Participatory Analysis and Management of Water and Ecosystem Services in the Upper Blue Nile Basin

By

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Copyright declaration

Abstract

Livelihoods in rural communities of the Ethiopian highlands are strongly dependent on ecosystem services (ESS). At the same time, they face many challenges and are typically characterised by extreme poverty. Little is known about the social-ecological context of ESS management, and how this impacts the livelihoods and poverty rates at a community level. Improved understanding of how local stakeholders interact with their surrounding ESS to support their livelihoods may inform more viable and realistic approaches to the sustainable use of ESS and maximize poverty alleviation. In this research, I applied a series of approaches including literature review, participatory rural appraisal (PRA), field experiments, computational modelling (particularly using hydrological and erosion models), and scenarios analysis to identify the most economic livelihood strategies to maximize poverty alleviation at the local scale, and to be environmentally sustainable.

First, I studied the current relationship between livelihoods and ESS, and how they are managed for poverty alleviation in the Ethiopian highlands using a combination of scientific and grey literature review. My analysis focused on the identification of the main physical processes that lead to degrading ESS, the formal and informal decision-making processes that are used to address these threats at the community level, and their relation to various levels of external intervention. I find that the main degradation processes are soil structure degradation and soil loss, but also reductions in groundwater recharge, river base flow, and carbon storage. Yet, government policies that aim to address these issues are based on a strongly centralized approach that is insufficiently tailored to the local natural and social-economic context. This may result in some short-term benefits but has a high risk of jeopardizing long term sustainability. The review outcome highlights the need for a participatory bottom-up approach to problem framing, and data generation and exchange to promote both environmental sustainability and poverty alleviation.

Following the outcome of this literature review, I develop my research methodological framework based on further review of the literature about participatory approaches to knowledge generation in the field of ecosystem services management to support sustainable development. To implement this framework, I conducted a detailed situation analysis of a representative case study (Debre Mawi watershed) in the upper Blue Nile. This watershed is exemplary for the Ethiopian and other tropical highlands where livelihood security is strongly

dependent on local ESS, particularly those provided by water and soils. This situation analysis research was conducted by applying PRA including various participatory methods, such as household questionnaires, semi-structured interviews with key informants, open community meetings, and small focus group discussions. These participatory techniques were complemented with detailed field observations through transect walks with farmers and ESS mapping. This situation analysis provided insights in the problems faced by stakeholders in the study area, and yielded options for improved livelihood and environmental sustainability. Poverty lock-in challenging strategies found through this participatory rural appraisal approach are crop irrigation and livestock fattening. For both strategies and domestic use, water scarcity was found to be the primary limiting factor. Therefore the next step of this research project focused on water availability.

With regard to water availability, I tested the hypothesis that groundwater and water harvesting increase water supply during the dry season for the local community using experimental data and modelling. I confirmed that soil and water conservation (SWC) interventions, which were implemented at degraded lands, are enhancing recharge by converting them into areas which actively contribute to recharge (referred throughout this thesis as "hillsides" because of their hydrological similarity to natural hillsides). I found that the area of such "hillsides" increased by 55% over a period of 4 years. The current (natural and regenerated) hillside area of Debre Mawi is 65.4% of the total catchment area; considering this area, groundwater recharge was calculated to amount to 1.4 million m^3 in 2016. I developed a groundwater table height simulation model and analyzed catchment-scale spatial and temporal variability of groundwater levels, which allowed me to confirm that groundwater increases water supply during dry season to residents of the lower parts of the catchments. For villagers living in the upper parts of the catchments, my experiment suggests that rooftop water harvesting is the best water source during the dry season.

Lastly, scenario analysis that links dry season water supplies with local poverty lock-in challenging strategies proves that animal husbandry is the best livelihood improving strategy for upper catchment residents, while crop irrigation is best suited for lower catchment residents' livelihoods. After fulfilling household's domestic water use need, rooftop water harvesting and groundwater respectively may enable farmers earning a profit estimated at US$69–7704 and US$1084–2504 during the dry season from a combination of animal fattening and crop irrigation. Overall, the methodology that I developed and the results that it generated are novel and significant because they identify a potential pathway to move out of sever poverty to a better livelihood within a sustainable environment. The research undertaken can be replicated for appropriate ESS management particular for hydrology-economic model development and policy, as well as for poverty alleviation in the Ethiopian-African rural highlands and to other rural communities worldwide that depend on ESS.

Statement of own work

I confirmed, this submission is my own work. Any work of others, whether published or unpublished is acknowledged by reference to the sources. Several chapters of this thesis are based on my field work data. The following extracts of this work have been submitted for publication or are in the latter stages of preparation for submission to peer-reviewed journals:

Chapter 2:

Alemie, T. C., Buytaert, W., Zulkafli, Z., Steenhuis, T. S., Timothy, K., Tilahun, S. A., Dagnew, D. C., Guzman, C. D., Tibebu, T. Y., Zegeye, A. D., Moges, M. A. and Kebede, G. A. 2017. Linking ecosystem services, environmental sustainability and poverty alleviation in the Ethiopian highlands. *Mountain research and development, submitted (review in progress).*

Chapter 4:

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Chapter 6:

Alemie, T. C., Buytaert, W., Ochoa-Tocachi, B. F., Steenhuis, T. S. and Tilahun, S. A. 2017. A distributed catchment–scale evaluation of the potential of soil and water conservation interventions to reduce storm flow and soil loss. *Land degradation and development research*, *in preparation.*

Furthermore, the results presented in this thesis based on collaborative research work with postgraduate students of Department of Civil and water resources Engineering, Bahir Dar University, Ethiopia to share stream flow, soil loss, precipitation and evaporation data.

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Chapter 1

Introduction

1.1 Research motivation

Poverty, which is mainly determined by the ability to provide one's basic needs, is a global challenge (FAO, 2005). These needs and poverty alleviation approaches vary across space and time. Under impulse of research initiatives such as the UK ESPA (Ecosystem Services for Poverty Alleviation) research programme, the potential of leveraging ecosystem services (ESS) as a means to alleviate poverty is receiving increasing scientific attention. Being largely rural areas, the link between ESS and livelihood is often very direct in mountain areas, making them geographical target areas. But ESS in mountain regions are often under severe threat from a variety of pressures while poverty is very pronounced. This makes it paramount to study how ESS can be managed, and relevant policies can be put in place, to optimize ESS to support mountain livelihoods. This is particularly relevant in the African highlands where over half of the population lives in rural areas, depending directly on locally grown food crops (Bationo et al., 2006).

This PhD research focuses on the analysis and management of ESS in the upper Blue Nile basin, using a participatory research approach which enables the involvement of the ESS users (farmers) in a detailed analysis of ESS, and in the practice of data collection and evidence generation on their ecosystem services. The desired outcome of this research is an improved ESS management to maximise poverty alleviation in the Ethiopian highlands. This study involves the Blue Nile basin headwater catchments, and looks specifically at Debre Mawi, Birr and Mizewa watersheds where livelihood security is strongly dependent on local ESS, particularly those provided by water and soils.

The Ethiopian highlands, which are endowed with a moderate temperature regime, rich soils and adequate rainfall, feed a large human population (88% of the total population) through mixed farming. They are also considered as natural water towers (Bayabil et al., 2010), and biodiversity hotspot areas (Hamza and Iyela, 2012). Livelihood security there as well as in the upper Blue Nile basin is strongly dependent on local ESS, particularly those provided by the water cycle and soils. Despite the highlands' potential for food production, and intensive efforts through interventions and by farmers, food availability per capita has been decreasing, and the ESS have been severely degraded (Ali and Surur, 2012). Earlier research has shown that the degradation of resources makes poverty in the basin worse (Shiferaw and Holden, 1999; Betrie et al., 2011). However, outputs of research focused only on the natural processes often contribute little towards poverty alleviation and environmental sustainability. The reason is the lack of contextualisation within the social-ecological system; instead treating the two systems separately and without considering farmers' experiences. This warrants further detailed and participatory research to investigate the social-ecological context of ecosystem degradation to understand how the interaction affects livelihood and the environment and then to understand how ESS management has to be supported to maximize poverty alleviation and environmental sustainability. Sustainability in this research context is considered as the combination of production of food and income and resources conservation that is necessary to meet the needs of the present generation without compromising the benefits of future generations, using farming and land management techniques that do not have negative impact on the environment and public health (Pretty, 2007; Chappell and LaValle, 2009; FAO, 2017). The proposed guiding principle for food and income generation is a wise way of farming using the available resources for potential production as efficiently as possible, while avoiding the unfavourable impacts on environment and land degradation (Joshi, 2011). In particular, the relevant criteria I consider in this thesis are that the identified strategies should be (1) environmentally friendly (i.e., without adverse impact on environment), (2) technically feasible, (3) socially acceptable (for their ongoing practicality by the local community), and (4) economically viable (i.e., a positive return of the cost). Hence, the three important indicators of these criteria are environmental, social and economic feasibility. I assess the first two criteria based on surveys, and especially focus group discussions, whereas the third indicator (which is the most determinant factor on the strategies since it is monetary value) was assessed using a cost-benefit analysis technique. Consequently the local community own the new strategies which were identified in this research, managing efficiently, updating as the existing circumstance to avoid risk (such as risk of climate change) and transferring knowledge of the strategy to new generation.

1.2 Research aims and objectives

The overall aim of this research is to leverage citizen science and ESS management for the sustainability of local livelihoods and the environment, by applying a participatory bottom-up approach with the involvement of local community in the prioritization of problems and solutions, and in evidence generation; to understand how the social- ecological systems interact with ESS (especially with water and soil related); and to understand how ESS management has to be supported to maximise poverty alleviation and environmental sustainability in the Ethiopian highlands. This aim was addressed through the following objectives under these three main topics:

1. Analysis of ecosystem services management for poverty alleviation in the Ethiopian highlands through literature review:
    - To understand how ESS are related to livelihoods in the Ethiopian highlands and what threats they face.
    - To understand the current management and policy processes of these ESS.
2. Participatory analysis of the relationship of ESS and livelihood strategies and their constraints in a representative case study in the upper Blue Nile basin:
    - To explore and prioritize the major bottlenecks and resources degradation processes that lead to further poverty.
    - To identify poverty lock-in challenging pathways and scenarios for livelihood improvement.
3. Participatory field experimentation and data collection to generate evidence with the following aims:
    - To explore how environmental data and models can help to remove some of the identified bottlenecks. For example, I hypothesise that the analysis of stream flow, groundwater water table height and other relevant data using hydro-economic modelling can generate evidence on whether water scarcity and fixed livelihood strategy (rain fed farming) are major bottlenecks to live with poverty or whether there is sufficient water to support livelihood practices and other livelihood strategies (crop irrigation and livestock fattening) can challenge poverty lock-in.
    - To develop methods to promote participatory knowledge generation and exchange based on the collected data and developed model. The developed method incorporates data of different disciplines (hydrology, soil science and social science) and results of participatory experiments. These data and results are processed using relevant models

with the aim of proving the advantage of expertise–local experience focused participatory ground-truth data and model integration, for knowledge generation and exchange in the field of ESS based focal livelihood improvement. This encourages participatory knowledge generation and exchange among scientists from different disciplines, among communities and between scientists and communities, and also between the scientists, community and policy-makers.

1.3 Research context

This research is part of a multi-disciplinary project which incorporates citizen science, hydrology, soil science and social science perspectives for problem framing and evidence generation for sustainable social-ecological interactions. The overall aim of the project is to maximize poverty alleviation through improved ESS management in the Ethiopian highlands. This research project started with reviewing previous research and work related to ESS and livelihood relationships in the Ethiopian highlands. The outcome of this review led to an in-depth situation analysis focusing on representative case study called Debre Mawi watershed. The results of this situation analysis in turn led to experiment-based evidence generation through participatory research and data collection at the field. Subsequently, all the data which were collected using participatory rural appraisal during the situation analysis and during the field experiments were analysed using combination of tools, in particular hydrological models and cost–benefit analysis techniques, in order to select poverty alleviation supporting ESS management scenarios.

1.4 Thesis outline

This thesis is divided into seven chapters. The present chapter describes the context of the thesis and its contribution to poverty alleviation and defines the aim and objectives that have guided the research. Chapter 2 critically reviews the relationships between ecosystem services, poverty alleviation and environmental sustainability in the Ethiopian highlands, with a brief discussion of background information in the catchment with regards to ESS (current ESS governance, poverty and resources degradation), summary and research directions. Chapter 3 then aims to experiment with participatory approaches for knowledge generation using a setup and specific objectives that are informed by the previous background research.

Chapter 4 mainly describes community-researcher's views on improved ESS management for livelihood and environmental sustainability through detail understanding of the local social-ecological environment, whereas chapter 5 presents the livelihood improving strategies which were proved through an integrated methodology combining participatory field experiments, data, and GIS-coupled hydrological modelling. Chapter 6 then builds on the work described in Chapter 4 by adapting the hydrological modelling, to check the impact of government-led and widely implemented soil and water conservation interventions in the study region on sediment concentration and discharge. Finally, Chapter 7 summarizes the research outcomes and highlights the main contributions of the thesis in the context of the stated aim and objectives. Future areas of research particularly with respect to hydrogeological characterization of the study region for more groundwater abstraction are highlighted.

Chapter 2

The nexus between ecosystem services, environmental sustainability and poverty alleviation in the Ethiopian highlands

Abstract

In Africa, over half of the population live in rural areas and depend directly on local ecosystems and the services they provide. A case in point is the Ethiopian highlands, where local ecosystem services (ESS) are under severe threat. In this chapter I analyse the relationship between ESS, environmental sustainability and poverty using a case study in Birr, Debre Mawi and Mizewa watersheds of the upper Blue Nile basin in North West Ethiopia, where 85% of the population consists of poor subsistence farmers. I found that current practices to provide ESS such as food, feed, income and fuel from the land are unsustainable and endanger the provision of these ESS for future generations. Loss of organic matter due to continuous cultivation has destroyed the soil structure, which has resulted in hardpan formation and a decreasing soil depth. This soil degradation in turn impairs other essential ESS such as groundwater recharge, base flow, and carbon fixation and storage. To minimize such degradation and to maintain the land productivity, the national government has developed various natural resources management options in a centralized manner. These have been implemented locally by means of governmental directives and the Bureau of Agriculture in particular, starting from region to district and at the kebele level. A main problem with this approach is that those directives are often not tailored and therefore suboptimal for local natural and socio-economic conditions. Consequently, those practices usually yield very few short-term benefits, and are therefore not maintained without further governmental intervention. This study analyses formal and informal decision-making processes related to ESS management made by the communities in the watersheds, where there have been different levels of intervention, and highlights the need for a participatory approach to problem framing, and data generation and exchange to promote both environmental sustainability and poverty alleviation.

2.1 Introduction

Poverty, which is the lack of, or the inability to achieve, a socially acceptable standard of living is a global challenge (FAO, 2005). Roser (2015) reported that 10% of the world people live under the current poverty line (US$1.90 per day). Over half of the African population live in rural areas, depending directly on locally grown crops or foods harvested from their immediate environment (Bationo et al., 2006). The world's second poorest country, Ethiopia, has 96.3% and 46.4% poor people who live in rural and urban areas respectively (OPHI, 2015). The Ethiopian highlands (areas >1500 masl) cover only about 40% of the total area of the country, but carry 88% of human population and 70% of livestock (Ayele and Heidhues, 1999; Amsalu and Graaff, 2007). These highlands are one of the most densely populated regions of Africa (Headey et al., 2014), and feed a large Ethiopian population through mixed farming (crop production and livestock keeping). The reason for the high population density is the moderate temperature, rich soils and adequate rainfall amounts, as well as the relative absence of major tropical diseases, which are common in the lowlands (Minale, 2013). Precipitation in these areas maintains the water resources, which include rivers, lakes, streams, swamps and flood plains. As such, these highlands provide 85% of all water in Sudan and Egypt (Bayabil et al., 2010). At the same time, they are biodiversity hotspots (Hamza and Iyela, 2012).

Livelihood security in the Ethiopian highlands depends strongly on local ESS (de Groot et al., 2012), particularly those related to soil and water (Notter et al., 2012) for the basic provisioning of food, feed, fuel and income. In this chapter, I focus on these provisioning ESS because these are the basics for livelihoods and are the central points of ESS management in these highlands where agriculture is the main living strategy. Malmborg et al. (2018) mentioned that the direct dependency on provisioning ecosystem services for livelihoods is particularly high in rural regions with widespread poverty. The others are mentioned indirectly: Loss of organic matter (supportive ESS) due to deforestation (regulating ESS) impacts on provisioning ESS (food and income). The major challenges to the livelihood security are low productivity of arable land and the limitations on how to use the available resources. Most farmers base their livelihood on unpredictable rainfed agriculture, and are practicing mixed farming of crops and livestock (Zegeye et al., 2010; White et al., 2011; Hamza and Iyela, 2012). Animals are kept mainly for draught power, but may provide milk, meat, manure, and economic security (Tschopp et al., 2010).

The population is growing at 2.3% per year (Minale, 2013), which puts increasing pressure on the agricultural sector. The household landholdings are shrinking, and farmers cultivate their small pieces of land continuously. Croplands have been expanded at the expense of forest and grazing lands. Crop production as well as food availability per capita has been decreasing, the land has been severely degraded (Ali and Surur, 2012), and some lands have to be abandoned. FAO (1986) estimates that some 50% of the highlands are significantly eroded, of which 25% are seriously eroded, and 4% have reached a point of no return. Coupled with growing populations, falling per capita food production, worsening poverty, loss of productive land because of land degradation, and poorly installed soil and water management practices undermine rural livelihoods and national food security (Shiferaw and Holden, 1999; Haile et al., 2006). To improve the agricultural production, technology packages such as generic fertilizer recommendations, and soil and water conservation measures have been promoted using an agricultural extension approach, focusing on upward accountability in Ethiopia (Cohen and Lemma, 2011).

Despite intensive state and farmer driven efforts, land degradation continues unabatedly. As a result, the already low agricultural yields are decreasing even further and put local livelihoods at risk. Feeding the present and future population while ensuring sustainable land management is becoming a major challenge (Haile et al., 2006). Most people are suffering from food insecurity, which is a sign of extreme poverty (Diouf et al., 2002). The highland farming communities mostly attribute the degrading conditions to religious causes (‘‘God punishes us by making everything worse’’). Their perception is that the increasing poverty and ESS degradation is the outcome of God’s punishment because they have not respected his wills (Ayele et al., 2014).

The objective of this chapter is to understand through a literature review the current management processes of ESS in the Ethiopian highlands, where 85% of the population are poor subsistence farmers. I focus mainly on three most representative watersheds (Birr, Debre Mawi and Mizewa) in the upper Blue Nile basin through a review of relevant studies. I reviewed previous research that focuses on the key soil and water related ESS for the rural community livelihoods in the Ethiopian highlands. I aim to understand how ESS management is related to poverty alleviation and environmental sustainability. Although poverty as defined by the ability to provide one’s basic needs is a global challenge, these needs and poverty alleviation approaches vary across space and time (FAO, 2005). In mountainous and developing regions, people live predominantly in rural areas and depend on their surrounding landscapes for multiple ecosystem services (ESS) that provide their basic needs (Sinare et al., 2016). In such areas, the link between ESS and livelihood is very direct. However, ESS degradation and poverty are severe. The main livelihood strategy to generate basic needs is agriculture, which is highly dependent on very dynamic and often unreliable climatic conditions. In addition ESS mismanagement occurs because of inappropriate practices induced by a lack of understanding of the natural system, as well as a lack of stakeholder integration. Hence there is scope for improved ESS management to support poverty alleviation and environmental sustainability, by targeting ESS and agriculture-dependent rural areas considering that it enables local to large scale development.

Related to the concepts that are used to define interventions in ESS and the evaluation of their impact on ecosystem services, Sinare et al. (2016) argued that most methods to assess ESS have been developed at large spatial scales and depend on secondary data. Such data is scarce in rural areas where poverty is widespread. For that reason, these regions are a major focus for substantial landscape investments that aim to alleviate poverty, but current methods fail to capture the vast range of ecosystem services supporting livelihoods, and can therefore not properly assess potential trade-offs and synergies among services that might arise from the interventions. Therefore, I adopt an integrated participatory method (Hossain et al., 2018) into social-ecological systems to assess the status of ESS and the benefits to livelihoods to analyse the potential for poverty alleviation and sustainable development. This approach is useful in many data poor regions and can be extrapolated across larger spatial scales with similar social-ecological systems.

2.2 Study region

In my review, I focused on papers that cover the upper Blue Nile basin in Ethiopia, (34°33'–39°45'E and 7°49'–12°42' N). It is one of the major tributaries of the Nile River (Mellander et al., 2013) and comprises a total area of 180 000 km^2. It has a tropical highland monsoon climate with a main rainy season between June and September (Gondo et al., 2010). Mean annual rainfall ranges between 800 to 2200 mm, while average minimum and maximum temperatures are 11°C and 26°C, respectively. Precipitation maintains different water resources such as the fresh water lake (Lake Tana). Lake Tana, which has many archaeological sites, is the main source of the Blue Nile River. It is the largest lake in Ethiopia and the third largest in the Nile basin. The basin has high potential for irrigation, hydroelectric power development, high value crops and ecotourism. I then focus more specifically on ESS management processes in 3 watersheds within the Blue Nile basin, i.e., the Debre Mawi, Mizewa and Birr watersheds, which I consider representative of the wider highlands (Figure 2.1). They are characterized as mountainous, highly rugged and dissected topography with steep slopes (Guzman et al., 2013) and variable soil losses (Tilahun et al., 2013a). These watersheds are drought-prone (McHugh et al., 2007) and most subsistence farmers are food self-insufficient, i.e., they cannot produce enough to cover fully their subsistence. Subsistence farmers are food insecure in general, i.e., they do not have adequate access at all times to sufficient, safe, nutritious food to maintain a healthy and active life; they are also not food self-sufficient in the sense that they are not able to meet their daily consumption needs particularly from staple food crops, from their own production (IFPRI, 2010).

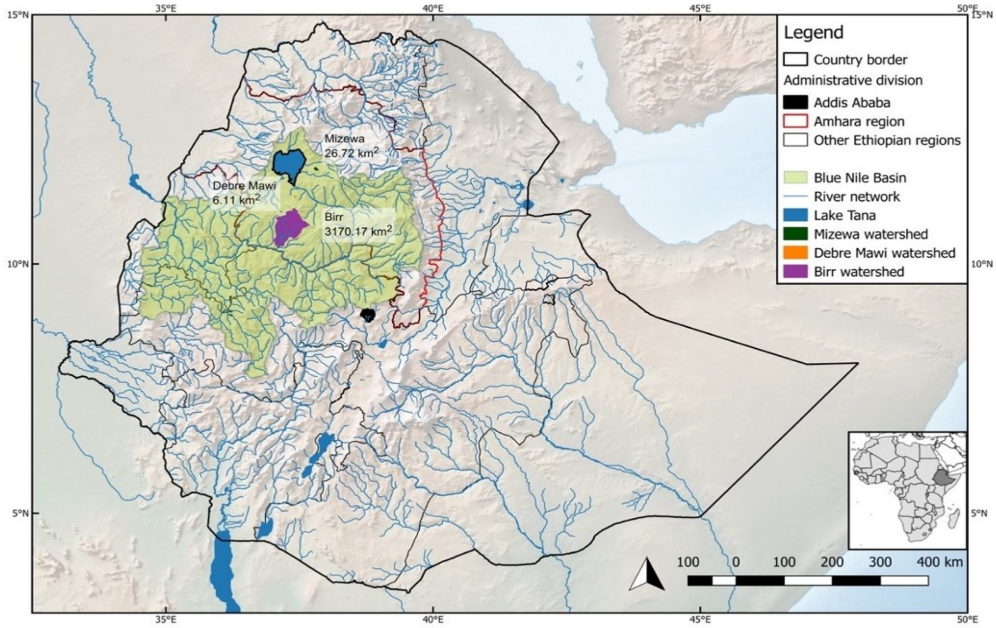


Figure 2.1: Location of the study area (the three watersheds and the upper Blue Nile basin).

2.3 Farmer management of ESS

The study catchments, as most headwaters of the upper Blue Nile basin, are dominated by subsistence farming (Zegeye et al., 2010; Easton et al., 2010; Ayele et al., 2014; Moges et al., 2014). Average farm size is one hectare of land for food crops production and livestock keeping

(Salami et al., 2010). Therefore, farmers are dependent on local ESS for their immediate needs, in particular food, feed, income and fuel. These ESS are generated from the farm plot, except for some animal feed and firewood, which is collected from communal lands. Continuous soil erosion and productivity loss (Tebebu et al., 2010; Guzman et al., 2013) ensues from the pressure from people and livestock exceeding its carrying capacity (Grepperud, 1996). In addition to continuous cultivation, the farmers' main survival strategy is cropland expansion (Ali et al., 2011). Based on a land use assessment in the Gilgel Abay catchment, Minale (2013) reported a loss of 72.3% of forests and 55% of both private and communal grasslands to croplands over the last 35 years. Farmers who have adjacent croplands to communal grazing and forestlands have been expanding their land slowly, even though it is not legal. Additionally, farmers cultivate sloping terrain and destroy well stabilized soil and water conservation structures to expand their croplands, and grow environmentally exotic tree species for income (Figure 2.2).

The acuteness of the degradation issues forces farmers to focus on short term survival and to ignore long-term sustainability. Traditional practices aggravate land degradation including hardpan formation, decreasing soil depth and land abandonment (Hanson et al., 2004). Intensification of cropping on sloping lands without suitable measures to replenish lost nutrients has led to widespread land degradation (Shiferaw and Holden, 1998) and associated with yield reduction. The changes have been dramatic for the traditional agricultural system, and the impacts are recently becoming evident. Vegetation cover has declined, the proportion of degraded lands has increased, the total annual soil loss rate is high and soil productivity is dwindling (Zeleke and Hurni, 2001). In the Debre Mawi watershed, Tebebu et al. (2010) reported that gully erosion losses have been increasing over time. In the period between 1980 and 2007, soil loss was 30.7 t/ha/year, and 530 t/ha/year from 2007 to 2008. For instance, a gully in the Birr watershed studied by Ayele et al. (2014) expanded 23 m, 1.9 m and 13 m (resp. length, depth and width) in less than 3 months, and lost 710 ton of soil. The degrading resources in turn hamper the ability of the land to provide further essential ESS such as groundwater recharge, by decreasing infiltration and increasing runoff through hardpan formation (Easton et al., 2008). This results in a vicious circle of decreased base flow and potentially a decrease in irrigated area and crop water availability in the root zone, which in their turn lead to decreased carbon fixation and storage as result of decreased crop growth.

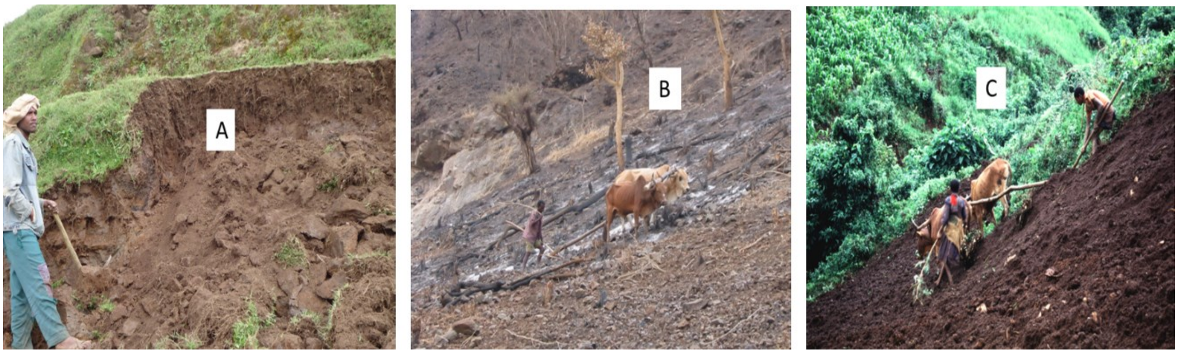


Figure 2.2: Farmers' strategies for their livelihood improvement (A: soil and water conservation structures destruction, B: deforestation, C: ploughing sloping terrains). Source of photos, A: Tilashwork Alemie, 2013, and B and C: Muluneh, 2010 *(*pictures from Gete Zeleke and Eva Ludi).

2.4 Government led ESS management

Globally, poverty reduction strategies have been applied in rural areas (IFAD, 2011), because more people are living in rural areas depending on agriculture, and poverty is worse for marginalized rural people (Oakley and Clegg, 1998). However, most poverty alleviation strategies have been focused on direct interventions, and in particular on the provision of facilities that are not locally available. Investments for the international donor community have concentrated on delivery of infrastructures that are usually expensive and that have not secured their ongoing operation and maintenance (Barder, 2009). These have also been implemented with limited attention to developing a sense of ownership by the local community, and without problem framing, i.e. without tailoring poverty issues and problem prioritization. However, more recent insights in the dynamics of poverty alleviation acknowledge that interventions need to be based on understanding of the detailed socio-ecological context of a specific location. In other words, poverty should be viewed as a global phenomenon but tackled at the local level using local indicators (Cobbinah et al., 2013).

In order to minimize ESS degradation, to maintain the productive capacity of the land and to improve livelihood, the central Ethiopian government has developed various management options and implemented them locally by means of a governmental directive. After the outbreak of famine in Ethiopia in 1973, different interventions were transferred and introduced to different parts of the country, particularly through the Bureau of Agriculture, starting from region to zone to district and kebele level (Gashaw, 2015). The development agents, who are working at the village level, have received technologies from the top level through a formal decision-making process, and focused on promoting standardized technology packages rather than on technology adaptation to local needs and desires, or integrating modern technology with farmers' own knowledge (Cohen and Lemma, 2011). For instance, most highlands are covered by soil and water conservation (SWC) structures. According to FAO (2003), the "intensified package approach", which puts heavy emphasis on accelerating crop production, using fertilizer and improved seed has been applied by agricultural extension without careful analysis of agro-ecological zones, markets, infrastructure, farmers' choice and other sustainable development options.

The government prioritization of cereal intensification a decade ago has played a pivotal role (Spielman et al., 2010). This policy guided the expansion of cereal farming on the expense of grazing and forest lands. As a result, the livestock subsector remains marginalized as compared to the cereals production, with little effort to improve animal productivity and animal health and promote better management of pastures and thus animal feed. This prevents the subsector to contribute its full potential to the agricultural economy. Instead this strategy aggravates poverty and environmental unsustainability, because it was enforcing the farmers to own fewer oxen, to cultivate smaller areas, and to rent out their land. Additionally, the decreased grazing land carries livestock population beyond its capacity, which leads to further land degradation, poorly nourished animals characterized by low productivity, and conflicts over communal grazing land. Furthermore, generic fertilizer and crop commodities were recommended by agronomists and applied on farmers' fields without detailed characterization of the farmlands as solutions to food security. For example, 100 kg DAP (21 kg P and 18 kg N) and 100 kg urea (46 kg N) ha^{-1} were being used for barley and other cereal crops production in the northern Ethiopian highlands in all soil types. Further research proved that the fertilizer recommendation was wrong in amount and type. The right recommendation has been N50P75K50, N25P0K50 and N25P50&75K25 in the Cambisol, Luvisol-1 and Luvisol-2, respectively for optimum barley production (Agegnehu et al., 2014). The degradation of natural resources is continuing unabatedly (Bekele and Drake, 2003) and the provisioning ESS, on which livelihood depends are thus degrading further.

Parallel to crop intensification, different land conservation or SWC options have been implemented in degrading and food deficit areas of the highlands, mainly by food-for-work and cash-for-work incentives (Shiferaw and Holden, 1998; Tefera and Sterk, 2010). This was done predominantly through a top-down approach, i.e., decisions for technology selection and implementation have been done from the top level (national, regional, zonal or district level) without involvement of farmers (FAO, 2003) and without adjusting them to local environmental conditions. Most SWC technologies introduced by NGOs in the early 1970s were transferred from other countries and applied in Ethiopia to mitigate drought and famine without modification (Shiferaw and Holden, 1998; Haile et al., 2006). Since 1980s, governmental extension programmes have also applied standard structural SWC technologies that are biased towards only reducing soil loss in almost all land uses (Gebreegziabher et al., 2009). These have long-term benefit (i.e., after 2 or 3 years) but short-term disadvantages, such as reducing the farmland area, and serving as shelters of crop pests (rodents). Haile et al. (2006) reported that SWC campaigns at the catchment are implemented by inflexible untrained extension staff, which rarely take into account site-specific characteristics. As a result, SWC structures are uniform throughout the catchment (with some misplacements), and this leads to further problem (sever ESS degradation and poverty). In general, most interventions by governmental and nongovernmental organizations cannot be considered a holistic approach to enhancing agricultural production for immediate benefit while maintaining long-term sustainability. The respective development actors from governmental and nongovernmental organizations have far less awareness about the potential of improved agronomic and vegetative/biological measures to reduce soil loss and more importantly to maintain and enhance overall productivity.

Despite the identified limitations in ESS management, some positive results can be identified in Ethiopia. Recently the implementation of biological/vegetation-based SWC is being encouraged at national level although limited studies exist that analyse the specific biological SWC impact on degraded lands and whether it is multipurpose (Sinore et al., 2018). Such information is very important for sustainable land management programs of the country. One example of such research is that of Sinore et al. (2018) who used experimental research to confirm that elephant grass and sesbania are effective biological practices for rehabilitating lands and improving soil properties through minimizing erosion.

Another example of positive results for biological/vegetation-based SWC practices located in the upper Blue Nile basin is the Amhara Regional Agricultural Research Institute, which conducts its research in the northern Ethiopian highlands, collaborated with an externally funded local NGO (Water and Land Resources Centre) to implement a demonstration approach fostering the adoption of biological measures to farmers in the Andit Tid catchment, which served as an observatory watershed. Andit Tid is a research site, which was selected as a typical example of highly degraded agricultural zones in Ethiopian highlands. It was established in 1982 by the Ethiopian Ministry of Agriculture supported by University of Bern, to monitor the impact of SWC measures on soil erosion. In a participatory approach, a promising grass species (phalaris) was selected by the farmers as a potential erosion reduction method. Phalaris is an evergreen, fast growing multipurpose grass sp., i.e., beneficial for soil and water conservation, forage, house construction, and for SWC structures sustainability (Figure 2.3).

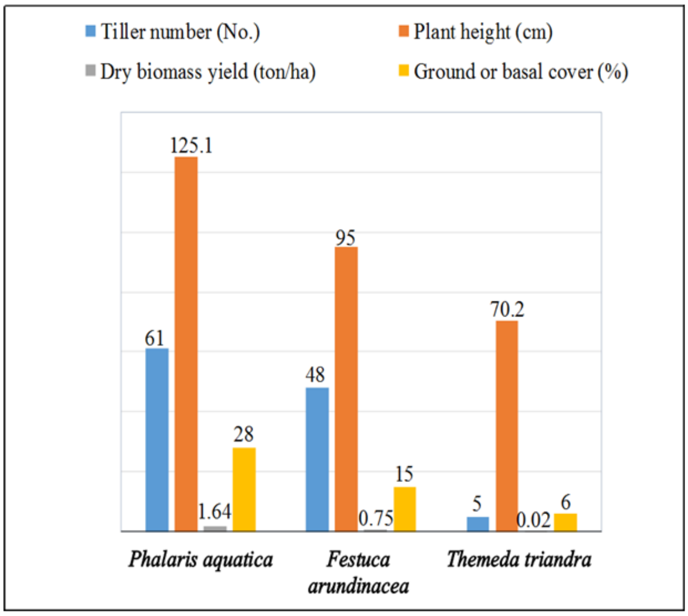


Figure 2.3: Performance of grass spp. in Ethiopian highlands (Source: Debre Birhan Agricultural Research Centre in Amhara Regional Agricultural Research Institute, Ethiopia).

But despite positive examples, there is an endemic issue of lack of awareness of land users about new technologies before they are enforced to implement them. Bewket (2007) reported that the involvement of the farmers was essentially limited to 'participation by consultation' and the farmers were rather persuaded to implement the conservation measures. The indigenous knowledge as well as farmers' competence to solve their problems have been usually underestimated and given less emphasis in the design of land management practices. In general, the applied science guidance by policy makers has lacked ample, exact and up-to-date knowledge from farmers about their land to modify the interventions accordingly the local current condition.

As a result, at least some of SWC practices are usually ineffective in increasing short term benefits and are not maintained without further governmental intervention in the study region. Most of the applied SWC interventions and particularly those implemented more than ten years ago have solely focused on physical structures, whose effects or benefits only come after two or three years. Sinore et al. (2018) also mentioned that throughout the history of combating soil degradation in Ethiopia, constructions of physical structures were given priority over biological practices for a long period. The low land allocation of 1ha per households is a main reason that farmers are unable to bridge an investment horizon of two years. Moreover, SWC structures such as stone bunds implemented against yield reduction and soil loss provide habitats for rodents and resulted in further crop yield reduction (Meheretu et al., 2014). In addition, some misplaced interventions have led to increasing degradation and poverty. This reduces farmers' trust in new interventions, and induces fear that these practices accelerate the decrease in ESS. This lack of trust often leads to peasants dismantling structures once the incentives are discontinued. According to Haile et al. (2006), in the course of the political changes in 1991, Ethiopian farmers began on a large scale to remove and modify SWC schemes that were previously established by the government under the food-for-work program. Holden et al. (2004) also described that various forms of conservation technologies have been commonly implemented through external food-for-work programs, and at least some of the introduced conservation structures were later removed by the farmers. Bewket (2007) mentioned that a majority of the farmers acknowledged that the introduced conservation technologies were effective measures against soil erosion and for improving land productivity at the beginning for the sake of their incentives. He also stated that of late, the plan of the sustainable adoption and widespread replication of the technologies became unlikely.

The major factors that were discouraging the farmers from adopting the technologies on their farms were found to be labour shortage, problems with the adequacy of the technologies to the farmers' requirements and farming system circumstances, and land tenure insecurity. The transferred SWC practices were found not to be socio-ecologically sound but to aggravate resources degradation and poverty. Social issues relate to the fact that they are labor intensive, and not adequate to the farmers' requirements and farming system circumstances. Ecologically, they are not compatible with the specific land feature and come with negative outcomes such as further land degradation, and reductions in groundwater recharge, soil organic matter and soil fertility. Many have concluded that land degradation is a widespread problem with a widespread failure of interventions (Haile et al., 2006). Therefore, many of these problems are basically related to the lack of a genuine involvement of the farmers in the decision making and conservation effort. These authors mentioned that to support soil conservation efforts in Ethiopia, a soil conservation research project (SCRP) established in 1981 was attempting to develop appropriate technologies, which are technically feasible, ecologically sound, economically viable and socially acceptable. The aim of the project was to monitor the ongoing effort to mitigate land degradation and to provide appropriate technologies and test them in large operational scales. However, the centralized planning, lack of incentives to farmers, weak technical and implementing capacity of the development agents and the land holding insecurity were not conducive for the scaling-up of the SWC activities as expected. Based on those findings, Bewket (2007) suggests that future interventions should carefully pursue a farmer-participatory approach, and farmers should participate in the decision-making process on the design of policies for sustainable land management and poverty alleviation (Vignola et al., 2010). Shiferaw and Holden (1998) also mention that poverty-environment trap breaking and sustainable development initiation require feasible policy and technologies that confer short-term benefits to the poor while conserving resource for future generation. Communities, scientists and policy makers should be connected and create learning environment for common understandings, thus for adaptive ESS management (Folke et al., 2005).

2.5 Conclusion

I analysed the current management dynamics related to ecosystem services, and their impact on poverty alleviation efforts and environmental sustainability in the Ethiopian highlands. The reviewed literatures specifically enable identifying the opportunities and challenges of poverty alleviation using soil and water related ESS management, and to formulate relatively sound suggestions on how to improve local livelihoods. I highlight deficiencies in the current ESS management strategies to maximize the poverty alleviation potential. The perspectives of local community have a tendency to focus on strategies that yield short-term benefits such as deforestation for clop land expansion and ploughing slopping land, but are not sustainable on the long term. Government-led interventions tend not to be compatible with the specific social-landscape conditions because of the top-down nature of interventions. To create awareness about such deficiencies to the main actors particularly at the state level and to researchers, I found key examples of these deficiencies, such as limitations of ESS management by farmers and government level stakeholders, and their outcomes in Debre Mawi, Birr and Mizewa watersheds, where interventions and research have been currently applied widely and actively. My research findings can therefore inform stakeholders, and be replicated in to other catchments of the upper Blue Nile basin and the Ethiopian highlands.

From a physical perspective, the studied area has clear potential for productive and sustainable mixed farming, which can rely on the functional integrity of the watershed's ecosystems– rivers, lake, forestlands and farmlands, and of decision makers. But the integrity of the overall social-ecological system is currently undermined by inappropriate government initiatives, including development workers and researchers. For instance, intervention practices have been planned and implemented without detailed analysis of relationships between the social and ecological systems that enable problem framing and prioritization of problems and their challenging solutions (Gashaw, 2015). Additionally, risk such as crop failure cannot be diversified against uncertainties of erratic rainfall and sever soil erosion. Kifile (2013) argued that most of the population (85%) insist on crops production and keeping a few oxen for ploughing, and on eucalyptus plantation. The formal decisions, particularly those related to fertilizer application and soil and water conservation are imposed by high-level governmental decision-makers and are implemented at farmer level without further refining as the specific local condition and farmers' knowledge. Top-down designed interventions are mostly implemented at village levels by farmers, guided by development agents, focusing on upward accountability. Earlier research that focuses on biophysical processes has also shown that degradation of resources makes poverty worse through time (Haile et al., 2006; Ali and Surur, 2012). Despite the intensive efforts and costly generic interventions, ESS degradation and poverty persist, even worsen through time. Because there is mismatch between top level decision makers, researchers and farmers.

My findings suggest that the availability of scientific information on soil and water processes may not be the major bottleneck to the implementation of sustainable farming, but that instead the access to relevant information at the local scale is missing (Mohammed, 2013). Actors in the study region such as development workers and researchers from governmental and nongovernmental organizations, as well as farmers lack actionable knowledge, which is applicable as the existing social-ecological condition, for immediate community livelihood improvement with sustainable resources management. The challenge now is to optimize the exchange of know-how between land users, scientists and planners or decision-makers for adaptive ESS management. The other bottlenecks related to sustainable resources management are centralized decision-making processes and the trend of implementing interventions through incentives such as food-for-work and cash-for-work. The farmers through state level guidance (particularly guided by development agents) implemented top-down interventions for the sake of receiving incentive pay-outs but once the incentive ceases the farmers start to dismantle interventions (Holden et al., 2004; Bewket, 2007; Spielman et al., 2010; Gashaw, 2015). To make the situation better for the agricultural smallholders, a participatory approach for problem framing, knowledge generation and exchange may be required (Figure 2.4).

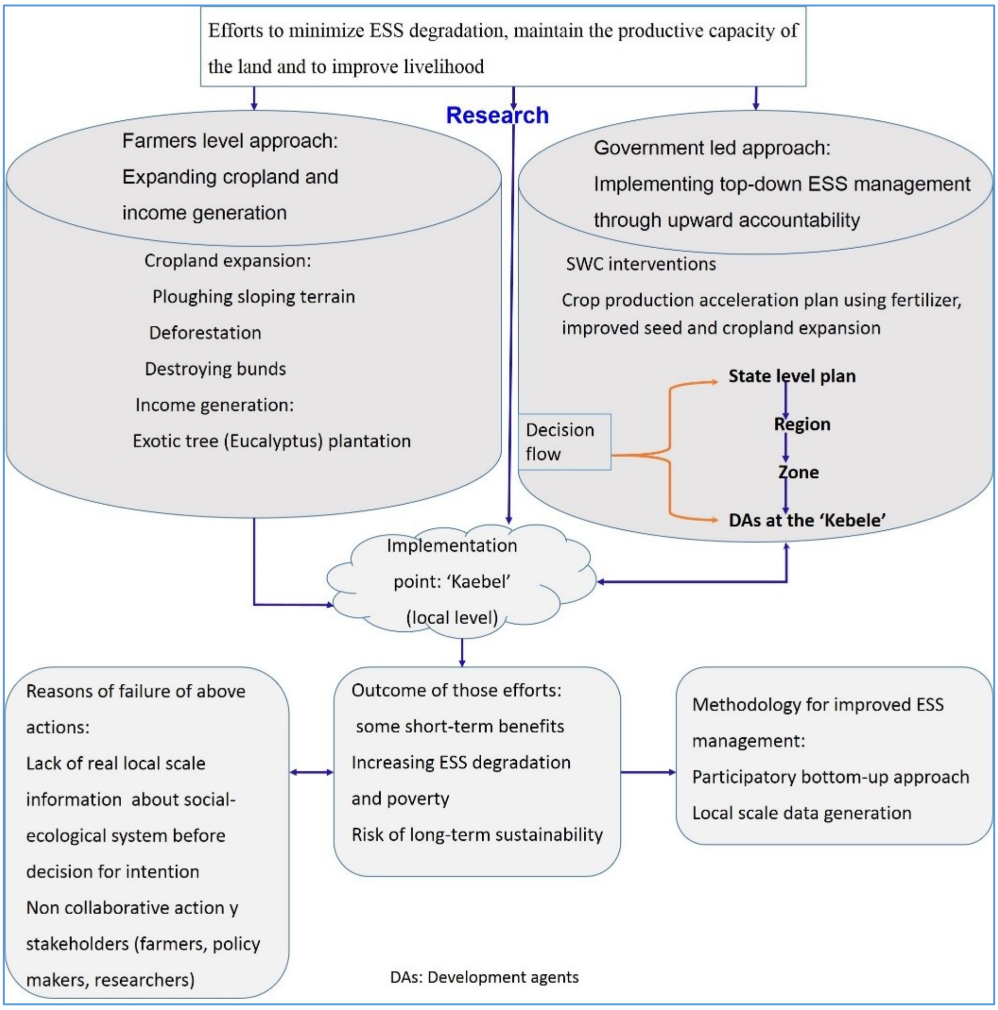


Figure 2.4: Influence diagram showing the links and unintended consequences of a top-down approach to ESS management.

