moisture and assessing its impacts on water sharing and crop yield for the Wadi Laba spate irrigation system, Eritrea. Irrigation and Drainage, 57: 41-56.

Mehari A, Van Steenbergen F, Schultz B. 2011. Modernization of spate irrigated agriculture: A new approach. Irrigation and drainage, 60:163-173.

Mekuria W, Aynekulu E. 2011. Exclosure land management for restoration of the soils in degraded communal grazing lands in northern Ethiopia. Land degradation & development, 24 (6): 528–538

Mekuria W, Yami M. 2013. Changes in woody species composition following establishing exclosures on grazing lands in the lowlands of Northern Ethiopia. African Journal of Environmental Science and Technology, 7(1): 30-40

Mengistu T, Teketay D, Hulten H, Yemshaw Y. 2005. The role of enclosures in the recovery of woody vegetation in degraded dryland hillsides of central and northern Ethiopia Journal of Arid Environments, 60: 259–281

Messina MG; Duncan JE. 1993. Irrigation effects on growth and water-use of Quercus virginiana Mill. on a Texas lignite surface-mined site. Agricultural Water Management, 24(4): 265-280.

Mitiku Haile, Kindeya Gebrehiwot. 2001. Local initiatives for planning sustainable natural resources management in Tigray, northern Ethiopia. Ethiopian Journal of Natural Resources 3, 303-326.

Munro RN, Deckers J, Haile M, Grove A, Poesen J, and Nyssen J. 2008. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena 75, 55-64.

Nyssen J, Veyret-Picot M, Poesen J, Moeyersons J, Haile M, Deckers J, Govers G. 2004. The effectiveness of loose rock check dams for gully control in Tigray, northern Ethiopia. Soil Use and Management 20, 55-64.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G. 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology 311, 172-187.

Nyssen J, Poesen J, Moeyersons J, Haile M, Deckers J. 2008. Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands-towards a sediment budget. Earth surface processes and landforms 33, 695-711.

Pielou EC. 1966.The measurement of diversity in different types of biological collections. Journal of Theoretical Biology, 13: 131-144

Shannon CE, W Weaver. 1962. The mathematical theory of com- munication. Univ. Illinois Press, Urbana, Ill.

Taye G, Poesen J, Van Wesemael B, Vanmaercke M, Teka D, Deckers J, Goosse T, Maetens W, Nyssen J, Hallet V. 2013. Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography 34(3): 236-259.

Timofeeva G, Treydte K, Bugmann H, Rigling A, Schaub M, Siegwolf R, Saurer M. 2017. Long-term effects of drought on tree-ring growth and carbon isotope variability in Scots pine in a dry environment. Tree Physiology: 37(8):1-14.

Van de Wauw J, Baert G, Moeyersons J, Nyssen J, De Geyndt K, Taha N, Zenebe A, Poesen J, Deckers J. 2008. Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. Catena 75, 117-127.

Van Steenbergen, F., Haile, A.M., Alemehayu, T., Alamirew, T. and Geleta, Y., 2011. Status and potential of spate irrigation in Ethiopia. Water Resources Management, 25(7), pp.1899-1913.

Virgo K, Munro RN. 1978. Soil and erosion features of the Central Plateau region of Tigrai, Ethiopia. Geoderma 20, 131-157.

Zegeye B, Lijalem D, Kassie A. 2014. Transition from Traditional to Modern Spate Irrigation: The Case in Kobo–Girana Valley, Amhara Region. In Erkossa,T. Hagos, H, & Lefore,N. Potential, development status, and challenges. International Water Management Institute, Colombo, Sri Lanka: 123-136.

6 Catchment runoff response as impacted by land use/cover and soil and water conservation

This chapter is based on:

Etefa G, Frankl A, Descheemaeker K, Taye G, Vanmaercke M, Lemma H, Zenebe A, Poesen J, Nyssen J. 2017. Catchment water budget modeling based on land use/cover and soil and water conservation. In preparation

Abstract

Understanding large scale spatio-temporal effects of land use/cover (LUC) and soil and water conservation (SWC) on hydrology is useful for the strategic catchment management. The objectives of this study are: 1) to analyse the effect of different LUC types and SWC structures on runoff coefficient under actual condition in 2004-07 in ten subcathcments of the basin, and 2) to develop a prediction model under a scenario of "business as usual" (no SWC) and under actual condition in 1935-36 in a semi-arid region through a spatially explicit analysis. A rainfall-runoff prediction model was developed at pixel scale (1.5 km x 1.5 km) based on existing plot scale runoff coefficients, LUC proportions and SWC. The pixel scale runoff depths from different LUC and SWC eventually provided catchment runoff discharges through additive approach and the results were compared with the measured river discharges at river outlets. The results show that different magnitude of runoff was generated per catchment under different conditions. Grazing land, bare and built-up areas have contributed larger runoff (57%) although its aerial cover is only about 24%. The higher runoff was predicted in Lower Tankwa catchment (RC = 25.56%) and Upper Tankwa (RC = 23.17%) while May Gabat (RC = 11.27%) produced lower runoff. The stronger agreement (R^2 = 0.86, $P < 0.001$) between predicted vs observed regression denotes the validity of the conceptual model for prediction of rainfall-runoff in semi-arid mountainous environment. The prediction of scenario under "business as usual" resulted in larger runoff coefficient (RC = 21.18%) as compared to the condition with SWC (RC = 16.86%), which is about 25% increase at overall catchment. Moreover, prediction under actual condition in 1935-36 showed significantly lower runoff (RC = 9.77%) as compared to runoff in 2004-07. The findings of this study confirmed that rainfall-runoff partitioning of a catchment is dependent on the type of LUC class and runoff controlling measures implemented in the catchment. Noteworthy, the prediction of runoff was overestimated as compared to the observed runoff at the outlet of rivers which can be other environmental and socio-economic factors that have not taken into account, errors transferred from interpolation of runoff coefficient and prediction without routing of runoff. Hence, in addition to the current SWC intervention in the study area, further intervention is very important to control runoff particularly in bare and built-up areas.

Keywords: rainfall-runoff, conceptual model, Northern Ethiopia, semi-arid

6.1 Introduction

River discharges in the study area largely depend on Hortonian flows, infiltration excess runoff, which is very common in semi-arid areas such as northern Ethiopia (Descheemaeker et al., 2006, Kang et al., 2001; Martı´nez-Mena et al., 1998). The fraction of rainfall changed to runoff and that reaches river outlets is highly variable in space and time. In dryland regions where scarcity of water is prevalent (rainfall is less than evapotranspiration) for all or part of the year (Kassas, 1995; Mortimore et al., 2009), understanding the water balance of a catchment is very important for catchment management.

The hydrological behaviour, occurrence and intensity of runoff, of semi-arid mountainous catchments is affected by a number of factors such as topography, soils, vegetation, land use, river morphology, structural geology and the spatio-temporal variation of climate (Güntner and Bronstert, 2004). The response of hydrological processes to different land use, cover and management (Eshleman, 2004) was assessed by several studies at different scales that have shown significant alteration of hydrological processes (Table 6.1). The increase of agricultural land at the expense of forest, savannah and natural grass lands has occurred all over the world over longer a period of time (Goldewijk, 2001), which has disrupted the hydrological cycle of drainage basins by changing the water yield of the area. Higher plant biomass such as forests have much higher rates of runoff abstraction than agricultural land leaving less water available for overland flows to streams (Bosch and Hewlett 1982). Increased mean annual discharge of rivers over long time series have been observed due to deforestation although precipitation was not statistically different during the period (Costa et al., 2003; Nugroho et al., 2013). The conversion of rangeland to agricultural land in the dryland ecosystem of US resulted in high recharge of groundwater due to increased infiltration (Scanlon et al., 2005). Plot scale studies in northern Ethiopia also showed higher runoff on rangeland than on cropland (Taye et al., 2013). Descheemaeker et al. (2006) reported that rehabilitation of degraded land with woody vegetation has resulted in significant decline of runoff in semi-arid region of northern Ethiopia.

Table 6.1 Effects of land use/cover (LUC) and management change on water balance components. NA = not available, (-) sign shows decrease while (+) shows increase of runoff. PET = evapotranspiration

Country / catchment	Spatial scale	LUC and SWC	Period (year)	Hydrological component (mean annual) Runoff (%)	PET (%)	Baseflow (%)	Discharge	Source
General (review of different climate)								
Review of different countries	NA	Afforestation of grassland Afforestation of shrub land and grassland	Vary	- 40 - 31	NA	NA	NA	Farley et al., 2005
Review of catchment experiments from all over the world	80 ha (average)	10% decrease in forest cover 10% decrease of hardwoods 10% decrease of brush or grass lands	Vary	NA	NA	NA	+40 mm +25 mm +10 mm	Bosch and Hawlett, 1982
Humid tropical and subtropical climate								
USA/ Mississippi River(Cedar, Illinois, Wabash, & Ohio Rivers)	NA	Increase soybean crop by 17.7% as pasture and perennial vegetation decreased	60	Decreased	Decreased	28 - 134	+9.2% to +102%	Zhang and Schilling, 2006
USA/Raccoon River watershed	NA	Agriculture increase by over 40%	87	NA	Decreased	Increased	Increased	Schilling et al., 2008
Central Brazil /Tocantins Basin	17.53 ha	Agriculture land increased from 30% to 49%	50	NA	-19.87	NA	+24%	Costa et al.,2003
India / Pune	NA	Urban land increase from 5.1% to 10.1% and cropland from 9.7% to 13.5% at the expense of semi-natural vegetation	20	NA	-8.1 to 5.9	NA	+0.03% to +7.6%	Wagner et al., 2013

Arid and semi-arid climate								
China/Heihe River	4.214 x 10^6 ha	Irrigated cultivated land increased by 31 % as the expense of grassland	34	- 27.32		Increased	Increased	
		Cultivated land decreased by 11%	5	+ 8.98				Wang et al., 2007
		Deforestation Reforestation Cropland expansion Cropland abandonment Urban expansion	20^{th} century	NA	+138 mm -422 mm +182 mm -379 mm -98 mm	NA	-138 mm Increased	Liu et al., 2008
China/Loess Plateau	0.1117 ha	SWC	22	-32%	NA	NA	-32%	Huang and Zhang (2004)
		construction of terraces and check-dams	50	NA	NA	NA	-1.14 mm	Zhang et al., 2014
		Construction of check dam	NA	NA	Decreased	NA	NA	Haung et al., 2013
Ethiopia/ Tigray	10 m^2, 28 plots	Afforestation of degraded land	2	Decreased	NA	NA	NA	Descheemaeker et al., 2006
	200 ha	Construction of dry masonry stone bunds and check dams, the abandonment of post-harvest grazing and the establishment of woody vegetation	6	-81	NA	NA	NA	Nyssen et al., 2010
Ethiopia/ Ziway	NA	10% decrease in rainfall 1.5^{0} decrease in temperature Increasing woodland and converting cultivated land	10 10 10	NA	-8% +2.5%	NA	-30% +20% -8%	Legesse et al., 2003

Soil and water conservation (SWC) practices are also another important factor that affects the hydrology of a catchment by altering the major hydrological components, mainly infiltration. For example, a decreased annual surface runoff and stream flow was reported by Huang and Zhang (2004) and Zhang et al. (2014) following the implementation of SWC practices (terrace, pasture, check dam, afforestation) in the Loess Plateau of China. In northern Ethiopia, the effect of different types of soil and water conservation on runoff coefficients have resulted in a smaller runoff coefficients as compared to the non-conserved areas (Taye et al., 2013). Impervious surfaces such as urban land, road and degraded land also alter hydrological processes and consequently the water budget of a basin. Several studies indicated that the increase in impervious surfaces increases storm runoff by reducing infiltration (e.g. Eshleman, 2004; Peters and Rose, 2001; Wijesekara et al., 2012).

Several studies indicate the occurrence of significant changes in LUC in northern Ethiopia at least for the last half century that vegetation declined while degraded land, cropland and built-up areas increased until large scale SWC are implemented in the last decades of 20th century (e.g. Alemayehu et al., 2009; de Mueleraere et al., 2014; Teka et al., 2013; Nyssen et al., 2010). However, the link between of LUC changes and the hydrologic response of large catchments remain unclear. Moreover, knowledge on the effect of massive SWC practices implemented in the region in recent times is also insufficient. The few studies available on runoff response to LUC changes and SWC implementation in northern Ethiopia are limited to plot scales (Descheemaeker et al., 2006; Taye et al., 2013) or small catchments (Nyssen et al., 2010).

Although knowledge on catchment hydrology is useful, the lack of long term data (e.g. river discharge data, meteorological data, soil, land use) is a major challenge for spatial and temporal modelling, model calibration and validation of catchment hydrology in developing countries especially in historical time (McNulty et al., 2016). Analysis of catchment hydrology with the help of appropriate hydrological models allows to understand the impact of LUC change and SWC implementation on the hydrological balance (Legesse et al., 2003; Bahremand et al., 2006; Batelaan and De Smedt, 2007; Wang et al., 2008; Ma et al., 2009; Hosseini et al., 2012). However, model development and calibration to evaluate the effects of land use, cover and management change on the rainfall-runoff partitioning in Northern Ethiopian, particularly in Geba catchment, is lacking. Amanuel et al (2013) have measured river discharges of Geba catchment from 2004-2007 and analysed the link between discharge and different catchment characteristics for the monitoring period. However, this study did not address the response of runoff to the change of LUC and SWC over longer periods. The present study, therefore, aims: 1) to analyse the effect of different LUC types and SWC structures on runoff coefficient in Geba catchment, 2) to develop a scenario of runoff response in the absence of SWC in a semi-arid region through spatially explicit analyses.

6.2 Materials and Methods

6.2.1 Study area

The study area, Geba catchment (Figure 6.1), is located in the Tigray region, North Ethiopian, between 13°16' to 14°15' North and 38°38' to 39°48' East. It covers an area of 5142 km^2 with elevations ranging from about 900 m a.s.l. at southwest to 3300 m a.s.l. near Adigrat in the north. The Geba River is one of the major tributaries of the Tekeze River which finally joins the Atbara River and the Nile in Sudan (Figure 6.1). The major sub catchments of Geba basin include: Suluh, Agula, Genfel, Ilala, May Ambes, May Gabat, Endaselassie, Bershwa, Upper Tankwa, Lower Tankwa and Chamey.

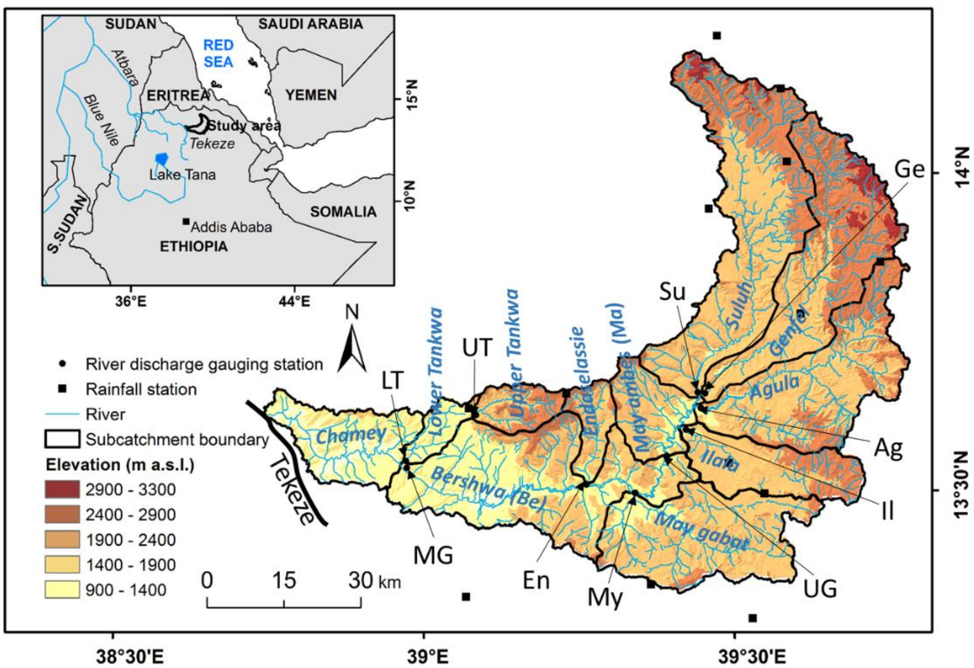


Figure 6.1 Study location showing river discharge gauging stations at the outlet of 10 basins: Suluh (Su), Genfel (Ge), Agula (Ag), Ilala (Il), Upper Geba (UG) (includes Su, Ge, Ag & Ma); May Gabat (My); Endaselassie (En); Middle Geba (MG) (include UG, My, En, Be); Upper Tankwa (UT); Lower Tankwa (LT) (influde UT). Chamey catchment is not part of this study due to lack of observed runoff data.

Geba catchment has a tropical and semi-arid climate with a bi-annual rainfall distribution ("belg" = small rain and "kremt" = main rain season). The main rainy season, which accounts for ca. 80% of the annual precipitation is short, restricted to mid-July - early September, but is characterized by intense showers and large drop sizes (Nyssen et al., 2005)). The rainfall is highly variable with an annual depth between 555 mm and 1200 mm. Annual evapotranspiration depth of the Geba catchment exceeds precipitation depth, except during the rainy season, ranging from 905 mm to 2538 mm. The mean annual maximum average air temperature ranges from 21 to 31 ºC and the mean annual minimum air temperature ranges from 3 to 16 ºC whereas the monthly average varies between 12 and 19 ºC.

6.2.2 Data sources

In the previous chapters the different factors for runoff abstraction in the Geba catchment were analysed. Here, in this chapter, we use these factors in a spatially distributed additive model. The outcomes are contrasted with seasonal discharge in the ten sub-catchments of the Geba catchement reported by Amanuel et al. (2013). Th latter have monitored runoff at the outlets ten sub-catchement (Figure 6.1) from 2004 to 2007 during the rainy season. These data was used to validate our model so that a scenario analysis were also done for the year 1935-36 and for a hypothetic current situation without physical SWC structures and without water harvesting dams. The same average seasonal rainfall depth that was recorded in the rainy season of 2004 to 2007 (when runoff monitoring was also done at the outlet of rivers) was used to analyze the effect of different LUC and SWC on catchment hydrology in 1935-36 and in present time. The rainfall recorded from July 12 to September 10 represents the major part of the summer rainy season (Amanuel et al., 2013). Major elements for which runoff coefficients are available were considered for the partitioning of rainfall. These include vegetation cover (shrubs and forest), cropland with SWC, rangeland with SWC (particularly stone bunds), bare and built-up areas (chapter 2) and abstraction in gullies (with and without check dams) (Etefa et al., 2017) as well as water harvested by micro-dams (Awulachew et al., 2007) (Table 6.3). Hence, existing runoff coefficients for different LUC and SWC (Table 6.2), which were obtained through the experimental research conducted in the study area at plot and gully reach scales were used for partitioning of rainfall at pixel scale.

Table 6.2 Runoff coefficients of different LUC and SWC structures in the study area (average of measured values). VETtot,w = weighted total vegetation, GC = gully with conservation, GNC = gully without conservation.

Factor	Scale	RC or abstraction*	Literature
Woody vegetation cover	10 m^2	RCtot = 165-37.6ln (VETtot, w)	Descheemaeker et al., 2006
Cropland, grazing land, slope, SWC	770 to 100 m^2	0.09 (cropland, SWC) 0.13 (cropland no SWC) 0.32 (grazing land, SWC) 0.43 (grazing land, no SWC	Taye et al., 2013
Check dam with and without vegetation	50 m	GC = 0.1167 GNC = 0.055	Etefa et al., 2017

*Abstraction by gullies with or without conservation

As the LUC maps used for this study contain mixed LUC for every pixel (Chapter 2), the portion of rainfall that is converted into runoff is a function of runoff coefficient and proportion of a LUC class at pixel scale. Based on this logic, rainfall partitioning was calculated successively for the different factors that influence runoff. The proportions of LUC were taken into account to calculate runoff for each pixel. For woody vegetation (forest and shrub), we considered that the vegetation of Geba catchment is characterized by open exclosure, forest and woodland (chapter 2). The dominant canopy cover of these vegetation type is assumed 40% – 65% whose average runoff coefficient is 11% (Descheemaeker et al., 2006). Runoff from vegetation was calculated as:.

$$Q1 = P \times RCveg \times Vp \quad (1)$$

Where Q1 = runoff depth for areas with woody vegetation, P = precipitation, RCveg = runoff coefficient for woody vegetation (%), Vp = vegetation proportion; precipitation and runoff throughout this section is presented in mm.

Table 6.3 Characteristics of sub-catchments of Geba basin for which discharge was monitored. Seasonal rainfall (Ps), seasonal discharge volume (Qs), runoff coefficient (RC). LT include UT; UG includes Su, Au, Ge, Il catchment and MG includes UG, My and En catchments (after Amanuel et al., 2013). RD = reservoir drainage area. See Figure 6.1 for the detail of catchment names.

