Impact of soil and water conservation interventions on runoff response under contrasting agro-ecologies of Upper Blue Nile basin, Ethiopia

(エチオピア青ナイル川上流域の対照的な農業生態系における
土壌・水保全策が流出応答に及ぼす影響)

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Tottori University, Japan

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ACRONYMS AND ABBREVIATION

λ	Curve Number method Lambda value
^{0}C	Degree Celsius
CN	Curve Number (value)
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIS	Geographic Information System
Ha	Hectares
HSG	hydrologic soil group
LU	Land Use
m.a.s.l	Meter above sea level
mm	Millimeter
MoA	Ministry of Agriculture
M oWR	Ministry of Water Resources
LULC	Land Use Land Cover
NGOs	Non-Governmental Organizations
NRCS	Natural Resource Conservation Service
NSE	Nash and Sutcliffe Efficiency
P	Precipitation
PET	Potential Evapotranspiration
Q	Runoff discharge
Qd	Daily runoff discharge
RC	Runoff Coefficient
S	Potential Maximum storage
SCS	Soil Conservation Service
SLM	Sustainable Land Management
SLMP	Sustainable Land Management Program
SWAT	Soil and Water Assessment Tool
SWC	Soil and Water Conservation
UBN	Upper Blue Nile

UBNB	Upper Blue Nile basin
UNDP	United Nations Development Program
USDA	United States Department of Agriculture
UTM	Universal Traverse Mercator
V	Flow velocity
WLRC	Water and Land Resource Center

Chapter 1

Introduction

1.1 Back ground

Ethiopia, with a total area of 1.1 million km², lies in the northeastern part of the Horn of Africa. The country is, often described as the water tower of East Africa, and the rainfall-runoff processes on the mountainous slopes are the source of the surface water (Derib, 2009), the potential of annual surface water which is estimated to be around 110 billion m^3 from 12 river systems (Fig 1-1), with unequal distributions over the country (Kebede et al., 2006) and the ground water resource is about 2.6 m^3 billion annually (MoWR, 2008). Despite the huge water resource potential, most of the surface water is lost as runoff and drains to the neighboring countries (nearly 85% of flow provided from the Highlands) which causes to limit the available water for crop production (Nyssen et al., 2005). As such, crop production is usually limited to 4-6 months rainy season, and the yields are very low and subject to weather-driven fluctuation. Despite the continuous food and water insecurity, less than 5% of the potential irrigable land and 1% of the hydropower potential have been developed. Nevertheless, increasing utilization of streams, springs, and lakes in drought-prone areas for irrigation and domestic purposes and climatic change are already contributing to local water insecurity. Many springs dried up within the last few decades in different parts of Ethiopia due to a combination of environmental degradation, siltation, and over pumping (Kloos and Legesse, 2010). Natural resources degradation is the main environmental problem in the country. Degradation mainly manifested through soil removal, nutrient exhaustion, deforestation, and run of surface water.

Figure 1-1 The main hydrographic basins of Ethiopia (Source: Billi et al. 2015)

Climatic conditions within the country are subject to large spatial variations in temperature and precipitation due to topographic-induced variations, ranging from semi-arid to humid and warm (i.e., tropical monsoon climate), and altitude ranges from 125 m a.s.l. at Danakil Depression to 4,620 m a.s.l. at Ras Dashen Mountain, the highest point in the country (Taddese, 2001; EMA 1988). The mean minimum annual temperature varies between less than 4 ^{0}C to 32 ^{0}C. The lowest mean annual temperatures are recorded at elevations over 2,300–2,600 m a.s.l., irrespective of their geographic position. At lower elevations, the temperatures noticeably increase and peak to 30 °C in the steppe area of Gore and to higher values in the Danakil Desert (Billi et al. 2015).

The annual precipitation from 36 years of gauge-calibrated satellite rainfall data, averaged all across the country, is (805 ± 460 mm), but given the complex physiography and the different seasonal and spatial influences of the prevailing air masses and winds, a large diversity is observed among various regions (Fenta et al., 2017) (Figure 1-2). The annual rainfall contrasts from as low as 100 mm year $^{-1}$ in the north east lowlands of Afar region to as high as 2,500 mm year^{-1} in the southwest highlands with high variation across the country (Hermans-Neumann et al., 2017). The main rainy season is from June to September (longer in the southern high-lands) preceded by intermittent showers from February to March; the rest of the year is mainly dry weather. Seleshi and Zanke (2004) examined changes in rainfall totals and rainy days frequency in Ethiopia, over the period 1965-2002; no trend was found in central and northern Ethiopia, but a significant decline in annual and June-September rainfall was shown in the eastern, southern and southwestern stations.

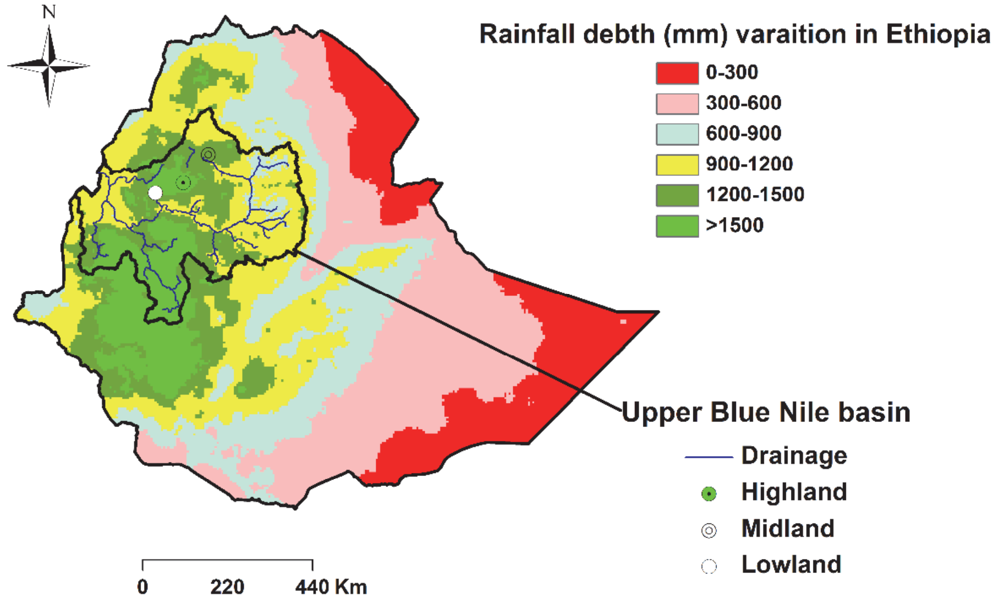

Figure 1- 2 Spatial distribution of annual rainfall during the period 1981–2016 (Source: Fenta et al. 2017).

Annual runoff ranges widely among rivers, given their large variability in watershed area and climatic conditions, with the lowest value (45 × 106 m^3 year^{-1}) recorded in the smallest stream and the largest (17,136 × 106 m^3 year^{-1}) (Billi etal. 2015).

The Upper Blue Nile basin (UBNB) is the source region of the Blue Nile River that drains large parts of the central and south-western Ethiopian Highlands. It has a drainage area of about 176,000 square kilometers (km^2) upstream of El Diem (Figure 1-2). Due to the summer monsoon occurring between June and September, more than 80% of the annual flow occurs from July to October and flows to the downstream countries due to the absence of storage capacity. Small tributaries in the mountainous region experience large fluctuations of streamflow due to the seasonal variation of precipitation (UNESCO 2004). The monthly discharge time series at El Diem, which is the main outlet of the basin, between 1921 and 1990, taken from the National Center for Atmospheric Research (NCAR, http://dss.ucar.edu/datasets/, accessed in March, 2006), produce a mean annual discharge of 49 cubic kilometers (km^3) with a minimum of 31 km^3 (between 1972 and 1984) and a maximum of 70 km^3 (1929). Annual rainfall ranges from over 2000 mm in the South to a 1000 in the Northeast (Figure 1-2). During the wet season in June–September approximately 70% of the annual rainfall is observed.

Cultivated areas, woodlands, and grasslands/ shrub lands occupy about 60%, 25%, and 7%, respectively, of the UBN basin (Kim et al, 2008). The most common land use patterns are grazing and rain-fed agriculture, and as a result soil erosion is a big issue for the entire basin.

1.2 Concepts and definitions

In this section, attempt has been made to give concise definitions to commonly used terms in this research. Soil is the mainstay of agriculture as it acts as a plant growth medium and repository for nutrients and water, but it is also closely linked to several other ecosystem services (Maetens, 2013). The intensive use of these soil functions causes widespread soil degradation, which in turn is an important driver of land degradation and desertification. Land degradation is defined as the loss of utility or potential utility through the reduction of or damage of physical, socio-cultural, or economic feature, and/or reduction of ecosystem diversity (Headworth and Steines, 2003). There may be a single cause or a complex mix of causes. While land degradation has no generally accepted definition, an irreversible decline of biological potential of the land and an important anthropogenic cause are essential aspects of land degradation (Eswaran et al., 2001).

Soil and water conservation is about solving the problem of land degradation, particular accelerated soil erosion. Accelerated soil erosion is a result of the operation of the physical forces of wind and water on soil, which has become vulnerable, usually because of human interference with the natural environmental (Habtamu, 2014). For this reason, soil erosion can be viewed as a symptom of bad land use and management.

Soil conservation refers to the protection of fertile top soil from erosion by wind and water and the replacement of nutrient in the soil by means of cover crops, terracing, contour farming crop rotation etc. SWC can defined as the combination of the appropriate land use and management practices that promotes the productive and sustainable use of erosion and other forms of land degradation (Senders 2004). SWC is not restricted to the protection of the threatened hillside or their rehabilitation by planting of trees. Its scope is much larger and it involves the whole agricultural and natural resource conservation. Generally, soil-water conservation includes all forms of human action to prevent and treat soil degradation (IIED, 1998). According to Habtamu (2014), the aim of soil-water conservation is to facilitate optimum level of production from a given area of land while keeping soil loss below a critical value and protections of the life supporting capacity of soils such as soil quality, soil depth, soil structure, water holding capacity and soil productivity.

1.3 Land degradation by water erosion

Soil erosion by water encompasses several often related processes of soil degradation caused by the detachment and transport of soil particles by rainfall, overland flow or subsurface flow (Boardman and Poesen, 2006). These processes include splash erosion (Moeyersons and De Ploey), interrill and rill erosion (Auerswald et al., 2009), gully erosion (Poesen et al., 2003) and piping erosion (Verachtert et al., 2011).

Soil erosion by water can be greatly aggravated by human activity as it is tightly linked with agriculture (Cerdà et al., 2009). It is one of the main causative processes of soil degradation and hence also land degradation and desertification. Soil erosion by water has important environmental and socio-economical impacts, both on-site and off-site. On-site impacts range from loss of nutrients and associated productivity decline (Bakker et al., 2004) to land losing its ecosystem service functions altogether (e.g. becoming impassable or impossible to cultivate due to gully development (Poesen et al., 2006). Off-site, soil erosion by water is a major source of non-point source pollutants and causes several problems such as sedimentation of reservoirs, deterioration of water quality and flooding. Through its effects on soil structure and (micro)topography, soil erosion by water also affects surface storage capacity of water, infiltration rates and runoff rates (Connolly, 1998).

In Ethiopia, soil erosion by water is by far the most serious problem especially in the highlands; which accounts 45% of the country’s area, over 85% of population, over 90% of the agricultural activities and 75% of the livestock population (Hawando, 1997). The soil degradation by water occurs particularly on cropland, with annual soil loss rates on average of 42 tonnes/ha for croplands, and up to 300 tonnes/ha in extreme cases (Hurni 1993). Population pressure, deforestation, intensified runoff from grasslands and related gullying, as well as high soil erosion rates from badlands (heavily degraded lands), overgrazing along with unsustainable land management practices are mentioned among others drivers for unprecedented rate of soil erosion. The practices of the small-scale farmers are the main cause' of these processes, although in recent decades they have started taking action alongside government initiatives.

1.4 Runoff response influencing factors

The response of runoff to rainfall cannot yet be predicted with certainty due to the complexity of hydrology in the watershed (Sivapalan, 2005). Both the spatial and temporal distribution of runoff, as well as the critical duration of flood producing rainfall, are influenced by many factors. Some of the major factors in the rainfall-runoff process are watershed properties (e.g. infiltration capacity, surface storage, initial moisture, and stream conveyance) and storm properties (e.g. location, magnitude, timing, and geographic distribution) and anthropogenic and climatic factors. For example, a drop of water falling in the form of precipitation usually traverses long path until it reaches the main stream. This long journey is accelerated or decelerated by land cover, soil conservation practice, soil type, rainfall intensity and watershed geomorphologic parameters (Tiwari et al., 2006). In addition, scale also plays an important role in affecting the runoff responses because scale introduces heterogeneity in the landscape descriptors. According to Wagesho (2014), no two watersheds or storms are exactly the same, considerable variation in the runoff response to rainfall can be expected. Hydrological response dynamics in different river basins are attracted by changes in land use, land management practice and climate (Wang, Liu, Kubota, & Chen, 2007).

Ethiopia has different agro-ecology systems, from dry to wet, and also many different altitudes, from lowlands to highlands, the runoff responses to various land management practices and land uses are not the same. Nyssen et al. (2001) reviewed twelve years long series runoff research by the Soil Conservation Research Project (SCRP) watersheds, runoff coefficients (RC) for small (< 1000 m^2) runoff plots are very variable (0 -50 %), and for small watersheds (0.73-6.73 km^2), RC varies from 5 to 45 % in the Ethiopian highlands.

Characteristics of an area where land management is to be implemented is crucial question for policy makers in the country. For example, cultivated land requires conservation measures different from those required on grassland. Forests, in turn, require other measures. According to Meless and Abtew (2016), landscape, land use/land cover, soils types, hydrological processes, and climate are highly variable within and across regions of Ethiopia, and their linkages to the success of environmental management practice has been overlooked during the water resource planning and design phases of structures.

The spatial runoff response of the UBN basin is the combination of many complex hydrological processes, depending on the watershed characteristics (e.g. vegetation, land management practice, land use/land cover, soil properties, antecedent conditions and rainfall characteristics). These spatial difference will have a paramount effect on the variability of runoff response and yield impacting the efficiency of land management practice.

1.5 Application of model to predict runoff

Estimation of runoff from a watershed is an important aspect and plays vital role in flood prediction and mitigation, planning and design effective soil and water management measures, water quality management, hydropower production and many other water resources applications. Models help to represent and simulate the actual hydrological processes so that areas most prone to severe damage and in need of greater soil and water conservation measures can be prioritized.

In Ethiopia many organizations working on the water resource development sector are applying the empirical model with little experimentation for the design of hydraulic structure, and to estimate soil losses from prevailing practices because hydrologic gauging stations are not widely available (Haregeweyn et al., 2016) in the country. Numerous methods have been used for surface runoff estimation in ungauged watersheds; such as, the runoff coefficient method, the rational formula, low flows and duration curve, regional regression equations, and runoff curve number methods. But, most of them are costly, time consuming and difficult to apply because of lack of adequate data. Simple methods for predicting runoff from watersheds are mainly imperative and often feasible in hydrologic engineering, hydrological modelling and in many hydrologic applications. Many of the commonly used watershed models employ some form of the Soil Conservation Service Curve Number (SCS, 1972) (CN) to predict runoff, which links runoff response to soils, land use, and 5-day antecedent rainfall (AMC), and not the cumulative seasonal rainfall volume. Despite its widespread use, however, the accuracy of the CN method has not been thoroughly analyzed (Ponce & Hawkins, 1996), especially countries like Ethiopia. Many review papers suggested that model parameters determined from local studies has been found to be more reliable than those taken directly from other secondary sources. But, it has to be calibrated and validated.

1.6 Sustainable land management in reducing runoff erosion

The development of Sustainable Land Management (SLM) practices to mitigate problems caused by soil erosion by water has been a key issue of research and policies at all levels of government in Ethiopia because of heterogeneous landscapes and diverse biophysical and socioeconomic contexts (Pender et al., 2006). According to Hurni (1996), sustainable land management (SLM) implies “a system of technologies and/or planning that aims to integrate ecological systems with socio-economic and political principles in the management of land for agricultural and other purposes to achieve intra- and intergenerational equity”. The pillars of SLM are: productivity, security, protection, viability and acceptability. Soil is a vital resource that provides food, feed, fuel, and fiber. It underpins food security and environmental quality, both essential to human existence. Protecting the soil from erosion is the first step toward a sustainable agriculture and hence sustainable development (Sullivan, 2004).

1.6.1 Principles of soil and water conservation (SWC)

SWC are activities that maintain or enhance the productive capacity of land in areas affected by or prone to soil erosion. Soil erosion, on the other hand, is the movement of soil from one part of the land to another through the action of water or wind. Thus, soil erosion by water is caused by raindrop impact surface sealing, and crust formation leading to high runoff rate and amount, high runoff velocity on long and undulating slopes, and low soil strength of structurally weak soils with high moisture content due to frequent rains. Therefore, SWC includes the prevention, reduction and control of soil erosion alongside proper management of the land and water resources. Effective erosion management involves: Reduction of the amounts and velocity of surface runoff, maintaining good soil cover through mulching and canopy cover, conservation and retention of soil moisture, prevention or minimizing the effects of raindrop impact on the soil, maintaining favorable soil structure for reducing crusting, re-shaping the slope to reduce its steepness and slope length so as to minimize runoff flows, maintenance or improvement of soil fertility, and removal of unwanted excessive runoff safely.

Based on these principles, erosion control measures are grouped into two broad categories:

- Preventive techniques, and
- Control measures.

The erosion preventative measures mainly comprise the agronomic soil and water conservation practices that improve land productivity without construction of structures**.** The erosion control measures involve the construction of various structures for the control, diversion or conservation of runoff, which is the focus of this study (Figure 1-3). They are very well recognized and have often been seen as the main measures in combating soil erosion (Hurni et al., 2008). According Herweg & Ludi (1999), three assumptions were made while they implementing mechanical/structural SWC measures in the Ethiopian highlands: (1) without SWC, erosion will decrease production in the long-run; (2) production will be stabilized or increased with SWC measures; (3) the expected stabilization or increase in production will be an incentive in itself for farmers to maintain SWC structures. For improved agricultural productivity, both the agronomic and structural measures of soil and conservation are necessary, especially on steeply sloping lands, where water conservation or drainage of excessive water are required.

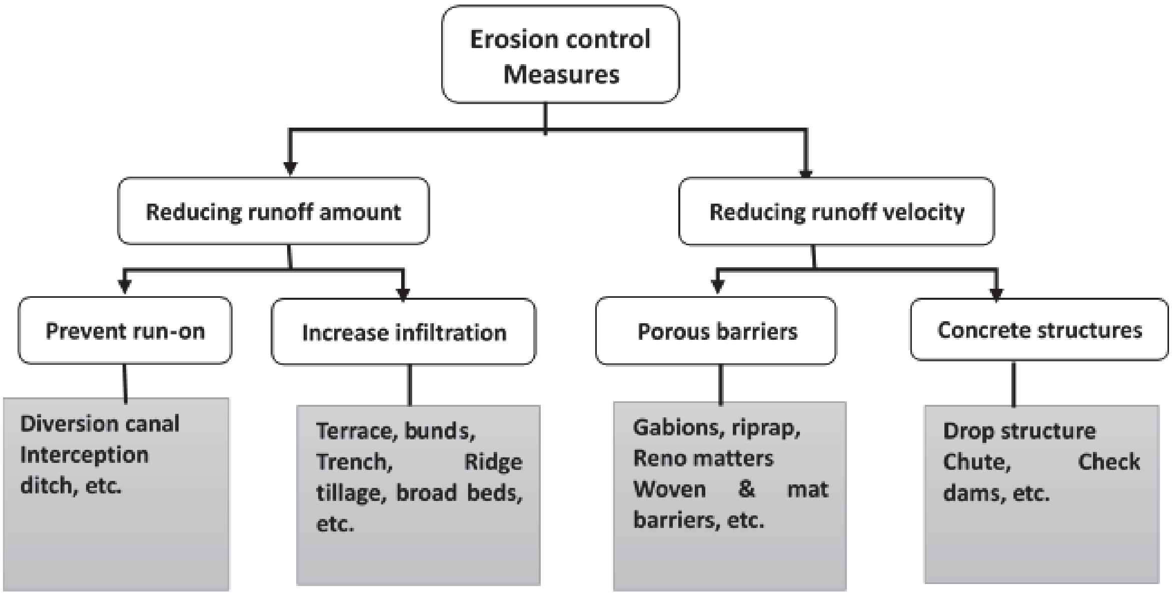

Figure 1-3 Flow chart depicting various methods of erosion control measures

1.6.2 Past efforts to control land degradation

Ethiopia experiences pervasive land, water and environmental degradation due to localized and global climatic anomalies. These leave the country to recurrent crop failures and severe food shortages. Low soil fertility coupled with temporal imbalance in the distribution of rainfall and the substantial non-availability of the required water at the required period are the principal contributing factors to the low and declining agricultural productivity. In response, various governmental and non-governmental (bilateral, multi lateral and NGOs) land management interventions have been implemented since the 1970s, and great efforts have been undertaken to conserve soil and water resources through various types of land management technologies (e.g., soil bund, fanya juu, stone-faced, soil bund combined with biological measures, short trenches, cut-off drains, check dams, hillside terraces, area closures, application of inorganic fertilizer). Despite all those efforts sustainability of the development work is always in question, and their response to decrease the existing runoff and soil erosion amount has not been evaluated, particularly in contrasting agro-ecologies of Upper Blue Nile basin of Ethiopia. In order to fill this information gap and support the country's effort in combating land degradation, a study that assesses the impact of soil and water conservation interventions on runoff response under various agro-ecology is of paramount importance.

1.7 Specific research questions

Runoff response to soil and water conservation measures under contrasting agro-ecologies (high, mid and low in both elevation and rainfall) and effects of SWC measures on runoff modeling in Ethiopia's Upper Blue Nile basin is in its infancy. Some of the research questions the paper attempts to address include:

- What type of SWC practice and where SWC are effective under the Blue Nile basin of Ethiopian?
- What are the factors significantly affects runoff response and generation under the Blue Nile basin of Ethiopian?
- Which land use produce the highest runoff across different agro-ecology?
- How is the accuracy runoff models (CN) in comparison with locally determined model parameters?
- How much runoff reduction can be achieved at watershed scale?

1.8 Research objectives

To address the knowledge gaps outlined in chapter 1 of this dissertation, this study is crucial. The overall objective of this study is therefore, to demonstrate and analyze the impact of different SWC measures on runoff response at various land use and slope classes in contrasting agro-ecologies and thereby, to contribute to better water resources management for Upper Blue Nile basin of Ethiopia. Therefore, the following specific objectives are formulated:

1. To analyze the spatial variability of rainfall-runoff relationship and its controlling factors and
2. To determine the ability of different soil and water conservation practices to reduce runoff and improve soil moisture availability in typical agro-ecology systems in Ethiopia’s Upper Blue Nile basin
3. To determine CN values for various SWC practices and test to what extent the effect of SWC practices can be captured with the most commonly used CN runoff estimation method
4. To analyze the hydrological responses of paired watersheds under existing SWC practices and identify factors that control runoff variation and
5. To investigate the effects of SWC measures on runoff under various management scenarios for better planning and management of water resources in the humid Ethiopian highlands.

1.9 Organization of the thesis

Each of the research objectives stated in section 1.8 is addressed in different chapters of this thesis (Fig 1-4). The thesis is organized into five chapters. After this introductory chapter, Chapter 2 examined the responses of runoff and runoff conservation efficiency to soil and water conservation practices within and between agro-ecology systems. Chapter 3 analyzes the runoff response to soil and water conservation measures and experimentally derived and tested the validity of the runoff curve number (CN) model parameter for the tropical humid highland climate of Kasiry watershed in northwest Ethiopia. Chapter 4 quantify and investigate the impact of soil and water management interventions on watershed runoff response and investigates the effect of various SWC management scenarios for the Kasiry watershed alone in a tropical humid highland of Ethiopia. The last chapter, Chapter 5, provides a general synthesis of the whole thesis, including conclusions, policy implications, limitations of the study, and avenues for further research.

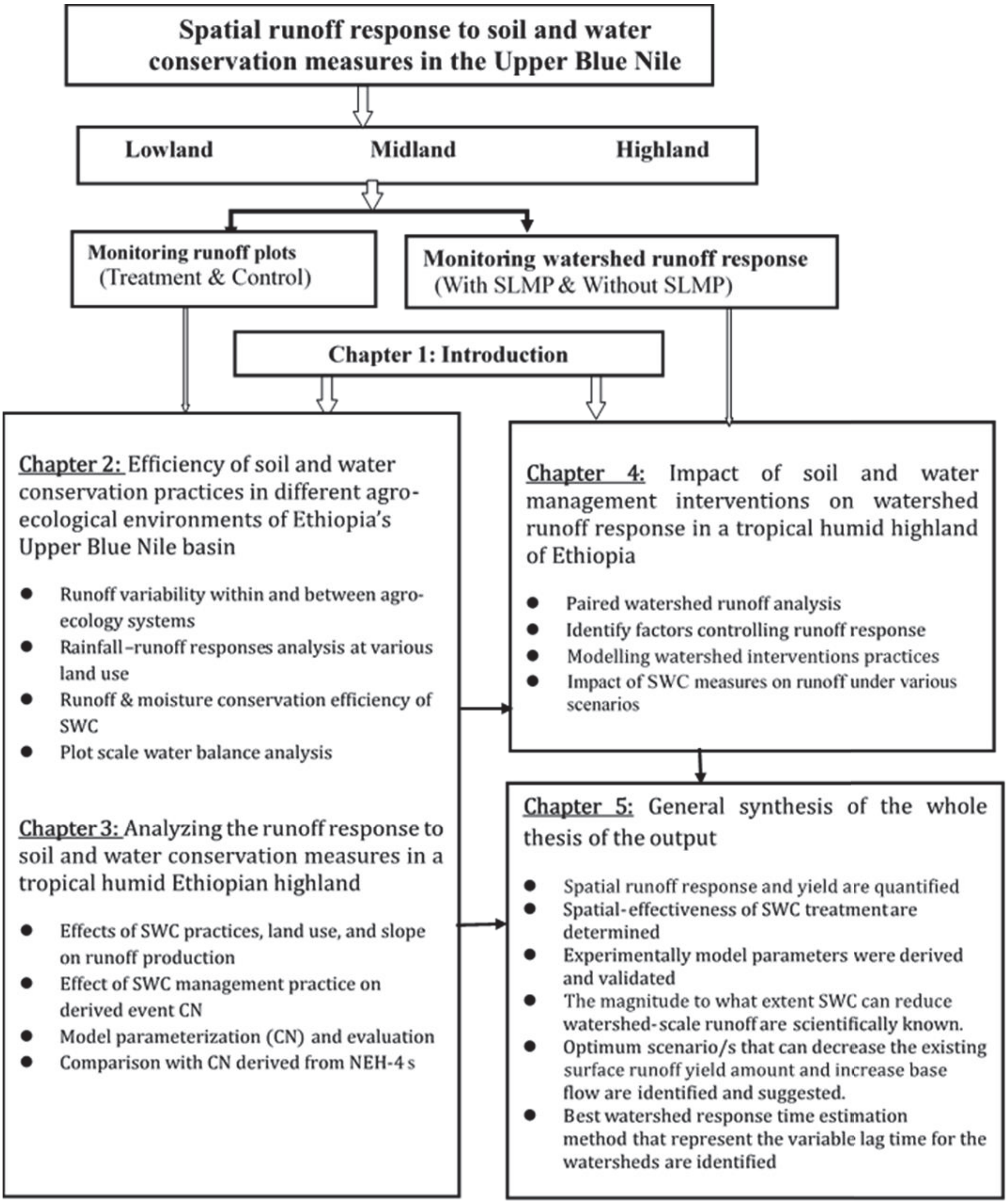

Figure 1- 4 General outline of thesis structure

Chapter 2

Efficiency of soil and water conservation practices in different agro-ecological environments of Ethiopia's Upper Blue Nile basin

This chapter is based on: Dagnenet Sultan, Atsushi Tsunekawa, Nigussie Haregeweyn, Enyew Adgo, Mitsuru Tsubo, Derege Tsegaye Meshesha, Tsugiyuki Masunaga, Dagnachew Aklog, Ayele Almaw Fenta and Kindiye Ebabu

2.1 Introduction

Over the last three decades, the government of Ethiopia and a consortium of donors have invested substantial resources to develop and promote sustainable land management practices as part of efforts to improve environmental conditions, ensure sustainable and increased agricultural production, and reduce poverty (Adgo et al., 2013; Adimassu et al., 2014; Amare et al., 2014; Haregeweyn et al., 2015; Haregeweyn et al., 2017; Herweg and Ludi, 1999; Kassie et al., 2009; Nyssen et al., 2000). Some of the major physical soil and water conservation techniques being used in the country include short trenches, soil and stone bunds, cut-off drains, check dams, hillside terraces, area closures, *fanya juu* (a Swahili word meaning 'throw uphill'), and *Zai* pits (a term in Burkina Faso use to refer digging pits that retain compost and direct water into the soil surrounding each plants to grow). Recently, physical structures have been combined with biological measures such as vegetation establishment to protect the soil against erosion (Amare et al., 2014). But despite these efforts, the sustainability of the development work is unclear. Due to low rates of adoption, most of the promoted practices have been only partially successful. In some cases, disadoption or reduced use of the techniques has been reported (Tadesse and Belay, 2004).