Chapter 3

Participatory approaches to the generation of knowledge for ecosystem services management and sustainable development: a review

3.1 Overview

In mountainous (Potosyan, 2017) and developing world regions such as Africa (Mellor, 2014; Muyanga and Jayne, 2014, Josephson et al., 2014; Jayne et al., 2014) most people live in rural areas and depend on ecosystem services (ESS) provided by their immediate environment (Malmborg et al., 2018). In such rural areas, livelihood security mainly depends on water and soil related ESS since the main livelihood strategy is agriculture (Malmborg et al., 2018; Muyanga and Jayne, 2014). ESS degradation and poverty are often endemic (OPHI, 2014), and agriculture is highly dependent on often-erratic climate conditions (Malmborg et al., 2018). For instance, Schirpke et al. (2016) emphasized that the ongoing loss of ESS is one of the greatest global challenges faced by decision-makers and society that needs urgent solution. At the same time, many regions suffer from acute scarcity of data about the environmental processes that govern ESS. Available information and knowledge is often not available to local people because of a lack of community participation in the knowledge generation processes (Josephson et al., 2014). Such marginalisation leads to inadequate knowledge creation and exchange on local human-environmental system dynamics and interrelations. Therefore, methodological development on more participatory approaches to the analysis of ESS potentials (= the hypothetical maximum yield of selected ESS), flows (= real supply in a particular area within a given time period) and demands (= currently consumed or used in a particular area over a given time period) is very useful (Wangai et al., 2016; Burkhard et al., 2014).

Leveraging rural ESS management for poverty alleviation is now receiving increasing attention as it provides a promising pathway for large-scale poverty alleviation and environmental sustainability (Fisher et al., 2014). Suich et al. (2015) argue for the development of an appropriate methodology to reduce the gap in understanding of the links between ESS and poverty, the dynamic of change, and how pathways out of poverty may be achieved based on the sustainable utilisation of ESS. To achieve this aim, it can be very beneficial to develop methodological strategies that incorporate the view of key stakeholders (including the focal community), interdisciplinary expertise, and policy-makers, in order to increase the sustainability of ESS supported livelihood, applying comprehensive actionable knowledge.

3.2 Existing approaches

Recently, an increasing body of research is available, which focuses on ESS management for human well-being (HWB). For instance, Koundouri et al. (2016) designated a methodological framework which mainly characterise the socio-economics of the study area aiming to achieve sustainable environmental and socio-economic management of freshwater ESS at European level. Grizzetti et al. (2016) reviewed and analysed the current literatures related to the water ESS in EU, and argued that biophysical assessment and socio-economic valuation should be conducted jointly to account for not only water services but also for the different values of ecosystem services (ecologic, social and economic) and to strengthen the recognition of human dependency on nature. Another group of researchers from nineteen institutions (Maes et al., 2016) developed an analytical framework which ensures that consistent approaches are used throughout the EU in support of the EU biodiversity strategy to 2020; they concluded that there is potential to develop a first EU wide ecosystem assessment on the basis of existing data if they are combined in a creative way; however, substantial data gaps remain to be filled before a fully integrated and complete ecosystem assessment can be carried out. Since these studies have been implemented in areas where there is limited data scarcity (in contrast to most developing countries), the above mentioned researches more or less met their objectives. But they also identify data gaps (Maes et al., 2016). In addition, they show only limited interdisciplinarity as they focused on science in socio-economic analysis of water ESS (Koundouri et al., 2016) and all focused on developed countries within Europe.

In a developing context, Wangai et al. (2016) conducted a review of studies on ESS. The main aim of their review was to assess the extent to which ESS studies have been conducted and applied in Africa. They reviewed 52 ESS-related studies, and contextualized their review further within the population projections for Africa in the next thirty years; hence, it enables to review the ESS research in Africa to date. In addition, it is useful to determine whether ESS research results address the concern of ESS supply and demand patterns in the spatially heterogeneous continent (Busch et al., 2012). Their results indicate a strong geographical bias towards South Africa, Kenya and Tanzania, and focused on ESS provided by watershed or catchment ecosystems; confirm that most of the 52 studies focused on more than one ESS category and provisioning ESS dominated across all ESS categories; and determine ESS trade-offs and synergies were barely addressed. Haase et al. (2014) and Balvanera et al. (2012) confirmed that little was attempted to explicitly address ESS supply-demand relationships, trade-offs and synergies.

Wangai et al. (2016) identify an urgent need to extend ESS studies to the entire continent, in order to capture the spatial and socio-economic uniqueness of various countries and focus more on local-scale assessments of multiple ESS, as a means for addressing ESS trade-offs, synergies and ESS supply-demand relations in Africa. According to Wangai et al. (2016), trade-offs occur when interests of various actors toward a given resource differ; but when interests concur, synergies may emerge. Hicks et al. (2013) also states trade-offs and synergies in viewpoint by analyzing relationship pathways of different stakeholders to their relevant ESS. Similarly, Wangai et al. (2016) mentioned that trade-offs and synergies among different types of ESS could only be possible when their characteristics and relationship pathways are analyzed collectively; however, they confirm that this type of analysis was missing in previous studies based solely on one category of ESS. Therefore, ESS assessments as well as participatory approaches to knowledge generation in the field of ESS have not often been tested in Africa yet. Overall, most current ESS assessment methods have been developed on large scales and rely on secondary data for the range of small landscape to large-scales ESS analyses (Malmborg et al., 2018; Sinare et al., 2016). Sinare et al. (2016) argue that the issue of serious data scarcity in rural areas, where poverty is also widespread, and suggested participatory activities to generate local knowledge by integrating science, new technologies and indigenous knowledge (Buytaert et al., 2014) as a potential option.

To explore a methodology for knowledge generation, which supports sustainable ESS management for human wellbeing in rural areas, and which is applicable in both developed and non-developed regions, the methodological framework of my research was developed based on recent research conducted by interdisciplinary network of researchers, reported by Hossain et al., (2018). These researchers aimed to identify worldwide priority research questions in the field of sustainable use of ESS for human wellbeing based on a conference workshop held for early career researchers. Ultimately they identified five interconnected main research themes from 140 questions they identified earlier. Their paper focuses on the significance of the identified research questions, followed by a consideration of possible approaches, such as frameworks, data, models and concepts to answer the questions (Table 3.1).The future research questions themes to sustainable use of ESS for HWB, determined by Hossain et al. (2018) are descried below:

Exploring the relationships between social-ecological systems: For social-ecological systems contextualization, the questions in this theme reflect that importance of natural and social scientists interactions and highlight the urgent need for greater interaction between these groups of scientists (Milner-Gulland, 2012), in order to adopt a multi-stakeholder participatory approach for improved ESS-livelihood relationship. Furthermore, the social-ecological system under examination can be understood very well and greater sustainable development can be achieved if natural-social scientists' knowledge is integrated with local community knowledge and policy makers' considerations (Robinson, 2004).

Improving awareness, collaboration and data availability: UNEP (2012) and UN (2014 reported that data unavailability at the regional (local) scale, particularly in developing countries, is one of the major limitations for conducting research, even though global and national scale data are available at increasingly high spatial and temporal resolutions. This research theme mainly aims to identify options and technologies exist to assist primary data collection and increased awareness of data-poor sectors in developing countries and remote field locations such as in Ethiopian highlands. In addition it highlights the need of exploring appropriate methods to use small-scale experiments to validate trends in data at large scales. The long-term success of ESS projects depends very much on the involvement of the local community. Because detailed knowledge of local conditions and of previous successes and failures known by the local community can be vital to success (Fish et al., 2011). However, local people's involvement in such types of projects is mostly passive and they have no decision-making powers (Pretty et al., 1995).Therefore, more participatory approaches are needed to improve communication and increase trust and collaboration between stakeholders (i.e., between academics from different fields–non–academic local communities).

Exchanging knowledge: Particularly relevant to the case under my study, this theme indicates the potential for action through 'bottom-up' grassroots societal movements, which have been significant in mobilizing ownership of issues, and community action and knowledge in areas of environmental science and sustainability (Seyfang and Smith, 2007).

Valuing ESS, including market and non-market valuation: This theme focuses on the need of exploring methods for meaningful estimates of ESS values, especially for those do not have direct (formal) market value so that these services can be accounted for in social-ecological systems. Hence the assumption is that if some value on ESS can be put, they are more likely to be considered in decision-making processes (De Groot et al., 2012), together with other financial/economic, ecological and social interests, to address the interlinked challenges of the community and environmental uncertainties for example health and climate change (Watts et al., 2015). The consequences of activities to manage ESS also requires an estimate of the supply of these services from the system in terms of monetary values. Following this there should be better understanding of whether there is market for ESS and how it can be regulated depending on the time and space scale of the supply and demand.

Sustainable management: Based on the main issue that policy makers are unable to develop and implement appropriate initiatives that will allow society to adapt to future environmental conditions (Knight and Harrison, 2014), this theme highlights the need for sustainable management of biodiversity and ESS (Geijzendorffer et al., 2015) mainly in the context of on-going climate change; suitable ESS approaches for providing evidences base for sustainable management of the environment; and appropriate decision-making processes that should be put in place to manage trade-offs between different ESS.

Possible future approaches to address the research questions about sustainable use of ESS for human wellbeing are presented as follow:

Tools and frameworks for decision-support: Out of a range of tools and frameworks to support decision-making for sustainable ESS management, mixed methodological approaches and the integration of different perspectives in mixed frameworks (Wegner and Pascual, 2011) provide important opportunities for future research. One of the best examples is the 'balance sheets approach' promoted in Turner et al. (2015); it brings together complementary-context-dependent types of ESS assessment, arguing for the use of a range of findings from different methods.

Methods for data collection: The worldwide increasing concern for the effects of environmental change on ecosystems and their benefits requires a shift from a focus of ecological research towards whole communities and landscapes involvement (Mace, 2013). Understanding of global change-biodiversity-ESS providing ecosystems relationships may benefit from experimental studies (Tobner et al., 2014; Beier et al., 2004) for data collection, especially with the involvement of the focal community. Additional insight can be provided by surveying analysis of environmental responses to global and regional changes, using relevant methods and technologies. Social science research methods, such as household surveys and focus group discussions, can be combined with technology (e.g. GPS, mobile technology, remote sensing, social media) to support research on long-term societal and environmental change in response to ecosystem change (Pocock and Evans, 2014; Water Research Commission, 2015).

Modelling: Modelling approaches or tools can be system dynamics and/or agent-based, and can provide insight on how systems and human behaviour will respond to environmental change and human development. These approaches are able to capture the dynamic and complex relationships between ESS and HWB. Multi-agent models in particular can be useful in modelling and exploring the dynamic behaviour of HWB in response to environmental change (Hossain et al., 2017). For example, Harfoot et al. (2014) developed the *Madingley model,* as a way to highlight the value of models that not only predict but also illuminate the mechanisms underlying ecosystem responses under different conditions. In the field of ESS-HWB relationships, local evidence needs to be collected and compared to support the modelling approach. Hence, models that intersect different disciplines and can be applied to solve the challenges of data unavailability across different scales are co-constructed using participatory methods (Hossain et al., 2016a; Etienne, 2014).

Linking science to policy: To answer these research questions, possible approaches need to create a central point that engages scientists, decision-makers and the general public in communicating knowledge and enacting decisions (Ishii, 2014). Mitlin (2008) mentioned that a proactive approach to integrating science with the needs of policy makers involves researchers working closely with and within decision-making bodies through formal or informal knowledge exchange partnerships and/or collaboratively determined research programmes. According to Lemos and Morehouse (2005) and Pohl et al. (2010), the most closely engaged level of co-production (collaborative, highly engaged co-working arrangements between different knowledge communities) of research is increasing popular approach for researchers working on socially and politically relevant research.

Enhancing interdisciplinary research: Addressing questions concerning ESS and HWB relationships requires the development of research approaches that have a broader outlook and a culture of interdisciplinary collaboration. In a changing world, the provision of interdisciplinary training and support respectively for socio-ecologists, and for long-term social-ecological monitoring and research projects can strengthen inter-disciplinary links and secure the future of sustainable ecosystems and societies. For example, active collaboration between fields (such as ecology, economics and social sciences) may provide innovative insight into ecosystem and social processes.

Overall, Hossain et al. (2018) highlighted the need for improved data availability, stakeholders' collaboration and knowledge exchange, which, in turn, can support the integrated valuation and sustainable management of ecosystems in response to global change. They also emphasized the need to consider a wider range of topics simultaneously (interdisciplinary expertise) concerned with the relationships between social and ecological systems (for tailoring problems and prioritise solutions) to ensure the sustainable management of ecosystems for human wellbeing. By adopting the research questions of Hossain et al. (2018), I defined my research themes including possible approaches to answer these research questions (Table 3.1) upon which the new interdisciplinary bottom-up participatory research approach was built in section 3.3.

Table 3.1: Summary of research themes and possible approaches to address them in the context of sustainable development and ESS management for human well-being (HWB).

Major identified research themes and their relevance in a context of ESS management for sustainable development
1. Understanding the relationships that define social-ecological systems: • Required for recognizing the early warning signals of an approaching tipping point in a social-ecological system (Folke, 2016). • Comprehensive understanding of the system under examination is required which is the most difficult aspect to address (Suich et al.; 2015). • There is an urgent need for greater interaction between natural and social scientists as well as other related actors such as landscape planners in order to adopt a multi-stakeholder significance, and highlights participatory approach in future work which incorporates also citizen science (Buytaert et al., 2014; Hadji-Hammou et al., 2017; Jull et al., 2017).
2. Improving awareness, collaboration and data availability: • It is the research theme to explore the availability of technologies and other options for the assistance of primary data collection and to increase awareness of data-poor sectors in developing countries and remote field locations; and discover the way how to use small-scale experiments to validate trends using data at large scale. • In contrast to the global and national scale, a lack of data at the local scale, in particular in developing countries, is one of the major limitations for knowledge generation to maximize sustainability. • Traditionally, in rural research, the process of knowledge transfer is predominantly linear and one-sided and has not recognized and integrated the expertise of practitioners and those who use services (Abma et al., 2017). • In most ESS management approaches on which long-term success of ESS projects depends very much, local people's involvement is passive and their decision-making power is minimal. • The important requirement is good quality data at the regional scale at which most planetary processes such as agriculture take place; data available from the local community, such as detailed knowledge of local conditions and of previous successes and failures, can be vital to success; and more participatory

approaches are needed to improve communication and increase trust, and closer collaboration between stakeholders involved in ESS management, as well as between academic disciplines and local communities is very essential.

3. Exchanging knowledge:

- It creates better integration between science and policy needs.
- It is the best way to communicate with the public to deal with ESS-livelihood relationships, and to encourage society to take greater ownership of the impacts for sustainable development and disaster risk management (Hedelin et al., 2017).
- This increases opportunities for the integration of public voices and views into local, national and international decision-making (Buytaert et al., 2014).
- It also considers the potential of 'bottom-up' grassroot societal movements such as they have significant importance in mobilizing ownership of issues and community action in areas of environmental science and sustainability.

4. Valuing ESS, including market and non-market valuation:

- It is a technique of creating appropriate methods or underlying assumptions to value non-monetary ESS to be integrated into the assessment of social-ecological systems and to be considered in decision-making processes.
- Methodological framework for ecological and biophysical research and socio-economic valuation research to support each other needs to be developed.

5. Sustainable management:

- It is very important to create suitable ESS management approaches in the context of changing environment such as climate change and for providing basic local capabilities for sustainable environmental management and improved livelihood.

Five possible approaches to answer the research questions and suggestions about these approaches

1. Tools and frameworks for decision-support:

- Mixed methods that integrate different perspectives and stages, which can be modified based on the type and scale of the study area (Izakoviˇcová et al., 2018), to provide relevant opportunities for future research and management (Halbe et al., 2018).

- Methods enable to bring together complementary, context-dependent types of ESS assessment, help to arguing for the use of a range of findings from different methods.

2. Methods for data collection:

- Improving understanding of the dynamics of ESS benefits from experimental studies (case studies in my case using PRA and participatory experiment).

3. Modelling:

- To capture the dynamic and complex relationships between ESS and HWB, relevant models need to be selected, developed and used.
- Local evidence needs to be collected to support the modelling approach through comparison.
- Participatory methods can be used in the co-construction of models, which intersect different disciplines.

4. Linking science to policy:

- By optimizing engagement between scientists, decision makers and the general public, the community issue can be central in communicating knowledge and enacting decisions.
- A proactive approach to integrating science with the needs of policy makers involves researchers working closely with decision-making bodies (informal and/or formal decision-makers) through knowledge exchange partnerships and/or collaboratively determined research activities.
- For example in my case: Public consultations for direct engagement in research can enable to improve traditional decision-making settings (decision after participatory knowledge generation).

5. Enhancing interdisciplinary research:

- Addressing critical questions concerning ESS and HWB requires the development of new relevant research approaches, a broader outlook and a fundamental shift towards a culture of interdisciplinary collaboration (Hossain et al., 2018).
- Therefore, the provision of interdisciplinary training for socio-ecologists, and support for long-term social-ecological monitoring and research projects, can serve to strengthen inter-disciplinary links and secure the future of healthy ecosystems and sustainable livelihoods in a changing world. Active collaboration between fields (ecology, economics and social sciences) may also provide novel insight into ecosystem and social processes.

3.3 The new research approach

Following the research question themes and their approaches to address them summarized in Table 3.1, and the methodology of Basco-Carrera et al. (2017) they developed for water resources management, in my thesis I aim to develop a holistic decision support framework which includes collaborative modelling, and enables to increase focus on stakeholder participation in modelling activities and insights for sustainable ESS management. This research method is an interdisciplinary bottom-up participatory research approach implementing for socio-ecological contextualization to achieve sustainable developments. The terminologies of the newly developed method are defined as follow:

Socio-ecological contextualization: It is a landscape approach to addressing often inter-connected social, environmental, economic and political challenges (Reed et al., 2016). This context helps to setup framed problems, consequently to prioritise solutions.

Interdisciplinary: The research method which is built by combining two or more academic disciplines or fields of study through involvement of two or more professions, technologies, departments, and local community and policy (Pedersen, 2016).

Bottom-up approaches: The motivation of the work started with ground truth information by considering the voices of the poor end users.

Participatory approaches and citizen science: Enabling the integration of voices of the stakeholders (including end users, eg, poor farmers), scientists, and decision makers in the field of ESS and livelihoods relationships. Citizen science the participation of general public (the end-user non-scientists) in the generation of new scientific knowledge (Buytaert et al., 2014); it also enables the generation of large-scale datasets (Hadji-Hammou et al., 2017); particularly valuable in ecological research (Klemann-Junior et al., 2017); this promotes the ongoing monitoring, knowledge generation and exchange and bottom-up flow of environmental issues for sustainable development solutions. Pettibone et al. (2017) through survey research method, found new insights into citizen science projects initiated by non-scientific actors.

This research method is developed focusing on the Ethiopian highlands as case study of the field, by adopting the research questions and suggestions of Hossain et al. (2018). This methodology considers all research themes and adds the elements (relevant in the field particularly in the case study) which were not considered by these authors. The main new elements are: strong end-user involvement (in situation analysis, i.e., for exploring major problems and their challenging solutions, data collection for evidence generation and incorporation of community insights in the computational modelling framework); bottom-up based (grounding the issues from users' voice; and experiment based to prove the feasibility of the pathways found with the focal community in this research through a case study socio-economic analysis).

This participatory research framework starts with a socio-ecological contextualization. As confirmed by my literature review outcome in chapter 2, such contextualisation is often lacking in current practices that promote ESS and livelihood relationships assessment and management in rural areas. The end-result of the framework is the identification of specific indicators of sustainable development. These two components are linked by a set of activities, which consist of problem identification and prioritization using participatory rural appraisal (PRA), solutions prioritization and pathways setup for sustainable development using PRA, ground-truth evidence generation through participatory field experiment with the local community, tools selection and development for data analysis based on field insights, computational analysis combining field insights and tools (such as hydrological model for groundwater and water harvesting quantification, soil loss analysis model for sustainable land management methods selection and socio-economic analysis for potential livelihood option selection) (Figure 3.1).

The identified research questions aim to provide a framework (guidance) for researchers, policy makers, funding agencies and the private sector to advance knowledge in ESS research and to develop and implement policies to enable sustainable future development. Moreover, the developed methodology can be extended further in future research in collaboration with governmental and non-governmental organizations (in mountainous rural worldwide regions). In particular, the methodological framework I develop aims to alleviate data scarcity, which is still a major issue in large parts of the world. For this, it relies strongly on the generation of ground-truth knowledge especially with the involvement of the local community (i.e., the farmers' knowledge gained through experience is being combined with scientific data and computational modelling for real knowledge generation for small to large scale sustainable development). The following chapters elaborate on the development and validation of the major elements of this framework.

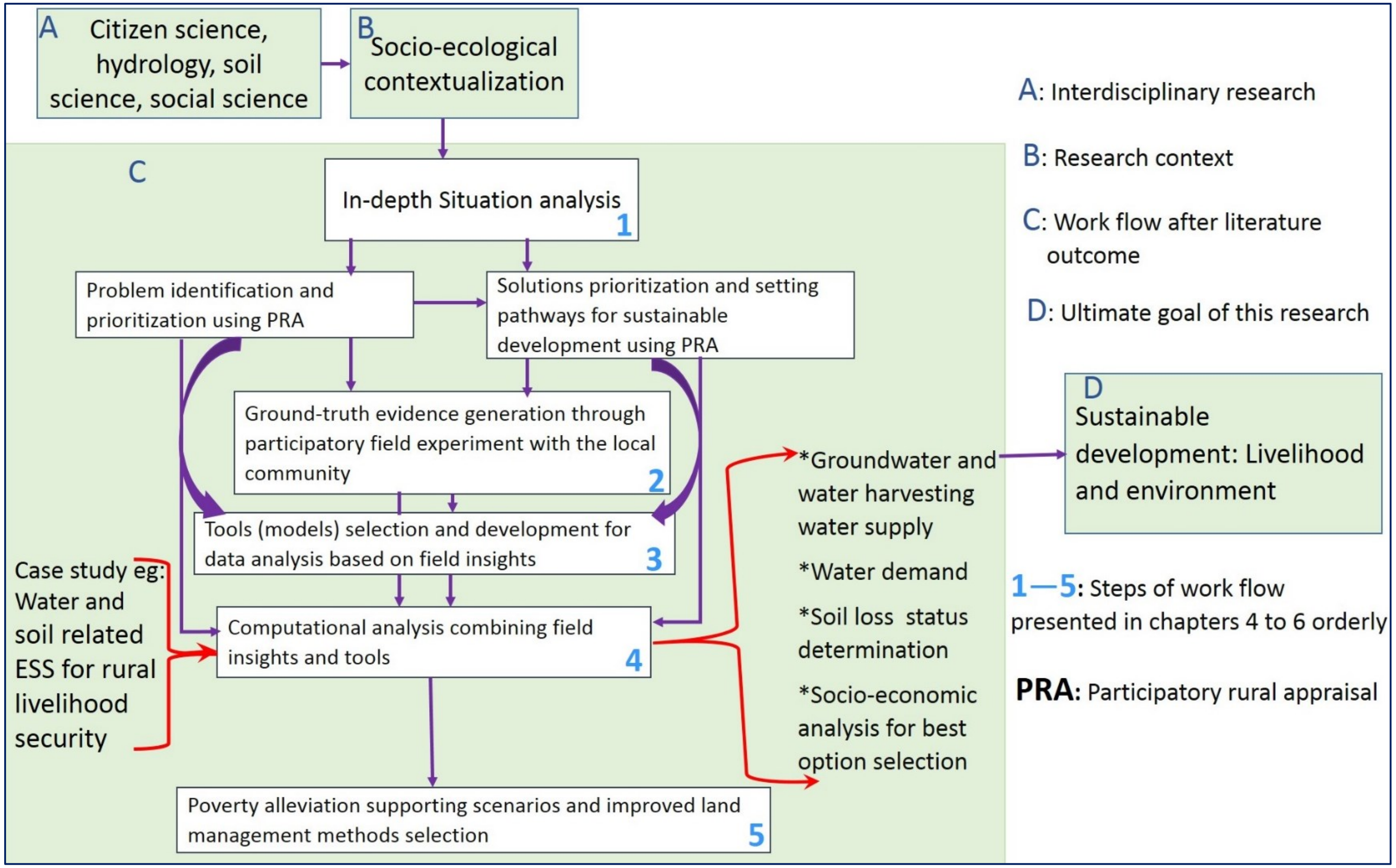


Figure 3.1: The conceptual framework of my research approach to address the identified research questions. The local community at Debre Mawi is used as a case study.

Chapter 4

Participatory analysis of livelihood strategies and their constraints in the upper Blue Nile basin

Abstract

Poverty is a global challenge that is largely determined by the capability to satisfy individual basic needs. Such needs and the different approaches adopted to escape poverty vary across space and time. My objective here is to understand the major impediments to implementing potential livelihood strategies that may lead to poverty reduction in the upper Blue Nile basin, where 85% of the population are poor subsistence farmers. This basin is exemplary of the Ethiopian and other tropical highlands, where livelihood strategies are heavily dependent on local ecosystem services (ESS), particularly those derived from water and soils. First, I analyse ESS-livelihood relationships in the Debre Mawi catchment in north-west Ethiopia with participatory rural appraisal (PRA) methods. Using a combination of biophysical and social assessment of ESS, I then identify and rank major ESS degradation processes that lead to poverty lock-in. Next using participatory experiments, I identify potential alternative ESS management strategies for improving livelihoods. I identify eight major ESS impediments or 'bottlenecks', namely water shortage, soil erodibility, crop pests, fixed rainfed agricultural livelihood strategy (the farmers insist only on rainfed crop and animal production), poor soil fertility, land shortage, livestock feed scarcity and inappropriate livestock breeds. The main biophysical processes that lead to poverty lock-in are soil erosion (mainly gully erosion causing reduction in arable land); drying up of streams reducing availability of drinking water for livestock; and unpredictable rainfall lowering crop production. Population growth, limited household assets and a top-down ESS management approach are the major poverty drivers, i.e. the root causes of poverty. The most important livelihood strategies to overcome poverty are identified as (i) crop irrigation, and (ii) livestock fattening. For both strategies, water scarcity was found to be the primary limiting factor. My results suggest that poverty alleviation efforts should focus on improving water availability during the dry season. Participatory field experiments identified rooftop water harvesting as a promising approach, which can support livestock production as a viable livelihood improvement strategy. My modelling suggests that depending on rooftop area, farmers can improve household income by US$136 to 14876 from

5 months beef fattening and US$69 to 7704 from 4 months sheep fattening. The installation of hand dug wells at locations where groundwater is available all year round may be a potential alternative, but this is hindered by the lack of information on groundwater availability.

4.1 Introduction

Poverty, defined as lack of income or productive resources to ensure sustainable livelihoods, is a worldwide problem (FAO, 2005). Ten percent of the world's people now live below the poverty line, earning less than US$1.90 per day (Roser, 2015). In Africa, over half of the population are subsistence farmers living in rural areas and are directly dependent on food crops harvested from their immediate environment (Bationo et al., 2006). In Ethiopia, which is the second poorest country in the world, 96% of the population are marginalized poor living in rural areas (OPHI, 2015). Research has shown that most of the Ethiopian highlands are endowed with a temperate climate, fertile soils and adequate rainfall; they also deliver 85% of the net surface water flow for Sudan and Egypt (Bayabil et al., 2010), and are biodiversity hotspots (Hamza and Iyela, 2012). These highlands are also one of the most densely populated regions of Africa (Headey et al., 2014), and feed 88% (Lemma, 2004) of the Ethiopian population through mixed farming systems (crop production and livestock keeping).

In the upper Blue Nile basin, farmers depend heavily on local ecosystem services (ESS), particularly those derived from water and soils. Despite the study region's physical potential for agricultural production, and intensive efforts made by farmers and through government interventions, food availability per capita has decreased recently, with water and soil ESS becoming severely degraded (Ali and Surur, 2012). As a result, poverty has increased. Most people here experience food insecurity, which is a characteristic of extreme poverty (Diouf et al., 2002). Existing research shows that resource degradation leads to increasing poverty in this basin (Shiferaw and Holden, 1999; Betrie et al., 2011). However, this research focuses only on physical processes, and does not explicitly consider poverty alleviation. Moreover, none of this work conceptualises the Ethiopian highlands as a social-ecological system; instead these studies treat the two systems separately and do not consider farmers' experiences of resource deterioration, which is my focus here.

Tackling poverty is now recognised as an international priority (IFAD, 2011). Poverty is most prevalent for people living in rural areas depending on agriculture for their livelihood (Oakley and Clegg, 1998). Consequently, targeting agriculture-dependent rural areas potentially offers the best prospects for large-scale poverty alleviation. While most of the previous poverty alleviation strategies studied have indeed emphasized rural areas (Bebbington, 1999), these have tended to focus upon the role of direct state intervention which is not always practical or possible. Similarly, actions taken by international agencies tend to concentrate on delivery of infrastructures that are usually expensive, without recognising their long-term operation and maintenance costs (Barder, 2009). In the upper Nile, these and other technologies have been implemented with limited attention to ownership or buy-in by local communities and without considering local expertise or capabilities. For example, generic fertilizer and soil and water conservation (SWC) interventions have been applied by successive governments on cropping land in the upper Nile basin, whereas poverty alleviation requires interventions that are based upon detailed understanding of the social-ecological context of specific locations. Consequently, despite the implementation of numerous state and international poverty alleviation initiatives over the last decades, improvements in livelihoods in the upper Nile have been very slow.

This limited success warrants the exploration of different approaches to the identification of livelihood strategies. The approach reported here was participatory analysis, with the aim of developing a grounded understanding of people's livelihoods in relation to ecosystem services provision. Participatory approaches comprise a wide range of different research techniques, but a common feature of each is the emphasis placed on building a grounded understanding of community issues that is sensitive to situated knowledges (Haraway, 1988), local socio-economic circumstances, gender and ethnicity, and embedded power relations (Chambers, 2012; Evans et al., 2009). A participatory approach therefore sees researchers working closely with focal communities to establish their concerns and interests to the phenomena under investigation, taking account particularly of marginal and excluded social groups, with the goal of helping their developmental needs. Consequently, participatory research is emancipatory (Aldridge, 2015) and can help to understand and frame poverty issues in the pursuit of poverty reduction (World Bank, 2001).

To explore the potential of such participatory, bottom-up approaches to the identification of livelihood strategies, I implemented a case study investigating the social-ecological context of ecosystem degradation in Debre Mawi watershed located in the upper Nile basin. Specifically, my research aimed to understand how local ESS (especially water and soil-related) management might be used to maximise poverty alleviation in the Ethiopian highlands. To achieve this aim, I identify first the major impediments and resource degradation processes that exacerbate poverty through participatory ESS analysis. These were then prioritized by a pairwise ranking method. ESS management strategies for improving livelihoods were next identified through participatory cognitive mapping (Elsawah et al., 2015). The main goal of the analysis was to identify the main policy intervention priorities (regarding both ESS management and infrastructure) to maximize poverty alleviation. As a test case, I analysed in more detail one of these priorities, namely the potential of water harvesting to improve local livelihoods.

4.2 Study region

The Debre Mawi watershed is situated in the headwaters of the Blue Nile, about 30 km south of Lake Tana (between 11º20'13" and 11º21'58" N, and 37º24'07" and 37º25'55" E). The watershed's total area is 716 hectares (ha), elevation ranges between 1950–2309 metres, and slopes vary from 8 to 30% (Figure 4.1). The maximum annual temperature occurs in March–April, ranging from 22–29ºC, with minimum temperature in November–December, with an annual range of 5 to 12ºC over the measurement period of 1996 to 2005. The watershed has a unimodal rainfall regime with an average annual rainfall of 1238 mm (Zegeye et al., 2010). June, July, August and September receive the largest shares of annual rainfall. Potential evapotranspiration is 2−3 mm/day in the rainy season and 4−5 mm/day during the dry season. The watershed is characterized as mountainous, highly rugged and dissected topography with steep slopes (Guzman et al., 2013) and has variable soil losses (Tilahun et al., 2013a).

Across the watershed, uplands were converted from forest to croplands in the 1980s following an increase in population. Initially, soil organic matter, agricultural yield and infiltration rates were all high and water springs were active throughout the year. However, as a direct result of continuous cultivation, deforestation and removal of all straw for fodder, soil organic matter decreased over time (Tebebu et al., 2017). This has resulted in soil aggregates breaking down and the soil becoming much finer, resulting in increased sediment concentrations in surface water (Tebebu et al., 2015, 2017; Zimale et al., 2016) and a reduction in the soil infiltration capacity. Consequently, lateral water flow started to increase, exacerbating soil erosion and decreasing base flow. The increase in surface runoff intensified gully erosion and periodically saturated valley bottoms. In the lower parts of the watershed, much land has been taken out of production by rapidly expanding active gullies (Tebebu et al., 2010). In addition, fertile topsoil has been lost due to rill erosion (Zegeye et al., 2010) from cultivated land, which covers more than 70% of the watershed area (Amare et al., 2014), leading to a reduction in crop yields.

Although I have not found any studies that present quantitative estimates of the relation between soil erosion and crop yield reduction for Debre Mawi, studies exist that indirectly indicate how soil erosion may causes cop yield reduction. Regarding soil fertility reduction due to soil erosion, Zegeye et al. (2010) reported that the annual rill erosion rate was 8 to 32 t ha^{-1} in Debre Mawi; and Tebebu et al. (2010) indicated that gully erosion caused crop yield reduction through crop area reduction (such as the total eroded area due to gully erosion increased from 0.65 ha in 2005 to 1.0 ha in 2007 and 1.43 ha in 2008). The outcomes of these studies, which were conducted in Debre Mawi watershed, are supported by more general studies on soil erosion and crop yield reduction. According to Alemu et al. (2013), erosion removes the most productive portion of the soil that is chemically active part such as organic matter, nutrients (nitrogen and available phosphorus) and clay fractions. Bationo et al. (2006) found that across Africa, 28% of the population is chronically hungry and over half are living on less than US$1 per day as a result of soil erosion induced soil fertility depletion. Hurni (1993) estimated an annual crop yield reduction of 1–2% in Ethiopia due to soil erosion.

Geographically the watershed can be divided into three parts. Tilahun et al. (2013a) reported that farmers cultivate both the upper part (slope, 0 to 6%) and middle part (slope, 6 to 27%) of the watershed. Most of the grasslands are found in the damper lower parts with slopes of 0 to 6%, comprising vertisols (locally known as *walka)*. The upper section and middle of the lands have nitosols (locally known as *dewol*) and vertic nitosols (locally known as *silehana)*. Rain-fed mixed farming is practiced here. More than 70% of the land is cultivated and crops grown are teff, maize, finger millet, grass pea, bread wheat, food barley, potato and field lupin (*Lupinus albus)*. Historically faba bean and pea were also cultivated. Currently, *Eragrostis tef*, *Zea mays*, finger millet and grass pea (*Lathyrus sativus*) are the major rainy season crops. There are also some rock outcrops (locally called *zinza soil*) in the watershed without vegetation cover; these have the poorest soil. Farmers keep livestock for different purposes, with cattle for traction, sheep and goats for bred for the market, and donkeys used to transport agricultural and non-agricultural goods.

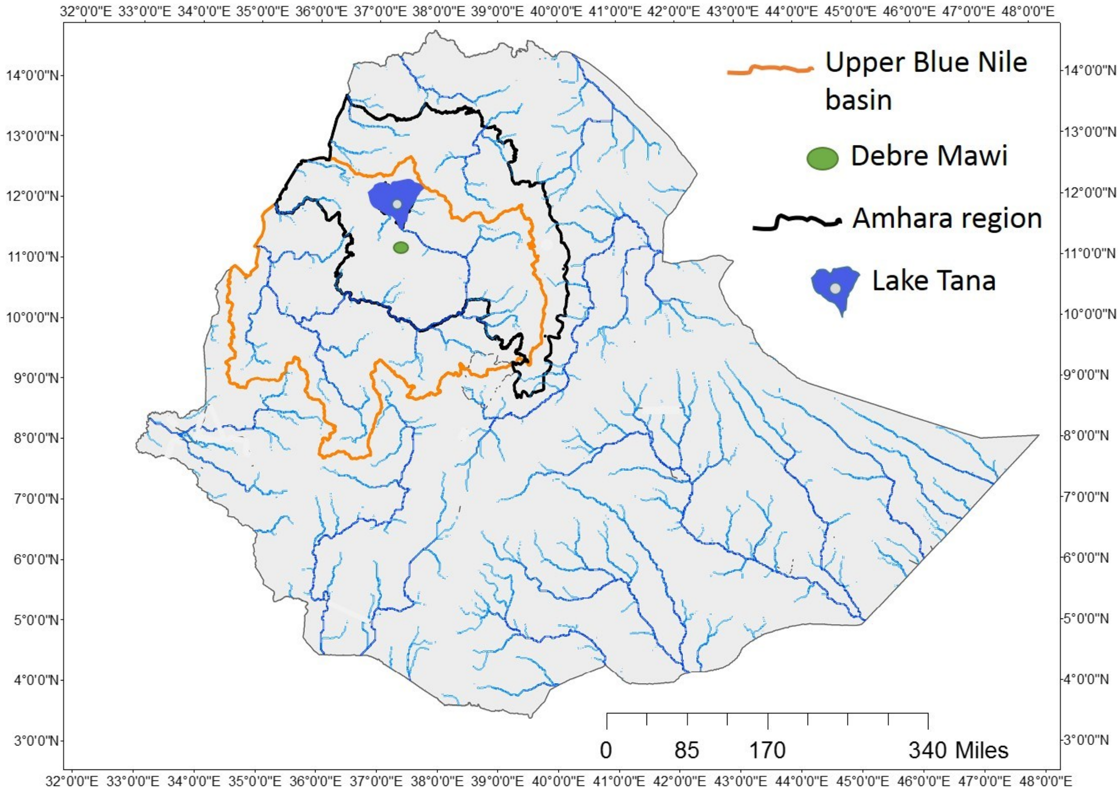


Figure 4.1: Location of the Debre Mawi watershed within the upper Blue Nile basin, Ethiopia.

4.3 Research methodology

4.3.1 Participatory rural appraisal

Following Fentahun and Gashaw (2014), I conducted a detailed situation analysis of the study area using various participatory methods, including household questionnaires, semi-structured interviews with key informants, open community meetings, and small focus group discussions. These participatory techniques were complemented with detailed field observations through transect walks with farmers and herders and ESS mapping. To avoid bias during the implementation of the participatory approach, I used a combination of tools, which included household surveys, semi structured interviews, focus group discussions, and mapping of ESS on the ground by farmers followed by checking of the map elements on the ground through transect walks. Maps were revised after they were copied on the paper with focus group members. Based on the outcomes of these survey methods, community-researchers participatory mental model framework was designed aiming to improve ESS management to livelihood and environmental sustainability. Consequently, commonly mentioned major problems and solutions in the above PRA methods were considered as the real (unbiased) major problems and solutions. In addition, at the start of each session, a detailed explanation of the purpose of the activity and its relevance for local development were explained, in the hope that this would promote honest and correct answers from the farmers.

Household surveys

To select the most representative respondents I used a random sampling method, taking account of gender and ethnicity, and following the rule of thumb (Yount, 2006) for sample size determination (Figure 4.2). Yount (2006) states that the sample sizes can be 100, 10, 5, 3 and 1 percent for 0–100, 101–1000, 1001–5000, 5001–10 000 and >10 000 population sizes respectively for comprehensive, large number survey questions.

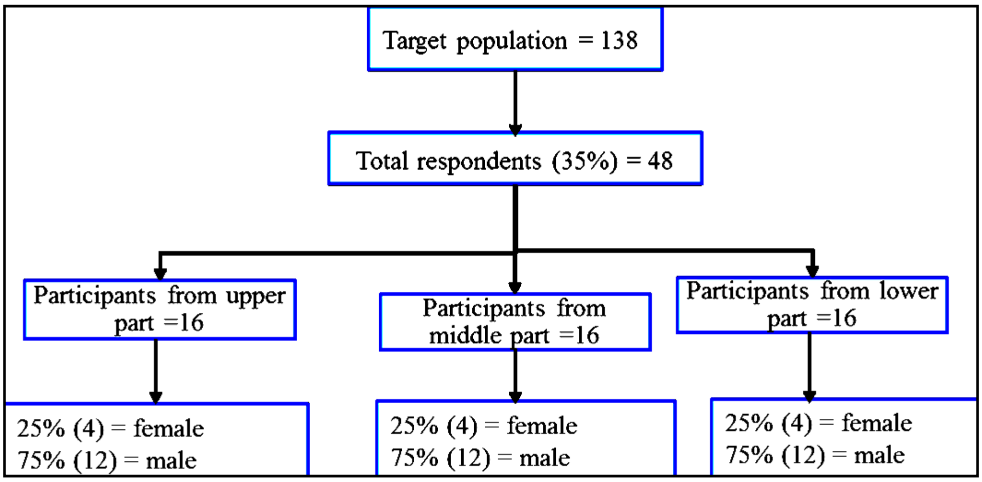


Figure 4.2: Overview and statistics of selected household respondents.

Semi structured interviews

Six farmers were selected for interviewing based on their extensive knowledge and experience of dry land arable farming and livestock management, their familiarity with the challenges posed by ESS provisioning issues, and their availability and willingness to participate in the research.

Focus group discussions and field observations

Three focus groups were convened, each consisting of 5-7 farmers from the three parts of the Debre Mawi watershed (5, 7 and 6 representatives in upper, middle and lower parts respectively) mainly from the interview sample. Participants were selected using purposive sampling, which assumes the composition of the group as fairly homogeneous (active farming representatives) but is sensitive to age and gender differences. This ensured that diverse viewpoints were represented in relation to community resource issues, which helped stimulate discussion about local trends in ESS use. To communicate with the farmers about abstract concepts such as ESS I used a more local way of description and conversation. For instance, I asked them to mention the major land uses and covers in their locality; where are they located in the watershed; what types of benefits are delivered by those land use elements (ecological elements) to them and other people, and to the environment such as for soil and water conservation; how they benefits from these land uses and covers; how the land uses/covers status and benefits have evolved in the past over time spans of 5, 10, 20, 30 years as well as their current status; the cause of the change; as well as possible solutions.

In each group, there was one female participant. I ensured that all participants contributed to these discussions. Prior to focus group discussions, a transect walk was undertaken with participants along the boundary of the 716 ha watershed. This was done to observe, experience, and make sense of how participants perceived and conducted ESS management practices, and to help researcher to better apprehend the challenges farmers and herders faced. One representative from each focus group with good knowledge of the boundary of the watershed participated in this transect walk. Each group then helped assist mapping the ESS on the ground using available local materials such as stone, ash, leaves, branches and grass with participants who had taken part in the transect walk advising on the exact location and distribution of ESS. During the mapping exercise, notes were taken of the types of ESS, their location and those community members who managed and benefited from their use. Once the mapping was complete, participants were interviewed on supplemental questions in group to complement the information mentioned in their map (Figure 4.3). A second transect walk was then completed to collect biophysical data to supplement farmers' perceptions and field observations. In total therefore, three transect walks were completed in three parts of the watershed (Figure 4.4).

Mapping and transect walk activities provided the necessary data to prepare a watershed level ESS base map. Once complete, this was presented to community representatives from the three focus groups to verify the mapping process and to provide an opportunity for discussion, revision and amendment (Figure 4.5). These discussions also provided the opportunity for focus group representatives to identify bottlenecks to more productive farming and the main drivers of ESS decline; these drivers and their underlying processes were prioritized by pair-wise ranking. Respondents also identified possible managing strategies that could be introduced to improve agricultural resilience, community adaptive capacity and farm livelihoods. I communicated with the farmers about agricultural resilience and adaptive capacity using their local terminologies. For instance:

"*You told me that before your agricultural production covers your food self-sufficiency, but recently it has been decreasing especially due to inconsistent rainfall that is not compatible with your cropping calendar, soil fertility declining and drying up of animal drinking water sources streams; but now most of you are food self-insufficient even for a single year (as you told me earlier), so what options are there to enable you to recover from such food limitation stress through improving your agricultural production and to improve your livelihood; regarding adaptive capacity: what possible options are there to produce enough agricultural production event though those adverse conditions are there*?".

