# Sustaining reservoir use through sediment trapping in NW Ethiopia

**Mulatie Mekonnen Getahun**

**Thesis committee**

**Promotor**
Prof. Dr L. Stroosnijder
Professor of Land Degradation and Development
Wageningen University

**Co-promotors**
Dr S.D. Keesstra
Associate professor, Soil Physics and Land Management Group
Wageningen University
Dr J.E.M. Baartman
Assistant professor, Soil Physics and Land Management Group
Wageningen University

**Other members**
Prof. Dr J. Wallinga, Wageningen University
Prof. A. Cerdà, University of Valencia, Spain
Prof. Dr J. Nyssen, Ghent University, Belgium
Dr. L.H. Cammeraat, University of Amsterdam

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# Sustaining reservoir use through sediment trapping in NW Ethiopia

**Mulatie Mekonnen Getahun**

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I dedicate this PhD thesis to the memories of my father, Ato Mekonnen Getahun, my mother, W/ro Asselef Biresaw and my sisters (Yeasabe Mekonnen, Balechiw Mekonnen and Yirbebu Mekonnen) whom I never forget forever. I admired my mam and dad forever, for sending me school to learn without having any formal education and for their generous support. They are my practical lessons of devotion, commitment, kindness and affection. I am proud of them ever. Were they alive, they would be very happy for me. May God rest them in peace!

## መታሰቢያ

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# Chapter 1

# Introduction

# Introduction

## 1.1 The problem

Koga reservoir is one of the largest reservoirs in northwest Ethiopia, Figure 1.1. It is a key project for the Ethiopian government, towards achieving food self-sufficiency at the regional level.

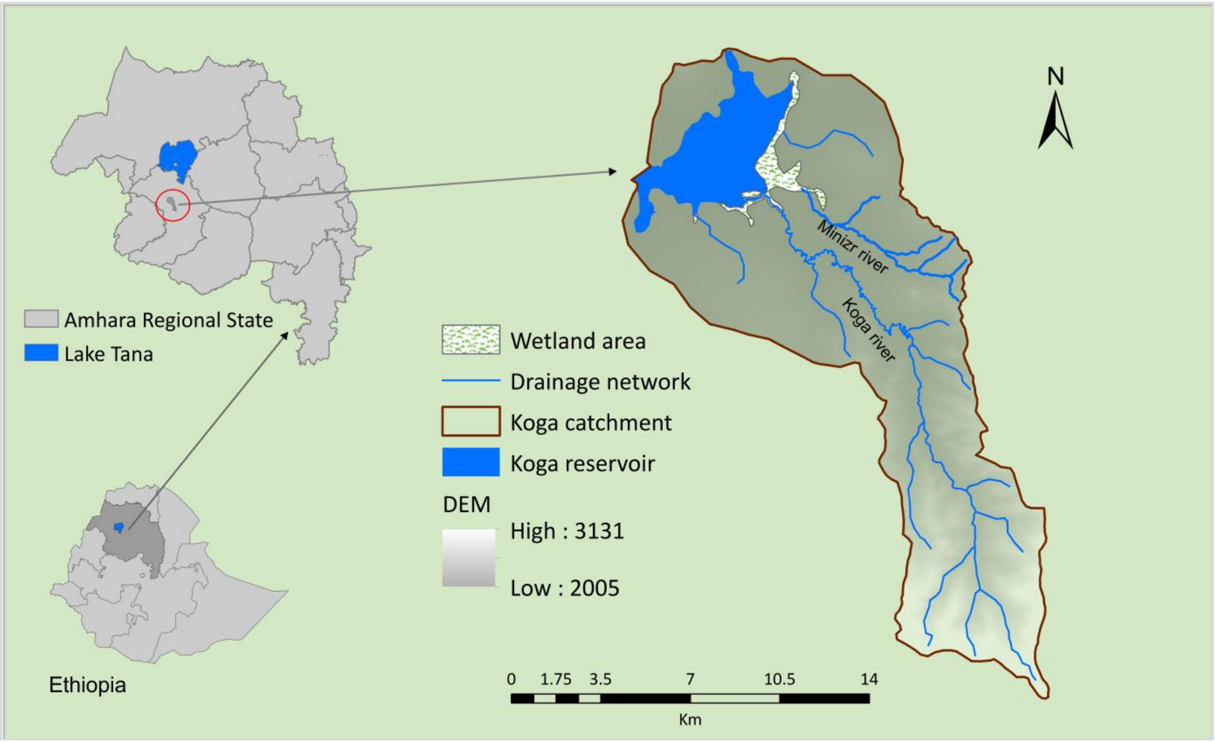


***Figure 1.1*** *Map of Ethiopia, Amhara Regional State and Koga reservoir*

Koga reservoir was constructed at the outlet of Minizr (20 km$^2$) and Koga (143 km$^2$) catchments in 2008 to collect surface runoff and river water for irrigated agriculture. Koga is the major river transporting water from Koga catchment to Koga reservoir and Minzr is the second largest river transporting water from Minizr catchment to Koga reservoir.

Koga reservoir can store about 83 million m$^3$ of water and the area inundated is about 17 km$^2$, hence the average depth (at maximum filling) is about 5 m.

At the time of construction (2008) the lifetime of the reservoir was estimated at 50 years. Sedimentation due to soil erosion in the catchments was estimated (using the Universal Soil Loss Equation) at 48,000 m$^3$ y$^{-1}$ with a sediment yield of 3.7 t ha$^{-1}$ y$^{-1}$ (MoWR, 2008). However, recent studies show that the reservoir is losing its storage volume at a much faster rate. For instance, Assefa *et al.* (2015) estimated at 84,800 m$^3$ y$^{-1}$ with a sediment yield of 6.0 t ha$^{-1}$ y$^{-1}$; Reynolds (2013) estimated at 700,000 m$^3$ y$^{-1}$ with a sediment yield of 55 t ha$^{-1}$ y$^{-1}$; and Yeshaneh *et al.* (2014) estimated at 269,000 m$^3$ y$^{-1}$ with a sediment yield of 26 t ha$^{-1}$ y$^{-1}$.

So, in spite of massive investments in soil conservation measures in the catchments, the reservoir lifetime is threatened by sedimentation. Rapid water storage loss due to sedimentation is becoming an important factor undermining the sustainable use of the reservoir. Figure 1.2 shows Koga reservoir with dark brown colour due to high suspended sediment concentration.

The reservoir represents an important economic value in the area. It can irrigate about 7,000 ha of land and benefit about 14,000 farmers living downstream of the reservoir. Currently farmers are producing fruits, crops and vegetables two or more times per year. Maize, potato, green pepper, cabbage, garlic, onion, tomato, carrot and beetroot are the main products largely produced by farmers from Koga irrigated agriculture.

The urban population of Merawi and Wetet Abay (the nearest towns) with an estimated population of 15,000 and large number of people living in Bahir Dar, the capital city of Amhara Regional State, are also benefiting from the irrigation infrastructure.

***Figure 1.2*** *Koga reservoir with dark brown coloured water due to high suspended sediment concentration*

The soil conservation measures that were constructed in the catchments were aiming at reducing sheet erosion by reducing the erosive power of overland flow due to runoff. Runoff is reduced by increasing infiltration and runoff speed is reduced by reducing slope length. So, considerable effort was made to implement soil bund and *fanya juu* ridges (reducing slope length) and micro-trench structures (increasing infiltration).  Over 144 km of soil/stone bunds and *fanya juu* ridges and >576 micro-trenches were constructed within Minizr catchment alone.

Apparently, the current approach to soil conservation is not sufficient to reduce the sediment load reaching the reservoir. This is the problem addressed in this thesis.

## 1.2 Scientific objective

The general objective of this study was to evaluate the sediment load at Koga reservoir and if that load is considered too high to design measures to lower that load.

Although authorities are concerned about the life time of Koga reservoir, available data on sediment load, as presented in the introduction (Section 1.1) are not consistent. Hence before we can design effective measures, we have to evaluate current sedimentation into the reservoir.

Parts of Koga catchment has received a lot of assistance in on-site physical soil conservation measures like *fanya juu*, soil bund and micro-trenches. The questions is how effective this investment has been in retarding sediment load into Koga reservoir.

Besides these more-or-less standard on-site physical soil conservation measures there maybe biological measures or off-site measures that are more effective. A specific challenge for the Koga system is that it contains a wetland and a floodplain and that we know very little of their function in relation to sediment trapping. These questions call for a firm literature study and depending on its outcome on some real-world experimentation with alternative (in the sense that they are yet unknown in the area) measures.

Finally the 'spatial' question should be raised. With a wide choice of measures, both physical and biological and on-site as well as off-site options there is a need for a kind of optimization in space. In other words, where to apply what?

## 1.3 State of the art

On-site soil erosion and off-site sedimentation are natural phenomena in landscape formation. However, human activities have accelerated natural erosion rates causing on- and off-site problems with soil degradation and sediment accumulation in undesirable locations (reservoirs, rivers, etc.). Human induced off-site sedimentation is the product of on-site soil erosion resulting either from point sources like mining and construction sites or non-point sources such as from agricultural areas and grazing lands.

In Ethiopia, rates of soil erosion are alarmingly high and sedimentation in reservoirs, lakes, and rivers is a serious problem (Haregeweyn *et al.*, 2006; Tamene *et al.*, 2006a). Many reservoirs which have been established for hydroelectric power, urban water supply and irrigation accumulate large amounts of sediment, resulting in shortage of water supply for these functions and decline in reservoirs water storage capacity. Some of the dams in the Amhara region of Ethiopia, like the dams of Adrako, Borkena and Dana (Amare, 2005; Kebede, 2012) have completely silted up before their design expectation period. Other dams in this region that have been constructed over the last decades are threatened by accelerated sedimentation.