Past efforts to develop and promote soil and water conservation practices had neglected the pronounced regional diversity of the country. Research by Haregeweyn et al., 2015;

Sultan et al., 2017 found that the impact of these interventions was influenced by both the type of measure and the agro-ecosystem under which it was implemented. Landscape, land use, soils, hydrological processes, and climate can be highly variable across regions, and their linkages to environmental management and its success are important aspects that must be understood and documented (Melesse and Abtew, 2016). In addition, Bayabil et al. (2010) illustrated that the effectiveness of a soil and water conservation practice depends on whether watershed runoff processes depend primarily on the local ecosystem, topography, or a combination of the two. The suitability of any soil and water management practice depends greatly upon the soil, topography, climate, cropping system, and resources available to farmers (Pathak et al., 2009). Overall, an agro-ecological approach can contribute substantially to sustainable intensification of agriculture, but this must be supported by an improved knowledge of the optimal conservation measure for each combination of site type and land use (Lampkin et al., 2015).

In Ethiopia, the distribution and amount of rainfall show great spatial and temporal variation, which is strongly influenced by altitude (Rientjes et al., 2013; Schmidt and Zemadim, 2013). Bekele-Tesemma et al. (2005) suggested that temperature (which is determined by the altitude) and rainfall are the two most important climatic factors that affect land management from a farmer's or development agent's point of view. Hurni et al. (2016) developed general soil and water conservation guidelines in which they noted that climate varies greatly within Ethiopia; it ranges from dry to wet, and covers a range of elevations from lowlands to highlands. As a result, it is not possible to apply the same soil and water conservation techniques everywhere. This conclusion was based on a feasibility study of different physical conservation measures that had been tested in micro-watersheds (Soil

Conservation Research Sites) in different agro-ecology systems that had been monitored 25 years ago (Herweg and Ludi, 1999).

Gradually, a few agro-ecology based studies have emerged, but most have focused on evaluation of the socioeconomic aspects (Hurni et al., 2015; Kassie et al., 2009; Matouš et al., 2013; Nigussie et al., 2016; Schmidt and Zemadim, 2013). Studies on the efficiency of soil and water conservation are few, and most have concentrated on the combination of a single agro-ecology with a specific conservation measure (Adimassu et al., 2014; Amare et al., 2014; Dagnew et al., 2015; Sultan et al., 2017; Taye et al., 2013). However, these studies also lack detailed information about the hydrological dynamics created by the conservation efforts across a range of land use, cover types, and slope classes. Best management practice should encompass a series of measures that are useful, proven to be effective, cost-effective, and generally accepted among conservation experts and the ultimate users for specific agro-ecology systems. Hence, critical analysis of the runoff responses and efficiency of the available measures under different agro-ecology systems is needed to evaluate which particular sustainable land management interventions are most likely to be successful in a given location, and this suggests a need for analyses that examine the interactions between various location-specific factors. The results of such observations will provide greater insight into how soil and water conservation affects the hydrological processes under different agro-ecology systems. To provide some of the missing knowledge, we used plot-level runoff measurements and hydrological analyses at three different agro-ecological sites in the Amhara and Benishangul Gumuz administrative regions of Ethiopia. Our objectives were (1) to analyze the spatial variability of rainfall-runoff relationship and its controlling factors and (2) to determine the ability of different soil and water conservation practices to reduce runoff and improve soil moisture availability in typical agro-ecology systems in Ethiopia’s Upper Blue Nile basin.

2.2 Materials and Methods

2.2.1 Description of the study area

We established experimental runoff plots to represent the different land use and cover types and different slope gradients at three experimental sites (Fig 2-1): the Guder and Aba Gerima watersheds from the Fagita Lekoma (10°57’N to 11°11’N, 36°40’E to 37°05’E) and Bahir Dar Zuria (11°25’N to 11°55’N, 37°04’E to 37°39’E) districts, respectively, of Amhara Region, and the Dibatie watershed from the Dibatie district (10°01’N to 10°53’N, 36°04’E to 36°26’E) of the Benishangul Gumuz Region. These sites were selected to represent three important agro-ecology systems in Ethiopia’s Upper Blue Nile basin that have different annual rainfall, elevation, experience with soil and water conservation, soil erosion rates, and land use and cover types (Tables 2-1 and 2-2).

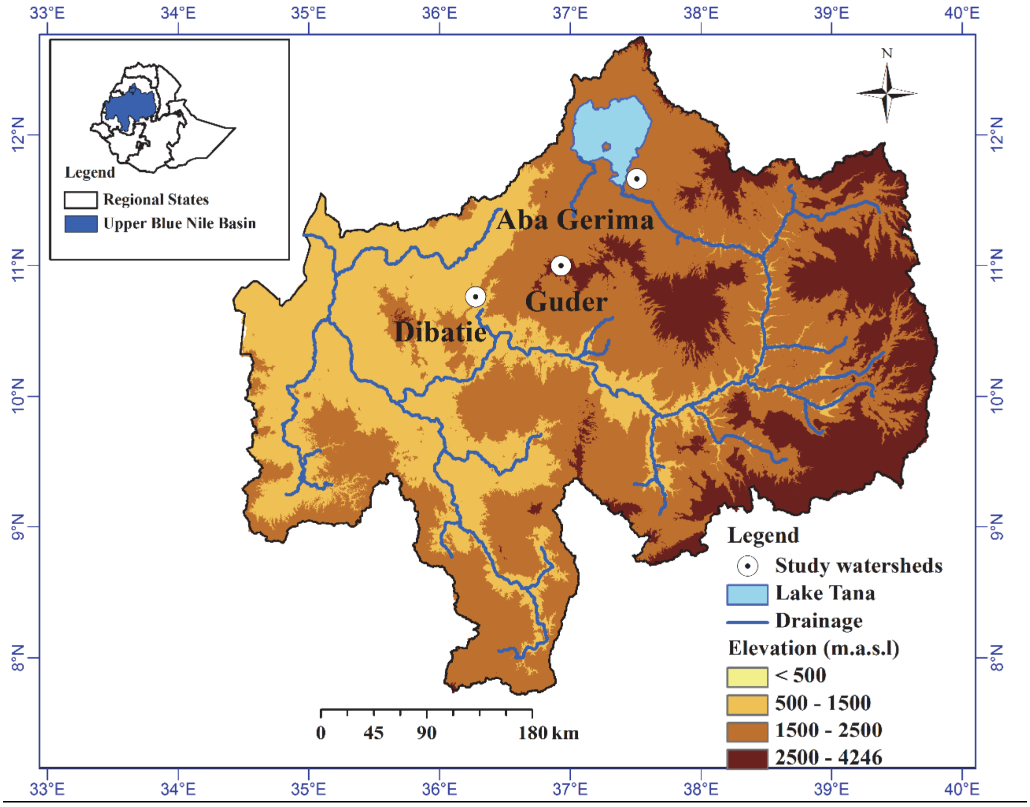

Figure 2- 1 Location of the study sites with different agro-ecology systems.

Each site has been part of the national government's regular extension programs and other public soil and water conservation interventions, but the experiences of these areas with other externally funded programs have varied greatly (Nigussie et al., 2016). The Aba Gerima watershed has been part of the Water and Land Resource Centre, which is funded by the Swiss Agency for Development and Cooperation, since 2011. The Guder watershed has received support for soil and water conservation initiatives from the World Bank under its Sustainable Land Management Programme since 2008. Dibatie has had no external funding support for conservation projects. The major but most common soil and water conservation measures implemented in the Upper Blue Nile basin of Ethiopia are the creation of soil bunds (i.e., raised soil embankment from the ditch is moved downhill that block the flow of water), *fanya juu* (i.e., raised soil embankment from the ditch is moved upslope), short trenches (i.e., excavating trenches along the contour at the hillside), and soil bunds combined with vegetation establishment to protect the soil (Haregeweyn et al., 2015) (Fig 2-2).

Although the overall slope at each site does not change, the effective slope length (the distance between conservation structures) decreases; the principle is to reduces the speed of the flowing water when it contacts each structure and the volume of water that reaches the slope downhill of that structure, thereby reducing the runoff volume. Using different designs, soil and water conservation measures are applied to even and uneven grounds in in the Upper Blue Nile basin.

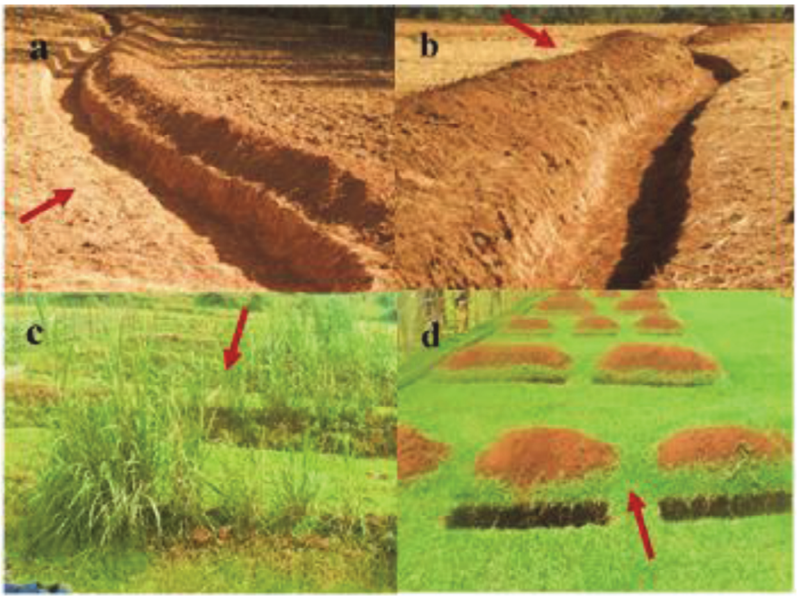

Figure 2- 2 Commonly implemented soil and water conservation measures for the major land uses in the three agro-ecology systems of Ethiopia's Upper Blue Nile basin: (a) soil bunds, (b) fanya juu in cultivated land, (c) soil bunds combined with planting of vegetation (here, elephant grass) in cultivated land, and (d) short trenches in grazing land. Red arrows indicate the slope direction.

2.2.2 Instrumentation and data collection

Each study site was equipped with a temperature sensor and datalogger (Mini-diver, Schlumberger Water Services, the Netherlands) and one manual rain gauge. The datalogger was programmed to measure the maximum and minimum air temperature at 10-min intervals.

We screened this data by taking the maximum and minimum temperatures from 144 readings and calculated a daily average temperature, which we used to calculate potential evapotranspiration at each site (see section 2.3 for details). The rain gauge recorded daily rainfall from June through October 2015, which is the rainy season. More than 86% of the rainfall in the region is concentrated during these months (Sultan et al., 2017).

We measured runoff at the plot scale using a total of 42 runoff plots (each 30 m long × 6 m wide) in the three agro-ecology systems: 18 at Guder, 12 at Aba Gerima, and 12 at Debatie. We used four to two replicates for the representative land use types (cultivated vs. non-agricultural land use) and slopes (gentle and steep). Each agro-ecology system comprised cultivated land in two slope ranges (5 and 15%), grazing land (15% slope), and degraded bush (35% slope) plots. However; the Guder site had two additional main land use types: *Acacia decurrens* plantations (5% and 25% slopes), and *Eucalyptus* spp. plantations (25% slopes). We divided the plots into a group with gentle slopes (<15°) and a group with steep slopes (≥15°).

Each cultivated land plot's had a different soil and water conservation treatment (soil bund, *fanya juu*, soil bund with vegetation establishment, and an untreated control). The other non-agricultural land-use types (grazing land, degraded bush, *Acacia decurrens* plantations, and *Eucalyptus* plantations) each had two treatments (short trenches and control). Based on their availability of sufficient soil and plant species and the ongoing sustainable land management practices, details of the soil bund with vegetation establishment treatment varied among the sites. In the Guder cultivated land plots, the soil bunds were reinforced and stabilized by planting vegetation such as treelucerne (*Cytisus proliferus*) and densho grass (*Pennisetum pedicellatum*) together, whereas elephant grass (*Pennisetum purpureum*) and vetiver grass (*Vetiveria zizanioides*) were planted at the Aba Gerima and Debatie sites, respectively.

At the lower end of each plot, we excavated a 9.7-m^3 pit with a trapezoidal cross section (Fig 2-3) and lined the pit with an impermeable geomembrane plastic to permit the collection of sediment and runoff. The pits were designed to accommodate the maximum runoff that would result from extreme rainfall events, predicted using the anticipated rainfall (based on historical records at the nearest meteorological station) and a runoff coefficient of 46% (Herweg and Ludi 1999; Haregeweyn et al.2016). The runoff depth corresponding to each daily rainfall was recorded and used for our runoff analysis. (See section 2.2.3 for details.) An equation that related the water depth in the pit to the volume of the pit was established for each trapezoidal pit by adding a known volume of water. Then, based on this relationship, the runoff volume was calculated from runoff depth measurements taken every morning at around 8:00 AM with a measuring tape at an average of six points in the pit to account for variations in water depth due to bottom irregularities. The effect of direct rain falling into the pit (estimated from the rain gauges) was subtracted from the total. The plots were also bounded at the sides to prevent inflows of runoff and sediment from the sides of the plot using sheets of corrugated metal inserted into the ground to a depth of 15 cm and protruding 20 cm above the ground (Fig 2-3c). Finally, the runoff depth was calculated by dividing the net runoff volume collected from the pit to the runoff plot area.

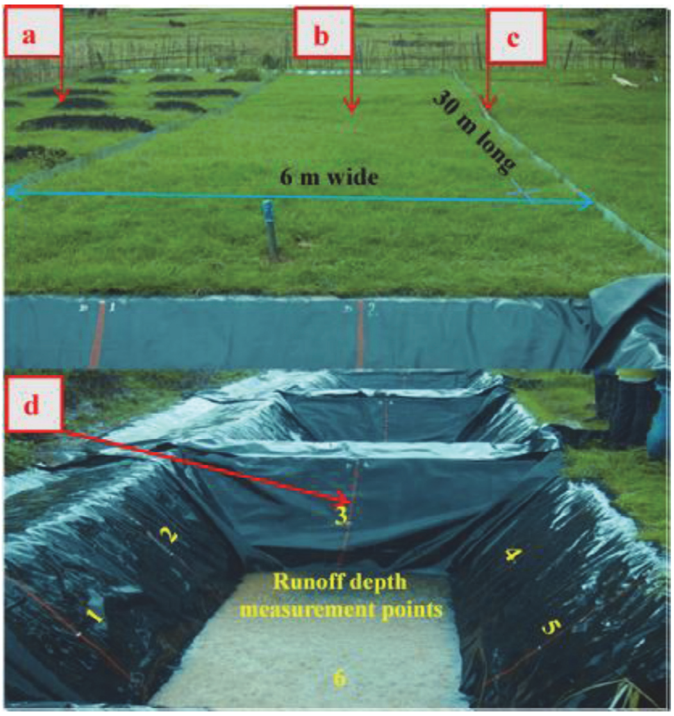

Figure 2- 3 Layout of the runoff plots established in grazing land in the Guder watershed: (a) plots with soil and water conservation measures; (b) plots without conservation measures; (c) corrugated iron sheets inserted in the ground to a depth of 15 cm to establish the plot boundaries; (d) runoff collection pit lined with impermeable geomembrane plastic. Water depth was measured at the six numbered points on the liner. Source:Sultan et al. (2017).

To characterize each site, the values of various soil variables were determined (Table 2-1). Three samples were taken from the top 30 cm of the soil profile at intervals of 10 cm for each land-use class and analyzed to determine the texture using the hydrometric method (Shieldrick and Wang, 1993) and the average of the particle-size distributions were used to characterize the site. To determine the bulk density, undisturbed soil samples were taken to a depth of 30 cm at 10-cm intervals using a core sampler with a volume of 100 cm^3. They were then oven-dried at 105°C for 24 h and weighed. The bulk density was determined by dividing the weight of the oven-dried soil samples by the volume of the soil core. Soil penetration resistance (*SPR*; kPa) was measured by using a hand-operated soil cone penetrometer (Hand penetrometer, Eijkelkamp Company, the Netherlands) with a cone (2-cm^2 base size) and a driving shaft graduated at 5-cm intervals. For each site, we calculated *SPR* as the average of 30 observations.

Table 2- 1 Main characteristics of the three research sites (Fig.2-1).

Characteristics	Dibatie	Aba Gerima	Guder
Mean elevation (m a.s.l.)	1490 Lowland	1998 Midland	2728 Highland
Mean daily temp.(°C)	18–29	17–31	15–24
Mean annual rainfall (mm)	1022	1343	2495
Major soil texture class	Clay	Clay	Clay loam
Soil types	Vertisols, Nitosols	Nitosols, Leptosols	Acrisols, Nitosols
Soil bulk density (g/cm^3)	1.11–1.44	1.21–1.40	0.83–1.34
Average soil penetration resistance (kPa)	2400	2200	1639
Agro-ecology zone [a]	Tropical hot humid (*Moist Kolla*)	Humid subtropical (*Moist Weyna Dega*)	Moist subtropical (*Wet Dega*)
Dominant crops [b]	Finger millet, teff, maize, groundnut	Teff, finger millet, wheat, maize, khat	Barley, teff, wheat, potatoes
Soil erosion severity [c]	Slight	Moderate	Very severe
Rainfall erosivity	High	Very high	Very high
Soil and water conservation activities	Low	High	Medium

Sources: Ebabu (2016), Nigussie et al. (2016); Sultan et al. (2017); surveys by the authors.

[a] *Moist Kolla* = 500 to 1500 m asl and 900 to 1400 mm annual rainfall; *Moist Weyna Dega* = 1500 to 2300 m asl and 900 to 1400 mm annual rainfall; *Wet Dega* = 2300 to 3200 (m asl) and ≥1400 mm annual rainfall (Hurni et al., 2016; Nigussie et al., 2016).

[b] Teff (*Eragrostis tef*); finger millet (*Eleusine coracana*); wheat (*Triticum aestivum*); maize (*Zea mays*); groundnut (*Arachis hypogaea*).

[c] Slight = 5–15 Mg ha^{-1} year^{-1}; Moderate = 15–30 Mg ha^{-1} year^{-1}; Very severe ≥ 50 Mg ha^{-1} year^{-1} (Haregeweyn et al., 2017).

Table 2-2 summarizes the characteristics of the soil and water conservation measures implemented in the runoff plots. The slope of the plot was measured with a clinometer (PM-5/360 PC Clinometer, Suunto, Finland). The dimensions of each conservation measure were based on the standard practices in the study area. The short trenches were installed in two rows across the slope by excavating the soil to a depth of 0.5 m: the upslope row comprised shorter lengths (1.4 m wide × 1.5 m long) separated by 0.5 m and the downslope row comprised longer lengths (1.4 m wide × 2.5 m long for the *A. decurrens*, grazed grassland, *Eucalyptus*, and degraded bush sites; 1.6 m wide × 6.0 m long for the cultivated sites) (Table 2-2). The long and short axis of the excavations was oriented perpendicular to the slope.

Table 2- 2 Characteristics of the 30 m long × 6 m wide runoff plots used to study the effects of land use and soil and water conservation (SWC) practices on runoff in Ethiopia.

Land use × slope group[a]	SWC treatment	Slope (%)	Spacing (m)[c]	Dimensions of SWC structures (m)[c]		Number of SWC per plot	Total no of plots per land use × slope group		
				Short	Long		Guder	Aba Gerima	Debatie
CL1	Control		—	—	—	0			
	Soil bund	5	7.8	—	1.6×6	3	4	4	4
	Fanya juu		7.8	—	1.6×6	3			
	Soil bund[b]		7.8	—	1.6×6	3			
CL2	Control		—	—	—	0			
	Soil bund	15	5.5	—	1.6×6	4	4	4	4
	Fanya juu		5.5	—	1.6×6	4			
	Soil bund[b]		5.5	—	1.6×6	4			
AD1	Control		—	—	—	0	2	—	—
	Short trench	5	2.9	1.4×1.5	1.4×2.5	15			
AD2	Control		—	—	—	0	2	—	—
	Short trench	25	1.7	1.4×1.5	1.4×2.5	20			
GR2	Control	15	—	—	—	0	2	2	2
	Short trench		1.7	1.4×1.5	1.4×2.5	20			
EP2	Control	25	—	—	—	0	2	—	—
	Short trench		1.7	1.4×1.5	1.4×2.5	15			
DB2	Control	35	—	—	—	0	2	2	2
	Short trench		1.7	1.4×1.5	1.4×2.5	20			

[a] Plot number codes refer to the land use: CL is cultivated land; DB is degraded bush; AD is *Acacia decurrens* plantation; EP is *Eucalyptus* spp. plantation; and GR is grazing land (1 with gentle slopes and 2 with steep slopes).

[b] the soil bund treatment comprised a soil bund combined with a vegetation strip (see the Methods section for details)

[c] 0 indicates no soil and water conservation structure, — indicates not applicable

2.2.3 Data analysis

We analyzed the plot data for seasonal runoff, runoff coefficient (*RC*), runoff conservation efficiency (*RCE*), and seasonal soil moisture availability. We quantified the relationships between daily rainfall and runoff depth by means of regression analysis. *RC* was calculated as follows:

$$RC = (\text{Runoff depth} / \text{Rainfall depth}) \times 100\% \tag{2-1}$$

Runoff conservation efficiency

RCE in each plot was calculated relative to runoff in the corresponding control plot using the following equation (Herweg and Ludi, 1999; Sahoo et al., 2016):

$$\boldsymbol{RCE} = \frac{\boldsymbol{A} - \boldsymbol{B}}{\boldsymbol{A}} \times 100\,\% \tag{2-2}$$

Where A = runoff loss from the control plot.

B = runoff loss from the corresponding plot with a conservation measure.

Seasonal moisture conservation efficiency

The change in seasonal water availability was analyzed for all runoff plots using the following water-balance equation (Dingman, 2015):

$$\Delta S = P - Q - ET \tag{2-3}$$

Where ΔS (mm) is the seasonal change in moisture stored in the soil (including deep percolation beyond the soil zone), P is seasonal precipitation (mm), Q is seasonal measured runoff (mm), and ET is seasonal evapotranspiration (mm). Since accurate field measurements are often difficult to acquire, evapotranspiration is usually estimated as the potential evapotranspiration (*PET*). Given the limited long-term meteorological data available for the study watersheds, we used the temperature-based method developed by Hargreaves and Samani (1985):

$$PET = 0.0023\boldsymbol{Ra}\left[\frac{\boldsymbol{T}_{\max} + \boldsymbol{T}_{\min}}{2} + 17.8\right]\left(\boldsymbol{T}_{\max} - \boldsymbol{T}_{\min}\right)^{0.5} \qquad (2\text{-}4)$$

Where Ra is solar radiation (mm/day) estimated based on the approach suggested by Allen et al. (1998), $T_{\max}$ is the daily maximum temperature (°C) and $T_{\min}$ is the daily minimum temperature (°C).

2.3 Results and Discussion

2.3.1 Runoff variability within and between agro-ecology systems

Table 2-3 summarizes the cumulative rainfall and cumulative runoff during the rainy season (June to October), *RC*, and *RCE* for all plots. The seasonal rainfall totaled 1568 mm for Guder, 1402 mm for Aba Gerima, and 881 mm for Debatie. The seasonal runoff from control plots in the Guder watershed ranged between 214 and 560 mm, versus 253 to 475 mm at Aba Gerima and 119 to 200 mm at Debatie. The highest runoff was 560 mm, in control plots of grazing land on steep slopes at Guder (GR2), and the lowest was 81 mm, in short trench plots on steep slopes at Debatie (DB2). The cumulative runoff was lowest at Debatie, which was the site with by far the lowest precipitation. Changes in precipitation regimes clearly have the potential to profoundly affect runoff and soil erosion. Lee et al. (1996) confirmed that a linear relationship existed between the precipitation depth and both runoff and soil erosion, with little difference in response to a change in storm frequency or intensity. The grazing land site on a steep slope (GR2) generated the highest seasonal runoff at Guder (560 mm), followed by the same site type at Aba Gerima (475 mm) and Debatie (134 mm); the high runoff in Guder might be related to frequent trampling by animals because the site was used for grazing livestock. As a result, we found compacted topsoil surfaces in grazing lands, with the highest soil penetration resistance (*SPR* ranging from 1990 to 2210 kPa), versus a maximum of 1100 to 1660 kPa for the other land uses. This reduced infiltration and thereby increased runoff. A similar analysis for the Upper Blue Nile basin showed that cattle on wet grazing soils caused additional compaction in the top 30 cm (Tebebu et al., 2015), leading to higher runoff production.

Although higher surface runoff is expected from control plots on steeper slopes (35%), surface runoff from plots with degraded bush was lower than that from the other land uses, except for cultivated land at Aba Gerima (Table 2-3). This can be explained, on the one hand, by the direct effect of raindrop interception by the vegetation canopy, which dissipates their energy and creates infiltration pathways (Castillo et al., 1997; Descroix et al., 2001; Morgan et al., 1986). On the other hand, vegetation decreases runoff indirectly by improving soil physical properties through the incorporation of organic matter (16.7% in Guder, for example,(Sultan et al., 2017)) and loosening of the soil by growing roots, thereby increasing the infiltration rate (Descheemaeker et al., 2006). Taye et al. (2013) explained this in a different way; they reported that *RC* decreased with increasing slope due to an increase in the content of coarse particles in the soil, which promoted infiltration. Similarly, Tebebu et al. (2015), who illustrated that, for saturation-excess runoff, water infiltrates on hillsides and erosion-inducing runoff occurs in the flatter, downslope parts of landscapes. This, in turn, affects the hydrology, since excess water flows more rapidly to valley bottoms as lateral flow, leading to gully formation (Bayabil et al., 2010). All of these factors may have combined to overwhelm the slope effect.

Table 2-3 Runoff conservation efficiency (RCE) and runoff coefficient (RC) for the different land uses and different soil and water conservation (SWC) practices in the three agro-ecology systems from June to October 2015 (i.e., during the rainy season).