Catchment	Area (km^2)	Ps (mm)	Qs (10^6 m^3)	RC	Vegetation (%)		Cropland (%)		Grazing land (%)		Bare & built- up (%)		RD area (Km)
			2004-07	**2004-07**	**2014**	**1935**	**2014**	**1935**	**2014**	**1935**	**2014**	**1935**	**2004-07**
Su	969	373	47	13	40	37	39	55	3	4	18	4	9
Ag	692	447	37	12	45	51	38	43	4	4	13	2	18
Ge	733	441	39	12	34	40	42	49	4	4	20	7	74
Il	341	387	18	14	20	36	43	53	8	3	29	8	51
LT	216	561	28	23	32	63	31	26	7	2	30	9	0
My	652	471	28	9	33	48	52	41	3	3	12	8	63
En	121	362	4	10	35	55	49	38	4	2	12	5	0
UT	130	580	14	18	35	68	31	24	5	2	29	6	2
UG	2957	439	143	11	36	43	41	47	5	4	18	6	152
MG	4592	481	177	8	35	49	47	42	4	3	13	6	215
Total	4808	554	205	13	36	50	40	40	5	3	19	7	215

Another partitioning of rainfall into runoff and abstraction occurred on cropland and grazing land with or without SWC. Taye et al. (2013) reported different runoff coefficient for these land uses with different types of SWC structures (stone bund, stone bund with trench and trench) in which the density used in their experiment on cropland ranges from 50 km km^{-2} at level areas to 76 km km^{-2} at steeper slope gradients, with an average density of 63 km km^{-2} and on grazing land they used an average stone bund density 81 km km^{-2} . But the density of stone bunds counted in our study area ranges from 4 km km^{-2} to 42 km km^{-2} with average density of 20 km km^{-2} (chapter 3), which means 1/3 on cropland and 1/4 on grazing land as compared to Taye et al. (2013) . Hence, to fit to the real situation of the study area the runoff coefficients reported by Taye et al. (2013) for cropland and grazing land with stone bunds, were interpolated between the coefficients measured on control plots and those measured for SWC structures (for the details of the calculation see appendix A5-1). Taye et al. (2013) reported a runoff coefficient of 0.09 for cropland with stone bund and 0.13 without stone bund. Similarly, they have reported runoff coefficient of 0.32 for grazing land with stone bunds and 0.43 without stone bunds (Table 6.2). The implementation of stone bunds in all cropland and grazing land is assumed based on the analysis of SWC density (chapter 3) that stone bunds were observed in all observed Google Earth images.

Based on this information runoff generated by cropland with SWC was calculated as:

$$Q2 = P \times RCcrop \times Cp \quad (2)$$

Where, Q2 = runoff from cropland, RCcrop = runoff coefficient of cropland, Cp = cropland proportion

The partitioning of rainfall on grazing land was also calculated using a runoff coefficient interpolated based on Taye et al. (2013) runoff coefficient on grazing land with and without stone bunds:

$$Q3 = P \times RCg \times Gp \quad (3)$$

Where, Q3 = runoff on grazing land, RCg = runoff coefficient of grazing land, Gp = grazing land proportion.

Furthermore, to incorporate the discharge from bare land, degraded areas and built-up areas, a runoff coefficient of 0.8 was assumed.

$$Q4 = P \times RCbb \times BBp \quad (3)$$

Where, Q4 = runoff from bare land and built-up land, RCbb = runoff coefficient for bare and built-up, BBp = Bare and built-up land proportion.

The total runoff from these four land use classes is:

$$Q5 = Q1 + Q2 + Q3 + Q4 \quad (4)$$

The abstraction of runoff in gullies through infiltration was also considered in the calculation of overall runoff coefficients of a pixel. Etefa et al. (2017) have analyzed the effect of gullies with SWC (stabilized) and without SWC (active) on runoff abstraction (see the paper for the detail) which was used to developed infiltration coefficient values for gullies with and without conservation. Average runoff volumes abstracted by gullies with conservation and without conservation were calculated using the average percentage of runoff reduced between the upper and lower section of gully reaches which then normalized for the same amount of water drainage in gullies. According to Etefa et al.(2017), 11.66% of 187 m^3 runoff volume is abstracted in 50 m length of gully reach with soil and water conservation while 5% of 311.5 m^3 runoff of volume is infiltrated in untreated gullies. These infiltration rates are only based on the effect of SWC. This means that an average runoff volume of 21.8 m^3 in gullies with soil and water conservation and 15.57 m^3 in untreated gully is abstracted in 50 m gully reach. If the amount of water infiltrated in untreated gully is normalized on the basis of the average runoff volume at the upper section of treated gully reach, it results in the average infiltration rate of 9.35 m^3. Hence, using 21.8 m^3 of runoff abstracted in treated and 9.35 m^3 in untreated gullies per 50 m, we calculated a coefficient of runoff in gullies with and without SWC which then applied to calculate the total runoff volume abstracted by a given density of runoff as follow: The detail calculation is given in appendix A5-2.

$$Igc = 436\ (m^3) \times \text{gully density (km)} \times \text{runoff of events} \quad (6)$$

Where Igc = Infiltration in gully with conservation at pixel scale

$$Ig = 187\ (m^3) \times \text{gully density (km)} \times \text{runoff of events} \quad (7)$$

Where Ig = Infiltration in gully without conservation at pixel scale

Uncertainty in the calculation of these coefficients and their application at the wide range of the Geba catchment is anticipated as the average infiltration rates were based on few gullies. Etefa et al. (2017) analyzed the infiltration coefficients in gully reaches based on SWC and lithology despite the fact that other factors in a gully and upstream of a gully (e.g. soil characteristics, slope gradient, gully length, gully width, gully age, LUC and size of contributing area, depth and intensity of rainfall, etc) can also determine infiltration rate in gullies. At a large scale, apparently it is difficult to know the degree of variation in gully reach and upstream catchment to estimate an accurate runoff draining to the gullies and infiltration rates in the gullies.

Moreover, abstraction of runoff by water harvesting micro-dams (reservoir) was also considered as a significant number of reservoirs was constructed in the Geba catchment since 1998 (Awulachew et al., 2007). The drainage area of these reservoirs ranges from about 0.72 km^2 to 33 km^2 which yield less annual runoff than the volume of the reservoirs. The situation of the reservoirs during their early years after construction is assumed to be the same to the situation in 2004-07 (no important sediment fill). Hence, as runoff from reservoir drainage area is negligible or zero (Rreservoir = 0), areas equal to the total drainage areas of reservoirs per sub-catchment were excluded from our model.

Finally, runoff discharge at river outlet of each sub-catchment is calculated by water abstracted in gullies and reservoir from the runoff vegetation, cropland with SWC, grazing land with SWC and from bare land and built-up areas.

$$Qe = Q5 – Igc – Ig \quad (6)$$

6.2.3 Data analysis

All input data were processed in raster form with 1.5 km x 1.5 km pixel size, rescaled from the 30 m resolution of DEM-SRTM of the study catchment, which approximately corresponding to the scale of LUC data (4.6 km^2). Runoff from by different LUC with or without SWC was calculated at this pixel size based on the fractional area of each LUC and conservation per pixel.

Total runoff volumes were calculated for ten catchments of the Geba basin for which river discharge data were available (Table 6.3). Runoff coefficients were used in order to calculate runoff response to the different situations of the catchment at different times:

$$RC = (SR/P) \times \%$$

Where RC, SR and P represent runoff coefficient, seasonal runoff and seasonal precipitation, respectively.

RC at catchment scale were compared by using the Kruskal Wallis test. Simple linear regression technique of predicted vs observed was applied to evaluate the model developed (Pineiro et al., 2008). The creation of raster data, calculation of all runoff at pixel scale and extraction to sub-catchment were done in ArcGIS environment.

6.3 Results

6.3.1 Rainfall – runoff partitioning at pixel and catchment scale

Different parameters used for the simulation of runoff from different LUC and SWC were calculated from existing databases (Table 6.4). It should be noted that the interpolation of the runoff coefficients are not error free as in some cases assumptions were made. Due to this, the runoff coefficients of different sub-catchments can be affected (overestimated or underestimated). For example, runoff coefficients for vegetation remains constant throughout all predictions due to the lack of baseline data concerning its ground cover (density). Regarding runoff coefficient of bare and built-up areas, there is no measurement we used as a basis to estimate RC on these land use/cover. But based on our experience that there is no or very few SWC practices on bare and built-up area are existing to abstract large runoff, we assumed about 75% of rainfall can be converted to runoff on bare and built-up areas. . Precipitation values for 2004-07 (Amanuel et al., 2013) are used in all simulations.

Table 6.4 Parameters used in the Geba runoff simulation. RCveg = runoff coefficient from vegetation, RCcrop = runoff coefficient from cropland, RCg = runoff coefficient from grazing land, RCbb = runoff coefficient from bare and built-up areas; RD = reservoir drainage

Scenario	RCveg (eq.1)	RCcrop (eq.2)	RCg (eq.3)	RCbb (eq. 4)	Gully density (km km^{-2})	% gullies conserved	RD area (km^2)
2004-07	0.11	0.1167	0.40	0.75	20	66	217
1935-36	0.11	0.13	0.43	0.75	3	75	0
2004-07 (without SWC)	0.11	0.13	0.43	0.75	20	0	0

The results of this study show that different LUC and SWC have generated different depths of runoff at pixel scale (1.5 km x 1.5 km pixel) (Figure 6.2). The partitioning of rainfall to different losses was analyzed in ten sub catchments of the Geba basin (Figure 6.2 and Table 6.5). Kruskal-Wallis test showed that there is significant differences ($P < 0.001$, $\alpha = 0.05$) in the depth of runoff on different LUC at the pixel scale. In all catchments larger runoff was predicted on bare and builtup lands (62.7 (±28.3) mm) while the least runoff was predicted on grazing land (10 (±5.7) mm). Rank comparisons indicate significant difference between bare land and vegetation, grassland and bare land and cropland and grassland. The comparison of catchments show that highest runoff was simulated at Lower Tankwa (176 mm) followed by Upper Tankwa (168 mm) catchment while Endaselassie catchment generated lower runoff (73 mm) at pixel scale (Figure 6.2). The maps of spatial distribution of runoff from LUC and runoff abstraction by gullies (Figure 6.3) also allow the comparison of depth of runoff generation within and between catchments.

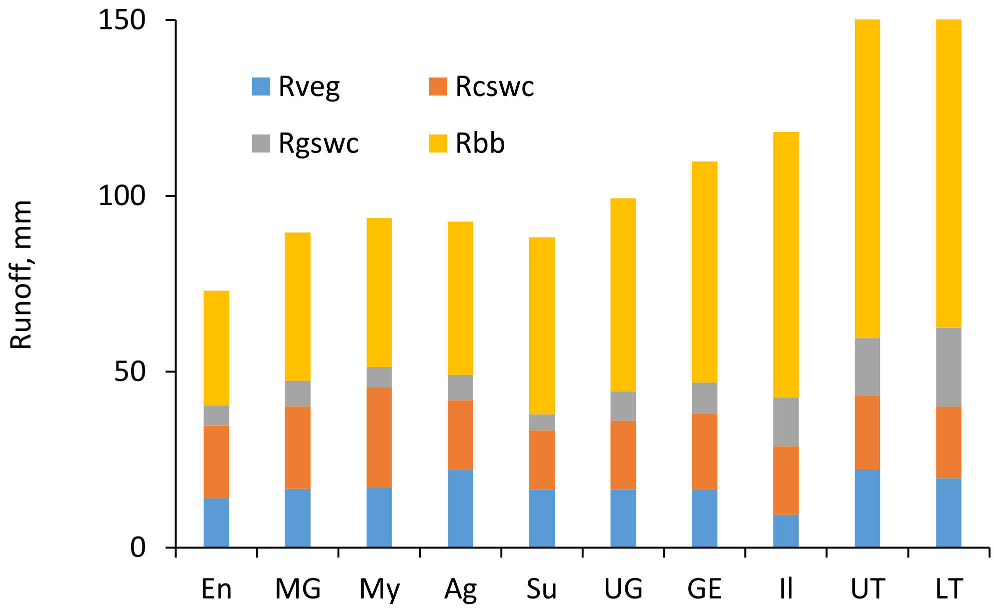


Figure 6.2 Runoff generation from different LUC at pixel scale in 2004-07

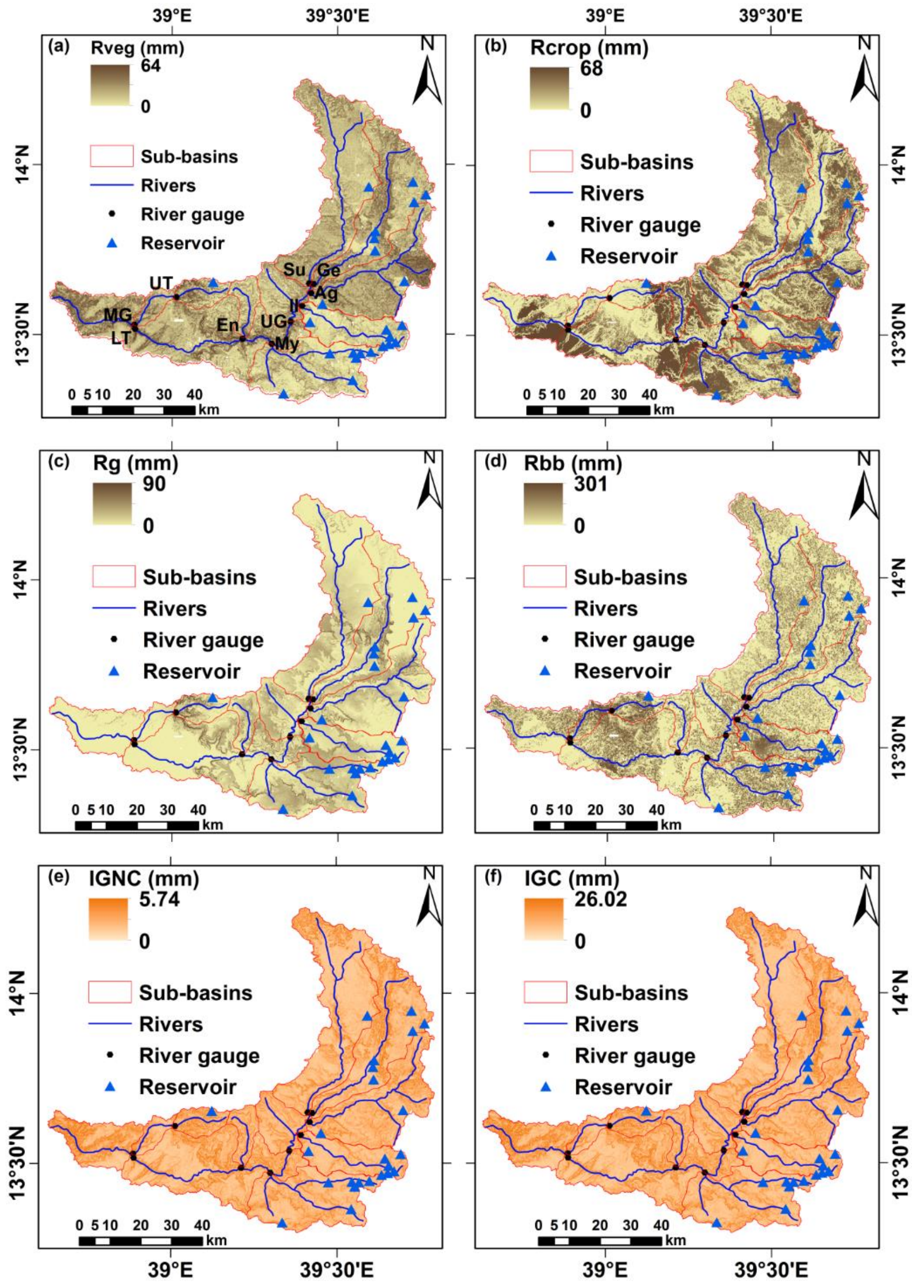


Figure 6.3 Spatial distribution of runoff generation by different land use/cover in 2004-07, a) runoff from vegetated area, b) runoff from cropland, c) runoff from grazing land, d) runoff from bare and built-up areas, e) abstraction in gullies without conservation, and f) abstraction in gullies with conservation.

Table 6.5 Predicted runoff volume on different LUC in ten sub catchments of Geba basin in 2004-07. Runoff after abstraction by: vegetation (Q1), cropland (Q2), grazing land (Q3) and bare and builtu-up area (Q4); abstraction by gully: with conservation (IGC), without conservation (IGNC); total runoff discharge (Q). LT include UT; UG include Su, Ag, Ge, Il and En, while MG include UG and My; RD = Reservoir drainage area. For the detail of catchment names see Figure 6.1.

catchment	Area km2		P mm	Runoff per LUC class (10^6 m^3)				Abstraction (10^6 m^3)		Q (10^6 m^3)	RC %
	Entire catch.	Minus RD		Q1	Q2	Q3	Q4	IGC	IGNC		
Su	969	960	373	15.76	16.30	4.30	48.34	22.74	5.02	56.93	15.9
Ag	692	674	447	14.91	13.36	4.82	29.37	17.37	3.84	41.26	13.7
Ge	733	659	441	10.87	14.24	5.81	41.41	17.38	3.84	51.11	17.59
Il	341	290	387	2.72	5.63	4.04	21.88	8.11	1.79	23.42	20.86
LT	216	216	561	4.27	4.38	4.85	24.54	5.78	1.28	30.98	25.56
My	652	589	471	10.07	16.83	3.33	24.97	19.61	4.33	31.26	11.27
En	121	121	362	1.69	2.50	0.70	3.94	2.28	0.50	6.06	13.82
UT	130	128	580	2.86	2.69	2.08	13.92	3.70	0.82	17.02	23.17
UG	2957	2805	439	45.97	55.18	23.16	154.38	79.70	17.61	199.36	16.19
MG	4592	4377	481	73.26	102.77	31.73	184.24	163.74	36.18	242.09	11.5
Total	4808	4593	454	77.53	107.15	36.58	208.78	34.04	7.52	273.06	16.96 (±4.86)

The runoff from woody vegetation (forest and shrubs), cropland with stone bund, grazing land with stone bund and other mixed LUC (bare land, settlement) is also presented as total runoff volume in each catchment (Table 6.5). Different total runoff discharges calculated in each catchment as Q1 (forest and shrubland), Q2 (cropland), Q3 (grazing land), Q4 (bare and built-up areas) and runoff volume abstracted by gullies with and without conservation based on their respective runoff coefficient and fractional area which eventually provided total runoff discharge per catchment. The prediction clearly shows that bare land and built-up area have generated the highest total runoff volume (208.78 x 10^6 m^3) whereas grazing land generated the least runoff volume (36.58 x 10^6 m^3) from the entire catchment (Table 6.5). Substantial amount of water was abstracted by gullies with check dams (34.04 x 10^6 m^3) where as gullies without conservation abstracted 7.52 x 10^6 m^3 runoff volume across all sub catchments but particularly in the upper Geba catchments. Hence, subtraction of the total volume of water abstracted in gullies with and without check dams from the runoff generated on LUC is important for accurate modeling of catchment hydrology.

In addition, reservoirs constructed in Geba catchment mainly at Upper Geba sub catchments (Su, Ag, Ge and Il) and May Gabat (Figure 6.3) has a large capacity to store rainstorms as their drainage areas are large (9 km^2 to 63 km^2) (Table 6.3) which receive about 14 x 10^6 m^3 seasonal rainfall in total. Hence, the total drainage area of the reservoirs in each catchment were excluded from the model before calculating the runoff generation by LUC at pixel scale.

6.3.2 Runoff model evaluation

Runoff discharges measured at the outlets of ten rivers in 2004 and 2007 during summer rain season (Amanuel et al., 2013) were used to validate our catchment hydrological model. Simple linear regression of predicted vs observed (Figure 6.4) graph showed a strong similarity (R^2 = 86, $P < 0.001$, n = 10) between predicted runoff coefficients and observed runoff coefficient with the mean ratios of predicted to measured runoff coefficient of 1.33 (±0.15) which is not far from 1. The intercept and slope of this model are also fine. The predicted runoff coefficient ranges from 11 at May Gabat to 26 at Lower Tankwa with mean 16.96 (±4.86) while observed runoff coefficient range from 8 to 26 with mean 13 (±4.5). The ratio of predicted to observed runoff coefficient ranges from 8 at Middle Geba to 23 at Lower Tankwa. The results depict that in all catchments runoff discharges predicted are systematically overestimated as compared to the observed data. The RMSE of this model is 4.26, quite a large value, which is about 33 % of the average observed runoff coefficient.