By highlighting results of previous discussions, observations and interviews, the resulting situation analysis was complemented by cognitive mapping (i.e., researchers-community participatory mental model about the ESS management for livelihood improvement and environmental sustainability) through another focus group discussion. Lastly managing strategies considered by farmers as most promising were identified for further analysis, on the basis that potentially they might improve current ESS management and enhance farming livelihoods while also minimising current patterns of resource degradation.

Figure 4.3: Photos of (A) focus group members mapping their ESS using locally-available materials; (B) discussion on ESS with focus group members and resource mapping exercise.

Figure 4.4: Photos of the transect walk with the focus group members: (A) transect walk; (B) discussion about the land feature.

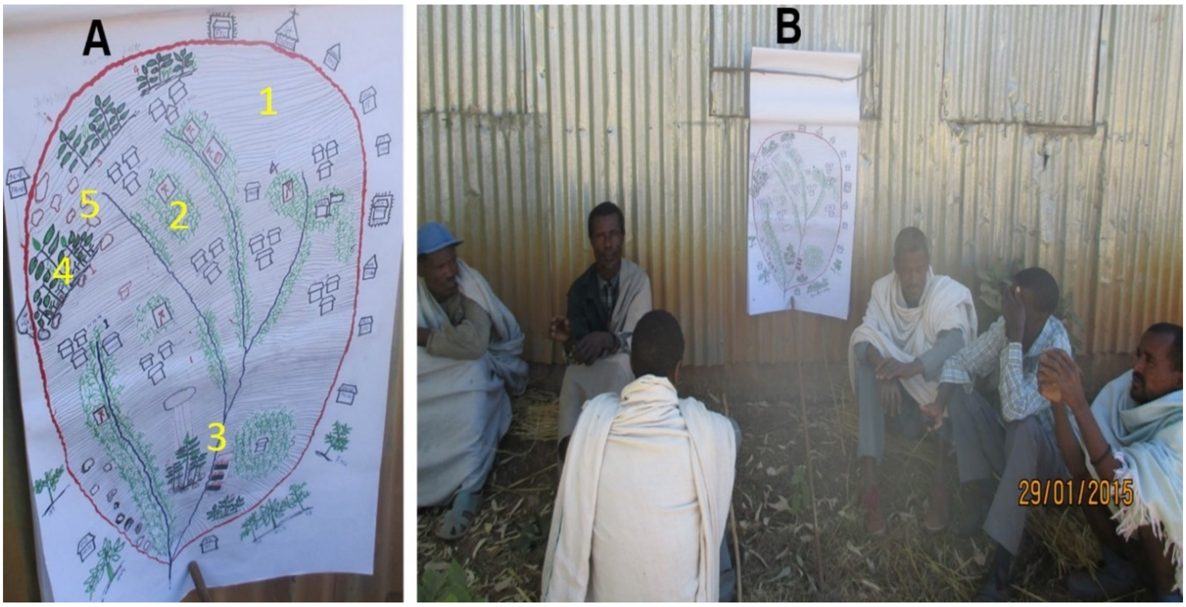


Figure 4.5: Photos of (A) the ESS base map at the watershed level (B) discussion about ESS base map with 7 focus group representatives. Numbers 1—5 present ESS providing ecosystem elements (1: cultivated land→ provisioning ESS; 2: grazing land→ provisioning and regulating; 3: water resources→ provisioning; 4: forestland→ provisioning, regulating and supportive; 5: stone→ provisioning, regulating).

Survey data analysis

The data collected as part of the situation analysis was analysed using quantitative and qualitative methods as appropriate. The questionnaire survey data was analysed applying descriptive statistics particularly frequency analysis using SPSS software, with focus group discussions, field observations and semi-structured interviews examined and summarized in relation to the quantitative data.

4.3.2 Evaluation of livelihood strategies

For the purpose of this study, the Debre Mawi watershed was divided into three parts based mainly on rainfall spatial variability, a criterion suggested by interviewees. Two common rooftop designs are used for collecting rainwater: surrounding and rectangular (Figure 4.6). To gather representative evidence on water harvesting for the whole Debre Mawi watershed, six (3 surrounding and 3 rectangular) experimental rooftops were selected per village. Rooftops were chosen in degraded sites where high overland flow generation was expected to reduce runoff that causes soil loss. 18 rooftops (6 per village, i.e., 6 x 3) were selected for this experiment with surface areas ranging between 70.5 m^2 and 155 m^2. The total rooftop area is 2066.7 m^2. The spatial variability and rooftop design effects on the amount of harvested rainwater (HRW) were analysed using one-way ANOVA and t-tests respectively at the 95% confidence level. For future HRW simulation, a simple equation (the product of rooftop area, precipitation and runoff coefficient) was calibrated using the 131 observed HRW volumes, and its simulation efficiency was evaluated using coefficient of determination (R^2) and Nash Sutcliffe efficiency (*NS*).

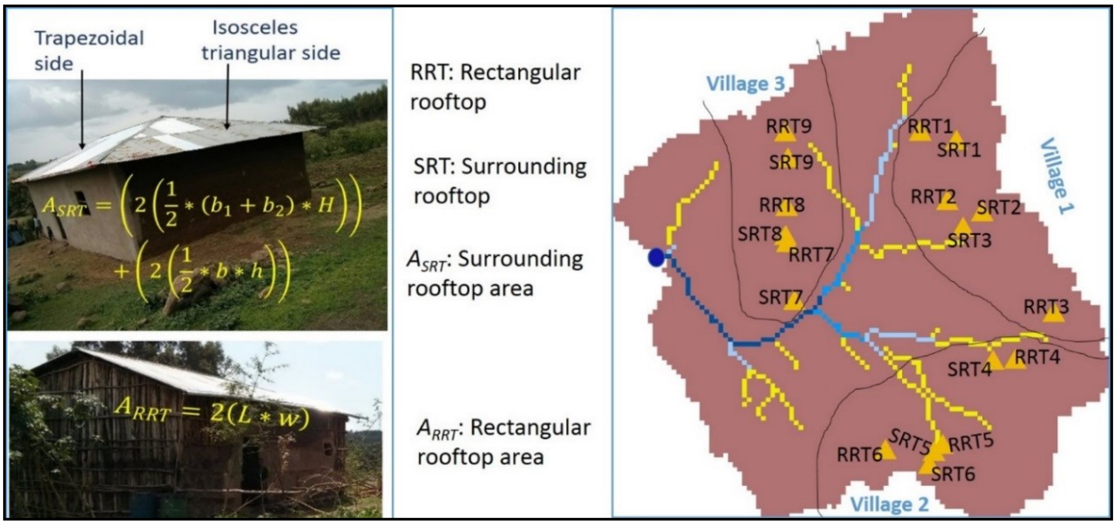


Figure 4.6: Designs of experimental rooftops and their locations at the Debre Mawi.

Subsequently, the crop water requirement (CWR) was determined using the CROPWAT 8.0 software developed by FAO, based on the FAO Irrigation and Drainage Paper 56. To determine the water requirements of crops, the FAO CROPWAT software incorporates the following steps:

(1) reference crop evapotranspiration, ET_0 analysis using weather station data such as altitude, latitude, longitude, temperature (maximum and minimum), humidity, wind speed and sunshine hours;

(2) effective rainfall determination based on information in step 1 and rainfall data;

(3) crop related parameters (crop coefficient, K_C and critical water depletion) calculation using previous steps and crop related parameters such as crop name and root depth;

(4) soil moisture (availability and depletion) analysis by incorporating additional variable to the software (soil textural class);

(5) CWR calculation.

For more details on the calculations behind each step, I refer to the software manual and related publications (FAO, 1998; Surendran et al., 2015).

Based on farmer preference, potatoes and hot peppers were selected as potential crops to be produced by irrigation in the region. Reference evapotranspiration, which is an input of CROPWAT, was calculated with the Penman–Monteith equation using monthly weather data of the Adet weather station located 10 km south of the site, for the period 2005–2015. The soil field capacity and permanent wilting points which are also the input of the software were determined based on the soil textural class. The input data for CWR analysis were derived from the variables and steps mentioned in the above 1-5 steps. Lastly, the animal drinking water requirement was determined from the literature. In the study region, the mean daily water consumption of beef cattle is 40 l and of sheep is 10 l per animal (Ward and McKague, 2007; Sileshi et al*.,* 2003; Birhan and Manaye, 2013).

Before determining crop area and number of animals that can respectively be irrigated and produced using rooftop water harvesting, the household water demand for domestic use that needs to be supplemented by HRW was calculated as follows:

$$HRW_{du} = WD_{du} - WA_{ews} \tag{4.1}$$

where HRW_{du} is harvested rainwater need for domestic use (m^3), WD_{du} is total water demand for domestic use (m^3) and WA_{ews} is water amount from existing sources, hand dug wells (m^3); the last two were determined using participatory rural appraisal research method. The cropland area for irrigation and the number of animals for fattening were then calculated based on the rest amount of harvested rainwater. Lastly, a comparison of the cost-benefit ratio (CBR) was made of the resulting four livelihood enhancing strategies, namely: potato irrigation, hot pepper irrigation, sheep fattening and beef cattle fattening followed by selection by ranking; the higher the CBR, the better the strategy for livelihood improvement. The cost that was considered in this analysis includes the following elements:

- pond installation (geo-membrane and plastic sheet for pond covering),
- water collection system installation cost,
- seed and animal purchase cost for respectively irrigation and fattening.

The benefits are described as the gross returns from these irrigation and fattening practices. For these farming strategies, the farmers will use family labour that technically also involves an opportunity cost. The time farmers spend on these practices is time they cannot spend on other things before, because it is free time between their two successive rain fed cropping calendars. The main limitation of these new livelihood strategies is initial investment but that can be covered by loan from government or other sources. The farmers will refund once they will get their return income. Regarding to depreciation (gradual decrease in economic value of the outcomes of these practices), continuous monitoring and facilitating market opportunity to sell with high price and to create demand is required. This is the responsibility of the socio economic extension experts especially in Ethiopia.

$$CBR_{Ind.option} = \frac{\sum Benefit}{\sum Cost} \tag{4.2}$$

where $CBR_{Ind.option}$ is benefit to cost ratio of individual option, for example, potato irrigation. For a scenario to be beneficial, the CBR has to be greater than 1.

4.4 Results and discussion

4.4.1 Ecosystem services and livelihood relationships trends in Debre Mawi watershed

Using the PRA approach described above (a combination of methodologies comprising household survey, semi-structured interviews, focus group discussions, resource mapping and field observation), 10 main natural capitals were identified that provide ESS for the focal communities. The most important from a livelihood perspective were water, land for cultivation and animal feed. However, the analysis revealed that due to land degradation, farmers were unable to benefit from four of the total 10 landscape elements mentioned in Table 4.1. Wild plants and animals have largely disappeared because of deforestation, with scrub and woods cleared to provide agricultural land expansion for the increasing population (Ebenezer, 2015). Wetlands and amenity lands have either been converted to arable land or swallowed up by gulley erosion; these have formed in valley bottoms after deforestation in upland parts of the catchment (Tebebu et al., 2015). Currently, the main livelihood strategies are arable production and oxen management for ploughing. Water resources, cultivated land and pasture land are thus the key natural capitals for the focal communities (Table 4.1).

Table 4.1: Main natural resources and essential ESS for the focal communities. Feed is a general term which can offer to pasture (grass grazed by animals) and other types such as hay, crop bran and straw. Green water is the rainwater that falls directly on the land (field), whereas blue water refers to surface and groundwater can be consumed for production and other services such as cleaning.

Natural capitals	ESS for the local community	ESS Category
Water resources (blue water)	Water for drinking, sanitation, irrigation	Provisioning
Cultivated land	Crop yield for food, income and animal feed	Provisioning
Pasture land	Feed (food & income), income (selling hay), hut thatching	Provisioning
	Land cover (conserve water and soil)	Regulating
Forest land	Wood products (fuel, construction)	Provisioning
	Land cover (conserve water and soil)	Regulating
	Shelter for wild animals, nutrient cycling, adds organic matter to soil	Supportive
Green water	Sources of all water such as water for drinking, sanitation, irrigation, swimming, and growth of forest, grass and other plants	Provisioning, supportive, regulating (it helps land covers to grow which intern reduce soil loss and runoff)
Stone	Reduce soil erosion and keeps soil fertility	Regulating
	Income generation (selling of stone)	Provisioning
Church	For praying, to resolve conflicts (spiritual)	Cultural
Wild plants	Food from non-timber products	Provisioning
Wild animals	Food	Provisioning
Wetlands	Green grass for livestock during dry season	Provisioning
Recreational landscape (fields)	Horse riding, ball and other cultural playing at flattened ever green fields	Cultural

**A church is of course a manmade structure, but I consider it an ESS because farmers consider various the landscape futures in their decision to build the church. For instance, it should be at the top of hill, allow for tree growth, and have holy water available close to it.*

** Holy water is the water which is sanctified by a priest for the purpose of the blessing of persons, places, and objects, or as a means of repelling evil.*

4.4.2 Poverty indicators in the Debre Mawi watershed

I analysed the livelihood status of the community based on a range of local and general indicators derived from the survey research and existing studies respectively. In the study area, virtually all people are poor and suffer food insecurity. Food crop (teff, maize, finger millet and grass pea) production is very low, only just meeting the needs for domestic subsistence (92% of respondents replied this); respondents generally preferred saving money to purchase fertilizer. Malnutrition is a serious problem as the local diet largely consists of only maize (Figure 4.7). Teff is grown as a cash crop to raise money for fertilizer purchase. In addition, the household survey showed that level of educational attainment was low, and health and wellbeing were poor (Table 4.2). Illiteracy is likely to be one factor that exacerbates poor agricultural production, since a literate farmer "would be able to manufacture, investigate and communicate basic information about agriculture and boost his production, otherwise he will not be able to do a good job, this will lead to low agricultural productivity'' (Masood et al., 2012, 2).

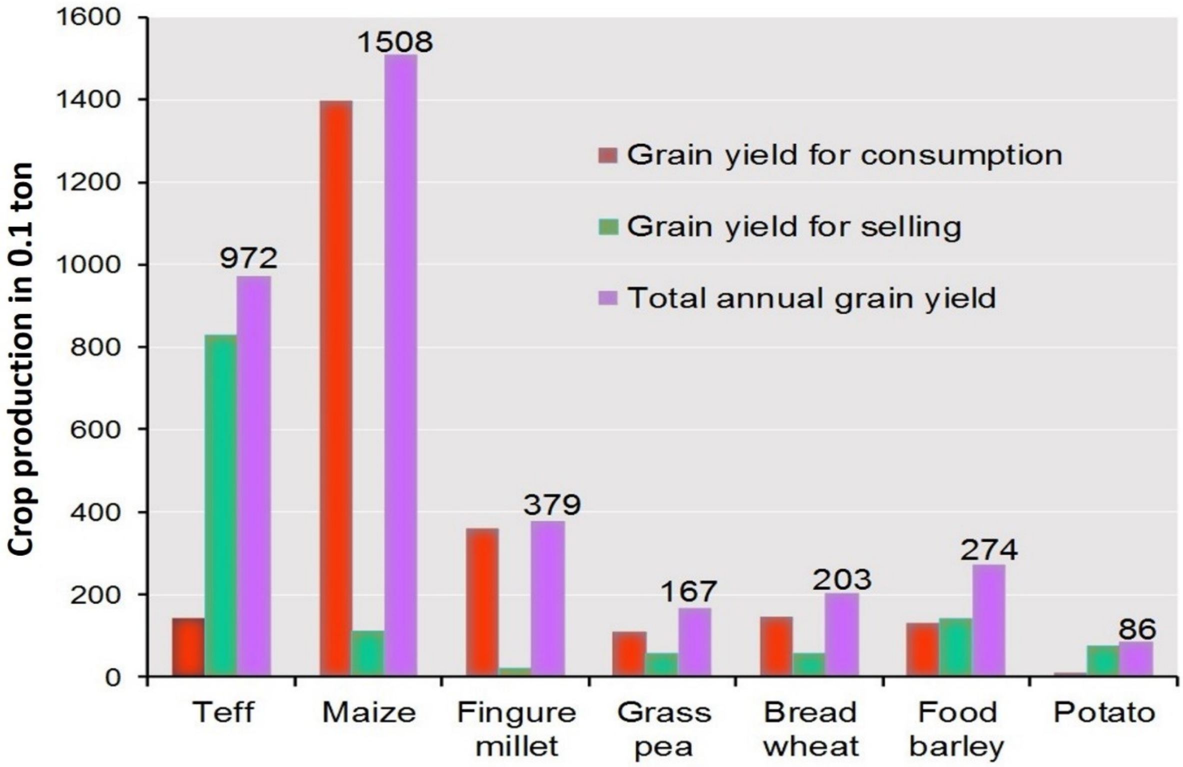


Figure 4.7: Annual grain production for consumption and selling in Debre Mawi watershed.

Table 4.2: Farmers' education and health services access.

	Variables	% of respondents (N=48)
Education of household heads	Illiterate	72
	Can read and write	10
	Grade 1-4	4
	Grade 5-8	10
	Religious knowledge	4
Health centre (clinic)	'In the Debre Mawi clinic, I have mostly been told that our health problem is beyond their expertise as well as facility; thus, I need to look for another place which is far; visiting far health centres is not a good option as there is no money to pay for these distance facilities'	100

Based on the survey results, four main wealth status indicators for households can be identified (Table 4.3): the size of their land holding (main), number of oxen, amount of savings and ownership of assets (eg. flour mill, eucalyptus tree plots). The saving was derived based on interview outcomes: the sources are selling of 'teff' grain yield and eucalyptus wood, except a few farmers whose additional income source is off-farm activity (mainly from flour mill). Using these criteria, no respondent can be considered wealthy in Debre Mawi; indeed, just 14% are living above the poverty line. Thus, poverty is endemic in the watershed, with natural resources becoming severely degraded despite the agricultural potential of the area, making the attainment of sustainable livelihoods a very serious challenge.

Table 4.3: Wealth status indicators in the study area.

Wealth status	**Wealth indicators**			
	Land size (ha)	Oxen (No)	Saving (Birr)	Others (type)
Rich	≥3	2−3 pairs	≥20000−30000	flour mill, eucalyptus
Medium	1.5–2: main factor	not mandatory	not mandatory	not mandatory
Poor	<1.5: main factor	not mandatory	not mandatory	not mandatory

**If the farmer has land scarcity, his daughter cannot marry. Because he cannot give her the required area of land for local marriage. But this is one opportunity for girls to join school.*

I found that population growth, the minimal level of household assets, and a 'top-down' governmental approach to ESS management (i.e., decisions for technology selection and implementation done from the state level and transferred to regional, zonal, district and village level without involvement of farmers (FAO, 2003) and without adjusting them to local environmental conditions) were the most important driving forces of poverty in the study area. In interview, a farmer told me that "currently seven households hold the land area that was owned by one farmer 20 or 30 years ago. The reason is that the number of farmers has increased, but the total land area remains the same". As a result, they practice continuous cultivation, ploughing on sloping terrains and planting of the non-native eucalyptus tree species, have all increased ESS degradation. The first two activities aggravate crop yield reduction through loss of organic matter and soil erosion, while eucalyptus is usually planted along streams and roads, reducing water availability by decreasing flow to streams (Chanie et al., 2013). Most farmers own a house (except for 4% who live in grass roof houses, all have corrugated iron sheet roof), a small plot of land and a few oxen (Figure 4.8 and 4.9), which limit the opportunities to move out of poverty.

In the literature, various reasons have been given for the poverty of Ethiopian farmers but poor ESS management is typically considered as the main contributory factor (Kabuya, 2015; Gashaw et al., 2014; Zerga, 2015). In the study region people are dependent on their immediate environment to generate ESS for their livelihoods. This requires an appropriate ESS management. However the current situation in the study area indicates that people are living in severe poverty because of increasing pressures related to climate variability and population growth (Gray and Mueller, 2012; Misra, 2014; Singh et al., 2013; Sinore et al., 2018). The farmers have tried to expand their croplands (see chapter 2) but this has often resulted in aggravating land degradation. At the same time, top-down government-led approaches that have been implemented to improve livelihood and environment often had adverse effects, which has been attributed to a lack of planning at the local level. As a result, land degradation and poverty have been increasing through time due to the improper ESS management (Bewket, 2007; Meheretu et al., 2014; Sinore et al., 2018). One specific reason for this is that most decisions for ESS management flow from the governmental level without considering specific local conditions or farmers' viewpoints. To minimize ESS degradation, most technologies such as generic SWC measures and fertilizer recommendations have been promoted through farm extension initiatives, focusing on upward accountability (Cohen and Lemma, 2011), i.e., through a hierarchical decision-making process that flows from National to Regional state to Zones to Districts and to *Kebeles*. Development Agents at *Kebeles* work at the village level and seek to guide farmers to implement interventions. According to Haile et al. (2006), most of these interventions do not fit with the actual local conditions and may even exacerbate poverty.

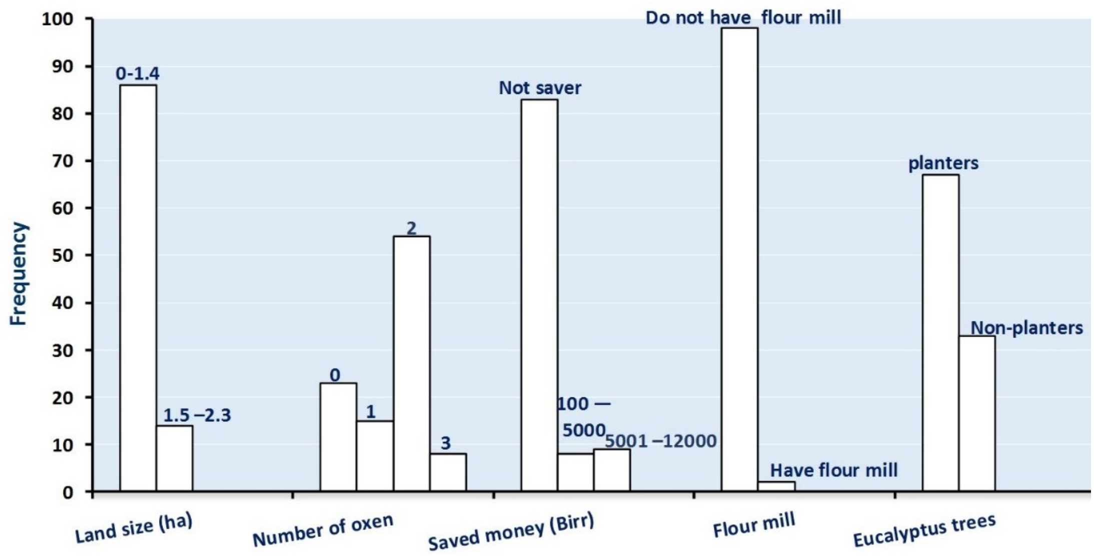


Figure 4.8: The current farmers' perceptions of their wealth status in Debre Mawi (N=48).

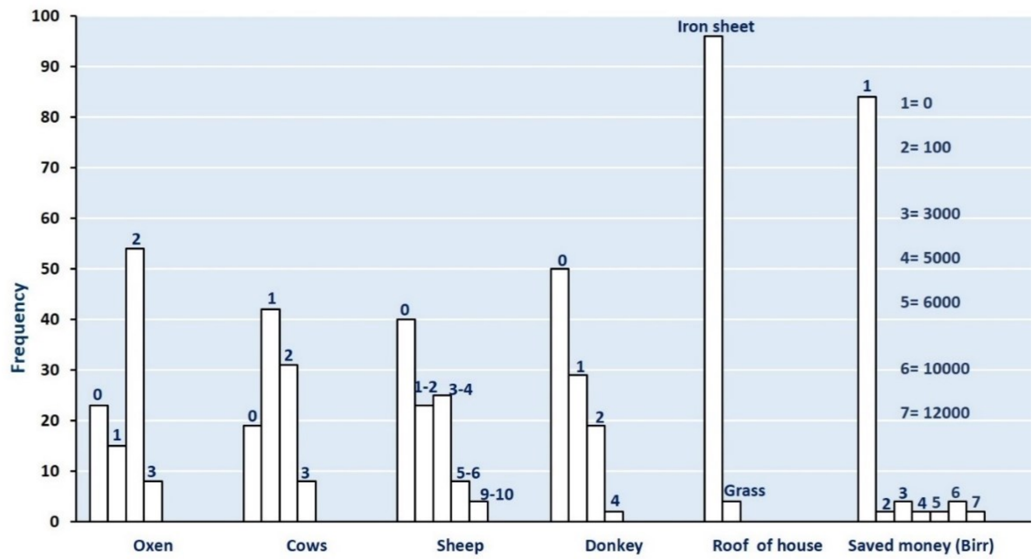


Figure 4.9: Main household assets as obtained from the PRA activities.

4.4.3 Major bottlenecks to a more sustainable use of ESS in the Debre Mawi watershed

In the context of this thesis, I define bottlenecks as constraints that prevent people from benefitting optimally from ESS to improve their livelihood and that can be mitigated. These can either be biophysical or socio-economic processes, and are strongly linked to the main drivers of poverty. However, the latter are broader and not necessarily related to ESS processes. From the PRA processes, I identify two main bottlenecks for a more sustainable use of ESS. A first bottleneck is geographic in nature and rooted in livelihood strategies: all community livelihoods in the watershed depend upon agricultural practice of one sort or another since it is part of the Ethiopian highlands which are considered as potential regions for agricultural production. Virtually all farmers and herders rely on an unchanged livelihood strategy based on either mixed rainfed crop production, livestock rearing, or a combination of both. This strategy has been further constrained by the impact of incipient climate change on rainfed agriculture for crop and animal production. Ethiopia's economy is tightly coupled with rainfall, yet there is a lack of institutional capacity to improve water availability to enhance food security (Stokes, 2010).

The second bottleneck is demographic: increasing population growth at 2.3% per year (Minale, 2013), places greater pressure on agricultural land area. In effect over time this is shrinking the average size of household landholdings. Tschopp et al. (2010) state that landholdings in the Ethiopian highlands had an average cropped area of 1.2 ha per household in 2007, which was projected to fall to 0.6 ha per household by 2015. Likewise, Regassa et al. (2010) observed that land size is key constraint for Ethiopian farmers. This land constraint leads to vegetation removal (deforestation for crop land expansion and fuel, and removal of all straw for fodder) and continuous cultivation. In turn, continuous vegetation removal and cultivation decreases soil organic matter, leading to structural deterioration and soil crumb structure starting to break down and become finer. The proportion of very small soil particles rises, leading to blockage of water infiltrating soil pores. Consequently, the permeable layers direct the water flow laterally, increase runoff and soil loss, and decrease base flow.

Based on results from the PRA, I found eight more specific bottlenecks. These issues were ranked based on their importance to community livelihoods (Table 4.4). Water is the most important, but it is in short supply during the dry season (for 6 months). Due to shrinking land availability and increasingly erratic rainfall, most farmers (96%) wanted to diversify their crop production using irrigation, but limited water availability prevents this possibility (Stokes, 2010). Water scarcity also affects livestock productivity: stream volume decreases over time and most are completely dry during January–May.

Soil erosion, which increases with decreasing organic matter and varies as soil type and slope (Lal, 1985; Ali and Surur, 2012; Geta et al., 2013; Tebebu et al., 2017), and crop pests such as pea aphid (*Acyrthosiphon pisum*) (Wale et al., 2003) and rodents are a second bottlenecks for poor farmers. These are the main causes of crop failure (90 and 69% of the responses respectively). Most farmers cultivate the upslope in the rainy season (Dagnew et al., 2015). As these lands are exposed to surface runoff, top soil erodes resulting in reduced soil depth; the resulting hollows and depressions act to generate and to concentrate surface overland flow to downstream gully dominated areas (Dabney et al., 2004). Most of the lower regions have black soil (vertisols) where gully initiation and development are very active (Natarajan et al., 2010*)*.

The predominant cropping strategy chosen by farmers is the third factor leading to poverty lock-in. Farmers insist on rainy season crops especially cereals production and keeping some cattle even though they (100%) have known that the production from both sectors decreases over time (Bishaw, 2009; Gecho et al., 2014; Mekasha et al., 2014; Gebremedhin and Tesfaye, 2015). For example, Yosef and Asmamaw (2015) observed that farmers tend to favour livelihood strategies based on subsistence rain-fed agriculture, even though it is not the most appropriate farming system for areas prone to erratic rainfall.

Decreased soil fertility due to loss of organic matter (Geta et al., 2013; Tebebu et al., 2017), land shortage, feed scarcity and inappropriate cattle breeds are the fourth set of factors that inhibit farmers' livelihoods. All farmers in the sample recognised that their cultivated land was infertile, requiring high fertilizer application. As a result of rising demand, fertilizer price increases: in effect, price rise is driven by decline in soil fertility (Gebremedhin and Tesfaye, 2015). Virtually all farmers commented on this point, with one noting "our current land cannot give any yield without fertilizer"; if fertilizer was not available, another stated that "we will stop production and die". This is challenging for all farmers as their cash resources are seldom sufficient to cover fertilizer purchases (Croppenstedt, et al., 2003). Across Africa, 28% of the population is chronically hungry and over half are living on less than US$1 per day as a result of soil fertility depletion (Bationo et al., 2006). Next to water scarcity, feed scarcity due to grazing land encroachment by gullies is the most significant factor affecting livestock productivity (Dejene et al., 2014; Altaye et al., 2014; Mekasha et al., 2014; Beriso et al., 2015). Overall, the current feed resources and particularly feed from grazing land pose limitations for an animal-focused livelihood strategy. In addition to grazing land encroachment by gullies, the other main reasons of feed scarcity are crop land expansion on the expense of grazing land, and labor shortage to collect feed and for feeding animals because free grazing is also not allowed totally in the study region.

Table 4.4: Major bottlenecks to benefit from ESS.

Issues	Water scarcity	Soil erodibility (rill and gully erosion) and crop pests (rodent and aphid)	Not optimised strategies for the best type of ESS management	Soil fertility declining, land& feed shortage and poor animal breed
Rank	1	2	3	4

4.4.4 Main biophysical processes perpetuating poverty

I found three biophysical processes that can be classified as bottlenecks that lead to poverty lock-in (see Table 4.5). Rill (Zegeye et al., 2010) and gully (Tebebu et al., 2013; Zegeye et al., 2014; Amare et al., 2014; Dagnew et al., 2015) erosion types are serious problems in the watershed. Sediment mobilisation from rain-fed farm fields is the main driver of land degradation, threatening farmer livelihoods (Guzman et al., 2013). Drying of streams also causes a decline in provisioning ESS, especially provided by livestock. Lastly, climate change is thought to affect ESS derived from crops (96% respondents), and according to survey data was the major reason of crop failure over the last five years after severe soil erosion. In focus group discussions, farmers reported that “in 2015 cropping season rain fell unexpectedly at the flowering stage of our most popular, income generating crop (teff). Consequently, yield of teff reduced by 50% from our usual harvest per household”.

Table 4.5: Main poverty trapping biophysical processes.

Biophysical processes	Soil erosion by rain water (runoff)	Drying of streams	Climate change (erratic rainfall)
Rank	1	2	3

4.4.5 Livelihood strategies to reduce existing bottlenecks in Debre Mawi

Strategies to reduce or remove bottlenecks were analysed and the best options were selected using the Debre Mawi watershed as a case study, in order to make use of the participatory cognitive map of ESS management developed earlier in this thesis. The link between issues and the map is mentioned as follows. Major bottlenecks (Table 4.4) and bottlenecks related to other active, dynamic ESS degradation processes, defined as poverty trapping biophysical processes (Table 4.5), are constraints or impediments of improved livelihood. By considering the information in the Tables 4.4 and 4.5 the cognitive map of the researcher-community participatory mental model which considers the long-term livelihood and environmental sustainability was developed. This model presents the steps of actions, contributions of relevant stakeholders, challenges and solutions of each step, and how participatory knowledge generation and exchange works for the sustainable development (Figure 4.10). The aim for this approach is to be flexible and generic enough to work also in similar regions in the world.

Some farmers (13%) felt that they could not improve their livelihoods in any meaningful sense, given their current small land holding and negligible access to ESS, typically fertile soil and water. However, 87% believed that there were other options they could follow. In focus group discussion, the most frequently mentioned bottom-up strategies to escape poverty (Kristjanson and Kuan, 2006; Schneider and Gugerty, 2011) identified by participants are listed in Table 4.6. Most farmers wish to produce horticultural crops at least in their homesteads using irrigation to mitigate the crop failure risk of climate change, and to generate income for fertilizer purchase. The second strategy mentioned was to switch to livestock rearing, in particular raising animals for selling. 71% of respondents commented that sheep fattening was preferable to beef fattening since sheep needed comparatively less feed and a smaller pasture area. However, dry season water scarcity was reported as a major problem in the area even for domestic consumption. Some farmers started digging wells without seeking expert advice, indicating a solution to the water availability issue is now urgently required.

4.4.6 Management options at the local level

Managing water availability is clearly a key requirement to improve livelihoods and make them more sustainable (Table 4.6; Figure 4.10). Figure 4.10 presents the link between current livelihood issues (bottlenecks), their consequences, and possible mitigation strategies. The figure also highlights how participatory knowledge generation and exchange could contribute by combining possible stakeholders, solutions and challenges for sustainable development. This results in a researcher-community participatory mental model cognitive map I developed based on a case study catchment. To access water for irrigation farming and animal fattening, farmers reported that integrating hand dug wells and rainwater harvesting with proper SWC techniques may be an ideal approach. Typically, the study area is now facing serious soil erosion hazard as a result of intense precipitation and drought in the same year. As a counter measure to the unpredictability of rain, land shortage and severe soil erosion, rainfall-runoff harvesting appears to be an effective option (Gatot et al., 2001). This could help to store water in the rainy season for raising crop production in dry spells, to control runoff (decrease erosion rate), to conserve the excess runoff water for livestock, and to improve farmers' income and food security. Currently, most cropping land in the uplands has been covered by in situ rainwater harvesting methods such as bunds, vegetative barriers and trenches by the government and NGO (Water and Land Resources Center project) based on community mobilization, to conserve soil and water. Farmers consider that this infrastructural work might also improve groundwater recharge in the lower catchment, but direct rainwater-runoff harvesting has rarely been attempted.

Table 4.6: Strategies to move out poverty, and their required management options.

S/N	Strategy type	Required management options in their ranks order		
1	Crop diversification using irrigation	Water availability (1)	High value crops (2)	Market opportunity creation (3)
2	Animal fattening	Water availability (1)	Enough feed (2)	Improved breed (3)

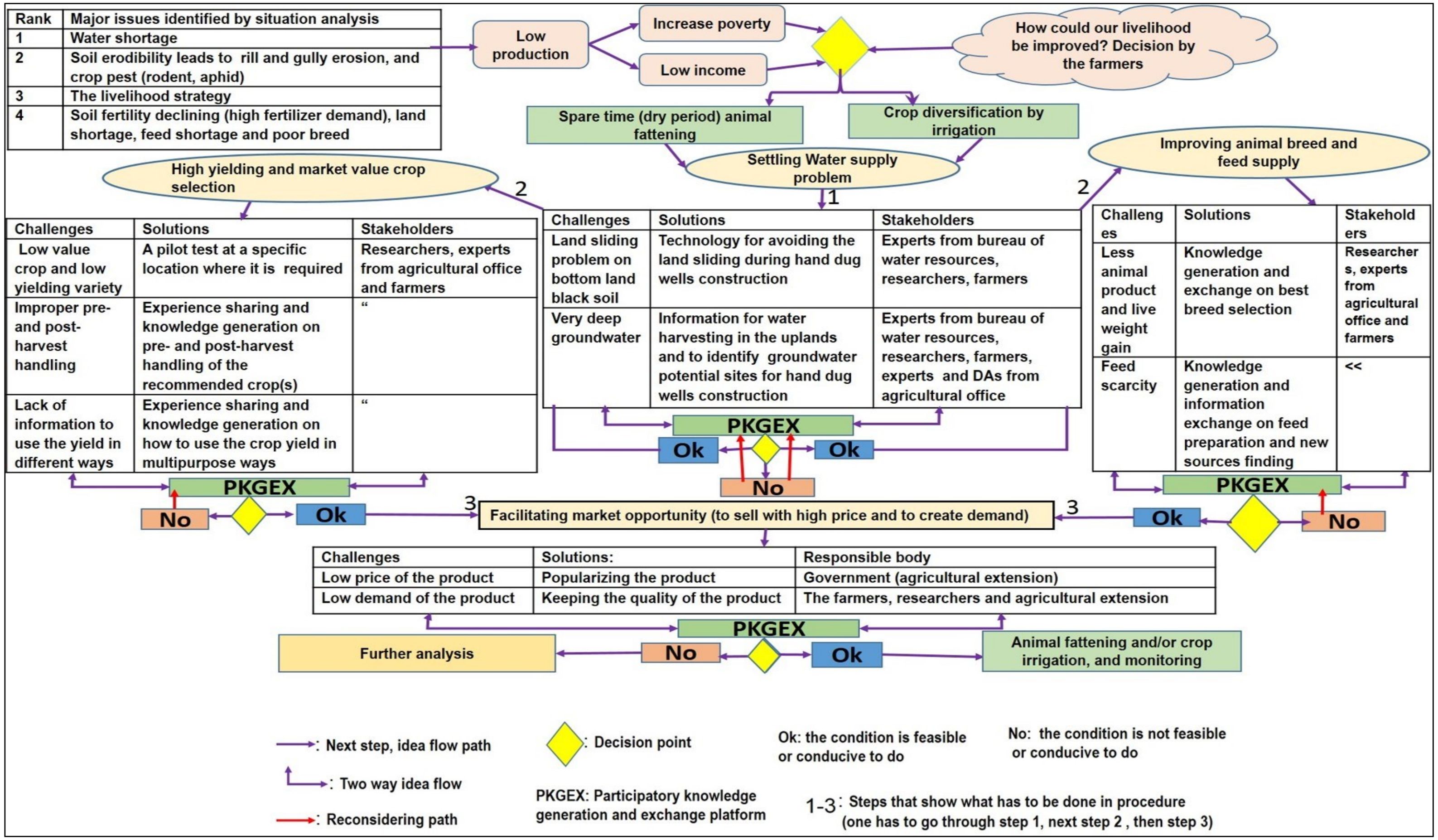


Figure 4.10: Cognitive map of the researchers-community participatory mental model about the ESS management for livelihood improvement in Debre Mawi.

4.4.7 Application: comparative advantages of rooftop water harvesting supported livelihood strategies

4.4.7.1 Quantifying rooftop water harvesting potential

As an application of the cognitive map, this section aims to explore a specific livelihood strategy to mitigate the major bottleneck, i.e., water scarcity, and to experiment with the implementation of a participatory knowledge co-creation process to support this strategy. It focuses on rooftop water harvesting, which as identified during the PRA activities as a potentially viable strategy. The application involves a participatory determination of the potential of rainwater harvesting. Barrels were used to collect, the rainfall on rooftops, through a system that connects rooftops to barrels; the rainwater depth in the barrel was recorded after every storm event from June to October 2016 (during rainy season). Then volume of harvested water was determined as the product of water depth in the barrel and its area. The largest and smallest amounts of harvested rainwater (HRW) using the experimental rooftops were respectively 140 and 71 m^3. Figure 4.11 shows high correlation (up to 0.98) between the total HRW volume and rooftop size during the observation period (15 Jun 2016–23 October 2016). For further comparison, the data was normalized as the ratio of sum of HRW volume to rooftop area. Using this ratio, the one-way ANOVA and t-test respectively confirm that the HRW amount is not affected by spatial or rooftop design variations (Table 4.7 and 4.8) at Debre Mawi.

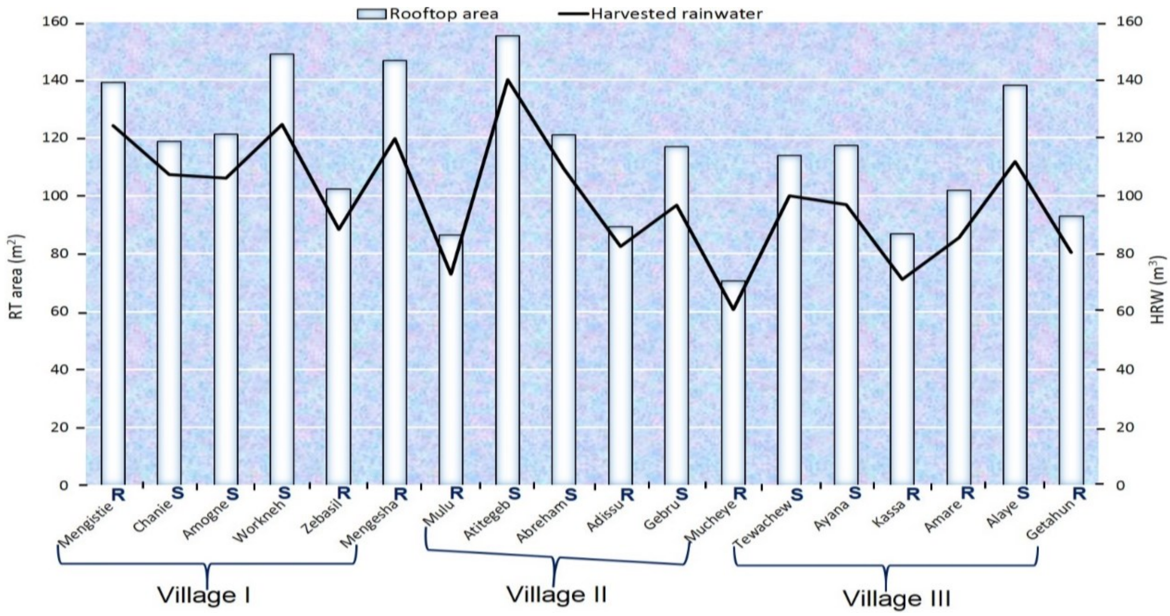


Figure 4.11: Rooftop, RT and harvested rainwater, total HRW relationships; household heads of experimental rooftops; *R*: rectangular, *S*: surrounding.

Table 4.7: Analysis of variance (ANOVA) for rooftop rainwater harvesting spatial variability determination. *df* (degree of freedom): the number of values in the final calculation of a statistic that are free to vary, *SS* (Sum of Squares): sum of the squares of the deviations from the means, *MS* (Mean Squares): average variations, are found by dividing sum of squares by the corresponding degrees of freedoms, *F-calc* (F-calculated): between groups variance/within group variance, *P-value*: the probability of getting a result at least as extreme as the one that was actually observed, given that the null hypothesis is true.: *F-crit* (F-critical): is found in the table considering significance level (α: alpha=0.05) and the degrees of freedoms of numerator and denominators respectively *df* of between groups and *df* of within group, if *F-calc* is greater than *F-crit*. then the null hypothesis is rejected.

RT design	*Source of Variation*	*SS*	*df*	*MS*	*F-calc.*	*P-value*	*F-crit.*
Rectangular	Between groups	0.002	2	0.001	0.74	0.52	5.14
	Within groups	0.007	6	0.001			
	Total	0.009	8				
Surrounding	Between groups	0.003	2	0.001	0.96	0.43	5.14
	Within groups	0.009	6	0.001			
	Total	0.011	8				
Watershed level	Between groups	0.004	2	0.002	2.01	0.17	3.68
	Within groups	0.016	15	0.001			
	Total	0.021	17				

Table 4.8: Determination of rooftop design effect on rooftop rainwater harvesting using t-test (*SD*: standard deviation, *t-calc*: calculated t-value, *t-crit*: critical t value and *P-value*: as mentioned in the above table 4.7).

Location	Rooftop design	*Mean*	*SD*	*t-calc*	*t-crit*	*P-value*
Village I	Rectangular	0.858	0.04	0.47	2.78	0.66
	Surrounding	0.871	0.03			
Village II	Rectangular	0.876	0.04	0.07	2.78	0.95
	Surrounding	0.878	0.04			
Village III	Rectangular	0.841	0.02	0.11	3.18	0.92
	Surrounding	0.838	0.04			
Watershed level	Rectangular	0.858	0.03	0.26	2.12	0.80
	Surrounding	0.862	0.04			

This strong relationship between rooftop area and amount of harvested rainwater indicates the annual rainfall amount is spatially homogeneous throughout the Debre Mawi watershed. The record during 15 June to 23 October 2016 showed that the total rainfall amount in villages 1, 2, and 3 are respectively 1072, 1036 and 987 mm. But there is daily rainfall amount difference between the three villages except between village 2 and 3 (Figure 4.12) as respondents believed that there is a daily storm event difference during the wet season between these villages. The farmers in Debre Mawi said that "when the rain rains in village 1, it does not rain in village 2 and/or 3 and vice versa, mostly; but the annual rainfall amount in the three villages is similar".