Site	**Land use × slope group** [a]	**SWC practice** [b]	**Cumulative rainfall mean±SD (mm)**	**Cumulative runoff mean ±SD (mm)**	**Runoff conservation efficiency (%)** [c]	**Seasonal *RC* (%)**
Guder	CL_{av}	Control	1567.6 ± 13.4	401.0 ± 1.6	—	26
		Soil bund		272.4 ± 1.5	32.1	17.4
		Fanya juu		264.3 ± 1.6	34.1	16.9
		Soil bund[b]		271.7 ± 1.8	32.2	17.3
	GR2	Control		560.4 ± 4.2	—	35.7
		Short trench		313.4 ± 2.1	44	20
	DB2	Control		214.3 ± 1.8	—	13.7
		Short trench		157.5 ± 1.4	27	10.0
	AD_{av}	Control		396.0 ± 5.1	—	25.3
		Short trench		211.3 ± 1.8	47	13.5
	EP2	Control		217.4 ± 2.2	—	13.8
		Short trench		155.5 ± 2.0	28	10.0
Dibatie	CL_{av}	Control	881.2 ± 11.7	199.7 ± 3	—	22.7
		Soil bund		103.4 ± 1.2	48	11.7
		Fanya juu		105.4 ± 1.2	47	12
		Soil bund[b]		97.3 ± 1.2	51	11
	GR2	Control		134.4 ±2.6	—	15.3
		Short trench		101.5 ± 1.8	25	11.5
	DB2	Control		119.4 ± 2.3	—	13.6
		Short trench		81.4 ± 1.2	32	9.2
Aba Gerima	CL_{av}	Control	1401.5 ± 13.7	253.3 ± 4.0	—	18
		Soil bund		158.1 ± 3.2	38	11.3
		Fanya juu		165.6 ± 2.5	35	11.8
		Soil bund[b]		163.4 ± 2.6	36	11.7
	GR2	Control		475.0 ± 7.2	—	40
		Short trench		213.8 ± 2.6	55	15.3
	DB2	Control		275.5 ± 3.9	—	19.7
		Short trench		151.8 ± 2.1	45	10.8

[a] Plot number codes refer to the land use: 1 and 2 refers gentle slopes (<15°) and a group with steep slopes (≥15°) respectively. CL_{av} is the average for cultivated land in both slope classes (CL1 and CL2 in Table 2); DB2 is degraded bush in land with a steep slope; AD_{av} is the average for the *Acacia decurrens* plantations in land with gentle and steep slopes; EP2 is the *Eucalyptus* spp. plantation in land with steep slopes; and GR2 is grazing land in land with a steep slope.

[b] The soil bund treatment comprised a soil bund combined with planting of vegetation[c] —not applicable

2.3.2 Variability of rainfall–runoff responses within and across the three agro-ecosystems

Taking into account the interactions between the soil and water conservation measures and the two dominant land uses, which were cultivated land on steep slopes (CL2) and grazing land (GR2), we calculated the rainfall thresholds required to generate runoff for both of these at each agro-ecology system (Fig. 2-4, Table 2-4). The threshold rainfall can be determined by plotting the daily runoff depth against the corresponding rainfall depth (Fig. 2-4) and performing least-squares regression (Descheemaeker et al., 2006; Girmay et al., 2009). The slope of the regression line represents how rapidly runoff depth increases with increasing rainfall depth after the rainfall threshold is exceeded. The threshold rainfall values were selected based on the probability of 80% of events below the threshold level rainfall failing to produce runoff. The higher the rainfall threshold and the lower the slope of the curve, the higher the infiltration rate and greater the storage capacity of the agro-ecology system's soil (Descheemaeker et al., 2006; Girmay et al., 2009).

The biggest rainfall event at Guder was 97 mm, versus 78 mm at Aba Gerima and 53 mm at Debatie. In the Guder watershed, most rainfall events greater than 6 and 5 mm produced runoff in cultivated land (CL2) and grazing land (GR2) on steep slopes, respectively (Table 2-4). For the same land use types, the largest threshold values were obtained at the Dibatie and Aba Gerima sites, with thresholds of more than 10 and 9 mm of rain, respectively. The slope of the rainfall–runoff curve also varied widely among the plots; values ranged between 0.10 and 0.45. The soil and water conservation practices using vegetated soil bunds and short trenches in the cultivated and grazing land plots resulted in a lower slope of the curve than in the corresponding control plots at all three sites (Table 2-4). This can be attributed to storage of runoff in depressions and slowing of the runoff flow by the conservation structures.

The response of runoff to rainfall at the moist subtropical site (Guder) began sooner (i.e., a lower rainfall threshold) than at the humid subtropical (Aba Gerima) and the tropical hot humid (Debatie) sites (Table 2-4). Sultan et al. (2017) reported that Guder receives long-lasting rainfall events with small amounts of rainfall, and yet that this site has a longer rainy season than other sites in the western and central highlands; nonetheless, the higher proportion of rainfall (63%) that represents light rainfall events influences subsequent availability of soil moisture. In addition, the heavy soils of the Guder watershed (Table 2-1) tend to retain moisture for a longer period, and this can lower the threshold rainfall compared with other sites. Therefore, small increases in precipitation could result in waterlogging and damage to soil and water conservation structures if subsequent precipitation occurs as intense storms that deposit more rain than the threshold value.

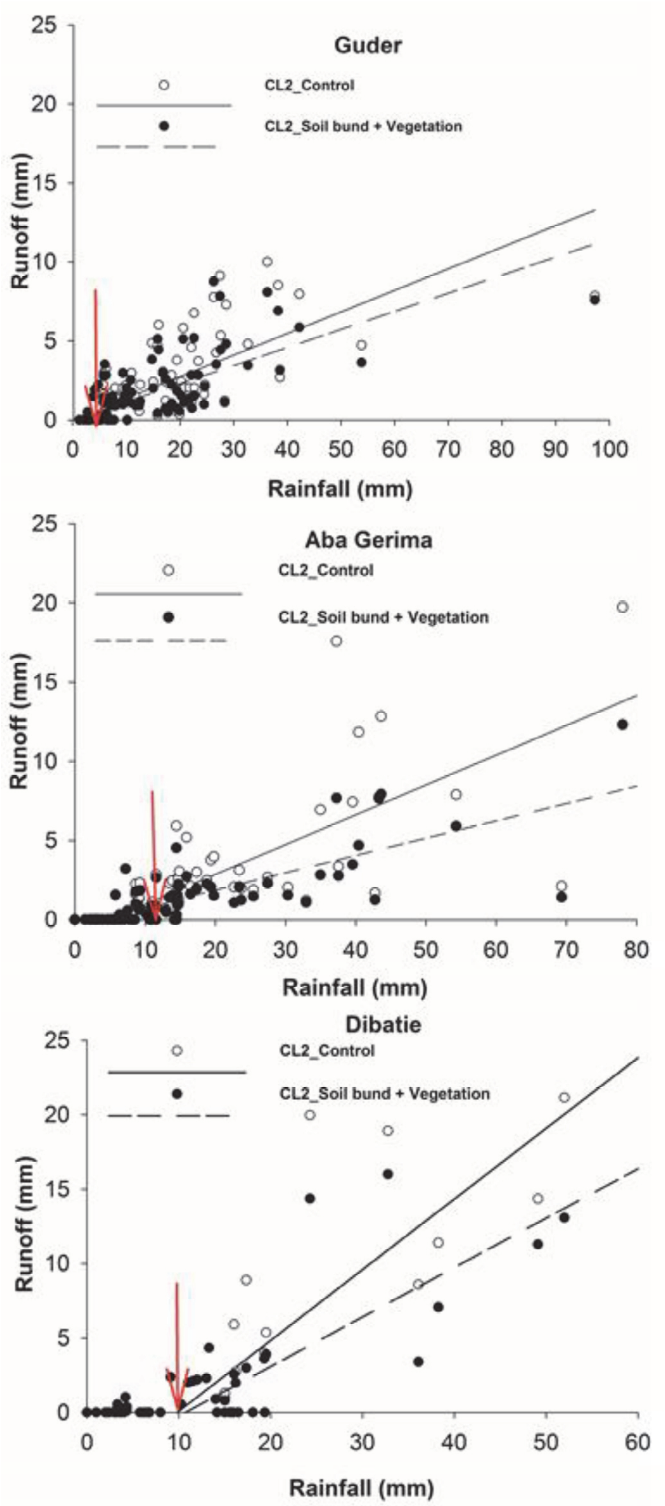

Figure 2-4 Regressions of runoff as a function of rainfall (excluding the events that produced no runoff) and its use to determine the rainfall thresholds (arrows) for six plot types: CL2 control, cultivated control plots on steep slopes; CL2 soil bund, cultivated plots on steep slopes with a soil bund combined with vegetation establishment.

Table 2-4 Rainfall threshold (T, mm) required to generate runoff, and slope of the rainfall–runoff curve (mm runoff/mm rainfall) for each plot at the three study sites. n, number of observations. Regression significance: *, $P < 0.05$; ns, not significant.

Site	Plot code [a]	*T*	Slope	R^2	*n*
Guder	CL2 control	6	0.107	0.35 *	70
	CL2 soil bund		0.097	0.37 *	70
	GR2 control	5	0.062	0.03 *	75
	GR2 short trench		0.041	0.03 *	75
Aba Gerima	CL2 control	11	0.182	0.41*	45
	CL2 soil bund		0.109	0.45 *	45
	GR2 control	9	0.412	0.38 *	46
	GR2 short trench		0.128	0.34 *	46
Debatie	CL2 control	10	0.450	0.67*	36
	CL2 soil bund		0.310	0.53*	36
	GR2 control	9	0.298	0.62*	38
	GR2 short trench		0.188	0.59*	38

[a] CL2 is cultivated land on steep slopes; GR2 is grazing land on steep slopes; soil bund is combined with vegetation establishment on steep slopes.

On average, the rainfall threshold values at our study sites are higher than those in semiarid regions of northern Ethiopia (the Tigray region). For example, Descheemaeker et al. (2006) obtained rainfall threshold values ranging from 3 to 16 mm in plots with different land use and cover types. Similarly, Girmay et al. (2009) reported that rainfall events >2 mm produced runoff in cultivated land, whereas rainfall events >3 mm produced runoff in both grazing land and plantation areas. This illustrates the lower interception capacity of vegetation canopies at semi-arid sites and the lower infiltration capacity of soils in drier environments (Pilgrim et al., 1988). It is worth noting that the experimental plot dimensions (5 m×2 m and 10 m×2 m in the previous studies, both of which were much smaller than the dimensions in the present study) can strongly affect the results of such studies, as the runoff amount is strongly influenced by scale effects (Bergkamp, 1998).

2.3.3 Effects of the soil and water conservation measures on *RC* and *RCE*

The percentage of seasonal rainfall lost as runoff (*RC*) from control plots in the Guder watershed ranged between 14 and 36%, versus 18 to 40% at Aba Gerima and 14 to 23% at Dibatie (Table 2-3), demonstrating the high variability of *RC* across the three studied environments. *RC* also differed between the control and treatment plots at each site. Monthly *RC* was highest in July and August in most treatments and decreased during September and October at all sites (Fig. 2-5). This can be explained by decreasing rainfall at the end of the rainy season combined with increasing vegetation cover during the rainy season, which would decrease runoff generation.

The knowledge provided by the present study about the *RC* of various land uses under different agro-ecology systems is essential to support estimates of runoff from a given watershed under a given land use. This, in turn, can help land managers to design appropriate water-harvesting structures, such as drainage canals, waterways, and reservoirs, and to predict flood hazards (Adimassu and Haile, 2011; Haregeweyn et al., 2016)

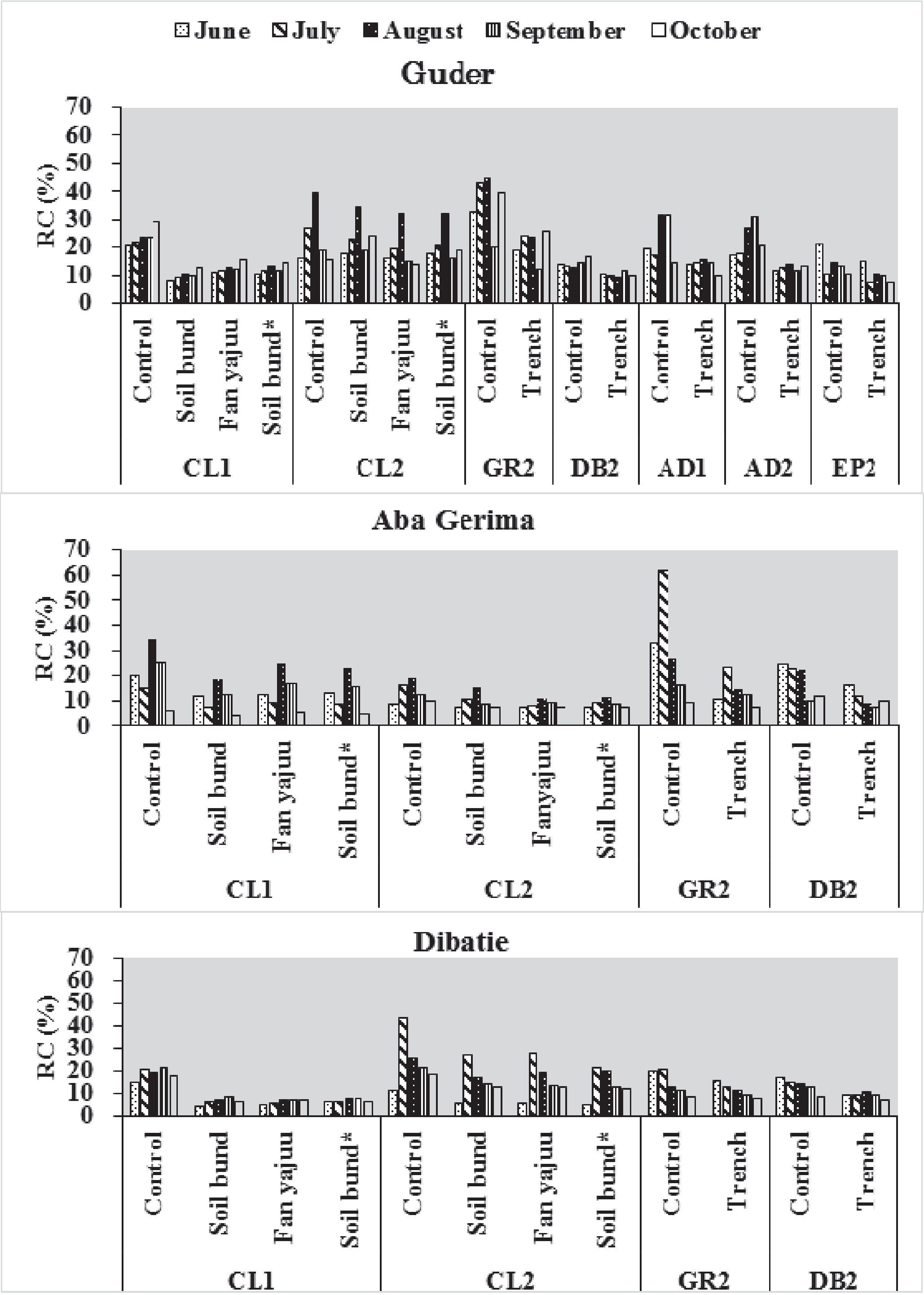

Figure 2-5 Seasonal patterns of runoff coefficient values (RC, %) under different combinations of soil and water conservation measures and combinations of land use (CL, cultivated land; GR, grazing land; AD, Acacia decurrens plantation; EP, Eucalyptus spp. plantation; DB, degraded bush), slope (1, gentle; 2 steep) and * is a soil bund combined with vegetation establishment.

At the Guder site, the *RCE* of the soil and water conservation measures ranged between 27 and 47%, versus 25 to 51% at Dibatie and 35 to 55% at Aba Gerima (Table 3). In general, the highest *RCE* was obtained for plots treated with soil bunds combined with vegetation establishment based on the average for cultivated land. The soil bunds combined with vetiver grass (*V. zizanioides*) at Debatie were more effective (*RCE* = 51%) than those with treelucerne (*C. proliferus*) and densho grass (*P. pedicellatum*; *RCE* = 32%) and elephant grass (*P. purpureum*; *RCE* = 36%). In contrast, Amare et al. (2014) obtained the lowest runoff values for soil bunds combined with elephant grass, followed by soil bunds combined with the legume species *Tephrosia* in the northwestern Ethiopian highlands, and they also suggested that vetiver grass required a longer establishment period before it could begin to conserve soil and water efficiently. For the plots in non-agricultural land, the highest *RCE* (55%) was obtained in GR2 plots treated with short trenches at the Aba Gerima site. On average, the establishment of soil and water conservation measures decreased runoff by 35, 41, and 42% at the Guder, Debatie, and Aba Gerima sites, respectively. Thus, there is strong evidence that the adoption of soil and water conservation practices can reduce runoff more in areas with low rainfall than in areas with high rainfall. This is because dry soils have higher infiltration capacity than wet soils during the rainy season (see seasonal potential evapotranspiration values in section 2.3.4 for details).

Higher *RCE* was obtained in all treatments in plots with a gentle slope than in the comparable treatment in plots with a steep slope due to the greater difference in runoff between the treated and control plots. In general, creating short trenches and soil bunds combined with vegetation establishment produce better runoff reduction than the other practices, especially in grazing land and cultivated land.

2.3.4 Effects of soil and water conservation on soil moisture availability

The combination of the distinctive features of the agro-ecology system, of the soil and water conservation practices, and of the associated hydrological processes affected the seasonal water availability in the plots (Fig 2-6). The seasonal potential evapotranspiration values determined using the Hargreaves and Samani (1985) equation were 579, 675, and 732 mm for the Guder, Dibatie, and Aba Gerima sites, respectively. The soil water availability (Fig.2-4) obtained by means of the water-balance method ranged from 428 to 830 mm, from 394 to 515 mm, and from 7 to 124 mm for the Guder, Aba Gerima, and Dibatie sites, respectively. The differences in these ranges can be attributed to differences in the frequency of rainfall (amount), soil type, runoff amount (Table 2-3), and potential evaporation among the different agro-ecology systems. On average, implementation of soil and water conservation measures increased seasonal water availability by about 139 mm compared with the control plot at the Guder site, versus 130 and 67 mm at the Aba Gerima and Debatie sites, respectively (Fig 2-6). This indicates that the infiltration and runoff dynamics were also influenced by slope length, because the reduction of slope length caused by installation of the conservation structures increased storage and thereby reduced the volume of runoff.

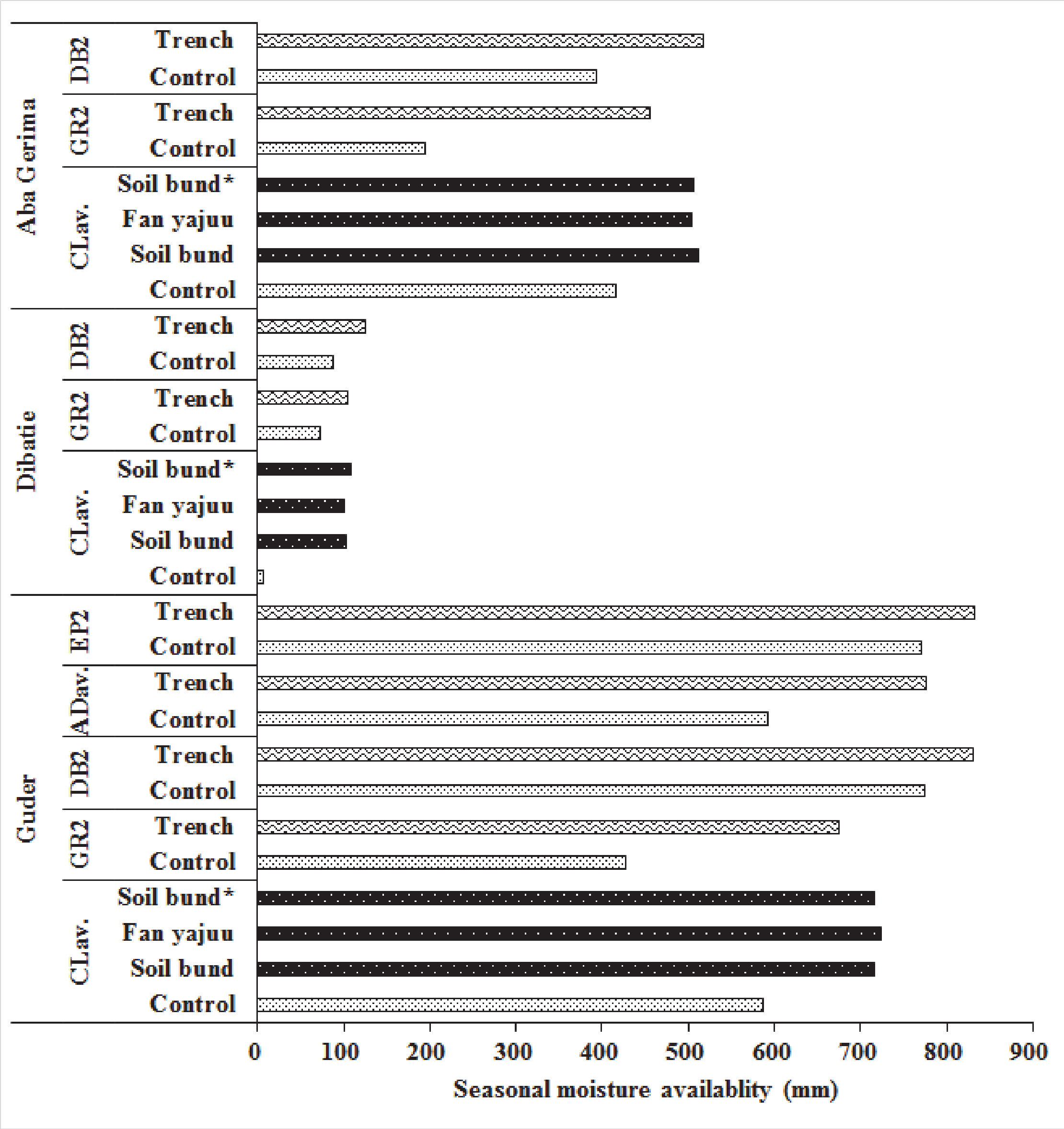

Figure 2- 6 Comparison of the effects of the different soil and water conservation (SWC) practices on water availability during each month of the rainy season for the different agro-ecology systems (n = 18 plots at Guder, 12 at Aba Gerima, and 12 at Dibatie). Codes represent combinations of land use (CL, cultivated land; GR, grazed grassland; AD, Acacia decurrens plantation; EP, Eucalyptus spp. plantation; DB, degraded bush) and slope (1, gentle; 2 steep; av, the average of the two slopes).

Our results indicated that areas with higher rainfall (e.g., Guder) had higher potential soil moisture, and therefore a lower rainfall threshold to generate runoff. (see section 2.3.2 for details.) This decreased the conservation efficiency of the various soil and water conservation practices (Table 2-3). Consequently, the role of management practices was more important; that is, it's more necessary to choose and design the optimal structure for these sites, i.e., where there is more runoff, there is more sediment transport capacity. Hence to control erosion and offsite transport of sediment, soil and water conservation planers need to focus on the safely disposal of the runoff to avoid risk of crop damage due to flooding or increase opportunities for sediment deposition from overland flow. This understanding helps to balance the soil erosion effect against the moisture retention/shedding effect of different measures.

Herweg and Ludi (1999) illustrated that runoff control requires a careful consideration of the design of soil and water conservation structures in relation to site characteristics. For example, in sub-humid or wetter areas with high rainfall, managers must prioritize both soil conservation and drainage of excess water. In addition, Nyssen et al. (2004) reported that in wet areas, investments in soil and water conservation may not be profitable at the farm level, although there are positive social benefits from controlling runoff and soil erosion at a regional level.

Although many of the methods discussed in this paper have been tried in the study area, they have not been widely adopted and have sometimes been dis-adopted where they were tried. To solve these problems, it will be necessary for the government and other stakeholders to increase knowledge transfer (extension) services to demonstrate the successful use of the techniques. In addition, the conservation structures all require ongoing maintenance. This agro-ecological classification and its related information assists in utilizing the research and field experience of one place to other places of identical soil, climatic and topographic conditions.

2.4 Conclusions

In this study, we provided an overview of the hydrological dynamics and effectiveness of soil and water conservation practices to reduce runoff under the common agro-ecology systems in Ethiopia's Upper Blue Nile basin. These results can guide managers towards the optimal choice of soil and water conservation measures under specific site conditions. Our study revealed that the responses of runoff and runoff conservation efficiency to soil and water conservation practices were highly variable both within and between agro-ecology systems. This high variation could be attributed to a combination of several factors: the type of soil (permeability), land use, soil water availability, the response of runoff to rainfall, and the prevailing climatic conditions (precipitation and potential evapotranspiration). These practices were highly effective in controlling runoff in the humid subtropical (*Moist Weyna Dega*) and tropical hot humid (*Moist Kolla*) agro-ecology systems, with average runoff reductions of 42 and 41%, respectively. The moist subtropical region (Guder) had a higher potential soil moisture availability, but a lower rainfall threshold to generate runoff. From these findings, implementation of short trenches (humid subtropical) in grazing land maximized the efficiency in conserving runoff (55%) due to temporary water storage in the short trenches, followed by infiltration. In contrast, vegetated bunds would be most effective in cultivated land, and short trenches would be effective in the two plantation types. Our results demonstrate the importance of studying each combination of agro-ecology system, site, and climate to scientifically determine the optimal conservation measures for that combination instead of making blanket recommendations for all systems that are likely to provide suboptimal results for many combinations. This understanding and the present results will help managers to choose the most effective conservation measures based on field trials and to test whether they will be equally applicable at other locations with similar soil, climatic, and topographic conditions.

Chapter 3

Analysing the runoff response to soil and water conservation measures in a tropical humid Ethiopian highland

This chapter is based on: Dagnenet Sultan, Atsushi Tsunekawa, Nigussie Haregeweyn, Enyew Adgo, Mitsuru Tsubo, Derege Tsegaye Meshesha, Tsugiyuki Masunaga, Dagnachew Aklog, and Kindiye Ebabu

3.1 Introduction

Since the 1980s, both government and non-government organizations have invested heavily in initiatives to tackle widespread land degradation in the Ethiopian highlands (Adgo, Teshome, & Mati, 2013; Adimassu, Mekonnen, Yirga, & Kessler, 2014; Amare et al., 2014; Benin & Pender, 2001; Gebrernichael et al., 2005; Haregeweyn et al., 2015; Herweg & Ludi, 1999; Hoben, 1995; J Nyssen, Haile, Moeyersons, Poesen, & Deckers, 2000; Sutcliffe, 1995). The most widely implemented soil and water conservation (SWC) practices include soil or stone bunds, grass strips, *fanyajuu* terraces (a Swahili word meaning 'throw uphill') and other physical structures (Dagnew et al., 2015; Haregeweyn et al., 2015). Recently, the combination of physical structures with biological measures has been implemented in arid to semi-humid lands; however, the effects of these practices on runoff and ways of representing them in runoff models have not been sufficiently evaluated.

Dagnew et al. (2015) argue that among the previous research reports, there is no common consensus on the effectiveness of SWC interventions implemented so far in Ethiopia. Bewket and Sterk (2002) and Herweg and Ludi (1999) found that SWC structures in many cases were not effective in reducing erosion over an extended time period. In semi-arid areas, SWC practices were generally effective in reducing runoff, erosion, land degradation and increasing base flow (Jan Nyssen et al., 2010). Furthermore, studies on the effectiveness of SWC structures on runoff and soil-loss reduction have mainly focused on stone bunds (Gebrernichael et al., 2005; Haregeweyn et al., 2017; Haregeweyn et al., 2016; Jan Nyssen et al., 2007; Taye et al., 2013). Many of these previous SWC studies in Ethiopia focused on the effectiveness of the physical SWC structures on runoff reduction with a particular focus on the semiarid regions in the north of the country (Haregeweyn et al., 2016; Jan Nyssen et al., 2010; Jan Nyssen, Poesen, & Deckers, 2009; Taye et al., 2013). A study by Haregeweyn et al. (2015) reported that the efficiency of such SWC measures are influenced by the type of measures and the agro-ecology under which they were implemented. However, data on the effectiveness of physical SWC structures such as soil trenches and bunds with or without biological measures and their effects on runoff model variables such as curve number (CN) are scant in such tropical humid regions. However, in the absence of extensive field studies and runoff measurements, models have been used to estimate site specific information.

SWC effectiveness is mainly determined from directly measured runoff values from various land-use treatments on the basis of runoff reduction or increase (Herweg & Ludi, 1999) or runoff coefficients.