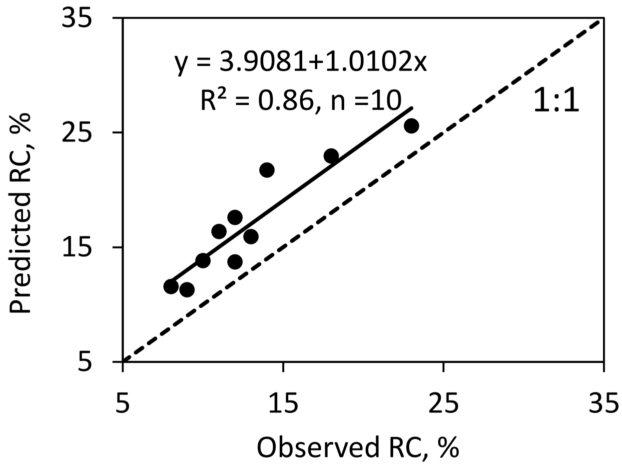


Figure 6.4 Predicted Vs observed runoff coefficient of the study area 2004-07

6.3.3 Prediction back in time (1935-36)

Based on the developed model, prediction of runoff discharge were performed back in time in 1935-36. The prediction shows that during 1935-36 more runoff was generated by vegetation (25.05 mm) followed by cropland (23.92 mm) because these LUC classes occupied a larger area as compared to the other land uses in each catchment (Figure 6.5). In addition, in 1935-36 less SWC (*daget*) (3 km km^{-2}) was practiced on cropland Comparisons among different LUC show that significantly small runoff was generated on grazing land (5.95 mm) than any other LUC. When catchments are compared, Lower Tankwa (100.53 mm) and Upper Tankwa (92.57mm) were generating the largest runoff while the upper Geba catchments were producing lower runoff at the pixel scale (Figure 6.5). Kruskal Wallis test performed between 1935-36 and 2004-07 showed significant temporal variation of runoff in different catchments. The results depicted that the proportion of rainfall converted to runoff discharge (273.06 x 10^6 m^3) in 2004-07 is significantly larger than the portion of rainfall changed to runoff discharge (129.35 x 10^6 m^3) in 1935-36 in the Geba catchment. Average runoff coefficient (9.77 ±2.5%) in the 1935-36 is significantly lower than runoff coefficient (16.96±4.86%) in 2004-07 (Figure 6.6). Over all, the rainstorm that lost as runoff to rivers is increased by more than two times at present time as compared to the earlier time (Table 6.5 and Table 6.6). The dispersion of the runoff coefficient among catchments is less in 1935-36 (SD = 2.5) than at present (SD = 4.86) indicating different intensity of LUC change in different catchment over the last 80 years. During both times, strong positive correlation between runoff coefficients and grazing, bare and built-up areas is observed while cropland area has a negative relation with runoff coefficient.

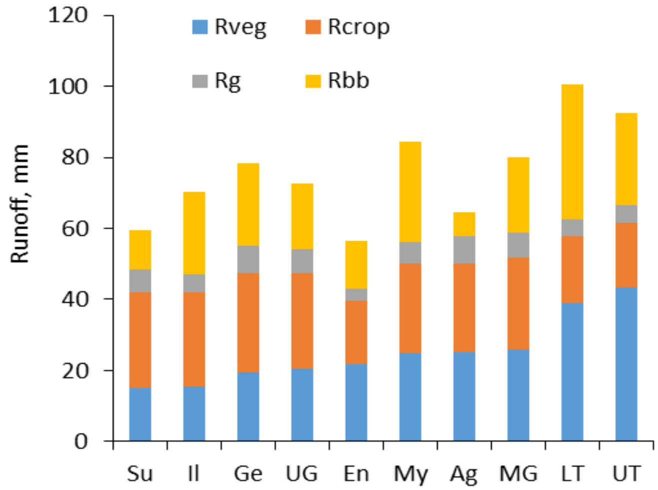


Figure 6.5 Runoff generation from different LUC at pixel scale in 1935-36. For the detail of catchment names see Figure 6.1.

Table 6.6 Runoff discharges by different LUC in 1935-36. Runoff after abstraction by: vegetation (Q1), cropland (Q2), grazing land (Q3) and bare and built-up area (Q4); total runoff discharge (Q); Gv = gully with vegetation, Gv- = gully without vegetation. For the detail of catchment names see Figure 6.1.

Catchment	Area Km^2	P mm	Runoff discharge (10^6 m^3)				Abstraction by gully (10^6 m^3)		Q (10^6 m^3)	RC%
			Q1	Q2	Q3	Q4	Gv	Gv-		
Su	969	373	14.71	25.83	6.21	10.84	21.67	3.10	32.83	9.09
Ag	692	447	17.36	17.30	5.32	4.64	16.49	2.36	25.77	8.33
Ge	734	441	14.25	20.62	5.57	17.00	17.78	2.54	37.12	11.46
Il	341	387	5.23	9.10	1.70	7.93	7.51	1.07	15.38	11.64
LT	216	561	8.40	4.10	1.04	8.18	5.28	0.76	15.68	12.94
My	652	471	16.22	16.37	3.96	18.43	15.59	2.23	37.16	12.10
En	121	362	2.65	2.16	0.38	1.64	2.08	0.30	4.45	10.16
UT	130	580	5.63	2.35	0.65	3.39	3.24	0.46	8.31	11.05
UG	2957	439	60.84	79.33	0.22	21.86	76.82	10.98	74.43	5.73
MG	4592	481	118.82	119.17	0.44	43.81	147.49	21.09	113.67	5.15
Total	4808	454	127.22	123.27	1.48	51.99	152.78	21.84	129.35	9.77 (±2.5)

6.3.4 Scenario prediction without SWC conservation intervention

The model was also applied to simulate a scenario for the effect of current LUC without SWC structures (stone bund, check dams and water harvesting reservoir), "business as usual" on runoff generation. When conservation intervention is excluded from the prediction model, the runoff coefficients are increased in all catchments (Figure 6.6) with an average difference of about 4.22 %. In other expression, the increase of RC under scenario of no SWC range from 13% to 45% with an average of 27% times the actual condition (Figure 6.6).

The scenario prediction under "business as usual", no SWC intervention, shows large increment in runoff coefficient especially on cropland and on grazing land. No change was observed on vegetated and bare and built-up lands as the same conditions to the actual condition were assumed for the simulation of no SWC scenario. Nevertheless, bare and built-up areas remain the most important source of runoff under this scenario (Figure 6.7 and Table 6.7). Overall, runoff volume has increased from 273.06 x 10^6 m^3 (under actual condition) to 403.84 x 10^6 m^3 when simulated under the absence of SWC (Tabel 5 and Table 6.7).

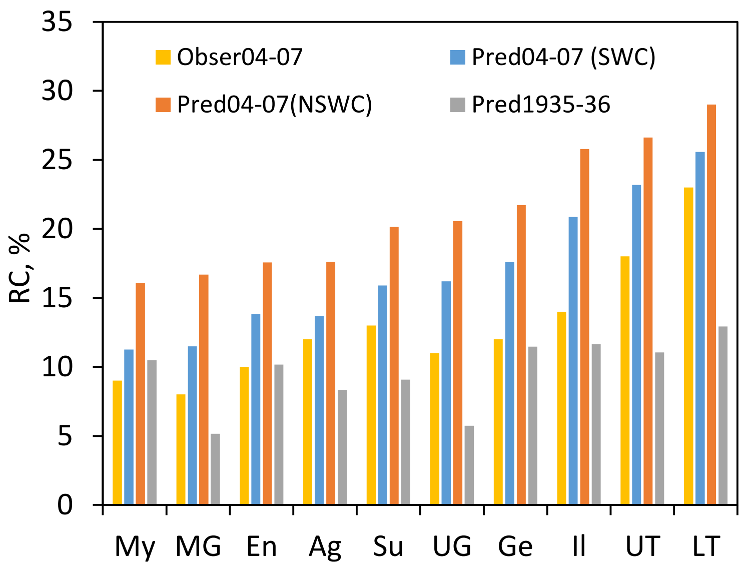


Figure 6.6 Different runoff coefficients (RC%): Observed in 2004-07 (Obser04-07), predicted in 2004-07 in real situation (SWC intervention) (Pred04-07 (SWC), prediction in 2004-07 with the scenario of no SWC intervention (Pred04-07 (NSWC) and prediction in 1935-36 under real situation. For the detail of catchment names see Figure 6.1.

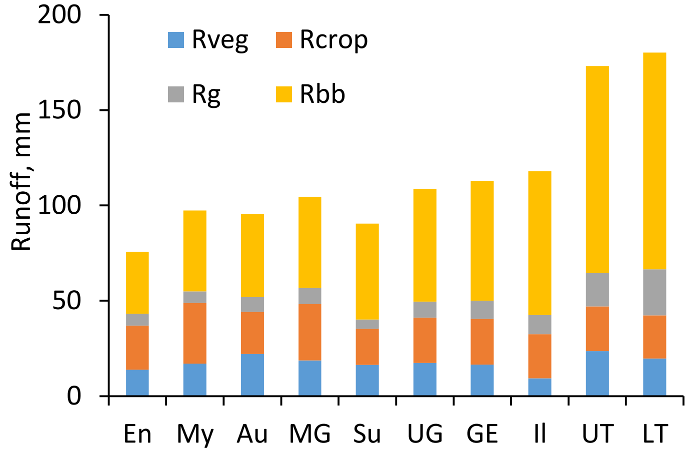


Figure 6.7 Runoff generation from different LUC at pixel scale under business as usual scenario in 2004-07. For the detail of catchment names see Figure 6.1.

Table 6.7 Runoff prediction for the scenario of absence of physical SWC structures in 2004-07. Runoff after abstraction by: vegetation (Q1), cropland (Q2), grazing land (Q3) and bare and built-up area (Q4); abstraction by gully without check dam (IGNC); total runoff of discharge (Q). For the detail of catchment names see Figure 6.1.

Catchment	Area Km^2	P mm	Runoff discharge (10^6 m^3)				IGNC (10^6 m^3)	Q (10^6 m^3)	RC%
			Q1	Q2	Q3	Q4			
Su	969	373	15.90	18.32	4.66	48.78	14.91	72.74	20.13
Ag	692	447	15.32	15.28	5.32	30.17	11.59	54.50	17.61
Ge	734	441	12.11	17.68	6.96	46.14	12.59	70.30	21.71
Il	341	387	3.20	7.90	3.41	25.76	6.21	34.06	25.78
LT	216	561	4.27	4.88	5.21	24.54	3.76	35.14	29.00
My	652	471	11.15	20.76	3.96	27.64	14.11	49.40	16.09
En	121	362	1.69	2.79	0.75	3.94	1.48	7.69	17.56
UT	130	580	3.06	3.03	2.27	14.11	2.44	20.04	26.62
UG	2957	439	51.41	70.21	24.81	175.27	54.61	267.10	20.57
MG	4592	481	86.37	135.40	39.05	219.52	111.64	368.69	16.69
Total	**4808**	**454**	**90.64**	**140.28**	**44.26**	**244.06**	**115.40**	**403.84**	**21.18**

6.4 Discussion

6.4.1 Rainfall – runoff partitioning under actual situation (SWC)

The results of the present study confirm the importance of existing database for the establishment of rainfall-runoff conceptual model for Geba catchment. Despite the lack of empirical runoff coefficient data that can represent the entire Geba catchment which is characterized by heterogenous biophysical elements, existing database on LUC, SWC, runoff measurement at plot scales and river discharge are systematically used to successfully develop the additive rainfall-runoff partitioning model for this catchment. Application of the existing runoff coefficient to the entire catchment was done with the concept of hydrologically similar catchment (similarity as a function of proximity and as a function of similar attributes of catchments) (Bloschl and Sivapalan, 1995) under the condition of lack of local coefficients (Merz et al., 2006).

The use of different LUC, i.e. vegetation (forest and shrubland), cropland with SWC (mainly stone bund), grazing land with stone bund, bare land and built-up area has resulted in generation of significantly different runoff. This is in line to the results of several research carried out on the effect of land use on runoff production (e.g. Defersha and Melesse, 2012; Descheemaeker et al., 2006; Maetens et al., 2012; Taye et al., 2013; Wei et al., 2007). The effect of vegetation cover on runoff is discussed by many researchers that low or insignificant runoff occurs when soil surface cover is high (greater than 65%) (Descheemaeker et al., 2006) and occasionally up to 90% of ground (Kosmas et al., 1997). The higher areal coverage and soil surface cover with vegetation in the study area could have resulted in low runoff generation. The effect of woody vegetation cover on the production of low runoff is explained by its higher interception and infiltration capacity caused by low flow velocity, high organic matter and high surface roughness (Bochet et al., 1998; Huber and Iroume, 2001; Morgan et al., 1986). Cropland is also another important factor affecting rainfall-runoff partitioning as cropland without conservation produces higher runoff than vegetated land (Cosmas et al., 1997) whereas cropland conservation structures generate lower runoff (Taye et al., 2013). In the present study where cropland has a high density of conservation structures (20 km km^{-2} (chapter 3) high rate of infiltration is expected allowing only about 11.67% of rainfall to be converted to runoff. Vancampenhout et al. (2006) found high moisture availability closer to stone bunds as compared to locations relatively far from the stone bunds in cropland confirming its effect on infiltration. Valentine et al. (2008) have also reported about the effectiveness of different SWC in reducing runoff not only at plot scale but also at catchment scale. The higher fraction of aerial coverage of cropland in the Geba catchment (Table 6.3) with an average percentage of 42% in 2014 (chapter 2), combined with massive SWC structures have resulted in lower runoff production in each sub catchment of the Geba basin. Although the overall fraction of grazing land, bare and built-up area is smaller than vegetation and cropland, they have produced significantly higher runoff per catchment as compared to vegetation and cropland. Overall, 57% of all runoff comes from grazing land, bare land and built-up areas that makes only circa 24 percent of the basin. This is in line with several research reports (e.g. Defersha and Melesse, 2012; Descheemaeker et al., 2006; Taye et al., 2013). The higher runoff from non-vegetated and cropland can be explained by low vegetation cover of the ground that allow interception and infiltration of runoff. The different magnitude of runoff generation from different land use and catchment is worthwhile in identifying the hotspot areas where immediate conservation or runoff control is required. Beside the effect of LUC, the measurement of effect of gullies with and without check dam on runoff reduction showed that large volume of discharge was abstracted by gullies especially in the conserved gullies which implies the importance of taking into account of gullies for water budget prediction model development. Construction of check dam in gullies reduces runoff by increasing infiltration rate of water in gullies as it obstacles the flows which decrease velocity and increase retention time of water (Etefa et al., 2017; Hassalni et al., 2009; Polyakov et al., 2014).

The summarized result of infiltration excess of rainfall on different LUC and subtraction of abstracted runoff in gullies with and without check dams at catchment scale represent the output of the conceptual model developed in the present study. Regression of runoff coefficient showed strong agreement between the predicted and observed runoff in the Geba catchment. This implies the usefulness of this model to apply for prediction of seasonal runoff generation in similar environment, semi-arid mountainous catchment. The good fit of this model also allows to strengthen confidence in the empirically obtained data on efficiency of biological and physical SWC during intense field campaigns (Descheemaeker et al., 2006; Taye et al., 2013; Etefa et al., 2017). However, the RMSE (4.26) of this model indicates the overestimation of runoff hence describing the model uncertainity in the prediction of runoff. Different explanations can be given for the larger error of this model.It is important to note that this model is developed to simulate runoff at pixel scale and the summation of pixel values is assumed as total runoff discharge at the outlet of a basin without taking into account the effect of routing, hence transmission loss of water on the way to the outlet of the rivers was ignored. Another reason for the overestimation of runoff can be linked to the errors of databases used for the development of the model. The point count and mapping errors of LUC and the interpolation of runoff coefficients in which assumptions were used in some cases could have affected the uncertainity of the model. For example, runoff coefficient of bare and built-up area were assumed as there was no measured data available to interpolate runoff coefficient for these LUC and we have probably exaggrated this coefficient. The biased estimation of runoff can be also associated with the error of observed data that in some runoff monitoring stations (e.g. Upper Tankwa and Middle Geba) there was gap of recording due to the destroy of divers by major flash floods (Amanuel et al., 2013). In such cases, crude extrapolations were made to fill the gap in which large errors introduced that might have transfered to our model. Moreover, although LUC and SWC are believed to be the most important factor to determine runoff coefficient, other elements such as lithology, soil type, slope gradient, rainfall intensity might have affected the model accuracy. Given all these problems for the uncertainity of the model, the small values for the intercept and slope of the model equation show the validity of the model. The ratio of predicted to observed which is greater than 1 in all catchment and the intercept of predicted vs observed regression (Figure 6.4) indicate that rescaling (routing) can be applied to the predicted runoff data.

6.4.2 Scenario: prediction under actual situation (1935-36) and without SWC (2004-07)

The prediction of rainfall-runoff partitioning in 1935-36 (past time) resulted in lower runoff coefficient as compared to 2004-07 (current time). This is not surprising as the large fraction (over 50%) of the catchment were covered with vegetation (forest and shrub) in 1935-36 (chapter 2). LUC change is the most important process that determines catchment hydrology by affecting major hydrological components such as infiltration and runoff (Canton et al., 2011; Martínez-Murillo et al., 2011). The higher total runoff from vegetation and cropland in each catchment in 1935-36 is linked to their proportion during past time. Grazing land, bare and built-up area in total constituted about 10% of the land areal coverage in 1935-36 (chapter 2). The increased runoff production in 2004-06 as compared to 1935-36 indicate the significant change of LUC over the last 80 years especially deforestation and expansion of grazing land with sparse vegetation, bare land and built-up areas.

The prediction of runoff under a scenario of absence of SWC in 2004-07 has resulted in higher runoff generation (RC = 21.18%) as compared to the actual condition (with SWC) (RC = 16.96%) in the same years. The increase of runoff coefficient for scenario prediction ranges from 13% to 45% per catchment with an average increase of 27%. The effect of vegetation on runoff generation in the “business as usual scenario” could be underestimated as we did not have (low) vegetation cover under the scenario of “business as usual”. Previous studies have evaluated that the aerial coverage of vegetation especially shrubland has been increased in the Tigray region through the implementation of exclosures to restore degraded land (Aerts et al., 2002; Descheemaeker *et al*., 2006; Mekuria and Aynekulu, 2011).

6.5 Conclusion

The existing database on the effect of LUC and SWC in our study area is very useful for the development of catchment water budget model. Understanding of the actual situations of the study area is required for interpolation of existing runoff coefficients. Different LUC are found to affect rainfall-runoff model as they have variable capacity of abstracting rainstorm falling on a catchment. The degree ground surface cover and proportion of area covered with vegetation account larger fraction of infiltration of rainwater in a catchment. The effect of cropland on the rate of production of runoff is pronounced when combined with SWC structures. Despite small areal coverage by grazing land, bare and built-up area the rate of runoff generated is very high as compared to vegetation and cropland uses particularly in 2004-07.

The conceptual model of catchment hydrology developed to predict runoff at both pixel (1.5 x 1.5 km) and catchment scale is evaluated by using regression technique in which the predicted runoff coefficients showed an agreement with the observed runoff coefficients (R^2 = 86, P<0.001). The RMSE of the model, however, shows large uncertainty of the model that the prediction of runoff result in about 30% overestimation of the observed runoff coefficient which can be explained by data sources, interpolation errors and assumptions made during estimation of runoff coefficients (e.g. bare land and built-up area coefficient, coefficient for runoff abstraction in gullies). All runoff coefficients of predicted runoff are higher than runoff coefficient of observed which can be used to determine routing of runoff at the outlet of the sub basins. Application of the model to simulate water budget in 1935-36 during large proportion of land was covered by vegetation resulted in significantly small runoff coefficient in all catchments of the Geba basin. The “business as usual” scenario prediction, absence of SWC and water harvesting reservoirs, showed 27% increase of runoff when compared to the actual situation prediction in 2004-07. The model is worthy for different programs carried out in the catchments specifically activities that take into account the potential volume of runoff discharges generated from the catchment with different LUC combined with SWC structures.

6.6 References

Aerts R, November E, Behailu M, Deckers J, Hermy M, Muys B. 2002. Forest rehabilitation: one approach to water conservation in Central Tigray. Ethiopian Journal of Water Science and Technology 6: 34-37.

Alemayehu F, Taha N, Nyssen J, Girma A, Zenebe A, Behailu M, Deckers S, Poesen J. 2009. The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). Resources, Conservation and Recycling, 53(4): 192–198.

Amanuel Z. 2009. Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, Northern Ethiopia, PhD thesis, KU Leuven, Belgium.

Amanuel Z, Vanmaercke M, Poesen J, Verstraeten G, Nigussie H, Mitiku H, Kassa A, Deckers F, Nyssen J. 2013. Spatial and temporal variability of river flows in the degraded semi-arid tropical mountains of northern Ethiopia. Zeitschrift für Geomorphologie, 57(2): 143–169.

Awulachew SB, Yilma AD, Loulseged M, Loiskandl W, Ayana M, Alamirew T. 2007. Water Resources and Irrigation Development in Ethiopia. Colombo, Sri Lanka: International Water Management Institute. (Working Paper 123).

Aynekulu E, Denich M, Tsegaye D. 2009. Regeneration Response of *Juniperus procera* and *Olea europaea* subsp cuspidata to Exclosure in a Dry Afromontane Forest in Northern Ethiopia. Mountain Research and Development, 29(2):143-152

Bahremand A, DeSmedt F, Corluy J, Liu YB, Poorova J, Velcicka L, Kunikova E. 2006. WetSpa Model Application for Assessing Reforestation Impacts on Floods in Margecany–Hornad Watershed, Slovakia. Water Resource Management, 21(8): 1373–1391.

Batelaan O, DeSmedt F. 2007. GIS-based recharge estimation by coupling surface–subsurface water balances. Journal of Hydrology, 337: 337– 355.

Bergkamp G. 1998. A hierarchical view of the interactions of runoff and infiltration with vegetation and microtopography in semiarid shrublands. Catena, 33:201–220.

Bloschl G, Sivapalan M. 1995. Scale issues in hydrological modelling: a review. Hydrological Processes, 9: 251–290.

Bochet E, Rubio JL, Poesen J. 1998. Relative efficiency of three representative matorral species in reducing water erosion at the microscale in a semi-arid climate (Valencia, Spain). Geomorphology, 23:139–150.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, 55: 2–23.

Cantón Y, Solé-Benet A, De Vente J, Boix-Fayos C, Calvo-Cases A, Asensio C, Puigdefábregas J. 2011. A review of runoff generation and soil erosion across scales in semiarid south-eastern Spain. Journal of Arid Environments, 75:1254–1261.

Costa MH, Botta A, Cardille JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, 283: 206–217.