Until recently, most studies and development activities that aim at reducing the sediment load in the reservoirs were focused on on-site soil and water conservation (SWC) measures on agricultural areas in the catchment. Off-site soil conservation measures is largely disregarded. Many technical and socio-economic opportunities were documented but adoption by farmers and actual improvements in the field are limited. In addition, such SWC measures are never designed to eliminate sediment loss and transport completely. In its best, these measures reduce soil loss till a Tolerable Soil Loss level. Hence, there will always be drainage out of a catchment that is loaded with some sediment.

According to Walling (2006), although on-site soil conservation measures result in reduced catchment sediment yields, sediment trapped by dams at the outlets of sub-catchments represent the dominant cause of reduced catchment sediment yields. Sediment storage dams (SSDs) are best examples, which have been implemented by the Ethiopian government in the Amhara region over the last decades. According to MERET (2008), one possible way to trap sediment in the sediment cascade is using SSDs to be built at the outlets of sub-catchments within the larger catchment. However, their efficacy in trapping sediment is not well known.

Natural sediment sinks, that include wetlands, floodplains and grassed waterways, are important off-site sediment trapping (ST) features. For example, in southwest France, floodplain sediment deposition rates ranged from 0.02 to 75 kg $m^{-2}$ $y^{-1}$ (Brunet & Astin, 2008) and the Imperial Valley wetland in California, USA showed a STE of 97% (Kadlec *et al.*, 2010). Even though floodplains and wetlands cover large areas in Ethiopia, especially bordering natural lakes and man-made reservoirs, their role in trapping the inflow sediment coming from the surrounding land and thus reducing rate of sedimentation is not well studied.

Vegetative ST measures (like grass barriers) can play a significant role in trapping sediments from overland flow by decreasing the speed and erosive potential of runoff water (Blanco-Canqui *et al.*, 2006). Although different studies had been conducted and information is available on the performance of such vegetative measures, especially in North America and Europe, there is a scarcity of quantitative information for tropical regions. Many grass species that could potentially serve as vegetative barriers have not been studied for their sediment trapping efficacy (STE), including the locally used grass species in the north-western Ethiopian highlands, Desho (*Pennisetum pedicellatum*), Senbelet (*Hyparrhenia rufa*), Sebez (*Pennisetum schimpri*) and Akirma (*Eleusine floccifolia*). Such local grass species may have better sediment trapping performance than the known ones. Therefore, instead of introducing and using vegetative species from other areas, evaluating the locally dominant and available species for their STE and using them is urgent.

To design and implement appropriate ST measures within a catchment and reduce sediment transport to downstream reservoirs, detailed information on the temporal and spatial distribution of erosion events and sediment source areas is essential (Herweg & Stillhardt, 1999; Mekonnen & Melesse, 2011). According to Verstraeten *et al.* (2003), to implement relevant sediment management measures within an upstream catchment, it is crucial to realize the severity of the sedimentation problem and the major factors controlling it.

Different approaches exist to estimate surface runoff, soil erosion and sediment yield from a catchment including models (Mekonnen & Melesse, 2011; Keesstra *et al.*, 2014a), sediment rating curves and river samplings (Yeshaneh et al., 2014), bathymetric surveys (Tamene et al., 2006a) and trapped sediment analysis (Baade *et al.*, 2012; Stefanidis & Stefanidis, 2012). Each approach has its advantages and disadvantages in relation to data requirement and availability, easiness for application and cost effectiveness. An approach requiring minimal and easily accessible input datasets and is cost effective, is the best approach in data scarce countries like Ethiopia.

## 1.4 Research hypothesis and research questions

Our hypothesis is that erosion can never be stopped sufficiently in NW Ethiopia and that on-site and off-site ST measures are needed to reduce the sediment load into valuable reservoirs till a safe level.

In other words, not all efforts should focus on soil conservation, but also on the safe routing of sediment-laden flows and on creating sites and conditions where sediment can be trapped, preferably in a cost effective or even profitable way.

Measures that promote sedimentation within farmers' fields are called 'on-site' measures and those outside the sphere of influence of individual farmers' fields are 'off-site' measures. On-site ST measures reduce overland flow velocity and thereby retard sediment in transport, resulting in sediment deposition within fields before sediment can be discharged into streams. Off-site ST measures reduce concentrated runoff velocity within (ephemeral) gullies and the river channel system thereby enhancing infiltration of water and deposition of sediment.

Integrated sediment trapping at catchment scale, which is implementing all possible on-and off-site ST measures at the required locations within the catchment, is assumed to reduce land-scape connectivity, enhance ST (sediment trapping/deposition) within the catchment and decrease sediment discharge at the outlet of a catchment.

To this end, the following research questions have been formulated dealt with in separate chapters

1. Is Minizr catchment an important source of sediment for Koga reservoir? If so, how much is the sediment load? Is there spatial and temporal variation? (Chapter 2).
2. What is the best method or approach to be used while implementing ST measures within a catchment, which helps to reduce sediment in transport to downstream reservoirs? (Chapter 3).
3. Are the locally dominant indigenous grass species in northwest Ethiopia (Desho, Senbelet, Akirma and Sebez) effective in trapping sediment from agricultural fields? What are the key functional traits, which will play a great role for ST? How much of the inflow sediment trapped by the grass barriers, with what STE? (Chapter 4).
4. How much sediment can be trapped by sediment storage dams? With what STE? Are they economically feasible for the small-scale farmers' in Ethiopia? (Chapter 5).
5. How much sediment is trapped by the existing physical ST measures, with what STE? How much sediment is trapped by natural sediment sinks, with what STE? Are man-made and natural sediment sinks reducing the Koga reservoir sediment load? (Chapter 6).
6. Is it possible to use a landscape model (LAPSUS_D) in the northwest Ethiopian highlands to help with integrated sediment trapping at catchment scale by optimizing the use of ST measures? (Chapter 7).

## 1.5 Research design

***Study area***

The study was conducted in the Minizr catchment in the North-western highlands of Ethiopia (UTM 1255891 - 1249499 N; 303559 - 310272 E; Adindan_UTM_Zone_37N, Figure 1.3) which is a source of water for the Koga reservoir. It covers an area of 20 $km^2$ with an elevation range of 2035 m at the outlet to 2283 m.a.s.l. at its highest point on the watershed divide. Slopes in the catchment range from 0-51% (average of 8%), while >80% of the catchment has slopes between 0-8%.

Land use within the catchment area includes 71% farmland, 18% grazing land, while plantation, bush land and settlement areas account for the remaining 11%. Average rainfall (2013-2015) was 1215 mm $y^{-1}$, which falls mainly between June to September, and is preceded and followed by one month of sporadic, low intensity rain. Average minimum and maximum temperatures are 11$^0$C and 26$^0$C. Based on FAO classification system, dominant soil types are Nitosols (62%), Eutric Vertisols (30%), Lithic Leptosols (6%) and Chromic Cambisols (2%) (MNREP, 1995).

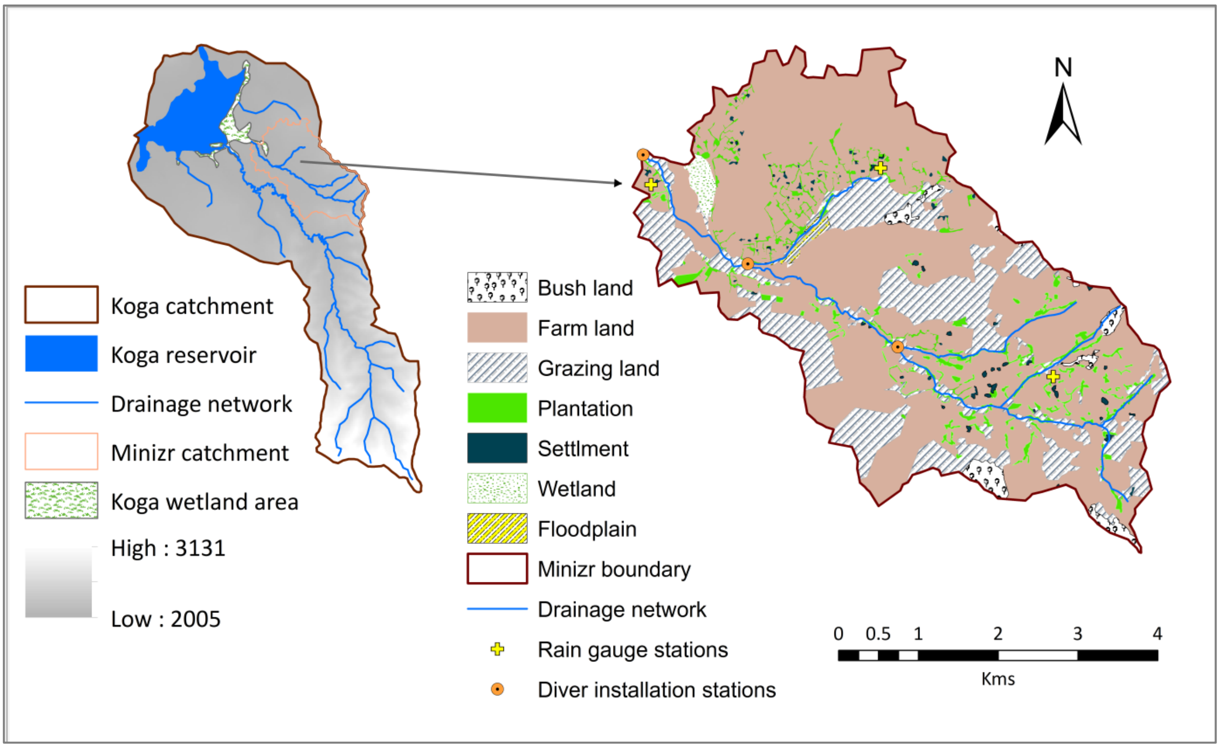


***Figure 1.3*** *location map of the study area showing Koga reservoir, Koga and Minizr catchments, rainfall and runoff-sediment discharge monitoring stations*

***Datasets and mapping***

Satellite images; SPOT 5 m and Google Earth 0.6 m resolutions, were used to prepare land use / land cover; to digitize and quantify the lengths of physical ST structures (soil bunds and *Fanya Juu*); to identify and map natural sediment sinks (wetland, floodplain and grassed waterways); to delineate areas affected by gully erosion and gully dimensions; and to digitize and determine the lengths of sediment transfer pathways. A topographic map 1:50,000 scale (EMA, 1987) was used to delineate the boundaries of sub-catchments and their drainage networks. A Digital Elevation Model (ASTER DEM 30 m; 2009) was used to derive the elevation and slope characteristics. GPS (Garmin GPS 60, 2 m accuracy) was used to collect track line of sediment pathways, catchment pour points, diver and rain gauge installation stations. Detailed descriptions of the datasets and mapping procedures were given in each chapter.