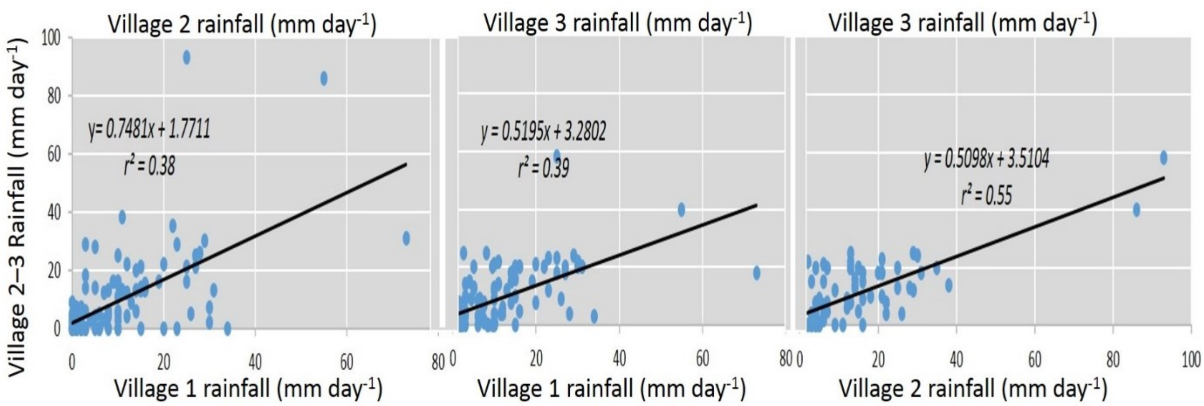


Figure 4.12: Correlation of daily rainfall between the 3 studied villages (15 June to 23 October 2016).

The data from the wet season period (15/6/2016 to 23/10/2016) indicates the observed and simulated harvested rainwater values are strongly correlated. The simulation efficiency of the equation is in the acceptable range (Enku and Melesse, 2014; Figure 4.13). Including experimental rooftops, the total rooftop area in the watershed is 23838.4 m^2. The 2005 to 2015 data indicates that the study area receives 1193 mm mean annual rainfall. Therefore, the total possible harvested rainwater using rooftops is 22741.8 m^3 with 10.7 m^3, 334.6 m^3 and 79.2 m^3 the least, largest and mean values respectively.

In order to implement rooftop water harvesting in practice, some technical challenges remain to be solved, such as temporary storage and water quality. For rooftop harvested rainwater collection, respondents indicated that a pond lined with ultra violet resistant plastic sheet (geo-membrane) may be able to provide the necessary volume. To avoid contamination and other risks, the pond needs to be covered using wood and plastic sheets. In order to connect rooftops to water storage, farmers currently use recycled plastic water bottles. In this set-up, the total cost of a rooftop water harvesting system is around US$ 231. Once installed, according to farmers this system can serve for 6 years with minimal maintenance. The potential problem with these ponds is the limitation of initial investment source for installation and damage by rodents.

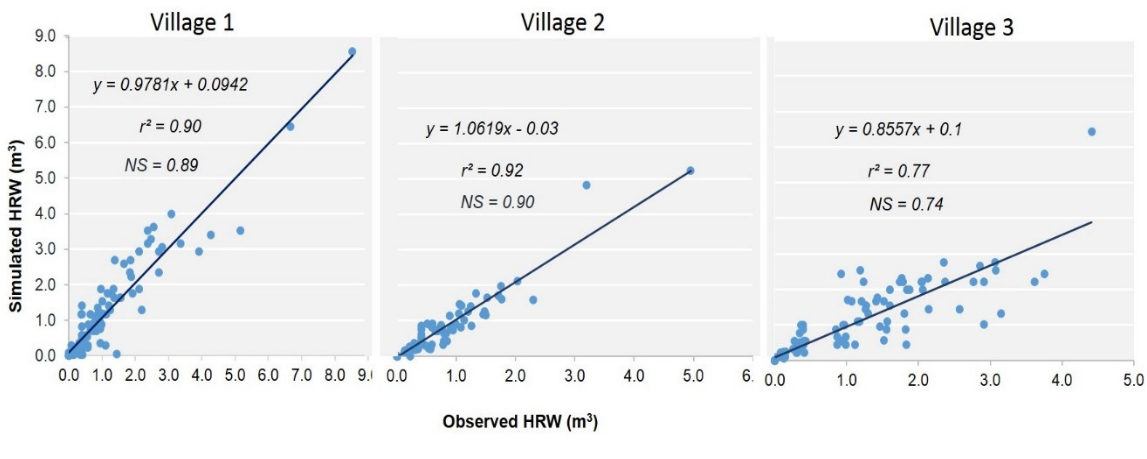


Figure 4.13: Comparison of the observed and simulated amounts of harvested rooftop water (HRW) for the rainy period (15/6/2016 to 23/10/2016).

In the Debre Mawi catchment, most farmers want to cultivate potato and hot pepper for subsistence needs (Amede and Delve, 2008), and fatten sheep and beef cattle for income generation (Bezabih et al., 2016; Amistu et al., 2016) in the dry season. Sheep and beef need to be fattened for 4–5 months respectively to achieve a good market price (Animut and Wamatu, 2014; Wolde et al., 2014). To capture higher market premia available during the Ethiopian Easter, farmers usually start fattening sheep in January and beef cattle in December to sell in May for the Easter holiday.

The CROPWAT outputs show that the potato and hot pepper irrigation water requirements are respectively 0.44 and 0.41 $m^3 m^{-2}$ over the growing season. The average water consumption of beef and sheep as found from literature (Table 4.9) is respectively 40 and 10 l per animal per day (Ward and McKague, 2007; Sileshi et al., 2003; Birhan and Manaye, 2013). However, before HRW is used for irrigation and animal fattening, domestic use has to be satisfied. Farmers are using hand dug wells for domestic use (human and their animals' consumption) but these wells supply only 20% of the household water requirement. Using PRA, I estimate that farmers need 48.06 m^3 more water per household on average for their domestic use in dry period than what hand dug wells can provide. Hence, the net minimum, mean and maximum HRW that can be used for fattening and/or irrigation is 10.7, 31.1 and 227.5 m^3 respectively (Table 4.10). On average, this net HRW helps farmers irrigate around 70.8 m^2 of potatoes, 76 m^2 of hot peppers, and to fatten 26 sheep and 5 beef (Table 4.11).

Table 4.9: Crop water requirement (CWR) and animal drinking water requirement (DWR) in the different strategies of livelihood improvement.

Crop	**Planting date**	**Harvest date**	**Irrigation water application**	**Irr.req (mm)**	**CWR ($m^3 m^{-2}$)**
Potato	15-Dec	23-Apr	14 times	439.7	0.44
Hot pepper	15-Dec	18-Apr	13 times	406.2	0.41
Animal	**Starting date for fattening**	**Selling date**	**Daily water requirement, DWR (m^3)**	**Days for fattening**	**Total DWR per animal (m^3)**
Sheep	1-Jan	1-May	0.01	120	1.2
Beef cattle	1-Dec	1-May	0.04	150	6

Table 4.10: Dry period (December–May) household water demand and sources relationship for domestic use.

Water sources/consumers	Minimum	Maximum	Mean	Daily per capita water requirement, *dwr* (m^3)
Hand dug wells, WA_{ews} (m^3)	5.4	18.9	12.24	
Consumers				
Family member (No)	2	8	5	0.005
Cattle (No)	0	10	6	0.04
Sheep (No)	0	10	3	0.01
Donkey (No)	0	4	1	0.04
HRW_{du} (m^3)	0	107.1	48.06	
Harvested rain water, HRW (m^3 $year^{-1}$)	10.7	334.6	79.2	
Net harvested water for pathways, *NHRW* (m^3)	10.7	227.5	31.14	

Table 4.11: Crop area and animal number can be supplied by harvested rainwater.

Pathways out of poverty	Crop/Animal type	Dry period water demand per unit crop or animal (m^3)	Number of animals or crop area that the NHRW can supply		
			10.7 m^3	**31.14 m^3**	**227.5 m^3**
Crop	Potato (area)	0.44	24.3 m^2	70.8 m^2	517 m^2
	Hot pepper (area)	0.41	26.1 m^2	76 m^2	555 m^2
Fattening	Sheep (No.)	1.2	8	26	189
	Beef cattle (No.)	6	1	5	37

4.4.7.2 Economic analysis of livelihood strategies

For this irrigation practice, farmers will use family labour which is cost free, i.e., they will not allot money for labour cost to this potato and hot pepper production. To fatten animals during this dry season, farmers can also use family labour and feed farm by-products such as crop residue, straw, hay, crop bran and local breweries by-products (Berhanu et al., 2009; Animut and Wamatu, 2014; Halala, 2015). Breweries by-products can be collected cost free or purchased cheaply particularly among poor women farmers who diversify their household income by making local alcohols such as '*areki*' and '*tella*'. Chanie (2014) did a comparative advantage analysis of three major crops growing in the same area but with different inputs requirements such as fertilizer, labor, seed and different outcome (yield and income). He selected the profitable crop using cost-benefit analysis (i.e., if the benefit to cost ratio is greater than one, the crop management is profitable). Following his methodology, I draw the cost-benefit analysis to compare HRW supported livelihood strategies, mentioned above, to select productive option(s).

The cost-benefit analysis proves fattening is more profitable than crop irrigation as the cost-benefit ratio (CBR) of return benefits to fattening costs relations is greater than one in all (Table 4.12). The farmers with the least assets can be most profitable in 5 months beef fattening, which would create an income of 3070 Birr during this period. The second profitable option for these group of farmers is 4 months of sheep fattening. Average amount asset possessing farmers at the watershed level can be most profitable by 5 months beef fattening; and their second option is sheep fattening. The farmers with the maximum amount of assets can generate the highest profit by sheep fattening, followed by beef fattening, and then irrigated potato production (Table 4.3; Figure 4.9). My estimates of the profits emanating from the water harvesting strategy are necessarily subject to uncertainties. These includes uncertainties due to variability such as climate change, decrease in water resources, increased animal and crop water requirement and changes in family composition. In addition, other challenges might be caused by risks such as animal and crops diseases and pests, and problems of market opportunity and demand. Lastly another problem for smallholder farmers might be related to feasibility of the selected livelihood options especially with respect to start up investment. This can potential be solved through loan from government or other sources.

Table 4.12: Benefit–cost analysis of pathways to poverty reduction in the study area (potato and hot pepper irrigation and beef cattle and sheep fattening).

Pathway options	Potato irrigation			Hot Pepper irrigation			Sheep fattening			Beef fattening		
HRW supply (m^3)	10.7	31.1	227 .5	10.7	31.1	227 .5	10.7	31.1	227 .5	10.7	31.1	227.5
Crop area/animal No.	24.3	70.8	517.0	26.1	76.0	555.0	8.0	26.0	189.0	1.0	5.0	37.0
Cop production (kg/ha)	33300	33300	33300	7600	7600	7600						
Ave. crop yield (kg)/animal (No.)	80.9	235.8	1721.6	19.8	57.8	421.8	8.0	26.0	189.0	1.0	5.0	37.0
Average unit price (birr/kg or animal)	10	10	10	20	20	20	1500	1500	1500	15000	15000	15000
Gross return (Birr)	**809.2**	**2357.6**	**17216.1**	**396.7**	**1155.2**	**8436**	**12000**	**39000**	**283500**	**15000**	**75000**	**555000**
Geo membrane cost	4515	4515	4515	4515	4515	4515	4515	4515	4515	4515	4515	4515
Plastic sheet for pond covering	240	240	240	240	240	240	240	240	240	240	240	240
Installation cost	1675	2285	9675	1675	2285	9675	1675	2285	9675	1675	2285	9675
Required seed (kg)/animal (No.)	5.0	14.7	107.3	0.5	1.0	1.5	8.0	26.0	189.0	1.0	5.0	37.0
Seed/animal unit cost	15	15	15	20	20	20	500	500	500	5500	5500	5500
Total seed/animal cost	75	221	1610	10	20	30	4000	13000	94500	5500	27500	203500
Total cost (Birr)	**6505**	**7261**	**16040**	**6440**	**7060**	**14460**	**10430**	**20040**	**108930**	**11930**	**34540**	**217930**
BCR	0.1	0.3	1.1	0.1	0.2	0.6	1.2	1.9	2.6	1.3	2.2	2.5
Net return (Birr)	-	-	1177	-	-	-	1570	18960	174570	3070	40460	337070

4.5 Conclusion and recommendation

I present an approach based on integrated social-applied sciences participatory research to examine how local ESS management can better support the sustainability of rural community livelihoods and environment. By conducting a detailed situation analysis of the study area using participatory rural appraisal (including household questionnaires, semi-structured interviews with key informants, open community meetings, small focus group discussions, resources mapping and field observations through transect walks with farmers), I identified and framed poverty issues, and prioritized new strategies to challenge poverty lock-in. By means of a situation analysis, I analysed the history of ESS-livelihood relationships trend and showed that water resources, cultivated land and pasture land are the current key elements out of ten total natural capitals for the three focal communities, and revealed that these capitals have been severely degraded due to land deterioration, particularly deforestation. As confirmed by my fieldwork and by the general poverty indicators derived from the survey research and existing academic studies, almost all people in the three communities are poor and suffer food insecurity due to the three main poverty drivers: population growth, minimal level of household assets, and a 'top-down' approach to governmental ESS management. I identified dry season water shortage is the primary issue out of the eight bottlenecks that are placing increasing pressure on land and resources degradation within the Debre Mawi watershed, and limit farmers' chances to develop alternative sources of livelihood. I have also identified three highly dynamic biophysical processes that lead to pronounced poverty lock-in, i.e. soil erosion (chiefly gully erosion), drying up of streams, and unpredictable rainfall. They cause respectively a reduction in arable land, and a decline of provisioning ESS especially from livestock and crop yield reduction.

Alternative strategies to challenge poverty lock-in are now urgently needed. From a range of potential strategies identified using the participatory rural appraisal approach, the two most important community focused solutions are crop diversification using irrigation, and livestock (sheep and cattle) fattening. For both options, I have argued that the lack of water availability is the main limiting factor, which needs to be resolved first. I therefore conclude that water harvesting and installation of hand dug wells for the upper and lower catchments respectively may have high potential for improving community ESS management. A feasibility analysis of water harvesting should be now focus upon the degraded uplands, where there is no surface and groundwater access, and severe soil erosion. I have argued here that for such areas, rainfall on the rooftops of houses can be harvested for dry season use. Groundwater accessibility assessment should be feasible in the lower catchments, particularly given upstream SWC measures on groundwater recharge. All these findings were derived from participatory work undertaken with the focal communities.

Poverty alleviation needs to ensure that it focuses on the poorest segment of society. Their experiences, and priorities must be taken into account in formulating any livelihood strategy. Therefore, I recommend further research to determine the practicalities of rainfall-runoff harvesting in the uplands, and more detailed analysis of the potential amount of groundwater for hand dug wells installation. Livestock and crop water requirements also need further study. Furthermore, it should be possible to integrate the accessible water resources with productive crop and livestock management. Based on the situation analysis, the main near future research components in my case study should be (1) determination of the rainfall−runoff volume; (2) analysis of the spatial and temporal variation of groundwater and (3) selecting the best ESS management options. Based on these research results, interventions should include the installation of relevant infrastructure. In order to turn my research into an example of "best practices" and to allow replication in other regions of the upper Blue Nile basin and similar regions, I explore here the practical example of using water harvesting by means of a participatory field experiment for rooftop water harvesting. I used 18 households' rooftops where data was collected by farmers after training. Based on data from 2016, on average, each household can harvest 79.2 m^3 rainwater per year.

Lastly, I compared four rooftop water harvesting supported alternative livelihood scenarios such as potato and pepper irrigation, and beef and sheep fattening, using combination of data analysis tools such as CROPWAT and FAO Penman–Monteith. Out of the total mean HRW amount, 48.06 m^3 supplies the domestic (household) needs, while the remaining 31.1 m^3 can be used for irrigation and/or fattening (for new livelihood improvement strategies). My benefit to cost ratio analysis proves, from the tested scenarios, that the best option for poverty alleviation is animal fattening using rooftops water harvesting instead of crop irrigation. Cattle fattening and sheep fattening respectively are the first and second livelihood improving options. Based on their rooftop size and household domestic water consumptions, the farmers able to get a profit of US$136 up to 14876 from 5 months cattle fattening, and US$69 to 7704 from 4 months sheep fattening.

This research aimed to address the recurrent academic debates on how to support agricultural livelihoods and poverty alleviation, and to implement participatory methods (particularly on how to include local knowledge in the decision-making process of ESS managements). Scientific debates have been focused on the ESS-livelihood relationships since 1970s in Ethiopia. But in much past research, the involvement of the farmers was essentially limited to 'participation by consultation' and the farmers were de facto persuaded to implement the new interventions that were planned at the state level. Indigenous knowledge as well as farmers' competence to solve their problems has usually been underestimated and given less emphasis in the design of land management practices (Bewket, 2007). As a result, at least some of the introduced technologies are usually ineffective in increasing short term benefits and are not maintained without further governmental intervention in the study region. There have been also some misplaced interventions that have led to increasing degradation and poverty. Many have concluded that land degradation is a widespread problem with a widespread failure of state-led interventions (Haile et al*.,* 2006). This reduces farmers' trust in new interventions, and induces fear that these practices accelerate the decrease in ESS. Bewket (2007) suggests that future interventions should carefully pursue a farmer-participatory approach.

My case study is representative of Ethiopian and African highlands and focuses on the issue of rural focal community livelihoods and ESS relationships. The potential of leveraging ESS as a means to alleviate poverty is receiving increasing scientific attention. Hence my findings, including my social-ecological contextualization based on a bottom-up approach, are replicable to the Ethiopian-African rural highlands and to other international ESS supported rural communities.

Chapter 5

A catchment-scale evaluation of the potential of groundwater abstraction and water harvesting to improve livelihoods in the Ethiopian highlands

Abstract

The objective of this chapter is to identify the best combination of groundwater abstraction and water harvesting to optimise water supply during the dry season to support livelihood improvement. My study region is Debre Mawi watershed, where 85% of the population are poor subsistence farmers. This watershed is representative for the Ethiopian and other tropical highlands where as shown in chapter 4 livelihood security is strongly dependent on local ecosystem services (ESS), particularly those provided by water and soils. Despite the high rainfall during the wet season, water scarcity prevails during the dry season, for domestic use and for agricultural diversification such as crop irrigation and animal fattening for rural livelihood resilience. To improve water supply during the dry season, I employed the PED model and water harvesting simulation technique to analyse experimentally collected data respectively to test the effectiveness of soil and water conservation practices to enhance recharge and to understand perched groundwater behaviour on the hillsides to optimize that groundwater withdrawal in the dry season and to quantify the amount of harvested rainwater from rooftops for dry period use. Experimental data collected for this water availability analysis consists of discharge data for 2010−2016 in the existing 95 ha gauged subcatchment of the 716 ha Debre Mawi watershed, on site meteorological data, groundwater depth data in eight hand dug wells and 18 piezometers, and rainwater amount collected on roofs. Subsequently, the model and experimental data are used to develop a spatial distributed model of temporal water availability in the watershed. Finally, this distributed model called Ecological Water Services and Availability Tool (EWSAT) is employed for analysing livelihood improvement scenarios. The results show that soil and water conservation (SWC) interventions decrease runoff and enhance recharge of the degraded soils. By fitting the PED model results to the current and previously collected discharge data, I found that after four years of implementation of the SWC practices, 55% of the degraded lands changed from producing overland flow to recharging the groundwater. For the year 2016, I found that the groundwater recharge in the 716 ha watershed

amounted to 1.4 million m^3. The simplified groundwater model, which simulates the water table height for a well as the quotient of sum of the recharge in the period of travel of interflow from the divide and the drainable porosity, fitted the observed hand dug well data well. The coefficient of determination (r^2) ranges between 0.84−0.97, except two wells for which the farmers did not volunteer to monitor the well. Travel times varied from 15 to 140 days, which means that all wells were dry within 5 months after the end of the rainy season, except if water was stored behind volcanic dykes associated with the geological faults. Combining a semi-distributed conceptual PED hydrology model, GIS tools, and water table heights in the Water Service Decision Tool, shows that groundwater is accessible throughout the watershed from May to October. During the remaining months, groundwater availability varies spatially, i.e., groundwater is accessible only in saturated lower catchments and hillside areas in portions of the watershed with deep soils that recharge the groundwater (even though the groundwater aquifer is very deep in hillsides). Therefore, for villagers living in degraded areas, rooftop water harvesting may be a better water source. Groundwater and rooftop water harvesting can increase water supply during the dry season to the lower and upper parts of the catchments respectively. Furthermore, scenarios analysis that links dry season water supplies with local livelihoods improvement strategies shows that animal husbandry is the best livelihood improving strategy for upper catchment residents, while crop irrigation is best suited for lower catchment residents' livelihoods. After fulfilling household's domestic water use need, rooftop water harvesting and groundwater respectively could allow farmers to earn a profit estimated at US$69–7704 and US$1084–2504 during the dry season from a combination of animal fattening and crop irrigation.

5.1 Introduction

Leveraging ESS management as a means of poverty alleviation receives increasing attention. In mountainous regions such as Ethiopian highlands, livelihood depends on ESS, particularly those provided by water and soil. In these highlands, 85% of the population consists of poor subsistence farmers that support their livelihood mainly by rain-fed agriculture, even though rain-fed agriculture is not an ideal farming system in erratic rainfall areas (Yosef and Asmamaw, 2015). The unpredictable monsoon rainfall and soil erosion are thought to be the dominant processes causing ESS degradation, which leads to further poverty in the study area (Amare et al., 2014). In this region deforestation and continuous cropping have led to loss of organic matter, severe soil erosion by precipitation, crop production failure due to inconsistent rainfall, and pronounced water scarcity during the dry season due to drying up of springs.

As a counter measure to the unpredictability of rainfall, land shortage and severe soil erosion, rainfall-runoff water harvesting is the best option (Gatot et al., 2001). This helps to store water during the rainy season for raising crops production in dry tracks, to control runoff (decrease erosion rate), to conserve the excess runoff water for animal drinking and for recharging purpose, and to improve farmer income and food security. Therefore, this chapter 5 explores the optimum combination of groundwater abstraction and rooftop water harvesting to optimise water supply during the dry season in a catchment, and identifies the best water resources supported scenarios for improving livelihoods. To achieve this objective, I employ a combination of experimental data and models to determine the effect of soil and water conservation practices on ground water recharge and to evaluate the availability of groundwater and rainwater from rooftops in order for determining scenarios in which ESS can be used optimally.

This study was carried out in the Debre Mawi watershed located in the sub-humid Ethiopian highlands just south of Lake Tana. Discharge data were collected from a 95 ha subwatershed together with watershed-scale groundwater level data from newly installed wells and piezometers, and harvested rain water using rooftops. In addition, models were applied, and optimum use of water resources was determined based on scenarios selected using participatory rural appraisal (described in chapter 4) together with model results and experimental data.

5.2 Material and methods

In this section I present first the PED model that was used to analyse the discharge data for determining the effectiveness of soil and water conservation practices and to calculate the recharge to groundwater. The PED model description includes a newly developed module for simulating well water height, and the Ecological Water Service and Availability Tool (EWSAT) that I developed for optimizing ecological water services and availability in mountainous watershed. Then, the watershed and the type of data collected are described. Next procedural methods for model-based data integration and upscaling are described. Subsequently, these models were applied in the Debre Mawi watershed. At the end, I analyse four scenarios (selected based on the participatory rural appraisal activities described in

Chapter 4) to improve livelihoods (the link between water supply and strategies to challenge poverty lock-in) in order to identify the optimal combination of intervention practices in the catchment.

5.2.1 PED model description

For the hydrological modelling, I adapted the Parameter Efficient Distributed (PED) hydrological model, which was developed for the Ethiopian highlands, and applied widely in the northern highlands (Collick et al., 2009; Steenhuis et al., 2009; Tesemma et al., 2010; Tilahun et al., 2013a, 2013b, 2015; Guzman et al., 2017; Zimale et al., 2016) to simulate river discharge. PED is a conceptual model that separates the watershed into three regions: periodically saturated (A_1), degraded (A_2) and permeable hillslopes (further on referred to as "hillsides", A_3). The other hydrology parameters of the model are maximum and initial soil storages per area ($S_{max1}, S_{max2}, S_{max3}, S_{init1}, S_{init2}, S_{init3}$) in mm, maximum groundwater storage (BS_{max}) in mm, and duration of interflow (τ*) after a rain fall event and half-life of the aquifer ($t_{1/2}$) in days.

The discharge (Q) at the outlet is a combination of the discharge of the three areas and can be written as:

$$Q = A_1 Q_1 + A_2 Q_2 + A_3 (Q_b + Q_i) \tag{5.1}$$

where Q_1 *and* Q_2 are saturated excess overland flow per unit area generated from the saturated and degraded area, A_1 and A_2 respectively whilst in A_3, which are also called "hillsides", the rainfall that does not evaporate after infiltration, eventually becomes either base flow (Q_b) or interflow (Q_i). For simplicity, I left out the subscript t with flow rate parameters.

Surface runoff is simulated as any rainfall in excess of soil saturation:

$$Q_{1,2} = \frac{S_{t-\Delta t,} - S_{max} + (P - PET)\,\Delta t}{\Delta t} \tag{5.2}$$

where P is precipitation (mm d^{-1}), PET is potential evapotranspiration (mm d^{-1}), $S_{t-\Delta t}$ is previous time step storage (mm), Δt is the time step (day: d), and S_{max} is the maximum water storage capacity in the root zone.

When soil moisture is less than the threshold (S_{max}) and precipitation is less than potential evaporation (*PET*), actual evaporation (*E*) is simulated as:

$$E = S_{(t-\Delta t)}\left[1 - exp\left(\frac{(P - PET)\Delta t}{S_{max}}\right)\right] \qquad (5.3a)$$

When the precipitation is greater than potential evaporation (*PET*), then:

$$E = PET \qquad (5.3b)$$

When the soil storage of the hillside area (A_3) is above field capacity (i.e., $S_{t3} > S_{max3}$), the recharge to the aquifer is calculated as:

$$Rech = S_{t3} - S_{max3} \quad \text{for } S_{t_3} > \quad S_{max3} \qquad (5.4)$$

where the subscript 3 indicates the hillside area.

The recharge routes to two reservoirs, i.e., a first order reservoir that produces base flow (Q_b) and a zero-order reservoir that produces interflow (Q_i) only after the base flow reservoir is filled. The base flow reservoir is filled up first and after the base flow reservoir is filled above BS_{max}, the interflow reservoir is filled up subsequently. When the base flow storage $BS_t < BS_{max}$, its outflow (Q_b) is calculated as:

$$Q_{b,t} = BS_{t-\Delta t}\left[1 - exp\left(-\frac{0.69}{t_{1/2}}\Delta t\right)\right] \quad \text{for } BS_t \leq BS_{max} \qquad (5.5)$$

The storage is calculated when the base flow reservoir is not filled up as:

$$BS_t = BS_{(t-\Delta t)} + \left(Rech - Q_{b,t}\right)\Delta t \;\; \text{for } BS_t \leq BS_{max} \qquad (5.6)$$

When the calculated storage is greater than the maximum storage (BS_{max}), BS_t is equal to the maximum storage, and percolation ($P_{erc,t}$) is calculated as the difference of the two:

$$BS_t = BS_{max} \quad \text{for } BS_t \geq BS_{tmax} \tag{5.7}$$

$$P_{erc,t} = BS_t - BS_{max} \tag{5.8}$$

5.2.1.1 PED groundwater and interflow module

Assuming that the slope of the hillslope is the only driving force, the interflow $Q_{i,t}$ can be obtained by averaging the percolation over the time, τ^*, which is period for the water to flow from the groundwater divide to the point of interest, e.g.,

$$Q_{i,t} = \frac{\sum_0^{\tau^*} P_{erc,t-\tau}}{\tau^*} \quad \text{for} \quad \tau \leq \tau^* \tag{5.9}$$

where τ is the time after the rainfall event that caused the percolation.

The water level in the well is made up of two components: a regional component that varies little over the year and a local seasonal component that directly responds to the rainfall and changes seasonally. The regional component is due to water that cannot flow down the hillslope because it is blocked by volcanic dykes or rock outcrops or by a groundwater table that underlays a region and that ultimately surfaces at a distant point. The height of the regional groundwater will be denoted by $h_{x,f}$.

The water table height $h_{x,t}$ can be determined for hillslopes where gravity is the only driving force by the sum of the recharge over the time τ^* divided by the drainable porosity, μ:

$$h_{x,t} = \frac{\sum_0^{\tau^*} P_{erc,t-\tau}}{\mu} \quad \text{for} \quad \tau \leq \tau^* \;\; and \; h_{x,t} \leq D_{x,w} - h_{x,f} \tag{5.10}$$

where $D_{x,w}$ is the height of the well (or soil surface above the reference level). In the case the water table intersect the surface, (i.e.,$h_{x,t} > D_{x,w} - h_{x,f}$) we set the water level equal to the soil surface, denoted as:

$$h_{x,t} = D_{x,w} - h_{x,f} \tag{5.11}$$

5.2.1.2 EWSAT model procedures

PED is a lumped model that divides the watershed into three conceptual representations ("regions"), and does not explicitly indicate the water table height distributions at the watershed level. As a result, the groundwater module in the PED model can only be used indirectly to determine the spatial and temporal distribution of the water table in the watershed. To address this issue, here I develop the EWSAT model in which I adapt the theoretical principles of the PED groundwater model so that it can be used in map the ground water availability in the watershed in a spatially distributed manner. This makes it possible to analyse groundwater availability in locations where the groundwater flow is obstructed by volcanic dykes or near periodically saturated areas, and to study the drivers of water table heights in other wells (mainly located in degraded areas) in more detail.

The procedures determine the water availability in the EWSAT model are as follows:

1. Google Earth was used together with knowledge of the watershed to delineate the periodically saturated areas, the degraded hillslopes and the "hillside" with good drainage;
2. The SRTM digital elevation model at 30 m resolution was employed to determine the contributing area, A_c, of each 30 by 30 m pixel using ArcGIS hydrology tools;
3. The fraction of contributing area (described as the ratio of groundwater flow contributing area (A_c) to the total flow contributing area of the watershed), f_{hill} for each pixel because of the hillside area was calculated with the map algebra raster calculator tool as:

$$f_{hill} = \frac{A_c}{A_T} \tag{5.12}$$

   where A_T is the total flow contribution area of the watershed.
4. Next, I calculated for each month, the average water table height for the group of wells located in the saturated and hillside areas, $\overline{H_{WT,shl}}$ that had a permanent groundwater depth throughout the year, as well as the group of wells located in degraded areas $\overline{H_{WT,\deg}}$ that fell dry sometime after the rainy season. The water table height for each

of the pixels in the degraded areas, $H_{WT,deg}$ that its contribution area fraction of the watershed is A_3 was then calculated as:

$$H_{WT,deg} = \frac{f_{hill}\overline{H_{WT,\text{deg}}}}{A_3} \tag{5.13}$$

And for each pixel of the hillsides and saturated area, the height of the groundwater, $H_{WT,shl}$ was determined as:

$$H_{WT,shl} = \frac{f_{hill}\overline{H_{WT,\text{shl}}}}{A_3} \tag{5.14}$$

5. Finally, the monthly water table height for each pixel in the watershed $H_{WT,wshd}$ was simulated as the combination of groundwater levels in Eq. 5.13 and 5.14 using the following map algebra raster calculator expression:

$$H_{WT,wshd} = con\left(\text{Is}Null\left(H_{WT,deg}\right), 0, H_{WT,deg}\right) + con\left(IsNull\left(H_{WT,shl}\right), 0, H_{WT,shl}\right) \tag{5.15}$$

where $H_{WT,wshd}$ (m) is the monthly water table height of each pixel of the study region. In order to obtain the average values for each month, the equations 5.13–5.15 were run separately 12 times.

5.2.2 Study area

The Debre Mawi watershed is located in the headwaters of the Blue Nile, about 30 km south of the Lake Tana (between 11°20'13" and 11°21'58" N, and 37°24'07" and 37°25'55" E). The total area of the watershed is 716 ha. The elevation ranges between 1950 and 2309 metres, and slopes are steep at 8 to 36%. The maximum annual temperature occurs in March–April, ranging from 22–29°C, whereas minimum annual temperature occurs in November–December with a range of 5 to 12°C. It has a unimodal rainfall regime with an average annual rainfall of 1238 mm (Zegeye et al., 2010). June, July, August and September receive the largest shares of the annual rainfall. Potential evapotranspiration is 2−3 mm/day in the rainy season and 4−5 mm/day during the dry season. The watershed is characterized as mountainous, with a highly rugged and dissected topography with steep slopes (Guzman et al., 2013) and spatially variable soil losses (Tilahun et al., 2013a). Currently, most upper catchment croplands particularly in the areas with degraded soils have been covered by SWC structures such as infiltration furrows, bunds and vegetation barriers by government forced community mobilization in the study region (Figure 5.1).

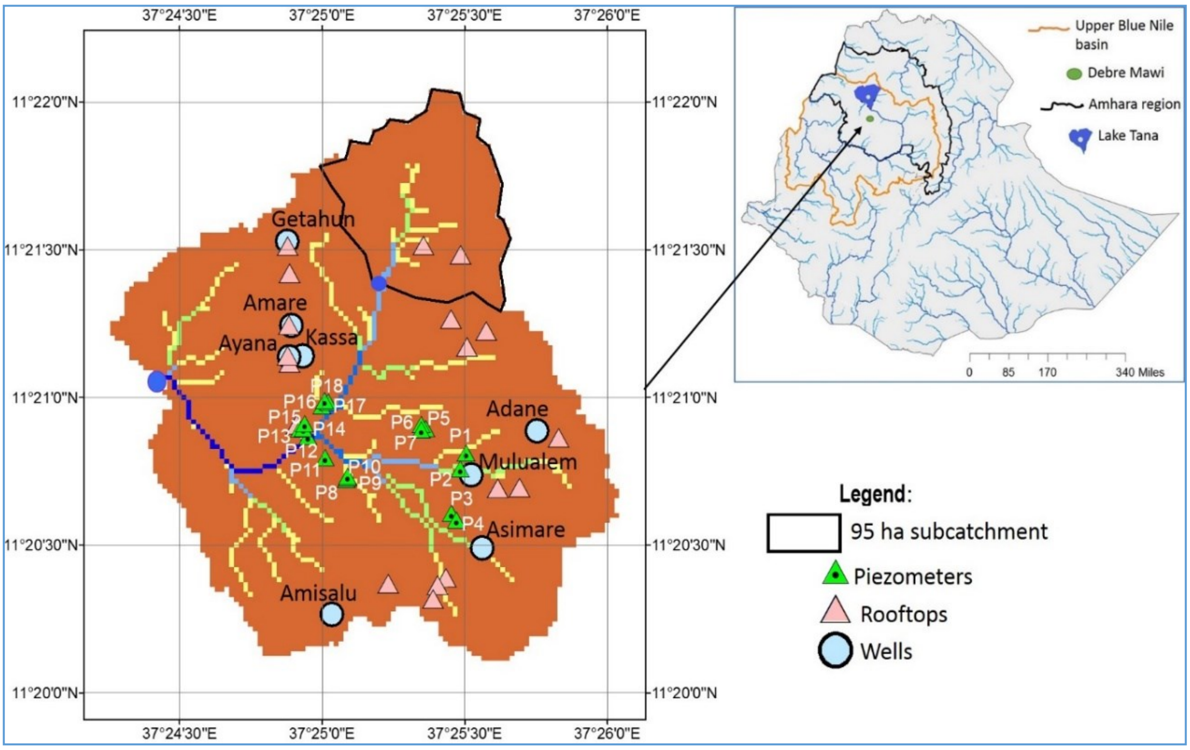


Figure 5.1: Location of piezometers, observed hand dug wells and rooftop water harvesting measuring sites installed to study water availability at Debre Mawi (wells are labelled by the farmers' names and piezometers are labelled by 'P' followed by numbers, i.e., P1–P18).

5.2.3 Data collection

To analyse the impact of SWC interventions on rainfall infiltration on the hillslopes ("hillsides") area fraction, I focused on a 95 ha subcatchment of the Debre Mawi watershed, where stream flow was determined since 2010 from gauging stations and a set of SWC structures were implemented during the dry season of 2012. In addition to the discharge data that I collected in 2016, I used discharge data collected by previous studies before, during and after the implementation of SWC structures (Tilahun et al., 2013a, 2013b, 2015; Dagnew et al., 2015, 2016; Guzman et al., 2015, 2016).

In the Debre Mawi watershed, as shown in the PRA analysis (chapter 4), there is an apparent contradiction between the perception of pronounced water scarcity during dry season particularly by the local community and the perception that infiltration area can be improved by SWC interventions implemented in 2012 has improved groundwater availability. The latter is perceived by the Debre Mawi residents and governmental stakeholders who led the implementation of these interventions (Dagnew et al., 2015). Previous research (Tilahun et al., 2015; Dagnew et al., 2015; Zegeye et al., 2010, 2014; Tebebu et al., 2010, 2015) in this watershed has focused only on analysis of discharge and soil loss. Using these data, Tilahun et al. (2015) and Dagnew et al. (2015) implemented the PED model only for a small 95 ha subcatchment of Debre Mawi, which showed that infiltration by hillsides recharges groundwater during 2010 to 2015.

Here I expand on this research by quantifying the impact of SWC interventions on groundwater recharge by developing an extension to the PED model theory that simulates well water height, and exploring the Ecological Water Service and Availability Tool (EWSAT) that I used for explicitly allocating water availability in mountainous watershed. I implement the PED model for the subcatchment of Debre Mawi using observed time series of discharge, soil loss, rainfall and evaporation data for the 2010 to 2016 period. I use this setup to evaluate the impact of SWC interventions on the catchment area that contributes to groundwater recharge, and thus indicates an improvement of groundwater availability. Then I determined catchment scale groundwater availability by updating the previous data using water table height data collected in 2016 by means of wells and piezometers, and area fractions of the three watershed regions delineated from Google Earth based on field observation.

To link the infiltration area improvement with groundwater availability, water table heights were measured using 8 hand dug wells and 18 piezometers distributed over the catchment. Water table heights of piezometers were recorded every morning (8:00am) during 28th of July–27th of October 2016. Hand dug wells were monitored by averaging two records taken every morning (8:00am) and evening (6:00pm), for different time periods, between July 2016–May 2017 (Table 5.1). The length of monitoring is based on drying up period of the wells and sometimes also on data collectors, as a few quitted monitoring before drying up of the well. In the hand dug wells, the water table varies throughout the year, particularly following rainfall events. The observations of water table height show that groundwater overflows (for example

Amare's well) during the wet season particularly during July−August, and reduces rapidly (wells of Ayana, Kassa, Getahun and Amare) with the offset of rainy season as the water in the hillslope shallow aquifers drains out to lower catchment (photos of wells are presented in Figure 5.2). The location of the wells and piezometers is shown in Figure 5.1. The depth of these wells and piezometers, their minimum water table levels observed during monitoring, diameters of wells and related descriptions are mentioned in Tables 5.1−5.2.

For the feasibility study of water harvesting, the Debre Mawi watershed was divided into three villages based mainly on rainfall spatial variability, a criterion suggested by interviewees; hence an experiment using rooftops including rain gauges (one rain gauge per village) was installed for collecting harvested rainwater and daily precipitation to gather representative water harvesting evidence for the whole Debre Mawi (Figure 5.1). To estimate the rooftop water harvesting potential for the dry season use, 18 experimental rooftops having two common rooftop designs named surrounding, *S* (9 rooftops) and rectangular, *R* (9 rooftops) were selected where the water harvesting system was installed as described in Figure 5.2; data required for quantification such as rooftop area, and daily precipitation and harvested rain water amount were recorded during 15 Jun 2016−23 October 2016 (Table 5.3).

Table 5.1: Dimensions and related descriptions of wells.

List of wells	Depth (cm)	Diameter of wells (cm)	Minimum water level (cm)	Installation year	Time period of monitoring	Remarks based on field observation
W1 (Amare)	1570	200	262	2016	6 Jul−Nov 2016	Its WTH closes to land surface and reduces rapidly with the rainfall
W2 (Kassa)	110	200	42	2016	6 Jul 2016−25 Mar 2017	The site dominated by rock outcrop soil
W3 (Ayana)	1170	180	41	2016	6 Jul 2016−26 Apr 2017	Similar to Kassa's well, but the soil is less rocky
W4 (Getahun)	1050	130	450	2016	6 Jul−31 Oct 2016	This farmer quit monitoring of the well before the water level reduced
W5 (Adane)	500	150	148	2015	19 Jul 2016−26 Apr 2017	Perennial well although water amount is little during dry season,
W6 (Mulualem)	233	190	25	2012	19 Jul−13 Dec 2016	Perennial, physically it looks that has good water supply, there are acacia trees close to it. But it is not protected well (the soil sliding down, its depth reduced from 11 to 2.3 m)
W7 (Asimare)	920	200	500	2015	19 Jul 2016−26 Apr2017	Perennial, protected well, there are acacia trees close to it
W8 (Amisalu)	710	180	62	2016	19 Jul 2016−8 May 2017	Perennial, its site looks rocky but green during dry season, it is close to acacia trees too

Table 5.2: Depths and minimum water levels of piezometers.

Piezometer label	Depth (cm)	Minimum water level (cm)	Piezometer label	Depth (cm)	Minimum water level (cm)	Piezometer label	Depth (cm)	Minimum water level (cm)
P1	300	73	**P7**	300	57	**P13**	300	57
P2	300	118	**P8**	300	0	**P14**	300	70
P3	340	185	**P9**	300	0	**P15**	300	51
P4	300	107	**P10**	300	0	**P16**	300	94
P5	300	0	**P11**	300	0	**P17**	340	0
P6	300	12	**P12**	340	126	**P18**	340	42

Table 5.3: Locations and dimensional areas of experimental rooftops.

Rooftop location	Household's name	Rooftop design	Rooftop area (m^2)
Village 1	Mengistie	*R*	139
	Chanie	*S*	119
	Amogne	*S*	121
	Workneh	*S*	149
	Zebasil	*R*	102
	Mengesha	*R*	147
Village 2	Mulu	*R*	86
	Atitegeb	*S*	155
	Abreham	*S*	121
	Adissu	*R*	89
	Gebru	*S*	117
	Mucheye	*R*	71
Village 3	Tewachew	*S*	114
	Ayana	*S*	117
	Kassa	*R*	87
	Amare	*R*	102
	Alaye	*S*	138
	Getahun	*R*	93

Figure 5.2: Photos of the 8 water table height monitoring wells (W1−W8), and water harvesting system installed for experiment. Photo of W6 was taken in 2015 before it was opened (during data collection, it was opened while its depth reduced from 11 m to 2.3 m due to the sliding down of the soil).

5.2.4 Methods for model–based data integration and upscaling

5.2.4.1 Testing effectiveness of SWC measures to increase recharge

To determine the recharge as affected by SWC structures, I fitted the discharge data at the outlet to the PED model result by varying fractions of the three areas (periodically saturated, degraded and not degraded hillslope, "hillside") without changing any of the other parameter values. A decrease in degraded area would indicate that direct overland flow was decreased and recharge increased. I used precipitation, evapotranspiration and storm flow data for the period of 2010−2016; these data were analysed using the PED model before (2010/2011), during (2012) and after (2014 and 2016 separately) to see the trend of long and short-term impact of SWC intervention.

5.2.4.2 Testing groundwater module

In order to test my module of groundwater table heights and the theory behind it, I fitted the observed water level data in the wells with the model output (simulated as the quotient of sum of the recharge in the period of travel of interflow and the drainable porosity) using the travel time over the recharge was added as the only fitting parameter. A drainable porosity was taken of 0.032 and was kept constant. Daily recharge for 2016 and 2017 for the "hillside" at the watershed level was simulated with the PED model using the calibrated values used for simulating the discharge of the 95 ha subwatershed.

5.2.4.3 Implementing the EWSAT model

The spatial and temporal variability of groundwater table height was investigated to identify potential sites for the installation of wells at the watershed level, by using a combination of the hydrological model with spatial analyst tools (implemented in ArcGIS). First, I identified with my knowledge of the Debre Mawi watershed patterns of degraded, periodically saturated areas, and the well-drained hillsides on Google Earth after which I delineated these areas. Subsequently, using the 30-m resolution SRTM digital elevation model, the contributing area, of each pixel was calculated for the entire Debre Mawi watershed using ArcGIS hydrology tools. Subsequently, monthly average water table heights were calculated using WTHs of the calibrated and tested groundwater module, mentioned in section 5.2.4.2 for distributed spatial-temporal WTHs analysis. Finally, the monthly water table height for each pixel in the watershed was calculated using the map algebra raster calculator tool. The detailed procedure of EWSAT model is described in section 5.2.1.2.

Based on the maps of groundwater table height, optimal sites for the installation of wells, blocking of lateral water flow and water harvesting were allocated. In the upper catchment, degraded and "hillside" watershed regions where groundwater respectively is nil, and available but very deep, water harvesting is the best dry season water source option. Whereas in the lower catchment, particularly in saturated regions where natural dykes are common, blocking of lateral water flow to these dykes improves the dry season groundwater availability on the expense of subsurface flow normally draining out the watershed. Subsequently, I compared the available water supply with the water demand of the community that would fulfil domestic use, and give the community the opportunity to improve their livelihood using new farming strategies such as crop irrigation and animal fattening. The volumetric groundwater per month was calculated following the method by Godfrey and Reed (2013) as follows:

$$V = \pi \frac{D^2}{4} h \qquad (5.16)$$

where V (m^3) is the volume of water in a well, D (m) is the diameter of a well, h (m) is the water table height in a well (referenced from sea level). The diameter of hand dug wells I used is 1.5 m based on a technical brief of the NGO Water Aid in January 2013, and average wells diameter, determined based on my wells dimensions record through field observation in the study area was 1.8 m which is very close to the value in this technical brief.