In the Ethiopian highlands, models have mainly been applied to estimate soil losses from prevailing practices rather than to simulate the effectiveness of SWC practices (Betrie, Mohamed, Griensven, & Srinivasan, 2011). Therefore, demonstrating the impacts of SWC practices by upscaling plot-level studies to the landscape using a modeling approach can be used to evaluate overall effects at the basin scale (Haregeweyn et al., 2017; Haregeweyn et al., 2016; Ullrich & Volk, 2009). One of the challenges of using a modeling approach is the selection of realistic model input parameters for field conditions with and without SWC practices, given regional variations in soils, climate, and practices, and often a lack of field data upon which to make the determination (Feyereisen et al., 2008). By extending field-scale measurements, we can use simulation modeling to assess and compare the influences of various SWC practices on hydrology in the tropical highlands of Ethiopia.

Accurate surface runoff estimation techniques suitable for ungauged watersheds are important in areas such as Ethiopia, where hydrologic gauging stations are not widely available (Haregeweyn et al., 2016). The runoff estimates can be used to assess the potential water yield of watersheds and plan water conservation measures; other benefits include obtaining estimates of ground water recharge and the reduction of sedimentation and flooding hazards downstream (Patil, Sarangi, Singh, & Ahmad, 2008). In many parts of Ethiopia, the low accuracy of hydrological models means that most man-made hydraulic structures are not optimally designed (Teka et al., 2013). Overall, the impact of SWC structures on the hydrological responses of catchments has been overlooked during the water resource planning and design phases of structures. Therefore, an understanding of the effect of SWC treatment on hydrological response is crucial for the proper design of water harvesting schemes and to resolve the conflicts between treating catchments with SWC measures and collecting water in reservoirs for irrigation (Taye et al., 2011).

Several approaches can be used to estimate runoff, from simple empirical rainfall–runoff models to conceptual and highly parameterized process-based models whose application is restricted to regions for which sufficient data are available (Haregeweyn et al., 2016; Jakeman & Hornberger, 1993). Jha and Smakhtin (2008) provided a review of hydrological methods used for surface runoff estimation in ungauged watersheds; such as, the rational formula, the runoff coefficient method, low flows and duration curve, regional regression equations, and runoff curve number methods. The most popular method for predicting event-based surface runoff volume from small watersheds is the SCS-CN method, now known as the Natural Resource Conservation Service (NRCS)-CN method developed by the USDA-Soil Conservation Service (SCS, 1972). The (NRCS)-CN method was developed from the statistical analysis of plot runoff data from the temperate climate of the United States. The model is documented in the NRCS National Engineering Handbook Section-4 (NEH-4) in tables (Ponce & Hawkins, 1996) that represent average values for samples taken over a broad area (Feyereisen et al., 2008). To simulate water balances and predict runoff from catchments covered by different land-use types, many hydrological models make use of this method (Descheemaeker et al., 2008), including CREAMS (Knisel, 1980), ANSWERS (Beasley, Huggins, & Monke, 1980), AGNPS (AGNPS, 1989), EPIC (Sharpley & Williams, 1990) and SWAT(Arnold, Williams, Srinivasan, King, & Griggs, 1994). Recently, the SCS-CN model was extended to estimate sediment yield and to model soil moisture (Reshmidevi, Jana, & Eldho, 2008; Singh, Bhunya, Mishra, & Chaube, 2008). Some researchers have also integrated the SCS-CN model into a GIS framework, coupled with remote sensed data, to extend the model's applicability to complex watersheds with high temporal and spatial variability (Geetha, Mishra, Eldho, Rastogi, & Pandey, 2007; Zhan & Huang, 2004) as cited in Bo, Qing-Hai, Jun, Feng-Peng, and Quan-Hou (2011). Despite its widespread use, however, the accuracy of the CN method has not been thoroughly analyzed (Ponce & Hawkins, 1996). The applicability of the NRCS model to watersheds different to those in which it was originally developed (the mid-west USA with a temperate climate) is contentious, because runoff mechanisms can be quite different in different climates. For example, in the USA, the dominant runoff mechanism is infiltration excess, whereas in an alternating dry and wet climate like the tropical highlands of Ethiopia, the dominant mechanism is saturated excess runoff (Liu et al., 2008; Steenhuis et al., 2009; S. Tilahun et al., 2013a; S. A. Tilahun et al., 2013b). For this reason, the CN determined from local studies has been found to be more reliable than those taken directly from the NEH-4 tables (Hawkins, 1993; Soulis & Valiantzas, 2012). Since the CN method's inception, several investigators have attempted to determine runoff CNs from small watershed rainfall–runoff data with the objective of either verifying the CN value given in the standard tables or to extend the methodology to soil–cover complexes and geographic locations not covered in the NEH-4 Handbook (Ponce & Hawkins, 1996). Most such experimental studies have concentrated on investigating the effects of slope, soil, antecedent moisture content, and rainfall intensity. In the highlands of Ethiopia, few investigations have derived CN values for local conditions reflecting the prevailing soils, land use, land management, slope, and SWC management practices on experimental derivation of CN (in northern Ethiopia, for example, (Descheemaeker et al., 2008)) and runoff coefficients. The main purpose of this study is to contribute a better understanding of the runoff response for better planning and management of water resources of the upper Blue Nile basin. To do so, we adopted integrated field experimentation and modelling.

The specific objectives of the study were to (1) assess the efficiency of various SWC practices in reducing surface runoff in the tropical humid highland climate region of the upper Blue Nile basin and (2) determine CN values for various SWC practices and (3) test to what extent the effect of SWC practices can be captured with the most commonly used CN runoff estimation method.

3.2 Methods

3.2.1 Study area description

The study was conducted in the Kasiry experimental watershed located in the upper Blue Nile basin at latitude 11°00′17″N and longitude 36°55′20″E, in Fagta Lekoma district in Awi zone of Amhara Regional State, Ethiopia (Fig 3-1). The slope ranges from 1% to 50% and the altitude varies from 2498 to 2857 m above mean sea level.

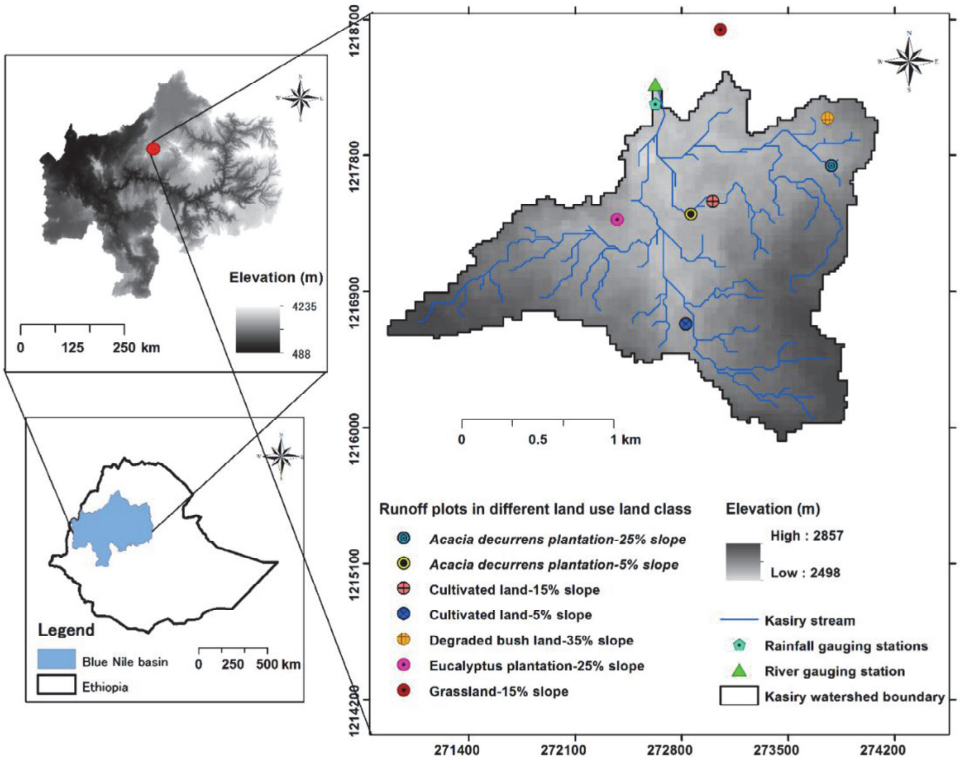

Figure 3-1 Location of Kasiry watershed in the upper Blue Nile basin, where 18 runoff plots representing different land-uses land classes (LULC) and slopes were established (Map projection is UTM, WGS 1984 zone 37N).

The annual rainfall distribution is unimodal. The rainy season extends from mid-May to the end of October. Annual rainfall for the period 2007 to 2014 obtained from the nearest meteorological station at Injibara (located 5 km far from the study site) averaged 2495 mm with a standard deviation of 395 mm. About 86% of the annual rain falls from May through September, with monthly averages during this period of 354, 362, 480, 540 and 411 mm, respectively (Fig 3-2). The average seasonal rainfall (2007–2014) and coefficient of variation (CV; in parentheses) of winter (Dec-Feb), spring (Mar-May), summer (June-Aug) and autumn (Sep-Nov) are 36 (0.74), 494 (0.69), 1382 (0.11) and 583 (0.12) mm, respectively. About 55% of the total annual rainfall falls in summer.

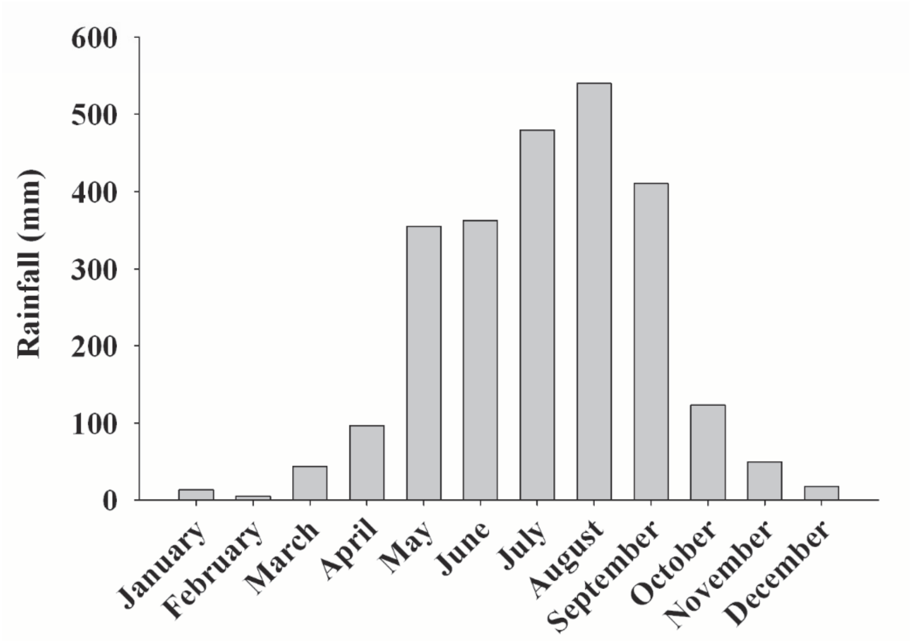

Figure 3- 2 Monthly rainfall for the period 2007 to 2014 at the Kasiry watershed as measured at Injibara station near to the watershed.

Temperature varies between the mean annual maximum of 25°C and mean annual minimum of 11°C across the elevation gradient. Annual average potential evapotranspiration of the Kasiry area was estimated using FAOCLIM 2.0 as 1161 mm, with the maximum monthly average daily potential evapotranspiration of 4.38 mm day^{-1} occurring in April. The mean annual rainfall divided by mean evaporation yields a desertification index of 2.15, which corresponds to a humid climate according to UNEP (1992). The upslope sections of the watershed are characterized by shallow soil profile whereas soils in the valley bottoms are very deep with almost a uniform profile. The dominant soil types in the watershed are red to reddish brown colored Nitisols and Acrisols (Nachtergaele & Batjes, 2012). We digitized and calculated the percentage area of the different land use types found in Kasiry watershed from a high resolution Google Earth image in a GIS environment, being guided by field observation points taken using a GPSMAP 62st/Garmin. On the basis of this analysis, we obtained that the watershed land use comprised cultivated land, acacia plantation, bush land, grazing land, and forest lands covering 39.1%, 30.1%, 17.5%, 9.5%, and 3.8% of the watershed respectively. Mixed crop and livestock farming is dominant in the study area, whereby both annual crop production and livestock management are practiced by small holder farmers to satisfy the basic needs of households. The major types of crop produced include teff (*Eragrostis tef*), maize (*Zea mays*), barley (*Hordeum vulgare)*, bread wheat (*Triticum aestivum*), potatoes (*Solanum tuberosum*), and field beans (*Vicia faba*). According to Attanandana and Yost (2003) Farmers of Ethiopian highlands have applied chemical fertilizers Di-Ammonium Phosphate (DAP) and urea to increase crop yields following a blanket recommendation, a situation in which fertilizers are applied to the field irrespective of site-specific and crop's nutrient requirement. In recent years farmers have been converting some crop production land to *Acacia decurrens* plantations mainly because of the higher economic return achievable through converting the wood into charcoal. The *A. decurrens* plantations have low investment costs and short (5–7 years) rotations. Livestock production is also an important component of the farmers' economic activities. The main livestock types kept by the small holder farmers are horses (*Equus caballus*), donkeys (*Equus africanus*), cattle (*Bos indicus*), goats (*Capra hircus*), and sheep (*Ovis aries*). Farmers keep animals mainly for one or more of the following reasons: (1) as investments; (2) as beasts of burden; and (3) to obtain manure as a household energy source. Overall, the crop and livestock are complementary components of the farming system with respect to nutrient cycling and fodder production. However, they also compete for space to some extent, which leads to intensification of land use and therefore land degradation processes (Haileslassie, Priess, Veldkamp, Teketay, & Lesschen, 2005). Therefore, information concerning such interactions is important to propose management measures for sustaining agro-ecosystem services.

3.2.2 Experimental setup and data collection

Experimental setup

A total of 18 experimental runoff plots (30 m long × 6 m wide, bounded at the sides and top) were established in May 2014. Plots were characterized by land use, slope, and SWC treatment (Table 3-1) which required them to be located in seven separated groups (land-use land classes; LULCs) within the watershed (Fig 3-1, Table 3-1). The five land-use types comprised cultivated land (CL) planted with potatoes (*Solanum tuberosum*) and beans (*Vicia faba*) and four non-agricultural (uncultivated) land-use types: grassland (GR), *Acacia decurrens* (AD), *Eucalyptus* spp. plantation (EP), and degraded bush land (DB) (Fig 3-3). The eight cultivated plots were divided into two groups of four plots, with one group on gentle slope of 5% (CL1 group) and one group on a steeper slope of 15% (CL2 group). Each of the four plots in the CL groups had a different SWC treatment (soil bund, *fanyajuu*, soil bund with biological treatment, and control). The AD plots were divided into two groups, one group of two plots on a gentle slope (AD1 group) and the other group of two plots on a steep slope (AD2 group). The other non-agricultural land-use types had only one group of two plots each, with only a single slope (steep) represented; therefore, they were designated DB2, EP2, and GL2, respectively. Each of the uncultivated groups had one of two treatments (trench or control) with different land use and slope: AD (5% and 25%), EP (25%), GR (15%), and DB (35%). The trenches were installed by excavating soil at a depth of 0.5 m in the arrangement of shorter length at the first row across the slope (1.4 m wide × 1.5 m long) and the longer length was in the next row (1.4 m wide × 2.5 m long) in a staggered way. In the CL plots, the soil bunds were reinforced and stabilized by planting a biological treatment such as tree lucerne (*Cytisus proliferus*) and densho grass (*Pennisetum pedicellatum).*

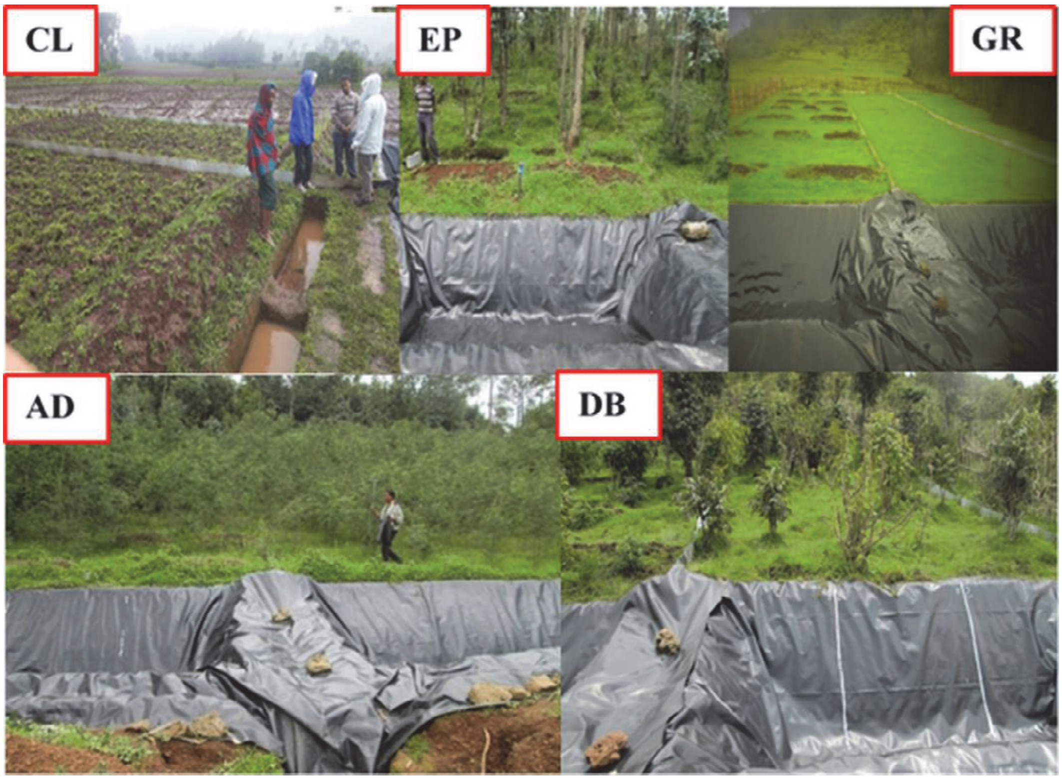

Figure 3-3 Runoff plots (6 m × 30 m) of different land uses and management types under study in the Kasiry watershed: (CL) cultivated land, (EP) eucalyptus forest, (GR) grazing land, (AD) Acacia decurrens, and (DB) degraded bush land. All photographs were taken during the wet season in 2015.

Plot characterization

To characterize the runoff plots, various soil variables were determined (Table 3-1). Twenty-one soil samples in total were taken from the top 30 cm depth at intervals of 10 cm down the profile for seven separated land-use land classes and analyzed for texture using the hydrometric method (Shieldrick & Wang, 1993). Three samples were taken for each land- use land-class and their average value was considered for the plot characterization. The soil samples were also analyzed for organic carbon (OC) using the Walkley–Black method (Jackson, 2005). The soil of the degraded land plot had a higher organic matter content than that of the other plots. Surface stoniness was assessed by sieving. In all plots, the rock fragment cover of soil surfaces was negligible. Soil depth measurement was carried out using auger hole observation at all sampling points during summer rainy season of year 2014s. At all sampling points soil was not deeper than 1 m, the maximum depth to which augering was extended. For bulk density determination, undisturbed soil samples were taken within the 0–10, 10–20, and 20–30 cm depth intervals using a core sampler of 100 cm^3. They were dried in an oven at 105°C for 24 h and the sample weighed. The bulk density of the soil was determined by dividing the weight of the oven dried soil samples by the volume of the soil core. Seasonal water table depth was monitored weekly by installing piezometer for each land use. The readings helped us assign criteria for hydrologic soil group (HSG). A constant head method was used to determine saturated hydraulic conductivity (K_{sat}) of undisturbed core samples. The slope gradient of the runoff plots was measured by clinometer.

Rainfall measurement

The study site was equipped with one automatic tipping bucket rain gauge (Hobo Data Logging Rain Gauge RG3-M, Onset Computer Corporation, Bourne, MA, USA) and one manual rain gauge (Figure 3-1). From tipping data measurement, tips of rainfall was recorded and counted, the tipping rain gauge tips whenever the bucket stores 0.2 mm of rainfall then the tips were changed in to event rainfall by taking the character of tropical rainfall into consideration, it has been considered that one event should have a duration of at least 15 min and be separated from other events by at least 30 min (Meshesha, Tsunekawa, Tsubo, Haregeweyn, & Adgo, 2014). These event rainfall from the tipping bucket rain gauge was used to determine the rainfall intensity and characterize rainfall in the study area during the period from 14 August to 9 October 2014. However; we used the data of manual rain gauge recorded from July through September for rainfall-runoff analysis since runoff was measured only on a daily basis for longer periods. During this period, 92 total daily rainfall events were measured manually (ranging from 0.3 to 54 mm).

Table 3-1 Characteristics of 30 m long × 6 m wide runoff plots used to study the effect of land use and soil and water conservation (SWC) practices on runoff in Ethiopia.

Land use × slope group	SWC treatment	Slope (%)	Spacing (m)	Soil depth (cm)	Number of SWC per plot	Soil type	Organic matter (%)	Dry bulk density (g cm^{-3})	Hydrological soil groups (SCS 1972)
CL1	Control	5	—	100	0	clay loam	6.8	1.1	D
	Stone bund		7.8		3				
	Fanyajuu		7.8		3				
	Soil bund *		7.8		3				
CL2	Control	15	—	100	0	clay loam	6.3	1.1	D
	Stone bund		5.5		4				
	Fanyajuu		5.5		4				
	Soil bund *		5.5		4				
AD1	Control	5	—	100	0	clay	2.3	1.4	D
	Trench		2.9		15				
AD2	Control	25	—	70	0	clay loam	5.3	1.1	D
	Trench		1.7		20				
GR2	Control	15	—	80	0	clay loam	8.9	1.0	D
	Trench		1.7		20				
EP2	Control	25	—	78	0	clay loam	6.2	1.0	D
	Trench		1.7		15				
DB2	Control	35	—	75	0	sandy loam	16.7	0.8	C
	Trench		1.7		20				

Plot number codes refer to land use represented: CL is cultivated land (CL1 planted with beans, whereas CL2 planted with potato); DB is degraded bush; AD is Acacia decurrens plantation; EP is Eucalyptus spp. plantation; and GR is grassland, 1 & 2 refers to gentle and steep slope respectively. * the soil bund treatment comprised a bund combined with a vegetation strip, 0 indicates no SWC structure, *Runoff collection*

Runoff data were measured on a daily basis, and the runoff depth corresponding to each daily rainfall was recorded and used for runoff analysis. At the lower end of each plot, a 9.7-m3 size trapezoidal trench (Fig.3-4) was excavated and lined with a geo-membrane plastic for the collection of sediment and runoff. The runoff collection trenches were designed to accommodate runoff resulting from extreme rainfall events using the maximum possible daily runoff based on anticipated rainfall and runoff coefficient. A rating curve relating the depth to volume of the trench was established for each trench by adding a known volume of water to the trench. Then based on this relationship, runoff volume was calculated from runoff depth measurements taken every morning at around 8:00 AM with a meter rule from an average of six measuring points in the trench to account for variations

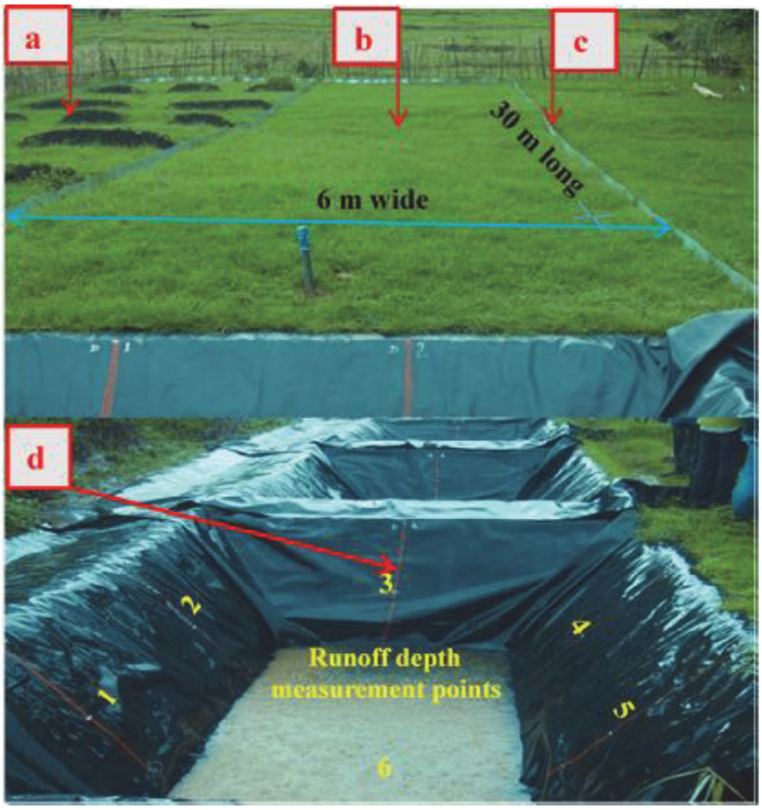

Figure 3- 4 Layout of runoff plots in grazing lands in the Kasiry watershed: (a) plots with soil water conservation (SWC) measures; (b) plots without SWC measures; (c) corrugated iron for plot boundaries; (d) runoff collection trench lined with a geo-membrane plastic. Water depth was measured at six points marked by red lines on the trench liner.

in water depth due to bottom irregularities. The effect of direct rain falling on the trench was subtracted. At the top of each plot, a run-off interception ditch was installed to protect the plots from ingress of overland flow. The plots were also bounded at the sides to prevent runoff and sediment flow into and out of the plot using sheets of corrugated iron inserted into the ground to a depth of 15 cm and protruding 20 cm above the ground.

3.2.3 Estimating efficiency of the SWC treatments in runoff reduction

All plot data were analyzed and interpreted using both the runoff coefficient (RC) and CN approaches (Fig. 3-5). The RC was used to assess the efficiency of the SWC measures while the CN approach was tested for its suitability to estimate runoff response in a humid tropical climate treated with different SWC conservation practices, considering that their effect was not explicitly addressed in the original equation. An unpaired student’s t-test was used to test for differences in mean daily plot runoff between SWC treatments for runoff plots within each land use and slope group.

Determination of the runoff coefficient

A runoff coefficient (RC) is the ratio of runoff to the corresponding rainfall both expressed as depth (mm) over the runoff plot. Runoff coefficients also indicate what proportion of rainfall becomes runoff (Fig 3-5). This means that the smaller the runoff coefficient of a given land use, the more effectively that rainfall is infiltrated and runoff is reduced. Knowledge of the RCs of various land uses is essential to estimate the amount of runoff collected from a given catchment under a given land use. To determine the impact of the SWC treatments, runoff and RC (%) values of the respective control practices were set at 100%. On this basis, the reduction or increase in percent was calculated for each treatment.