***Data collection methods and analysis***

The data collection methodologies used in this research were intensive field survey and observation, interviewing stakeholders, a comprehensive literature review of scientific journal articles, multi-location field experiments, runoff and sediment yield modelling, field level primary data measurements, Satellite Imagery and DEM analysis. Data analysis was done using excel; IBM SPSS statistics 22 software; a daily resolution runoff and sediment yield model, LAPSUS_D and ArcGIS 10.2.1 spatial analyst. A hydrometer method was used for texture analysis. Each of the data collection and analysis methods have been described in each chapter.

## 1.6 Definition of terms and concepts

According to ISSS (1996), a catchment/watershed is defined as the area which supplies water by surface and subsurface flow from rain to a given point in the drainage system.

A vegetative ST measure is a band of growing vegetation (trees or grasses) across the slope, to slow runoff, increase infiltration, and cause sediment to be deposited. A grass strip/barrier is a band of grass laid out on cultivated land along the contour to trap sediment in transport.

Structural ST measures are embankments across the slope, to slow runoff, increase infiltration, and cause sediment to be deposited (For example soil/stone bunds, micro-trenches).

Critical sediment source areas or erosion hotspots are parts of the catchment with high erosion rates and high sediment transport capacities (McDowell & Srinivasan, 2009; Mekonnen & Melesse, 2011) while sinks are areas of infiltration and sedimentation, which lower hydrological connectivity and decrease the area-specific runoff and sediment yield (Lesschen *et al.*, 2009).

Sediment storage dams are physical structures or barriers built of stone, gabion or concrete and located within large sized and deep gullies or inside temporary river channels to trap sediment (MERET, 2008).

Soil/stone bund is an embankment along the contour, made of soil and/or stones, with a basin at its upper side to reduce or stop overland flow and its effect in causing erosion (Hurni, 1986).

According to Bracken *et al.* (2015) sediment connectivity can be used to explain the continuity of sediment transfer from a source to a sink in a catchment that occurs via transport vectors (e.g. water, wind, glaciers, gravity, animals).

Verstraeten and Poesen (2000) defined sediment trapping efficacy (STE) as the proportion of the incoming sediment that is deposited, or trapped, in a reservoir or behind sediment trapping measures (check dam /sediment storage dams or grass barriers or SWC structures).

Integrated sediment trapping can be defined as implementing all required sediment trapping measures at the most appropriate spatial locations within a catchment to decrease runoff velocity and sediment transport and thus increase sedimentation. Integrated sediment trapping focuses on technological integration as part of an integrated catchment management approach (MOARD, 2005), which is integrating sectors, systems, technologies, resources, etc within a catchment to solve natural resource degradation and other related problems (like health and education) focusing on community participation.

A wetland is a lowland area, such as a marsh or swamp, that is saturated with moisture (American Heritage Dictionary, 2011).

A floodplain a nearly flat plain area along the course of a stream or river that is naturally subject to flooding (Goudie, 2004).

## 1.7 Conceptual framework and thesis outlines

This thesis consists of eight chapters. The introductory chapter describes the problem statement, scientific objectives, state of the art, research hypothesis, specific research questions, research design and definition of key terms.

Chapters 2 to 7 build on each other and form together the conceptual framework of this thesis (Figure 1.4). Most chapters are based on scientific papers that have been published or have been submitted to peer reviewed journals, all of which are stand alone and independent.

Chapter 2 attempts to estimate the sediment load and take away the uncertainty of the amount of sediment entering Koga reservoir. Intensive field measurements took place for three years (2013-2015). This provides insight in the spatial and temporal variations of sediment load within the catchment. The role of sediment transfer pathways density on landscape connectivity and sediment yield is also evaluated.

Chapter 3 investigates what is already known about sediment trapping measures. It presents an overview on the sediment trapping efficacy (STE) of physical and vegetative sediment trapping (ST) measures at global scale, reviewing more than 90 scientific journal articles, case studies, government reports, conference proceedings and book chapters. In addition there are participatory field observations and stakeholders' interviews.

This review leads to three promising directions of research. Since we can expect effective sediment trapping using grass strips we evaluated a number of species in a field trial described in Chapter 4. Since we found that drainage channels, gullies and footpaths are main sediment transfer pathways, sediment dams are also considered an interesting option which we investigated in Chapter 5. Finally it is worthwhile to know the trapping efficacy of existing man-made soil and water conservation structures in the catchment such as soil bunds, *fanya juu* and micro-trenches (Chapter 6). The same holds for the existing natural sediment sinks like the floodplain, the wetland and different waterways.

Chapter 7 tries to identify the best approach for implementing a combination of sediment trapping measures within the Minizr catchment using the daily resolution LAPSUS_D model.

The final chapter is a synthesis of previous chapters. It not only summarizes the main results but also discusses the scientific value of the thesis and its limitations. Furthermore attention is given to recommendations for policy, extension and further research.

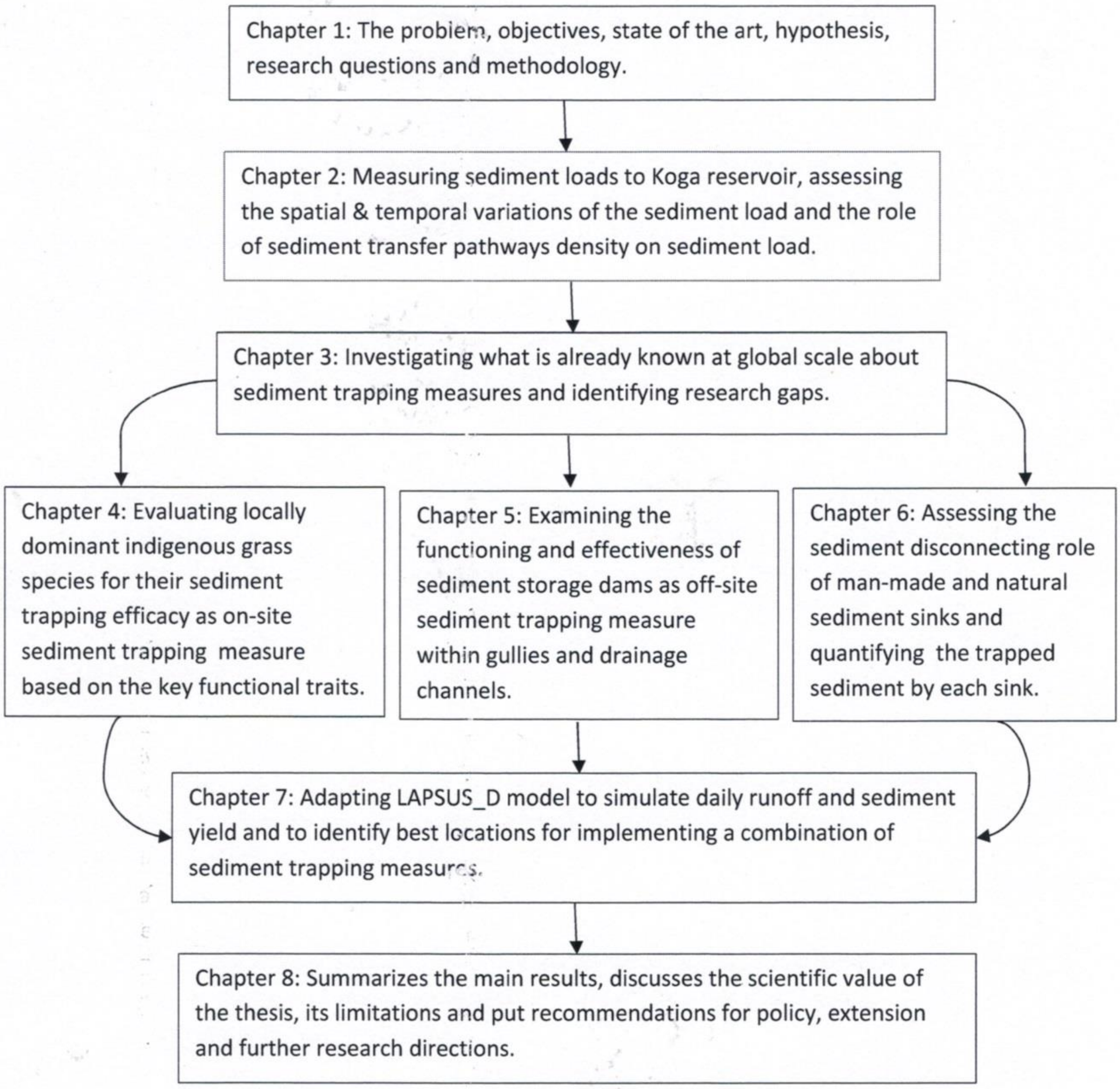


***Figure 1.4*** *Conceptual framework of the thesis*

# Chapter 2

# Spatial and temporal variations of sediment entering Koga reservoir, NW Ethiopia

This paper is submitted as:
Mulatie Mekonnen, Saskia D. Keesstra, Jantiene EM Baartman, Leo Stroosnijder, Rens JH Masselink.
Spatial and temporal variations of sediment entering Koga reservoir, NW Ethiopia.
Earth Surface Processes and Landforms