Defersha M, Melesse M. 2012. Field-scale investigation of the effect of land use on sediment yield and runoff using runoff plot data and models in the Mara River basin, Kenya. Catena 89:54–64.

de Muelenaere S, Frankl A, Haile M, Poesen J, Deckers J, Munro N, Veraverbeke S, Nyssen J. 2014. Historical landscape photographs for calibration of Landsat land use/cover in the Northern Ethiopian highlands. Land Degradation & Development, 25(4): 319–335.

Descheemaeker K, Nyssen J, Poesen J, Raes D, Mitiku H, Muys B, Deckers S. 2006. Runoff on slopes with restored vegetation: a case study from the semi-arid Tigray highlands, Ethiopia. Journal of Hydrology, 331: 219–241.

Eshleman KN. 2004. Hydrological consequences of land use change: a review of the state-of-science. In: Ecosystems and Land Use Change (R Defries, G Asner, S Houghton, Eds.), pp. 13–29, Geophysical Monograph Series 153, American Geophysical Union, Washington, DC (UMCES Scientific Series No. 3786).

Etefa G, Frankl A, Zenebe A, Poesen J, Nyssen J. 2017. Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. Journal of Hydrology, 545: 299–309.

Farley KA, Jobbagy EG, Jackson RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Global Change Biology, 11: 1565–1576.

Goldewijk KK. 2001. Estimating global land use change over the past 300 years: The HYDE Database. Global Biogeochemical Cycles, 15(2):417–433.

Güntner A, Bronstert A. 2004. Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas. Journal of Hydrology, 297(1): 36–161.

Hassanli AM, Nameghi AE, Beecham S. 2009. Evaluation of the effect of porous check dam location on fine sediment retention (a case study). Environmental monitoring and assessment, 152(1-4): 319–326.

Haung J, Hinokidani O, Yasuda H, ASCE M, Kajikawa Y, Li S. 2013. Effects of the check dam dystem on water redistribution in the Chinese Loess Plateau. Journal of Hydrologic Engineering, 18:929–940.

Hosseini M, Ghafouri AM, Amin MSM, Tabatabaei MR, Goodarzi M, Kolahchi AA. 2012. Effects of land use changes on water balance in Taleghan catchment, Iran. Journal Agricultural Science and Technology, 14: 1159–1172.

Huang M, Zhang L. 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrological Processes, 18: 1885–1898.

Huber A, Iroume A. 2001. Variability of annual rainfall portioning for different sites and forest convers in Chile. Journal of Hydrology, 248: 78–92

Kang S, Zhang L, Song X, Zhang S, Liu X, Liang Y, Zheng S. 2001. Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau of China. Hydrological Processes, 15: 977–988.

Kassas M.1995. Desertification: a general review. Journal of Arid Environments, 30: 115–128.

Kosmas D, Danalatos N, Cammeraat LH, Chabart M. 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena, 29: 45–59.

Legesse D, Vallet-Coulomb C, Gasse F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. Journal of Hydrology, 275: 67–85.

Liu M, Tian H, Chen G, Wei Ren W, Zhang C, Liu J. 2008. Effects of Land-Use and Land-Cover Change on Evapotranspiration and Water Yield in China during 1900-2000. Journal of the American Water Resources Association, 44(5): 1193–1207.

Ma X, Xu J, Luo Y, Aggarwal SP, Li J. 2009. Response of hydrological processes to land-cover and climate changes in Kejie watershed, south-west China. Hydrological processes, 23(8): 1179–1191.

Maetens W, Vanmaercke M, Poesen J, Jankauskas B, Jankauskiene G, Ionita I. 2012. Effects of land use on annual runoff and soil loss in Europe and the Mediterranean: A meta-analysis of plot data. Progress in Physical Geography, 36(5): 599–653

Aerts, R., Maes, W., November, E., Negussie, A., Hermy, M. and Muys, B., 2006. Restoring dry Afromontane forest using bird and nurse plant effects: direct sowing of Olea europaea ssp. cuspidata seeds. Forest Ecology and Management, 230(1): 23-31.

Aerts, R., Van Overtveld, K., November, E., Wassie, A., Abiyu, A., Demissew, S., Daye, D.D., Giday, K., Haile, M. and TewoldeBerhan, S., 2016a. Conservation of the Ethiopian church forests: threats, opportunities and implications for their management. Science of the Total Environment, 551: 404-414.

Aerts, R., Van Overtveld, K., November, E., Wassie, A., Abiyu, A., Demissew, S., Daye, D.D., Giday, K., Haile, M., TewoldeBerhan, S., Teketay, D., Teklehaimanot, Z., Binggeli, P., Deckers, J., Friis, I., Gratzer, G., Hermy, M., Heyn, M., Honnay, O., Paris, M., Sterck, F.J., Muys, B., Bongers, F. and Healey, J.R., 2016b. Conservation of the Ethiopian church forests: Threats, opportunities and implications for their management. Sci Total Environ, 551-552: 404-14.

Alderwish, A.M., 2010. Induced recharge at new dam sites—Sana'a Basin, Yemen. Arabian Journal of Geosciences, 3(3): 283-293.

Alemayehu, F., Taha, N., Nyssen, J., Girma, A., Zenebe, A., Behailu, M., Deckers, S. and Poesen, J., 2009. The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). Resources, Conservation and Recycling, 53(4): 192-198.

Amanuel, Z., 2009a. Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, northern Ethiopia PhD. Thesis, KULeuven University, Belgium.

Amanuel, Z., 2009b. Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, northern Ethiopia, PhD thesis,K.U. Leuven, Belgium.: 374pp.

Amare, T., Zegeye, A.D., Yitaferu, B., Steenhuis, T.S., Hurni, H. and Zeleke, G., 2014. Combined effect of soil bund with biological soil and water conservation measures in the northwestern Ethiopian highlands. Ecohydrology & Hydrobiology, 14(3): 192-199.

Araya, A., Keesstra, S. and Stroosnijder, L., 2010a. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia. Agricultural and Forest Meteorology, 150(7): 1057-1064.

Araya, A., Keesstra, S.D. and Stroosnijder, L., 2010b. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia, Agricultural and Forest Metereology, vol 150, pp 1057-1064.

Asmamaw, L., Mohammed, A. and Lulseged, T., 2011. Land use/cover dynamics and their effects in the Gerado catchment, northeastern Ethiopia. International Journal of Environmental Studies, 68(6): 883-900.

Bard, K.A., Coltorti, M., DiBlasi, M.C., Dramis, F. and Fattovich, R., 2000. The environmental history of Tigray (Northern Ethiopia) in the Middle and Late Holocene: a preliminary outline. African Archaeological Review, 17(2): 65-86.

Belay, K.T., Van Rompaey, A., Poesen, J., Van Bruyssel, S., Deckers, J. and Amare, K., 2015. Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? Land Degradation & Development, 26(7): 680-689.

Bellhouse, D., 1981. Area estimation by point-counting techniques. Biometrics: 303-312.

Betts, H.D., Trustrum, N.A. and Rose, R.C.D., 2003. Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. Earth Surface Processes and Landforms, 28(10): 1043-1058.

Billi, P., 2015. Geomorphological Landscapes of Ethiopia. In: Billi,P (Ed.), Landscapes and Landforms of Ethiopia. University of Ferrara, Ferrara, Italy.: pp 3 - 32.

Bombino, G., Gurnell, A., Tamburino, V., Zema, D. and Zimbone, S., 2009. Adjustments in channel form, sediment calibre and vegetation around check-dams in the headwater reaches of mountain torrents, Calabria, Italy. Earth Surface Processes and Landforms, 34(7): 1011-1021.

Borst, L. and De Haas, S., 2006. Hydrology of sand storage dams: A case study in the Kiindu catchment, Kitui District, Kenya. VU University Amsterdam, Amsterdam, The Netherlands.

Bos, M.G., 1989. Discharge measurement structures. Discharge measurement structures.

Bouma, J. and Dekker, L.W., 1978. A case study on infiltration into dry clay soil I. Morphological observations. Geoderma, 20(1): 27-40.

Brancaccio, L., Calderoni, G., Coltorti, M. and Dramis, F., 1997. Phases of soil erosion during the Holocene in the highlands of Western Tigray (Northern Ethiopia): a preliminary report. In: Bard, K. (Ed.), The environmental history and human ecology of Northern Ethiopia in the Late Holocene. Istituto Universitario Orientale, Napoli, pp. 30– 48.

Brouwer, C., Goffeau, A. and Heibloem, M., 1985. Irrigation Water Management: Training Manual No. 1-Introduction to Irrigation. Food and Agriculture Organization of the United Nations, Rome, Italy.

Byragi, R. and Aregai, M., 2011. Effect of Land Cover Dynamics and the Relative Response to Water Resources in Middle Highland Tigray. Ethiopia: the Case of Areas AroundLaelay-Koraro, 2: 868-873.

Calvo-Cases, A., Boix-Fayos, C. and Imeson, A., 2003. Runoff generation, sediment movement and soil water behaviour on calcareous (limestone) slopes of some Mediterranean environments in southeast Spain. Geomorphology, 50(1): 269-291.

Castillo, V., Mosch, W., García, C.C., Barberá, G., Cano, J.N. and López-Bermúdez, F., 2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). Catena, 70(3): 416-427.

Chen, L., Wei, W., Fu, B. and Lü, Y., 2007. Soil and water conservation on the Loess Plateau in China: review and perspective. Progress in Physical Geography, 31(4): 389-403.

CSA, 2008. Summary and Statistics Report of the 2007 Population and Housing Census. Federal Democratic Republic of Ethiopia Population Census Commission. December 2008, Addis Ababa, Ethiopia.: pp113.

Daniels, R.B., Gamble, E.E., Bartelli, L.J. and Nelson, L.A., 1968. Application of the Point count method to problems of Soil Microbiology. Soil science, 106(2): 149-152.

de Mûelenaere, S., Frankl, A., Mitiku, H., Poesen, J., Deckers, J., Munro, N., Veraverbeke, S. and Nyssen, J., 2014. Historical landscape photographs for calibration of Landsat land use/cover in the northern Ethiopian highlands. Land Degradation & Development, 25: 319-335.

Deasy, C., Titman, A. and Quinton, J.N., 2014. Measurement of flood peak effects as a result of soil and land management, with focus on experimental issues and scale. Journal of environmental management, 132: 304-312.

Deressa, T., Hassan, R.M., Alemu, T., Yesuf, M. and Ringler, C., 2008. Analyzing the determinants of farmers' choice of adaptation methods and perceptions of climate change in the Nile Basin of Ethiopia. Intl Food Policy Res Inst.

Descheemaeker, K., Nyssen, J., Poesen, J., Raes, D., Haile, M., Muys, B. and Deckers, S., 2006a. Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia. Journal of Hydrology, 331(1-2): 219-241.

Descheemaeker, K., Nyssen, J., Rossi, J., Poesen, J., Haile, M., Raes, D., Muys, B., Moeyersons, J. and Deckers, S., 2006b. Sediment deposition and pedogenesis in exclosures in the Tigray highlands, Ethiopia. Geoderma, 132(3-4): 291-314.

Desta, G., Nyssen, J., Poesen, J., Deckers, J., Mitiku, H., Govers, G. and Moeyersons, J., 2005. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray Highlands, northern Ethiopia. Soil Use and Management, 21: 287-297.

Diaz-Ramirez, 2014. Porous Check Dams on Flow Routing and Sediment Transport in Agricultural ditches: A Case Study in the Mississippi Delta.

Emiru, N., Gebrekidan, H. and Tibebe, D., 2012. Analysis of land use/land cover changes in western Ethiopian mixed croplivestock systems: the case of Senbat watershed. Journal of Biodiversity and and Environmental Sciences (JBES), 2: 8-17.

Engdawork, A. and Bork, H.R., 2014. Long-term indigenous soil conservation technology in the Chencha area, southern Ethiopia: origin, characteristics, and sustainability. Ambio, 43(7): 932-42.

Eswaran, H., Rice, T., Ahrens, R. and Stewart, B.A., 2003. Soil calassification - a Global desk reference. CRC Press, Washington, D.C. 280pp.

Etefa, G., Frankl, A., Zenebe, A., Poesen, J. and Nyssen, J., 2017. Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. Journal of Hydrology, 545: 299-309.

FAO, 2010. Global Forest Resources Assessment: Main report. Foresty paper 163, FAO. Rome, Italy.

FAO, 2011. The State of Food Insecurity in the World: How does international price volatility affect domestic economies and food security?. Rome, Italy.: 55.

Fensham, R., Fairfax, R., Holman, J. and Whitehead, P., 2002. Quantitative assessment of vegetation structural attributes from aerial photography. International Journal of Remote Sensing, 23(11): 2293-2317.

Fisher, B.G., Amos, C.B., Bookhagen, B., Burbank, D.W. and Godard, V., 2012. Channel widths, landslides, faults, and beyond: The new world order of high-spatial resolution Google Earth imagery in the study of earth surface processes. Geological Society of America Special Papers, 492: 1-22.

Fisseha, G., Gebrekidan, H., Kibret, K., Yitaferu, B. and Bedadi, B., 2011. Analysis of land use/land cover changes in the Debre-Mewi watershed at the upper catchment of the Blue Nile Basin, North West Ethiopia. J. Biodivers. Environ. Sci, 1: 184-196.

Frankl, A., Nyssen, J., De Dapper, M., Haile, M., Billi, P., Munro, R.N., Deckers, J. and Poesen, J., 2011a. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology, 129(3-4): 238-251.

Frankl, A., Nyssen, J., De Dapper, M., Haile, M., Billi, P., Munro, R.N., Deckers, J. and Poesen, J., 2011b. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology, 129(3): 238-251.

Frankl, A., Poesen, J., Haile, M., Deckers, J. and Nyssen, J., 2013a. Quantifying long-term changes in gully networks and volumes in dryland environments: The case of Northern Ethiopia. Geomorphology, 201: 254-263.

Frankl, A., Poesen, J., Moeyersons, J. and Nyssen, J., 2015a. Gully development in the Tigray highlands. In: Billi, P. (ed.), Landscapes and Landforms of Ethiopia. Dordrecht, Springer: 191-200.

Frankl, A., Seghers, V., Stal, C., De Maeyer, P., Petrie, G. and Nyssen, J., 2015b. Using image-based modelling (SfM–MVS) to produce a 1935 ortho-mosaic of the Ethiopian highlands. International Journal of Digital Earth, 8(5): 421-430.

Frankl, A., Zwertvaegher, A., Poesen, J. and Nyssen, J., 2013b. Transferring Google Earth observations to GIS-software: example from gully erosion study. International Journal of Digital Earth, 6(2): 196-201.

Friedman, J.H., 1991. Multivariate adaptive regression splines. The annals of statistics: 1-67.

Friedman, J.H. and Silverman, B.W., 1989. Flexible parsimonious smoothing and additive modeling. Technometrics, 31(1): 3-21.

Fritz, S., McCallum, I., Schill, C., Perger, C., Grillmayer, R., Achard, F., Kraxner, F. and Obersteiner, M., 2009. Geo-Wiki. Org: The use of crowdsourcing to improve global land cover. Remote Sensing, 1(3): 345-354.

Gebrekirstos, A., Mitlöhner, R., Teketay, D. and Worbes, M., 2008. Climate–growth relationships of the dominant tree species from semi-arid savanna woodland in Ethiopia. Trees, 22(5): 631-641.

Gebresamuel, G., Singh, B.R. and Dick, O., 2010a. Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. Acta Agriculturae Scandinavica Section B–Soil and Plant Science, 60(3): 211-226.

Gebresamuel, G., Singh, B.R. and Dick, Ø., 2010b. Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. Acta Agriculturae Scandinavica Section B–Soil and Plant Science, 60(3): 211-226.

Gebru, T., Eshetu, Z., Huang, Y., Woldemariam, T., Strong, N., Umer, M., DiBlasi, M. and Terwilliger, V.J., 2009. Holocene palaeovegetation of the Tigray Plateau in northern Ethiopia from charcoal and stable organic carbon isotopic analyses of gully sediments. Palaeogeography, Palaeoclimatology, Palaeoecology, 282(1-4): 67-80.
Goldewijk, K.K., 2001. Estimating global land use change over the past 300 years: the HYDE database. Global Biogeochemical Cycles, 15(2): 417-433.
Goldewijk, K.K. and Ramankutty, N., 2004. Land cover change over the last three centuries due to human activities: the availability of new global data sets. GeoJournal, 61(4): 335-344.
Gutiérrez, Á.G., Schnabel, S. and Contador, F.L., 2009. Gully erosion, land use and topographical thresholds during the last 60 years in a small rangeland catchment in SW Spain. Land Degradation & Development, 20(5): 535-550.
Hadush, G., 2012. Modeling of Hydrological Process in the Geba River Basin in the northern Ethiopia. PhD thesis (unpublished), Vrij University, Brussels, Belgium.
Hahm, W.J., Riebe, C.S., Lukens, C.E. and Araki, S., 2014. Bedrock composition regulates mountain ecosystems and landscape evolution. Proceedings of the National Academy of Sciences, 111(9): 3338-3343.
Haregeweyn, N., Poesen, J., Nyssen, J., Verstraeten, G., De Vente, J., Govers, G., Deckers, S. and Moeyersons, J., 2005. Specific sediment yield in Tigray-Northern Ethiopia: assessment and semi-quantitative modelling. Geomorphology, 69(1): 315-331.
Haregeweyn, N., Tsunekawa, A., Nyssen, J., Poesen, J., Tsubo, M., Tsegaye Meshesha, D., Schu tt, B., Adgo, E. and Tegegne, F., 2015a. Soil erosion and conservation in Ethiopia: A review. Progress in Physical Geography, 39(6): 750-774.
Haregeweyn, N., Tsunekawa, A., Tsubo, M., Meshesha, D., Adgo, E., Poesen, J. and Schütt, B., 2015b. Analyzing the hydrologic effects of region-wide land and water development interventions: a case study of the Upper Blue Nile basin. Regional Environmental Change: 1-16.
Hassanli, A.M., Nameghi, A.E. and Beecham, S., 2009. Evaluation of the effect of porous check dam location on fine sediment retention (a case study). Environmental monitoring and assessment, 152(1-4): 319-326.
Helming, K., Römkens, M. and Prasad, S., 1998. Surface roughness related processes of runoff and soil loss: a flume study. Soil Science Society of America Journal, 62(1): 243-250.
Herweg, K. and Ludi, E., 1999. The performance of selected soil and water conservation measures—case studies from Ethiopia and Eritrea. Catena, 36: 99-114.
Hood, M.J., Clausen, J.C. and Warner, G.S., 2007. Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development1. JAWRA Journal of the American Water Resources Association, 43(4): 1036-1046.
HTS, 1976a. Tigrai Rural Development Study (TRDS). Hunting Technical Services Ltd.,Hunting Techinical services, Borehamwood.
HTS, 1976b. Tigrai Rural Development Study, Annex 1. Land and vegetation resources. Hunting Technical Services Ltd: Hemel Hempstead (G.B.).
Hu, Q., Wu, W., Xia, T., Yu, Q., Yang, P., Li, Z. and Song, Q., 2013. Exploring the use of Google Earth imagery and object-based methods in land use/cover mapping. Remote Sensing, 5(11): 6026-6042.
Huang, J., Hinokidani, O., Yasuda, H., Ojha, C.S., Kajikawa, Y. and Li, S., 2012. Effects of the check dam system on water redistribution in the Chinese Loess Plateau. Journal of Hydrologic Engineering, 18(8): 929-940.
Huang, M. and Zhang, L., 2004. Hydrological responses to conservation practices in a catchment of the Loess Plateau, China. Hydrological Processes, 18(10): 1885-1898.
Hudson, N., 1993. Field measurement of soil erosion and runoff, 68. Food & Agriculture Org.
Hughes, A.O., Prosser, I.P., Stevenson, J., Scott, A., Lu, H., Gallant, J. and Moran, C.J., 2001. Gully erosion mapping for the national land and water resources audit. CSIRO land and water, Canberra, technical report, 26: 01-20.
Hurni, H. and Wiesmann, U., 2010. Global change and sustainable development: A synthesis of regional experiences from research partnerships. University of Bern. Switzerland. Perspectives of the Swiss

National Centre of Competence in Research (NCCR) North-South, University of Bern,Vol. 5. Bern, Switzerland: Geographica Bernensia, 578 pp.

IUSS, 2015. World reference base for soil resources 2014, Revised 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources reports No. 106. FAO, Rome, Italy.

Kidane, G., Dejene, A. and Malo, M., 2010. Agricultural based Livelihood Systems in Drylands in the Context of Climate Change: Inventory of Adaptation Practices and Technologies of Ethiopia. Environment and Natural Resource working paper 38, FAO, Rome, 57pp.

Knight, J., Spencer, J., Brooks, A. and Phinn, S., 2007. Large-area, high-resolution remote sensing based mapping of alluvial gully erosion in Australia's tropical rivers, Proceedings of the 5th Australian Stream Management Conference. Charles Sturt University, pp. 199-204.

Lacombe, G., Cappelaere, B. and Leduc, C., 2008. Hydrological impact of water and soil conservation works in the Merguellil catchment of central Tunisia. Journal of Hydrology, 359(3): 210-224.

Lambin, E.F., Geist, H.J. and Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. Annual review of environment and resources, 28(1): 205-241.

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G. and Folke, C., 2001. The causes of land-use and land-cover change: moving beyond the myths. Global Environmental Change, 11(4): 261-269.