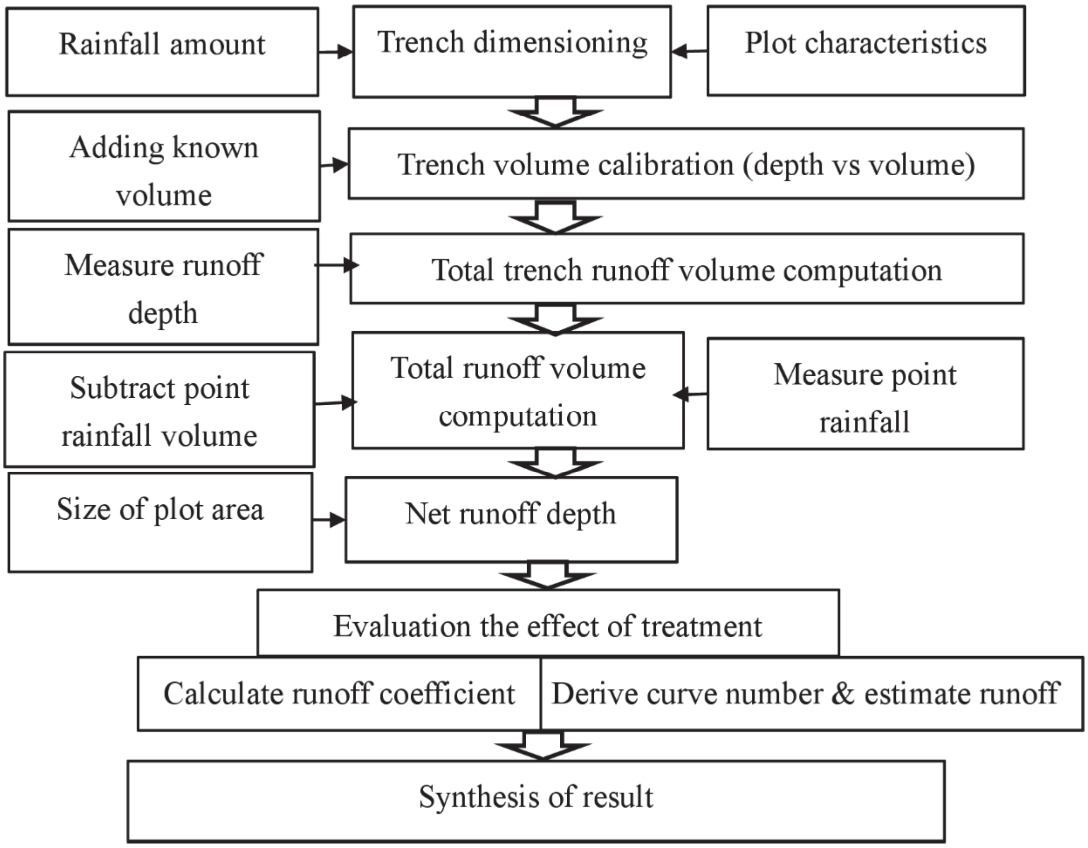

Figure 3-5 Flowchart of the methodology used for runoff plot data collection and analysis in the Kasiry watershed.

Derivation of curve number for various SWC practices

The existing NRCS runoff model is expressed as (SCS, 1972):

$$Q = \frac{(P - \lambda S)^2}{(P + (1 - \lambda) S)} \qquad P > \lambda S, \tag{3-1}$$

where P is the rainfall (mm), Q is runoff (mm), and λ is the initial abstraction ratio (the ratio of initial abstraction to maximum potential retention, Ia/S) which is a nondimensional value ranging between 0 and 1 and in the existing (NRCS)-CN method is assumed to have a value of 0.2 (Haan & Schulze, 1987). In most studies, λ is simply set to 0.2. S is the maximum potential retention (mm) obtained from (SCS, 1972):

$$S = \frac{25400}{CN} - 254 \tag{3-2}$$

where CN ranges from 0 to 100. The CN represents an empirical relationship between land use, hydrologic soil group, and antecedent moisture content (AMC) (SCS, 1972). In this study, the CN for the plots under different land uses and management practices was determined experimentally from 18 plots (30 m long × 6 m wide) using measured rainfall and runoff data. First, a series of available daily rainfall (P, mm) and corresponding runoff (Q, mm) depth data were compiled. These data were filtered by removing the pairs of P–Q data with runoff factors that exceeded rainfall ($C = Q/P \geq 1$) (Hawkins, 1993). Then, the scatter data were assumed to be described by a log-normal distribution about the median. Hjelmfelt Jr (1991) employed a similar approach in his investigation of the curve number procedure.

The specific procedure was as follows: First, the maximum potential retention S was computed from each pair of daily runoff volume Q and rainfall volume P as shown in Eq. (3-3) (Hawkins, 1993):

$$S = 5\left(P + 2Q - \sqrt{4Q^2 + 5PQ}\right) \tag{3-3}$$

Second, the mean (μ) of the logarithms of the seasonal maximum potential retention S was determined from (Hawkins, 1993):

$$\mu_{\log S} = \frac{\sum \log S}{N} \tag{3-4}$$

where, N is the number of observations in the rainfall–runoff record. The logS, which is the mean of the transformed values is the median of the series of the maximum potential retention if the distribution is lognormal.

The geometric mean (GM) of the maximum potential retention S is the anti-logarithm of the mean (logS) (Hawkins, 1993):

$$S_{GM} = 10^{\mu_{\log S}} \tag{3-5}$$

Then the median CN value is determined as follows (Hawkins, 1993):

$$\mathrm{CN} = \frac{25400}{\mathrm{S_{GM}} + 254} \tag{3-6}$$

Using the derived event runoff median CN for all land-use treatments, runoff was calculated using Eq.1 (SCS, 1972) and compared with measured runoff by using statistical methods such as coefficient of determination (r^2).

To compare the derived median CN with tabulated CN values, the following procedure was followed: The tabulated CN was obtained from the published value presented in the NRCS National Engineering Handbook Section-4 (NEH-4) (Part 630, Hydrology) standard tables (USDA-NRCS, 2001). Values of CN were assigned based on a combination of land use, hydrologic soil group, and treatment class from the plot characteristics (Table 3-1). The NEH-4 tables have insufficient information on the effects of various physical SWC treatments on CN. Contoured and terraced structures for agricultural lands (cultivated land) are the only treatments included. Land treatments for nonagricultural lands are not explicitly presented. Therefore, assigning a CN value to land under different conditions than presented in the standard tables requires subjective judgment. Here, the assumption for the NRCS average table curve number (CN2) corresponded to 5% slope. The values obtained were adjusted for slope by the following empirical equation given by Huang, Gallichand, Wang, and Goulet (2006):

$$\mathrm{CN}_{2\alpha} = \mathrm{K} \times \mathrm{CN}_2 \tag{3-7}$$

$$\mathrm{K} = \frac{322.79 + 15.63\alpha}{\alpha + 323.52} \tag{3-8}$$

where: $\mathrm{CN}_{2\alpha}$ is the slope-adjusted CN, α is slope (m m^{-1}) ranging from 14% to 140%, and K is a conversion factor.

3.3 Results

3.3.1 Rainfall intensity analysis

We analyzed the event rainfall data recorded using the tipping bucket rain gauge between 16:41 on 14 August 2014 and 15:35 on 2 December 2014 (Fig 3-6). A total of 141 rainfall events recorded during this period were used to determine the average rainfall intensity of these events (Fig 3-6). The maximum event rainfall depth during this period was 41 mm that fell over a span of 8 hours. The maximum intensity recorded was 45.1 mm h^{-1} on 16 September (29 mm depth for 0.62 hours). The number of rainfall events in four event-size classes were 0–5 mm, 94; 5–10 mm, 24; 10–20 mm, 19; and 20–50 mm, 4. This shows that a higher proportion of rainfall (63%) in the study area comes in the form of light rainfall events.

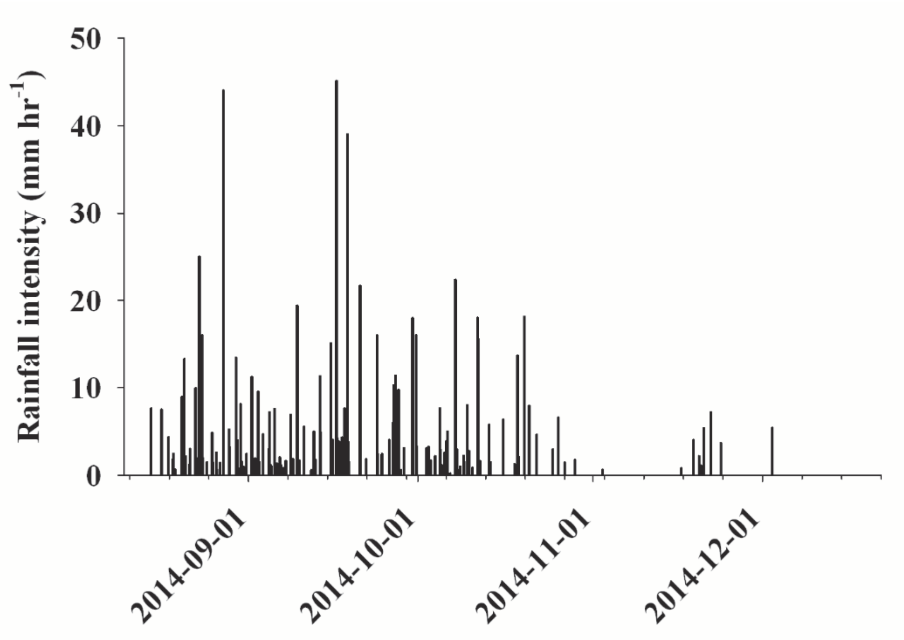

Figure 3-6 Rainfall intensity of discrete events measured by tipping bucket rain gauge at the Kasiry watershed site.

3.3.2 Effects of SWC practices, land use, and slope on runoff

Daily, monthly, and overall seasonal (July through September) runoff response from the plots varied from 0.07 to 30, 18 to 249, and 134 to 440 mm, respectively (Table 3-2). The soil bunds combined with a biological measure had the lowest runoff depth (140 mm) compared to the other SWC treatments on the CL plots (140 to 287.4 mm). On average, SWC structures in the CL plots reduced runoff by 44% as compared to the untreated control plots. Seasonal runoff coefficients (RCs) were much higher for the steep cultivated (CL2) plots planted with potatoes (0.16–0.34) than for the gently sloped cultivated (CL1) plots planted with beans (0.06–0.11). The RC doubled as the slope changed from 5% to 15% in the CL plots. The RC from cultivated croplands treated with soil bunds combined with or with no biological measures varied between 11% and 12.5%, whereas the values from control plots were in the range 10.6%–34.6%.

Incorporating the SWC technique of trenches aligned normal to the slope significantly contributed to the effect of vegetation on the runoff process in the non-cultivated plots. Trenches reduced runoff and the runoff coefficient by 65% and 61% as compared to untreated control (i.e., conventional practice) plots respectively. For all the non-agricultural plots, the RCs were clearly higher on control plots without SWC structures (0.11–0.33) than on the plots with trenches (0.05–0.1) (Fig 3-7). The effect of slope on RC in the AD plots was the reverse of what would be expected, with a lower RC on the plots with the steeper slope gradient (Fig 3-7).

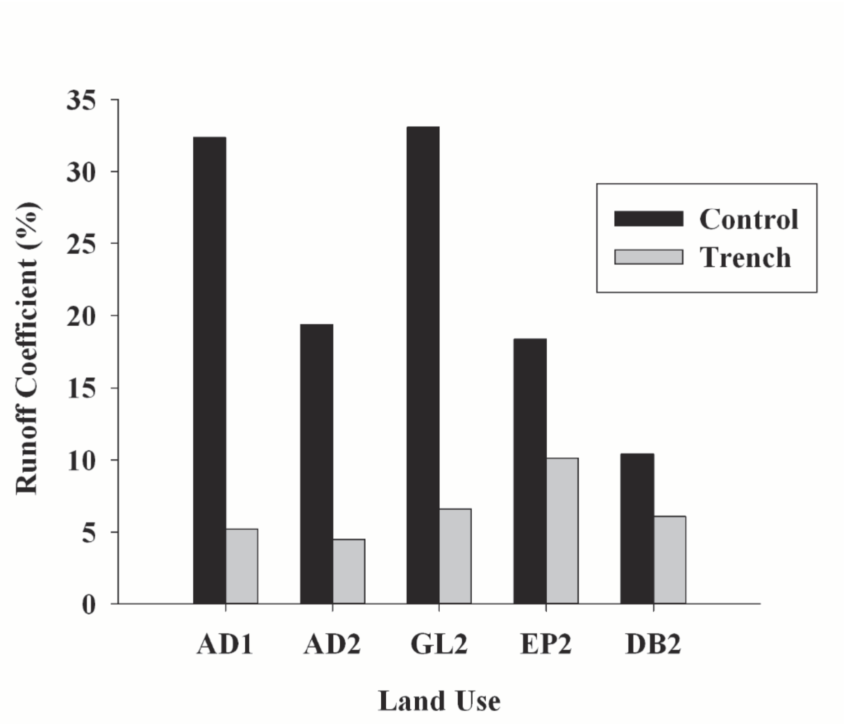

Figure 3-7 Runoff coefficients from plots of different land use and slope class with and without trenches. AD, Acacia decurrens; EP, eucalyptus forest; GL, grassland, DB, degraded bush land; 1, gentle slope; 2, steep slope.

Average runoff was significantly less *from* plots with SWC measures than from untreated control plots ($p < 0.05$) (Table 2). However, no significant differences were found between SWC management practices within the same land use. In the gently sloped cultivated (CL1) plots, only the runoff from the soil bund with biological measure was significantly different from that of the untreated control plot. On the steep cultivated (CL2) plots, runoff from all the plots with SWC measures was significantly less than from the untreated control plot (Table 3-2), but no significant difference existed among the SWC treatments. These results confirm that the efficiency of the SWC measures improved as the slope increased.

Table 3-2 Impact of soil and water conservation (SWC) practices on runoff and runoff coefficient (RC) for different land uses and SWC practices in the Kasiry watershed for the period 1 July–30 September 2014.

Land use × slope group	SWC treatments	Cumulative Rainfall ±SD(mm)	Cumulative Runoff ±SD (mm)	Relative impact on runoff (%)	RC (%)
CL1	Control	1270.5 (11.3)	134.75 (3.3) a	100	10.6
	Soil bund		85.84 (2.7) a	–36	6.7
	Fanyajuu		86.85 (3.2) a	–35	6.8
	Soil bund*		74.09 (1.9) b	–45	5.8
CL2	Control	1270.5 (11.3)	440.06 (6.8) a	100	34.6
	Soil bund		231.81 (4.2) b	–47	18.2
	Fanyajuu		230.92 (3.7) b	−47	18.2
	Soil bund*		206.01 (3.1) b	−53	16.2
AD1	Control	1270.5 (11.3)	411.81 (6.8) a	100	32.4
	Trench		66.01 (1.1) b	−84	5.2
AD2	Control	1270.5 (11.2)	246.89 (4.5) a	100	19.4
	Trench		56.80 (0.9) b	−77	4.5
GL2	Control	1270.5 (11.3)	420.90 (6.0) a	100	33.1
	Trench		83.67 (1.3) b	−80	6.6
EP2	Control	1186.0 (11.6)	218.01 (3.8) a	100	18.4
	Trench		120.25 (1.6) b	−45	10.1
DB2	Control	1270.5 (11.2)	131.81 (2.3) a	100	10.4
	Trench		78.03 (1.1) b	–41	6.1

SD, standard deviation; Sets of daily runoff values for plots were compared within each land use; values followed by the same letter within a land use and slope class do not differ significantly ($p = 0.05$). * The soil bund treatment comprised a bund combined with a vegetation strip.

3.3.3 Effect of SWC management practice on derived event CN

Runoff

The overall derived median event runoff CN for the different land uses varied from 87.2 for the cultivated land treated with soil bunds to 95.9 for the untreated plots on grazing land (Table 3-3). The CN was higher for cultivated land with steep slopes (93.3–95.6) than for cultivated land with gentle slopes (87.2–90.1). In other words, CN was positively correlated with slope. The coefficient of determination (r^2) values of runoff estimated from event runoff CN and measured runoff lay between 0.1 and 0.73, implying that the derived event CN explains about half of the variation in the runoff data. However, for cultivated plots (CL1, CL2) and non-agricultural plots such as EP2 (Trench), AD2 (Trench), and GR2 (Trench), the r^2 values were between 0.1 and 0.4. For these plots, the overall CN did not adequately describe runoff.

The overall impact of applying SWC practices reduces the CN by 3 units and increases the maximum storage parameter S by 8 mm compared with untreated control plots on various land uses and slope (Fig 3-8). Applying SWC practices increased the storage parameter on the different land uses by 14 mm on GR, 11 mm on AD, 7 mm on CL, 5 mm on EP and 1.4 mm on DB (Table 3-3). This information will be used for Ethiopian highlands with similar environments and climatic settings.

Table 3-3 The runoff measured and estimated for different SWC practices implemented under different land-use types.

			Measured		Estimated				
Land use × slope group (1)	SWC practice (2)	*n* (3)	Mean rainfall depth (mm) (4)	Mean runoff depth (mm) (5)	S (±SD) (mm) (6)	Median event CN (7)	Mean runoff depth (mm) (8)	r^2 (5) & (8)	SE (5) & (8)
CL1	Control	38	±16.8 (12.8)	1.9	±27.87 (0.44)	90.1	4.9	0.23	6.9
	Soil bund	38		1.1	±37.43 (0.41)	87.2	3.6	0.15	5.9
	Fanyajuu	38		1.2	±35.02 (0.42)	87.8	3.9	0.15	6.2
	Soil bund*	38		0.9	±37.00 (0.39)	87.3	3.7	0.13	6.0
CL2	Control	38	±16.8 (12.8)	4.5	±11.78 (0.63)	95.6	7.6	0.35	7.5
	Soil bund	38		3.2	±17.29 (0.49)	93.6	6.0	0.38	6.3
	Fanyajuu	38		3.2	±17.36 (0.47)	93.6	6.0	0.37	6.4
	Soil bund*	38		2.8	±18.18 (0.49)	93.3	5.8	0.39	6.1
AD1	Control	49	±15.7 (13.2)	5.1	±14.20 (0.51)	94.7	7.8	0.72	5.1
	Trench	49		0.9	±29.31 (0.57)	89.6	4.7	0.33	5.6
AD2	Control	49	±15.7 (13.2)	2.9	±20.04 (0.67)	92.7	6.3	0.64	5.4
	Trench	49		0.8	±27.36 (0.71)	90.3	5.0	0.26	6.2
GR2	Control	38	±15.3 (13.2)	5.5	±10.66 (0.63)	95.9	6.7	0.73	5.6
	Trench	38		1.2	±24.67 (0.61)	91.1	6.1	0.25	6.8
EP2	Control	35	±16 (13.1)	3.4	±18.78 (0.56)	93.1	8.7	0.32	7.8
	Trench	35		1.9	±23.93 (0.53)	91.4	5.2	0.1	8.1
DB2	Control	37	±15.5 (13.06)	2.3	±25.80 (0.45)	90.7	4.9	0.54	5.1
	Trench	37		1.1	±27.27 (0.47)	90.3	4.8	0.46	5.1

* The soil bund treatment comprised a bund combined with a vegetation strip. The number of events (*n*), storage parameter (S), curve number (CN), standard deviation (SD) of the estimate of S for each land use and management type, standard error (SE) and coefficient of determination (r^2) of the measured and estimated runoff.

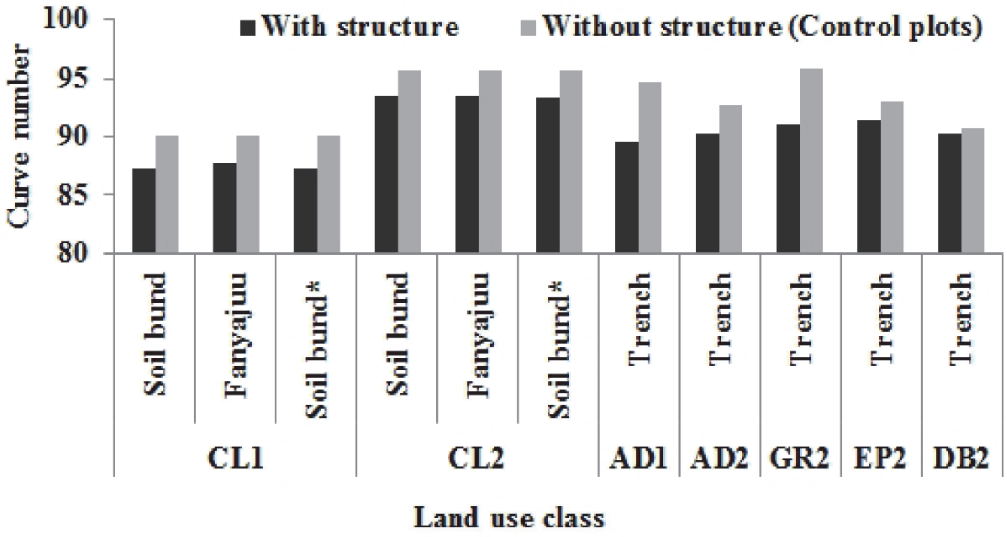

Figure 3- 8 Derived curve numbers for plots of comparable land type with and without SWC practices.
** The soil bund treatment comprised a bund combined with a vegetation strip.*

Adjustment of NEH-4 CN for slope

We computed CNs without slope correction using the standard NEH-4 CN table (USDA-NRCS, 2001) from the relationship between land use, hydrologic soil group, and treatment class. Hydrologic soil group was assigned based on texture and saturated hydraulic conductivity, depth to the impermeable layer, and depth to the water table (SCS, 1972). All plots fell within hydrological soil group D except for the degraded bush land, which was in Group C (Table 3-1). Then, the computed CN was slope-corrected using the approach of Huang et al. (2006) (Table 3-4). For the steeper plots with slope ranging from 15% to 35%, the CN increased by 0.4, 0.7, or 1.0. No difference occurred on the 5% slope, both for cultivated land and AD, because the NEH-4 CN method assumes a 5% slope.

Comparison with CN derived from NEH-4 table values

The slope-corrected CN value for the plots tabulated from NEH-4 varied from 78 to 93.4 (Table 4). The absolute error, or difference between derived event CN and slope corrected NEH-4-CN, ranged from 2.9 to 15.7. The standard table CN values were on average 10 units less than the derived values.

Table 3- 4 Comparison of event-derived CN, standard NEH-4 CN, and slope- corrected NEH-4 CN.

Land use × slope group	Treatment	Standard NEH-4 CN	Slope-corrected NEH-4 curve number	Error due to slope corrected (NEH-4) CN	Event derived CN	Error between event-derived CN & slope corrected NEH-4 CN
(1)	(2)	(3)	(4)	(5) = |(4) − (3)|	(6)	(7) = |(6) − (4)|
CL1	Control	93	93.0	0.0	90.1	2.9
	Soil Bund	81	81.0	0.0	87.2	6.2
	Fanyajuu	81	81.0	0.0	87.8	6.8
	Soil bund*	80	80.0	0.0	87.3	7.3
CL2	Control	93	93.4	0.4	95.6	2.2
	Soil Bund	81	81.4	0.4	93.6	12.2
	Fanyajuu	81	81.4	0.4	93.6	12.2
	Soil bund*	80	80.4	0.4	93.3	12.9
AD1	Control	79	79.0	0.0	94.7	15.7
	Trench	79	79.0	0.0	89.6	10.6
AD2	Control	79	79.4	0.7	92.7	13.3
	Trench	79	79.4	0.7	90.3	10.9
GR2	Control	84	84.4	0.4	95.9	11.5
	Trench	84	84.4	0.4	91.1	6.7
EP2	Control	79	79.7	0.7	93.1	13.4
	Trench	79	79.7	0.7	91.4	11.7
DB2	Control	77	78	1.0	90.7	12.7
	Trench	77	78	1.0	90.3	12.3

* The soil bund treatment comprised a bund combined with a vegetation strip.

Runoff was estimated using both the standard NEH-4 CN values and the CN values derived from the rainfall–runoff dataset and each set of estimated values were compared with the corresponding measured values. The estimates obtained from the derived CNs much better represented the measured values ($r^2 = 0.63$) than did those obtained by the standard CNs ($r^2 = 0.05$) (Figure 3-9).

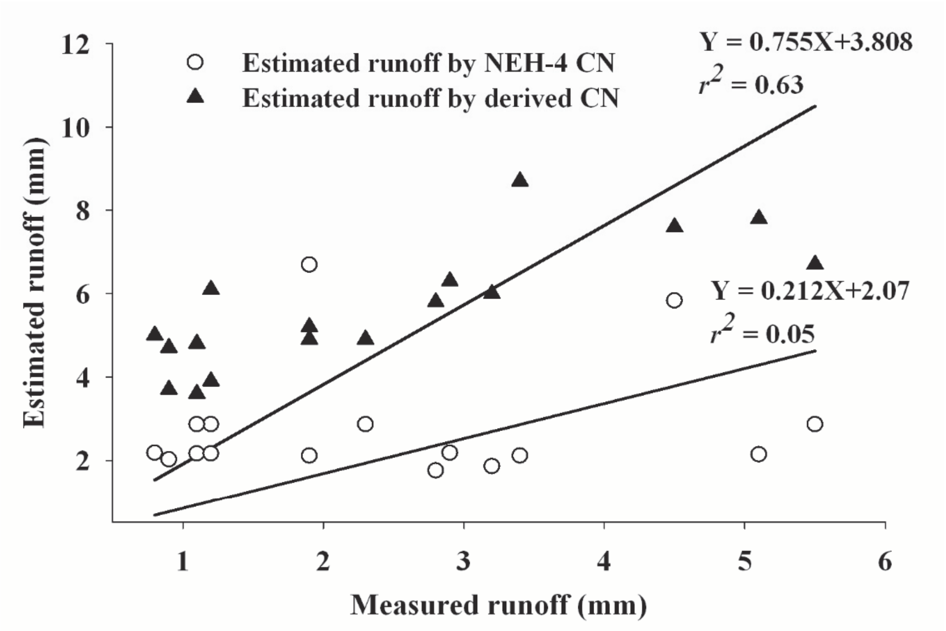

Figure 3- 9 Mean measured runoff versus mean runoff estimated using event derived CNs and NEH-4 table CNs.

3.4 Discussion

3.4.1 Reliability of the experimental data

In this study, experimental runoff plots were established to represent different land use and slope gradients on Kasiry experimental watershed. This watershed was purposefully selected to represent the tropical humid highlands of Ethiopia, considering the annual rainfall, altitude and land use land cover types in humid highland regions. Both rainfall and runoff measurements at the plot scale were monitored during the period July to September since much of the rainfall in the region is concentrated in these three months of the main rainy season. Daily rainfall-runoff data which were fairly distributed over the three months have been analyzed and interpreted to achieve the objectives of this study. We believe that the available data from this study gives a first good indication on the magnitude of rainfall-runoff occurring events specific to the study site. However, replication of the experiment over years and establishment of additional representative observation sites might be needed to give a broader picture about the effectiveness of SWC practices under the highly variable eco-hydrological environment of the Upper Blue

Nile Basin.

Although our results indicate differences in runoff responses, RCs and CNs among the treatments, caution is needed when interpreting this result. The rainfall depths measured by our single rain gauge that was used for all runoff plots further add to uncertainties on the estimated RCs and CNs due to spatial variation in rainfall that is not picked up by our single rain gauge. Bayabil, Tebebu, Stoof, and Steenhuis (2016) illustrated the rainfall in monsoon climates is more variable over short distances than rains in temperate climates. Rainfall in the Ethiopian highlands significantly varies in space (Bitew et al., 2009).

Furthermore, the inherent variations of each plot could not be captured. These uncertainties are often accounted for by installing replicate plots. The replication of such a block (30 m long × 6 m wide) was not possible in our study for several reasons. On one hand, due to the rugged highland topography, soil properties and slope angles vary on a small spatial scale. On the other hand, farm size is on average below 1 ha, so that a replication would involve different farmers, crop rotations, and farm operations and hence these makes it unmanageable and expensive.

3.4.2 Effects of SWC practices, land use, and slope on seasonal runoff production

Despite those uncertainties mentioned above, the results reveal clear differences in runoff and RCs among plots with SWCs and control plots (without SWCs). Compared to the control plots, runoff and RCs values for all plots with SWC structures were considerably reduced ($p<0.05$) (Table 3-2), though to different levels compared to the control treatment. This runoff difference is a result of increased depression storage and hence increased transmission loss of water due to the installed SWC measures. In line with our results, Herweg and Ludi (1999) investigated the impact of different physical SWC measures on runoff, soil loss, and crop yield in the Ethiopian sub-humid highlands.