# Spatial and temporal variations of sediment entering Koga reservoir, NW Ethiopia

*Abstract*

*Soil erosion within a catchment does not only remove the soil but also reduces the water storage capacity of downstream reservoirs because of sedimentation. In Ethiopia, this is a major problem in many reservoirs, including the Koga reservoir in NW Ethiopia. This study was conducted in Minizr catchment to quantify the amount of sediment entering Koga reservoir, to identify potential sediment source areas at sub-catchment scale, to assess temporal variation in sediment production on daily, monthly and yearly basis and to identify sediment transfer pathways (STPs), which could enhance sediment connectivity and facilitate sediment transport. Insight herein could help to intervene the siltation problem of the reservoir. To collect runoff and sediment discharge data, three hydrological monitoring stations, each consisting of a pressure transducer (diver) and staff gauge were installed both at the outlet of the main catchment above the reservoir and at the outlets of two sub-catchments. Data was collected at the outlet of the main catchment for three years (2013-2015) and at the outlet of the sub-catchments for two years (2014-2015). Results show that on average ~43,000 t (21.5 t ha$^{-1}$ ) sediment entered Koga reservoir annually. Midre-Genet sub-catchment had the highest density of STPs (4.7 km km$^{-2}$) and gullies, which contributed most to the total sediment measured (19,400 t y$^{-1}$) followed by Adibera sub-catchment (13,100 t y$^{-1}$). Tume-Shafrie sub-catchment with the lowest STPs density and without gullies, contributed the least to the total sediment measured (6,700 t y$^{-1}$). Temporally, daily and monthly sediment discharges were highest in July and August. Drainage channels, gullies and footpaths were found to be the main STPs enhancing sediment connectivity and transport. As a result, large amounts of sediment are entering Koga reservoir, which considerably compromise its water holding capacity. Therefore, sediment trapping measures, which helps to trap the sediment, enhance sedimentation within the catchment and disconnect the sediment connectivity functions of the STPs will help to decrease the sediment entering the reservoir.*

## 2.1 Introduction

Construction of dams to collect surface water for irrigation, human and animal consumption and electric power generation is carried out at an increasingly fast rate all over the world, resulting in more than 45,000 registered large dams (WCD, 2000; ICOLD, 2007), together storing ~11,000 km$^3$ of water (Chao *et al.*, 2008). However, many dams are seriously threatened by sedimentation and are losing their water storage capacity, with an estimated yearly average of 0.5-1% (Walling, 2006; Basson, 2008).

Water erosion plays a large role in transporting sediments from upstream catchments to downstream reservoirs. Although any slope, and any place where water flows is potentially a sediment transfer pathway (STP), rivers, gullies and roads are important STPs (Poesen *et al.*, 2003; Morgan, 2005; Bracken *et al.*, 2015). An increase in the density of STPs will increase sediment transport while disconnecting STPs reduces sediment transport and increases sedimentability (Fryirs, 2012; Mekonnen *et al.*, 2016b; Thompson *et al.*, 2016). To study the processes involved in sediment transport over particular pathways, the concept of connectivity was used (Bracken et al., 2015; Parsons *et al.*, 2015; Masselink *et al.*, 2016), which allows studying catchment scale processes in a holistic way. The concept of connectivity works with source areas, STPs and sinks, and tries to identify how processes within these different units in the system interact. Sediment connectivity can be used to explain the (dis)continuity of sediment transfer from a source to a sink in a catchment that occurs via transport vectors (e.g. water, wind, animals) (Bracken et al., 2015).

Disconnecting STPs through efficient sediment trapping (ST) measures could help to increase sediment deposition and reduce downstream sediment loads (Keesstra *et al.*, 2009; Baartman *et al.*, 2013; Mekonnen *et al.*, 2016a; Mekonnen et al., 2016b). Identifying the STPs within a catchment helps to implement ST measures where they can disconnect the STPs to enhance ST (Lloyd *et al.*, 2016). Implementing ST measures at the most appropriate locations where they can disconnect landscape units, is believed to be the most efficient way to reduce reservoir sedimentation (Mekonnen *et al.*, 2014).

Sediment discharge from a catchment is highly variable both temporally and spatially (Hagmann, 1996; Yeshaneh *et al.*, 2014; Buendia *et al.*, 2016), which is because the processes driving catchment sediment dynamics have proved to be highly variable in space and time (Liu *et al.*, 2012). Over recent decades, there has been an increased interest in quantifying sediment loads of intra-annual (within a year) variability in addition to inter-annual (between years) in order to improve understanding of suspended sediment loads at a higher temporal resolution (Smith *et al.*, 2003; Seeger *et al.*, 2004). This increased interest for intra-annual variability arose because it was shown that for many catchments only a small part of the catchment and only a few heavy rain storms on specific dates produced the bulk of annual sediment yield (Hagmann, 1996; Ziadat & Taimeh, 2013).

Therefore, it is important to have better insights in the spatial and temporal variability of the intra-annual sediment budget of a catchment. Where are the sources of the sediment? Are there hotspots of sediment production/sedimentation in the system? Which are the most vulnerable moments in the year that the sediment is transported to the outlet of the system? Insights into these dynamics can help to identify sediment sources, to design improved land management strategies, to reduce sediment production, to decrease sediment transport capacity within the system; and finally, to allow the STPs to pass through areas where the sediment can be trapped (Stroosnijder, 2009; Bracken et al., 2015; Lloyd et al., 2016; Mekonnen et al., 2016b). According to Herweg and Stillhardt (1999) and Mekonnen and Melesse (2011), identifying the critical sediment discharging periods and the respective erosion hotspots producing the sediment are vital to design and implement suitable ST measures.

In Ethiopia, the rates of on-site soil erosion and downstream sedimentation in water reservoirs are alarmingly high (Haregeweyn *et al.*, 2006; Tamene *et al.*, 2006a). Many reservoirs which have been established for hydroelectric power, drinking water supply and irrigation accumulate larger amounts of sediment than expected (Amare, 2005; Kebede, 2012). Koga reservoir is one of the largest reservoirs constructed in the northwest highlands of Ethiopia to collect surface runoff for irrigated agriculture. It is constructed at the outlets of Koga and Minizr catchments. It stores up to 83 million $m^3$ of water and can irrigate ~7000 ha of land. The reservoir is expected to benefit ~14,000 farmers living below the dam in the irrigation command area to produce crops, vegetables and fruits (MoWR, 2008).

However, the reservoir lifetime is threatened by high sedimentation rates. Figure 2.1 shows the brown, high sediment laden water of the Koga and Minizr rivers, draining into the Koga reservoir. Yeshaneh et al. (2014) found that the upper part of Koga catchment (~98 $km^2$) alone contributed ~252 000 t $y^{-1}$ (25.6 t $ha^{-1}$ $y^{-1}$) of sediment to the Koga reservoir. Sediment yield from the other contributing catchment, the Minizr catchment, has not been measured yet. The Minizr catchment has characteristics that differ from the upper Koga catchment in terms of topography, soil type and land management interventions. In addition, the Minizr catchment has natural sediment sinks like a wetland and a floodplain which can play an important role in disconnecting the STPs and trapping sediment (Mekonnen et al., 2016c).

Therefore, the main objectives of this study in the Minizr catchment, northwest Ethiopia were to: (i) estimate the sediment entering Koga reservoir from Minizr catchment and evaluate its temporal (daily, monthly and yearly) and spatial (sub-catchment scale) variation and (ii) identify potential STPs and evaluate their role on the spatial variations of sediment discharge for sediment control measures using the concept of connectivity.


***Figure 2.1*** *Examples of high suspended sediment loads in the Minizr (a) and Koga (b) rivers. These rivers both drain into the Koga reservoir (c) (photo by Mulatie Mekonnen, 2012)*

## 2.2 Materials and methods

*Study area*

The study was conducted in the Minizr catchment in the North-western highlands of Ethiopia (UTM 1255891 - 1249499 N; 310272 - 303559 E; Adindan_UTM_Zone_37N, Figure 2.2) which is an important source of water for the Koga reservoir. It covers an area of 20 km$^2$ with elevation ranging between 2035 m at the outlet to 2283 m.a.s.l. at its highest point on the watershed divide. Slopes in the catchment range from 0-51% with a mean slope of 8%. More than 80% of the catchment has slopes between 0-8%.

Land use within the catchment area includes 71% farmland, 18% grazing land, while plantation, bush land and settlement areas account for the remaining 11%. Mean annual rainfall (2013-2015) is 1215 mm, which falls mainly as high intensity rainfall from June to September, and is preceded and followed by one month of sporadic, low intensity rain. Average minimum and maximum daily temperatures are 11$^0$C and 26$^0$C, respectively. Dominant soil types are Nitosols (62%), Eutric Vertisols (30%), Lithic Leptosols (6%) and Chromic Cambisols (2%) (MNREP, 1995). Table 2.1 shows the slope, elevation and dominant soil types of the sub-catchments of the Minizr catchment.