For villagers who are far from groundwater sources, water harvesting, especially rooftop water harvesting (which is easier to install compared to plot level harvesting) is the best option to fulfil dry season water need. To determine the potential of rooftop water harvesting, I conducted field experiment using 18 rooftops to gather representative water harvesting evidence for the whole Debre Mawi. These rooftops consisted of 9 surrounding and 9 rectangular rooftops, with a total, smallest and largest area of respectively 2067 m^2, 71 m^2 and 155 m^2. The spatial variability and rooftop design effects on harvested rainwater (HRW) amount were proven by one-way ANOVA and t-test respectively, employing a 95% level of confidence. For HRW prediction, a simple equation (the product of rooftop area, precipitation and runoff coefficient) was calibrated using the 131 observed HRW volumes, and its simulation efficiency was evaluated using coefficient of determination (R^2) and Nash Sutcliffe Efficiency (*NSE*). Using the total rooftop area observed during 2016, the total amount of HRW at catchment level was simulated by equation:

$$Q = A \frac{P}{1000} 0.8 \qquad (5.17)$$

where Q (m^3) is volume of harvested rainwater from rooftop, A is area of rooftop (m^2) and P is precipitation (mm).

5.2.4.4 Scenarios analysis for livelihood improvement

To identify the best livelihood improving option(s) for the local community at the catchment level, the relationship between the possible water supply quantified in section 5.2.4.3 and the community water need was analysed. For this purpose, the crop water requirement (CWR) was determined using CROPWAT 8.0 for potatoes and hot peppers, which were selected as potential crops to be produced by irrigation in the region. As model input, reference evapotranspiration was calculated with the Penman–Monteith equation using mean monthly climatic data of 2005–2015 from the weather station at the location of Adet 10 km south of the site as mentioned in chapter 4. The soil field capacity and permanent wilting point were determined based on the soil textural class data. The other livelihood improving option is beef and sheep production. The drinking water requirement of the animals was determined from literature. In the study region, the mean daily water consumption of beef is 40 l and of sheep is 10 l per animal (Ward and McKague, 2007; Sileshi et al*.,* 2003; Birhan and Manaye, 2013).

Before determining crop area and number of animals, which can respectively be irrigated and fattened using groundwater abstraction wells and rooftop water harvesting, I determined the household water demand for domestic use that needs to be supplemented by additional wells installation and HRW. Then cropland area for irrigation and number of animals for fattening were calculated based on the rest amount of groundwater and harvested rainwater.

Lastly, a benefit-cost ratio (BCR) comparison was implemented between the four livelihood improving strategies (potato irrigation, hot pepper irrigation, sheep fattening and beef fattening) followed by selection by ranking; the higher the BCR, the better the scenario for livelihood improvement.

$$BCR_{Ind.option} = \frac{\sum Benefit}{\sum Cost} \qquad (5.18)$$

where $BCR_{Ind.option}$ is the benefit to cost ratio of each individual option, for example, of potato irrigation using groundwater or water harvesting. To select the scenario as beneficial, the BCR should be greater than 1 otherwise the option should be rejected.

5.3 Results

5.3.1 Discharge at the outlet

The observed and simulated discharge values which were analysed using the data which were collected before, during and after the implementation of SWC interventions show a decreasing trend (Figure 5.3) with a lack of significant difference trend in the corresponding rainfall (Table 5.4).

Table 5.4: Analysis of variance (ANOVA) of weekly rainfall between the years: 2010, 2011, 2012 and 2016.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups (years)	2911.95	3	970.7	0.97	0.41	2.65
Within groups	204375.3	204	1001.9			

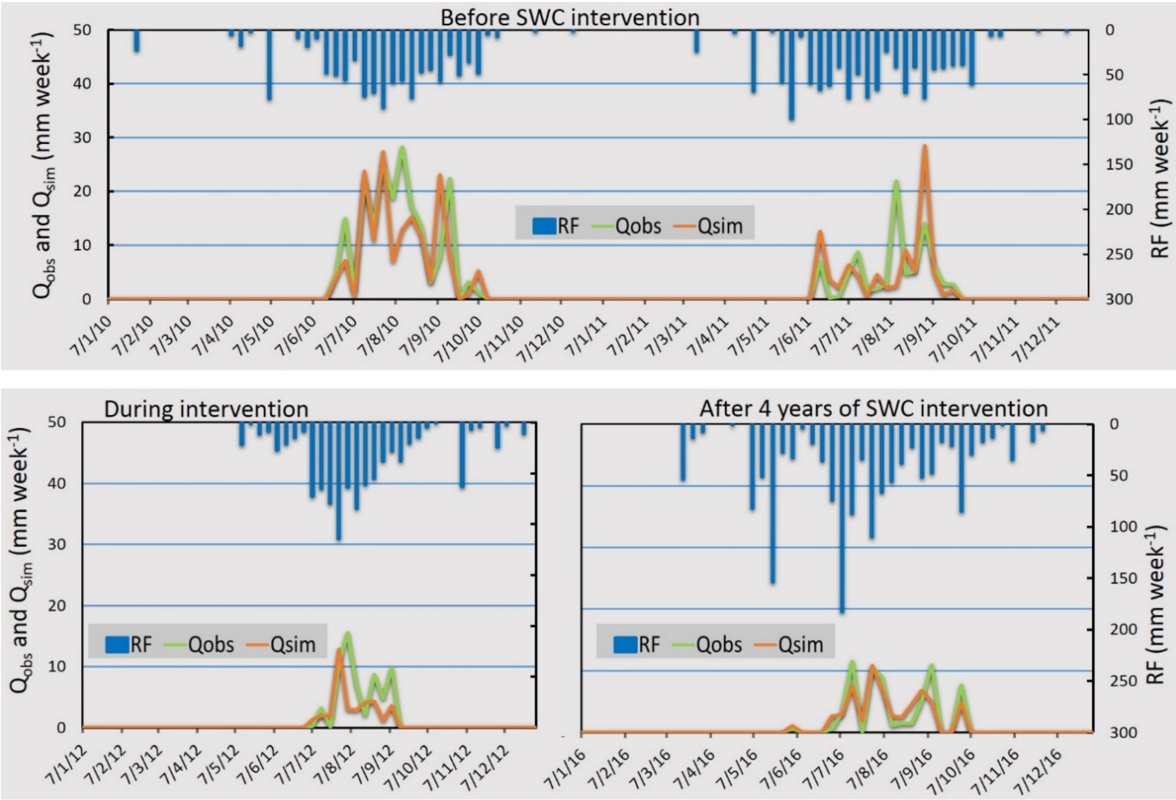


Figure 5.3: Trend of effect of SWC interventions on discharge versus time of their implementation (RF: rainfall, Qobs: observed discharge and Qsim: simulated discharge).

5.3.2 Piezometer data in the watershed

The water level observations of the piezometers are shown in Figure 5.4. Piezometers P1−P4 which are located in the eastern section in the upland (Figure 5.1) maintain a water level in the measuring period, 28 July to 27 October 2016. Since these piezometers are located in the uplands this indicates that the discharge down the hill is hindered by a barrier which is likely a volcanic dyke that occur widely in this watershed and affect the hydrology greatly. Piezometers P5−P11 located on the midslope positions contain water during the rain phase but then drain rapidly. This part of the watershed is dissected by gullies that provide ways for the groundwater to flow rapidly to the outlet of the watershed. The remaining piezometers P12−P18 are located in the valley bottom lands with the vertisols. Piezometers P12−P16 maintain a relatively constant level during August and September when the bottom lands become saturated and the level is restrained by the soil surface. Any excess rainwater flows overland to the watershed outlet. After September the water levels start to decrease with the rate dependent on the location in the watershed.

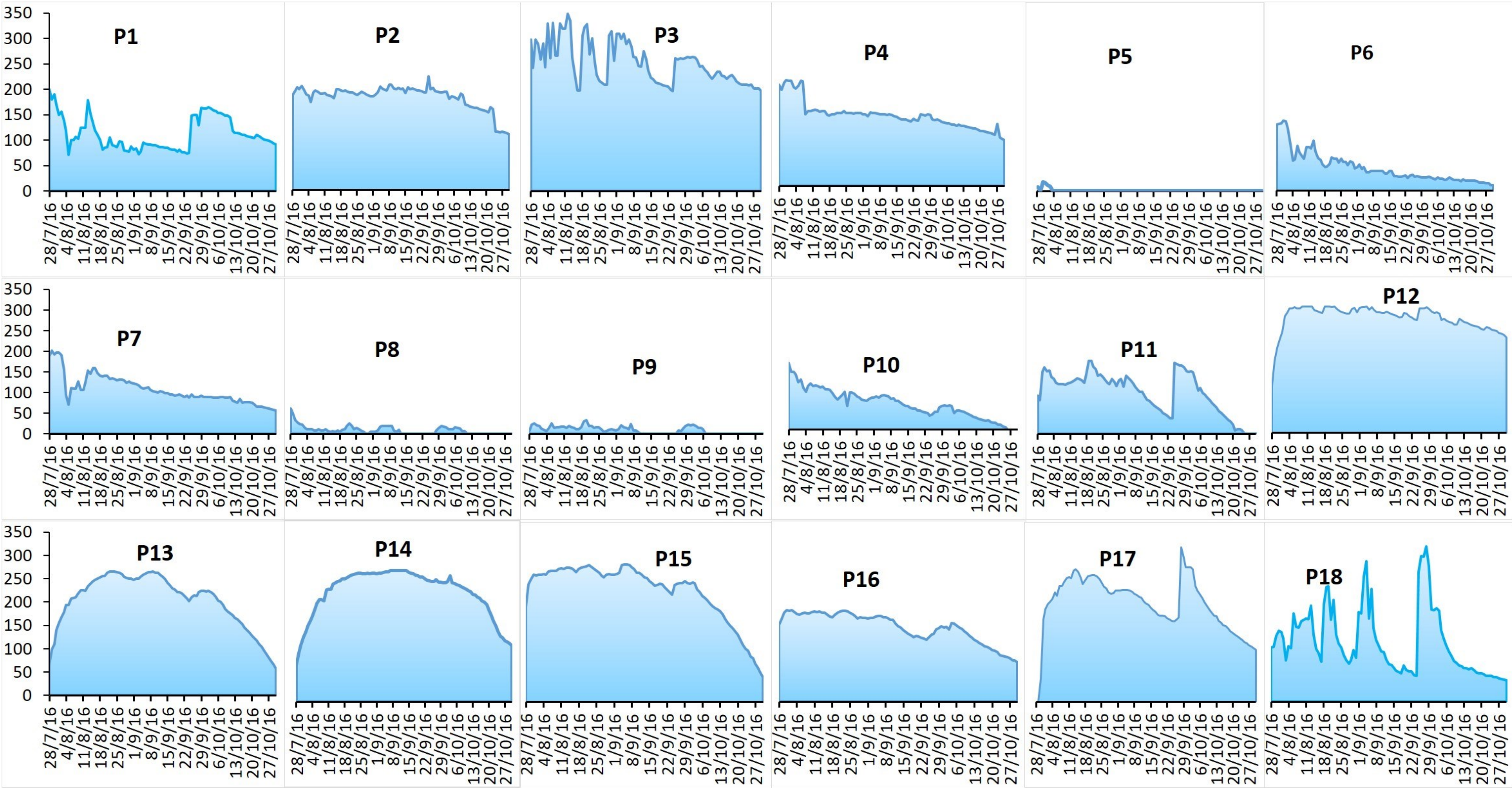
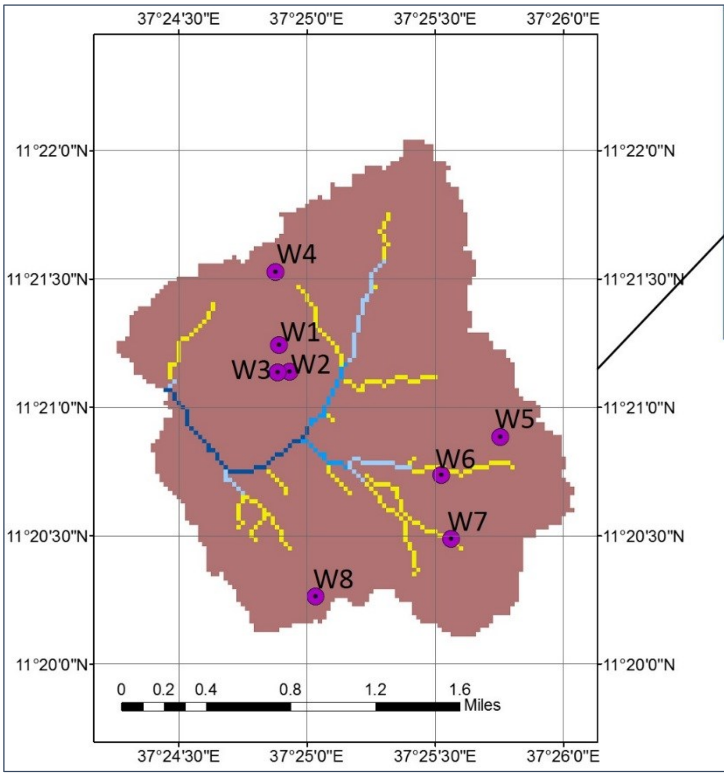


Figure 5.4: Water table height (WTH) monitored using piezometers in 2016. The labels (P1–P18) refer to the number of the piezometer as depicted in Figure 5.1 (water level in cm on the y-axis).

5.3.3 Hand dug wells data in Debre Mawi watershed

Water levels in eight hand dug wells were observed during July 2016−May 2017. Wells 1−4 were located in the eastern and north eastern part of the watershed and wells 5−8 were located in the eastern and southern part of the watershed (Figure 5.5). The latter group of wells were located near faults as could be derived from the line of Acacia trees that were in line with the well. Wells 5−7 were in the same location as piezometers P1−P4 that indicated that water levels could be maintained for a longer period after the rainy phase. The wells in Figure 5.6 show clearly that the water levels increased during the rainy phase, then decreased after the rainy phase ended and then either became dry or reached a steady level. In accordance with the piezometer measurements, water levels in wells 5 and 7 remained high during the dry season. Well 8 had also a permanent water level during the dry season but at a lower level. Wells located on the west site fell dry during the dry season with the exception of well 4 that maintained its level. In wells 4, 5, 7 and 8 the ground water table came close to the surface and water levels were relatively constant during the rainy period.



Well number	Farmer's name
W1	Amare Addis
W2	Kassa Tizazu
W3	Ayana Tizazu
W4	Getahun Demil
W5	Adane Gebeyehu
W6	Mulualem Jemberie
W7	Asimare Hailu
W8	Amisalu Mengistie

Figure 5.5: Location of hand dug wells that were observed in the rainy season in 2016 and the dry season in 2017 in the Debre Mawi watershed.

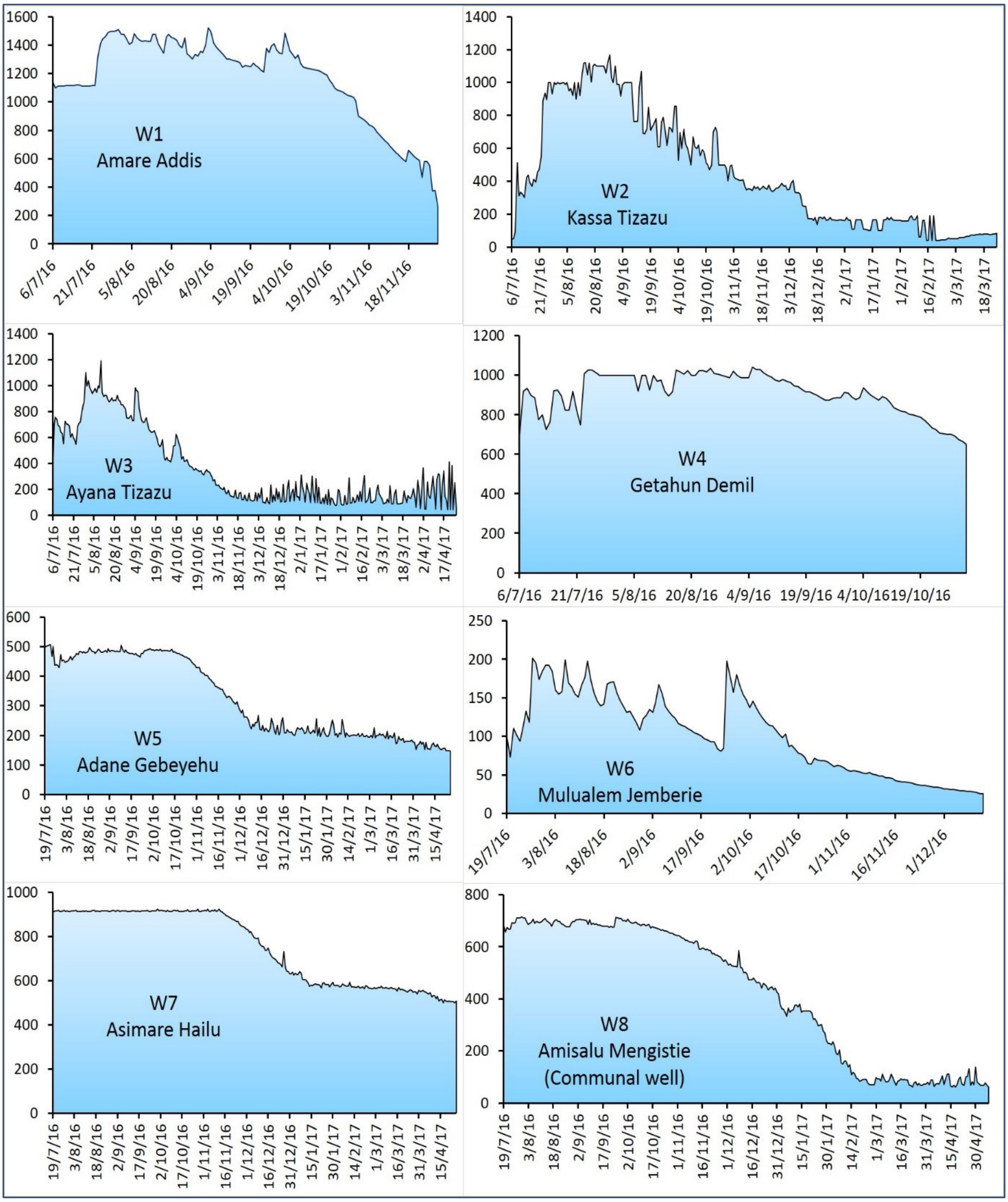


Figure 5.6: Water table height (WTH) monitored using wells in 2016 and 2017. The labels (W1–W8) refer to the number of the wells as depicted in Figure 5.5 (water level in cm on the y-axis).

5.3.4 Rooftop water harvesting

During my field experiment, which lasted for 131 days (15th of June to 23rd of October 2016), harvested rainwater and rainfall data were measured in the three villages. Comparing my observations to simulations values obtained from rainfall (Eq. 5.17), I found a very good fit. The coefficient of determination (r^2) and Nash–Sutcliffe efficiency (*NSE*) values are as high as 0.77 to 0.92 and 0.74 to 0.90 (Figure 5.7). This confirms that rooftop water harvesting is easily simulated using only two input variables: precipitation and rooftop area. I then used my simulation model to extrapolate the potential of water harvesting towards my entire study region, which contains 289 rooftops. The possible harvested rainwater from the smallest and largest rooftop catchments is 10.7 m^3 and 334.6 m^3 respectively, with a mean value of 79 m^3.

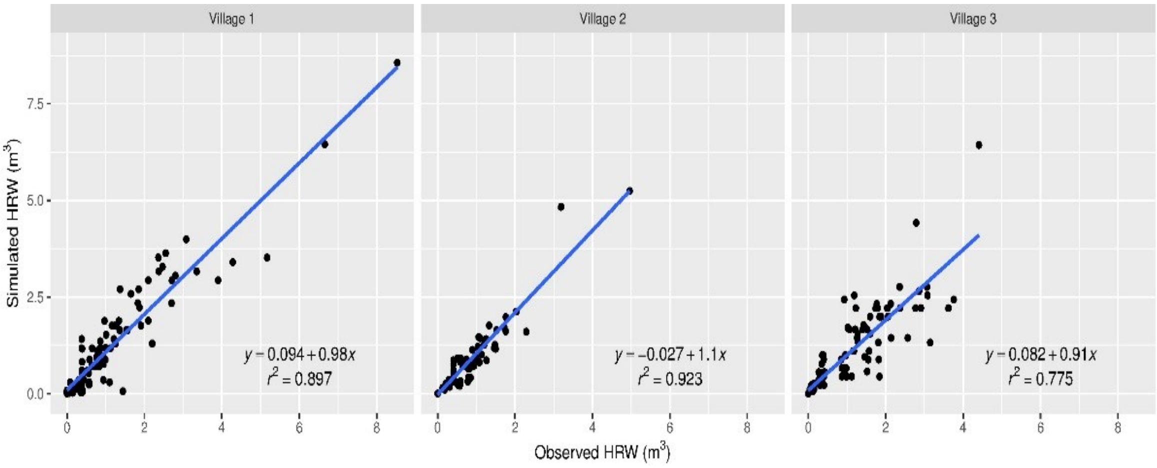


Figure 5.7: Fit between observed and simulated rooftop water harvesting (HRW) over the studied period of the rainy season (15/6/2016 to 23/10/2016).

5.4 Discussion

5.4.1 Impact of soil and water conservation practices on groundwater recharge

In the PED model concept, the part of the watershed that infiltrates rainfall instead of generating overland flow and soil loss, is referred to as the *hillside area fraction* of the watershed. During the 2012 dry season, the government in Debre Mawi tried to treat almost all degraded (i.e., overland flow and soil loss generating) watershed areas using SWC interventions through community mobilization. Within the PED concept, this is equivalent to changing degraded lands to the aforementioned *hillside area*. The local communities have suggested that these SWC practices may improve groundwater availability, which in turn counteracts their dry season water scarcity. Observations of area fractions are only available for 2016, i.e. after the intervention. Therefore, I estimated the area fractions from before the interventions by implementing the PED model for the 95 ha subcatchment using the available times series data as follows. The area fractions in the PED model were calibrated using data of the 95-ha subwatershed for respectively 2010/2011 (before intervention), 2012 (during intervention), and 2014 and 2016 (after intervention). Here, the model was calibrated for the observations of 2016. Subsequently, only the area fractions were changed to fit the discharge observations of the previous years. I found an optimal fit for the period of 2010/2011 with a hillside area fraction of 42% (i.e., before SWC intervention). The optimal fit for 2012 results in a hillside area fraction of 80% (increased by 38% during intervention), which then increased further to 97% in 2016 (Table 5.5; Figure 5.8).

It should be noted that these values are subject to model uncertainty, particularly due to over estimation of change of the hillside region of the watershed which is unrealistic in just a few years. This can only be addressed with a more rigorous calibration and testing based on in-depth on-site observations, which is further elaborated in the next section. Nevertheless, the gradual improvement is consistent with the findings of Gebreegziabher et al. (2009), who reported that SWC technologies implemented by governmental extension programmes have a long-term benefit (i.e., after 2 or 3 years). However, as noted by Guzman et al. (2017) the advantages of the soil and water conservation intervention decrease over periods longer than 6 years. These results are also consistent with field observations and my knowledge about the hydrological processes. In Debre Mawi, variation of A_1 is mainly dependent on upstream drainage source, and expansion of gully in the lower catchment which is dominated by vertisols, which are known to slide easily during wet season. In the 2012 dry season, SWC practices were implemented mainly in the upper catchment degraded croplands. In the wet season of that year, these interventions improved infiltration (increased drainage source) and increased the saturated area fraction in the bottomland. In the following years wet seasons such as during 2014 and 2016 gully expansion increased due to more drainage source to bottomland, early saturation of the bottomland soil and increased sliding of the vertisols, and caused reduction in saturated area of the watershed.

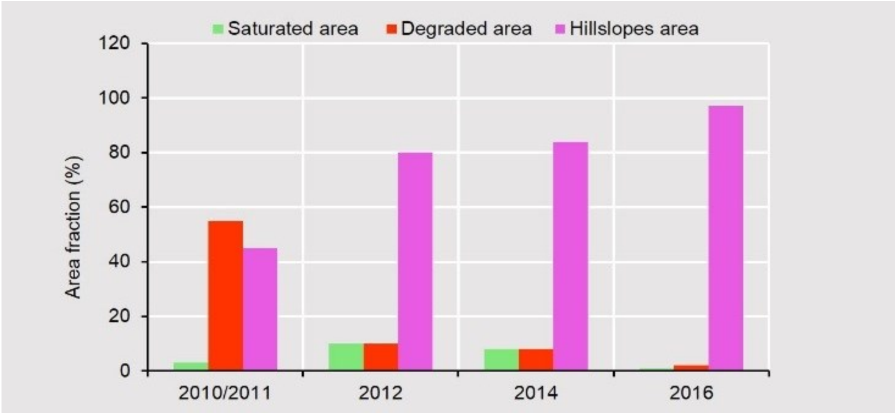


Figure 5.8: The impact of SWC interventions on the hillside area.

Table 5.5: The PED hydrology model parameter values optimized to determine the effect of SWC on hillsides area.

Model parameters		Years for analysis			
		2010/2011	**2012**	**2014**	**2016**
Area fraction (%)	A_1 *(saturated)*	3	10	8	1
	A_2 *(degraded)*	55	10	8	2
	A_3 *(hillside)*	42	80	84	97
Soil maximum storage (mm)	S_{max1}	80	80	80	80
	S_{max2}	10	10	10	10
	S_{max3}	60	60	60	60
Soil initial storage (mm)	S_{init1}	15	15	15	15
	S_{init2}	5	5	5	5
	S_{init3}	10	10	10	10
Aquifers and interflow	Bs_{max} (mm)	25	25	25	25
	BS_{init} (mm)	5	5	5	5
	Half-life, $t_{½}$ (day)	45	45	45	45
	t star, τ^* (day)	100	100	100	100
Nash–Sutcliffe efficiency, *NSE*		0.59	0.51	0.91	0.74

**The effect of SWC interventions was determined using data of 2016 for calibration of all parameters of the model and data of the other years to estimate the change in area fractions.*

5.4.2 Uncertainty of the PED model fluxes

To evaluate the PED model predication ability, an uncertainty analysis was implemented based on observations of rainfall, potential evapotranspiration and stream flow data (Figure 5.9) using MATLAB software in the following procedure. First, the model parameters such as three area fractions, soil and groundwater maximum storages (S_{max} and BS_{max}), half-life of the aquifer ($t_{1/2}$) and travel time (tau) were combined and 10 000 parameters were sampled randomly from this combination and distributed uniformly using Latin Hypercube sampling method (presented by grey region of Figure 5.10). This sampling method also presents the lower and higher boundaries of each parameters of the model. Then the flow at a 7 days' time step was simulated using the PED model. Next the model simulation efficiency was evaluated using NSE, where the black lines in Figure 5.10 represent behavioural parameter combinations (when NSE > 0.65 and the best NSE=0.82).

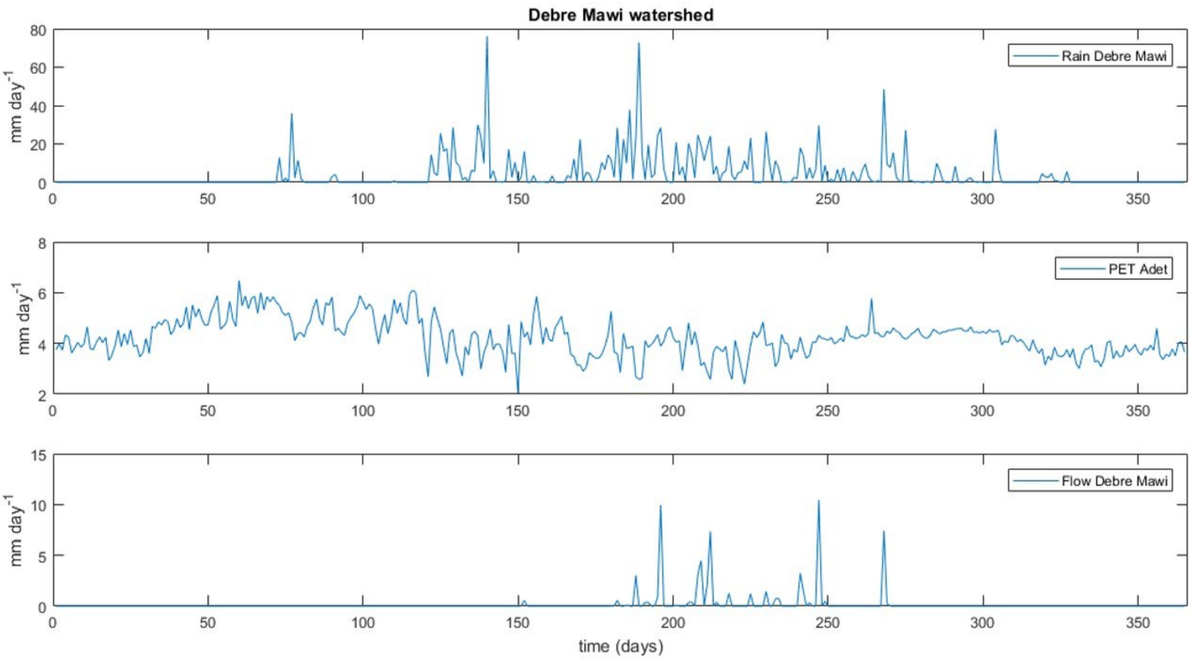


Figure 5.9: The 2016 time series precipitation, potential evapotranspiration and storm flow (discharge) data.

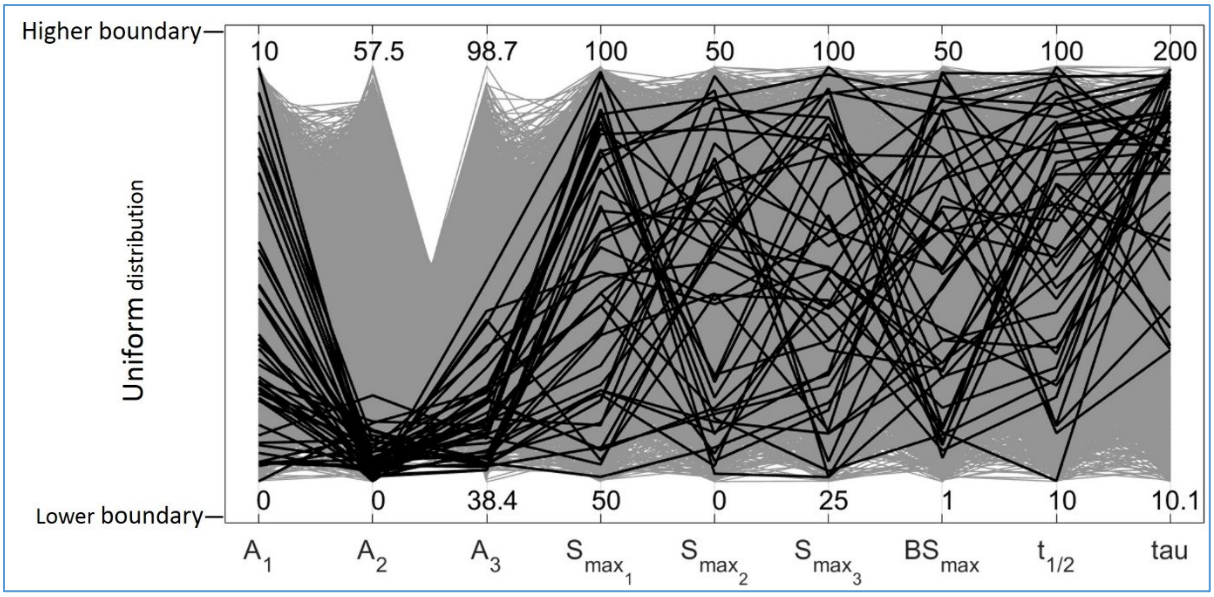


Figure 5.10: Parameter sampling and distribution using Latin Hypercube sampling method.

Subsequently, using the Generalised Likelihood Uncertainty Estimation (GLUE), the confidence intervals of discharge were calculated (Figure 5.11). Finally the uncertainty analysis in the annual water balance (budget) determined the range of the estimates from lower and upper boundaries.

The results show that surface flow (runoff) is more certain than subsurface flow (base flow and interflow) for the case of discharge. In the subsurface water fluxes, recharge was over estimated, the percolation optimum value is far from the boundaries whereas addition to groundwater is better estimated (Figure 5.12). Overall, the subsurface flow estimation is more uncertain than surface flow. Although it is the good start to counteract dry season water scarcity through groundwater availability analysis and to improve livelihood through agricultural diversification in the study area, uncertainty of the PED fluxes needs improvement through appropriate model parameters calibration. In this case, the model variables of subsurface flow analysis need further refining than the surface flow parameters, but this is beyond the scope of this thesis.

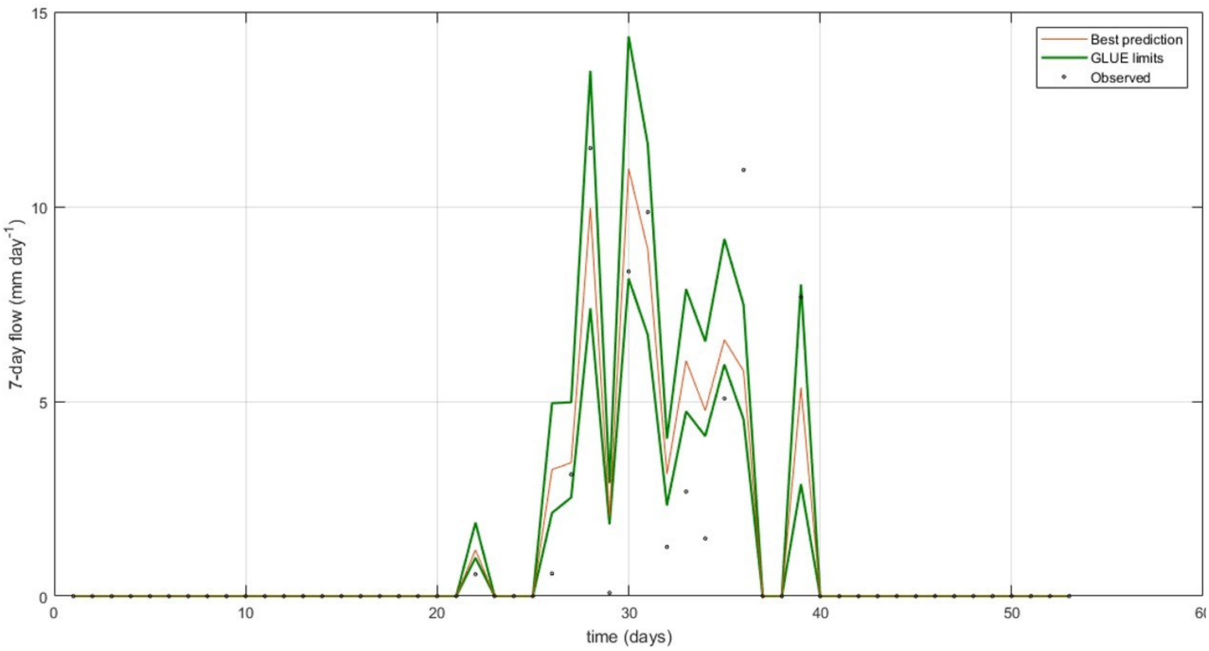


Figure 5.11: GLUE: the red line presents the best model simulation where NSE= 0.82; the lower and upper green lines are the GLUE limits which respectively are the lower and the upper boundaries.

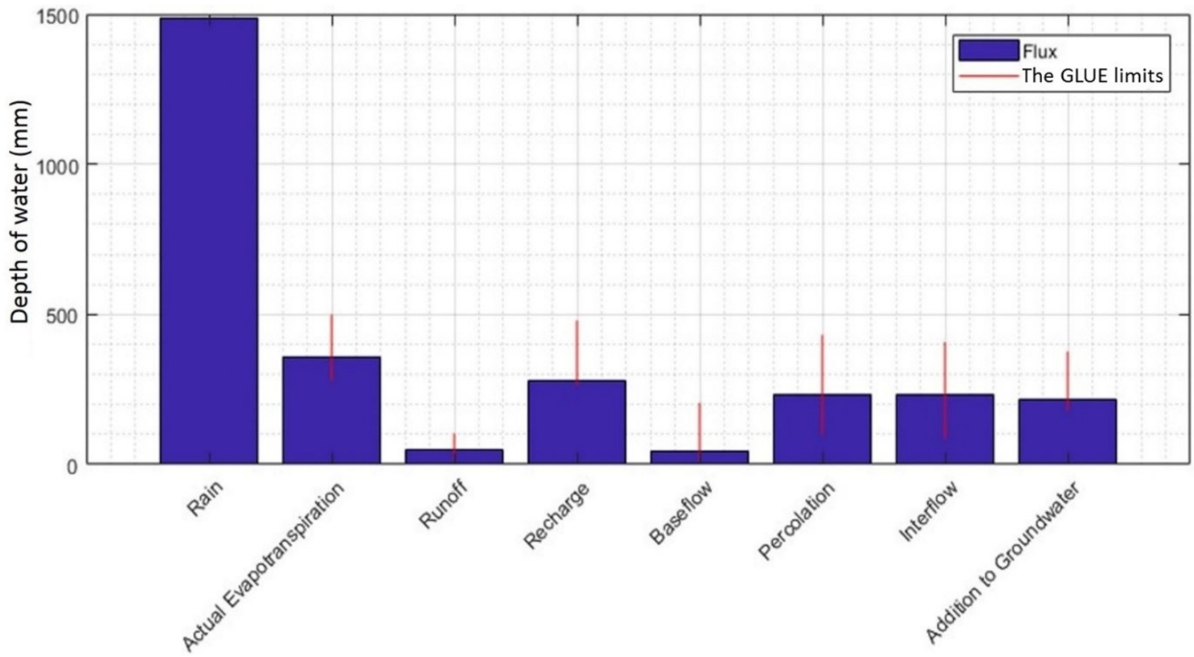


Figure 5.12: Uncertainty of the PED model fluxes in the annual water budget. The minimum and maximum values of the line shows respectively the lower and upper boundaries; and the top of bar graph indicates the optimum value.

Based on the hypothesis that hillside areas promote recharge. Because data of area fractions are not available except for 2016, I confirmed this through modelling based on field observation, during 2010 to 2015. Using a delineated hillside area from Google Earth, the total groundwater recharge from the 2016 wet season precipitation in Debre Mawi watershed is estimated at 1.4 million m^3 (Figure 5.13).

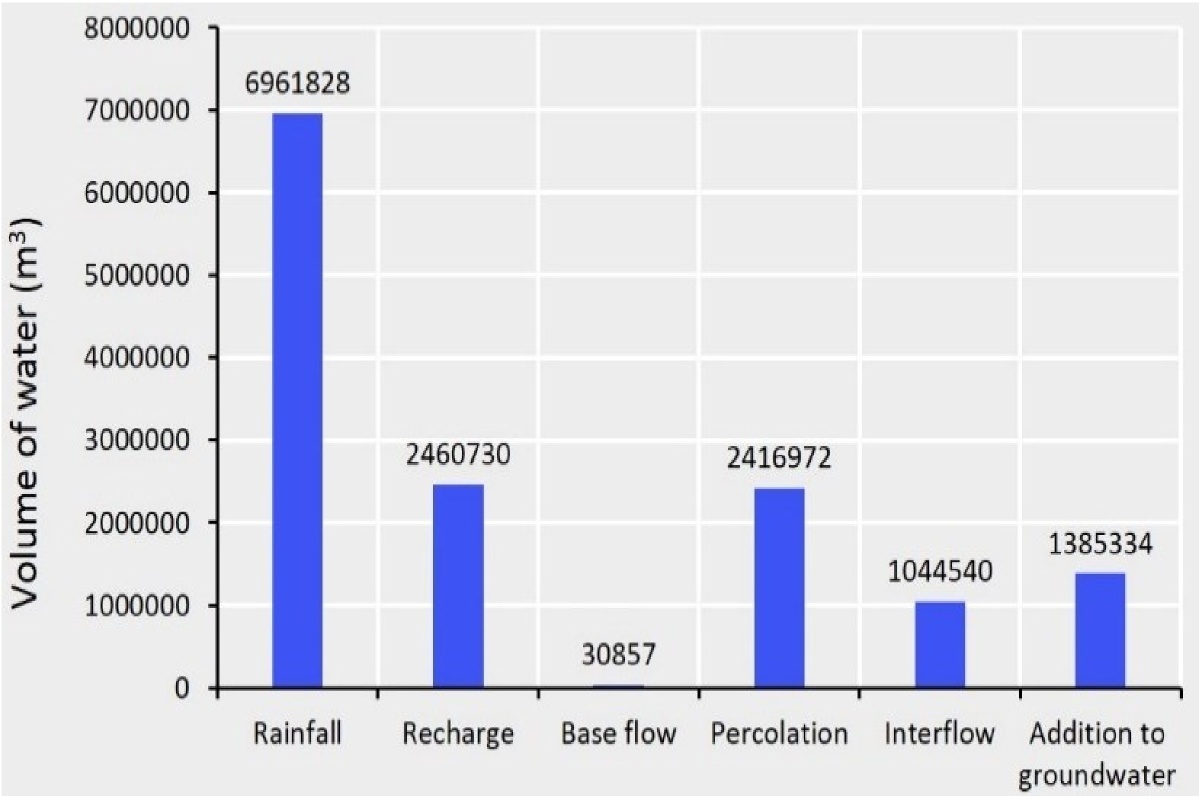


Figure 5.13: Estimated volumes for rainfall, subsurface flow and groundwater recharge in the 716 ha Debre Mawi during the 2016 wet season. The relationships between the fluxes described in Figure 5.12, where the fluxes in this figure are derived as the product of fluxes in Figure 5.12 and catchment area, were described in Eqs. 5.1–5.9; addition to the ground water is the difference between recharge and the sum of base flow and interflow.

5.4.3 Groundwater table height simulation using the PED hydrological model

The simulation of the water table heights in the hand dug wells was relatively simple. Based on the groundwater table height observations using wells, I determined first the minimum level in the well (Table 5.6). Then, I simulated the recharge with the PED model for the hillside area using a $S_{max,3}$ value of 30 mm (which is slightly smaller than for the 95-ha subwatershed). Finally, I fitted for each well the travel time, τ^*, that I used in (Eq. 5.10) to obtain the well water level with the simulated recharge values. When the calculated water table height intersected to the soil surface, I set it equal to the surface (Eq. 5.11).

The observed and predicted water height of wells are shown below in Figure 5.14. The input data, the fitted travel time values, and well depth together with the r^2 are given. In general, a good fit is obtained with R^2 values over 90% for 5 of the eight wells (Table 5.6; Figure 5.15). In the beginning of the rainy season water levels in the well were overestimated. The reason was that the model assumed that all water percolating from the root zone arrived at the groundwater. However, in the beginning of the rainy season some of this water is used to wet up the soil profile. Hence there is overestimation in the beginning. In addition, the predictions for two wells had a poor r^2 although the trend was predicted correctly. One reason can be the data of these two wells were affected by quitting of the data collector (Getahun's well) and sliding down of the top side of the well since it is not protected well by the farmer (Mulualem's well).

My observations show that there are variable and steady water table height dynamics which vary respectively rapidly and slowly in response to rainfall. These two types of groundwater behaviours were analysed further by comparing them to the model run in two modes: by considering the WTH variation as the rainfall event variability, and by keeping it relatively fixed (steady) unlike the rainfall variability. For three of the total 8 wells (Asimare, Amisalu and Adane), water table heights were simulated very well using the steady groundwater behaviour version of the model; on the other hand, the variable water table heights of wells were simulated very well using the variable groundwater behaviour model.

Table 5.6: Summary of hand dug well simulations. t-star values were obtained such that observed and predicted values agreed best. Regression coefficient and slope are obtained by regressing observed vs predicted values.

	Owner	well depth, m	t-star, days	regression coefficient	slope
1	Amare Addis	15.7	110	0.84	1.00
2	Kassa Tizazu	11.0	75	0.94	1.00
3	Ayana Tizazu	11.7	55	0.91	0.96
4	Getahun Demil	10.5	47	0.29	1.02
5	Adane Gebeyehu	5.0	75	0.97	1.01
6	Mulualem Jemberie	2.3	16	0.46	1.17
7	Asimare Hailu	9.2	103	0.96	1.02
8	Amisalu Mengistie	7.1	130	0.94	1.00

For four of the total 8 wells (Getahun, Asimare, Amisalu and Adane), water table heights were restrained by the soil surface, while for the four remaining wells water was not affected by the soil surface.