They considered that runoff reduction was actually excessive as it led to increased waterlogging hazard. Jan Nyssen et al. (2010) found that S increased by 6 mm on cropland with trenches and "good stone bunds" and by 2 mm on land with "medium stone bunds". A sub-watershed scale (8 to 12 ha) study on the effects of SWC (Mekuria et al., 2015) reported 26 to 71% runoff reductions due to implementation of SWC practice in sub-humid highlands of Ethiopia. In contrast, small (10%) runoff reduction effects of graded SWC structures were documented for more humid highlands in Ethiopia at a smaller runoff plot scale ((Herweg & Ludi, 1999; Hurni, Tato, & Zeleke, 2005) as cited in Taye et al. (2013).

Previous studies reported that soil bunds alone could reduce soil loss and runoff in the highlands of Ethiopia (Haregeweyn et al., 2015; Herweg & Ludi, 1999; Hurni et al., 2005). However, Amare et al. (2014) asserted that the efficiency of soil bunds was improved in combination with biological measures; it reduced runoff by 28%, than soil bunds alone. Similarly, we found soil bunds combined with a biological measure (such as tree lucerne and densho grass) had the lowest runoff depth and RCs compared to the other SWC treatments on the CL plots (Table 3-3).

Our results showed that trench on non-agricultural contributed to the effect of vegetation in the reduction of runoff and RCs. This can be explained by an increase in the storage parameter S on the plots with trenches (Table 3-3). Our findings support the explanation of Jan Nyssen et al. (2010), who attributed a low recorded RC in the May Zeg Zeg catchment of northern Ethiopia's Tigray region to the positive influence of SWC measures. Trenches significantly reduced the RC in the AD plantations on both gentle and steep slopes (Table 3-3). In the degraded bush land plots, the trenches had less effect on the RC. We attribute these differences in behavior to soil characteristics (Table 3-1) and rainfall variability at the hill slope.

This study reveals considerable effects of land use on runoff and RCs in the control plots. The higher seasonal runoff (440 mm) and RCs (34.6) values of CL2 relative to other land uses attributed to the excessive tillage operation and other human interventions for potato cultivation. Mwendera and Saleem (1997) also reported that reduction in infiltration rates was greater on soils which had been tilled and exposed to very heavy trampling; which could cause higher RCs, while, Taye et al. (2013) reported that soil tillage contributed to lower RC and soil loss in cropland. Amare et al. (2014) found a four-year average annual runoff value of 302 mm on cropland with 10% slope ground, which is close to the value reported for fallowed land (325 mm) in the central highland of Ethiopia (Adimassu et al., 2014). Most of the seasonal runoff values observed at different in our study sites (Table 3-2) are a closest agreement with the previous studies. The observed higher seasonal runoff (421mm) and RCs (31.1%) on grazing land was the result of frequent grazing and trampled by animal. In a similar study, Taye et al. (2013) reported the highest seasonal runoff on grazing land with 5 to 16% slope ground. The average runoff coefficient reached close to 50% in freely open communal grass land on steeper slopes (15–25%) (Alemayehu, Amede, Böhme, & Peters, 2013).

Topographic factors (slope length and steepness) have long been considered one of the major factors governing the amount of runoff from the catchment, as indicated in several runoff models such as TOPMODEL (Beven & Kirkby, 1979), CREAMS (Knisel, 1980) and SWAT (Arnold et al., 1994). Our result reveals that, runoff and RCs significantly increased as the slope increases from 5% on CL1 to 15% on CL2, which is consistent with the general notion that the runoff increases with the slope of the watershed. This can be attributed to the fact that the larger slope reduces the time of travel of the rainfall-generated runoff on the watershed, and therefore, provides lesser duration of stay in the plot allowing lesser infiltration (Mishra, Chaudhary, Shrestha, Pandey, & Lal, 2014). Similarly, in the semi-arid hilly loess region of China, Zhu and Zhu (2014) illustrated that with an increase of slope angles, runoff per unit area slightly increased on short slope plots (7 m long), but it decreased after reaching a maximum at 15 ◦ on long slope plots (20 m long). Except for the minimum depth of runoff; all other runoff related variables (e.g. runoff depth & mean CN value) increase with slope (Ebrahimian, Nuruddin, Soom, Sood, & Neng, 2012). In contrast; our result showed that lower RC on the plots with the steeper slope gradient (AD2) than gentle slope (AD1) (Table 3-2). The steeper plots had well-established and more dense vegetation than the plots on the gentler slope (Fig 3-10), and this vegetation effect may have overwhelmed the slope effect.

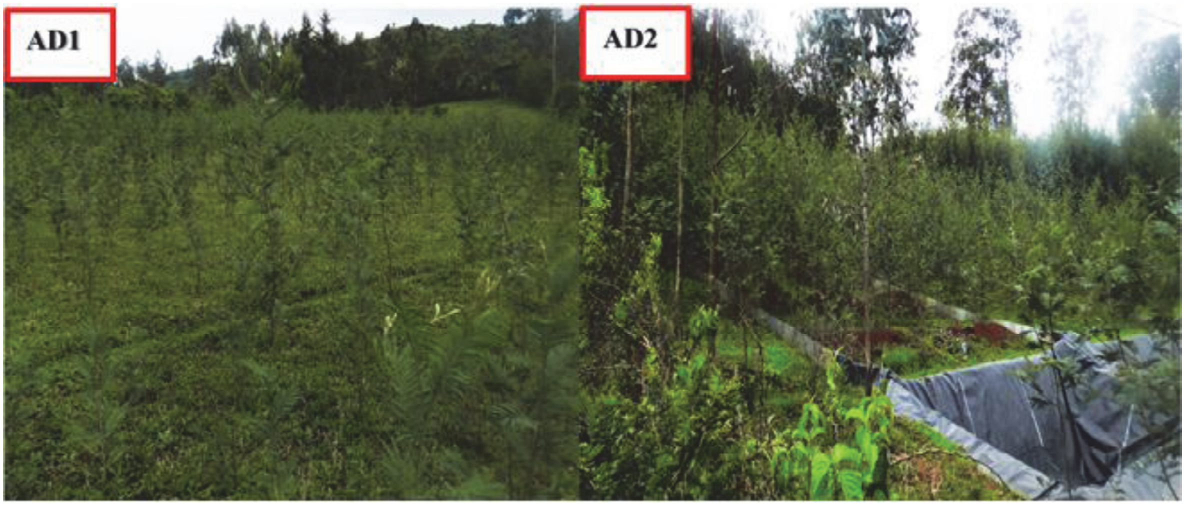

Figure 3-10 Acacia decurrens plantation on gentle (AD1) and steep (AD2) slopes at the Kasiry watershed.

A similar observation was reported in Tigray, northern Ethiopia by Taye et al. (2013), where the RC decreased with increasing slope gradient in both crop land and rangeland. They attributed this trend to an increasing rock-fragment content, which promoted infiltration, with increasing slope gradient.

3.4.3 Effect of SWC management practice on runoff estimates from derived event CN

The results showed that runoff estimates were less accurate in plots treated with a SWC practice. For cultivated land, the r^2 was lower than for the other land uses, possibly because the occasional tillage opened the soil structure and increased infiltration, or because the crops themselves, potatoes (*Solanum tuberosum*) on the steep plot and beans (*Vicia faba*) on the gently sloped plot, enhanced infiltration. An increase in surface runoff (CN value) due to steeper slopes (CL2) can be explained by reduction of initial abstraction, decrease in infiltration rate, and reduction of the recession time of overland flow(Ebrahimian et al., 2012). The *A. decurrens* plantation on the steep slope was older, more stabilized, and with a higher density of SWC structures and biomass than the *A. decurrens* plantation on the gentle slope.

The installation of trenches increased the storage parameter S on the GL and AD land use types relatively more than it did on other land uses, yet had little effect on DB. This effect indicates that the infiltration–runoff dynamics on the GR, AD, CL, and EP plots were controlled by slope length, because the reduction of slope length by the installation of structures increased storage and thereby reduce the volume of runoff. In the case of the DB plots, the infiltration–runoff dynamics appeared to be controlled by the sandy loam soil, because the control and trench plots displayed no differences in their derived storage parameter.

Although the application of SWC practices increased the storage parameter and reduced runoff, it degraded the reliability of runoff prediction by the CN method. Similarly, Descheemaeker et al. (2008) found a similar reduction in the reliability of the CN method with increasing vegetation cover: as the runoff depths decreased, the runoff prediction based on curve numbers became less accurate. However, it should be noted that the prediction errors become less important as the runoff diminishes.

3.4.4 Comparison with CN derived from NEH-4 table values

The current study indicates that for the majority of plots the standard table CN values were lower than the CN values derived from rainfall-runoff data (Fig 3-11). The NRCS method calculates the curve number from annual series of maximum events; only the rainfall–runoff data pairs with the largest runoff for each year are used. Because larger events tend to produce lower CNs, including all the smaller events in the calculation raises the CN (Feyereisen et al., 2008). The geometric mean lognormal method used in the present research included all small rainfall–runoff data pairs. To confirm this effect, we compared the CN values obtained from larger and smaller rainfall–runoff events on the CL plots in our study. For smaller rainfall events varying from 1.7 to 12 mm, the corresponding runoff was 0.07 to 1.8 mm and the calculated CN varied between 98 and 87. For larger rainfall events of 30 to 54 mm, runoff varied from 8 to 30 mm and calculated CN varied from 70 to 54. Similarly, Ajmal, Waseem, Ahn, and Kim (2015) found that NEH-4 CNs estimated runoff poorly in the monsoon climate of South Korea because the tabulated CN values were too low. In contrast, Mishra et al. (2014) obtained CN values for cultivated land in three slope classes of 1%, 3%, and 5%. The values were quite close to the NEH-4 CN values. This agreement suggested that the NEH-4 CN standard values were applicable to their watershed in Roorkee, India.

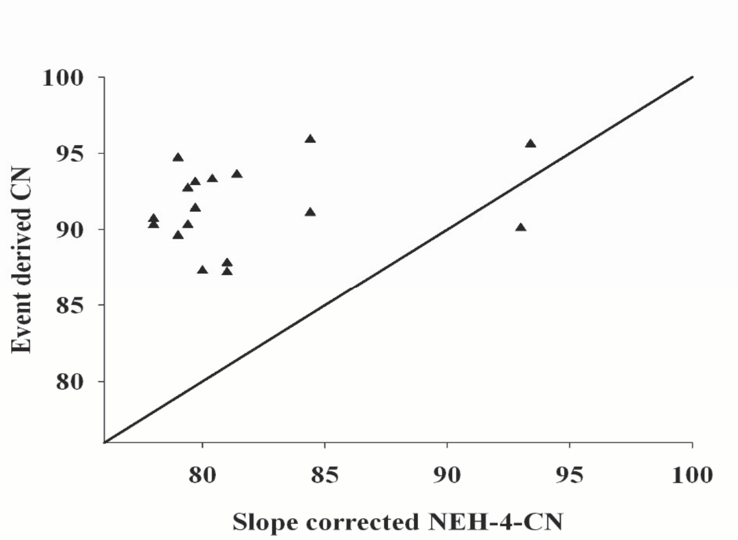

Figure 3- 11 The event-derived CN versus the corresponding slope- corrected NEH-4 table CN value. The 1:1 line is shown for reference.

To overcome the empirical shortcomings of the standard CNs being developed in the specific environment of the USA, various researchers have attempted to establish new CN values for local conditions (in China, for example, Bo et al. 2011). Others have tried to add parameters to the SCS-CN model to reflect the effects of factors such as slope gradient, rainfall intensity, and soil moisture conditions. In our study, the derived CNs accounted for various combinations of land use, slope, and SWC management treatments on agricultural and non-agricultural plots, and therefore provided more accurate runoff estimates in the tropical humid highland setting than could be obtained from standard CNs obtained from the NEH-4 table.

3.5 Conclusions

The study showed the efficiency of SWC management practices on runoff and has provided a solid basis for selecting event runoff CNs for different land uses and vegetation types in the tropical highlands of the Blue Nile basin. The finding indicated that combining soil bunds with vegetation in cultivated lands reduced runoff by 49%, and incorporating trenches across the slope on non-cultivated plots reduced runoff by 65%. Furthermore, the runoff predictions using CN method were found to be less accurate for plots treated with a SWC practice, but runoff was relatively accurately predicted with the CN method on plots representing non-agricultural land uses. Overall, the derived CNs gave much better predictions of measured runoff than CNs obtained from the standard NEH-4 table. Hence, the use of derived CNs rather than the standard NEH-4 table CNs is a more reliable method for estimating runoff for non-agricultural lands where no SWC measures have been applied in similar tropical humid highland situations. Our results show that to reflect the effect of SWC practices on runoff in hydrologic simulation exercises, hydrologic models that use a CN approach will need to be parameterized with separate sets of curve numbers to account for the various SWC practices.

Chapter 4

Impact of soil and water conservation interventions on watershed runoff response in a tropical humid highland of Ethiopia

This chapter is based on: Dagnenet Sultan, Atsushi Tsunekawa, Nigussie Haregeweyn, Enyew Adgo, Mitsuru Tsubo, Derege Tsegaye Meshesha, Tsugiyuki Masunaga, Dagnachew Aklog, and Kindiye Ebabu

4.1 Introduction

In Ethiopia, soil erosion by water, and the resulting land degradation and recurrent drought are major problems that the country has faced for many years (Bewket and Sterk 2003; Nyssen et al. 2004). The livelihood of many farmers in the highlands has been seriously affected by the environmental degradation that has resulted from continuous soil erosion by water. In response, various government and non-government land management interventions have been implemented since the 1970s, and great efforts have been undertaken to conserve soil and water resources (Adgo et al. 2013; Adimassu et al. 2014; Amare et al. 2014; Benin and Pender 2001; Gebrernichael et al. 2005; Haregeweyn et al. 2015; Herweg and Ludi 1999; Hoben 1995; Nyssen et al. 2000; Sutcliffe 1995). In general, traditional off-contour furrows were replaced by imported soil and water conservation (SWC) interventions such as soil or stone bunds, grass strips, trenches, *fanyajuu* terraces (a Swahili word meaning "throw uphill"), and other physical structures (Dagnew et al. 2015; Tebebu et al. 2015). Recently, physical structures have been combined with biological measures in arid to semi-humid areas (Amare et al. 2014). In addition, Adimassu et al. (2017) emphasized that physical SWC practices combined with agronomic SWC practices are essential to increase both provisioning and regulating ecosystem services.

Efforts targeting wider geographic regions began after the implementation of the

Sustainable Land Management (SLM) Program in 2008 (Ebabu 2016; Haregeweyn et al. 2015). In 2012 a government-led large-scale watershed management program was launched as part of the ambitious Agricultural Growth and Transformation Plan (MOFED 2010), which annually treats over 3000 community watersheds (>40,000 ha of land) with physical and biological SWC measures and affects more than 15 million people (Tebebu et al. 2015). In most cases, the conservation interventions have predominantly used top-down approaches following government directives (Amdihun et al. 2014). To date, most studies on landscape interventions to control runoff and erosion processes in the Ethiopian highlands have focused on the semiarid regions in the north of the country (Fenta et al. 2016; Haregeweyn et al. 2012; Haregeweyn et al. 2016; Nyssen et al. 2010; Nyssen et al. 2009; Taye et al. 2013). Soils in north (the Tigray Region) are generally coarser, covered by rock fragments, and have higher infiltration rates than those in the sub-humid Blue Nile basin, which are more clayey and much wetter (Tebebu et al. 2015). Haregeweyn et al. (2015) reported that the impact of SWC interventions are influenced by the type of measures and the agro-ecology under which they were implemented.

Generally, the hydrological impact of soil conservation practices is to reduce and delay surface runoff and hence decrease soil erosion (Herweg and Ludi 1999; Huang and Zhang 2004); peak flows are also reduced but remain strong for longer periods of time after watershed management (Nyssen et al. 2010).

Quantitative impact studies include those using the paired watershed approach, which establishes statistical relationships for watershed outlet responses (i.e., surface runoff, base flow, and peak flow) between two paired watersheds; any hydrologic differences between them are considered to be indicative of treatment effect (von Gunten 1993; Zégre et al. 2010). Examples include process monitoring and quantification several years before and after watershed management (Huang and Zhang 2004; Mekonen and

Tesfahunegn 2011; Nyssen et al. 2010), statistical comparisons of several (generally homogenous but small) watersheds (Bingner 1996; Shipitalo and Edwards 1998; Shipitalo et al. 2006; Zenebe et al. 2013) as cited in Nyssen et al. (2010), and model simulation trough calibration and validation with measured values (Haregeweyn et al. 2016; Nyssen et al. 2010; Sultan et al. 2016; Zégre et al. 2010). In the absence of extensive field studies and runoff measurements, models have been used to estimate site specific information (Sultan et al. 2016). They are suitable to simulate various combinations of different scenarios of land and water management in a watershed and therefore they are useful for comparative analysis of different options and as a guide to what best management practices can be adopted. Several approaches can be used to estimate runoff, from simple empirical rainfall-runoff models to conceptual and highly parameterized process-based models (Haregeweyn et al. 2016; Jakeman and Hornberger 1993). The most popular method for predicting event-based surface runoff volume from small watersheds is the Soil Conservation Service curve number (SCS-CN) method (SCS 1972). Blue Nile Basin is one of the least planned and managed sub-basins of the Nile (Haregeweyn et al. 2017; Schmidt and Zemadim 2013). Many previous studies have examined the impact of investments in sustainable land and watershed management in the Blue Nile basin derived implicitly from economic analyses (Schmidt and Zemadim 2013), whereas some plot-level studies in the central and western highlands of the Upper Blue Nile Basin (UBNB) (Adimassu et al. 2014; Amare et al. 2014; Herweg and Ludi 1999; Sultan et al. 2016) have focused primarily to evaluate soil bunds on croplands. Other basin-scale studies (Haregeweyn et al. 2016; Kebede et al. 2011; Kebede et al. 2006; Seleshi et al. 2008; Steenhuis et al. 2013) have mainly concentrated on the hydrological aspects within a complex landscape and multiple land use and management systems, which might not provide useful information about where and to what extent land management interventions have affected hydrological processes.

Very few studies have examined the impacts of physical SWC structures on hydrology and the extent of runoff reduction in tropical humid regions at the watershed scale (Assegahegn and Zemadim 2013; Dagnew et al. 2015; Engda et al. 2011; Mekuria et al. 2015; Tebebu et al. 2015). Even these studies lack detailed quantitative information on the comprehensive effects of SWC intervention options on runoff reduction across spatially distributed land uses and land covers. Hence, analysis of runoff by using a hydrological CN model that takes into account the combined effects of biophysical practices and their extent of coverage across different land uses within a watershed will provide insight on how specific conservation investments improve hydrological processes. The replicability of land resource management can be justified if the intervention approach and the impacts are well assessed and studied (Alemayehu et al. 2009). Therefore, we first analyzed the hydrological responses of paired watersheds under existing SWC practices and identified factors that control runoff variation. Second we investigated the effects of SWC measures on runoff under various management scenarios for better planning and management of water resources in the humid Ethiopian highlands. To do so, we adopted integrated field measurement and modelling with validation by measured runoff data.

4.2 Materials and Methods

4.2.1 Description of the study area

The study was conducted in two gauged experimental watersheds in the UBNB. The Kasiry watershed, with an area of 399 ha, was designated as the "treated area" because trenches were constructed there as a conservation measure over the past 4 years and it has more plantation (*Acacia decurrens* and eucalyptus) cover (SWC structures cover 8% of the total area). An adjacent watershed area (Akusity) has a virtually identical soil composition and an area of 343 ha. It was designated as the "untreated" watershed, because only marginal efforts at conservation had been made there (SWC structure cover 3.2% of the area and it has less plantation) (Fig 4-1). The experimental watersheds are located at 11°00’17’’N–11°00’20’’ latitude and 36°55’20’’E–36°56’10’’E longitude in northwestern Ethiopia (Fig 4-1). In the treated (Kasiry) watershed, experimental runoff plots (30 m long × 6 m wide, bounded at the sides and top) were established in May 2014 (Fig 4-1). The plots were characterized by land use, slope, and SWC treatment to determine CNs in our recent study (Sultan et al. 2016).

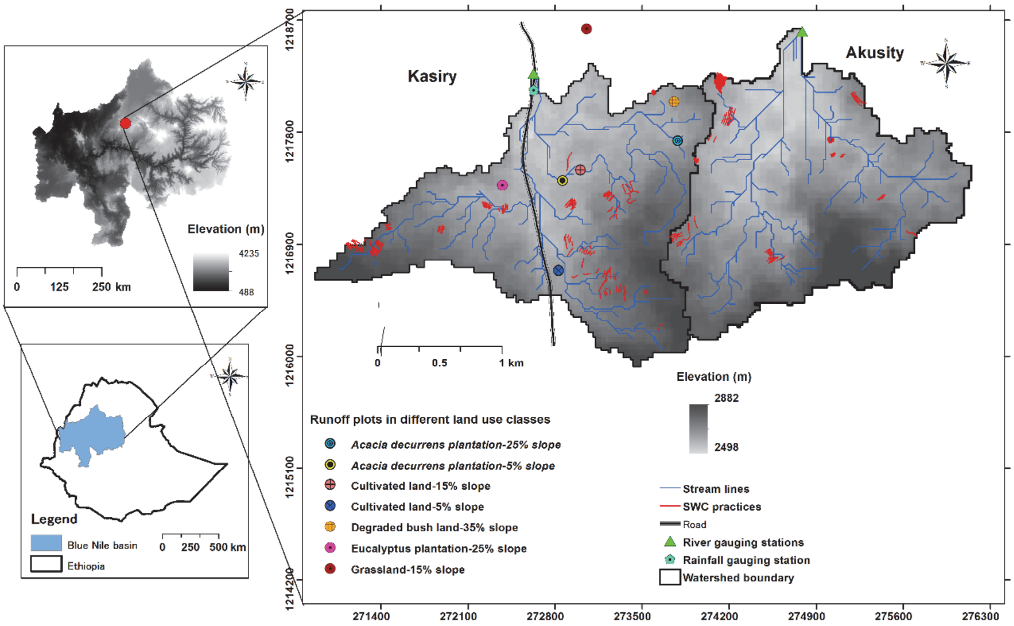

Figure 4- 1 Locations of the paired watersheds and experimental plots

The watershed topography ranges from gently sloping (dominantly used for crop production and residences) to more steep and very steep hills (mostly used for *A. decurrens* plantations and grazing). The Kasiry watershed is more highly populated than Akusity and it has been more frequently cultivated; consequently, it has lost most of the top layer of fertile soil. In both watersheds, farmers constructed water ways to evacuate excess surface runoff from the area; unfortunately, these actions facilitated the development of gullies and gully networks. The upslope sections of the watersheds are characterized by shallow soil profiles, whereas soils in the valley bottoms are deep with almost uniform profiles. The dominant soil types in the watershed are red to reddish brown colored Nitisols and Acrisols. Temperature varies across the elevation gradient between the mean annual maximum of 25°C and mean annual minimum of 11°C. Annual average potential evapo-transpiration at the study site is about 1160 mm, and maximum potential evapotranspiration occurs in April.

4.2.2 Rainfall measurement

One manual gauge recorded daily rainfall from July through November and May through October during the rainy seasons of 2014 and 2015, respectively. The seasonal rainfall in these periods are 1562 and 1899 mm, respectively. Annual rainfall for the period 2007 to 2014 obtained from the nearest meteorological station at Injibara (located 5 km from the study site) averaged 2495 mm, which is much higher than the values reported for other watersheds in the western and central highlands of Ethiopia. For example, the mean annual rainfall reported at the Ajeni (Herweg and Ludi 1999), Debre Mewi (Amare et al. 2014), and Gelessa (Adimassu et al. 2014) watersheds were 1300, 1240, and 1400 mm, respectively. The mean annual rainfall divided by mean evaporation in the study area yields a desertification index of 2.15, which corresponds to a humid climate according to UNEP (1992).

4.2.3 Runoff discharge measurement at the watershed outlets

Stream flow (discharge) for the paired watersheds was measured continuously (every 10 min) during the rainy season in 2014 and 2015. River flow level measurements were made using both manual and automatic (diver) measurement techniques (Fig 4-2). Two pressure meters (a TD–diver and BARO–diver; Mini-diver, Schlumberger Water Services, the Netherlands) were installed at each monitoring station. Atmospheric and water pressures were recorded continuously with pressure transducers. The TD–diver measured the pressure at the bottom of the river bed, which is the sum of pressure related to the water height and the air (atmospheric pressure). The BARO–diver measured atmospheric pressure. The TD–diver was programmed to take measurements at 10-min intervals, and the BARO–diver was programmed to take measurements every 30 min. Data from the BARO–diver were used to correct the air pressure measurements of the TD-diver. To calculate water depth, atmospheric pressure measured by the BARO–diver was subtracted from the pressure measured by the TD-diver with Diver–Office software (VanEssen 2006). The depth of the water level (column) obtained from the software was calibrated with manual staff gauge readings. These manual calibration readings were taken from staff gauges (three times a day, at about 7:00 AM, 1:00 PM and 6:00 PM, and additionally during peak flows) in both watershed outlets. The diver readings were linearly regressed on the staff gauge readings for each station ($r^2 = 0.83$ and $r^2 = 0.85$ for the Kasiry and Akusity watersheds, respectively; Fig 4-3). Therefore, more manually defined flow depths (= staff gauge readings) were used for discharge analysis.

Figure 4- 2 Typical monitoring station with staff gauges (vertical poles) and a TD-diver at the deepest point of the river cross-section.

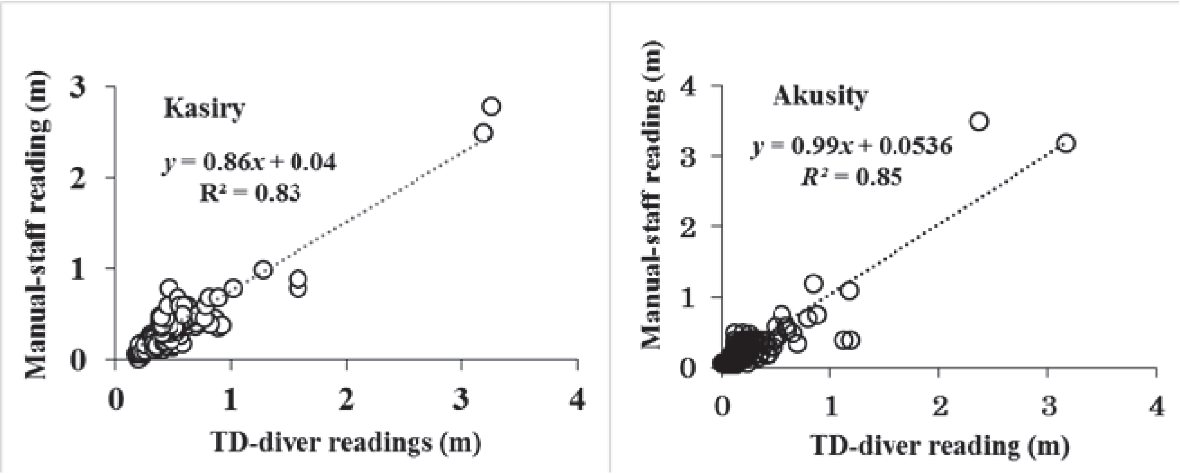

Figure 4- 3 Relationship between staff gauge and TD-diver flow depth readings at both sites.

Stage-discharge curve

Because continuous measurements of discharge are usually not feasible (as was the case in our study), records of discharge were computed from the relationship between stage (H, m) and discharge (Q, $m^3\ s^{-1}$); that is, we used a rating curve where $Q = f(H)$. The rating curves were produced after we surveyed the cross-sections of the river channels and measured flow velocity at different flow stages. The volume of water passing a section per second was calculated using the area-velocity method (Hudson 1993),

$$Q = V_{av} \times A_{cs}, \qquad (4\text{-}1)$$

where V_{av} is the average velocity (m/s), and A_{cs} is the cross-sectional area (m^2). Flow velocity measurements were taken using the float method (surface velocity), because of measuring flow velocity with a current meter was impossible during flash floods, but also measurements were made using the current meter at different flow depth during low flows. Each float velocity measurement was carried out over a distance of 20 m (10 m upstream and 10 m downstream of the cross-section) and repeated 3 times to reduce random variations (Zenebe et al. 2013). The mean value of these surface velocity measurements was converted to the average stream velocity using Prony’s equation (Graf 1998; Zenebe et al. 2013)

$$V_{\mathrm{av}} = 0.8\ V_{\mathrm{s}}\,, \tag{4-2}$$

where V_{av} = average velocity (m s^{-1}) and V_{s} = surface velocity (m s^{-1}).