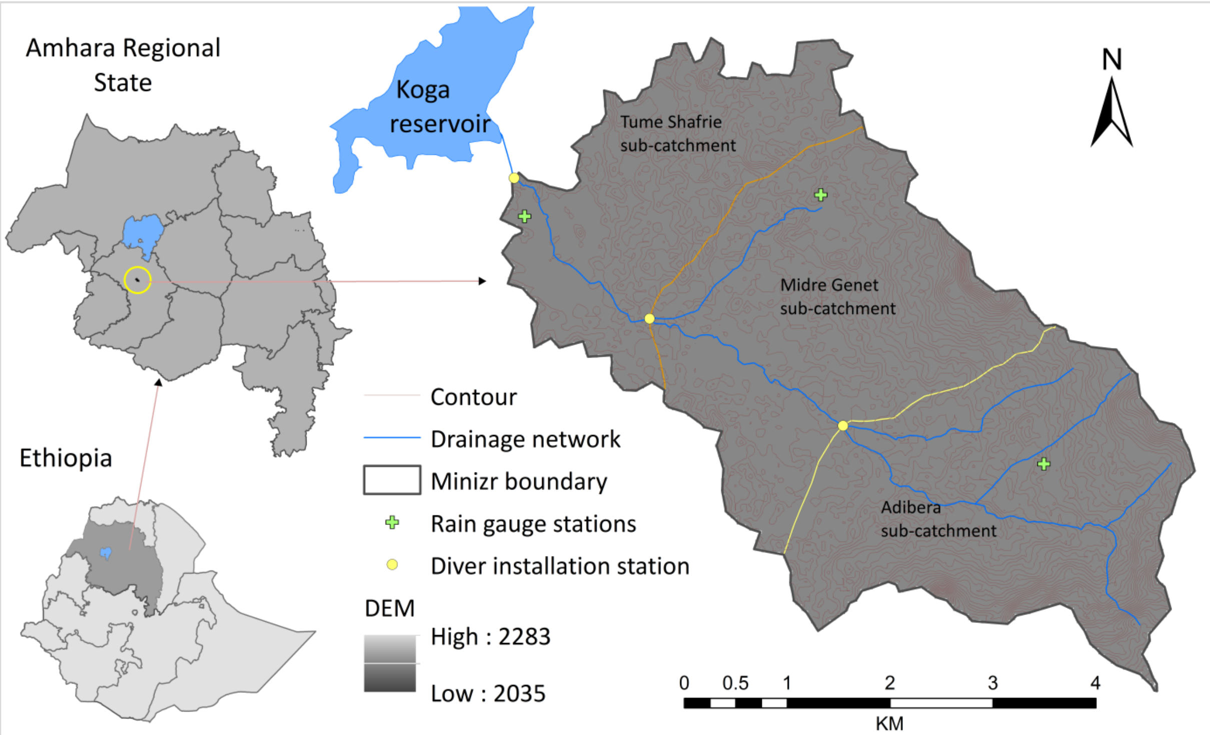


***Figure 2.2*** *Location map of Minizr with sub-catchments, rain gauge and diver installation stations.*

*Mapping*

A Digital Elevation Model (ASTER DEM 30 m; 2009) was used to delineate Minizr catchment using an automatic delineation method and to generate slope and elevation characteristics. A topographic map 1:50,000 scale (EMA, 1987) was used to delineate the boundary of each sub-catchment (Adibera, Midre-Genet and Tume-Shafrie). ArcGIS 10.2.1 software was used for mapping and a GPS (Garmin 60, ~2 m accuracy) was used to indicate locations of rain gauge and diver installation stations and to collect pour points of the catchment outlets. Moreover, GPS helped to track STPs and accurately digitize them on Google map.

*Estimating runoff*

To collect runoff and sediment discharge data, three hydrological monitoring stations consisting of pressure transducers (divers) and staff gauges were installed at the outlet of the main Minizr catchment and at the outlets of two sub-catchments, Adibera and Midre-Genet (Figure 2.2). The data collection station for the third sub-catchment, Tume-Shafrie, was at the same location as the main catchment because they have the same outlet. The monitoring stations were established on relatively stable and steep cross sections with uniform water flow and channel dimensions.

***Table 2.1*** *area coverage, average slope, elevation and dominant soil types of the Minizr sub-catchments*

| Sub-catchments | Position within the main catchment | Area (ha) | Average slope (%) | Elevation (m) | Dominant soil type |
|---|---|---|---|---|---|
| Adibera | Upstream | 780 | 10 | 2059-2283 | Nitosols |
| Midre-Genet | Middle | 760 | 7.5 | 2049-2221 | Vertisols |
| Tume-Shafrie | Lower/outlet | 500 | 7 | 2035-2127 | Nitosols |

Stream water level was monitored continuously at the outlet of the main catchment for three years (2013-2015) and at the outlets of the two sub-catchments for two years (2014-2015) with a temporal resolution of 15 minutes during the rainy seasons. Stream channel width was measured directly in the field using tape meter. River flow velocity (m $s^{-1}$) was measured using the Valeport 'Braystoke' Model 001 current meter at different water depths. During peak flow, we measured the flow velocity at 10 cm intervals, starting from the peak until the water height reached its minimum. This measurement was done three times and the mean value was considered for each height. Runoff discharge ($m^3$ $s^{-1}$) was then calculated using Eq. 2.1 multiplying the channel width (m), water depth (m) and river flow velocity (m $s^{-1}$) (FAO, 1993). The measured discharges in $m^3$ $s^{-1}$ were converted to daily discharge ($m^3$ $day^{-1}$). Daily runoff discharges were summed up to find monthly and annual discharges.

$$Qw = A*V \qquad 2.1$$

Where, Qw is discharge in $m^3$ $s^{-1}$; A is channel cross sectional area ($m^2$) and V is flow velocity (m $s^{-1}$)

*Estimating sediment discharges*

Sediment entering Koga reservoir from Minizr catchment was calculated from suspended sediment concentration samples and Eq. 2.2 (McGregor & Cook, 2006; Blanchard *et al.*, 2011). Daily measured suspended sediment concentration was used without developing a rating curve since the daily collected data was considered more representative. A one-litre suspended sediment sample was collected every day during the rainy seasons of 2013-2015. The staff gauges were used to follow the change in the water level that helped to collect suspended sediment samples when changes in water level occurred. If water level changed significantly during a day due to heavy rainfall, two or more sediment samples were collected per day at different river water flow heights. These samples were then mixed and a one-litre sub-sample was taken for further analysis. A total of 411 one-litre samples (137 in year 2013; 141 in year 2014; and 133 in year 2015) were collected at the outlet of the main catchment. The collected samples were oven dried at 105 $^{0}$C for 24 hours and the dry sediment mass was used to calculate suspended sediment concentration (g $l^{-1}$). Daily sediment discharge (t $day^{-1}$) was calculated using Eq. 2.2 by multiplying the estimated daily water discharge ($m^3$ $s^{-1}$, see above) and the suspended sediment concentration (g $l^{-1}$) measured for that same day. Daily discharges were summed up to find monthly and annual discharges.

$$Qs = Qw * Cs * K \qquad 2.2$$

Where, Qs is sediment discharge (t $day^{-1}$); Qw is water discharge ($m^3$ $s^{-1}$); Cs is concentration of suspended sediment (g $l^{-1}$) and K is 86.4, which is a coefficient to express Qs in t $day^{-1}$.

*Identifying sediment source areas*

Within a large catchment, sediment source areas can be identified using e.g.: (i) erosion models (Van Rompaey *et al.*, 2001; Mekonnen & Melesse, 2011; Keesstra *et al.*, 2014b), (ii) suspended sediment discharge measurements at the outlets of sub-catchments (Syvitski & Milliman, 2007; Yeshaneh et al., 2014) and (iii) field survey methods during and after rainstorms (Bewket & Sterk, 2003; Zegeye *et al.*, 2010).

In Minizr catchment the spatial variation in sediment production was assessed dividing the larger catchment into sub-catchments and measuring suspended sediment discharge at the outlets of each sub-catchment (*see above, estimating sediment discharge*). We classified Minizr catchment into 3 sub-catchments (Figure 2.2).

*Identifying sediment transfer pathways*

With the advent of high resolution satellite imagery, sediment transfer pathways (STPs) can be identified and studied (Otto et al., 2009). We identified major STPs such as rivers, footpaths and gullies and observed their sediment transport function during an intensive field survey with GPS walks. Sample GPS tracks were collected following STPs which aids in identifying and digitising them from the satellite imagery. Lengths of STPs were digitized and quantified from Google Earth (Quick bird) Imagery using Arc GIS 10.2.1. To check location accuracy, overlaying (layering GPS shape files over digitized shape file) was applied. STPs density was calculated by dividing the total STPs length by the catchment area.

Gullies are not only STPs but also sources of sediment influencing catchment sediment yield. In southern New South Wales for the Warragamba catchment, for instance, sediment yields from gullied catchments of 29, 52, and 510 ha were at least one order of magnitude higher than for un-gullied catchments (Armstrong & Mackenzie, 2002). In this study, gully affected land was quantified using Google Earth Satellite Imagery and GPS. GPS tracks made around gully affected lands were used for verification while digitizing gullies on the image. Moreover, four gullies were selected before the start of the rainy season and their change in dimension (length, width and depth) was measured at the end of the rainy season and the volume (V, $m^3$) of sediment generated was calculated using Eq. 2.3.

$$V = (L2 * A2) - (L1*A1) \qquad 2.3$$

Where L2 is newly developed gully length (m); L1 is gully length (m) before development; A2 newly developed gully area ($m^2$) and A1 is gully area ($m^2$) before development.