Based on these simulations of water levels in wells, I divided the wells in two groups that I used in my further analysis for determining the spatial variability of water tables in the entire Debre Mawi watershed using the EWSAT procedure. One group that is mainly located in the degraded regions, where the water tables vary rapidly and are not intersecting the surface, and another group where the water tables are relatively constant because the water is forced to surface by volcanic dykes. Thus, the volcanic dykes determine whether water is available during the dry season.

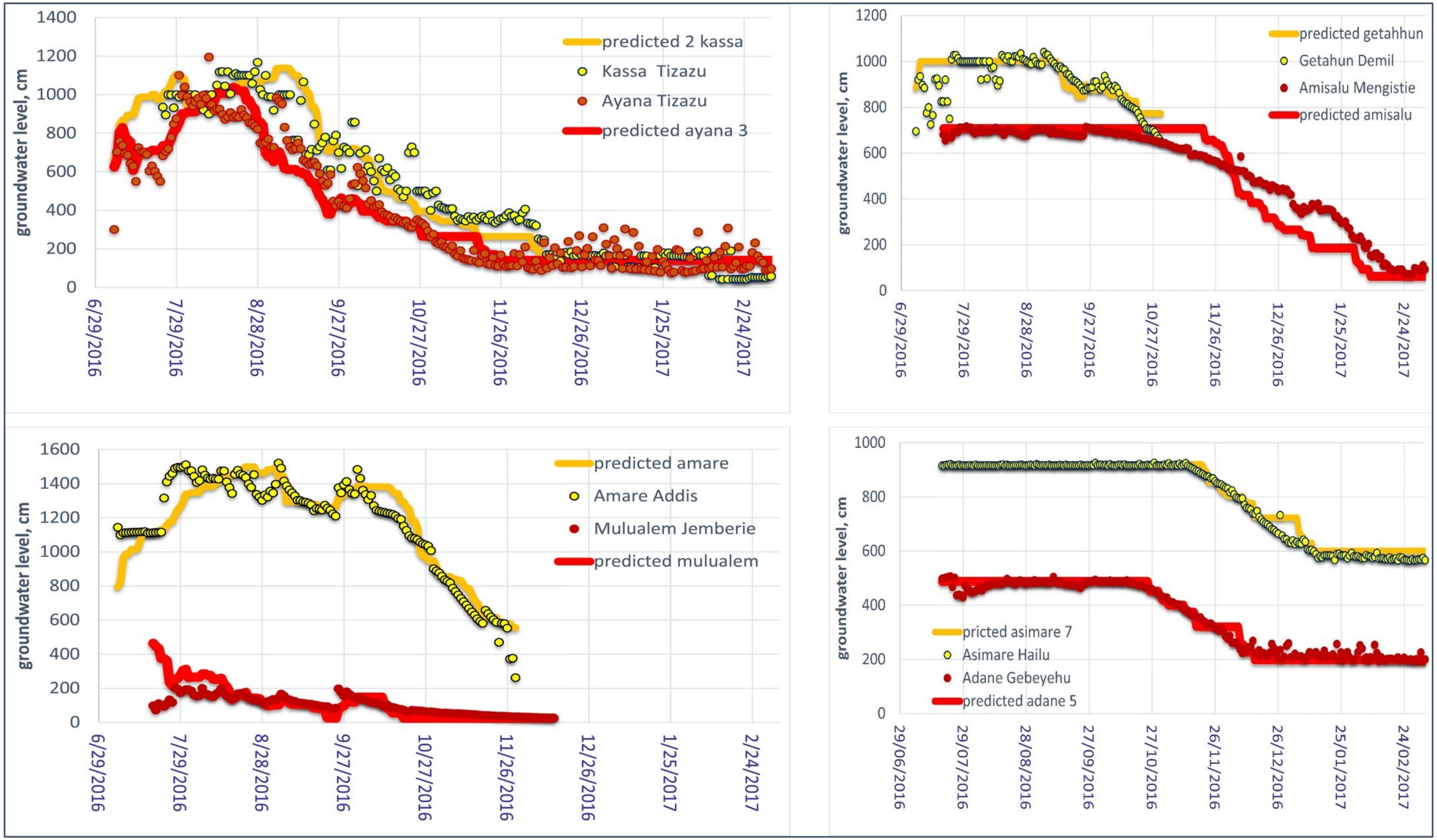


Figure 5.14: Observed and predicted water table heights of the 8 monitored wells.

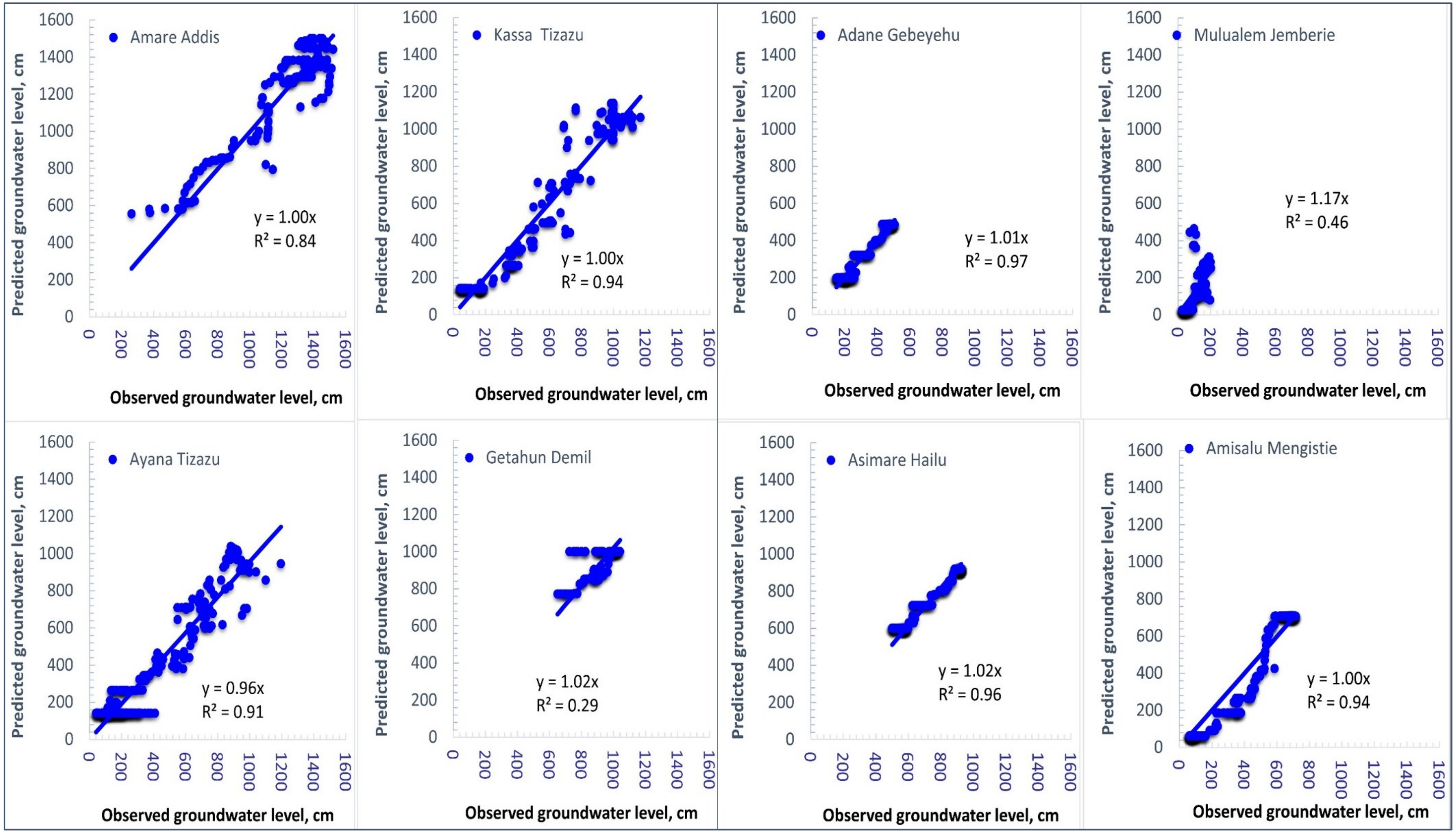


Figure 5.15: Correlation between observed and simulated water table heights.

5.4.4 Simulating distributed groundwater table heights using the EWSAT hydrological model

In order to identify potential locations for groundwater wells, it is necessary to create a spatial map of the depth and yield of groundwater. The previous section showed that the conceptual PED model is able to simulate the groundwater depths adequately. However, being a lumped model, PED does not allow explicit spatial mapping of the groundwater table height. To overcome this issue, I implemented a spatial extrapolation of the results of PED. For this, I simulated first the monthly water table heights (WTHs) for the year 2016 at a monthly time step. Then I calculated monthly WTHs at pixel level by combining the WTH values obtained from the PED model with ArcGIS spatial analyst tools. The current hillside area fraction of the full 716 ha catchment of Debre Mawi, which was delineated from Google Earth and field observation, is 65.4% (Figure 5.16).

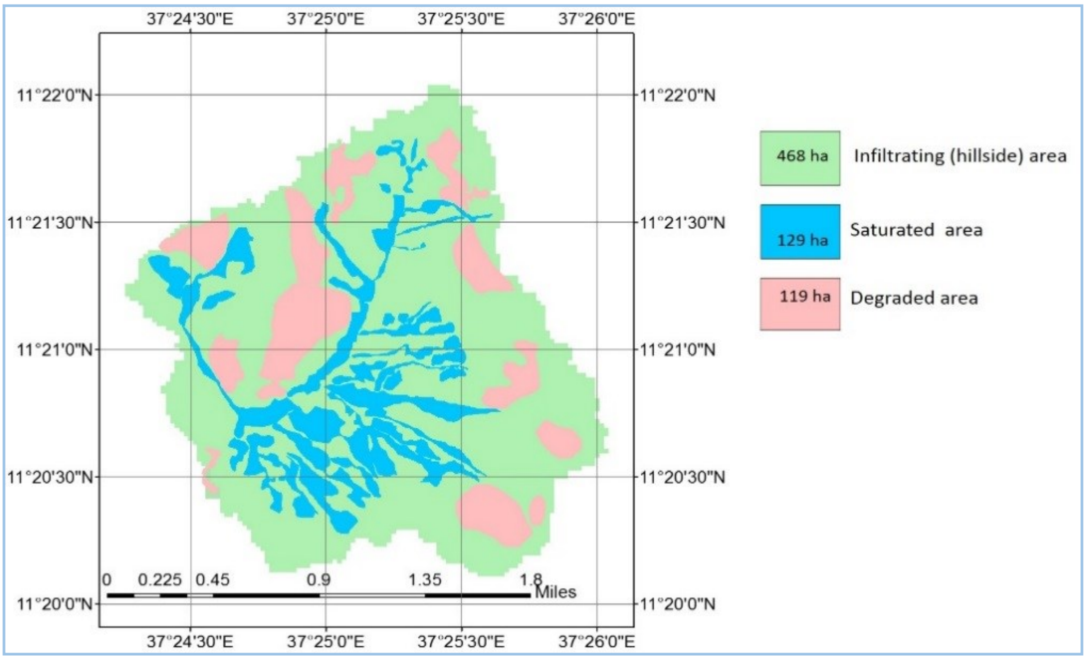


Figure 5.16: The three area fractions of the 716 ha Debre Mawi watershed in 2016.

Based on this combined PED-ArcGIS groundwater level analysis, I delineated the regions within the Debre Mawi watershed, for which WTH is predicted as reaching the surface and constant during the rainy season and variable over time during the rainy season. The constant head wells are associated with lava dykes and perennial therefore. The wells of Adane's, Asimare's and Amisalu's, which give the best fit to model simulation (r^2: 0.97, 0.96 and 0.94

resp, Table 5.6.), and piezometers (P_2 and P_{12} which relatively indicate less temporal WTH variability) are good examples of perennial wells (Figure 5.4). Contrastingly, the three wells of Amare's, Kassa's and Ayana's are examples of degraded areas that do not have groundwater potential during the dry season.

In the figure below I present the water tables of the two group of wells between the PED model and the EWSAT procedure. It can be observed that the trends are the same. The perennial wells have water throughout the year while the remaining wells (called "variable") have water only during the rainy period and the beginning of the dry period (Figure 5.17).

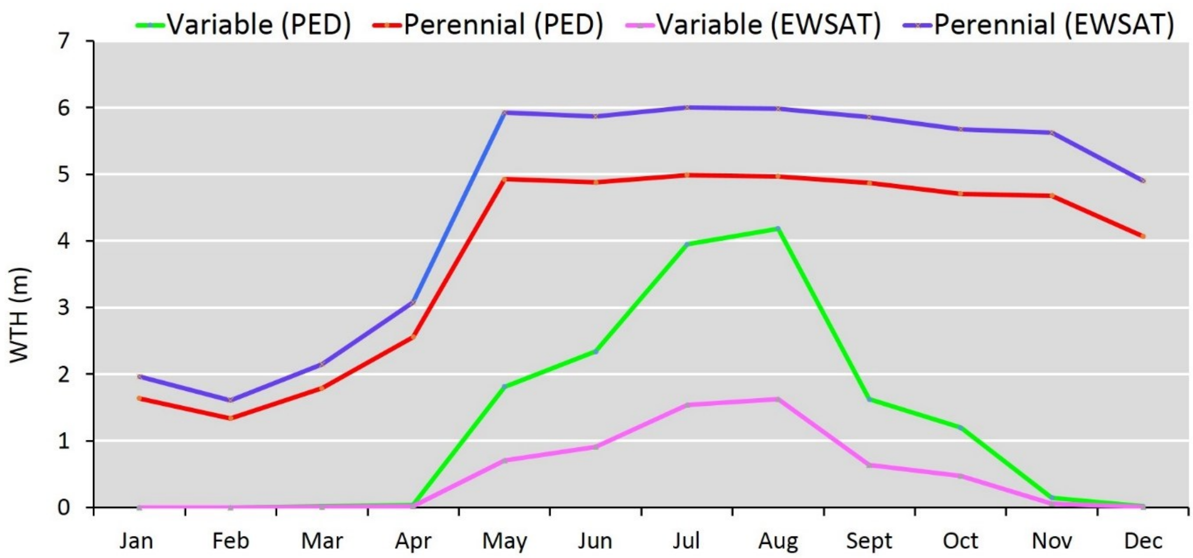


Figure 5.17: Trend in mean monthly spatial and temporal groundwater table height in the Debre Mawi watershed as simulated using the combination of PED and GIS tools.

PED was tested using lumped observed data and simulated regional water table heights of the variable and perennial wells. Because of the distributed nature of the EWSAT model, water table heights were calculated for each pixel. For this, I considered the PED output as observation to determine the reliable values of EWSAT. For both types of groundwater behaviours, EWSAT predicts water table height values well because the lower and upper bounds of EWSAT were found to bracket the values for PED (Figure 5.18).

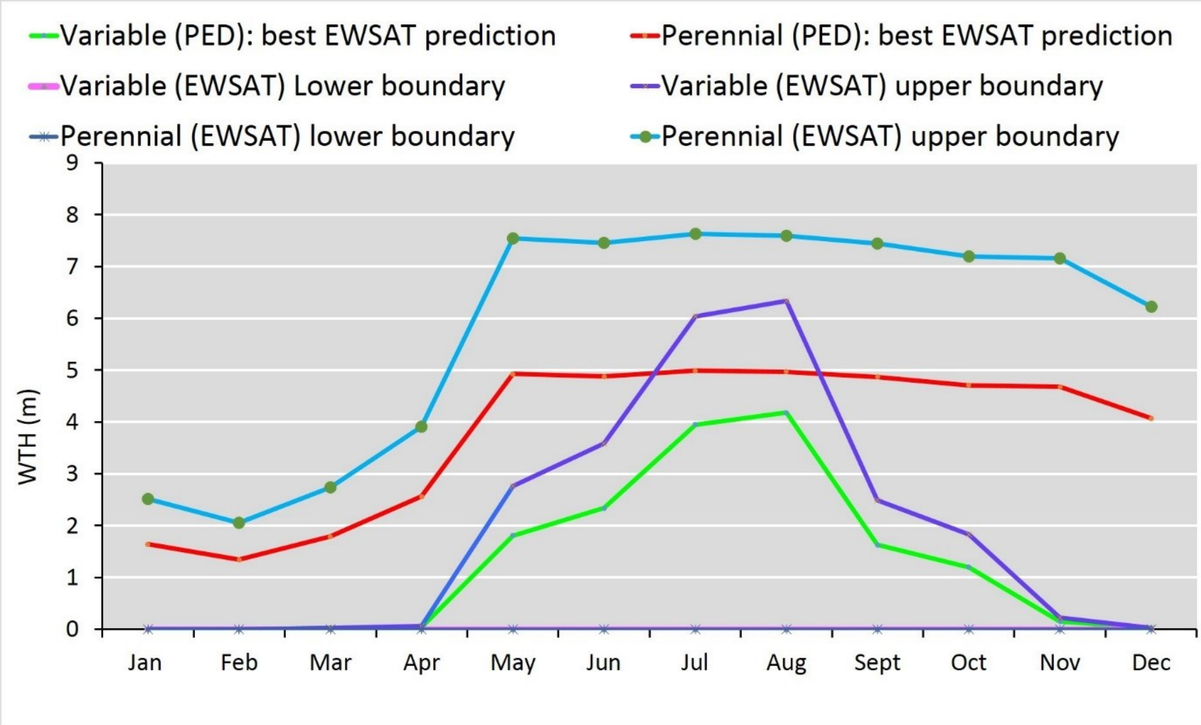


Figure 5.18: EWSAT prediction ability tested with the PED simulation WTH values.

Based on the EWSAT procedure, I developed the spatial-temporal distribution of water table heights for the entire Debre Mawi watershed. Figure 5.19 shows that groundwater is only accessible in areas with presence of a lava dyke surrounded faults (yellow to blue colours). The remainder of the catchment (indicated in red) does not show groundwater potential.

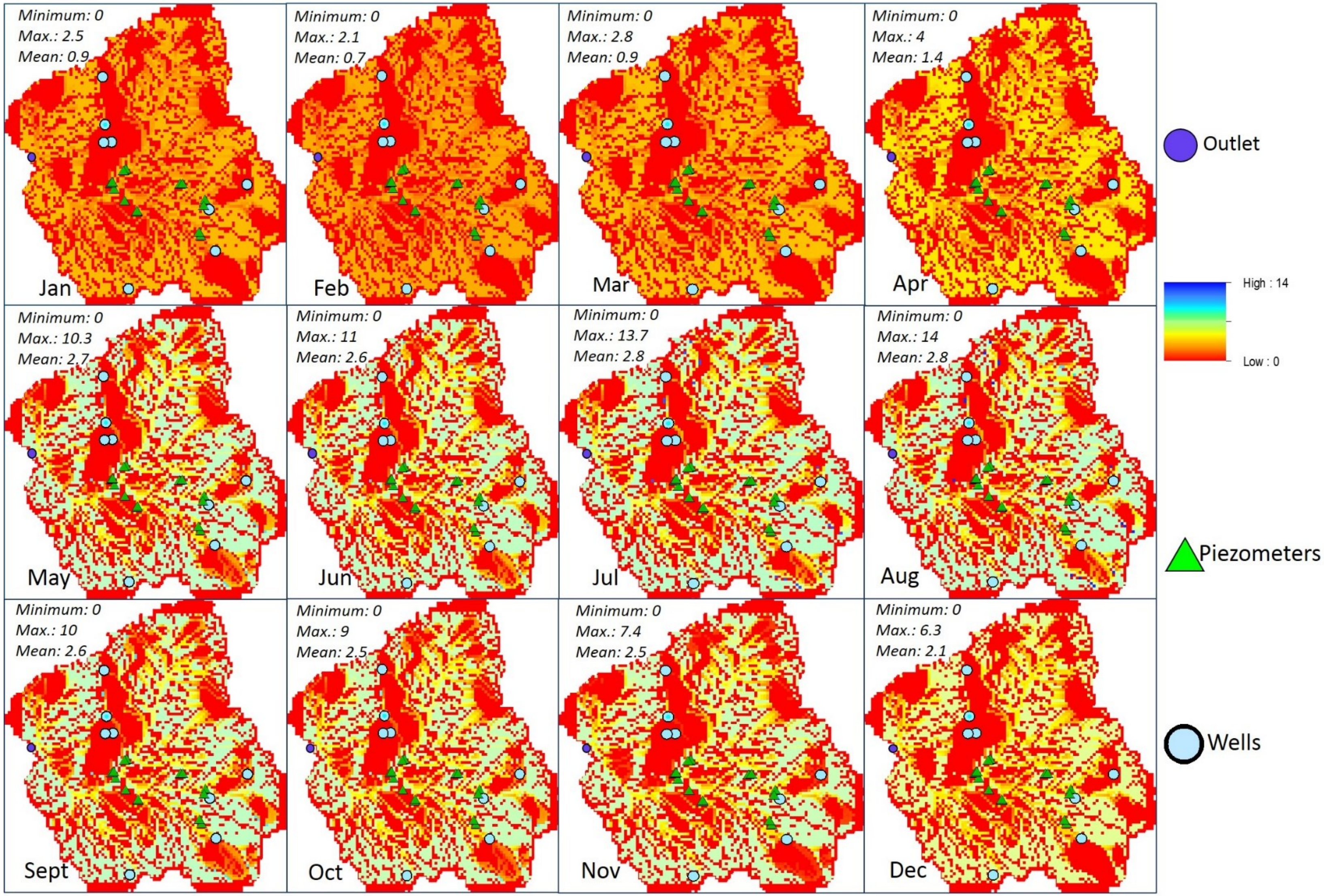


Figure 5.19: Maps of the average water table height for each month of 2016 at the 716 ha Debre Mawi watershed.

Therefore, villagers living in degraded areas cannot rely on groundwater wells for dry season water availability, and therefore need to look for alternative water sources, such as building rooftop water harvesting infrastructure. Contrastingly, installing groundwater pumping wells is the best option for hillside and lower catchment residents because it does not require building infrastructure for water harvesting and storage. For this, potential locations (i.e., faults surrounded by rocks) should be identified using geological indicators. Field observations suggest that trees such as acacia are a useful indicator of groundwater availability. It is better to install wells at these faults because lateral water flow can be blocked, which means that the wet season recharge that moves as interflow can be conserved instead of draining out the catchment as subsurface flow. As confirmed by farmer views obtained during field observation through the participatory transect walk and experiment, big trees especially Acacia are growing at natural faults surrounded by barriers (dykes) in Debre Mawi. Such locations keep green during dry season due to groundwater availability throughout the year. This was further confirmed by the experimental wells (Asimare's, W7 and Amisalu's, W8) and piezometer 2 which were installed in the line of Acacia trees and maintain water table heights longer (Figure 5.2 and 5.4). Hence to block the later water flow that is moving out the watershed as subsurface flow for dry period use, groundwater pumping wells should be installed at these faults. When the groundwater is pumped out from these wells, more lateral flow will drain in to these wells instead of pass over to the outlet.

The possible monthly groundwater amount that the lower catchment farmers can access from steady wells is estimated in Table 5.7. However to avoid groundwater depletion, the field capacity of the wells should be studied. If groundwater wells are overpumped, recharging may not make up for the water that is taken, eventually causing wells to dry and salt to build-up in the soil (Casanova et al., 2016). In the hillsides, groundwater levels tend to be very deep, which makes it difficult to install water abstraction wells. Therefore rooftop water harvesting is also the better option in these locations.

Table 5.7: The mean monthly groundwater volume that the lower catchment farmers can access from perennial wells during 2016 at Debre Mawi. As described in section 5.2.4.3 (Eq. 5.16) the monthly volumetric groundwater (*V*, m^3) was calculated as the product of the well cross-sectional area (πR^2) and the well depth (h, m).

Month	Water volume (m^3)	Month	Water volume (m^3)
Jan	2.90	Jul	8.81
Feb	2.37	Aug	8.78
Mar	3.16	Sept	8.60
Apr	4.52	Oct	8.32
May	8.71	Nov	8.27
Jun	8.62	Dec	7.19

5.4.5 Scenarios for livelihood improvement

Based on my estimations of water availability, four livelihood improvement scenarios were compared in the upper catchment:

1. harvested rainwater supported irrigation of potato;
2. harvested rainwater supported irrigation of pepper;
3. harvested rainwater supported sheep production;
4. harvested rainwater supported beef production.

In the lower catchment, the farmers have two water sources options, i.e., rooftop water harvesting and groundwater abstraction wells; therefore, twelve scenarios were compared in this lower region of the watershed to select best option from the following possible water source to improved livelihood strategies link: (1) rooftop water harvesting supported potato and pepper irrigation, and sheep and beef fattening, (2) groundwater, supplying the same crop area and animal number which can be supplemented by rooftop water harvesting and (3) using groundwater at its full potential, maximising crop area and animal numbers.

In the Debre Mawi catchment, as the existing situation (food self-insufficiency) the farmers want to cultivate potato and pepper for subsistence needs even though these are also cash crops (Amede and Delve, 2008), and sheep and beef fattening for income generation (Bezabih et al., 2016; Amistu et al., 2016) during the dry season. Sheep and beef need to be fattened for 4–5 months respectively to achieve a good market price (Animut and Wamatu, 2014; Wolde et al., 2014). To capture a higher market premium available during the Ethiopian Easter, farmers usually have to start fattening sheep in January and beef in December to sell in May for Easter holiday. The CROPWAT outputs show that the potato and pepper irrigation water requirements are respectively 0.44 and 0.41 m^3 m^{-2} over the growing season. The daily livestock water requirement was found from the literature; as presented in Table 4.9, the average water consumption of beef and sheep is respectively 40 and 10 l per animal per day (Ward and McKague, 2007; Sileshi et al., 2003; Birhan and Manaye, 2013).

The groundwater and HRW can be used for irrigation and animal fattening only after the domestic needs are met. Farmers are using communal hand dug wells for domestic use (human and their animals' consumption), even though these wells supply only 20% of the household water requirement. Indeed, I estimate that farmers need 48.06 m^3 more water per household on average for their domestic use in the dry season. As a result, the net HRW which can be used for fattening and/or irrigation is 10.7, 31.1 and 227.5 m^3, (resp. min, mean and max, depending on the roof area), while possible groundwater amount for fattening and/or irrigation that varies as the domestic water use need per household is respectively 870, 822 and 763 m^3 for min, mean and max family member and asset possessing farmers. Households with a large number of family member and number of animals, will use much water for their domestic use, and will therefore have less net water for fattening and/or irrigation, for example 763 m^3 in this analysis (Table 5.8). On average, the net HRW helps farmers irrigate 70.8 m^2 potato plots and 76 m^2 hot pepper plots, and to fatten 26 sheep and 5 beef; using groundwater, they can irrigate 1868 m^2 potato plots and 2005 m^2 hot pepper plots, and fatten 685 sheep and 137 beef on average (Table 5.9).

For this irrigation practice, farmers do not have the costs of purchasing fertilizer since they will grow in their homesteads where they use manure and house waste. They will also use family labour which is cost free. To fatten animals during this dry season, farmers can also use family labour and feed farm by-products such as crop residue, straw, hay, crop bran and by-products of local breweries (Berhanu et al., 2009; Animut and Wamatu, 2014; Halala, 2015). Brewery by-products can be collected for free or purchased cheaply, particularly from the female headed poor farmer families, who make local alcohols such as *areki* and *tella* to increase their income. For the installation and pumping of groundwater abstraction wells the farmers in Debre Mawi are also using family labour. They are lifting water from the wells using local materials as described in Figure 5.2 in well 4 (W4) and manual labour. As a result, there is no need of purchasing special equipment for water pumping.

To the upper catchment villagers, the benefit-cost analysis (Chanie, 2014) proves that meat production is more profitable than crop irrigation as the benefit to cost ratio (BCR) is > 1 in all rooftop sizes to fattening relations. The farmers with least amount of asset can be most profitable in 5 months of beef fattening and get US$ 135.5 during this period. The second profitable option for these group of farmers is 4 months' sheep fattening. Farmers who have the average number of family members and animals at the watershed level can be most profitable by fattening 5 heads of beef cattle; with sheep fattening as a second option. The farmers with the maximum number of family members and animals can generate the highest profit by sheep fatting, followed by beef fattening, and thirdly potato production by irrigation. Whereas to the lower catchment inhabitants, the third option (using groundwater to its full potential) for livelihood improvement is a profitable scenario for all community groups (i.e., for minimum, mean and maximum asset or animal, and family member possessing farmers) except in the case of beef fattening for farmers that have the maximum amount of assets. For these farmers, BCR of options 2 and 3 are similar. Option two is the best option for them, because there is no additional benefit from increased number of animals. From the livelihood options, crop irrigation is more profitable than animal fattening for lower catchment farmers. In the optimal, idealized conditions of my study, all farmers in lower catchment can generate a benefit of more than 6 fold of their cost (Table 5.10) in potatoes and peppers irrigation.

My research explores the development of livelihood strategies for water resources management that challenge poverty lock-in and are aware of the social-ecological context. The example elaborated here shows how local knowledge and local resources can be incorporated during the subsequent stages of problem identification, solution finding, and impact analysis of the new strategies on livelihood. However, I found that existing tools available for catchment scale water resources analysis are useful with little modification. In particular, although the lumped PED model is straightforward to manipulate and has been widely applied in the study region, it simulates fluxes indirectly. I further refined the tool with the EWSAT post-processing algorithm, to identify locations for groundwater availability and abstraction. The cost-benefit analysis was also done using one year data. To minimise uncertainty that may come with the PED model and one year data analysis, I highlight further rigorous tool development and continuous monitoring of these new strategies. This is particularly useful to check their profitability in terms of cost-benefit analysis, and the products demand availability in places such as Debre Mawi, and in similar worldwide regions, even for other bottom–up livelihood strategies.

Table 5.8: Dry period (December–May) household water demand and sources relationship for domestic use.

Water sources/consumers	Minimum	Maximum	Mean	Daily per capita water requirement, *dwr* (m^3)
Hand dug wells, WA_{ews} (m^3)	5.4	18.9	12.24	
Consumers				
Family member (No)	2	8	5	0.005
Cattle (No)	0	10	6	0.04
Sheep (No)	0	10	3	0.01
Donkey (No)	0	4	1	0.04
HRW_{du} (m^3)	0	107.1	48.06	
Harvested rain water, HRW (m^3 $year^{-1}$)	10.7	334.6	79.2	
Possible groundwater amount per well (m^3)	870	870	870	
Net harvested water for pathways, *NHRW* (m^3)	10.7	227.5	31.14	
Possible groundwater amount per well for pathways (m^3)	870	763	822	

Table 5.9: Crop area and animal number that can be supported by harvested rainwater and groundwater use.

Pathways out of poverty	Crop/ Animal type	Dry period water demand per unit crop or animal (m^3)	Number of animals or crop area that NHRW can supply			Number of animals or crop area that GW can supply		
			10.7 m^3	31.14 m^3	227.5 m^3	870 m^3	822 m^3	763 m^3
Crop	Potato (area)	0.44	24.3 m^2	70.8 m^2	517 m^2	1977 m^2	1868 m^2	1734 m^2
	Hot pepper (area)	0.41	26.1 m^2	76 m^2	555 m^2	2122 m^2	2005 m^2	1861 m^2
Fattening	Sheep (No.)	1.2	8	26	189	725	685	635
	Beef (No.)	6	1	5	37	145	137	127

**NHRW*: net harvested rain water; *GW*: groundwater

Table 5.10: Benefit-cost ratio (BCR) analysis of livelihood scenarios in the study area (potato and hot pepper irrigation, and beef and sheep fattening). BCR is the ratio of return to the input and management costs of individual livelihood option; if BCR is < 1 then the scenario is not profitable and has to be rejected.

Rooftop water harvesting supply	***Potato irrigation***			***Hot Pepper irrigation***			***Sheep fattening***			***Beef fattening***		
Water amount (m^3)	11	31	228	11	31	228	11	31	228	11	31	228
Crop area/animal No.	24	71	517	26	76	555	8	26	189	1	5	37
Gross return (Birr)	809	2358	17216	397	1155	8436	12000	39000	283500	15000	75000	555000
Total cost (Birr)	6505	7261	16040	6440	7060	14460	10430	20040	108930	11930	34540	217930
BCR	***0.1***	***0.3***	***1.1***	***0.1***	***0.2***	***0.6***	***1.2***	***1.9***	***2.6***	***1.3***	***2.2***	***2.5***
Net return (Birr)	-	-	1176	-	-	-	1570	18960	174570	3070	40460	337070
Groundwater supplying a similar crop area and animal number as HRW	***Potato irrigation***			***Hot Pepper irrigation***			***Sheep fattening***			***Beef fattening***		
Water amount (m^3)	870	822	763	870	822	763	870	822	763	870	822	763
Crop area/animal No.	24	71	517	26	76	555.0	8	26	189	1	5	37
Gross return (Birr)	809.2	2357.6	17216.1	396.7	1155.2	8436	12000	39000	283500	15000	75000	555000
Total cost (Birr)	3075	3221	4610	3010	3020	3030	7000	16000	97500	8500	30500	206500
BCR	***0.3***	***0.7***	***3.7***	***0.1***	***0.4***	***2.8***	***1.7***	***2.4***	***2.9***	***1.8***	***2.5***	***2.7***
Net return (Birr)	-	-	12606	-	-	5406	5000	23000	186000	6500	44500	348500

Groundwater supply as its potential	***Potato irrigation***			***Hot Pepper irrigation***			***Sheep fattening***			***Beef fattening***		
Water amount (m^3)	870	822	763	870	822	763	870	822	763	870	822	763
Crop area in m^2/animal No.	1977	1868	1734	2122	2005	1861	725	685	636	145	137	127
Gross return (Birr)	65843	62210	57745	32254	30474	28287	1087500	1027500	953750	2175000	2055000	1907500
Total cost (Birr)	9103	8766	8352	3813	3768	3713	365500	345500	320917	800500	756500	702417
BCR	***7.2***	***7.1***	***6.9***	***8.5***	***8.1***	***7.6***	***3.0***	***3.0***	***3.0***	***2.7***	***2.7***	***2.7***
Net return (Birr)	56740	53444	49393	28441	26706	24574	722000	682000	632833	1374500	1298500	1205083

5.5 Conclusions

I explored the integration of hydrological models, GIS tools and experimental data to identify the optimal livelihood strategies with regard to water use for local communities in the Ethiopian highlands. In particular, I aimed to identify the catchment−scale potential of both groundwater abstraction and water harvesting, to optimize water supply during the dry season for domestic use and agricultural diversification flows. For this, I implemented first an analysis of observed groundwater heights using the PED hydrological model, which enabled me to prove that SWC technologies are enhancing groundwater recharge. Next, I combined water table height simulation techniques derived from the PED model, with GIS tools and experimental data to quantify the maximum possible supply of groundwater at the watershed level. For 2016, I found an amount of 1.4 million m^3. This setup also enabled me to show that interflow is leaving the watershed via subsurface flow, and that the WTH in degraded, and saturated and hillside areas respectively varies rapidly and slowly in response to rainfall events. The WTH at degraded areas approaches zero during dry season. This is unlikely at the other two watershed regions where dykes and faults are common. These subsurface structures enhance groundwater availability to the entire year, with some reductions during dry season even. However, groundwater aquifers in hillsides are very deep which complicates the installation of water pumps. Next, I developed a parsimonious method for spatio-temporal mapping of groundwater variability, which allowed me to identify regions where lateral water flow blocking occurs, which is mostly in the lower part of the catchment. Therefore, the lower catchment villagers can access groundwater during the dry phase. In addition, they can also harvest rainwater using their rooftops. For the villagers that live in the upper catchment and are located far from the groundwater potential sites, water harvesting is the only water supply option during the dry season.

Lastly, I explored the economic benefits of making better use of groundwater and rooftop water harvesting, using a cost-benefit analysis of 4 economic scenarios: potato irrigation, pepper irrigation, sheep production and beef production. Cattle and sheep production are respectively the first and second livelihood improving options using rooftop water harvesting for the upper catchment farmers. For the lower catchment community members, these two crops irrigation using groundwater are best options.

Overall, the approach and findings I explored in this chapter help to understand how to support local ESS management to maximize poverty alleviation in the Ethiopian and other tropical highlands, where the majority of the population consists of subsistence farmers and depends on local ESS. However, to ensure the sustainability of these pathways, the analysis presented here should be complemented with the water quality analysis and geological characterization of the catchments. The latter is particularly important to find natural faults for the installation of groundwater wells. Although I did not discuss the results with farmers because of time limitations, it is to be expected that the acceptance rate is high because the demand of these strategies was determined in a bottom-up and participatory way.

Chapter 6

A distributed catchment–scale evaluation of the potential of soil and water conservation interventions to reduce storm flow and soil loss

Abstract

Finding effective ecosystem services (ESS) management practices to counteract land degradation and poverty is becoming increasingly urgent in the Ethiopian highlands, where livelihood security is strongly dependent on local ESS, particularly those provided by water and soil. 85% of the population consists of poor subsistence farmers who depend on rainfed agriculture to fulfill basic needs such as food, income and fuel. Most of them are also suffering from food insecurity, mainly as a result of land degradation. In this chapter, I test the effect of widely implemented soil and water conservation (SWC) interventions on storm flow and its sediment concentration using a representative case study, i.e., Debre Mawi in the upper Blue Nile basin of the Ethiopian highlands. For this, the hydrological model, PED was implemented using time series data from an intensively monitored 95 ha subcatchment. Subsequently, I upscaled these results to the catchment-scale outflow and soil loss of the entire Debre Mawi watershed (716 ha). The PED model is conceptualized by three types of watershed regions, i.e. saturated (A_1), degraded (A_2), and permeable watershed regions called hillsides (A_3). Soil loss is expected from A_1 and A_2, because both regions generate surface flow. A_3 instead generates discharge as subsurface flow through base flow and interflow, and it is the source of groundwater recharge. Next, I mapped the current outflow and soil loss status at catchment level. Lastly, I selected site specific land management methods, i.e. (1) soil and water conservation interventions at degraded land; (2) gully treatment where gully initiation and expansion is expected; and (3) groundwater availability improvement through blocking lateral water flow for dry season. The latter is particularly important since dry season water scarcity is very challenging in the study region. The results confirm that SWC interventions reduce the extent of degraded lands by around 53% during 4 years of their implementation, i.e., these interventions are reducing runoff and soil loss, and enhancing recharge. The model results of spatial and temporal outflow and sediment concentration also confirmed that degraded lands are the main sources of discharge and soil loss. Main occurrence was found during May to July (resp.73–148 mm and 9–28 kg m^{-3} during 2016). During the dry season (November–April),

flow generating areas are mainly hillsides, i.e., this indicates that the precipitation which joins interflow moves out the catchment via subsurface flow. This highlights the need of appropriate subsurface water management to improve dry season groundwater availability. Overall, I recommend primary interventions such as SWC intervention at degraded areas, and blocking lateral water flow in hillsides as appropriate soil and water conservation to the sustainability of environment and livelihood.

6.1 Introduction

Leveraging rural ecosystem services (ESS) management as a means of poverty alleviation receives increasing attention (Fisher et al., 2014; Dile et al., 2013). The link between ESS and livelihood is often very direct and poverty is severe in rural areas where income source is agriculture that is highly dependent on climatic conditions (Jalan and Ravallion, 1998). Despite increased intellectual and theoretical consideration of the linkages between ESS and poverty alleviation globally, there has been limited awareness on how to use and frame them in the regional socio-ecological context (Pinho et al., 2014). In mountainous regions, for example the Ethiopian highlands, community level livelihoods and even the national economy depend on rural ESS, particularly those provided by water and soil. These highlands host 88% of the total population of the country where 85% are poor subsistence farmers who lead their livelihood mainly by rain-fed agriculture even though this is not a novel farming system to erratic rainfall areas (Yosef and Asmamaw, 2015).

As in many other regions in the developing world, soil erosion (Ananda and Herath, 2003) and inconsistent monsoon rainfall are the most serious ESS degrading processes leading to further poverty in the study area (Amare et al., 2014). In the study region, severe soil erosion by precipitation, crop production failure due to inconsistent rainfall and pronounced animal drinking water scarcity during the dry season happen in the same year; particularly, streams which are used as animal drinking water sources tend to dry up. Because these issues jeopardize the sustainability of livelihoods and the environment, there have been academic debates and government-led interventions, particularly SWC structures since 1970s that aim to improve ESS management to challenge poverty lock-in. As a countermeasure to dry season water scarcity and sever soil erosion, rainfall-runoff water harvesting has been put forward as the best option (Gatot et al., 2001). This helps to conserve rain water in the rainy seasons to control runoff (decrease erosion rate) and to enhance recharge which in turn improves dry season stream flow and increases the groundwater table to facilitate water abstraction using wells for animal drinking water, household domestic use and also for irrigation. This water conserving practice thus improves farmers' income and food security through improved production from animals and /or crops (Ilstedt et al., 2016).

This chapter aims to examine the effect of widely implemented SWC interventions on discharge and sediment concentration using available hydrological data (discharge and soil loss data collected at 95 ha subcatchment during 2010-2016). In particular, I aim to identify the 2016 runoff and soil loss prone locations including their temporal variability at the catchment scale using on-site observation based area delineation from Google Earth and further analysis using GIS tools in order to identify intervention sites. To achieve these objectives the methodology consists of (1) a model-based evaluation of SWC interventions to increase the catchment area that contributes to water infiltration and recharge ("hillsides area" in the terminology of the PED model), which in turn reduces storm flow and soil loss, (2) mapping the spatial and temporal variability of the average monthly outflow and sediment concentration at the watershed level. The principle of reducing discharge and soil loss through SWC interventions is that these technologies can convert some areas of the catchment from a degraded state to a "permeable hillslope" (hillside) state, thus increasing infiltration (Dagnew et al., 2015). At the same time, this increased infiltration decreases storm flow and soil loss during the wet monsoon season (Dunne and Black, 1970). The enhanced infiltration increases water availability in lower catchment streams and groundwater abstraction wells during several months of the dry season. I prove this using discharge and soil loss data collected before, during and after the implementation of SWC interventions in a 95 ha subcatchment and combining this with the PED hydrology and erosion model. Then, I upscaled the analysis to the whole Debre Mawi catchment (716 ha). Subsequently, the spatial and temporal variability of storm flow and sediment concentration of average monthly flows was determined by combining the PED model with GIS tools.

6.2 Methods

6.2.1 Location

In the Ethiopian highlands, the Debre Mawi watershed is located in the headwaters of the Blue Nile, about 30 km south of Lake Tana (between 11°20'13" and 11°21'58" N, and 37°24'07" and

37º25'55" E). The total area of the watershed is 716 ha. The elevation ranges between 1950–2309 metres, and slopes are steep at 8 to 36%. The maximum annual temperature occurs in March–April, ranging from 22–29ºC, whereas minimum annual temperature occurs in November–December with a range of 5 to 12ºC. The catchment has a unimodal rainfall regime with an average annual rainfall of 1238 mm (Zegeye et al., 2010). June, July, August and September receive the largest shares of the annual rainfall. Potential evapotranspiration is 2−3 mm/day in the rainy season and 4−5 mm/day during the dry season. The watershed is characterized as mountainous, highly rugged and dissected topography with steep slopes (Guzman et al., 2013) and has variable soil losses (Tilahun et al., 2013a). Since 2012, government-led SWC interventions have been implemented widely to counteract soil erosion through community mobilization but typically the impact of these interventions has not been monitored very well, which is the main focus of this chapter.

To analyze the SWC interventions impact on discharge and soil loss, this chapter focuses on a 95 ha subcatchment of Debre Mawi watershed, where a gauging station (monitoring both surface and subsurface flow) is located, and most of the SWC structures were implemented in 2012, before the monsoon wet season. I used time series of precipitation, evapotranspiration and storm flow data for the period of 2010−2016 to determine the impact of SWC structures on degraded land area fraction. To observe the trend of long and short-term impact of SWC, these data were analyzed using the PED model before (2010/2011), during (2012) and after (2014 and 2016 separately) their implementation (Figure 5.1). The model was calibrated for the current year (2016); then only the area fractions were changed for the other periods.

6.2.2 Analysis of discharge and soil loss with PED and GIS tools

The possibility of reducing storm flow and soil loss by enhancing infiltration through SWC structures implementation was evaluated using the parameter efficient distributed (PED) model. In this chapter I adapted the PED hydrological and erosion model which has been developed and applied widely in the study region (Collick et al., 2009; Steenhuis et al., 2009; Tesemma et al., 2010; Tilahun et al., 2013a, 2013b, 2015; Guzman et al., 2017; Zimale et al., 2016) to simulate discharge and soil loss at gauged station. In principle, this model lumps the total study area into three regions with diverging hydrological behaviour: saturated (A_1), degraded (A_2) and permeable hillslopes, called hillsides (A_3) areas (regions). A_1 and A_2 generate direct runoff (Q_1 *and* Q_2) whilst in region A_3 rainfall infiltrates (percolates) and eventually either recharges the groundwater storage and produces base flow (Q_b) or flows as interflow (Q_i). As a result, total discharge at the watershed level (Q) is the sum of direct runoff generated from saturated area Q_1 and degraded area Q_2, and base flow and inter flow generated from hillsides (Q_1+Q_2+Q_b+Q_i). The other hydrological parameters of the model are maximum and initial soil storages per area (S_{max1}, S_{max2}, S_{max3}, S_{init1}, S_{init2}, S_{init3}) in mm, maximum groundwater storage (BS_{max}) in mm, duration of interflow (τ*) and half-life of the aquifer ($t_{1/2}$) in days. Discharge simulation begins with the basic water balance equation in PED for a time step of Δt and ends up with interflow (Q_i) analysis as mentioned in chapter 5 (Eq. 5.1 to 5.9).