We used the following general equation to develop rating curves (Dessie et al. 2014; Kennedy 1984; Zenebe et al. 2013),

$$Q = c\left(H - H_{\mathrm{o}}\right)^{n}, \tag{4-3}$$

where c and n are fitting coefficients, and H_0 is a constant that represents the gauge reading corresponding to zero discharge. The coefficient n is largely explained by the shape of the cross-section. For relatively deep, narrow rivers, the exponent n will commonly exceed 2 and sometimes 3 (Dessie et al. 2014). The paired river cross-sections in this study were characterized by irregular shapes and deep profiles, leading to relatively high values of n, as shown by the rating curves (Fig 4-4).

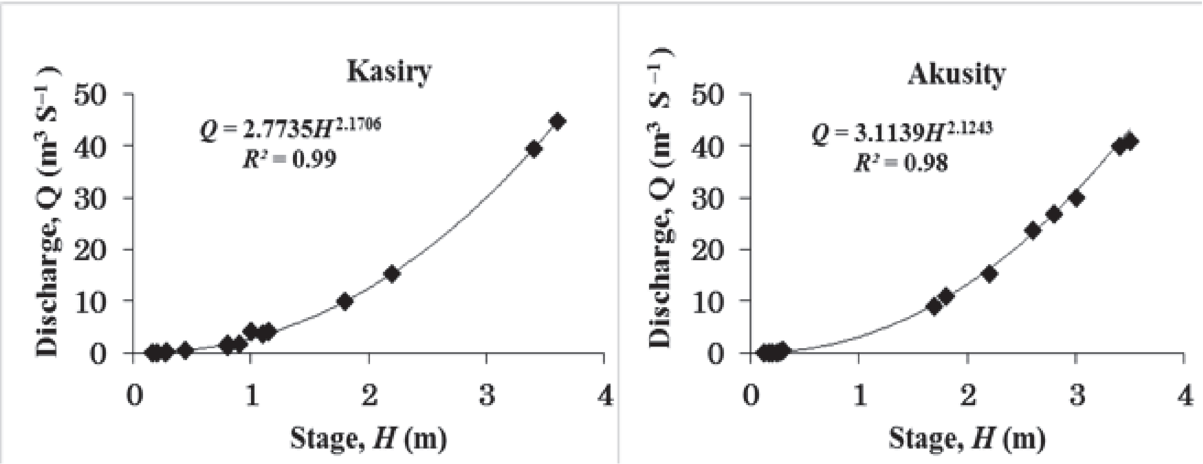

Figure 4- 4 A typical stage (flow depth) to river discharge (Q) rating curve for the paired watersheds at the downstream gaging stations at both sites.

Conversion to continuous river discharge series

Based on the rating curve equations (Fig 4-4), all adjusted depths measured at 10-min intervals (Fig 4-3) were converted to instantaneous river discharge records. The resulting continuous runoff discharge series was integrated on a daily basis to obtain the daily runoff discharges (Q_{d}, m^3 day^{-1}).

4.2.4 Base flow separation

Surface runoff volume was calculated by subtracting base flow from river discharge volume in WHAT (Web-based Hydrograph Analysis Tool) software (Lim et al. 2004; Lim et al. 2005). Daily surface runoff depth (d, in m/d) was calculated as

$$d = \frac{\sum_{\mathrm{i=1}}^{24} (Q - \mathrm{bf}) \times t}{A_{\mathrm{w}}}, \tag{4-4}$$

where bf is base flow (m^3 s^{-1}), t is daily time interval (86400 s/d), and A_w is watershed area (m^2).

4.2.5 Survey of bio-physical features of the watershed

Watershed soil and topography characteristics

Soil depths were measured by auger hole observations at all sampling points during the rainy season. At all sampling points, the soil was not deeper than 1 m in the Kasiry watershed and 1.58 m in the Akusity watershed. Various soil variables were determined (Table 4-1). Fifteen soil samples for each watershed were taken from the top 30 cm of soil at 10-cm intervals for five land-use classes; they were analyzed for texture using the hydrometric method (Shieldrick and Wang 1993). Bulk density and moisture content of the soils were determined from undisturbed soil samples taken from the 0–10, 10–20, and 20–30 cm depth intervals using a 100 cm^3 core sampler. Samples were dried in an oven at 105 °C for 24 h and then weighed. The bulk density of the soil was obtained by dividing the mass of the oven-dried soil samples by the volume of the soil core sample. The moisture content of the soil was determined by dividing the mass of water lost through drying by the volume of the sample. Soil compaction is the densification and reduction in porosity associated with changes in soil structure and (usually) an increase in strength and a reduction in hydraulic conductivity (Soane and Van Ouwerkerk 1994). The compaction of soil can lead to excessive runoff and erosion (Fleige and Horn 2000). To characterize soil compaction, soil penetration resistance (SPR; N/cm^2) was measured by using a hand-operated soil cone penetrometer (Hand penetrometer, Eijkelkamp Company, the Netherlands) with a cone (2 cm^2 base size) and a graduated driving shaft (at 5-cm intervals). For each land use, six penetration measurements were taken for a total of 30 observations in each watershed. The average SPR for the top 30 cm of soil was determined by dividing the average force (N) per unit base area (cm^2) required to push the penetrometer through a specified small increment of soil. Finally, the results were converted from N/cm^2 to the standard unit (kPa) by multiplying by 10.

Table 4- 1 Soil characteristics of the paired watersheds.

	Kasiry				Akusity			
Land use	Soil depth (cm)	Soil type	Dry bulk density (g cm^{-3})	SPR (kPa) at a given soil moisture (%)	Soil depth (cm)	Soil type	Dry bulk density (g cm^{-3})	SPR (kPa) at a given soil moisture (%)
CL	100	clay loam	1.1	1140 (47)	158	loam	1.25	1100 (47.3)
PL	70	clay loam	1.1	1710 (65)	72	loam	1.32	1720 (38.5)
GL	80	clay loam	1.0	1900 (45.3)	140	loam	1.1	2210 (50.4)
NF	78	clay loam	0.83	1210 (29.1)	92	loam	0.83	1110 (58.3)
DB	75	sandy loam	0.83	1460 (50)	120	loam	1.0	1300 (58.1)

Land-use codes: CL, cultivated land; PL, plantation; GL, grassland; NF, Natural forest; and DB, degraded bush. SPR: soil penetration resistance.

Topographic information (slope) was extracted from the Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) (http://earthexplorer.usgs.gov/) with GIS software. The study watersheds are predominantly characterized by steep slopes (>30%; Table 4-2).

Table 4- 2 Slope classification of the paired watersheds.

Slope class	Kasiry coverage		Akusity coverage	
(%)	(ha)	(%)	(ha)	(%)
0–10	59.4	15.01	49	14.3
10–20	119	29.5	89.7	26.2
20–30	98	24.5	77.8	22.7
>30	123	31	126.6	36.9

Assessment of land use/land cover and treatment measures

Land use/land cover and SWC treatment measures were digitized from high resolution Google Earth images from 2015 and data from field observation points with location data from a GPSMAP 62st handheld navigator (Garmin). Finally, a watershed map including the proportion of land cover and showing the distribution and coverage of SWC treatment measures was produced with ArcGIS version 10.1 software.

Five major land-use types were identified in both watersheds. Cultivated cropland was the dominant land-use type: it accounted for about 41% and 39% of land use on the Kasiry and Akusity watersheds, respectively. The percentages of other land-use types for Kasiry were plantation (30%), bush land (17.5%), grazing land (9.5%) and forest lands (3.8%). For Akusity, they were grazing land (17.8%), forest land (16.2%), and plantation (10.2%). Bush land consists of natural plants below 2 m in height (including bush, shrubs, and riverine vegetation). Grazing land consists of seasonal and permanent grass cover used for grazing, usually on valleys bottom and sloped terrain. Plantations consist of planted *A. decurrens* and eucalyptus. Forest consists of natural and long-lived planted forests, e.g., bushes and conifers. The plantation coverage of the Kasiry watershed was greater than that of Akusity. The vegetation cover in both watersheds increased over the last four years, especially in acacia and eucalyptus plantations for charcoal and fuel wood production. Acacia has a higher economic value for local farmers as compared to other crops

(Nigussie et al. 2016). Field observations and discussions with local farmers revealed that the farming system in the study watersheds is principally crop oriented. Cultivation of cereal crops is the dominant farming system, but farmers also grow potato in winter and spring. The dominant crops grown in the area are teff (*Eragrostis tef*), barley (*Hordeum vulgare*), and wheat (*Triticum aestivum*). Livestock rearing is also an integral part of the farming system. Even though extensive SWC conservation measures such as soil bunds, *fanyajuu*, trenches, and bunds combined with biological measures (Fig 4-5) were established under the regional Bureau of Agriculture with the support of the SLM Program in the sub-humid highlands of the region, SWC structural works covered only 8% of Kasiry and 3.2% of Akusity. The only structural measures observed during the field assessment were a trenches on hillsides of the watersheds (Fig 4-5C). These trenches were installed by excavating soil at a depth of 0.5 m and staggering a shorter length in one row across the slope (1.4 m wide × 1.5 m long) and a longer length in the next row (1.4 m wide × 2.5 m long).

Figure 4- 5 Commonly implemented soil and water conservation measures for major land uses in the humid highlands of Ethiopia: (a) fanyajuu, (b) a soil bund on cultivated land (c) and trenches on a hillside of bush and grassland.

4.2.6 Modelling the hydrologic effect of watershed-scale SWC interventions

We used the well-known SCS-CN method (SCS 1972) to model intervention practices. CNs were determined locally from rainfall and runoff data at the experimental plot scale (30 m long × 6 m wide) under different land uses, slopes, and SWC practices in an earlier study at the treated (Kasiry) watershed (Sultan et al. 2016). These plot-scale calibrated curve numbers (CN) were used to simulate runoff at the watershed scale. We chose this method for its flexibility, simplicity, and ability to model the extent of combined effects of land use and SWC measures to reduce runoff under different scenario options.

Spatial representation of CN values at the watershed scale

Layers of slope, SWC practice, and land use were prepared and intersected using overlay analysis in a GIS environment. A total of 4773 polygons were produced, each having three layers of properties. Based on experimentally determined CN information, each polygon at the watershed level was spatially assigned a CN value according to plot information. Each polygon had two SWC management options (i.e., CN values): "with" or "without" SWC interventions. The "with" SWC intervention assumes a CN value obtained from a plot for a specific land use, SWC type, and slope. Polygons with no SWC management practices (without SWC) were represented by CN values taken from control plots having land use and slope information only. Here, the CN values taken from the plot level represented slopes of 5, 15, 25, or 35% even though the watershed had a continuous range of slopes (Table 4-1). Therefore, to represent the actual slope of the watershed, the CN value for the intersected polygon was adjusted for slope by the following empirical equations given by Huang et al. (2006),

$$\mathrm{CN}_{2\alpha} = K \times \mathrm{CN} \tag{4-5}$$

$$K = \frac{322.79 + 15.63\alpha}{\alpha + 323.52} \tag{4-6}$$

where $CN_{2\alpha}$ is the slope-adjusted CN, α is slope (m m^{-1}) ranging from 14 to 140%, and K is a conversion factor. Finally, to produce CN maps, GIS techniques were used to identify the spatially distributed CN values along the watershed taking into account the specific characteristics of each watershed.

Runoff prediction with the CN method

After generating the CN map, runoff depth (Q_i, mm) was ascertained for each rainfall event by using the existing Natural Resource Conservation Service (NRCS) runoff model (SCS 1972), which is represented in Eq. (7). S indicates the initial abstraction of rainfall by soil and vegetation; it was computed for each polygon by using Eq. (8).

$$Q_i = \frac{(P_i - \lambda S)^2}{(P_i + (1-\lambda)S)} \qquad P > \lambda S \qquad (4\text{-}7)$$

$$S = \frac{25400}{CN} - 254, \qquad (4\text{-}8)$$

where P_i is the depth of rainfall event i, and λ is the initial abstraction ratio (a nondimensional value between 0 and 1). In this study, a constant value of $\lambda = 0.2$ was used to correspond with locally determined CNs and to make our estimates compatible with those provided by the classical SCS-CN method documentation. This value was effectively used in predicting rainfall-runoff relationships in the Ethiopian highland by (Bayabil et al. 2016).

The runoff volume (Q_v, m^3) for the watersheds after a rainfall event was computed by multiplying the runoff depth (Q_i, mm) by the area (A_i, m^2) for each polygon in the ArcGIS tool. Assuming that the total runoff (Q_T, m^3) at the watershed outlet is the sum of the partial Q_i (i_1 to $_n$) coming from each of the n different intersected layers in the watershed, then the total is

$$Q_T = \sum_{i=1}^{n} Q_i A_i \qquad (4\text{-}9)$$

Scenario setup

Potential scenarios were developed and examined to determine the impact of SWC management on predicted runoff yields. We used two options with the application of CN values determined from the experimental plots to spatially represent to the Kasiry watershed, with and without SWC practices. The “with” scenarios assume best SWC practices (such as soil bunds, *fanyajuu*, trenches, and soil bunds with biological conservation measures) are applied as noted in Table 4-3 for specific land uses based on ongoing practices of the SLM Program. The “without” scenario assumes no SWC measures are implemented.

Table 4- 3 Change in runoff yield under various soil conservation scenarios at Kasiry.

Scenario	Explanation
0	Current conditions (2015), 8% of Kasiry watershed treated with SWC
1	Worst case scenario at Kasiry (without SWC interventions)
2	SWC intervention implemented on selected land-use types that generate the highest runoff at Kasiry watershed
3	SWC practices implemented fully across the entire watershed
4	Spatial variability of runoff among the different land-use types during a maximum rainfall event

Current runoff yield was calculated using a 2015 map of land-use type, slope, and SWC area coverage, and this value was used as the baseline for the Kasiry watershed. To determine the spatial variability of runoff among the different land-use types, we used current runoff estimates among the different land-use types for a maximum rainfall event. For each land-use type, we extracted the mean (mm) and cumulative (%) runoff yields using the zonal statistics module of ArcGIS.

Model validation

Like other hydrological models, the SCS-CN model produces a degree of uncertainty associated with the estimates. We evaluated the applicability of the plot-derived model to the watershed by using the Nash-Sutcliffe Efficiency (NSE) statistic (Nash and Sutcliffe 1970), which has been widely used in the evaluation of model performance (Moriasi et al. 2007).

NSE is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared with the measured data variance ("information"). The efficiency (E) proposed by Sutcliffe (1995) is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. It is calculated as

$$\boldsymbol{NSE} = 1 - \frac{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \left(\boldsymbol{E_i} - \boldsymbol{O_i}\right)^2}{\sum_{\boldsymbol{i}=1}^{\boldsymbol{n}} \left(\boldsymbol{O_i} - \overline{\boldsymbol{O}}\right)^2} \qquad (4\text{-}10)$$

where n is the number of observations or samples, O is the observed value, E is the estimated value, $\bar{O}$ is the mean of observed values, and i is a counter for individual observed and predicted values.

The general methodology used for assessing the impact of SWC intervention on runoff response is shown in Fig 4-6.

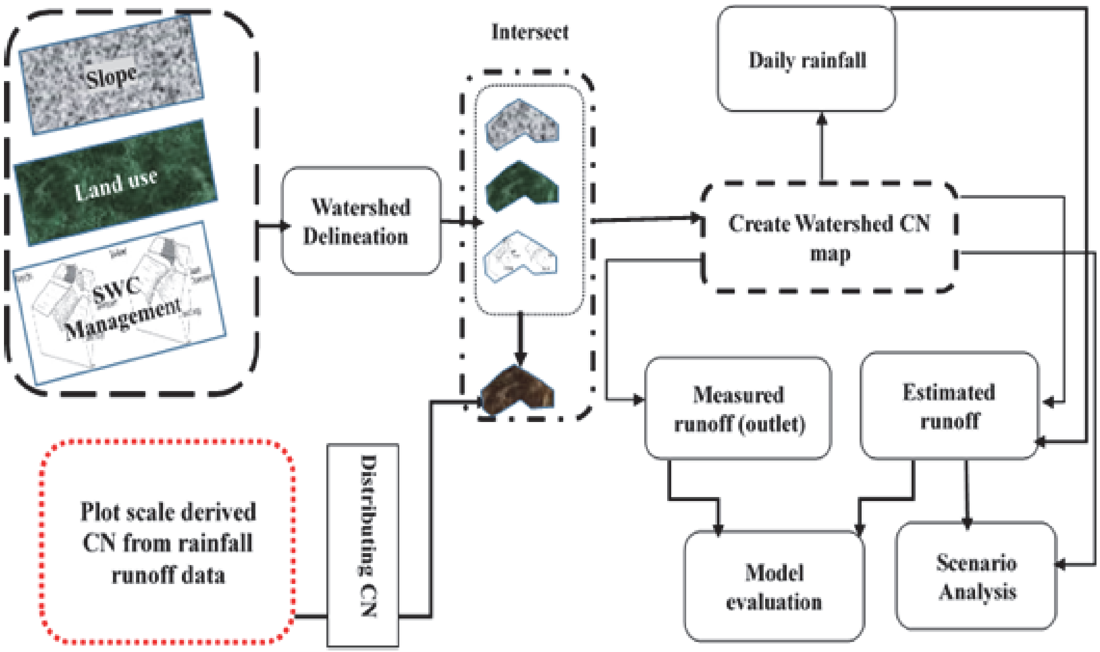

Figure 4- 6 Methodological framework for assessing the effects of integrated land management at the Kasiry watershed by using a GIS application.

4.3 Results and Discussion

4.3.1 Paired watershed runoff analysis

Mean seasonal surface runoff discharge during July to November of 2014 and May to October of 2015 (Table 4-4) was higher from the Kasiry watershed (614 mm) than from Akusity (361 mm). The mean daily surface runoff depths (5.1 and 2.4 mm at the two watersheds, respectively) showed significant variation (r^2 =0.67, $P<0.05$) during 2015. The mean seasonal runoff coefficient (RC) also varied between the watersheds (Table 4-4). An estimated 27% and 26% of the total mean seasonal runoff was exported as base flow at the Kasiry and Akusity watersheds, respectively (Table 4-4). The greatest runoff contribution was observed in August, when the mean surface runoff for 2014 and 2015 in Kasiry was 176 mm and that for Akusity was 117 mm. Runoff started in the beginning of the rainy season (May to June), and the discharge was greatest from August to September.

Weekly totals of surface runoff were plotted versus weekly rainfall during the rainy season of 2015 (Fig 4-7). Despite the fact that the two watersheds are adjacent and have similar characteristics, the runoff response was quite different. The reason why these paired watersheds behaved so differently is a critical question that we explore below.

Table 4- 4 Summary of runoff data for the paired watersheds from July to November of 2014 and May to October of 2015.

Watershed	Season	Rainfall (mm)	Surface runoff (mm)	Base flow (mm)	Runoff coefficient (%)
Kasiry	2014 July to November	1562.0	458.2	199.2	0.29
	2015 May to October	1899	770.0	311.9	0.41
	Average	1730.8	614.1	225.6	0.35
Akusity	2014 July to November	1562.0	327.9	139.4	0.21
	2015 May to October	1899.5	396	114.5	0.20
	Avg.	1730.8	361.9	126.9	0.21

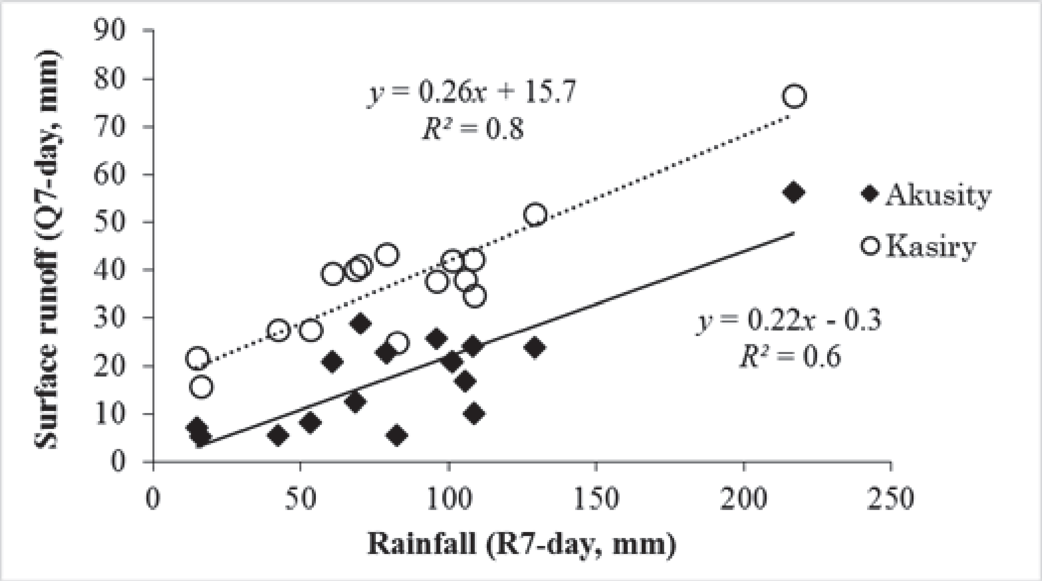

Figure 4- 7 Weekly surface runoff vs. rainfall (2015) using model I linear regression.

During peak rainfall events (e.g., 97 mm fell on 7 August 2015), the untreated Akusity watershed responded sooner and with larger flood events than did the treated Kasiry watershed. The daily peak surface runoff was 30 mm at Akusity and 26 mm at

Kasiry (Fig 4-8) during this rainfall event, and the hydrologic response factor (ratio of peak runoff to rainfall) was 0.26 and 0.18, respectively. These differences might be due to differences in slope and shape between the watersheds. There were more highly sloped (>30%) areas in the Akusity watershed than in Kasiry (Table 4-2). The shape of Kasiry was elongated leaf-like whereas that of Akusity was compact and funnel-like, which reduced the time of concentrated runoff; this difference may have affected peak runoff response during peak rainfall events.

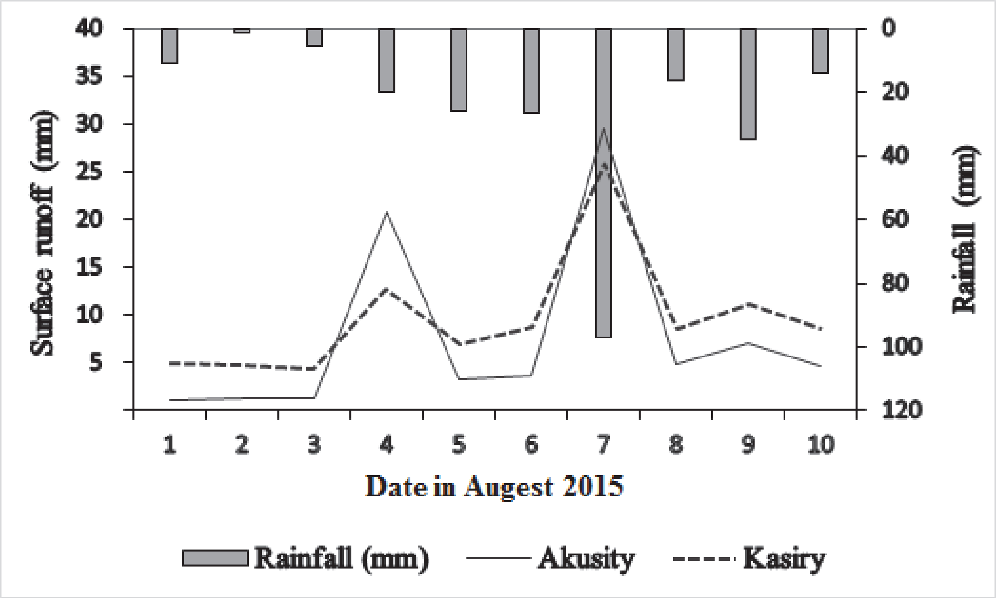

Figure 4- 8 Peak rainfall-runoff responses of the paired watersheds in August 2015. Rainfall is on the right axis and surface runoff on the left.

4.3.2 Factors controlling runoff responses between paired watersheds

Although surface runoff is expected to be better captured and controlled in watersheds with greater coverage by SWC structures and acacia plantations, the surface runoff flow of Kasiry was higher under base flow conditions than that of Akusity. Consistent with expectations, the rate of seasonal sediment export at Kasiry (9727 t km^{-2}) from total seasonal flow was about half that at Akusity (18,385 t km^{-2}) (Ebabu 2016). The surface runoff difference could be influenced by one or more of the following factors: (1) Differences in the estimated SWC coverage between the paired watersheds were too small to exert a clear impact.

(2) High spatial variation in rainfall was not picked up by our single rain gauge installed within the Kasiry watershed (Fig 4-1). We confirmed the variability of rainfall by installing additional rain gauges during 2016 in both watersheds and observed high rainfall variability among the rain gauges (up to a 103% coefficient of variation). A recent study by Bayabil et al. (2016) demonstrated that rainfall in monsoon climates is more variable over short distances than it is in temperate climates, and rainfall in the Ethiopian highlands has been shown to vary significantly in space (Bewket and Conway 2007; Bitew et al. 2009).

(3) Land use/land cover varied between the two watersheds. Specifically, cultivated land and acacia plantations are relatively larger in the Kasiry watershed (see the land-use section). Cultivation causes higher runoff rates due to deterioration of soil structure by excessive tillage (Arshad et al. 1996; Gilley and Doran 1997; Tesfahunegn 2015). The area of acacia plantation at the Kasiry watershed is about 2.5 times that in Akusity. These areas are densely planted (1-m spacing) and have more canopy cover, which affects the direct sunlight energy obtained by plant species under the trees. As a result, we found sealed and compacted topsoil surfaces under the trees due to the direct impact of intercepted rain dropped from the leaf canopy (Fig 4-9). This reduced infiltration and thereby increased runoff. Higher SPR values (1720 kPa) were also observed in the soil in the plantations as compared with those of other land uses (Table 4-1). According to Tebebu et al. (2015), hardpan formation increases peak flow immediately following storm events because of major modifications in the length of the path of subsurface flow.

(4) Soil characteristics such as depth (thickness) are very important in soil-water processes and strongly affect water infiltration and runoff generation (Neitsch et al. 2011), and Kasiry had shallower soil than Akusity (Table 1).

(5) In Kasiry, about 2.6 ha of land was covered with paved roads, and this watershed also had a larger number of settlements (about 105 dwellings), both of which could increase the watershed runoff coefficient. Chithra et al. (2015) reported that increasing the area of impervious surfaces strongly alters hydrology by reducing infiltration and increasing surface runoff; in addition, as impervious surfaces were removed, peak flows and total runoff continued to decrease under a variety of climatic conditions.

(6) Differences in watershed area and drainage density between the paired watersheds could be a cause of the variation. Kasiry was 56 ha larger than Akusity. There was also a clear difference in drainage density between Kasiry (14.3 km km^{-2}) and Akusity (9.1 km km^{-2}) (Fig 4-1). A high density may indicate that a "mature," well-developed channel system exists, which would facilitate the rapid movement of surface runoff from hill slopes.

Figure 4- 9 A typical Acacia decurrens plantation, indicating (a) density and canopy cover and (b) surface sealing under the canopy.

In general, the paired watersheds each had their own morphometric characteristics that governed runoff response. There were various factors affecting runoff responses that we did not account for in our analysis; hence, the paired watershed comparison was limited by uncontrolled runoff factors, and we were unable discern the effect of SWC structures on runoff reduction. To see the extent of runoff reduction and the clear impact of SWC practices, we used a modelling approach on the treated Kasiry watershed.