## 2.3 Results

*Runoff and sediment discharges*

On average ~43,000 t of suspended sediment and ~4,500,000 $m^3$ runoff is entering Koga reservoir annually (Table 2.2). In area specific terms, mean sediment yield was 21.5 t $ha^{-1}$ $y^{-1}$, varying from 17-27 t $ha^{-1}$ $y^{-1}$. Highest annual sediment discharge was recorded in 2013 and lowest sediment discharge in 2015, which corresponds to rainfall amounts, which were also highest in 2013 and lowest in 2015. Annual rainfall amount and runoff, and runoff and sediment discharges showed a good relationship with the coefficient of correlation ($R^2$) = 0.94 and ($R^2$) = 0.95, respectively.

***Table 2.2** Annual runoff and sediment entering Koga reservoir from Minizr catchment (2013-2015)*

| year | Rainfall (mm) | Runoff ($m^3$) | Sediment (t) | Sediment yield (t $ha^{-1}$ $y^{-1}$) |
|---|---|---|---|---|
| 2013 | 1,431 | 5,820,000 | 54,000 | 27.0 |
| 2014 | 1,269 | 4,424,000 | 39,700 | 20.0 |
| 2015 | 944 | 3,267,000 | 34,900 | 17.5 |

The largest amount of sediment entering Koga reservoir within one month was recorded in July (14,900 t), followed by August (12,300 t) (Table 2.3). From the total sediment entering Koga reservoir, 63% was transported in July and August. Runoff discharge showed an increasing trend from May to September and reduced in October. July showed the highest mean suspended sediment concentration (~12 g $l^{-1}$) followed by August (8.9 g $l^{-1}$).

Daily runoff and sediment discharges showed a good relationship for all rainy months with the coefficient of correlation ($R^2$) ranging from 0.71 to 0.93, with the overall coefficient of correlation at 0.70 (Figure 2.3). Base flow increases the daily runoff discharges towards the end of the rainy season as observed in the graph (Figure 2.4).

***Table 2.3*** *Mean (2013-2015) monthly rainfall, suspended sediment concentration, runoff and sediment discharges at Minizr catchment.*

| Month | Mean monthly rainfall (mm) | Mean monthly runoff ($m^3$) | Mean monthly sediment concentration ($g\ l^{-1}$) | Mean monthly sediment load (t) |
|---|---|---|---|---|
| May | 82 | 251,000 | 6.2 | 1,890 |
| June | 191 | 568,000 | 7.6 | 5,400 |
| July | 383 | 1,078,000 | 12.2 | 14,900 |
| Aug | 291 | 1,189,000 | 8.9 | 12,300 |
| Sept | 240 | 1,306,000 | 5.9 | 8,100 |
| Oct | 28 | 112,000 (15 days) | 4.4 | 370 |
| STDEV | 131.8 | 509,628.7 | 2.7 | 5730.3 |