Lanckriet, S., Derudder, B., Naudts, J., Bauer, H., Deckers, J., Haile, M. and Nyssen, J., 2015. A Political Ecology Perspective of Land Degradation in the North Ethiopian Highlands. Land Degradation & Development, 26(5): 521-530.

Lenzi, M.A. and Comiti, F., 2003. Local scouring and morphological adjustments in steep channels with check-dam sequences. Geomorphology, 55(1): 97-109.

Lepers, E., Lambin, E.F., Janetos, A.C., DeFries, R., Achard, F., Ramankutty, N. and Scholes, R.J., 2005. A synthesis of information on rapid land-cover change for the period 1981–2000. BioScience, 55(2): 115-124.

Lesschen, J.P., Cammeraat, L.H. and Nieman, T., 2008. Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. Earth Surface Processes and Landforms, 33(10): 1574-1584.

Li, Z., Wu, P., Feng, H., Zhao, X., Huang, J. and Zhuang, W., 2009. Simulated experiment on effect of soil bulk density on soil infiltration capacity. Transactions of the Chinese Society of Agricultural Engineering, 25(6): 40-45.

Maitima, J.M., Mugatha, S.M., Reid, R.S., Gachimbi, L.N., Majule, A., Lyaruu, H., Pomery, D., Mathai, S. and Mugisha, S., 2009. The linkages between land use change, land degradation and biodiversity across East Africa. African Journal of Environmental Science and Technology, 3(10).

Meire, E., Frankl, A., De Wulf, A., Haile, M., Deckers, J. and Nyssen, J., 2013. Land use and cover dynamics in Africa since the nineteenth century: warped terrestrial photographs of North Ethiopia. Regional Environmental Change, 13(3): 717-737.

Mekuriaw, A., Heinimann, A., Zeleke, G., Hurni, H. and Hurni, K., 2017. An automated method for mapping physical soil and water conservation structures on cultivated land using GIS and remote sensing techniques. Journal of Geographical Sciences, 27(1): 79-94.

Mengistu, D.A., Waktola, D.K. and Woldetsadik, M., 2012. Detection and analysis of land-use and land-cover changes in the Midwest escarpment of the Ethiopian Rift Valley. Journal of Land Use Science, 7(3): 239-260.

Mitiku, H., Herweg, K. and Stillhardt, B., 2006. Sustainable land management–A new approach to soil and water conservation in Ethiopia. Mekelle University, Mekelle, Ethiopia, University of Berne, Berne, Switzerland.

Molina, A., Govers, G., Putte, A., Poesen, J. and Vanacker, V., 2009. Assessing the reduction of the hydrological connectivity of gully systems through vegetation restoration: field experiments and numerical modelling. Hydrology and Earth System Sciences, 13(10): 1823-1836.

Muelenaere, S., Frankl, A., Haile, M., Poesen, J., Deckers, J., Munro, N., Veraverbeke, S. and Nyssen, J., 2014. Historical landscape photographs for calibration of Landsat land use/cover in the Northern Ethiopian highlands. Land Degradation & Development, 25(4): 319-335.

Mukai, S., 2017. Gully Erosion Rates and Analysis of Determining Factors: A Case Study from the Semi-arid Main Ethiopian Rift Valley. Land Degradation & Development, 28(2): 602-615.

Munro, R.N., Deckers, J., Haile, M., Grove, A., Poesen, J. and Nyssen, J., 2008a. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena, 75(1): 55-64.

Munro, R.N., Deckers, J., Haile, M., Grove, A.T., Poesen, J. and Nyssen, J., 2008b. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena, 75(1): 55-64.

Namadi, P.H., Saghafian, B. and Rostami, M., 2014. The numerical investigation of the effect of subsequent check dams on flood peaks and the time of concentration using the MIKE 11 modeling system (Case study: Golabdareh catchment, Iran), River Flow 2014. CRC Press, pp. 1745-1750.

Nyssen, J., Clymans, W., Descheemaeker, K., Poesen, J., Vandecasteele, I., Vanmaercke, M., Zenebe, A., Van Camp, M., Haile, M. and Haregeweyn, N., 2010. Impact of soil and water conservation measures on catchment hydrological response—a case in north Ethiopia. Hydrological Processes(24): 1880-1895.

Nyssen, J., Frankl, A., Haile, M., Hurni, H., Descheemaeker, K., Crummey, D., Ritler, A., Portner, B., Nievergelt, B., Moeyersons, J., Munro, N., Deckers, J., Billi, P. and Poesen, J., 2014. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. Sci Total Environ, 485-486: 164-79.

Nyssen, J., Haile, M., Moeyersons, J., Poesen, J. and Deckers, J., 2000. Soil and water conservation in Tigray (Northern Ethiopia): the traditional technique and its integration with introduced techniques. Land Degradation & Development, 11: 199-208.

Nyssen, J., Haile, M., Naudts, J., Munro, N., Poesen, J., Moeyersons, J., Frankl, A., Deckers, J. and Pankhurst, R., 2009a. Desertification? Northern Ethiopia re-photographed after 140 years, Sci Total Environ, pp. 2749-55.

Nyssen, J., Haile, M., Naudts, J., Munro, N., Poesen, J., Moeyersons, J., Frankl, A., Deckers, J. and Pankhurst, R., 2009b. Desertification? Northern Ethiopia re-photographed after 140 years. Science of the Total Environment, 407(8): 2749-2755.

Nyssen, J., Naudts, J., De Geyndt, K., Haile, M., Poesen, J., Moeyersons, J. and Deckers, J., 2008a. Soils and land use in the Tigray highlands (Northern Ethiopia). Land Degradation & Development, 19(3): 257-274.

Nyssen, J., Petrie, G., Mohamed, S., Gebremeskel, G., Seghers, V., Debever, M., Hadgu, K.M., Stal, C., Billi, P. and Demaeyer, P., 2016a. Recovery of the aerial photographs of Ethiopia in the 1930s. Journal of Cultural Heritage, 17: 170-178.

Nyssen, J., Petrie, G., Mohamed, S., Gebremeskel, G., Seghers, V., Debever, M., Hadgu, K.M., Stal, C., Billi, P., Demaeyer, P., Haile, M. and Frankl, A., 2016b. Recovery of the aerial photographs of Ethiopia in the 1930s. Journal of Cultural Heritage, 17: 170-178.

Nyssen, J., Poesen, J., Descheemaeker, K., Haregeweyn, N., Haile, M., Moeyersons, J., Frankl, A., Govers, G., Munro, N. and Deckers, J., 2008b. Effects of region-wide soil and water conservation in semi-arid areas: the case of northern Ethiopia. Zeitschrift für Geomorphologie, 52(3): 291-315.

Nyssen, J., Poesen, J., Gebremichael, D., Vancampenhout, K., D'aes, M., Yihdego, G., Govers, G., Leirs, H., Moeyersons, J., Naudts, J., Haregeweyn, N., Haile, M. and Deckers, J., 2007. Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. Soil and Tillage Research, 94(1): 151-163.

Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Haile, M. and Lang, A., 2004a. Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. Earth-Science Reviews, 64(3-4): 273-320.

Nyssen, J., Poesen, J., Moeyersons, J., Haile, M. and Deckers, J., 2008c. Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands-towards a sediment budget. Earth surface processes and landforms, 33(5): 695-711.

Nyssen, J., Poesen, J., Moeyersons, J., Haile, M. and Deckers, J., 2008d. Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands–towards a sediment budget. Earth surface processes and landforms, 33(5): 695-711.

Nyssen, J., Poesen, J., Moeyersons, J., Luyten, E., Veyret-Picot, M., Deckers, J., Haile, M. and Govers, G., 2002. Impact of road building on gully erosion risk: a case study from the Northern Ethiopian Highlands. Earth Surface Processes and Landforms, 27(12): 1267-1283.

Nyssen, J., Poesen, J., Veyret-Picot, M., Moeyersons, J., Haile, M., Deckers, J., Dewit, J., Naudts, J., Teka, K. and Govers, G., 2006. Assessment of gully erosion rates through interviews and measurements: a case study from northern Ethiopia. Earth Surface Processes and Landforms, 31(2): 167-185.

Nyssen, J., Vandenreyken, H., Poesen, J., Moeyersons, J., Deckers, J., Haile, M., Salles, C. and Govers, G., 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology, 311(1): 172-187.

Nyssen, J., Veyret-Picot, M., Poesen, J., Moeyersons, J., Haile, M., Deckers, J. and Govers, G., 2004b. The effectiveness of loose rock check dams for gully control in Tigray, northern Ethiopia. Soil Use and Management, 20(1): 55-64.

Oostwoud Wijdenes, D.J. and Bryan, R., 2001. Gully-head erosion processes on a semi-arid valley floor in Kenya: a case study into temporal variation and sediment budgeting. Earth Surface Processes and Landforms, 26(9): 911-933.

Pankhurst, R., 1995. The history of deforestation and afforestation in Ethiopia prior to World War I. Northeast African Studies, 2(1): 119-133.

Parimala Renganayaki, S. and Elango, L., 2013. A review on managed aquifer recharge by check dams: a case study near Chennai, India. Int. J. Res. Eng. Technol, 2: 416-423.

Patton, P.C. and Schumm, S.A., 1975. Gully erosion, Northwestern Colorado: a threshold phenomenon. Geology, 3(2): 88-90.

Pender, J.L. and Kerr, J.M., 1998. Determinants of farmers' indigenous soil and water conservation investments in semi -arid India. Agricultural Economics 19: 113-125.

Poesen, J., Nachtergaele, J., Verstraeten, G. and Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena, 50(2): 91-133.

Polyakov, V., Nichols, M., McClaran, M. and Nearing, M., 2014. Effect of check dams on runoff, sediment yield, and retention on small semiarid watersheds. Journal of Soil and Water Conservation, 69(5): 414-421.

Potter, K.W., 1991. Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. Water Resources Research(27): 845-855.

Ramankutty, N. and Foley, J.A., 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biogeochemical Cycles, 13(4): 997-1027.

Reid, R.S., Kruska, R.L., Muthui, N., Taye, A., Wotton, S., Wilson, C.J. and Mulatu, W., 2000. Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of southwestern Ethiopia. Landscape Ecology, 15(4): 339-355.

Reij, C., Scoones, I. and Toulmin, C., 1996. Sustaining the soil: Indigenous soil and water conservation in Africa. Earthscan Publications, Ltd., London.

Remaître, A., Van Asch, T.W., Malet, J.-P. and Maquaire, O., 2008. Influence of check dams on debris-flow run-out intensity. Natural Hazards and Earth System Science, 8(6): 1403-1416.

Romero-Diaz, A., Alonso-Sarriá, F. and Martínez-Lloris, M., 2007. Erosion rates obtained from check-dam sedimentation (SE Spain). A multi-method comparison. Catena, 71(1): 172-178.

Römkens, M. and Prasad, S., 2006. Rain Infiltration into swelling/shrinking/cracking soils. Agricultural water management, 86(1): 196-205.

Saebo, H.V., 1983. Land Use and Environmental statistics obtained by point sampling. Central Burea of Statistics of Norway. Artikler 144.: 35pp.

Salleh, K.O. and Mousazadeh, F., 2011. Gully erosion in semiarid regions. Procedia - Social and Behavioral Sciences, 19: 655-661.

Serneels, S. and Lambin, E.F., 2001. Proximate causes of land-use change in Narok District, Kenya: a spatial statistical model. Agriculture, Ecosystems & Environment, 85(1): 65-81.

Shi, H. and Shao, M., 2000. Soil and water loss from the Loess Plateau in China. Journal of Arid Environments, 45(1): 9-20.

Shockey, W.R., 1969. Point sampling of land use in the Washita Basin, Oklahoma.

Sidibé, A., 2005. Farm-level adoption of soil and water conservation techniques in northern Burkina Faso. Agricultural Water Management, 71(3): 211-224.

Spencer, R.D. and Hall, R., 1988. Canadian large-scale aerial photographic systems(LSP). Photogrammetric Engineering and Remote Sensing, 54(4): 475-482.

Tadesse, G., Zavaleta, E., Shennan, C. and FitzSimmons, M., 2014. Policy and demographic factors shape deforestation patterns and socio-ecological processes in southwest Ethiopian coffee agroecosystems. Applied Geography, 54: 149-159.

Taye, G., Poesen, J., Van Wesemael, B., Vanmaercke, M., Teka, D., Deckers, J., Goosse, T., Maetens, W., Nyssen, J., Hallet, V. and Haregeweyn, N., 2013a. Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography, 34(3): 236-259.

Taye, G., Poesen, J., Wesemael, B.V., Vanmaercke, M., Teka, D., Deckers, J., Goosse, T., Maetens, W., Nyssen, J. and Hallet, V., 2013b. Effects of land use, slope gradient, and soil and water conservation structures on runoff and soil loss in semi-arid Northern Ethiopia. Physical Geography, 34(3): 236-259.

Tefera, M.M., 2011. Land-use/land-cover dynamics in Nonno district, central Ethiopia. Journal of Sustainable development in Africa, 13(1): 123-141.

Teka, K., Van Rompaey, A. and Poesen, J., 2013. Assessing the role of policies on land use change and agricultural development since 1960s in northern Ethiopia. Land Use Policy, 30(1): 944-951.

Tesfaalem, A., Frankl, A., Haile, M. and Nyssen, J., 2016. Catchment Rehabilitation and Hydro-geomorphic Characteristics of Mountain Streams in the Western Rift Valley Escarpment of Northern Ethiopia. Land Degradation & Development, 27(1): 26-34.

Tesfamichael, G., 2009. Regional groundwater flow modelling of the Geba basin, northern Ethipia, PhD thesis, K.U. Leuven, Belgium. 275pp.

Tesfamichael, G., De Smedt, F., Miruts, H., Solomon, G., Kassa, A., Kurkura, K., Abdulwassie, H., Bauer, H., Nyssen, J., Moeyersons, J., Deckers, J., Mitiku, H. and Nurhussen, T., 2010a. Large-scale geological mapping of the Geba basin, northern Ethiopia. Tigray Livelihood Paper No 9, VLIR – Mekelle University IUC Program, 46 pp. ISBN 978-90-8826-134-3.

Tesfamichael, G., De Smedt, F., Miruts, H., Solomon, G., Kassa, A., Kurkura, K., Abdulwassie, H., Nyssen, J., Bauer, H., Moeyersons, J., Deckers, J., Mitiku, H. and Nurhussen, T., 2010b. Large-Scale Geological mapping of the Geba basin, northern Ethiopia. Tigray Livelihood Paper No. 9: 46.

Tesfaye, C. and Gebrethadik, E., 1982. Hydrogeology of Mekelle Aea (ND37 - 11). Ministry of Mines and Energy, Ethiopian Institute of Geological Survey. The Provisional Military Government of Socialist Ethiopia. Memoir No.2, Addi Ababa, Ethiopia. 50pp.

Tielens, S., 2012a. Towards a soil map of the Geba catchment using benchmark soils. PhD. Thesis, KULeuven University, Belgium.

Tielens, S., 2012b. Towards a Soil Map of the Geba Catchment using benchmark soils. PhD thesis, K.U. Leuven, Belgium. 226pp.

Turner, B., Meyer, W.B. and Skole, D.L., 1994. Global land-use/land-cover change: towards an integrated study. Ambio. Stockholm, 23(1): 91-95.

Valentin, C., Poesen, J. and Li, Y., 2005. Gully erosion: Impacts, factors and control. Catena, 63(2-3): 132-153.

Van de Wauw, J., Baert, G., Moeyersons, J., Nyssen, J., De Geyndt, K., Taha, N., Zenebe, A., Poesen, J. and Deckers, J., 2008. Soil–landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. Catena, 75(1): 117-127.

van den Elsen, E., Hessel, R., Liu, B., Trouwborst, K.O., Stolte, J., Ritsema, C.J. and Blijenberg, H., 2003. Discharge and sediment measurements at the outlet of a watershed on the Loess plateau of China. Catena, 54(1): 147-160.

Vancampenhout, K., Nyssen, J., Gebremichael, D., Deckers, J., Poesen, J., Haile, M. and Moeyersons, J., 2006. Stone bunds for soil conservation in the northern Ethiopian highlands: Impacts on soil fertility and crop yield. Soil and Tillage Research, 90(1-2): 1-15.

Vanmaercke, M., Poesen, J., Broeckx, J. and Nyssen, J., 2014. Sediment yield in Africa. Earth-Science Reviews, 136: 350-368.

Virgo, K. and Munro, R., 1978. Soil and erosion features of the Central Plateau region of Tigrai, Ethiopia. Geoderma, 20(2): 131-157.

Woien, H., 1995. Deforestation, information and citations. GeoJournal, 37(4): 501-511.

Xiang-zhou, X., Hong-wu, Z. and Ouyang, Z., 2004. Development of check-dam systems in gullies on the Loess Plateau, China. Environmental Science & Policy, 7(2): 79-86.

Xu, J., 2005. Temporal variation of river flow renewability in the middle Yellow River and the influencing factors. Hydrological Processes, 19(9): 1871-1882.

Xu, Y., Fu, B. and He, C., 2013. Assessing the hydrological effect of the check dams in the Loess Plateau, China, by model simulations.

Zeimetz, K.A., Dillon, E., Hardy, E.E. and Otte, R.C., 1976. Using Area Point Samples and Airphotos to Estimate Land Use Change. Transition, 93(22): 24.

Zhang, L., Podlasly, C., Ren, Y., Feger, K.H., Wang, Y. and Schwärzel, K., 2014. Separating the effects of changes in land management and climatic conditions on long-term streamflow trends analyzed for a small catchment in the Loess Plateau region, NW China. Hydrological Processes, 28(3): 1284-1293.

Martínez-Murillo JF, López-Vicente M, Poesen J, Ruiz-Sinoga JD. 2011. Modelling the effects of land use changes on runoff and soil erosion in two Mediterranean catchments with active gullies (South of Spain). Landform Analysis, 17: 99–104.

Martı´nez-Mena M, Albaladejo J, Castillo VM. 1998. Factors influencing surface runoff generation in a Mediterranean semiarid environment: Chicamo watershed, SE Spain. Hydrological Processes, 12: 741–754.

Mekuria W, Aynekulu E. 2011. Exclosure land management for restoration of the soils in degraded communal grazing lands in northern Ethiopia. Land degradation & development, 24 (6): 528–538

McNulty S, Cohen ME, Sun G, Caldwell P. 2016. Hydrologic modeling for water resource assessment in a developing country: The Rwanda case study. In: Lachassagne, P. and M. Lafforgue (eds). Forest and the Water Cycle: Quantity, Quality, Management. Cambridge Scholars Publishing.

Merz R, Blöschl G, Parajka J. 2006. Regionalization methods in rainfall–runoff modelling using large catchment sample. In: V. Andreassian, A. Hall, N. Chahinian & J. Schaake (Eds), Large Sample Basin Experiments for Hydrological Model Parameterization: Results of the Model Parameter Experiment–MOPEX (pp. 117-125). IAHS Publ. 307.

Morgan RP, Finney HJ, Lavee H, Merrit E, Noble CA. 1986. Plant cover effects on hillslope runoff and erosion: evidence from two laboratory experiments. In: Abrahams, A.D. (Ed.), Hillslope Processes (pp. 77–96). Allen and Unwin, Boston.

Mortimore M, Anderson S, Cotula L, Davies J, Faccer K, Hesse C, Morton J, Nyangena W, Skinner J, Wolfangel C. 2009. Dryland opportunities: a new paradigm for people, ecosystems and development, IUCN, Gland, Switzerland; IIED, London, UK and UNDP/DDC, Nairobi, Kenya.

Nugroho P, Marsono D, Sudira P, Suryatmojo H. 2013. Impact of land-use changes on water balance. Procedia Environmental Sciences, 17: 256–262.

Nyssen J, Vandenreyken H, Poesen J, Moeyersons J, Deckers J, Haile M, Salles C, Govers G. 2005. Rainfall erosivity and variability in the Northern Ethiopian Highlands. Journal of Hydrology, 311(1): 172-187.

Nyssen J, Clymans W, Descheemaeker K, Poesen J, Vandecasteele I, Vanmaercke M, Amanuel Zenebe, Van Camp M, Mitiku Haile, Nigussie Haregeweyn, Moeyersons J, Martens K, Tesfamichael Gebreyohannes, Deckers J, Walraevens K. 2010. Impact of soil and water conservation on catchment hydrological response – a case in north Ethiopia. Hydrological Processes, 24(13): 1880–1895.

Peters N.E, Rose S. 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. Hydrological Processes, 15: 1441–1457.

Pineiro G, Perelman S, Guerschman JP, Paruelo JM. 2008. How to evaluate models: Observed vs. predicted or predicted vs. observed?. Ecological modelling, 216: 316–322.

Polyakov V, Nichols M, McClaran M Nearing M. 2014. Effect of check dams on runoff, sediment yield, and retention on small semiarid watersheds. Journal of Soil and Water Conservation, 69(5): 414–421.

Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Global Change Biology, 11(10):1577–1593.

Schilling KE, Jha MK, Zhang YK, Gassman PW, Wolter CF. 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. Water Resources Research, 45(7), http://doi.org/10.1029/2007WR006644.

Stomph TJ, de Ridder N, Steenhuis, ST, Van De Giesen, NC. 2002. Scale effects of hortonian overland flow and rainfall-runoff dynamics: laboratory validation of a process-based model. Earth Surface Processes and Landforms, 27: 847–855.