Tilahun et al. (2013b, 2015) developed a sediment transport module for PED, which is described here briefly. In the study region, there are two natures of sediment transport: transport limited and source limited. The model represents the sediment concentration in the water when there is equilibrium between deposition and entrainment of sediment with a_t, and the conditions when entrainment of soil from the source area is limiting with a_s. The threshold between both is typically after 500−600 mm of effective rainfall. The other important parameter is the active rills indicative variable, *H*, which is expressed as the fraction of the runoff-producing area containing actively forming rills. In the study region, it has been estimated that *H* begins at the value of 1 during the beginning of the monsoon wet season and reduces to zero after around 500 mm of cumulative effective precipitation. Similar to previous work (Tilahun et al., 2013b), here I set H=1 initially and up to the middle of July; H=0.5 thereafter and up to end of July; then H=0.25 in August; finally, H=0 onwards. Combining these parameters, the sediment load, Y (kg m^{-2} day^{-1}) is simulated:

$$Y = (A_1 Q_1 [a_{s1} + H(a_{t1} - a_{s1})] Q_1^n) + (A_2 Q_2 [a_{s2} + H(a_{t2} - a_{s2})] Q_2^n) \quad (6.1)$$

Equation 6.1 can be rewritten to simulate sediment concentration, *C* (kg m^{-3} d^{-1}):

$$C = \frac{y}{Q} = \frac{(A_1 Q_1^{1.4} [a_{s1} + H(a_{t1} - a_{s1})]) + (A_2 Q_2^{1.4} [a_{s2} + H(a_{t2} - a_{s2})])}{A_1 Q_1 + A_2 Q_2 + A_3 (Q_b + Q_i)} \quad (6.2)$$

where A_1–A_3 are the areas of the three regions of the watershed, Q_1–Q_2 are respectively the discharges from A_1 and A_2, Q_b and Q_i are discharges from A_3, *n* is an exponent set to 0.4. These values were selected on the basis of calibrations presented in recent studies in the study region (Tilahun et al., 2013a, 2013b, 2015; Guzman et al., 2017), and the other variables are as mentioned higher.

After the hillsides area fraction is increased through the implementation of the SWC structures (which implies that intervention improves infiltration, then reduces storm flow and soil loss), the spatial and temporal variability of discharge and soil loss at the watershed level was investigated using the PED model results combined with ArcGIS spatial analyst tools. First the current saturated, degraded, and hillside area fractions of the 716 ha Debre Mawi, were delineated from Google Earth and field observation. With this area fraction and the hydrology and erosion model parameter sets fixed during the analysis of effect of SWC intervention on hillsides area fraction improvement, the current monthly discharge and sediment concentration at the catchment level were simulated. Subsequently two specific soil and water conservation interventions were selected and prioritized: SWC intervention on degraded land, and blocking lateral flow. For the spatial analysis, I used the SRTM DEM at 30 m resolution, and the current three areas fractions of the 716 ha Debre Mawi watershed, delineated from Google Earth. First, total, saturated, degraded and hillside areas flow accumulations were calculated separately using the ArcGIS hydrology tools. Then the fraction of flow, *f*, for each pixel of the three watershed regions was calculated with the map algebra raster calculator tool as:

$$f_{hill} = \frac{A_{hill}}{A_T} \quad (6.3)$$

where A_{hill} is the contributing area on the well-drained hillside of the pixel and A_T is the total area of the watershed. For the degraded area, I find similarly:

$$f_{deg} = \frac{A_{deg}}{A_T} \quad (6.4)$$

where A_{deg} is the contributing area on degraded hillside of the pixel. For the saturated area it is:

$$f_{sat} = \frac{A_{sat}}{A_T} \quad (6.5)$$

where A_{sat} is the contributing area on the periodically saturated of the pixel.

Next, based on the daily flows calculated for the three regions in the PED model (Eqs.5.2, 5.5 and 5.9), the cumulative flows for each month of each pixel, Q are calculated as:

$$Q_1 = \frac{f_{sat} Q_{month,1}}{A_1} \quad (6.6)$$

$$Q_2 = \frac{f_{deg} Q_{month,2}}{A_2} \quad (6.7)$$

$$Q_3 = \frac{f_{hill} Q_{month,3}}{A_3} \quad (6.8)$$

Where Q_1, Q_2 is the overland flow for each pixel in the satuated and degraded area, respectively, Q_3 is the interflow (Q_i) and base flow (Q_b) for each pixel in the well-drained hillside, $Q_{month,}$ is the cumulative monthly flow simulated by the PED model with additional subscripts for areas 1 (saturated), 2 (degraded) and 3 (well-drained hillside). Finally, A is the fraction of the total area of the three regions based on the subscript.

Therefore, total catchment level monthly discharge per pixel was simulated as the sum of the storm flows simulated by Eqs. 6.6–6.8 using the following map algebra raster calculator expression for the storm flow spatial and temporal variability mapping at 716 ha Debre Mawi.

$$Q_{pixel} = \text{con}(\text{IsNull}(Q_1), 0, Q_1) + \text{con}(\text{IsNull}(Q_2), 0, Q_2) + \text{con}(\text{IsNull}(Q_3), 0, Q_3) \quad (6.9)$$

where Q_{pixel} (m) is the spatial discharge map at the watershed level. Equations 6.6–6.9 separately were run 12 times to determine the annual monthly values.

Following the storm flow spatial and temporal analysis, sediment concentration was also presented for each pixel, Y_{pixel}, at the 716 ha Debre Mawi catchment by replacing the monthly runoff loss $Q_{month,1}$ and $Q_{month,2}$ for the satuated and degraded area by the monthly sediment

loss $Y_{month,1}$ and $Y_{month,2}$ in Eqs. 6.6–6.9. Since it was assumed that the well-drained hillslope had only subsurface flow, there was no sediment loss from that area, hence: $Y_{month,3} = 0$
The monthly cumulative concentration can be obtained simply as:

$$C_{pixel} = \frac{Y_{pixel}}{Q_{pixel}} \quad (6.10)$$

where Y_{pixel} (kg m^{-2} month^{-1}) is sediment load and C_{pixel} (kg m^{-3} month^{-1}) is sediment concentration per pixel.

6.3 Results and discussion

6.3.1 SWC impact on runoff and soil loss

Soil erosion is a worldwide problem and has become a major global concern because of the severe impacts on agriculture and environment. Ethiopia is a country with severe erosion issues, and erosion caused by intense rainfall is common in the highlands (Wudneh, et al., 2014), and particularly in rural areas such as Debre Mawi (Tesfaye et al., 2016). Teshome et al. (2013) also mentioned that soil erosion by water is a major challenge to food security, environmental sustainability and particularly for rural development in Ethiopia. At the Debre Mawi watershed in the Ethiopian highlands, SWC interventions to counteract water erosion have been implemented widely. The effectiveness of these interventions is present through modelling. Trends and effects of SWC practices on discharge and soil loss over time (before and after intervention) are shown using the 2010-2016 time series storm flow and sediment concentration data collected at a 95 ha gauged subcatchment (Figure 5.3: discharge; Figure 6.1: sediment concentration).

The PED model was calibrated on the 95 ha subcatchment of Debre Mawi, using data of the years 2010–2016, comprising of time periods before the soil and water conservation intervention (2010/2011), during intervention (2012), and after intervention (2014 and 2016). The modelling results show that the SWC interventions implemented on degraded land enhance infiltration, as well as recharge by changing degraded hillslope land features into permeable hillslope ("hillside") land features. This situation reduces storm flow and sediment concentration (Wei et al., 2016; Figures 5.3, 6.1). Out of the three watershed regions, the degraded area fraction that is the main source of discharge and sediment was decreased by 45% due to SWC, implemented in 2012 dry season and showed reducing progress by 47% in 2014 and 53% in 2016 since the effect of most SWC interventions progresses gradually. At the same time, the hillside area fraction was increased by 38, 42 and 55% respectively in 2012, 2014 and 2016. Gebreegziabher et al. (2009) reported that SWC technologies implemented by governmental extension programmes have long-term benefits (i.e., after 2 or 3 years). The PED hydrology and erosion model simulated discharge and sediment concentration very well. There is a good fit between the weekly model prediction and observation such as NSE values for discharge and sediment concentration respectively are as high as 0.51–0.89 and 0.50–0.80. In these discharge and soil loss analyses, the model simulation efficiency with NSE of 0.50–0.60 is considered to be satisfactory (Moriasi et al., 2007). In addition it shows an increasing trend because it was calibrated using data collected in 2016 (Table 6.1).

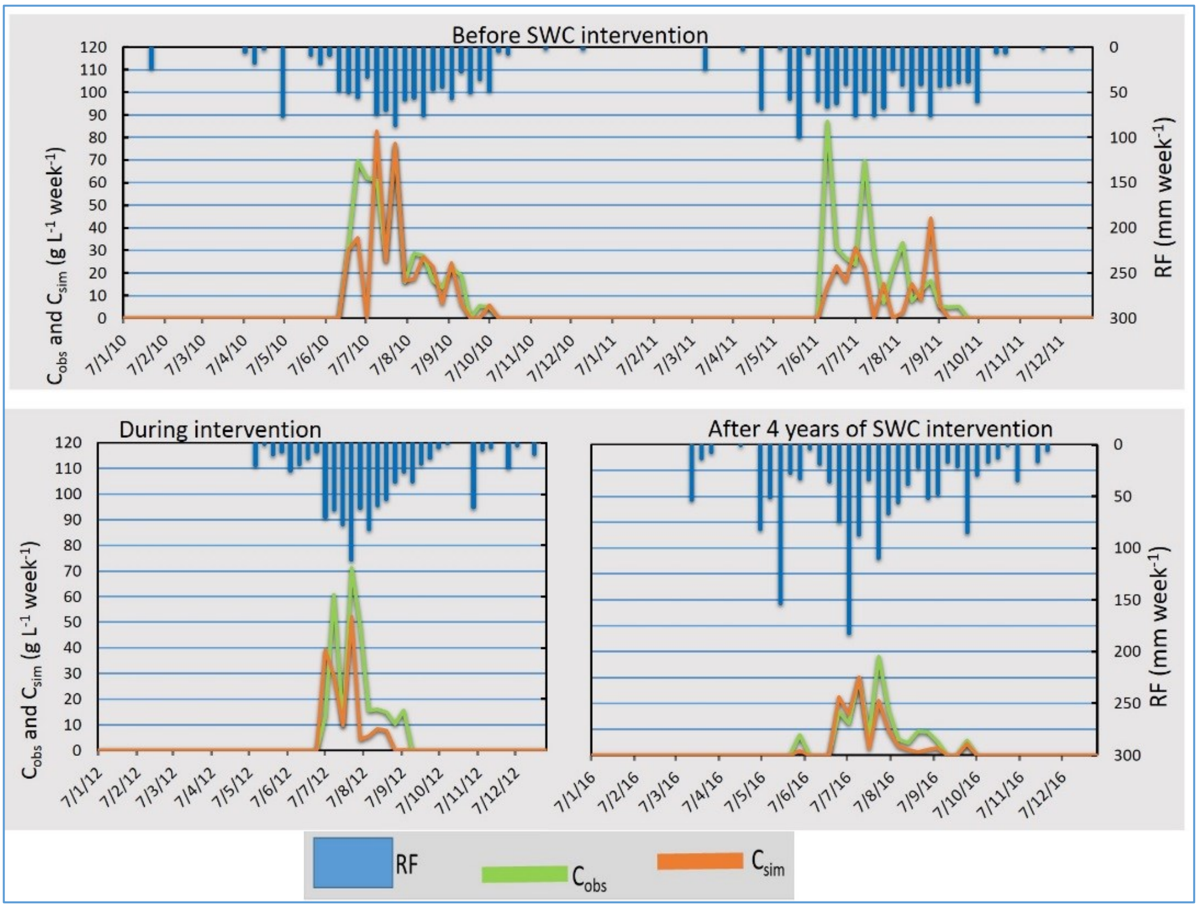


Figure 6.1: Impact of SWC interventions on sediment concentration (RF: rainfall, C_{obs} and C_{sim} respectively are observed and simulated sediment concentration).

Table 6.1: The optimized parameter values of the PED hydrology and erosion model.

Hydrology model parameters		Years for analysis			
		2010/2011	2012	2014	2016
Area fraction (%)	A_1 *(saturated)*	3	10	8	1
	A_2 *(degraded)*	55	10	8	2
	A_3 *(hillside)*	42	80	84	97
Soil maximum storage (mm)	S_{max1}	80	80	80	80
	S_{max2}	10	10	10	10
	S_{max3}	60	60	60	60
Soil initial storage (mm)	S_{init1}	15	15	15	15
	S_{init2}	5	5	5	5
	S_{init3}	10	10	10	10
Aquifers and interflow	Bs_{max} (mm)	25	25	25	25
	BS_{init} (mm)	5	5	5	5
	Half-life, $t_{½}$ (day)	45	45	45	45
	t star, τ^* (day)	300	300	300	300
Nash–Sutcliffe efficiency, *NSE* (-)		0.59	0.51	0.89	0.82
Erosion model parameters					
Source limit					
a_{s1}		3	3	3	3
a_{s2}		3	3	3	3
Transport limit					
a_{t1}		6	6	6	6
a_{t2}		14	14	14	14
NSE		0.50	0.59	0.76	0.80

6.3.2 Catchment-scale discharge and sediment concentration spatial and temporal occurrence

The 2016 saturated, degraded and hillside area fractions of the 716 ha Debre Mawi, which were delineated from Google Earth and field observation are respectively 18, 17 and 65%, (Figure 6.2). With this area fraction and the hydrology and erosion model parameter sets in Table 6.1, the combined PED-ArcGIS model shows that the highest monthly surface flow occurred during July, followed by the flows in August, May, September, October and June respectively in 2016 at Debre Mawi watershed. There was also some storm flow in March generated from degraded land (Figure 6.3) due to 74 mm rainfall in this month, whereas during January, February and April the rainfall was less than 1mm. Figure 6.3 shows that there is storm flow in the yellow to blue areas of the watershed while there is no storm flow in the red region. Considering the total annual flow, most input from precipitation moves out of the watershed via subsurface flow (since the hillsides area, A_3 fraction is far larger than the other two watershed regions, i.e., 65%) orderly followed by flows from degraded and saturated regions (Figure 6.4). Whereas the normalized value (discharge to area fraction ratio) proves that the annual outflow from Debre Mawi is mainly due to storm flow from the degraded watershed region (46% of the total) and the second and third sources respectively are outflows from saturated (36%) and hillside (18%) regions (Figure 6.5).

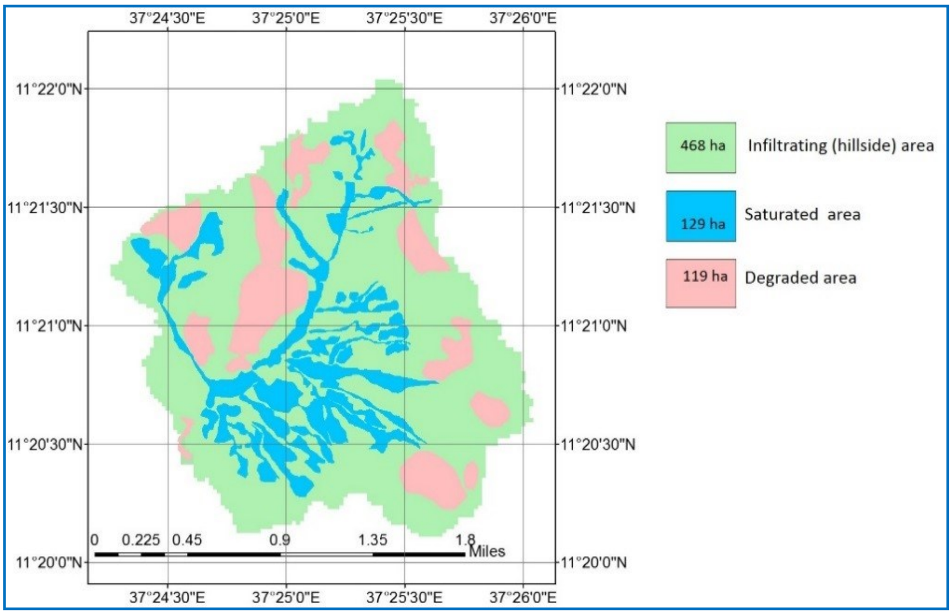


Figure 6.2: The three area fractions of 716 ha Debre Mawi watershed in 2016.

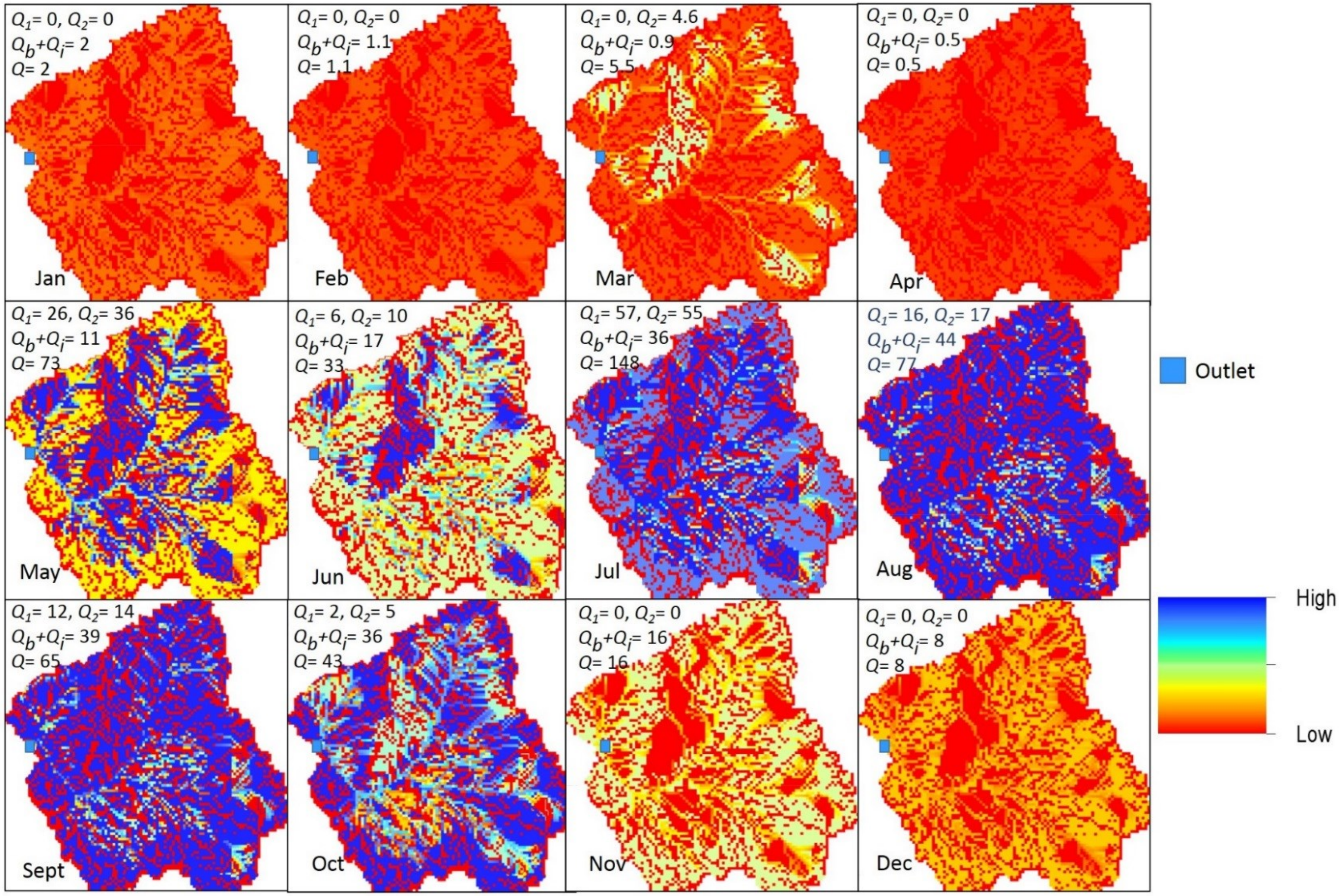


Figure 6.3: Monthly discharge, Q (mm) at the outlet and its outflow sources from the three regions of the watershed (Q_1, Q_2 and Q_b+Q_i respectively from saturated, degraded and hillside watershed regions); Q_b is base flow and Q_i is interflow.

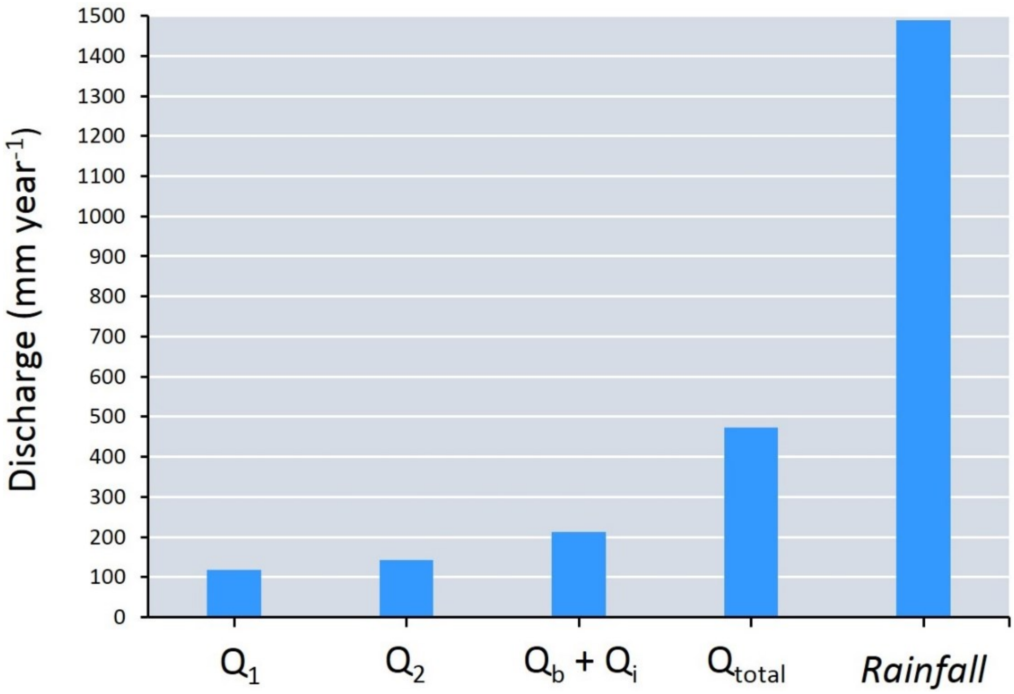


Figure 6.4: The 2016 annual rainfall and discharge produced by the present area fractions of the three watershed regions (*Q_1*: runoff from area 1, saturated area; *Q_2*: runoff from area 2, degraded area; and *Q_b+Q_i*: sum of base flow and interflow generated by area 3, hillside).

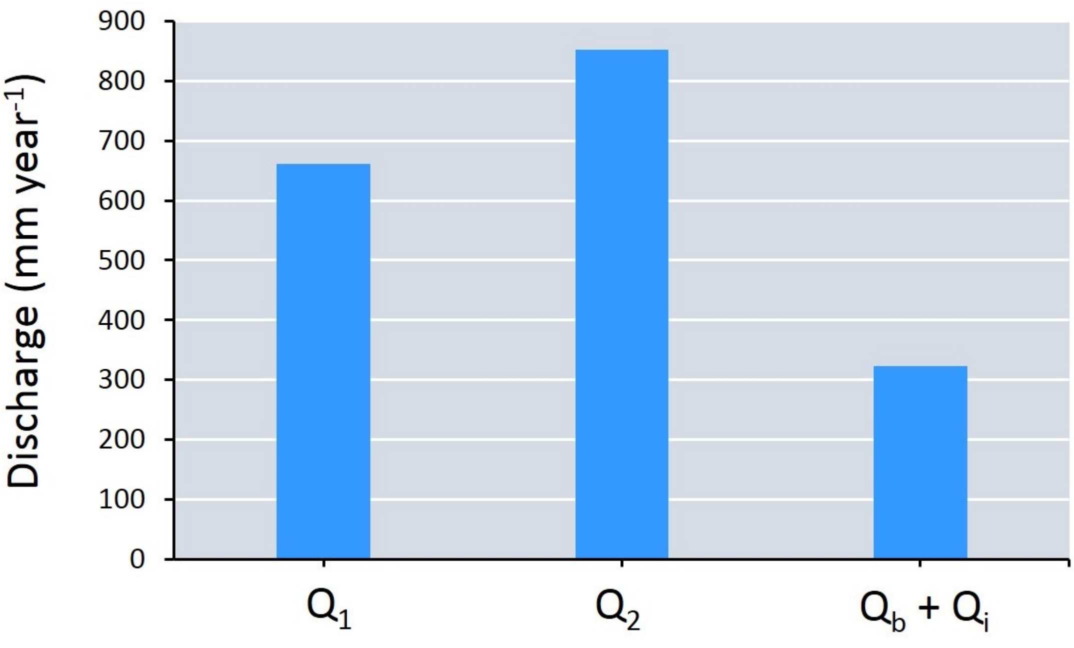


Figure 6.5: The 2016 normalized annual discharge values (annual discharge in mm per year as described in Figure 6.4 divided by area fraction, unit less, per watershed regions such as: $\frac{Q_1}{0.18}, \frac{Q_2}{0.17}, \frac{Q_3}{0.65}$) to compare the flow contribution of the three watershed regions.

Regarding soil erosion, the simulated annual sediment concentration in 2016 was 67.7 kg m^{-3}. Similar to the storm flow, there is sediment concentration only in yellow to blue regions of the watershed; there is no sediment concentration in the red region (Figure 6.6). The largest share (41%) was in July, proceeded by June (22%), May (13%), March (12%), August (6%), September (4%) and October (2%). Since most croplands are ploughed during Jun and July, the topsoil is disturbed and the vegetation cover from sown crops is minimum (Materu, 2016). Therefore, soil erosion, and especially rill erosion, is severe during this period. The high sediment concentration before this period was transport limited because the cumulative rainfall was less than 500 mm. Contrarily, sediment concentration decreases since August despite high rainfall because of source limitations. This is caused by the stabilization of the disturbed soil as a result of cultivation and better crop land cover as compared to the crop planting period (Figure 6.7). This was also confirmed by Guzman et al. (2013) reported the occurrence of high sediment concentrations with low flows at the beginning of the rainy season, while high flows and low sediment concentrations occur at the end of the rainy season in this study region.

This GIS based discharge and sediment loss analysis confirms that the primary land management of SWC interventions, should be implemented first at the degraded land, and then at saturated regions, as shown by the normalized discharge analysis and sediment concentration-cumulative rainfall relationship (refer Figure 6.3–6.7). Figure 6.3 confirms that outflows from degraded and saturated watershed regions are generated during the wet season. This is further confirmed by Figure 6.6, which shows that degraded regions of the watershed transport a higher amount of soil with overland flow. The continuous outflow particularly during the dry season contributed by hillsides (Figure 6.3) indicates blocking lateral flow especially to natural dykes bounded faults is the possible solution to improve dry season groundwater table, subsequently to install groundwater abstraction wells to counteract the dry season water scarcity in the study region.

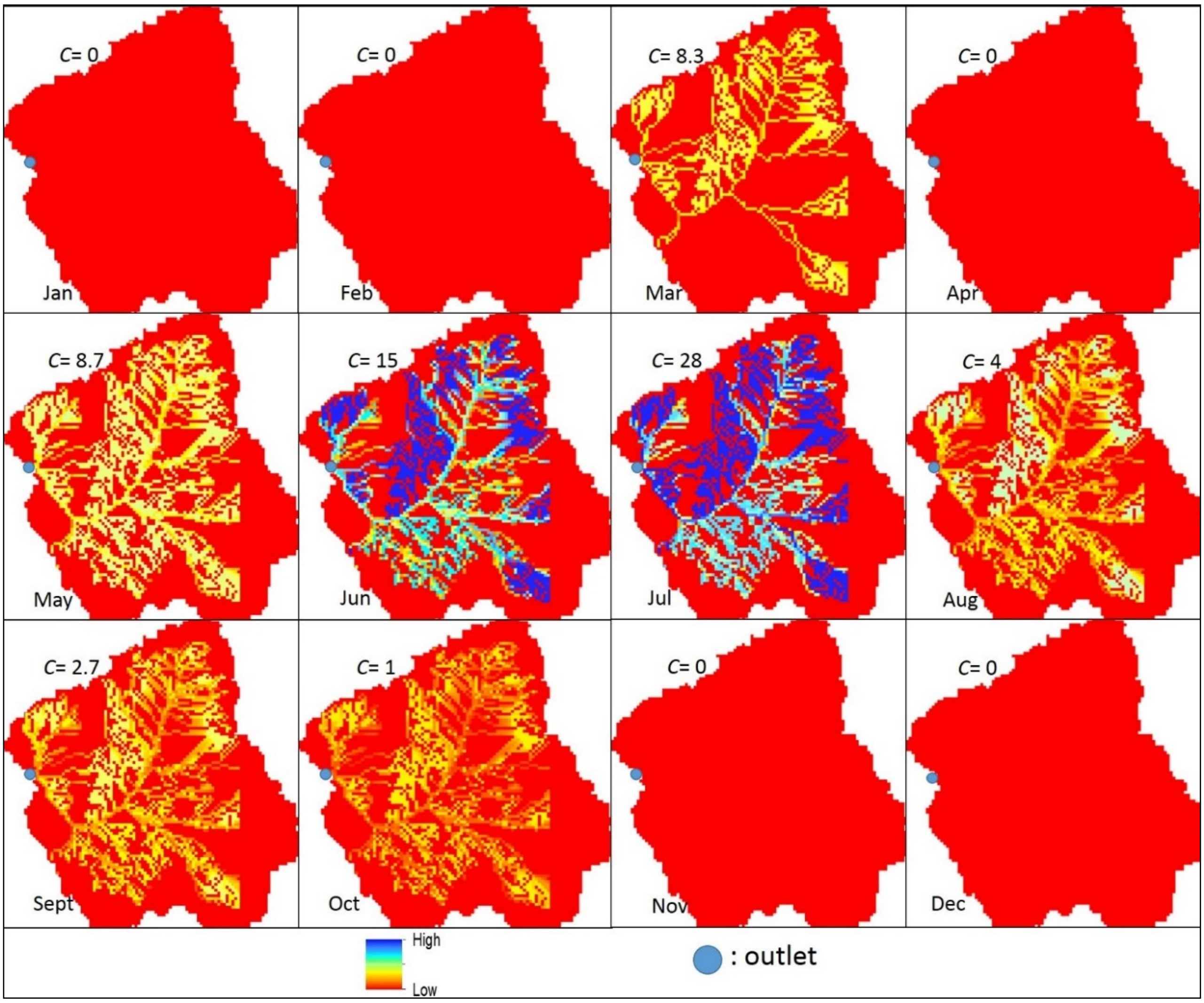


Figure 6.6: Spatial and temporal distribution of the monthly sediment concentration, C (kg m^{-3}) at Debre Mawi watershed for 2016.

Figure 6.7: The monthly cumulative rainfall of 2016.

6.4 *Conclusions and recommendations*

I deployed an integration of the parameter–efficient−distributed (PED) hydrological and erosion model with GIS tools to evaluate the catchment-scale discharge and sediment concentration status in the Ethiopian highlands. I analysed the effect of widely implemented in situ SWC interventions on discharge and soil loss, using an experimental 95 ha subcatchment as a case study, and found that widely implemented SWC technologies are able to reduce storm flow and sediment concentration by converting poorly infiltration hillslope (degraded) land into permeable hillslope (hillside) land. The trend of reduction was estimated and compared to baseline data collected during 2010/2011 (before SWC intervention). This is presented in Figure 5.3 and 6.1 for respectively discharge and sediment transport. The erosion component of the PED model predicts that the SWC practices implemented on degraded land in 2012 reduced this land area fraction by 53% 4 years after implementation of intervention.

Subsequently, the monthly discharge and sediment concentrations simulated with the PED model were mapped into space using GIS tools and the SRTM digital elevation model, which resulted in maps of the spatial and temporal outflow and sediment concentrations at catchment scale. From this, I found that the "hillside" area fraction of the watershed generates the largest amount of annual outflow (45%) followed by the degraded area (30%). The minimum outflow was from saturated areas (25%). Temporally, the highest flows occurred during May–July when the vegetation cover was minimum and the soil was disturbed due to cultivation for crop planting following the farmers' calendar. During the other months, and particularly during the dry season only hillsides contribute to flow. This allows for spatial identification of the sources of (subsurface) interflow, which can improve groundwater availability during the dry season, if it is managed well, for instance by blocking lateral water flow.

Similar to discharge, sediment concentration, which was generated only from the degraded and saturated regions, was high at the beginning of rainy season when the land is under cultivation. Its temporal distribution is respectively 13%, 22%, 41%, 6%, 4% and 1.5% in May, Jun, July, August, September and October. Based on field observations, the saturated regions, where gullies are dominated, are considered as the main sources of sediment during August and September. Considering the outcomes of this research, degraded lands are the main sources of sediment. These watershed regions also contribute a large share of the discharge (in addition to the hillsides). The normalized discharge values for degraded, saturated and hillsides areas resp. are 46, 36 and 18%. This indicates that degraded lands are the most discharge sensitive watershed regions. In view of the productivity and sustainability of the livelihood strategies explored in previous chapters, priority should be given to degraded lands treatment in the Debre Mawi watershed (i.e., SWC interventions at degraded lands to change these lands to permeable lands, hillsides). The second management priority needs to be implemented at hillsides where the largest amount of discharge (45% in 2016) is generated. I suggest that the most appropriate intervention is the blocking of lateral water flow, generated by hillsides, to increase groundwater availability, to improve dry season water supply (since dry season water scarcity is a pronounced problem in the study region).

With regard to future research, detailed groundwater investigations should be a priority. In particular, further insights are needed on how geological features impact subsurface flows and how this affects groundwater availability. Furthermore, more plot level experiments are needed to compare the effects of SWC interventions on soil loss, runoff and recharge, and comparison of positive and negative effects of SWC practices (such as serving as shelters for rodents and shading effects on crop growth) to refine further the opportunity cost assessment. From the SWC interventions that already in practice such as bunds, vegetative barriers, bunds integrated with vegetative barriers and ditches in the study region, bunds integrated with vegetative barriers appear to be most effective and cost efficient, because the biological components support bunds very well (soil and water conserved well) and the farmers can harvest grass for livestock; these in turn improve the farmers' crop and animal production. In comparison, physical structures such as bund are less effective as they can host pests that damage crop and grass (Meheretu et al., 2014; Walie and Fisseha, 2016).

Regarding to the model application, more rigorous models than PED exist. For instance, the Soil and Water Assessment Tool (SWAT) is a comprehensive distributed watershed model used to address various environmental issues including discharge and soil loss assessment at a range of geographic and temporal scales (Tuppad et al., 2011). However it requires a large number of parameters, and has not been tried as extensively in the study area particularly in Debre Mawi, and there was time limitation to analysis the data using this sophisticated SWAT model. Therefore I used the PED model for discharge and soil loss analysis because it is relatively parameters efficient (uses 9 parameters), less sophisticated to implement in a short time frame, and has been tested and applied widely in the study area including in Debre Mawi (Tilahun et al., 2013a, 2013b, 2015; Guzman et al., 2017). As described in section 5.4.2 (Figure 5.9-5.12), the uncertainty of the PED model fluxes suggests the need for detailed calibration and validation of the model using more detail ground-truth information that can be collected with local community to improve implementation of the interventions.

Chapter 7

Summary and conclusions

7.1 Summary of thesis

In Ethiopia and worldwide, leveraging ecosystem services management to maximize poverty alleviation is receiving increasing attention. In the Ethiopian highlands, which carry 88% of the total population of the country, the link between livelihood and ESS is very direct. Around 85% of the population is characterised by subsistence-based livelihoods, and this is increasing with time. Earlier research has reported that poverty is becoming worse even though government led interventions targeting food security have been implemented widely since 1970. In order to manage local ESS effectively to support improvement of livelihoods, a detailed insight into the social−ecological interaction between people and ecosystem processes is required. This knowledge is necessary to investigate the available resources, needs of local community and policy regarding to ESS management, and for the creation of tools that can be used to explore poverty lock-in challenging livelihood strategies. My research improved the approach of understanding of local ESS management to maximize poverty alleviation. It highlighted the importance of participatory research for gaining local understanding to support development, for example as a means of ground−truthing water supply−demand algorithms.

The incorporation of local knowledge in small to large scale research to support sustainable local livelihoods is considered to be a major challenge, and an essential component in future management of water and other ecosystem services. The presented research worked towards addressing this through problem framing and prioritization of solutions using participatory rural appraisal; ground-truth evidence generation as framed problems−solutions with the local community, and confirming this using a computational modelling frame work. The research approach is developed for the Ethiopian highlands and similar worldwide regions. I started with identifying the scientific state-of-the-art in the field of ESS and livelihoods relationships, and emerging questions related to this interface, and in particular on the implementation of bottom-up approaches and strategies to foster the involvement of focal community to integrate ground truth information. On the basis of this review, I developed a methodology that aims to leverage experience-based local knowledge to address data gaps, and to implement interdisciplinary research that enhances the incorporation of required expertise for complete ESS management for human wellbeing. I did this by implementing experiments of participatory knowledge co-creation, using as a case study in the upper Blue Nile, and more specifically its headwater catchments such as Birr, Mizewa and Debre Mawi, where the dependence of livelihoods on ESS is very pronounced. The thesis addresses these research areas through the following approaches: (1) synthesising the link between ecosystem services, environmental sustainability and poverty alleviation through a literature review, by analyzing formal and informal decision-making processes related to ESS management within the communities in the watersheds, where different levels of interventions exist, the need for a participatory approach to problem framing is very pronounced, and data generation and exchange can promote environmental sustainability and poverty alleviation; (2) implementing a process of participatory community-researchers to promote end-user elicitation and evidence generation on improved ESS management. This aims to understand the major impediment, i.e., constraints such as bottlenecks and biophysical processes perpetuating poverty which were described in-detail in chapter 4, to implementing potential livelihood strategies that may lead to poverty reduction in the upper Blue Nile basin the case under study and the other big similar regions of the world where livelihoods depend on ESS and data scarcity is a big challenge; (3) field experimental and model−based generation of evidence to support livelihood improvement and to identify the best combination of management methods (groundwater abstraction and water harvesting) to optimise water supply during the dry season in the case study. My major finding is that the physical SWC impact and lateral flow blocking can be characterised with respectively plot level experiment and geological characterization; (4) implementation of a distributed catchment–scale evaluation of the potential of soil and water conservation interventions to reduce storm flow and soil loss with the following objectives: to assess the effects of soil and water conservation practices on discharge and sediment concentration using a hydrological and erosion model, to map the current outflow and soil loss status at catchment level and to select site specific land management methods particularly soil and water conservation interventions; and (5) summarizing how each research area has been addressed and providing recommendations for future research.

7.2 Contribution to knowledge

The main scientific knowledge contribution of this research is to explore how to implement an interdisciplinary, bottom-up, and participatory research approach to generate socio-ecological knowledge that can support sustainable development. This approach has been part of an academic debate since the 1970s in Ethiopia that focuses on how to incorporate the local knowledge for sustainable agricultural livelihood and environment, but has so far often failed to generate the intended results. At the same time, similar questions are gaining traction in the international research community, in particular related to the generation of interdisciplinary expertise, focal community participation, and bottom-up problem identification and solution suggestion. This is very timely and acute. For example, Mubita et al. (2017) asserted that participation has not led to local's empowerment for sustainable livelihood-environmental development because participatory methodologies have failed to change and challenge the bureaucratic, centralized and administrative structures that control decision-making and resource allocation. This is attributed to the fact that participatory research was planned without understanding of social-ecological context. My participatory research approach consisted of creating a methodology for knowledge generation and exchange among farmers and between farmers and researchers about local socio-ecological condition, with the aim to create locally friendly livelihood improving strategies that represent the interest and knowledge of the focal community and do not conflict with the existing bureaucratic structure. My research elucidated locally based strategies to challenge poverty lock-in and to represent local knowledge in a modelling framework to overcome some of these issues. To achieve this contribution a method was developed by adapting a participatory rural appraisal (PRA) research method from social science, which is a cost effective and experience based knowledge generation method, updated by real field data collection with the local community, and quantified through modelling to upscale quantitative evidence generated by the pilot studies.

As reported by Campbell (2001), many current practices are modelled on or borrowed PRA techniques directly from qualitative social research through paying little attention to the limitations of the techniques. Most PRA techniques are implemented when quick access to socioeconomic data is required but they tend to result in biased outcomes and professional shortcomings because of the limited time available for field research. This often results in random meetings with individuals who happen to be available or accessible easily (i.e., near the road, in the project office, or at their houses rather than out in the fields). The prominent role of group interviews such as focus groups discussions is especially problematic because of the need to carefully select participants and to manage the group interview.

To circumvent these issues, I developed a rigorous method by complementing the existing PRA elements (household survey, key informant interview and focus group discussions) through a set of complementary activities: ESS mapping on the ground by community, field observations with the local community through transect walk, budgeting enough time for field research, doing interviews and discussions at the field where the issues I and the community members were discussing were found, and giving particular attention for focus group members selection and managing the group as discussed in detail in chapter 4 in section 4.3.1. In addition, through the PRA approach, the community representatives suggested data collection and they participated in data collection at the field for evidence generation. The farmers' experience based ground-truth insight was also incorporated in the computational modelling framework. In this method, PRA helps to understand how the poor currently depend on ESS in the study region, how the management of local ESS can be used to increase the benefits of ESS for the poor, and what the current bottlenecks are. A participatory experiment−based strategy for data collection promotes participatory knowledge generation and exchange among community as well as between community and researchers. This was then extended using a computational modelling approach, by applying a hydrology and an erosion model respectively to quantify water availability for livelihood improving strategies management (crop irrigation and animal production) and to understand the status of soil erosion for the identification of appropriate land management interventions.

This bottom-up participatory research approach is typically not well presented in existing poverty alleviation strategies in the rural regions worldwide, and its incorporation is considered an important step in the future improvement of agricultural livelihood. This research involved the development of a hydro-erosion-economic model, which utilised insights and information gained in the field survey and experiment, representing the most relevant aspects of the farmers' environment. This modelling framework also contains a tool for investigating the impacts of the newly suggested livelihood strategies to challenge poverty lock-in on the income of the local community. Application of the model selected relatively better livelihood strategies per village at the catchment-scale. The model results also highlight that in situ SWC interventions, implemented on degraded lands in the study region improve permeability and enhances recharge; and reduce surface discharge and sediment concentration. Additionally, the model provides evidence for the potential groundwater abstraction, and rooftop water harvesting infrastructure installation, both of which improve farmer income through increased crop yields and animal production. The PRA in learning cycle, usage of tools, methods and approaches are explained in detail in chapter 3.

Contributions to knowledge:

The overall contribution to knowledge of this project is the development of a methodological approach to co-create social-ecological data and process them using advanced computational models to generate a knowledge base on ESS in data scarce regions. This includes a strategy of identifying the role and need for data collection for constraining the model results, and quantitative aspects of the work in general and participatory approach in particular. In particular, the four most important knowledge contributions of this research project in Debre Mawi watershed are: (1) an improved understanding of the livelihood strategies to challenge poverty lock-in for the Ethiopian highlands. The proposed strategies are tested through survey and experimental research whether they are feasible to smallholder farmers. I find that they are technically feasible because they are similar to the farmers' existing livelihood strategies, with important input to appropriate link of available resources and livelihood practices. They are also feasible with minimum cost because of the limited requirements for labour and fertilizer except initial installation cost, and are expected to be profitable on the basis of a cost-benefit analysis for all farmers in the locality. The trade-offs associated with these strategies may be the initial installation cost of rooftop water harvesting infrastructures (the subsistence farmers might have money limitation to start the strategies) and also potentially problems related to crops pest, animal disease and marketing (i.e., accessibility, demand). (2) A methodology of upscaling social science data collected using PRA into real evidence generation through participatory field experiments. (3) The development of a hydro−economic model based on insights obtained with the local community in the field, which can be used as a tool to replicate the model outcomes to other rural communities in highlands of Ethiopia and Africa that depend on ESS, and to other similar regions worldwide. And (4) a method to promote participatory knowledge generation and exchange based on the collected data and the developed model.