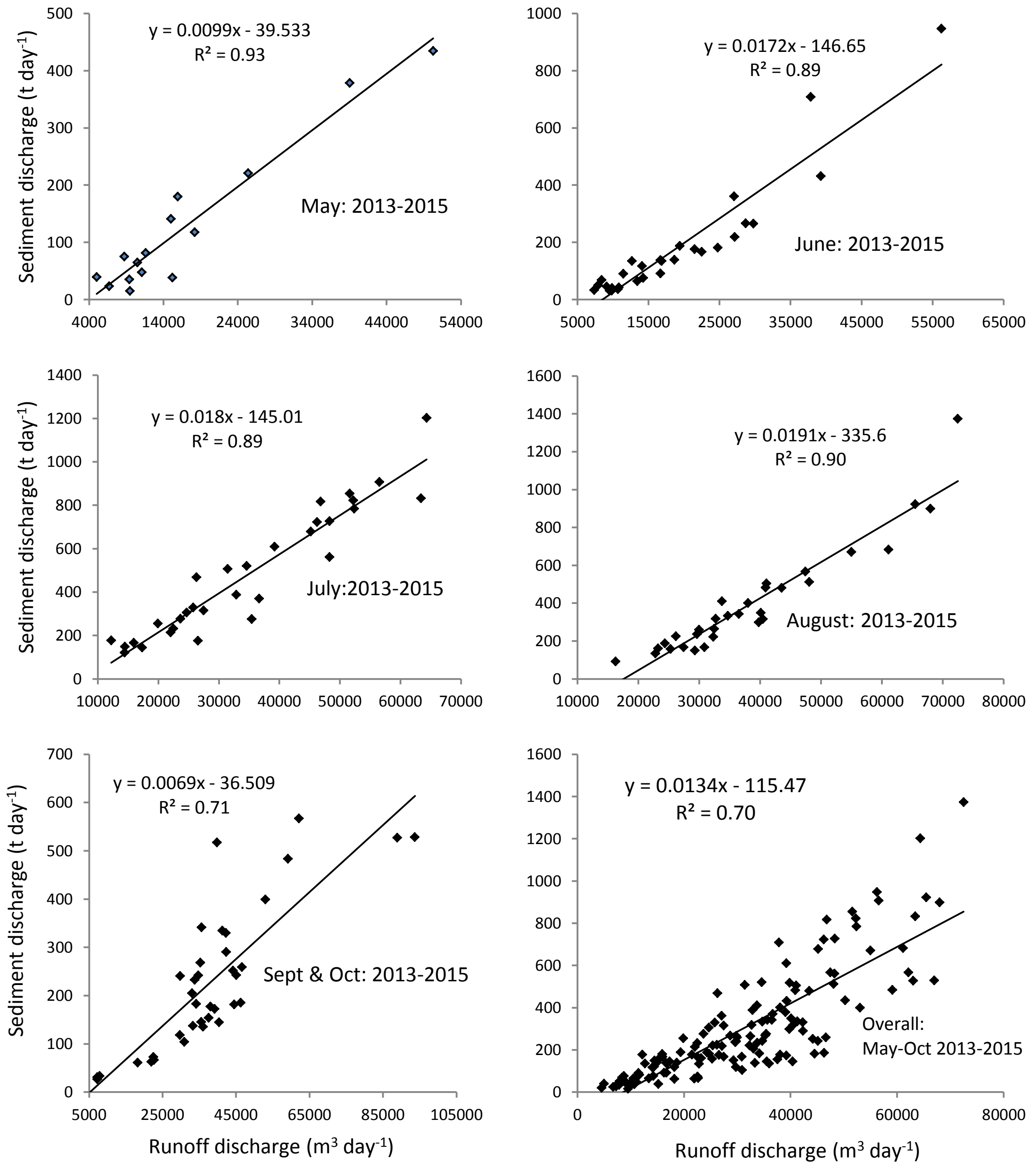


***Figure 2.3*** *Relationship between daily runoff and sediment discharges from 2013-2015 at Minizr catchment*

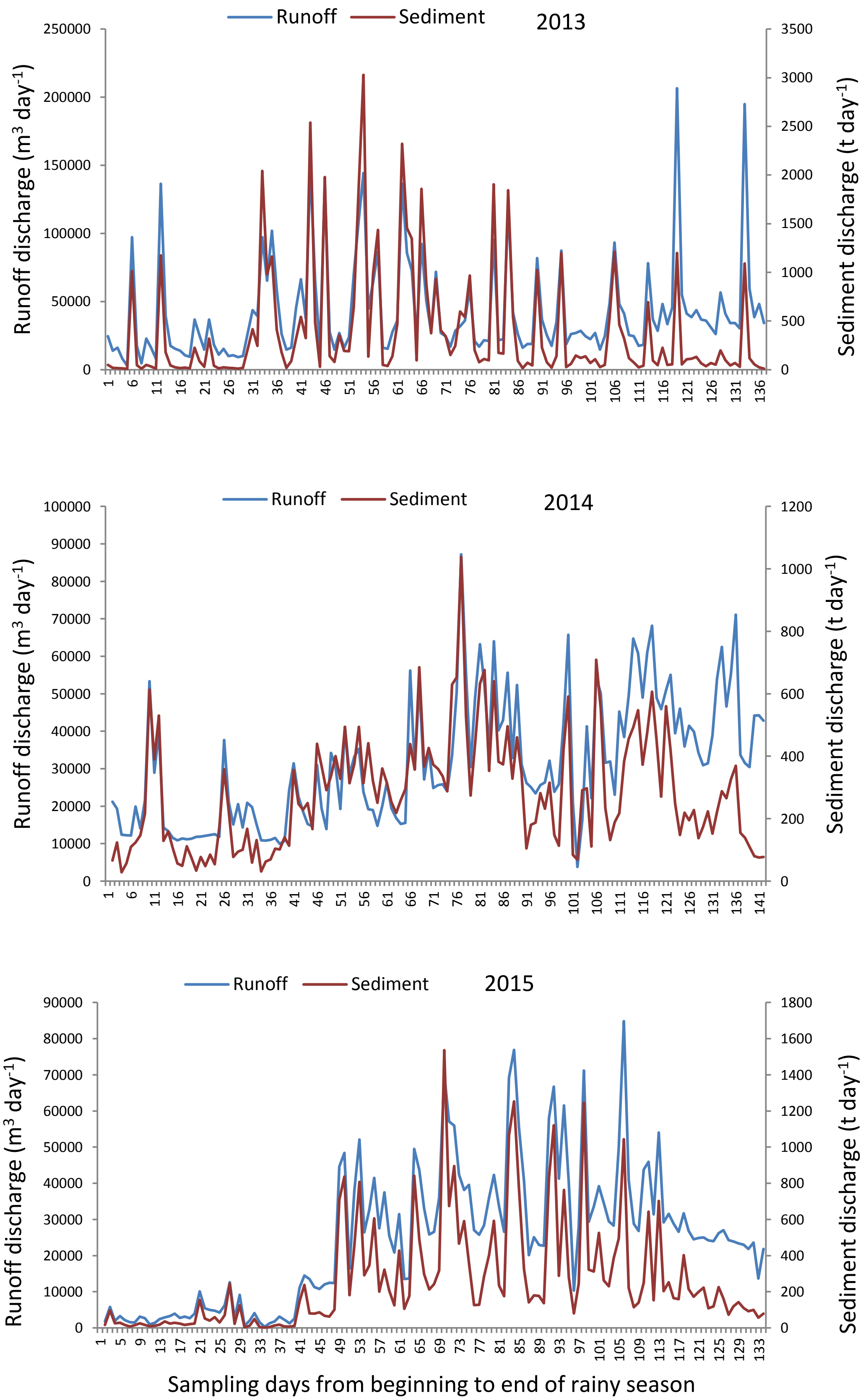


***Figure 2.4*** *daily runoff and sediment discharges at Minizr catchment from 2013-2015*

***Sediment source areas at sub-catchment scale***

The Midre-Genet sub-catchment produces approximately three times more sediment than Tume-Shafrie sub-catchment, indicating a large spatial variation for sediment production within the Minizr catchment. Mean annual sediment discharges from the three sub-catchments showed that Midre-Genet (middle catchment) generated the most sediment (~19,400 t) followed by Adibera (upper catchment; ~13,100 t) and Tume-Shafrie (lowest catchment; ~6,700 t). Area specific sediment yield (in t $ha^{-1}$ $y^{-1}$) was found to be 25.5, 16.8 and 13 at Midre-Genet, Adibera and Tume-Shafrie sub-catchments, respectively.

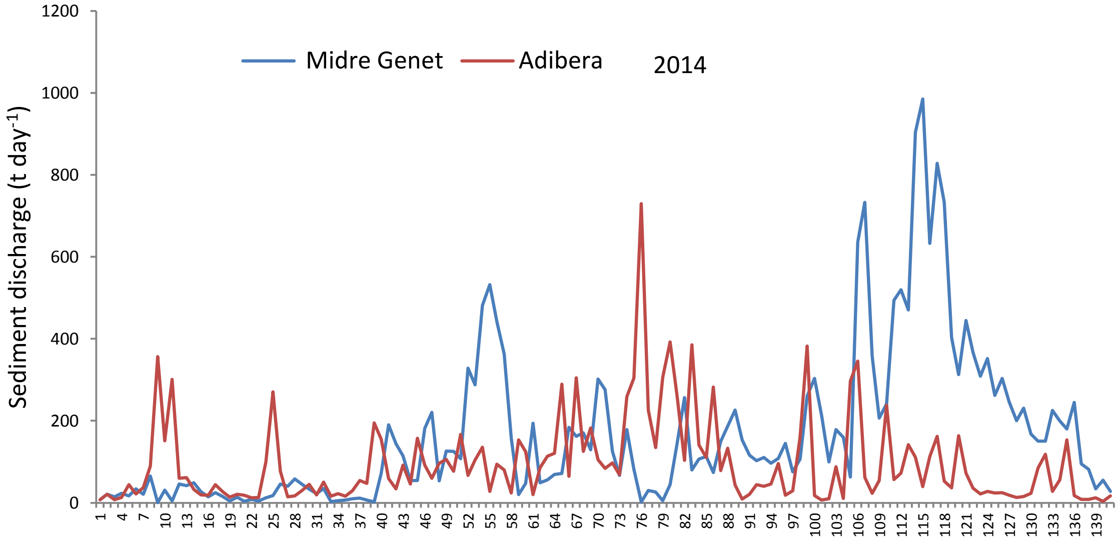


***Figure 2.5*** *Daily sediment discharge from Midre Genet and Adibera sub-catchments*

Sediment yields of the sub-catchments are not independent because the lower and middle sub-catchments receive sediments from upstream, we deduct the sediment measured at the upper catchment from the lower one. Unlike the two sub-catchments (Adibera and Midre-Genet) sediment deposition occurs along Minizr river within Tume-Shafrie sub-catchment during rainfall events, which serves as sediment source for the next events. This increased the uncertainty for the daily sediment discharge for this catchment and hence we used the annual average data for sediment yield. Mean daily sediment discharge was higher from Midre-Genet sub-catchment than Adibera towards the end of the rainy season (Figure 2.5).

***Sediment transfer pathways***

Sediment is generated in different parts of the catchment, such as on agricultural fields, in gullies and from riverbanks, which is then transported to the catchment outlet through sediment transfer pathways (STPs). In Minizr catchment a total of ~84 km of STPs were identified with an overall mean density of 4.0 km $km^{-2}$, consisting of gullies (~6.6 km), permanent rivers (~16.7 km), intermittent rivers (~23 km) and footpaths (~37.5 km) (Table 2.4). STP density was ~4.7, ~3.8 and ~3.6 km $km^{-2}$ for Midre-Genet, Adibera and Tume-Shafrie, respectively. Figure 2.6 shows a location map of existing STPs (rivers, footpaths and gullies), gullied areas and example pictures of STPs. The catchment comprises about 25 ha of gullied areas of which, about 60% was located in Midre-Genet and the remaining 40% in Adibera. There was no gullied area in Tume-Shafrie sub-catchment. The four measured gullies showed an annual development rate of 28 m long, 7 m wide and 2.5 m deep generating about 1950 $m^3$ sediment to downstream rivers.


***Figure 2.6*** *Location map of sediment transfer pathways (a), and example pictures of a footpath (b), a gully (c), and a river (d) in Minizr catchment.*

***Table 2.4*** *Lengths of sediment transfer pathways within the three sub-catchment*

| Sub-catchments | Sediment transport pathways | | | | | |
|---|---|---|---|---|---|---|
| | Intermittent rivers (km) | Permanent rivers (km) | Gullies (km) | Footpaths (km) | Sum | STPs density (km $km^{-2}$) |
| Adibera | 7.2 | 5.5 | 2.7 | 14.5 | 29.9 | 3.8 |
| Midre-genet | 12.8 | 3.2 | 3.9 | 16.0 | 35.9 | 4.7 |
| Tume-Shafrie | 3.0 | 8.0 | 0 | 7.0 | 18.0 | 3.6 |
| Sum | 23 | 16.7 | 6.6 | 37.5 | 83.8 | |

## 2.4 Discussion

***Sediment load to Koga reservoir***

Daily, monthly and yearly suspended sediment discharges of Minizr catchment were calculated from the measured river discharge ($m^3\ s^{-1}$) and suspended sediment samples ($g\ l^{-1}$). On average ~43,000 t of suspended sediment is entering Koga reservoir annually. Annual sediment yield ranged from 17 t $ha^{-1}$ in the year 2015 to 27 t $ha^{-1}$ in the year 2013 with an average value of 21.5 t $ha^{-1}$. This result agrees with the findings of previous studies in northwest Ethiopian highlands. For example, ~25 t $ha^{-1}$ $y^{-1}$ (Setegn *et al.*, 2010; Yeshaneh et al., 2014) and 8.6-55 t $ha^{-1}$ $y^{-1}$ (Mekonnen *et al.*, 2015b). The result was also within the range of 3-49 t $ha^{-1}$ $y^{-1}$ found by Tamene et al. (2006a) in the northern part of Ethiopia.

Koga reservoir is receiving this amount of sediment from the 20 $km^2$ Minizr catchment. Considering the entire runoff and sediment source area of the reservoir, Koga catchment (163 $km^2$, excluding the reservoir), large amounts of sediment are expected to enter the reservoir. With a sediment yield of 21.5 t $ha^{-1}$ $y^{-1}$ and average dry bulk density obtained from six reservoirs (1.26 t $m^{-3}$; Tamene et al. (2006a) in the northern part of Ethiopia, approximately 278,000 $m^3$ of sediment is entering Koga reservoir from the whole Koga catchment annually, which agreed well with 269,000 $m^3$ (Yeshaneh et al., 2014). Koga reservoir is losing ~0.33% of its storage volume annually and 0.04% (43,000 t; 34,000 $m^3$) is the contribution of Minizr catchment. This will considerably compromise its water holding capacity and influence the ~14,000 subsistence farmers' households who are using the reservoir water for irrigated agriculture downstream of the reservoir. Therefore, immediate actions should be taken to trap the sediment and hence reduce its transport to the reservoir by implementing ST measures within the catchment disconnecting the sediment transfer pathways.

***Temporal variations of sediment discharge***

Sediment entering Koga reservoir showed inter-annual and intra-annual variations. Annual sediment discharge was higher in 2013 (~54,000 t) than in 2014 (~39,700 t) and 2015 (~34,900 t). Two probable causes for these differences have been identified: a reduction in rainfall amount and construction of new ST measures. Rainfall in 2015 was 487 mm lower and in 2014 it was 325 mm lower than in 2013. In 2015, there was shortage of rainfall in the whole of Ethiopia, with droughts occurring in some parts of the country. New ST measures are constructed every year by the Bureau of Agriculture on untreated areas, which contributes to the reduction of sediment discharge.

Among the rainy months, most sediment was produced in July (~14,900 t), followed by August (12,300 t). Out of the total sediment discharged from May to October, 63% was discharged in July and August. Daily sediment discharge was highest from the beginning of July to the end of August. This implies that Intra-annual (monthly and daily) sediment discharge and suspended sediment concentration were higher in the middle of the rainy season (July and August) than in the beginning and the end of the rainy season. This increase in sediment concentrations is most likely due to an increase in i) gully erosion because of increased sub-surface flow and ii) river bank erosion because of increased runoff flow inside river channels in July and August. Tebebu *et al.* (2010) found that sub-surface flow played a bigger role in gully formation and development than surface runoff at Debre Mewi watershed. Rijkee *et al.* (2015) also found that sub-surface flow is an important cause of gully formation and development at Minizr catchment. In this study, during July and August extensive signs of subsurface flows were visible in and around gullies. With the implementation of SWC structures on all fields in the upland areas, infiltration increased substantially. The additional infiltration decreases overland runoff, and therefore, increases ground water flows toward the lowlands where gullies are located. This increase in ground water flows makes the area more susceptible to gully erosion through subsurface flow mechanisms in July and August. In addition to gully erosion, during our field surveys we observed river channel erosion and river bank slides in July and August due to high rainfall amounts and increased volume of runoff within the channels contributing sediment to the river system.