Taye G, Poesen J, Wesemael BV, Vanmaercke M, Daniel Tekaa, Deckers J, Goosse T, Maetens W, Nyssene J, Hallet V, Nigussie Haregeweyn. 2013. Effects of land use, slope gradient and soil and water conservation techniques, on runoff and soil loss in a semi-arid Northern Ethiopia. Physical Geography, 34(3): 236–259.

Teka K, Van Rompaey A, Poesen J. 2013. Assessing the role of policies on land use change and agricultural development since 1960s in northern Ethiopia. Land Use Policy, 30(1): 944–951.

Valentin C, Agus F, Alamban R, Boosaner A, Bricquet J-P, Chaplot V, De Guzman T, De Rouw A, Janeau J-L, Orange D. 2008. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. Agriculture, Ecosystems & Environment, 128:225–238.

Vancampenhout K, Nyssen J, Desta G, Deckers J, Poesen J, Haile M Moeyersons J. 2006. Stone Bunds for Soil Conservation in the Northern Ethiopian Highlands: Impacts on Soil Fertility and Crop Yield. Soil & Tillage Research, 90: 1–15.

Wagner PD, Kumar S, Schneider K. 2013. An assessment of land use change impacts on the water resources of the Mula and Mutha Rivers catchment upstream of Pune, India. Hydrology and Earth System Sciences, 17: 2233–2246.

Wang G, Liu JL, Kubota J, Chen L. 2007. Effects of land-use changes on hydrological processes in the middle basin of the Heihe River, northwest China. Hydrological processes, 21: 1370–1382.

Wang S, Kang S, Zhang L, Li F. 2008. Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China. Hydrol. Process, 22: 2502–2510.

Wei W, Chen L, Fu B, Huang Z, Wu D, Gui L. 2007. The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China. Journal of Hydrology, 335: 247–258.

Wijesekara GN, Gupta A, Valeo C, Hasbani J-G, Qiao Y, Delaney P, Marceau DJ. 2012. Assessing the impact of future land-use changes on hydrological processes in the Elbow 30 River watershed in southern Alberta, Canada. Journal of Hydrology, 412: 220–232.

Zhang YK, Schilling KE. 2006. Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change, Journal of Hydrology, 324: 412–422.

Zhang L, Podlasly C, Ren Y, Feger KH, Wang Y, Schwärzel K. 2014. Separating the effects of changes in land management and climatic conditions on long-term streamflow trends analyzed for a small catchment in the Loess Plateau region, NW China. Hydrological Processes, 28: 1284–1293.

7 General discussion and conclusion

7.1 Land use, cover and management in historical times (before 1936)

Data on the history of land use (the attributes of part of the Earth's land surface and immediate subsurface) and land cover (the purposes for which humans exploit the land) (Turner et al., 1993) are rarely available for Ethiopia (Pankhurst 1995; Woien 1995). There is no evidence when and in what quantity the land use/cover types have occurred in Ethiopia in earlier times. It is very common to encounter in literature that about 40% of the land was forested at the turn of the 20th century (e.g. Bishaw, 2001; Bariso, 1995; Tadesse et al., 2014). Some authors argue that this figure is only a speculation and not substantiated with evidence, except for the verbal circulation of the original information (McCann, 1997; Pankhurst 1995; Woien 1995). Even Ethiopian officials (Ethiopian Relief and Rehabilitation Commission) have presented that the forest cover was 44 % in 1885, 16% in 1950 and only 4% in 1985 to argue that the deforestation was a cause for the occurrence of drought and famine in 1985 (McCann, 1997). The overestimation was due to a lack of systematic survey data at that time (McCann, 1997). The reconstruction of the environmental history in northern Ethiopia for the period of the Holocene indicated that most part of highlands were alleged to be forested (Bard, 2000; DiBlasi, 1997; Nyssen et al., 2004; Pankhurst, 1990). However, the extent of the vegetation cover and distribution in the region remains unknown as almost no systematic survey on the vegetation history had been done (DiBlasi, 1997). The rediscovery of Italian aerial photographs (1930s - 1940s) by Nyssen et al. (2016) is found very useful to carryout evidence-based research on the history of land use/cover for the past 80 years. This allows stretching back by at least 30 years as compared to the previous studies on land use/cover using aerial photographs which start from 1965 in the region (e.g. Alemayehu et al., 2009; de Mûelenaere, 2014; Munro et al., 2008; Teka et al., 2013).

In the present study carried out in the Geba catchment , in northern Ethiopia, based on the analysis of the 1935-36 aerial photography, only about 6% of forest cover was observed during the second quarter of the 20th century. In the fractional map of forest distribution, a relatively high forest cover was found along Atsbi Horst, south of Mekelle, aroud Abi Adi and around Hawzen (Figure 1.1). The total vegetation (forest, shrub, woodland, bushes) cover of the study area was more than 55% in 1935-36. Although the density of the vegetation was not directly measured, it is estimated to be at least 50% ground cover, based on the methodology used to count land use/cover types (Chapter 1, section 1.2.2). Nyssen et al. (2009, 2014) reported that the landscapes in the southern part of the Tigray region were already without vegetation, except the scattered trees in the landscapes, in the second half of the 19th century and the second quarter of the 20th century. The divergence of our results from the previous studies can be explained by the high environmental variability in the region. Meire et al. (2013) found dominance of woody vegetation cover followed by cropland in 1868 – 1941 in southern Tigray which is similar to our results. The prevalence of cropland across landscapes in northern Ethiopia is reported in all studies of environmental history which is cited as the main course of land degradation (Bard, 2000; Hurni, 1988; Nyssen et al., 2004). It is apparent that agriculture was the sole economic source in past times, particularly in Africa which makes agriculture the most important driving force of land degradation (Lambin et al., 1997, 2001; Goldewijk, 2001). It has been the mode of humans to convert and to modify the natural ecosystem into agricultural land over a long period of time (Ramankutty and Foley, 1999).

The results indicate a significant impact of biophysical factors on the distribution of different land use/cover types. This is linked with the suitability of biophysical elements for land use/cover. For instance, the fraction of cropland was influenced by the slope gradient, elevation and soil suitability types (see Chapter 2).

Many indigenous people - particularly in Africa and Asia - have a complex and very old commitment of the ecological maintenance through their traditional practices (Alcorn, 1993). In northern Ethiopia, native forests have been maintained by the longstanding tradition of conserving sacred forests, particularly church forest, for many centuries (Aerts et al., 2016). In this region, there has also been a tradition of soil and water conservation (lynchet), practiced by local people mainly in their cropland (Nyssen et al., 2000). Lynchet - locally named as *daget* - is a bed of grass strip left uncultivated between farm plots and used as a limit of the farm but also used as soil erosion control. In this study (Chapter 2), lynchets having density an average of 3 km km^{-2} was measured in 1935-36 spatially distributed over the study area depending on the density of the cropland. The stabilized gully condition in the 19^{th} and early 20^{th} century (Frankl et al., 2013) and also found in this study (Chapter 2) could be linked to the indigenous soil and water conservation practices in the region and to the presence of a relatively good vegetation cover.

7.2 Land degradation from the late 1930s to the 1990s

Land use/cover change and degradation has a long history in Ethiopia particularly in its northern part (Bard, 2000; Frankl et al., 2011; Meire et al., 2013; Nyssen et al., 2004, 2009, 2015). Although the land degradation is extensive in Ethiopia, the degradation - including deforestation and erosion - is pervasive particularly in the northern and central highlands of Ethiopia (Getahun 1988; Hurni, 1990); due to this reason the semi-natural vegetation of the northern Ethiopian highlands are covered with wooded grasslands at present (Friis, 1992).

Land degradation in northern Ethiopia from the 1940s to 1990s has been directly linked to the national and regional political instability, social and policy change and climate as well. The war by the Italians in the 1930s, famines, drought and civil war (1974 – 1991) (Lanckriet et al. 2015) were among the major shocks that took place in the region that led to land degradation culminating in the second half of the 20th century (Nyssen et al., 2014). The land tenure system during feudal times (till 1974) assuring which landholding only belongs to a small group (Cohen 1974), can be one major cause of land degradation as soil and water conservation were not a part of the system (Teka et al., 2013). According to Nyssen et al. (2015), land mangement was at its optimal level in northern Ethiopia (only until 1940s).

Although land degradation was prevalent over the last century there are several research studies which prove that the most severs land degradation has occurred from the mid-20th century to the 1980s. There is a strong agreement between many land use/cover studies in the region that the clearance rate clearance of vegetation was very high (Munro et al., 2008; de Muelenaere et al., 2012; Teka et al., 2013; Alemanyehu et al., 2009). Even the remnant native forests and the trees observed in landscapes in the beginning of the 20th century had been removed after the 1940s (Nyssen et al., 2014). The fraction of grassland and bare lands increased and the shrubland decreased from 1965 to the 1980s (Teka et al., 2013). Frankl et al. (2013) documented gullies were less active and had low densities in the 1960s as compared to the 1980s and 1990s, which indicates the progressive land degradation due to the clearance of remnant vegetation and the absence of soil and water conservation particularly until the 1980s.

7.3 Runoff and geomorphological response to the clearing of vegetation

Land degradation already occurred in northern Ethiopia during the first half of the 20th century (Nyssen et al., 2009, 2015; Meire et al., 2013), which implies that the environmental deterioration in the region began with the evolution of agriculture in earlier times (Holocene) (Bard, 2000; Nyssen et al., 2004). The presence of gullies was identified in the region in 1868, which indicates the occurrence of rapid runoff response (Nyssen et al., 2009; Frankl et al., 2011). The removal of vegetation - especially from slopes - could be the possible reason for the development of gullies (Nyssen et al., 2009; Frankl et al., 2011, 2013). Vegetation is very important to land use to determine the initiation and development of gullies especially in semi-arid areas (Gutiérrez et al., 2009; Poesen et al., 2003). The result of our study on gully occurrence in northern Ethiopia (Chapter 2) in 1935-36, with an average density of 1.14 km km^{-2}, confirms the findings of previous studies. The majority of these gullies vegetated along their channels and banks as it was also reported by Frankl et al. (2013). The conservation of vegetation in gullies in 1935-36 could entail that the trees in gullies were not the most preferred ones to cut. Another reason could be associated to the good vegetation cover in the catchment of gullies ; in this study (Chapter 1), it is documented that the fraction of woody vegetation cover constitutes about 55 % in the study area in 1935-36. A catchment with a dense vegetation cover produces little runoff (Descheemaeker et al., 2006; Zhang et al.,2004) so that the impact of flash floods in the downstream is minimized or negligible.

7.4 Current land use/cover and soil and water conservation

Northern Ethiopia has been under the transformation of an environment recovery since the 1980s and particularly 1990s extensive soil and water conservation was implemented in the region (Hagos, 1999). In the present, during the assessment and mapping of soil and water conservation (Chapter 2), an average stone bund density of 20 km km^{-2} has been measured in the study area, which has a positive association with cropland. Currently, the environment of northern Ethiopia has shown significant changes compared to times before three decades, despite backlogs in the in the implementation of the programme (Keeley and Ian Scoones, 2000). The physical and biological soil and water conservation brings about many positive environmental changes, such as the stabilization of gullies and river banks, the reduction of soil erosion, the increase of infiltration and soil moisture, the decrease in the runoff and sediment transport (Alemayehu et al., 2009; Descheemaeker et al., 2006; Nyssen et al., 2009; Frankl et al., 2013; Desta et al., 2005; Munro et al., 2008). Virtually, all these studies indicate a rise in vegetation cover in recent times, for the first time in the last half century, which is mainly due to the establishment of exclosures on degraded communal lands. In our study, the present vegetation cover is still lower than the fraction of vegetation before 80 years although the share of the total woody vegetation (forest, shrub, woodland) cover (ca. 40%) is dominant in the study area. Cropland contributes the greater share (42%) of land use/cover of the study area in the present with a small increase compared to 1935-36. Alemayehu et al. (2009) and Teka et al. (2013) reported a larger cropland share in the 1980s as compared to the present and the 1960s. There is an inconsistency in reporting the proportion of bare land in northern Ethiopia: partial studies indicate a decrease (Teka et al, 2013), or an increase (Alemayehu et al., 2009). The latter matches with our result. Moreover, in the present study, an increase of water body and built-up areas is in line with to other reports (Alemayehu et al., 2009; Teka et al., 2013). The driving forces for the distribution of land use/cover variablity were rarely measured in previous studies. In the present study, the effect of different factors - including topography, climate, lithology, socio-economic factors (specifically proximity factors: road, town, population density) on the distribution of land use/cover - were analyzed, in which different associations were obtained (see Chapter 1).

A quantification of the status of gully erosion at present shows a mechanical stabilization (check dams), yet the density of gullies was higher compared to the 1960s to the1980s (Frankl et al., 2013). Similar results have been obtained in the present study: the density of gullies is currently larger than the density in 1935-36. During both periods, the gullies were stabilized, i.e. with vegetation (1935-36) and with check dams and vegetation (2014) (Chapter 2). The distribution of gullies is associated with topography (slope gradient) as was also reported by Frankl et al. (2013). This is an evidence for the prevalence of severe land degradation in northern Ethiopia, when the vegetation on the slopes had vanished.

The other way round , exclosures do not only play a role so as to intercept rainfall and allow its infiltration, but our experiments also show that - if carefully managed spate irrigation can be practiced, in which the runoff from gullies is diverted into exclosures. This has the additional advantage that less runoff will be present in the downstream sections of the gully, giving them an opportunity for healing.

7.5 Runoff response to 80 years of catchment changes

In hydrology, a water budget is described as the volume of water flowing in (precipitation, groundwater flow) and flowing out (runoff, discharge, evapotranspiration, infiltration) of a system (Bras, 1989). Due to the heterogeneity of catchments, it is difficult to generalize the streamflow response based on the result of individual catchments (McDonnell et al., 2007) besides its intrinsic lithological and geomorphic characteristics, land use/cover, catchment management and soil and water conservation are the main factors affecting different hydrological processes. Several researchers have assessed the response of hydrological processes to land use/cover and soil and water conservation that showed a significant alteration in hydrological processes (Bosch and Hawlett, 1982; Descheemaeker et al., 2006; Legesse et al., 2003; Liu et al., 2008; Wang et al., 2007; Zhang and Schilling, 2006).

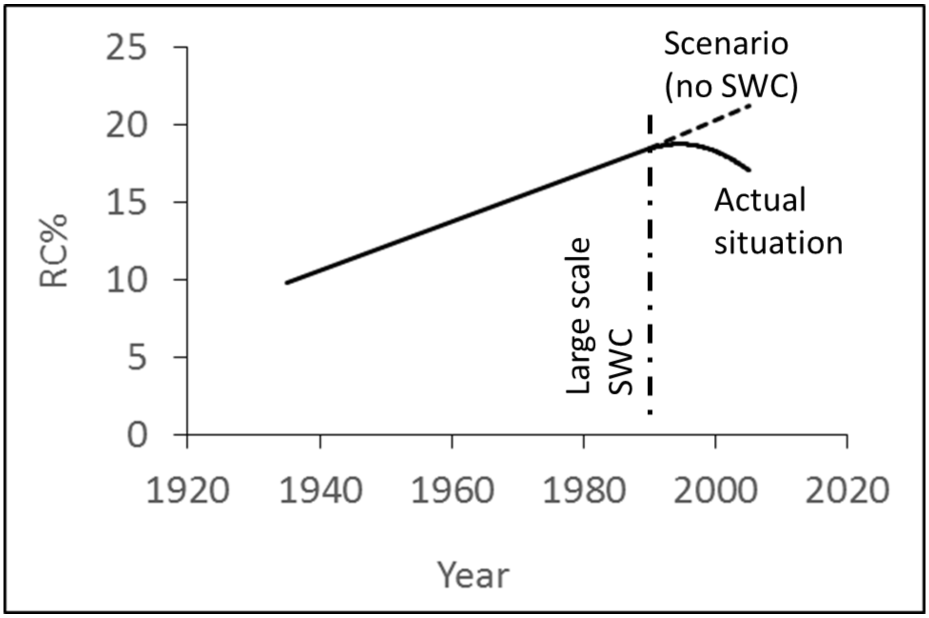


Figure 7.1 Conceptual model of runoff response (RC%) of the study area through time under changing SWC conditions. The start and two final points of the curve are the findings of this study. The scenario without SWC and the modeled RC% of 1935-36 were used to represent a 'business-as-usual' trend. Starting from the 1990s, this trend has been curbed to reach the actual situation. Note that the scenario without SWC is probably an underestimation as it took only into account the absence of physical SWC implementation, but could not consider the biological SWC.

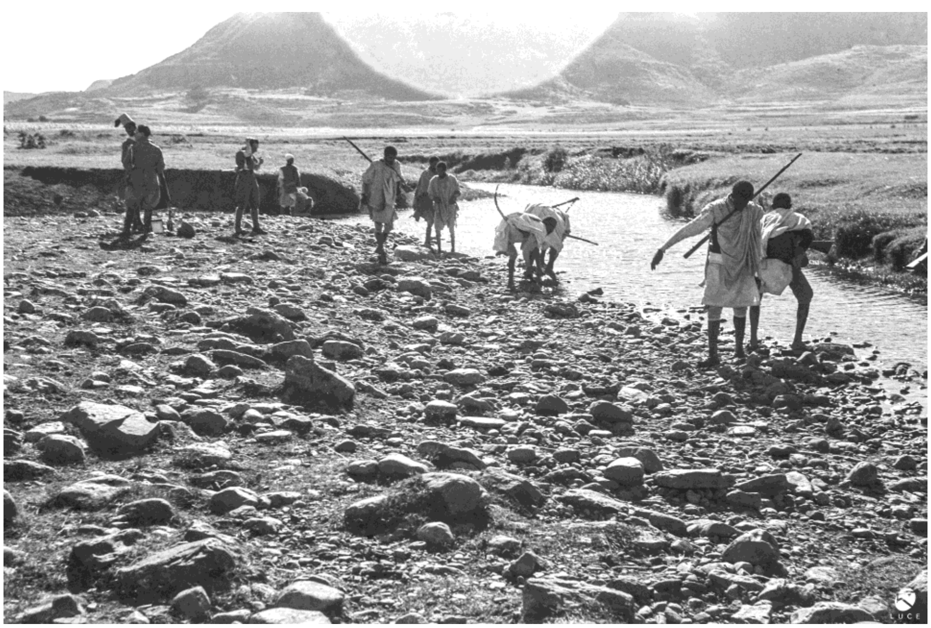


Figure 7.2 A river near Mekelle in November 193. In this, and several other terrestrial photos taken in the 1930s in the dry season, substantial baseflow is conspicuous.

Strong baseflow at that time of the year is in line with storm runoff that is much lower than nowadays, as indicated by the conceptual model (Fig. 7.1) © Istituto Luce Cinecittà.

In this study, the runoff after abstraction by the various land use/cover classes was determined for ten catchments in which a high runoff generation (57%) was observed on grazing land, bare land and built-up area which together make up about 24% of the Geba catchment. The effects of gully management on the runoff reduction in gullies was analyzed (Chapter 3), in which gullies with check dams and vegetation were abstract a substantial amount of the runoff volume (8% - 18%)_ while gullies without conservation can abstract only 5% - 6% (measured over 50 m gully reaches).

Based on the developed databases on land use/cover and soil and water conservation as well as the existing data on runoff and river discharge, a simple conceptual catchment on seasonal runoff response was produced (Figure 6.1). The rainfall - runoff partitioning at pixel scale on the different land use/cover classes and SWC interception were summed to obtain a catchment runoff discharge which was then compared with the measured seasonal river discharge. A strong agreement between this predicted and the observed runoff ($R^2 = 0.86$, $P < 0.001$, $n = 10$) denotes the strength of our model in order to predict the seasonal runoff of a catchment. Based on this result, predictions of hydrology under real conditions in the 1930s and the scenario in 2004-07 (assuming no conservation) were done to create the conceptual model (Figure 6.1). The result indicates that the storm runoff generation was significantly smaller in 1935-36 as compared to the runoff in 2004-07 that leads to observed change in baseflow (Figure 7.2). The model also indicates that the runoff coefficient increases with time under the absence of soil and water conservation intervention which results in a significantly higher runoff when compared to the discharge in actual condition. Thanks to the implementation of SWC in the region, a reduction of runoff response occurs. Based on the results of this study, the stone bund practice which has been widely implemented on cropland, is suggested to be also constructed on bare land. Moreover, water harvesting from different impervious surfaces (rock outcrops, built-up area) could have multiple advantages (reduce of soil erosion and land degradation, increase of the ground water recharge, etc.).

7.6 Scope for controlling the runoff response in other degraded mountainous regions

The study area, the Geba catchment, has diversified bio-physical elements (climate, topography, soil, lithology and land use/cover). These elements make it representative for northern Ethiopia but also for other semi-arid and mountainous regions. These natural elements and the extensive soil and water conservation implemented in the catchment were found to be excellent explanatory factors for a conceptual ranfall-runoff modeling. The used large datasets and the extensive field works done during the entire research period strengthen the validity of this conceptual model to be replicated in semi-arid and mountainous environment with different conditions (e.g. soil and water conservation practices).

7.7 General conclusion

The understanding of the biophysical history of a catchment and its impact on runoff response is very important for the catchment's present and future management and for the operation of different activities in the catchment. Although many reports on land use, degradation, management and hydrology are existing in Ethiopia, particularly in northern Ethiopia, long term studies are rare. This study aimed at the assessment of the effects of different land use/cover shares, soil and water conservation practices on the hydrology of the Geba catchment over the last 80 years (1935-2014).