7.3 Summary of main findings

7.3.1 Linking ecosystem services, environmental sustainability and poverty alleviation in the Ethiopian highlands

Despite the highlands' potential for food production, and intensive efforts through interventions and by the farmers to increase agricultural production, food availability per capita has been decreasing and the ESS have been severely degraded. In chapter 2, a literature review was implemented to understand what types of strategies have been implemented by the stakeholders (such as farmers, government, and researchers) to counteract poverty and continuous land degradation. This chapter analyses formal and informal decision−making processes related to ESS management made by the communities in the watersheds, where there have been different levels of intervention, in the Ethiopian highlands using a combination of scientific and grey literature review, and highlights the need for a participatory approach to problem framing and data generation and exchange, to promote both environmental sustainability and poverty alleviation.

Main chapter findings:

In this chapter 2, I found that the main degradation processes are soil structure degradation and soil loss, but also reductions in groundwater recharge, river base flow, and carbon storage. Yet, government policies that aim to address these issues are based on a strongly centralized approach that is insufficiently tailored to the local natural and social-economic context; this may result in some short-term benefits but has a high risk of jeopardizing long-term sustainability. As a potential alternative, I confirmed the usefulness of bottom-up approaches to identifying livelihood improvement strategies by means of community surveys and participatory field experiments.

7.3.2 Participatory analysis of livelihood strategies and their constraints in the upper Blue Nile basin

Poverty, which is strongly determined by the capability to satisfy individual basic needs, is a global challenge. Such needs and approaches adopted to escape poverty vary across space and time. As suggested by the review research outcome in chapter 2, Chapter 4 aimed to understand the major impediments to implementing potential livelihood strategies that may lead to poverty reduction in the upper Blue Nile basin. For this, I elucidated community-researchers' views on improved ESS management to support livelihood and environmental sustainability through detail understanding of the local social-ecological environment. I applied the following main research methodologies: participatory rural appraisal including household surveys, semi structured interviews, focus group discussions and field observations. The survey data was analysed by applying descriptive statistics, and focus group discussions, field observations and semi-structured interviews. These results were examined and summarized in relation to the quantitative data.

This participatory method makes it possible to explore the following at the catchment level under study: trends of ecosystem services and livelihood relationships; major bottlenecks to benefit from ESS; main biophysical processes perpetuating poverty; livelihood strategies for overcoming poverty; and management options at the local level in the Debre Mawi watershed. Next, the combination of the two most relevant management options obtained by the participatory rural appraisal research methodology were evaluated further through field experiment and hydro-economic modelling. The optimal livelihood strategy combines rooftop water harvesting with crop irrigation and animal production. A scenario analysis based on the benefit to cost ratio makes it possible to select relatively profitable livelihood strategy.

Main chapter findings:

Eight major ESS impediments or 'bottlenecks' were identified using PRA. These are water shortage, soil erodibility, crop pests, a fixed rainfed agricultural livelihood strategy (the farmers insist only on rainfed crop and animal production), poor soil fertility, land shortage, livestock feed scarcity and inappropriate livestock breeds. By means of the PRA methodology, I also identified the main biophysical processes that lead to poverty lock-in, i.e. soil erosion (mainly gully erosion causing reduction in arable land); drying up of streams, which reduces the availability of drinking water for livestock; and unpredictable rainfall which lowers crop production. In the study region, population growth, limited household assets and a top-down ESS management approach are the major poverty drivers. The most important livelihood strategies to overcome poverty which I found are identified as crop irrigation and livestock fattening. For both of these strategies, water scarcity was found to be the primary limiting factor. The PRA research results also suggest that poverty alleviation efforts should focus on improving water availability during the dry season. The participatory field experiments identified rooftop water harvesting as a promising approach, which can support livestock production as a viable livelihood improvement strategy.

7.3.3 A catchment–scale evaluation of the potential of groundwater abstraction and water harvesting to improve livelihoods in the Ethiopian highlands

Leveraging ESS management as a means of poverty alleviation receives increasing worldwide attention. In mountainous regions such as Ethiopian highlands, livelihood depends on ESS, particularly those provided by water and soil. In these regions, severe soil erosion by precipitation, crop production failure due to inconsistent rainfall and the dry season pronounced water scarcity happen in the same year. As a counter measure to water erosion, government-led SWC interventions have been widely implemented in the Ethiopian highlands. As a follow-up on the findings of chapter 4, chapter 5 presents a methodology to achieve the objective of identifying the best combination of groundwater abstraction and water harvesting to optimise water supply during the dry season. To attain this objective, the methodology consists of a model-based evaluation of water availability under different livelihood improving scenarios (i.e., potato and/or pepper irrigation, and/or sheep and/ or beef production). This was implemented focusing on a case study (Debre Mawi watershed).

The principle of enhancing recharge by SWC interventions, which is described in detail in chapter 5, is that these technologies increase infiltration in upper catchments. The increased infiltration in turn increases water availability in lower catchments during the dry season. This increased infiltration also decreases overland flow and thus soil loss. Currently, most upper catchment croplands, and degraded areas in particular, have been covered by SWC structures such as ditches, bunds and vegetation barriers by government led community mobilization at Debre Mawi. This may increase the fraction of infiltrating hillslopes (hillsides) areas. Consequently, dry season stream flow and groundwater can be enhanced. This was proved using discharge data which were collected before, during and after the implementation of SWC interventions, and using groundwater table height data following four steps: (1) testing the impact of SWC interventions on hillside area fraction improvement using a 95 ha gauged subcatchment data and modelling; (2) checking the constraining potential of the 2016−2017 wells groundwater table height data on the hydrological model using the present hillside area fraction, which was delineated from Google Earth and field observation; (3) upscaling and spatial and temporal mapping of the groundwater table height variability using GIS methods; and (4) identifying groundwater potential sites for water abstraction wells installation, and sites for water harvesting and lateral water flow blocking. Relating to lateral water flow blocking, I found that the existence of subsurface barriers at the catchment determine whether a well will be permanent ("steady") if it is installed at a natural fault in-between dykes (barriers). As a result, these wells will have more potential if there would also be continuous inflow of water to these faults possibly from hillsides. Finally, a set of livelihood improvement scenarios (the link between water supply and strategies to challenge poverty lock-in) were compared in order to identify the optimal combination of intervention practices at catchment level. Based on the quantified water supply (groundwater and harvested rain water amount) available during the dry season, the best (in terms of profitability) livelihood improving strategies, were identified among 4 potential options that were previously selected using a participatory rural appraisal.

Main chapter findings:

(1) The model confirmed that soil and water conservation (SWC) interventions, which were implemented at degraded lands improve infiltration hillslopes (hillsides) area by 55% during 4 years of their implementation, i.e., these interventions are enhancing recharge; (2) the current hillside area of Debre Mawi is 65.4%; considering this area, groundwater recharge was calculated to amount to 1.4 million m^3 in 2016; (3) in this thesis under chapter 5, a groundwater model is developed, to simulate water table height (WTH), which fitted well to observed WTH data (coefficient of determination, r^2 values range between 0.84−0.97) except in a few wells which were not monitored well; (4) the spatial and temporal variability of groundwater, which was determined combining a semi-distributed conceptual hydrology model, GIS tools and wells and piezometers WTH data, confirmed that during May to October groundwater is accessible throughout the watershed, whereas during the remaining months, groundwater varies spatially, i.e., groundwater is accessible only in saturated (during wet season) lower catchments and hillside areas (even though the groundwater aquifer is very deep in hillsides);

(5) for villagers living in degraded areas, it is confirmed that rooftop water harvesting is the best water source during the dry season.

Overall, the research under chapter 5 confirms that groundwater and rooftop water harvesting increase water supply during the dry season to lower and upper catchments respectively. Furthermore, scenarios analysis that links dry season water supplies with local livelihoods improvement strategies proves that animal husbandry is the best livelihood improving strategy for upper catchment residents, while crop irrigation is best suited for lower catchment residents' livelihoods. After fulfilling household's domestic water use need, rooftop water harvesting and groundwater respectively enable farmers earning a profit estimated at US$69–7704 and US$1084–2504 during the dry season from a combination of animal fattening and crop irrigation.

7.3.4 A distributed catchment–scale evaluation of the potential of soil and water conservation interventions to reduce storm flow and soil loss

Finding effective ecosystem services (ESS) management practices to counteract the increasing land degradation and poverty is becoming increasingly urgent in the Ethiopian highlands, where the livelihood security is strongly dependent on local ESS particularly those provided by water and soil. Exploring effective land management practices to challenge increasing sediment loads in major Ethiopian rivers is becoming increasingly urgent, especially in view of ongoing the construction of several hydroelectric dams (such as the Grand Ethiopian Renaissance Dam on the Blue Nile River).

Chapter 6 proves the effect of widely implemented soil and water conservation (SWC) interventions on sediment concentration and on its transport (storm flow) focusing on representative case study, i.e., Debre Mawi in the upper Blue Nile basin of Ethiopian highlands, through the implementation of a modelling approach and watershed monitoring data of a 95 ha gauged subcatchment. The catchment-scale outflow and sediment concentration were also mapped using ArcGIS. The research under chapter 5 meets three main objectives:

(1) To assess the effects of soil and water conservation practices on discharge and sediment concentration using the parameter efficient distributed (PED) hydrology and erosion model.

Using this model I analysed the effect of SWC practices by running the model before, during and after the interventions. Deviations in this relationships are attributed to SWC interventions.

(2) To map the current outflow and soil loss status at catchment level.

(3) To recommend site specific land management methods particularly soil and water conservation interventions.

Main chapter findings:

The model confirmed that SWC interventions that are implemented at degraded lands, reduce these lands' area (changed to permeable hillsides) by 53% during 4 years of their implementation, i.e., these interventions are reducing runoff and soil loss, and enhancing recharge. Subsequently, the status of spatial and temporal outflow and sediment concentration was confirmed: the degraded lands are the main sources and main occurrence is during May–July. The dry period (November–April) outflow (discharge) sources are mainly hillsides; this indicates that the precipitation which joins interflow moves out the catchment via subsurface flow even during the dry season.

Therefore, for appropriate soil and water conservation at Debre Mawi, it is recommended that the on-going SWC interventions should be expanded to be applied at the current degraded land. This includes treatment of gullies in the saturated part of the watershed (based on filed observation and PRA results, gully initiation and expansion is prevailing in the lower saturated catchment of the watershed, covered by vertisol that aggravates gully expansion) as well as blocking lateral flow in hillsides and saturated watershed regions, to natural reservoirs (which are the result of geological faults and are situated between dykes) to enhance groundwater availability during the dry season when farmers are suffering from water scarcity particularly for their livestock.

7.4 Recommendations for future work

While this study has addressed a large range of issues related to the understanding of ecosystem services, particularly water management in the context of maximizing poverty alleviation and environmental sustainability in the upper Blue Nile basin, there are a number of research areas that would benefit from further research. These are discussed below. The overall participatory bottom-up research framework, while capable of replicating the technique of involving citizen science (knowledge from the local community) with scientific knowledge to frame poverty issues and its lock-in challenging solutions would benefit from a more permanent knowledge exchange and monitoring. Continuous participatory monitoring (which is not practical in most rural mountainous farming regions, such as the Ethiopian highlands) helps to adapt unexpected circumstances particularly climatic change for livelihood resilience.

The hydrology−economic modelling framework and its findings presented in chapters 4 and 5, help to understand how to support local ESS management to maximize poverty alleviation in the Ethiopian and other tropical highlands, where the majority of the population consists of subsistence farmers and depends on local ESS. However, to ensure the sustainability of these pathways, the analysis presented here should be complemented with analysis of water quality. It will also benefit from a more detailed groundwater modelling component, particularly for the geological characterization of the catchments. The latter is particularly important to find natural faults for the installation of groundwater abstraction wells. Although in this research the farmers have already been taught how to install the rooftop water collecting infrastructure during a rooftop water harvesting experiment, participatory demonstration on the groundwater abstraction wells installation and easy water lifting techniques should be next step of this research.

While the groundwater modelling component is primarily developed by this research and the result has most pronounced economic impact for local community in the study region, this modelling framework can be further improved by including additional behavioural aspects. These mainly include, the incorporation of additional crops, climate and policy scenarios. Significant improvements can be made through additional data collection techniques. While a combination of PRA and hydrology-erosion-economic modelling provides detailed quantitative and qualitative information quickly and efficiently to maximize poverty alleviation, the addition of objective data provided through sensors (particularly for groundwater abstraction wells monitoring) would further assist in constraining the model, as well as for collecting more accurate data. It is envisaged that the PRA-hydro erosion-economic modelling and data collection framework developed during this project will be utilised and improved in further research proposed in the upper Blue Nile basin, the other Ethiopian and African highlands and worldwide ecosystem services based regions.

7.5 Concluding remarks

For the adaptive and sustainable ecosystem services management to maximize poverty alleviation at all scales, the incorporation of data representing local scale information is essential. The availability of ground-truthed information on the social-ecological context is limited, particularly in developing regions of the world where the impacts of ESS degradation and absence of local knowledge on poverty are most acute. This lack of information forms one of the major barriers to successful local ESS management, particularly water management for poverty alleviation. Addressing this issue, i.e., creating relevant tools to assess the impacts of changing climate (such as drying-up of animal drinking water sources streams and crop production failure due to inconsistent rainfall), and socio-economic needs for livelihood resilience, represents an important aspect of hydrological-economic research. In this thesis, an approach whereby qualitative and quantitative information is collected through participatory rural appraisal (PRA) including household survey, semi-structured interviews, focus group discussions and transect walk based field observation, and field experimental data such as storm flow, groundwater table height and harvested rainwater amounts are presented, and applied to a case study at Debre Mawi, the upper catchment, in the upper Blue Nile with the subsequent insights and data used to develop a hydro-economic modelling framework. The model is used to explore mainly the impacts of land management practices (especially soil and water conservation interventions in the study region) on water availability and use (groundwater and harvested rain water) and their impacts on farmer welfare in the study area.

The results highlight that due to enhanced groundwater recharge in lower catchments because of upstream SWC interventions, and the simplicity of rooftop rainwater collecting (for the upper catchment residents who are far from surface and groundwater sources) the possibility of setting-up of poverty lock-in strategies (pepper and potato irrigation and cattle and sheep fattening) is very likely to have a significant impact to farmer income. The research also highlights that groundwater resources may potentially can be exploited better (other than the current strategies proved by this research), which may lead to increased production of crops and/or animals and to increased farmers' income.

Overall, this project investigates a research design combining local knowledge and scientific hydrology-economic modelling into water supported poverty lock-in challenging strategies in a data scarce region where livelihood security is strongly dependent on rural ESS. This research highlights pathways towards improved ecosystem services management, in particular the development of improved strategies for water resource management and farming, for poverty alleviation in Ethiopian highlands and similar developing world regions where the ESS−livelihood link is very pronounced.

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Appendix

Appendix A

Literature review guide

- How is the status of livelihood and ESS relationship in the focal community? And what are the root causes of poor livelihood and unsustainable environment?
- What are the main actions by stakeholders (farmers, government and researchers) to counteract poverty and environmental unsustainability?
- What is (are) the outcome (s) of those actions? (failure, success)
- If failure what are the main reasons for failures?
- Recommendation (s) to design appropriate research methodology to find solutions to support local ESS management to improve the rural community livelihoods.

Appendix B

Participatory Rural Appraisal (PRA) research method guide

Part I: Procedural guideline for the situation analysis

- Secondary information such as climatic and demographic data will be collected through literature review and from respective organizations.
- Primary data will be collected through focus group discussion, field observation, semi-structured interview and questionnaire survey:
- For both focus group discussion and semi-structured interview, key informants from a community who are actively dependent on the local ESS and have a good understanding of the related problems, and relatively has long farming experiences (both males and females) will be selected.
- For ease of our work especially for field visit with farmers, we will divide the watershed in to upper, middle and bottom parts.

I. **Focus group discussion:** A total of three focus group discussions having a group member of 6 to 8 will be conducted from the upper, middle and lower parts of the watershed.

- For the focus group discussion, we will select a position which enables us to view the whole watershed. During the discussion we will facilitate each group to map the ESS, other resources and infrastructures on the ground in the whole watershed.
- The map of each group will be sketched on paper and used in field observation.

II. **Field observation:** We will gather information from direct observations via transect walks in the three parts of the watershed independently first. We will combine finally.

- By using the sketched maps, everything on the map will be crosschecked on the ground with each group in each subpart of the watershed. In this case, the focus group in the upper part of the watershed will visit only the upper part, and the other two groups will do the same.
- During the transect walk we will collect **people's perceptions on** biophysical data such as soil depth, erosion status, vegetation cover and all other required data. And the major problems will be identified in each physical land feature as farmers' perception.

- After the three transect walks, we will make an ESS base map at the watershed level. After that, we will call three representatives of the focus groups from each subpart of the watershed and discuss about all information in the final map for consensus, and modification based on the additional suggestions from the representatives.
- With these 9 focus group members we will analyze the interaction of the three parts of the watershed. How the ESS managements in one part affect or improve benefits from ESS in other parts and vice versa. In the meantime farmers will be invited to list major bottlenecks for their benefits from ESS and the major processes by which ESS are affected.
- Accordingly they will prioritize the main problems and processes (by pair-wise ranking).
- Based on prioritized problems and processes, farmers will be invited to mention pathways for improvement **of resilience/adaptive capacity/livelihoods**. Finally, options or scenarios from the farmers for the development will be identified.

III. **Semi structured interview**: Number of interviews will depend on data saturation, i.e. when interviews do not provide any new or additional insights, or the gathered information will be repetitive.

- We will start the interview with general but pertinent, open-ended questions.
- Interviewees will be given freedom to raise relevant issues of their own.
- Additional insights during interview should be included in the next interview.

IV. **Questionnaire survey:** Detail closed and open-ended questionnaire will be used to collect primary data. Totally, 48 households will be selected, **ideally through random sampling**, from the upper, middle and lower part of the watershed (15 in each part of the watershed). And care will be taken for the mix of gender and age, **ethnic communities**.

V. Data synthesis or summarization

- To summarize all information and make ready for the next step of the research, the collected data will be analysed using both quantitative and qualitative methods. Descriptive statistical analysis will be used to analyse quantitative data that will be collected by questionnaire survey, for example by using SPSS software.

- Data that will be gathered through focus group discussions, field observation and semi-structured interview will be summarized in relation to the quantitative data and the literature review.

Part II: Checklist for focus group discussion and semi-structured interview

A. Ecosystem services (ESS) trends

1. What are the major land uses and covers in the watershed? Where are they located in the watershed?

2. What types of ESS are delivered by the ecological systems here? And where (spatial scale) are these ESS delivered and used?

ESS categories	**List of ESS**	**Where are the ESS delivered in the watershed**	**Special scale ESS are used in the watershed**
Provisioning			
Regulating			
Supporting			
Cultural			

3. Which ecosystem services are important for the well-being of the local people, and in what way? Who uses these ESS other than the local people, how?

Important ESS for the local people well-being	**Who is most benefited from local community (gender, wealth status, age, education and others will be considered)**	**In what way they are important for those groups of people (for direct consumption, income, other)**	**Who uses these ESS other than the local people**	**How others use these ESS**

4. What are the major livelihood practices? And to which type (s) of ESS are they related? How?

5. How have the land uses/covers and livelihood practices trends been in the past 5 years? (What has been changed to what, and what has been increasing, decreasing, not changing?)

6. What are the recent trends of changes in the supply of the ESS (both in quantity and quality) and what factors are driving such changes?

7. What are the major processes that affect the most important ESS? (List and rank them).

8. What types of the most important uncertainties have you understood, including the trends of climate? How do you relate with the trends of ESS change?

9. Which group of the community currently suffers most by such uncertainties?

10. Which ESS play a central role for the relief of those most affected groups of people? How?

11. What scenarios or options do you recommend to improve the provisioning of these ESS?

12. What opportunities are available for these ESS improvement?

13. What capacity exists in the community to manage ecosystems to optimise benefits from these ESS?

14. What adaptive measures have been taken before? By whom (by farmers or by externals)

15. What success stories exist in the area that ecosystems have been managed for ESS maximization?

16. What data, knowledge and information gaps still exist to complement scenarios or options you have mentioned for improvement?

B. ESS governance

1. What are the major current institutional mechanisms that have dominant role in natural resources management? How are they implemented? Who takes the responsibility for facilitation? What are their main strengths and drawbacks?

2. Who decides on the land use changes? How? Why?

3. How formal and informal decisions are made on livelihood practices? (no. of tillage, fertilizer, irrigation, other)

4. Which kind of ESS decisions are taken individually or collectively? By whom?

5. What are the common rules to regulate the ESS governance? (Both formal and informal)

6. How the formal and informal responsibilities to regulate the ESS governance are allocated at different scales?

7. What kind of knowledge/information is used/not used in decision-making? What role does the local knowledge play in decision-making?

8. What types of actors are wrongly included/excluded in decision-making? Why?

9. Why people participate in the ESS governance? (in both formal and informal)

10. How is the linkage between the formal and informal decision- makers? Who are the most influential? Who can make decisions to change the delivery or use of ESS?

11. When do the formal decision-makers make the local community aware about the new planning processes? How? For what purpose?

12. How can the relationships between formal and informal decision- makings be improved?

13. What are the recurring conflicts of interest in decision-making? Around what issues are they raised?

14. What mechanisms for conflict resolution exist?

15. What would be the most desirable decision-making scenario (s) on ESS for poverty alleviation and environmental sustainability?

16. What type of new information is required to improve the ESS governance? To which governance scale?

C. Livelihoods and poverty

1. What changes have been observed in the local livelihoods in the last 5 years?

2. What dimensions/constituents of well-being are most deteriorated (material, health, social relations, security, freedom of action)? In what ways are they related to the trends of ESS?

3. What are the current development and poverty alleviation activities supported by government and NGOs? What and how are they doing? How do you comment such interventions?

4. What are the major bottlenecks of the local people especially the poor to benefit from ESS? Are there specific pathways socially or ecologically dependent that constrain people from getting out of poverty (or poverty traps)?

5. Can the local people mobilise alternative pathways (are there alternative pathways for getting rid of yourself from poverty traps) to improve your well-being? How?

6. What types of scenarios or options do you recommend to improve the livelihood according to the pathways you have mentioned?

7. Who are the winners/losers of these pathways? (gender, age, education, wealth status, others will be considered)

8. What opportunities are available for these pathways?

9. What kind of biophysical, social, institutional or other information is lacking to complement the pathways?

* What about the other facilities? (Road, market for both input and output, education, health, other) Discuss about their accessibility, impacts on ESS and livelihood.

Part III. Questionnaire survey

General Information

Zone ____________________ Woreda: ______________Kebele:___________

Sub-Kebele /Gote: ____________________ Household No (code): _____________

Respondent's Name: ______________ Ethnicity______________

Residence (Born here/migrant) ____________Date: ____________

Part One: Demographic information

S/N	Name of HH members	Sex (M/F)	Age	Relation with head of HH: **code 1**	Marital status: **code 2**	Educational status: **code 3**	Occupation: **code 4**
1	Respondent						
2							
3							
4							
5							
6							

Code 1:	**Code 2**	**Code 3:**	**Code 4:**
1=Head 2=Spouse 3=Son/daughter 4=Son/Daughter-in-law 5=Father/Mother 6= Sister/Brother 7=Father/Mother-in-low 8=other_____________	1=Married 2=Single 3=Widowed 4=Divorced 5=other	1=Illiterate 2=Can read & write only 3=Elementary (1-4) 4=Junior (5-8) 5=High school (9-10) 6=Above high school 7=Religious knowledge	1=Agricultural activities 2=Off-farm laborer (masonry, pottery, selling of beverage, other) 3=Combination of the two 4=Not engaged b/se he/she is student, disabled, other

Part Two: Household assets

S/N	Asset item	Quantity (No.)	Market value (Birr)	S/N	Asset item	Quantity (No.)	Market value (Birr)
1	Oxen			12	Radio		
2	Cows			13	Phone/mobile		
3	Donkey			14	Improved stove		
4	Bulls			15	Bicycle		
5	Horse			16	Bed		
6	Mule			17	Chair/sofa		
7	Small ruminant (sheep/goat)			18	Table		
8	Calves			19	Grass roofed house		
9	Chicken			20	Corrugated iron sheet house		
10	Bee hives			21	Others (specify)		
11	Farming tool in set						

Part Three: Ecosystem services and their accessibility to the community

<table>
<tr><th colspan="3">Question</th><th>Response</th></tr>
<tr><td colspan="3">1. What are the major natural capitals you have understood from the ecosystem</td><td>Water resources (rivers, streams…), cultivated land, pasture land, forest land, biodiversity, landscape beauty, wetlands, others…</td></tr>
<tr><td colspan="4">2. What types of ESS can be obtained from these ecosystem elements, and how do you get benefits from these ESS?</td></tr>
<tr><td>S/N</td><td>Types of natural capital</td><td>ESS from these natural capitals</td><td>The way how the farmers can be benefited from these ESS</td></tr>
<tr><td>2.1</td><td>Water resources</td><td></td><td></td></tr>
<tr><td>2.2</td><td>Agricultural land</td><td></td><td></td></tr>
<tr><td>2.3</td><td>Pasture land</td><td></td><td></td></tr>
<tr><td>2.4</td><td>Forest land</td><td></td><td></td></tr>
<tr><td>2.5</td><td>Wetlands</td><td></td><td></td></tr>
<tr><td>2.6</td><td>Biodiversity</td><td></td><td></td></tr>
<tr><td>2.7</td><td>Landscape beauty</td><td></td><td></td></tr>
<tr><td>2.8</td><td>Other</td><td></td><td></td></tr>
<tr><td colspan="3">3. Is there any ESS that you want to collect but not accessible?</td><td>Yes/No, If yes, please explain why?</td></tr>
</table>

4. What about the ecotourism? Is there any landscape or any feature in the area that can attract tourists?

5. What modification such features and landscapes need to be more attractive***?***

6**. Institutional mechanism for ESS management:**

6.1. Who makes decisions on the distribution of natural capitals and ESS?

(Key local decision making bodies, government or other)

Natural capitals	**Primary decision making body**	**Other participating institutions**	**Remarks**
Water supply (household)			
Water supply (irrigation)			
Herb/NTFPs			
Pasture land			
Forest			

6.2. How is your access to those resources? (Sufficient, less, enough) Please explain……..

6.3. Do the local people have equal access to these resources? **Yes/No**. If no, what is the main reason for such unequal distribution? (Ethnicity, economic condition, other) please explain.

6.4. In your opinion, how can we make ESS more equitable to all?

6.5. Have you seen any conflict on ESS utilization and distribution? **Yes/No**. If yes, related to which resources and why?

6.6. How do you resolve conflicts at local level? Which institutions involve and how do they make decision?

Part Four: Land use pattern by the household

Land use type	**Area (ha)**	**Fertility status**	**Slope type**	**Soil depth**	**Soil type**
Cultivated land for rainfed crops production					
Cultivated land for irrigated crops production					
Grazing land					
Forest land/ plantation					
Homestead farms with perennial crops					
Abandoned land					
Others, specify					
Total land area (ha)					

*Do you have rented in/out land? How much ha? Rent in______, from whom? __________ for what purpose? _______________Rent out _______, to whom?_______________

Part Five: Cropping pattern in the last five years

1. Which crops have you grown commonly in the last five years? Why do you select them? Please rank the selection criteria.

Crop type	**Total annual production/qu**	**For household consumption in qu**	**For selling in qu**	**Price /qu**	**Why do you select them: use Code**
Cereals					
Pulses					
Oil crops					
Vegetables					
Fruits					
Other					

Code: 1=Suitable for the area (good for SWC) 4=High yielding
2=preferable for household consumption 5=Others
3=Better economic value (price)

2. Historical change in main crops production (over the last 5 years)

Crop type	Total production			Main reason
	Increasing	Decreasing	Not changing	

3. Does the harvested yield from your own cropland meet your family's food requirement? **Yes/No**.

3.1 If no, for how many months can it be enough? ____________

3.2 How do you get enough food for your family for the other months? Rank the mechanisms

S/N	Mechanisms	For how many months can it be enough	Crop product availability to purchase		Total payment for purchasing
			Local market (in their village)	Outside market	
1	Food aid				
2	Participation in food/cash for work programs				
4	Gifts from friends/ relatives				
5	Purchase (Crop type)				
5.1					
5.2					
5.3					
6	Other, specify				

4. Have you been using improved crop varieties and fertilizer? **Yes/No**.

S/N	If yes				If No, what is the reason? **Use Code**
	Crop variety	Starting year	Main reason	Any change in production (increased/ decreased/ no change)	
1					
2					
3					
Inorganic fertilizer					
1	DAP				
2	Urea				
3	Other				
Organic fertilizer					
1	Compost				
2	Farm-yard manure				
3	Others				
Code: 1=Not available locally 2=Little or no knowledge on the use and application 3=No significant change in yield comes					4=Expensive 5=Others

4.1 Who decides on the use of improved crop varieties and fertilizers? Why?

4.2 Do you think or have an observation that new technologies affect the environment? How?

4.3 In your opinion, which new crop variety (varieties) and fertilizer(s) may improve the land productivity and household income? Please explain.

5. Have you been using agriculture calendar since the last five years? If yes fill in the table in months of a year?

Crop types	Variety	Seed rate	Fertilizer rate kg/ha		Plowing				Sowing	Weeding	Harvesting	Yield (quintal/ha)	
			Urea	DAP	1st	2nd	3rd	4th				Good year	Bad year

6. Have you encountered crop failure in the last five years? **Yes/No**. If yes rank main reasons.

Reasons for crop failure	**Rank**	**Reasons for crop failure**	**Rank**
Poor seed quality		Crop pest/ disease	
Rainfall irregularity		Sever erosion	
Frost		Water logging	
Poor farm management		Other	

7. How do you use the following labour sources to manage your crop production activities?

S/N	Labour source	For which agricultural activity: **Use code**	When (Month)
1	Household labour (who: wife, son…)		
2	Hired labour		
3	Labour exchange		
4	Others		
Code: 1=Plowing 2=Weeding 3=harvesting 4=other			

*If you hire workers, would you specify the wage rate you pay? (Birr per labor) __________

Part Six: Livestock rearing pattern in the last five years

1. Livestock management practices (annual estimate)

S/N	Type of livestock	Feed sources: **use code**	Feeding system (at home or free grazing)	Feeding calendar (Months)	Rearing cost (Birr)	Selling place (locally/outside market)	Total income (Birr)	Any change in the livestock production in the last 5 years	Main reason for the change
1									
2									
Code for feed sources: 1.Grass from grazing land 2.Hay (harvested grass) 3.Straw (crop by product) 4.Other									

2. What type of grazing land have you been using?

Grazing land	**Area (ha)**	**Distance (km)**	**Any change in grass quality or quantity in the last 5 years?**	**Main reason for the change**
Private land				
Communal land				
Other				

3. How do you solve the livestock feed shortage? Rank the solutions in order of importance.

A. Feed purchase **B**. Migration for grazing **C**. Reducing livestock number **D**. other, ____

4. Do you have grazing land access in neighbouring villages? **Yes/No.** If yes, how often are your animals allowed to graze in that grazing land? Daily/seasonally…

5. What are the major issues/uncertainties that hamper your livestock productivity?

Major issues/uncertainties	**Explain the reasons**	**Major issues/uncertainties**	**Explain the reasons**
Lack of grazing land		Unfavourable climatic conditions	
Grazing land degradation		Lack of manpower for management	
Lack of sufficient water supply for cattle		Animal health problem	

6. What do you think for the improvement of livestock production in this area?

Part Seven: Irrigation

1. Have you (yourself and other villagers) been practicing in irrigation farming? If yes go to next questions

2. What type of crops do you grow using irrigation and how do you manage them?

Crop type	Area coverage (ha)	Irrigation schedule	Water amount per application	your normal crop yield (qtl/year)

3. How do you decide times and volumes of irrigation?

4. Where do you get your irrigation water from?

5. How far is your water source from crops?

6. Do you pay for some/all of your water (monitory or some other kind of payment - how much?)

7. Do you sell some/all of your water? How much do you charge?

8. What is the yield of the water source(s)? -try to estimate based on duration of pumping and other.

9. How much water do you get from the water source(s) you mentioned?

10. Do you have any other methods for collecting water on your land? (E.g. rainwater harvesting etc.)

11. Have you noticed a change in groundwater levels? How do you describe the trend? Why?

12. Are there any problems with irrigation in your village? Yes/ No

13. If yes, which kind of problems?

- Water shortage (amount)
- Water timing ("late")
- Water quality
- Other:____

14. What is the reason of this problem?

- Poor infrastructure (poor technical aspect/channel)
- Lack of collaboration between farmers using water for irrigation
- Polluted water (harmful chemicals in water)

- Other:___________________________________

15. Is there a Water User Association in this village? Yes/No
16. If yes, are you satisfied with its work? Yes/No
17. If not, what should be improved? ____
18. When you need information, where (whom) do you turn to?
    - Neighbors
    - Religious leader/group
    - Village government/council
    - Other
19. What do you suggest for the improvement of irrigation farming in this area? Please describe in relation with the optimization of the effectiveness of rainfall.

Part Eight: Biodiversity

1. Have you been collecting wild products? **Yes/No.** If yes, which and how much wild products (herbs & non-timber forest products) do you collect (in kg/year)? How often do you collect them?

2. How much do you consume and/or sell those collected products? And, if you sell them, how much money do you earn from them every year?

3. How do you understand their current status compared to 5 years ago both in type and quantity? (Increased, decreased, not-changed) please specify the main reason?

Part Nine: Fresh water, Energy sources and Sanitation

I. Fresh water sources and consumption

S/N	**Questions**	**Response**
1.1	**Fresh water sources and supply**	
1.1.1	What is the main source of household freshwater supply?	Individual pipeline, public tap, rivers, streams springs, Others……
1.1.2	Is the water available from above sources sufficient for your daily household needs?	**Yes/No**. If no, please specify the reason. How it challenges your life?
1.1.3	How many months and from which alternative sources do you have to fetch your fresh water from alternative sources?	No of months:……. Alternative sources: Individual pipeline, public tap, rivers, streams, springs, Others…
1.1.4	Who is mainly responsible for fetching water?	Men, women, children, others
1. 2	**Fresh water consumption**	
1.2.1	Do you know the amount of freshwater that you require to fulfil your household demand?	**Yes/No**
1.2.2	How much water do you use per day?	Please specify in litres (…..) or in other……
1.2.3	Do you have any quality related problems with the current freshwater supply?	**Yes/No**, If yes, please specify and explain the cause
1.2.4	Do you pay for your freshwater use?	**Yes/No**, If No, please go to question 3.
1.2.5	How much do you pay for it? Has it fixed price?	Please specify……..

1.3. What do you recommend for the freshwater quantity and quality improvement?

2. Household energy sources and supply

Types of uses	Main source	Cost of main sources (monthly)	Alternative sources	Cost of alternative sources (monthly)
Lighting				
Cooking				
Heating				
Others				

2.1 Who collects fuel wood mostly in a year? (Mother/ wife, son, daughter, father, other…)

2.2 For how long do you walk to collect fuel wood (average in hours and km/month)?

3. Basic sanitation and solid waste management practice

3.1 What type of sanitary facility do you have? **I.** Interior toilet with flush mechanism **II**. Interior toilet without flush mechanism **III**. Public toilet **IV**. Others

3.2 How do you manage your household solid waste?

I. Using disposal pit **II**. Disposal in to river or stream **III**. Community collection

IV. Open burning **V**. Use for composting **VI**. Others

Part Ten: Soil erosion and Soil and water conservation

1. Have you encountered soil erosion problem in your farm land/watershed? **Yes/No**

2. If yes, how serious is it? (very severe, severe, moderate, some) **Underline it**

3. If yes, which erosion type? Rank them:

I. Sheet erosion **II**. Rill erosion **III**. Splash erosion **IV**. Gully erosion

4. How do you describe the erosion pattern within the past five years? Why?

II. Highly increasing **II**. Moderately increasing **III**. Highly stabled **IV**. Moderately stabled

5. In which part of the watershed has highly sever erosion occurred? (Upper, middle, bottom) **underline,** and which type of erosion**?**

6. In which month has erosion been more severe? _________.Why? ________________

7. What are the main erosion causing factors in your farmland/watershed? Rank them? (topography steepness, high rainfall, low vegetation cover, poor land management, other_)

8. How do you recognize the impacts of soil erosion in your area? (yield redaction, removal of top soil, increase inputs demand, Other __________)

9. Have you tried to minimize soil erosion in the past five years? **Yes/No**. If yes How? (using SWC measures, crop rotation, using agricultural inputs, Other___________)

10. Effectiveness of conservation measures that have been implemented in the watershed?

Types of SWC measures	Highly effective	Moderately effective	To some extent effective	Ineffective	Who decides on their implementation	Who implements them
Soil bund						
Stone bund						
Fanya juu						
Trenches						
Waterway/cut-off drain						
Check dam						
Grass strip						
Mulching/crop residue						
others						

11. How have these conservation measures been constructed? (food for work, cash for work, community mobilization, others ________________)

12. Have you maintained these conservation measures? **Yes/ No**. If no why?

13. Have negative effects encountered due to SWC measures implementation? **Yes/No**. If yes, what are they? Please explain their cause (s)

14. What is your suggestion for effective soil and water conservation?

Part Eleven: Household income/ expenses and Migration in the past 5 years

1. Household income and expenses (monthly)

Monthly income		**Monthly expenses**	
Income source	**Income amount (Birr)**	**Expense source**	**Cost (Birr)**
Wage		Food	
Farm products		Cloth	
Wood and wood products		Health	
Others		Education	
		sanitation	
		Energy	
		Other	

- Have you ever taken credit(s)/loan(s) Yes/No
- If yes, from whom? (bank, relatives, other) ____________ and for what purpose? _________
- If no, why not?
- What are the main social networking events that you have been commonly participating?
- How much money have you spent within the last 12 months for social networking?
- How difficult it was to participate in social networking?
- What is the most optimal form of accumulating money, in your opinion?

2. Have you been practicing in any of the following migration?

Types of migration	**When and where?**	**Main reasons**
Seasonal		
Temporary		
Permanent		

Part Twelve: Infrastructure facilities

S/N	Infrastructure	Accessibility 1=Easily 2=difficult 3=Not yet	Distance form house: <u>use code</u>	Provider
1.	Public Telephone			
2.	Weather road			
3.	Bus station (transportation access)			
4.	Market center			
5.	Grain mill (woficho bet)			
6.	Input supply shop/cooperative			
7.	Primary school (up to grade 4)			
8.	Junior secondary school (grades 5 to 8)			
9.	Senior secondary school (grades 9 to 10)			
10.	Health center (clinic)			
11.	Veterinary clinic			
12.	Major water source for animals (wet season)			
13.	Major water source for animals (dry season)			
<u>Code for distance:</u> <u>A</u>.<30min <u>B.</u> 30min to 1:00 <u>C.</u> 1:00 to 1:30 <u>D</u>. 1:30 to 2:00 <u>E</u>. 2:00 to 3:00 <u>F</u> >3:00				

Part Thirteen: Transportation for marketing

1. The main mode of transport used to carry goods from home to market or market to home. (Use tick Mark)

On shoulder / human	On donkey or mule.	Horse	Vehicles	Other (specify)

2. In the on shoulder mode of transportation, who mostly used to? _______

3. Who decides on the money management?

Part Fourteen: Extension services

1. Have you received any agricultural extension service? **Yes/No**.

2. If yes, who is the main agricultural extension service provider in your area? (governmental extension (DAs and experts), research centers, NGOs, others ______)

3. In which area did you receive training? (Crop production and management, animal production and forage development, soil and water conservation, irrigation, forest management and utilization, other________)

4. Have you get enough knowledge? **Yes/No,** explain your answer

Part Fifteen: Environmental uncertainties

1. Have you noticed/been observing any changes in precipitation? **Yes/No**, if yes,

I. Changes in timing: early rainfall/late rainfall **II.** Rainfall amount: more/less/no change

2. Have you felt any change in temperature? **Yes/No,** If yes,

I. Day time: hotter / colder **III.** Changes in cold winters (if yes, since when?)

II. Night time: hotter /colder **IV**. Changes in hot summers (if yes, since when?)

3. Is wind speed decreased or increased through time? Do you know the reason?

4. Does dust particle brought by wind affect agricultural production? **Yes/ No**. If yes, how?

5. What do you think about the status of hail occurrence through time? (Decreasing, increasing, no change)

6. What are the most common natural disasters in your area? **I**. Landslides **II**. Erosion **III**. Floods **IV**. Droughts **V**. Hailstorms **VI**. Lightning **VII**. Any other

7. What preventive/mitigating measures have been applied for minimizing the effects of natural disasters?

8. Have you ever attended any awareness creation programme on natural disasters such as flooding, droughts and landslides? **Yes/No**, if yes, please specify.

9. What is your opinion for mitigation or adaptation of these disasters?

Part Sixteen: Social Capital

1. Do you give and accept from your neighbours following types of assistance? *(tick)*

Types of assistance	Give to neighbours	Accept from neighbours
Agricultural work		
House construction		
Preparation for social ceremonies		
Money		
Food		
Other:______________________		

2. How much influence do you think people like yourself can have in making this village a better place to live?

- A lot
- Some
- Not very much
- None

3. Have you been involved over the past 2 years in any government/NGO-organized workshop/training course? Yes/No

4. If yes, please describe: ___________________________________

5. In times of trouble whom do you turn to for financial support?

- Relatives
- Rich villagers
- Bank (loan)
- Religious leader/group
- Informal village organization/group
- Other:_____________________________________

6. Whom do you turn to for non-financial support (moral guidance, advice?

- Relatives
- Neighbours
- Elders' court
- Religious leader/group
- Other:____________________________

Appendix C

Participatory field experiment and data collection guide

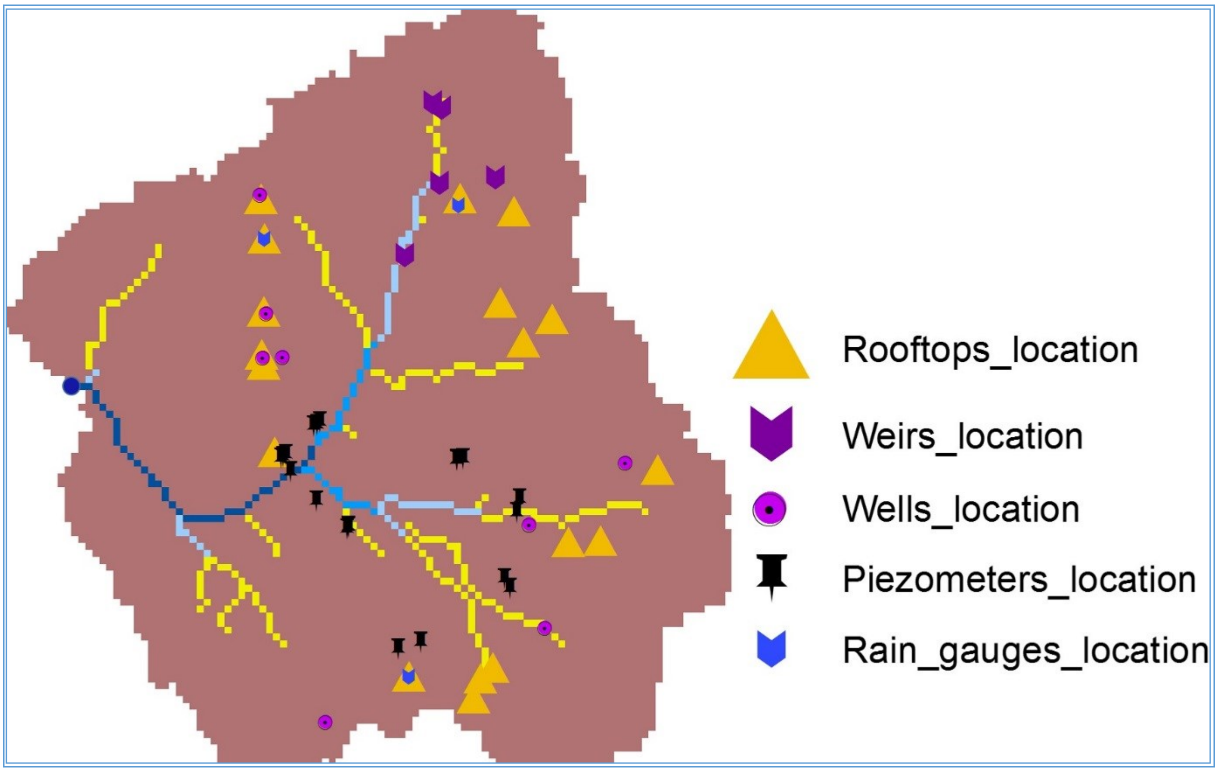
1. Rooftop water harvesting experiment using 18 households

2. **Flow rate and soil loss monitoring using 5 spatially distributed gauging stations (weirs)**

3. Groundwater table height monitoring

4. Catchment-scale rainfall spatial and temporal variability monitoring using manual and automatic rain gauges (installed at 3 locations at watershed)

5. All installed instruments for experiment and data collection in the 716 ha Debre Mawi watershed



Appendix D

Poverty alleviation maximizing ESS management options selection using data and modelling

- Water availability investigation using data and modeling (combining PED and ArcGIS tools),
- Water demand analysis for domestic use and agricultural diversification to improve livelihood, for example crops water requirement determination using CROPWAT8.0,
- Catchment-scale best poverty lock-in challenging ESS management strategies selection through scenarios comparison and cost-benefit analysis.