4.3.3 Modelling watershed interventions practices

Curve number (CN) maps for runoff prediction

Runoff generation mainly relied on CN values, which are a function of soil type, slope, management practice, and land use. CN values ranged from 87 to 97 in the Kasiry watershed (Fig. 10). On average, CN values of 87–90, 90–93, and 93–97, covered about 6.7%, 38.6%, and 54.6% of the watershed, respectively. These spatially distributed CN values closely reflect actual conditions of the Kasiry watershed as well as the runoff potential. Low CN values mean that the surface has a high potential to retain water, whereas high values indicate that the rainfall can only be stored to a limited extent.

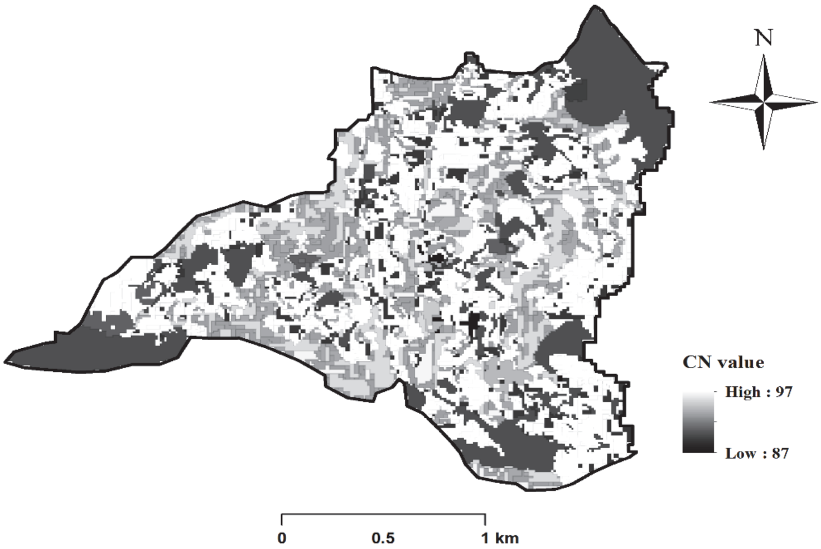

Figure 4- 10 Runoff curve number (CN) map for the Kasiry watershed.

Impact of SWC measures on runoff under various scenarios

On-site SWC measures were trenches on the hillsides of the northeastern part of the Kasiry watershed (scenario 0, Table 4-3). SWC intervention under current conditions reduces seasonal surface runoff by 5.2% (Table 4-5). Without any SWC installations (scenario 1), seasonal runoff would increase by about 45 mm (Table 4-5). Assessed soil and water conservation practices had limited desirable effects under current conditions due to the limited coverage and the placement of the SWC installations. Our results are consistent with those of Tebebu et al. (2015), who illustrated that, for saturation-excess runoff, water infiltrates on hillsides and erosion-inducing runoff occurs in the flatter, downslope parts of landscapes. SWC installations in such cases would be more effective at the bottom of slopes.

In a plot-level runoff analysis in (Sultan et al. 2016), the seasonal runoff depth was significantly higher for three land uses: cropland (440 mm), grazing land (421 mm), and acacia plantation (412 mm). Therefore, we simulated runoff yield for SWC interventions on these selected land-use types in scenario 2. The recommended SWC interventions were soil bunds combined with biological conservation measures on cultivated land and trenches on grazing and plantation lands. Our analysis revealed that seasonal runoff at Kasiry could be reduced substantially (34%) by implementing these SWC interventions on these three land uses (Table 4-5). This change is a result of increased depression storage and hence increased transmission loss of water due to the implemented SWC measures. The combination of different soil and water conservation measures had the potential to reduce surface runoff; planners and developers can use this information to target specific development interventions for each land use. The findings of this study are in line with similar studies on the impact of SWC measures in this region and elsewhere. A sub-watershed scale (8–12 ha) study on the effects of SWC (Mekuria et al. 2015) reported 26–71% runoff reductions due to the implementation of SWC practices in sub-humid highlands of Ethiopia. In contrast, small (10%) runoff reduction effects were documented for more humid highlands in Ethiopia at a smaller plot scale (Herweg and Ludi 1999; Hurni et al. 2005).

Scenario 3 included the implementation of SWC measures fully across the entire Kasiry watershed (399 ha). This scenario included the already-installed SWC measures, and the remaining area was treated with trenches on degraded bush areas, plantations, grasslands, and forests and with soil bunds and soil bunds with biological conservation measures on cultivated lands. A runoff reduction of 35% was achieved in this scenario as compared to the baseline scenario. The reduction under this full SWC coverage was similar to that of scenario 2; thus, implementation of SWC measures on bush land and natural forest had little impact on runoff reduction.

In a similar study, Haregeweyn et al. (2016) analyzed the possible effects of SWC practices on surface runoff in the UBNB using the runoff coefficient method and demonstrated that proper implementation of SWC measures could decrease surface runoff by up to 38%. Nyssen et al. (2010) also showed that watershed management had a positive influence on the hydrology of the May Zeg Zeg watershed in northern Ethiopia, with a 81% decrease of the annual runoff coefficient (from 8% before catchment management to 1.6% after it).

Table 4- 5 Summary of simulated runoff under different SWC scenarios at Kasiry watershed.

Period	Rainfall (mm)	Predicted seasonal surface runoff yield (mm)			
		Scenario 0	Scenario 1	Scenario 2	Scenario 3
Seasonal (May to Oct.)	1899	800.6	844.9	525.8	521.3
Mean	300	133.4	140.8	87.6	86.6
SD	165	86.03	83.3	51.2	50.7
CV (%)	0.55	0.64	0.6	0.6	0.58
Runoff coefficient (%)		0.42	0.47	0.28	0.27
Runoff change by SWC scenario (%)			+ 5.2	−34	−35

A large amount of runoff causing serious soil erosion can be expected when a single severe rainfall event occurs. In scenario 4, we evaluated the effect a maximum rainfall event across different land uses because this knowledge will be critically important to design better SWC strategies (Amare et al. 2014). A single rainfall event exceeding 97 mm is very rare in the highlands of Ethiopia. Shang et al. (2011) reported the maximum daily rainfall observed in the highlands of Ethiopia (1953–2006) was 86.9 mm. Therefore, we assessed the role of land use and management under existing conditions in affecting runoff using the largest rainfall event we observed (97 mm). The mean predicted runoff depth (mm) for the existing land use for the entire Kasiry watershed varied from 71.5 mm (natural forest) to 83.5 (cultivated land) and 84.9 mm (grazing land) (Table 6). Grazing land is frequently trampled by animals, and grasslands had the highest SPR (2210 kPa; Table 1). A similar analysis for the UBNB showed that cattle on wet grazing soils caused additional compaction in the top 30 cm (Tebebu et al. 2015). An SPR of approximately 2000 kPa was found to be a critical threshold value that can limit root capacity to penetrate and also restrict soil water movement (Hamza and Anderson 2005). Our SPR measurements are similar to those of other studies in humid regions. For example, in the Anjeni watershed, Tebebu et al. (2016) observed mean SPR values of 141 kPa (forest land), 1776 kPa (cultivated land), and 1948 kPa (pasture land).

Taye et al. (2013) observed the highest seasonal runoff on sloped (5–16%) grazing land in semi-arid northern highlands of Ethiopia. The higher runoff from cropland is mainly attributed by excessive tillage and other human interventions such as weeding, fertilizer application, and harvesting. According to Mwendera and Saleem (1997), reduction in infiltration rates was greater on soils that had been tilled and exposed to very heavy trampling.

Runoff from forest land is low due to the low dry bulk density of the soil (0.83 g cm^3; Table 4-1). Leaf litter increases the organic content of the soil through decomposition by 10.1% as compared to other land uses (Ebabu 2016). Similarly, Mohammad and Adam (2010) reported that natural vegetation provides multiple advantages. Gandini and Usunoff (2004) obtained low CN values in forest lands as compared to other land uses in

Argentina. In addition, in forest lands, loss through interception is high, which in turn reduces runoff. Descheemaeker et al. (2006) reported that runoff depths over two rainy seasons varied from less than 2 mm in a church forest to almost 400 mm in degraded grazing land in the northern Tigray Highlands of Ethiopia. Based on the above results, we conclude that land uses that produce high runoff need to be prioritized for SWC development projects.

Table 4- 6 Runoff contribution from various land use/land cover (LULC) types at Kasiry.

LULC	Area (ha)	Mean runoff depth (mm)	Cumulative runoff depth (%)
CL	154.2	83.6	41.1
FL	14.1	71.5	3.2
GL	37.93	84.9	10.3
PL	118.9	78.6	29.7
DB	68.1	71.5	15.6

LULC codes: CL, cultivated land; FL, forest land ; GL, grassland: PL, plantation (*Acacia decurrens* and eucalyptus); and DB, degraded bush land.

SCS-CN model evaluation

During 2015, approximately 60 rainfall events were used for the evaluation of the CN model. Rainfall events ranged from 5 to 97 mm. The runoff predicted at the watershed scale based on the results of the experimental plots was close to the observed runoff measured at the Kasiry outlet (R^2=0.8, NSE= 0.5). NSE ranged from $-\infty$ to 1, with NSE = 1 being the optimal value. Values between 0 and 1 are generally viewed as acceptable levels of performance, whereas values < 0 indicate that the mean observed value is a better predictor than the estimated value, which indicates unacceptable model performance (Krause et al. 2005; Moriasi et al. 2007), both as cited in Ebrahimian (2012). Spatially representing CN at the watershed scale provided superior runoff predictions as compared to measured runoff value. This may be because the overall slopes of the Kasiry watershed are steep, and consequently, plot-level CN values would be larger when adjusted by the method of Huang and Zhang (2004). Our results are in line with those of

Grove et al. (1998), who found a greater percent increase in runoff depth using distributed versus composited CN. Soulis and Valiantzas (2012) predicted runoff by using the CN heterogeneous system approach and compared the predicted runoff to that predicted by the SCS-CN method using a single optimum CN value and found that runoff was overestimated in heterogeneous approach. In addition, Bhuyan et al. (2003) reported that the agricultural non-point source pollution model overestimated runoff depth when using a CN based on average CN conditions. Overall, our findings agree with the explanation of Jetten et al. (1999): models including CN tended to overestimate rather than underestimate runoff, particularly for larger rainfall events.

4.4 Conclusion

The aim of this study was to better understand the effects of landscape interventions on hydrological responses of watersheds as well as the extent of interventions that can be implemented to reverse the current trend of unsustainable land use land management in the sub-humid highlands of Ethiopia. An analysis of the impact of SWC measures across different land use and cover types through a spatially distributed runoff modelling approach at the Kasiry watershed showed a 34% reduction in surface seasonal runoff when appropriate interventions were implemented on selected land-use types. Measures included the use of soil bunds combined with biological conservation measures on cultivated land and trenches on grazing and plantation lands. However, current SWC practices had a limited effect because of the limited coverage and the placement of the SWC installations. The accuracy of the model in quantifying simulated runoff processes was in good agreement with measured runoff (NSE=0.5).

To explore policy options for upscaling sustainable land management activities, it is important to understand the factors that affect runoff responses, the potential of SWC interventions in reducing runoff in the watershed system, and to prioritize land uses for interventions based on their potential runoff yield. Therefore, the results on the magnitude of runoff reduction under optimal combinations of soil and water measures and land use will support decision-makers in selection and promotion of valid management practices that are suited to particular biophysical niches in the tropical humid highland of Ethiopia.

Chapter 5

General conclusion and recommendation

5.1 Conclusion

Special attention is given on the effectiveness of various types of soil and water conservation practices (SWCPs) on runoff reduction at different land uses, and environmental factors controlling runoff response under contrasting agro-ecologies of Upper Blue Nile basin of Ethiopia.

The responses of runoff, runoff coefficient and runoff conservation efficiency to soil and water conservation practices were highly variable both within and between agro-ecology systems at plot scale. Our result showed that on average runoff reduction by SWC ranges from 35% (Guder) to 42% (Aba Gerima). Nevertheless, the efficiency of individual SWCPs in reducing runoff was found to be highly variable within agroecology. Vegetated bunds were most effective (51%, Dibatie) in reducing runoff from cultivated land, whereas short trenches were effective in Grass land (55%, Aba Gerima).

Furthermore, the importance of combining vegetation with physical structure as a factor controlling runoff was confirmed. Soil bund with vegetation management (such as: treelucerne, densho grass, vetiver grass and elephant grass) are more effective in reducing runoff than soil bund techniques alone. Based on our field trials and test, SWCPs should not be equally applicable at different locations with heterogeneous soil, land cover, climatic, and topographic conditions.

On average, SWCPs were highly effective in controlling runoff in the humid subtropical and tropical hot humid agro-ecology systems. The moist subtropical region (Guder) had a higher potential soil moisture availability, but a lower rainfall threshold to generate runoff. Hence, it’s more necessary to choose and design the optimal structure for subtropical region sites. Soil and water conservation planners need to focus on the safely disposal of the runoff to avoid risk of crop damage due to flooding or increase opportunities for sediment deposition from overland flow.

Furthermore, we have inquired the effect of SWC practices on experimentally derived runoff curve number (CN) model parameter for the tropical humid highland climate and tested the validity. The model parameters (CN) derived from our local studies has been found to be more reliable and higher value than taken from other secondary sources (National Engineering Handbook Section-4 table value). Hence, the CN method had to be re-evaluated and the effect of SWC practices on runoff requires parameterization with separate sets of CN value for each SWC practice.

Subsequently, we analyzed and quantified to what extent SWC practices can reduce runoff at watershed-scale. Despite the fact that the paired watersheds are adjacent and have similar characteristics, the runoff response was quite different and did not explain a substantial effect of SWC on runoff. This suggests that consideration of other factors affecting runoff on the watershed system is crucial. On the other hand, we predicted the runoff response with validated CN. Implementation of selected SWC on targeted land uses (cultivated land, grass land and plantation) can reduce runoff by up to 34%. The magnitude of runoff reduction under various combinations of soil and water measures and land use are crucial in selection and promotion of valid management practices that are suited to particular biophysical niches. To explore policy options for upscaling sustainable land management activities, it is important to understand the factors that affect runoff responses, the potential of SWC interventions in reducing runoff in the watershed system, and prioritize land uses for interventions based on their potential runoff yield.

5.2 Recommendations for further research and applications

Given the labor-intensive, time-consuming and expensive nature of plot and watershed scale runoff measurements, additional large coordinated research projects extensively using the existing experimental sites and additional new sites are questionable to be set up. In this regard, future hydrological studies should consider time series data of runoff responses and its relationship with sustainability land management interventions. Another important aspect that has not been dealt with and need consideration in the future research concerning the different temporal resolutions of event runoff measurements. A detailed rainfall-runoff response analysis on the event scale is essential to determine maximum flood events which would help proper designing of hydraulic structures planning and flood prevention as well. In addition, it can contribute to the identification of the important factors that control temporal and spatial variability of runoff.

Plot and watershed scale runoff measurements and consequently model parameters (such as CN and RC) derived at a local scale in different parts of Ethiopia were reported. Nevertheless, these studies had not been up scaled to larger basin. Future studies should extrapolate local-scale determined model parameters to larger basin through validation with measured data would help to estimate runoff accurately, and important to regulate runoff and reduce soil at river basin scale and downstream countries which are affected by frequent flooding and reservoir sedimentation.

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SUMMARY

Ethiopia is, often described as the water tower of East Africa, and the rainfall-runoff processes on the mountainous slopes are the source of the surface water, the potential of surface water which is estimated to be around 110 billion m^3 a^{-1}, with unequal distributions over the country. Soil erosion by water is the most serious threat in Ethiopian highlands, thereby degrading land and causing socio-economic problems. In response, various governmental and non-governmental land management interventions have been implemented since the 1970s, and great efforts have been undertaken to conserve soil and water resources through various types of land management technologies (e.g., soil bund, *fanya juu*, stone-faced, soil bund combined with biological measures, short trenches, cut-off drains, check dams, hillside terraces, area closures). Despite all those efforts sustainability of the development work is always in question, and their response to decrease the existing runoff and soil erosion amount has not been evaluated, particularly in the Upper Blue Nile basin (UBNB) of Ethiopia.

The spatial runoff response of the UBNB is the combination of many complex hydrological processes, depending on the watershed characteristics (e.g. land management practice, land use/land cover, soil properties, antecedent conditions and rainfall characteristics). These spatial difference will have a paramount effect on runoff response and yield impacting the efficiency of land management practice. For these reasons; adequate understanding of the runoff response in contrasting agroecology (high, mid and low in both elevation and rainfall) to various soil and water conservation (SWC) practices in UBBN is crucial to develop sustainable water resources management strategies in the region. The overall objective of this study is therefore, to demonstrate and analyzing spatial runoff responses to different SWC measures at various land use and slope classes and thereby, to contribute to better water resources management for Upper Blue Nile basin of Ethiopia. More specific objectives include: (1) to analyze the spatial variability of rainfall-runoff relationship and its controlling factors (2) to determine the ability of different SWC practices to reduce runoff and improve soil moisture availability in typical agro-ecology systems (3) to determine CN values for various SWC practices and test to what extent the effect of SWC practices can be captured with the most commonly used CN runoff estimation method (4) to analyze the hydrological responses of paired watersheds under existing SWC practices and identify factors that control runoff

variation; and (5) to investigate the effects of SWC measures on runoff under various management scenarios for better planning and management of water resources under the conditions of Upper blue Nile Basin; Ethiopia. This study comprises five chapters described as follows:

Chapter 1 presents the introductory section of this study. It sets out an overview of the background for the study, focusing on water resource potentials, physical features, soil erosion problem, runoff response factors, model application, principles of soil and water conservation, the country's experience in soil conservation activities and types of technology, Subsequently, it presents the research gaps, study objectives and organization of the thesis.

Chapter 2 investigates efficiency of soil and water conservation practices in different agro-ecological environments of Ethiopia's Upper Blue Nile basin. The analysis is based on runoff plots from three sites each representing a different agro-ecological environment (high, mid and low in both elevation and rainfall) in Ethiopia's Upper Blue Nile basin. The plots at each site represented common land use types (cultivated vs. non-agricultural land uses) and slopes (gentle and steep). Seasonal runoff from control plots in the highlands ranged between 214 and 560 mm, versus 253 to 475 mm at midlands and 119 to 200 mm at lowlands. The three SWC techniques (soil bund, *fanya juu*, soil bund combined with biological measures) applied in cultivated land increased runoff conservation efficiency by 32 to 51%, depending on the site. At the moist subtropical site in a highland region, SWC increased soil moisture enough to potentially cause waterlogging, which was absent at the low-rainfall sites. Soil bunds combined with Vetiveria zizanioides grass in cultivated land and short trenches in grassland conserved the most runoff (51 and 55%, respectively). Runoff responses showed high spatial variation within and between land use types, causing high variation in SWC efficiency. Our results highlight the need to understand the role of the agro-ecological environment in the success of SWC measures to control runoff and hydrological dynamics. This understanding will support policy development to promote the adoption of suitable techniques that can be tested at other locations with similar soil, climatic, and topographic conditions.

Chapter 3 analyzes the runoff response to soil and water conservation measures in a tropical humid Ethiopian highlands. The analysis is based on daily rainfall and runoff depth from 18 runoff plots (30 m long × 6 m wide) representing the five main land use types with various SWC practices and two slope classes (gentle and steep). The effect of SWC practices on runoff response and experimentally derived and tested the validity of the runoff curve number (CN) model parameter. The CN values were derived using the lognormal geometric mean CN procedure. Runoff was significantly less from plots with SWC measures where an average reduction of 44% and 65% were observed in cultivated and non-agricultural lands, respectively. Runoff on plots representing non-agricultural land was relatively accurately predicted with the derived CN method, but predictions were less accurate for plots treated with a SWC practice. The results indicate that predicting the effect of SWC practices on runoff requires parameterization with separate sets of CN value for each SWC practice.

Chapter 4 quantify and investigate the impact of soil and water management interventions on watershed runoff response in a tropical humid highland of Ethiopia. Firstly, a paired-watershed approach was employed. Secondly, a calibrated curve number hydrological modelling was applied for the Kasiry watershed alone. The paired-watershed approach showed a distinct runoff response between the two watersheds (kasiry and Akusity) however the effect of SWC measures was not clearly discerned being masked by other factors. On the other hand, the model predicts that, under the current SWC coverage at Kasiry, the seasonal runoff yield is being reduced by 5.2%. However, runoff yields from Kasiry watershed could be decreased by as much as 34% if soil bunds were installed on cultivated land and trenches were installed on grazing and plantation lands. In contrast, implementation of SWC measures on bush land and natural forest would have little effect on reducing runoff. The results on the magnitude of runoff reduction under optimal combinations of soil and water measures and land use are crucial in selection and promotion of valid management practices that are suited to particular biophysical niches in the tropical humid highland of Ethiopia.

Chapter 5 provides a general synthesis of the whole thesis, including conclusions, policy implications and avenues for further research. The findings of this study provided an overview of the hydrological dynamics and effectiveness of SWC practices to reduce runoff under the common agro-ecology systems and contributed a solid basis for selecting event runoff CNs for different land uses and vegetation types in Ethiopia’s UBBN. In addition, it also explains the effects of SWC practice on hydrological responses of watersheds as well as the extent of interventions that can be implemented to reverse the current trend of unsustainable land use land management through a spatially distributed runoff modelling.

The responses of runoff, runoff coefficient and runoff conservation efficiency to soil and water conservation practices were highly variable both within and between agro-ecology systems. This high variation was attributed to a combination of several factors: the type of soil (permeability), land use, soil water availability, the response of runoff to rainfall, and the prevailing climatic conditions (precipitation and potential evapotranspiration). Our finding allows managers towards the optimal choice of soil and water conservation measures under specific site conditions instead of making blanket recommendations for all systems. Furthermore, model parameters (CN) derived from our local studies has been found to be more reliable than taken from other secondary sources (National Engineering Handbook Section-4 table value). Thus, this finding capitalize modelling exercise on the effects of SWC practices on runoff requires parameterization with separate sets of CN value for each SWC practice. To explore policy options for upscaling sustainable land management activities, it is important to understand the factors that affect runoff responses, the potential of SWC interventions in reducing runoff in the watershed system, and prioritize land uses for interventions based on their potential runoff yield. Future hydrological studies should consider time series data of runoff responses and its relationship with sustainability land management interventions.

学位論文概要

エチオピアは東アフリカの給水塔と言われるのは斜面での降雨-流出の過程が地表水の源となるからである。地表水は約1,100兆 $m^3 a^{-1}$で、所により分布は異なる。水の土壌浸食は土地の等級を下げ、社会経済学的問題を招き、エチオピア高原で最大の脅威である。1970年代より政府内外の手で管理対策がとられているが、開発努力が続くかどうかは疑問視され、対策で流出量や土壌侵食が減少するかは特にエチオピア青ナイル川上流域(UBNB)では未査定である。

UBNBでの空間流出応答は種々の要因の組み合わせで、空間の違いが流出応答や土地管理策の効率化に大きな影響を与えている。そのため対照的な農生態系(高度と降雨の程度が高中低)で行われるUBNBの土壌および水保全(SWC)の理解は当地域での持続可能な水資源管理戦略に欠かせない。本研究の全般的な目的は種々の土地利用や斜面での異なったSWCに対する空間的な流出応答の明示と分析で、ひいてはエチオピア青ナイル川上流域の水資源管理向上である。詳細: (1)降雨-流出関係の空間的変動、それを左右する要素の分析 (2)流出を減らし、代表的な農生態系での土壌水分向上のための各種SWC策の効果 (3)様々なSWC策のCN値を定め、最も普及しているCN流出推測法はどこまでSWC策の効果を捉えられるかテスト(4)現行のSWC策の水文応答を2か所1組の流域で分析し流出変動の決定要素を判明(5) エチオピアUBNBで水資源管理向上に向けた様々な管理シナリオでのSWC策の効果調査。本研究は以下の5章である：

第1章は本研究の序文であり、背景の概要である。焦点は水資源の可能性、物理的特徴、土壌侵食問題、流出応答要素、モデル応用、土壌と水保全の原則、エチオピアの土壌保全活動や技術タイプ。次に研究の隙間、研究目的、論文の構成である。

第2章では、エチオピアUBNBの異なる農生態環境下での土壌水保全対策の効率を探る。土地利用のタイプ(農地と非農地)および斜面(緩急)の違いがあり、コントロール地の季節的な流出量は高原で214から560mm、中程度の所で253から75mm、低地で119から200mmだった。SWC技術3種(築堤、段々畑、築堤と生物学的策の組み合わせ)使用の農地で流出保全効率上昇は32から51%だった。水分の多い亜熱帯高原では築堤とベチバー、草原でのショートトレンチの流出保全が最高だった。土地による流出応答の差は大きく、SWC効率も大きく異なった。この結果、流出管理と水文動力のSWC策成功には農生態系環境の理解が欠かせないことがわかった。

第3章は高湿度のエチオピア熱帯高原で土壌や水保全対策への流出応答の分析である。土地利用タイプ5種とSWC策、2種の斜面(緩急)を代表する18の区画(30 m×6 m)の1日の降雨・流出量を元にして分析した。流出応答へのSWC策効果は流出曲線指標(CN)モデルパラメータの有効性テストとした。CN値は対数正規幾何平均CN手順で出した。SWC対策を

した農地と非農地での流出は大きく減った。SWC策の効果予測には別のCN値パラメータ化の必要性が判明した。

第4章では高湿度のエチオピア熱帯高原での流域流出応答への土壌水保全対策の影響の数値化と調査。まず流域を2か所1組とし、次にカシリ流域のみに基準化したCN水文モデルを応用した。2か所の流域(カシリとアクシティ)の違いで、SWC策の効果は他の要因に隠れ、明確な識別不可だった。しかし農地に築堤し、放牧地やプランテーションのトレンチで、最大34%の減少が可能である。対照的に低草原地や天然林でのSWC対策はほとんど流出量減少に無効だった。

第5章は論文全体の合成で、結論、政策への示唆、今後の研究への切り口を含む。本研究結果は、通常の農生態系での流出を減らすSWC策効果の水文ダイナミクスの概要を示し、エチオピアUBNBでのさまざまな土地利用や植生での流出事象CNを選ぶ際の根拠となる。さらに流域での水文応答へのSWC策効果や現行の非持続可能な土地利用や土地管理の傾向を空間的な流失モデルによる反転策の範囲も示す。

流出、流出係数、土壌や水保全対策への流出保全効率は、農生態系ごと、また農生態系内でも大きく異なり、複数の要因の組み合わせと思われる：土壌の種類(透水性)、土地利用、土壌水分量、降雨への流出応答、天候(降水量、蒸発可能性)。本研究結果で、全体への包括的な提言の代わりに特定の地域の状況に最適な土壌と水保全対策が可能となる。さらに、我々の現地調査から得たモデルパラメータ(CN)は二次的ソースからの他より信頼性が高いことがわかった。そこで、この結果より、SWC策効果のモデリングを生かすには、個々のSWC策に別のCN値セットを取りパラメータ化する必要が判明した。効果的政策のためには、流出応答要因の理解、分水界系の流出減少へのSWC策の可能性、流出量予測に基づく土地利用の優先順位が重要である。 今後の水文研究では流出応答の一連のデータ、持続可能な土地管理策との関係を考慮すべきである。

LIST OF PUBLICATIONS

Dagnenet Sultan, Atsushi Tsunekawa, Nigussie Haregeweyn, Enyew Adgo, Mitsuru Tsubo, Derege Tsegaye Meshesha, Tsugiyuki Masunaga, Dagnachew Aklog, Ayele Almaw Fenta and Kindiye Ebabu. 2017. Efficiency of soil and water conservation practices in different agro-ecological environments of Ethiopia's Upper Blue Nile basin. Journal of Arid Land (Accepted, this article covers **Chapter 2**).

Dagnenet Sultan, Atsushi Tsunekawa, Nigussie Haregeweyn, Enyew Adgo, Mitsuru Tsubo, Derege Tsegaye Meshesha, Tsugiyuki Masunaga, Dagnachew Aklog and Kindiye Ebabu. 2017. Analyzing the runoff response to soil and water conservation measures in a tropical humid Ethiopian highland. 2017. Physical Geography, 38(5):423-447 (Published online, this article covers **Chapter 3**).