In order to achieve the objective of the quantification of land use/cover of the Geba catchment from 1935 to 2014, aerial photographs (AP) which had been taken in the 1930s by the Italian Military and Google Earth images (GE) of 2014 were utilized. Seven land use/cover types (cropland, shrubland, forest, grazing land, bare land, settlement and water body) were counted on both the AP and GE images, then analyzed and mapped. The results showed significant changes in the percent cover and LUC spatial shifts during the last eighty years. Cropland showed an approximately constant areal cover over 80 years, from 39% in the 1930s to 42% in 2014. The spatial area shifted however at the expense of the other observed LUC classes. The woody vegetation proportion has undergone a significant change. Shrubland reduced significantly from 48% in the 1930s to 37% in 2014. During the last 80 years, deforestation has continued to drop the forest cover from about 6.3% through an absolute minimum in the 1970s – 1980s to less than 2.3%. The built-up area, grassland and bare land increased during this period. Slope gradient is important in order to determine the LUC distribution, which has a negative association with cropland and a positive with woody vegetation cover. Soil suitability, lithology and population density are also very important to influence the distribution of cropland, shrubland and forest. The fractional maps, created based on important explanatory factors for three main land use/cover (cropland, shrubland and forest), indicate a good agreement with the observed proportions.

Another objective of this study was to assess and a map the density and the distribution of soil and water conservation and the gully occurrence with and interval of 80 years (Chapter 2). Despite the severe land degradation and implementation of soil and water conservation in northern Ethiopia to counteract the environmental deterioration, quantifications of gully and SWC densities have been rarely been done. We measured the densities of these features on 22 aerial photographs /GE and extrapolated it to the study area. *Daget* (lynchet) was the traditional SWC practice in the study area before 80 years while stone bund is the introduced SWC, it has been widely implemented at present not only on cropland but also on grazing land and degraded shrubland. A density of 3 km km^{-2} of *daget* in the 1930s and 20 km km^{-2} of stone bund in 2014 was measured in the catchment. These densities are positively correlated with the occurrence of cropland.

Gullies were observed in 91% of the observed scenes which denotes its prevalence in the region. The density of the gullies increased from 1.14 km km^{-2} in 1935-36 to 1.59 km km^{-2} in line with the continued deforestation of the catchment (Chapter 1). Nevertheless, a large portion of gullies was found inactive during both times: 75% in 1935-36 and 66% in 2014. In earlier times the gullies vegetated and at present the gullies are widely conserved through the construction of check dams.

The effects of check dams on the runoff response in gullies were also quantified in this study (chapter 3). Variations in different discharge parameters (lag times, peak discharge, and runoff volume) were found within and among gully reaches with and without management interventions in two dominant lithologies (sandstone and limestone). Installing check dams increases the magnitude of the runoff volume reduction. In the present study, runoff abstraction was significantly larger in gullies with check dams or vegetation (8% – 18%) as compared to the untreated gullies (4% – 6%) within and across lithologies. The gully management with check dams and the subsequent sediment accumulation and vegetation growth results in a significant reduction of runoff in gullies by increasing the infiltration which may eventually lead to a groundwater recharge and an improvement of the base flow to streams and reservoirs.

The development of the database through Chapter 1-3 and the existing data on the plot runoff and the monitored river discharge bring about the development of a long term water budget modeling for the Geba catchment. Land use/cover and soil and water conservation are the main factors affecting the various hydrological processes. The effects of the stone bunds established in cropland and grazing land had also been taken into account. Hence, the runoff coefficients for vegetated areas, cropland and grazing land were interpolated from the plot scale data, based on the actual situation of land cover/use. The runoff generation after abstraction by the land under different land use/covers and the abstraction by check dams was determined on a pixel scale in ten catchments. The total runoff volume in each catchment was derived from the pixel scale rainfall-runoff partitioning as the additive values of runoff on four land use/cover categories and the gully abstraction.

The rainfall-runoff partitioning additive model for each catchment was evaluated using the observed river discharge in which a strong similarity was observed. This model was applied in order to predict the hydrology of the study area 80 years ago (1935-36) and also the catchment's hydrology in the scenario of the absence of soil and water conservation intervention in 2004-07. There is a significant difference in the runoff generation between 1935-36 and the present with and without SWC and also between the scenario (no SWC) and actual condition (with SWC) in 2004-07. Although the fraction of grazing land, bare land and built-up area is small (24%) compared to the proportion of vegetation and cropland, 57% of the runoff is generated from these covers in the Geba catchment. Hence, the further implementation and maintenance of SWC, particularly on bare land is needed to control the further land degradation and the increase of soil moisture and ground water.

7.8 Future research

This study has analyzed the impact of LUC and SWC on runoff production in the Geba catchment, based on use of field measurements, interpolation and extrapolation of historical and current remotely sensed imagery. To understand the response of runoff to different conditions of the catchment, assessment and mapping of LUC and SWC were done. Important results are obtained with regard to LUC changes (Chapter 2), SWC implementation (Chapter 3), runoff response to SWC (check dams) (Chapter 4), response of vegetation growth to spate irrigation diverted from gullies (Chapter 5) and impact of LUC and SWC on catchment hydrology (Chapter 6). During this study, several researchable that need further attention have also been identified.

So far many studies were carried out on LUC in semi-arid environments including northern Ethiopia. The scale of most of the previous studies carried out in northern Ethiopia is limited relatively to a short period (mostly second half of 20th century) with some exceptions and to small catchments while our study was aimed at investigating LUC change over 80 years at a scale of the Geba catchment, northern Ethiopia. Despite large spatial and temporal scale as compared to most of the previous studies, our study is limited to two time points only (1935 and 2014). In this study the LUC of the intervening periods was not studied due to limitations of time. The comparison of change between two times (1935-36 and 2014) is seemingly linear which may not corresponds to the actual changes between these two times. Without the consideration of scale variation, there is inconsistency between our findings and previous reports on the change of some LUC that some studies indicate the increase of shrubland, forest and decrease of bare land over the last three decades. In our study this was not observed as we could only compare the condition of 2014 with 1935-36 in which shrubland and forest were better in the historical time. Hence, the analysis of changes in the intermediate period could show the dynamic changes of LUC over the long time. This would also allow to fully understand the deforestation rate and to evaluate the effect of soil and water conservation in the region.

As discussed in chapter 2 of this thesis, the Italian aerial photograph database which was recently discovered was used for the study of LUC in 1935-36. The use of these APs is also a challenge as they are characterized by their obliqueness except for the central photos of assemblage and have small overlapping areas impeding orthorectification with conventional photogrammetry methods. Due to this reason, point count technique was applied to assess the density of LUC and to create fractional maps at 1.5 km x 1.5 km scale. We would recommend further research activities on the use of the APs and fractional mapping of LUC.

- As point counting is the best option to extract data from these AP due to the reasons mentioned, it is recommended to compare the point count technique with photogrammetry using the central photos of the AP sets.
- The resolution of the fractional map of LUC is coarse as the point counting was made at the scale of photographs. The application of such coarse LUC map for further studies (e.g. extraction of LUC at small watershed) could affect the result. Hence, assessment and mapping of LUC at high resolution is suggested.

Similar to the LUC study, the density and mapping of SWC in 1935-36 was done based on the Italian APs. The densities of SWC and gully were measured using transect lines since photogrammetry processing is difficult for the oblique photographs. In addition, digitizing of SWC structures and gullies is time consuming and difficult to apply at large scale (e.g. Geba catchment). As the orientation of SWC (stone bund) and gullies frequently changes, the application of transect lines could result in error if the direction of transect lines is locally not perpendicular to to the orientation of gullies and SWC. Hence, it is important to compare the result of the technique of transect line to measure linear features (gully and stone bund) with the result of other technique such as digitizing these features and measuring their density in a GIS environment at catchment scale.

The effect of check dams on runoff in gullies was quantified in northern Ethiopia where massive SWC practices have been implemented in which interesting results were obtained. In this study, the effect of check dams, vegetation and lithology variation on runoff were evaluated. However, due to its cost and technical difficulties, only five gully reaches (10 V-notches) were used in this study. Although gullies with and without check dams were replicated across lithologies, they were not replicated within the lithologies. The effect of other factors like soil type, gully width and length, age of gully, upstream catchment characteristics, rainfall, etc, were not analyzed although high variability of the factors could determine runoff response in gullies. In field condition, it is very difficult to control the effect of other factors even though some factors (e.g. slope gradient) were kept similar in all gullies. Thus, the response of runoff in gullies with and without check dams shall be studied for a large sample of gullies with varying characteristics with replications. The effect of different biophysical factors on runoff can be somehow controlled if the measurement is carried out before and after check dam implementation, but this is only appropriate to evaluate the effect of new check dams, unless the study is carried out over long time. Moreover, such a study demands financial and technical capacity to have replications and representative areas in a wide range of catchments.

7.9 References

Aerts R, Van Overtveld K., November E, Wassie A, Abiyu A, Demissew S, Daye DD, Giday K, Haile M, TewoldeBerhan S .2016. Conservation of the Ethiopian church forests: threats, opportunities and implications for their management. Sci Total Environ, 551: 404-414.

Alcorn J. 1993. Indigenous Peoples and Conservation. Conservation Biology,7(2): 424-426.

Alemayehu F, Taha N, Nyssen J, Girma A, Zenebe A, Behailu M, Deckers, Poesen J .2009. The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). Resour Conserv Recy, 53(4): 192-198.

Bard KA, Coltorti M, DiBlasi MC, Dramis F, Fattovich R. 2000. The environmental history of Tigray (Northern Ethiopia) in the Middle and Late Holocene: a preliminary outline. Afr Archaeol Rev, 17(2): 65-86.

Bariso T. 1995. Deforestation and Environmental Degradation in Ethiopia: The Case of Jam Jam Province. Northeast African Studies, 2(2): 139-155.

Bishaw B. 2001. Deforestation and Land Degradation in the Ethiopian Highlands: A Strategy for Physical Recovery. Northeast African Studies, 8(1): 7-26.

Bosch JM and Hewlett J. D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. of Hydrology, 55: 2-23

Bras RL. 1989. Hydrology: An Introduction to Hydrologic Science (Addison-Wesley series in civil engineering). ISBN 10: 0201059223, Addison-Wesley.

Cohen M. 1974. Peasants and Feudalism in Africa: The Case of Ethiopia. Canadian Journal of African Studies, 8(1): 155-157.

de Muelenaere S, Frankl A, Haile M, Poesen J, Deckers J, Munro N, Veraverbeke S, Nyssen .2014. Historical landscape photographs for calibration of Landsat land use/cover in the Northern Ethiopian highlands. Land Degrad Dev, 25(4): 319-335.

Desta G, Nyssen J, Poesen J, Deckers J, Mitiku H, Govers G, Moeyersons J. 2005. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray Highlands, northern Ethiopia. Soil Use and Management, 21: 287-297.

DiBlasi M 1997. Pollen-analytical approaches to the study of Late Holocene Environmental History and Human Ecology on the Shire Plateau of Northern Ethiopia. In: Bard A, (ed). Preliminary results of multidisciplinary project. Instituto Universitario Orientale, Napoli.

Frankl A, Nyssen J, De Dapper M, Haile M, Billi P, Munro RN, Deckers J, Poesen J. 2011. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). Geomorphology, 129: 238-251.

Frankl A, Poesen J, Haile M, Deckers J, Nyssen J. 2013. Quantifying long-term changes in gully networks and volumes in dryland environments: The case of Northern Ethiopia. Geomorphology, 201: 254-263.

Friis I. 1992. Forests and Forest Trees of Northeast Tropical Africa: Their Natural Habitats and Distribution Patterns in Ethiopia, Djibouti, and Somalia. HMSO Kew Bulletin, Additional Series 15, Middlesex, U.K.

Getahun A. 1978. Zonation of Highlands of Tropical Africa: The Ethiopian Highlands. Working Paper, Addis Ababa.

Goldewijk KK. 2001. Estimating global land use change over the 1930s 300 years: the HYDE database. Glob. Biogeochem. Cycles, 15(2): 417-433.

Gutiérrez ÁG, Schnabel S, Contador FL. 2009. Gully erosion, land use and topographical thresholds during the last 60 years in a small rangeland catchment in SW Spain. Land Degradation & Development, 20: 535-550

Hagos F, Pender J, Gebresilassie N, 1999. Land Degradation in the Highlands of Tigray, and Strategies for Sustainable Land Management. ILRI Socio-Economic and Policy Research Working Paper, vol. 25. International Livestock Research Institute, Addis Ababa.

Hurni, H. 1989. Late Quaternary of Simen and other mountains in Ethiopia. In: Mahaney, W. (Ed.), Quaternary and Environmental Research on East African Mountains. Balkema, Rotterdam, pp. 105– 120.

Hurni, H. 1990. Degradation and Conservation of Soil Resources in the Ethiopian Highlands. In Messerli B and Hurni H, (Ed.), African Mountains and Highlands: Problems and Prospective, 51–63. Marceline, Mo: Walsworth Press, for the African Mountains Association (AMA).

Keeley J and Scoones I. 2000. Knowledge, power and politics: the environmental policymaking process in Ethiopia. Journal of Modern African Studies, 38 (1): 89–120.

Lambin EF, Ehrlich D. 1997. Land-cover changes in sub-Saharan Africa, 1982– 1991: application of a change index based on remotely sensed surface temperature and vegetation indices at a continental scale. Remote Sens. Environ, 61(2):181– 200

Lambin EF, Turner BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C. 2001. The causes of land-use and land-cover change: moving beyond the myths. Glob Environ Change,11(4): 261-269.

Lanckriet S, Derudder B, Naudts J, Bauer H, Deckers J, Mitiku Haile Nyssen J. 2015. A political ecology perspective of land degradation in the north Ethiopian highlands. Land Degrad Dev, 26: 521–530.

Legesse D, Vallet-Coulomb C, oise Gasse F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia, Journal of Hydrology, 275: 67–85.

Liu M, Tian H, Chen G, Wei Ren W, Zhang C, Liu J. 2008. Effects of Land-Use and Land-Cover Change on Evapotranspiration and Water Yield in China During 1900-2000. Journal of the American Water Resources Association, 44(5): 1193–1207.

McCann C. 1997. The plow and the forest: narratives of deforestation in Ethiopia, 1840-1992. Environmental History, 2(2): 138-159.

McDonnell J, Sivapalan M, Vaché K, Dunn S, Grant G, Haggerty R, Hinz C, Hooper R, Kirchner J, Roderick M. 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. Water Resources Research, 43(7). W07301, doi:10.1029/2006WR005467

Meire E, Frankl A, De Wulf A, Haile M, Deckers J, Nyssen J. 2013. Land use/cover dynamics in Africa since the nineteenth century: warped terrestrial photographs of North Ethiopia. Reg Environ Chang, 13(3): 717-737.

Munro RN, Deckers J, Haile M, Grove A, Poesen J, Nyssen J. 2008. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigrai, Ethiopia: Photo-monitoring with an interval of 30 years. Catena, 75(1): 55-64.

Nyssen J, Haile M, Moeyersons J, Poesen J, Deckers J. 2000. Soil and water conservation in Tigray (Northern Ethiopia): the traditional technique and its integration with introduced techniques. Land Degradation & Development, 11: 199-208

Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M, Lang A. 2004 Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. Earth-Sci Rev, 64(3): 273-320.

Nyssen J, Haile M, Naudts J, Munro N, Poesen J, Moeyersons J, Frankl A, Deckers J, Pankhurst R. 2009.. Desertification? Northern Ethiopia re-photographed after 140 years. Sci Total Environ, 407(8): 2749-2755.

Nyssen J, Frankl A, Mitiku Haile Hurni H, Descheemaeker K, Crummey D, Ritler A, Portner B, Nievergelt B, Moeyersons J, Munro N,Deckers J, Billi P, Poesen J. 2014. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. Sci Total Environ, 485–486: 164–179.

Nyssen J, Petrie G, Mohamed S, Gebremeskel G, Seghers V, Debever M, Hadgu KM, Stal C, Billi P, Demaeyer P . 2016. Recovery of the aerial photographs of Ethiopia in the 1930s. J Cult Herit, 17: 170-178.

Pankhurst R .1995. The history of deforestation and afforestation in Ethiopia prior to World War I. Northeast African Studies, 2(1): 119-133.

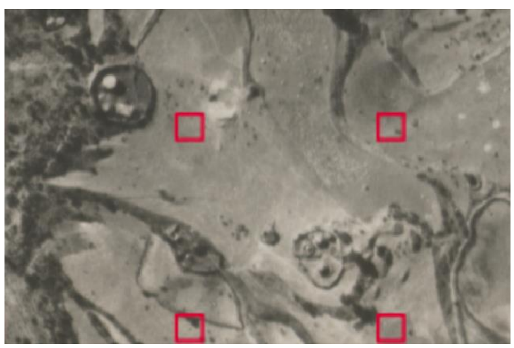
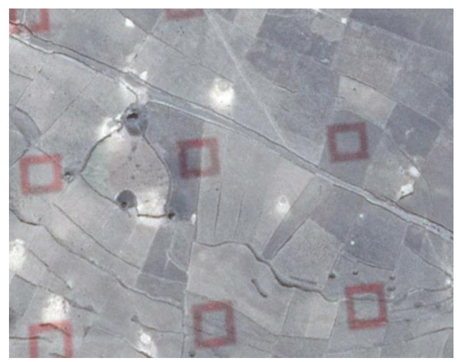
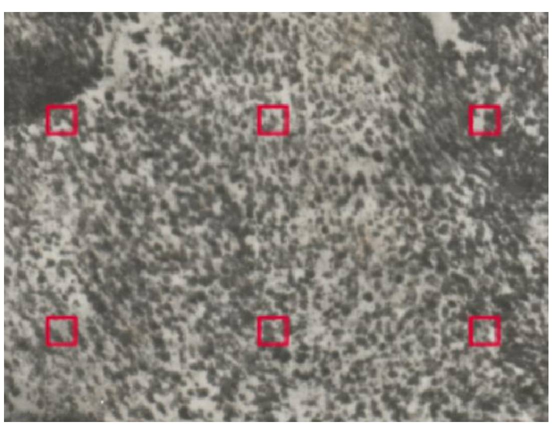
Poesen J, Nachtergaele J, Verstraeten G, Valentin C. 2003. Gully erosion and environmental change: importance and research needs. Catena, 50: 91-133.

Ramankutty N, Foley JA. 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Glob Biogeochem Cycles, 13(4): 997-1027.
Tadesse G, Zavaleta E, Shennan C, FitzSimmons M . 2014. Policy and demographic factors shape deforestation patterns and socio-ecological processes in southwest Ethiopian coffee agroecosystems. Appl Geogr, 54: 149-159.
Teka K, Van Rompaey A, Poesen J. 2013. Assessing the role of policies on land use change and agricultural development since 1960s in northern Ethiopia. Land Use Policy, 30(1): 944-951.
Turner BL, Hyden G, Kates RW. (eds). 1993. Population Growth and Agricultural Change in Africa. University Press of Florida, Gainesville.
Wang G, Liu JL, Kubota J, Chen L. 2007. Effects of land-use changes on hydrological processes in the middle basin of the Heihe River, northwest China. Hydrol process, 21, 1370 -1382.
Woien H. 1995. Deforestation, information and citations. GeoJournal, 37(4): 501-511.
Zhang L, Dawes, WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resour. Res., 37(3): 701–708
Zhang YK and Schilling KE. 2006. Increasing streamflow and baseflow in Mississippi River since the 1940 s: Effect of land use change, Journal of Hydrology, 324: 412–422

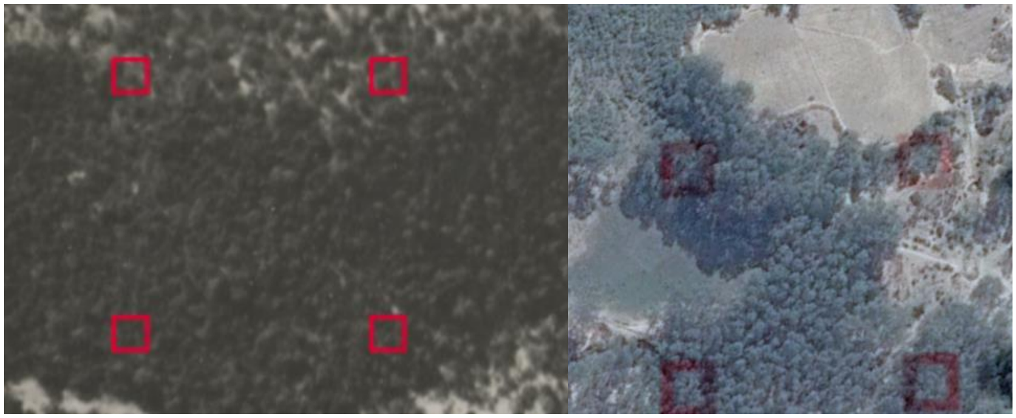
8 Appendices

Appendix A1

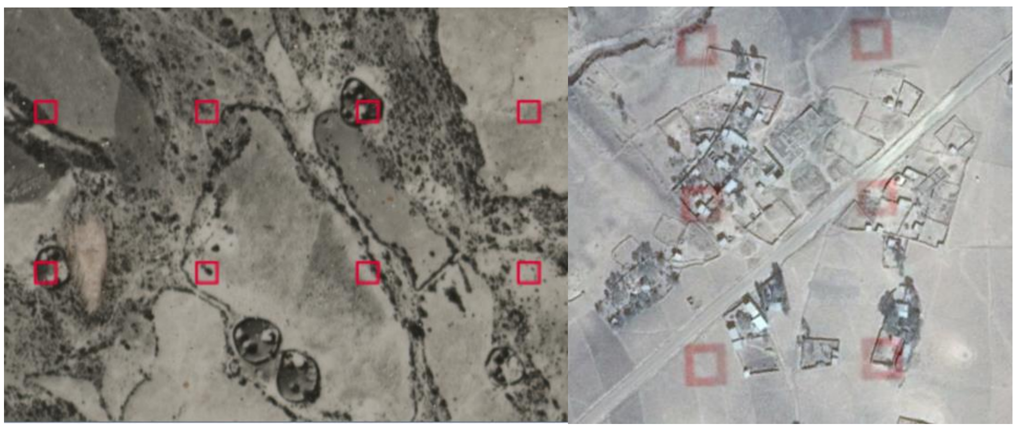
This appendix contain keys used for identification of different land use/cover on aerial photograph and Google Earth images. In aerial photography photo interpretation elements such as pattern, association, tone, etc were used to identify the classes especially to differentiate grazing land, bare land from cropland, and shrubland from forest. In Google Earth, LUC were easily identified. Only the land use/cover of the area within the small squares was tallied. The pair of AP and GE images do not necessarily belong to the same location. The aim is to show the keys used for interpretation of LUC.

LUC	Aerial photographs	Google Earth images
Cropland		
Shrubland		

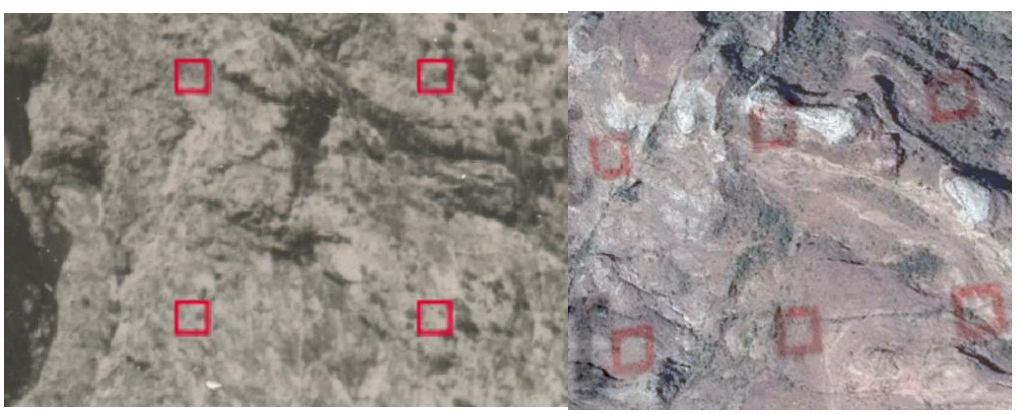
Forest



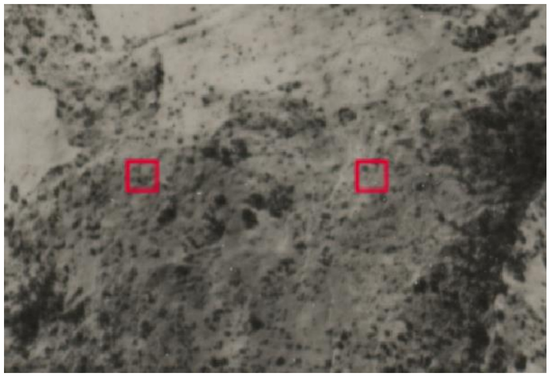
Built-up

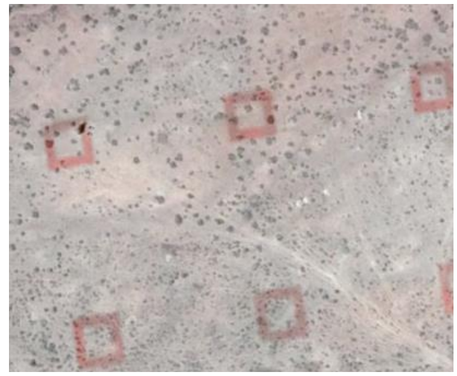


Bare land

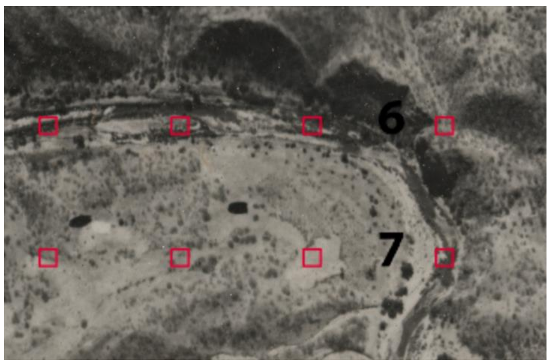


Grazing land



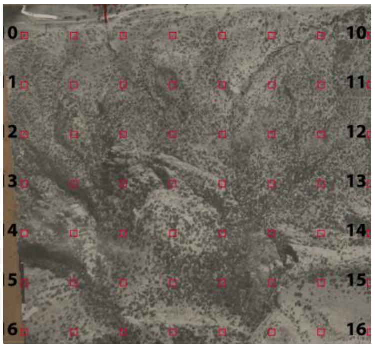


Water body

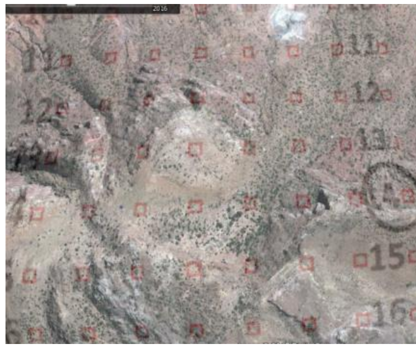


Appendix A2 LUC in 1935-36 (Italian AP) and 2014 (Google Earth image) and terrestrial photographs. These photographs help to visually compare the condition of land use/cover in two time.

Wukro 1936-01-27 (No.4)

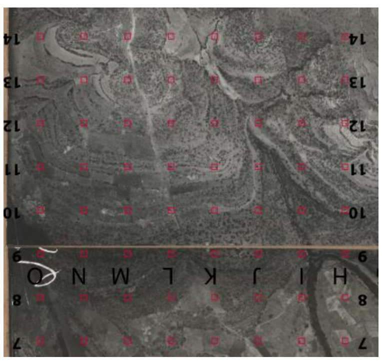


Google Earth 2014



2015

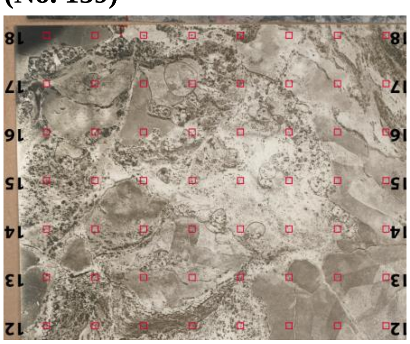
Hawuzen 1936-01-10 (No. 56)



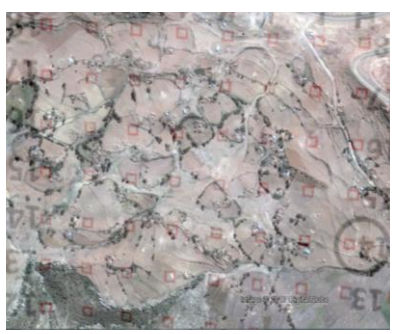
Google Earth 2014

2015

Hawuzen 1935-11-02 (No. 159)

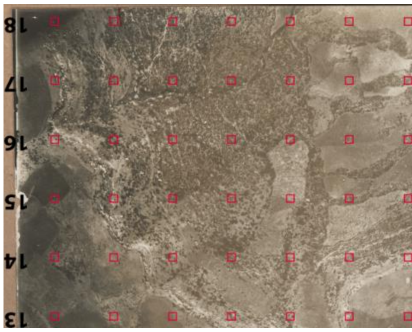


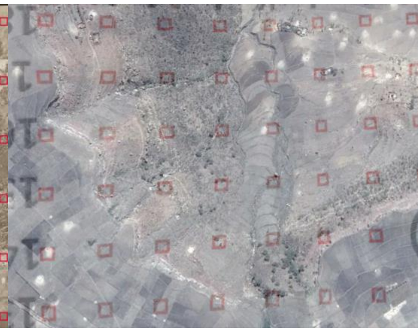
Google Earth 2014



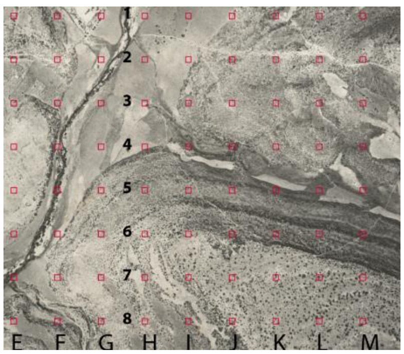
2015

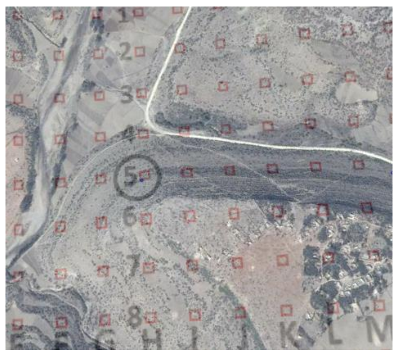
Hawuzen 1935-11-02 (No. 157) | **Google Earth 2014** | **2015**





Mariam Debresina 1936-01-22 (No. 145) | **Google Earth 2014** | **2015**





Appendix A3 Contains climate variables which were interpolated based on the data obtained from meteorological stations and satelite deriven data.

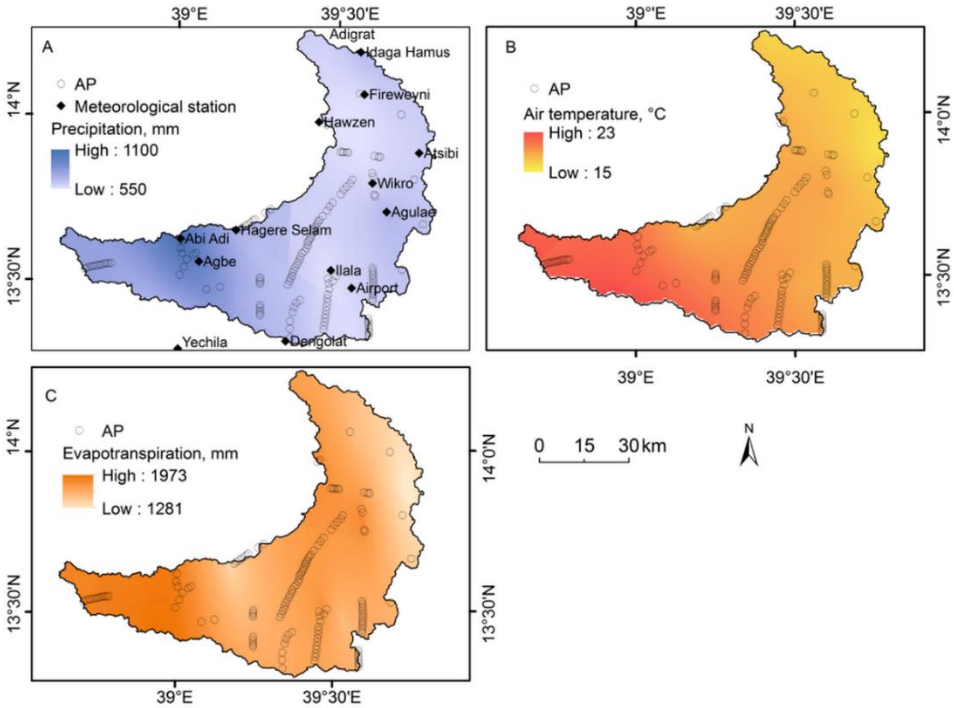


Figure A3-1 Maps of climate variables for the Geba catchment (A) Mean annual precipitation and location of meteorological stations, (B) Mean annual air temperature, (C) Mean annual evapotranspiration. AP: Location of Italian Aerial photo

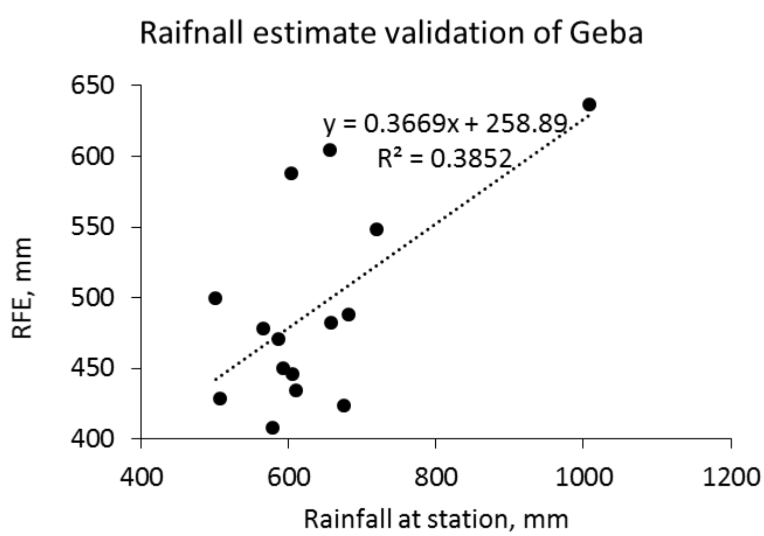


Figure A3-2 Correlation between satellite deriven Rainfall Estimate (RFE) and meteorological station in and nearby Geba catchment

Appendix A4 Location of gully reaches from Google Earth

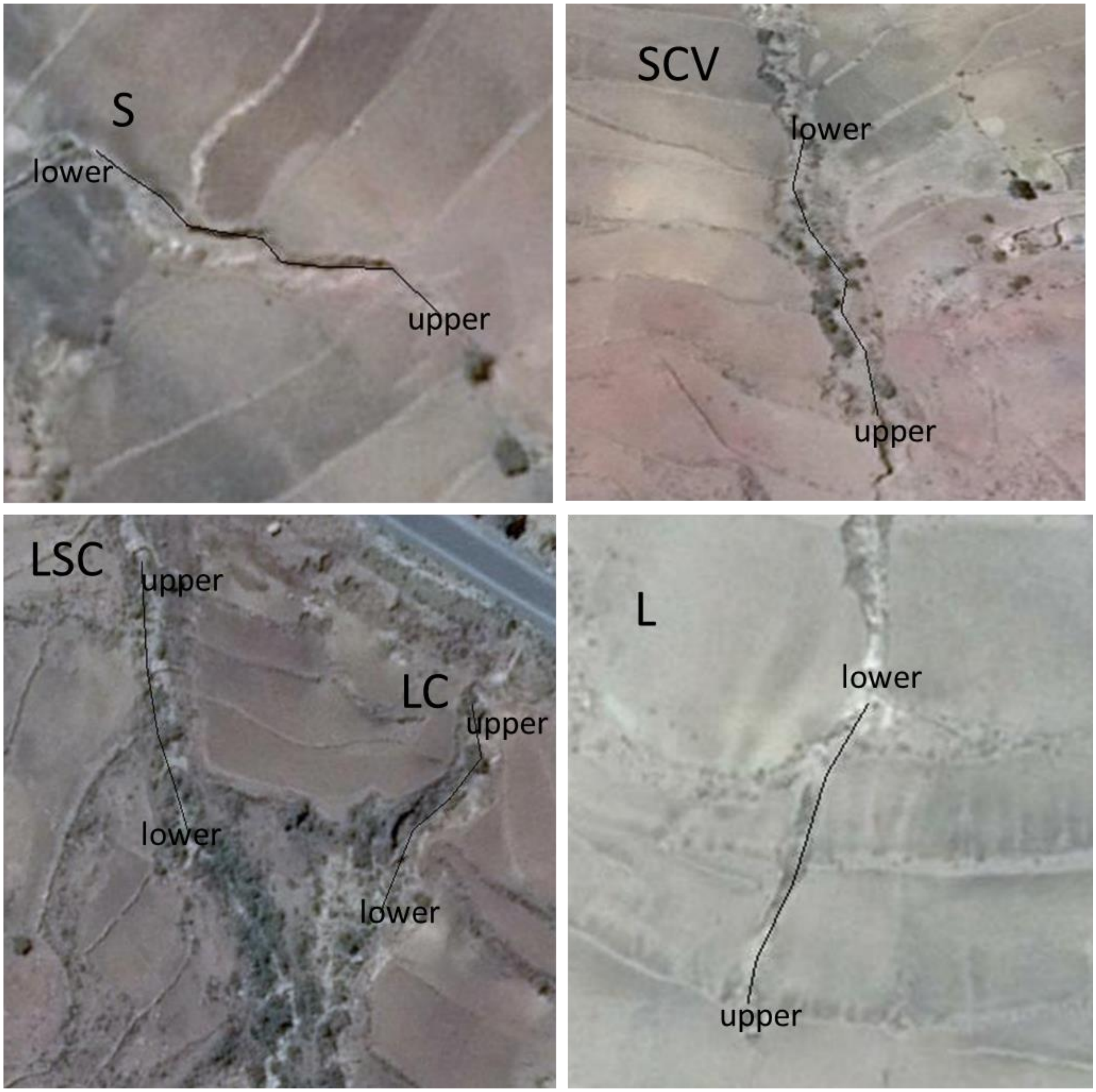


Figure A4-1. Gully reaches from Google Earth. Upper = upper section, lower = lower section, S = gully reach in sandstone without check dam and vegetation; SCV = gully reach in sandstone with check dams and vegetation; L = gully reach in limestone without check dam and vegetation; LC = gully reach in limestone with check dams but without vegetation; and LCV = gully in limestone with check dams and vegetation

Appendix A5 Interpolation of runoff coefficient on cropland and grazing land and abstraction coefficient in gully with and without conservation.

Appendix A5-1 Runoff coefficient of cropland and grazing land

Runoff coefficient of cropland and grazing land with stone bund is based on Taye et al. (2013). They reported runoff coefficient of 0.09 on cropland with stone bund density of 63 km km^{-2} and runoff coefficient of 0.13 measured on control cropland. In the Geba catchment, we measured stone bund density of 20 km km^{-2} which is 1/3 of the stone bund density used for 0.09 runoff coefficient. Hence, we linearly interpolated runoff coefficient between 0.09 and 0.13 as follow:

RCcrop = (1/3 * 0.09) + (2/3 * 0.13) = 0.03 + 0.0867 = 0.1167

Similarly, Taye et al. (2013) reported runoff coefficient of 0.32 on grazing land with stone bund density of 81 km km^{-2} and runoff coefficient of 0.43 measured on control grazing land. The stone bund measured in our case is 20 km km^{-2} which is 1/4 of the stone bund density that resulted in 0.32 runoff coefficient. Hence, based on these data, runoff coefficient from grazing land with 20 km km^{-2} was linearly interpolated between 0.09 and 0.13 as:

RCg = (1/4 * 0.32) + (3/4 * 0.43) = 0.08 + 0.3225 = 0.4025

Therefore, runoff coefficients on cropland and grazing land with SWC (stone bund) in the Geba catchment are 0.1167 and 0.4025 respectively.

The runoff coefficient of daget, traditional SWC in 1935-36, was also calculated. But as the density of daget was negligible (3km km^{-2}) as compared to the density of stone bund (62 km km^{-2}) by Taye et al. 2013, runoff coefficient for cropland in 1935-36 was assumed equal to the runoff coefficient of cropland without SWC, reported by Taye, which is 0.13.

Appendix A5-2 Coefficient of runoff abstraction in gully

In Etefa et al. (2017) the percentage of runoff abstracted in 50 gully reach (standardized length) was calculated for both treated (with check dams and vegetation) and untreated gullies. They have reported an average reduction of 11.6% of 187 m^3 of runoff in gully with SWC and 5% of 331.5 m^3 in gully without SWC which means 21.81 m^3 in treated gully and 9 m^3 in untreated gully.

Gully reaches	Average reduction, %	Average runoff volume at upper section, m^3	Volume reduced, m^3	Normalized reduced volume, m^3
Treated (SCV, LC, LCV)	18+8+9/3 = 11.67	233+27+301/3=187	0.1167*187 =21.81	21.81
Untreated (S, L)	4+6/2 = 5	542+81/2 =311.5	0.05*311.5 =15.575	9.35

See Table 4.3 in Etefa et al. (2017)

Normalized reduced volume was needed to have equal amount of water draining to gully reach with and without soil and water conservation.

These normalized volumes, per 50 m gully reach, were used to calculate the abstraction of runoff for any given gully density with swc (Igc) and without conservation (Ig) per event as:

Igc = (21.8/0.05 km) x Dgc = 436Dgc

Ig = (9.35/0.05 km) xDg = 187Dg

Where Dgc = density of gully with SWC; Dg = density of gully without SWC, density in km km^{-2}

References

Etefa G, Frankl A, Zenebe A, Poesen J, Nyssen J. 2017. Effects of check dams on runoff characteristics along gully reaches, the case of Northern Ethiopia. Journal of Hydrology, 545: 299–309.

Taye G, Poesen J, Wesemael BV, Vanmaercke M, Daniel Tekaa, Deckers J, Goosse T, Maetens W, Nyssene J, Hallet V, Nigussie Haregeweyn. 2013. Effects of land use, slope gradient, soil, and water conservation techniques, on runoff and soil loss in a semi-arid Northern Ethiopia. Physical Geography, 34(3): 236–259.