Once plant cover establishes towards the end of the rainy season, erosion from agricultural field is negligible (Easton et al., 2010; Mekonnen et al., 2015a). Results from this study showed, however, that although agricultural fields were covered with crops and there was an increased land cover in the catchment, sediment discharge amounts continued to be large up to the end of the rainy season, although with a decreasing rate. This is because part of the catchment underlain by Vertisols is ploughed by farmers during the high rainfall periods (from mid-August to mid-September) to plant legume crops like chick pea (*Cicer arietinum*) and grass pea (*Lathyrus sativus*). Another reason for maintained sediment discharge throughout the season is gully and river bank erosion, which showed active development in July and August as mentioned above.

***Spatial variation in sediment production***

From an applied (management) perspective, the small scale catchment is the scale at which catchment managers most often make decisions (Aksoy & Kavvas, 2005; MOARD, 2005). Accordingly we classified our catchment into three sub-catchments Midre-Genet (760 ha), Adibera (780 ha) and Tume-Shafrie (500 ha) and quantified sediment production.

In the middle catchment, Midre-Genet, most sediment was produced (~19,400 t), followed by the highest catchment, Adibera (~13,100 t) and the lowest catchment, Tume-Shafrie (~6,700 t). For this spatial variation in sediment production, three possible factors were identified. Firstly, sediment transfer pathways (STPs); the density of STPs was higher for the sub-catchment with high sediment discharge, Midre-Genet (4.7 km $km^{-2}$), which implies an increase in landscape connectivity and sediment transport. STP density was lower in the sub-catchment with relatively low sediment discharge, Tume-Shafrie (3.6 km $km^{-2}$), which implies lower sediment connectivity and less sediment transport. Catchment sediment production and STP density showed a direct relationship with $R^2$ = 0.88. Secondly, gully erosion is a contributing factor. After identifying that Midre-genet was the sub-catchment contributing most sediment to the catchment outlet, we found that gullies develop fast and contribute large amounts of sediment in this sub-catchment. Annual average gully development rate was found to be 28 m long, 7 m wide and 2.5 m deep. The evaluated four gullies generated 1950 $m^3$ of sediment to downstream rivers. Rijkee et al. (2015) investigated three gullies in the same catchment and found a soil losses of 74 t $ha^{-1}$ $y^{-1}$. Sixty percent of the area affected by gully erosion was found in Midre-Genet, which is another reason for increased sediment production compared to the other sub-catchments.

Adibera is the second sub-catchment in sediment production, in which 40% of the gully affected land was found. Tume-Shafrie sub-catchment did not experience any gully erosion and showed the least sediment production. Finally, availability of natural sediment sinks plays a role in spatial sediment variation. At the outlet of Tume-Shafrie sub-catchment a 24 ha wetland is found with a sediment trapping efficacy of 85% (Mekonnen et al., 2016c) in which a large part of the sediment could be deposited.

Differences in soil erosion triggering factors like land use/cover, slope, rainfall and soil type within a catchment will cause spatial variation in sediment production. In Minizr catchment, However, there was no large difference among the sub-catchments in land use/cover and rainfall. Land use/cover was dominated by agricultural fields followed by grazing lands in all sub-catchments. Rainfall (mm $y^{-1}$) was almost similar, 1229 (Adibera), 1175 (Midre-Genet) and 1239 (Tume-Shafrie). Slope was different for the sub-catchments (Table 2.1).Concerning the soil type Adibera and Tume-Shafrie are dominated by Nitosols whereas Midre-Genet is dominated by Vertisols, which will create variation in soil erosion.

***Reducing sediment discharge***

To reduce the sediment entering Koga reservoir a holistic catchment scale treatment is preferred. Such an approach could for example consist of: (i) Implementing measures, which help to disconnect the sediment connectivity functions of STPS; (ii) Treating gully erosion using gully treatment measures (like check dams, sediment storage dams, plantations); (iii) Riverside plantations to treat riverbank erosion; (iv) Conserving natural sediment sinks like wetlands by designing management strategies because agricultural expansion has strongly affecting the existence of the wetland at Minizr catchment (Mekonnen et al., 2016c) and (v) Treating the most sediment source area first and moving to the least.

In this study, the amount of sediment entering Koga reservoir, spatial and temporal variation in sediment discharge and the role of STPs in connecting the landscape and enhancing sediment transport were assessed for the Minizr catchment. All of these will help to design and implement appropriate ST measures within the catchment. To develop complete information further studies are recommended, on sediment contributions from STPs like gullies, footpaths, river channels. Spatial variation in sediment production was assessed at sub-catchment scale but to know specific locations of sediment source areas cell-based studies are recommended at higher spatial resolution. Sediment load of the Koga reservoir from the total runoff contributing catchments was estimated based the measured data from Minizr catchment, which will serve as an awareness creation for decision makers and extension agents, however, further study for the total catchment or up-scaling studies from small catchments is recommended.

## 2.5 Conclusions

Minizr catchment is an important source of runoff water for Koga reservoir and provides on average, 4,500,000 $m^3$ runoff annually, mainly in the rainy season. With this runoff 43,000 t of sediment is entering Koga reservoir annually (21.5 t $ha^{-1}$ $y^{-1}$). Spatially, Midre-Genet sub-catchment is the main source of the sediment because of higher sediment transfer pathway (STP) density and a large area affected by gullies. Annual sediment discharge was higher in the year 2013 than in 2014 and 2015. Intra-annually sediment discharge was highest in July and August. Drainage channels, gullies and footpaths were found to be the main STPs enhancing sediment connectivity and transport. As a result large amount of sediment is entering Koga reservoir. Therefore, sediment trapping measures, which enhance sedimentation within the catchment and disconnecting the sediment connectivity functions of the STPs are needed. When implementing these measures priority areas should be addressed first. If sedimentation of the Koga reservoir continues its sustainable use will be in question and the large number of beneficiaries of the irrigation agriculture produces will be in problem.

# Chapter 3

# Soil conservation through sediment trapping: a review

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# Soil conservation through sediment trapping: a review

*Abstract*

*Preventing the off-site effects of soil erosion is an essential part of good catchment management. Most efforts are in the form of on-site soil and water conservation measures. However, sediment trapping using off-site measures can be an alternative (additional) measure to prevent the negative off-site effects of soil erosion. Therefore, not all efforts should focus solely on on-site soil conservation, but also on the safe routing of sediment-laden flows and on creating sites and conditions where sediment can be trapped. Sediment trapping can be applied on-site and off-site and involves both vegetative and structural measures. This paper provides an extensive review of scientific journal articles, case studies, governmental reports, conference proceedings and book chapters that have assessed soil conservation efforts and the sediment trapping efficacy (STE) of vegetative and structural measures. The review is further illustrated through participatory field observation and stakeholders interview. Vegetation type and integration of two or more measures are important factors influencing STE. In this review, the STE of most measures was evaluated either individually or in such combinations. In real landscape situations, it is not only important to select the most efficient erosion control measures, but also to determine their optimum location in the catchment. Hence, there is a need for research that shows a more integrated determination of STE at catchment scale. If integrated measures are implemented at the most appropriate spatial locations within a catchment where they can disconnect landscape units from each other, they will decrease runoff velocity and sediment transport and, subsequently, reduce downstream flooding and sedimentation problems.*

## 3.1 Introduction

Soil conservation will remain an important topic in the 21$^{st}$ century. As increasing pressure mounts on agricultural lands to feed an ever growing global population, land exploitation and unabated soil erosion will occur, especially in developing parts of the world (Lal, 2001), and in other regions were the intensification of agriculture is taking place (Cerda *et al.*, 2009; Zema *et al.*, 2012) or where natural or human-driven disturbances take place: forest fires (Lasanta & Cerdà, 2005), landslides (Douglas *et al.*, 2013), heavy rainfall events (Ziadat & Taimeh, 2013), land abandonment (Cerdà, 1997b). The exploitation of land resources results from a number of factors including extensive deforestation for fuel wood, expansion of cultivation into steep erosion-prone areas and over grazing pressures (Zeleke, 2000; Bewket, 2002; Ritsema, 2003; Amsalu & de Graaff, 2007). The impacts of uncontrolled on-site (or in-field) soil erosion can result in sedimentation off-site causing a reduction in water storage capacity of reservoirs downstream, in addition to reduced water quality from increasing water turbidity and pesticide runoff that is introduced into lakes and rivers through agricultural runoff, thereby affecting riverine habitats and sensitive ecological processes (Morgan, 2005; Chiu *et al.*, 2007; Hrissanthou *et al.*, 2010; Rodrigues & Silva, 2012).

Soil research and extension has mainly focused on measures that reduce or prevent on-site erosion. Although successes have been reported (Schwilch *et al.*, 2013), overall adoption and up-scaling of these measures by farmers is disappointing (Stroosnijder, 2012). Therefore, alternative approaches are needed to decrease soil erosion and thus help to ensure the longevity and viability of agricultural practices (Leh *et al.*, 2013).

This paper explores one such alternative for soil conservation, known as sediment trapping (ST). The rationale for ST is that in many practical situations, especially in developing nations, soil erosion is often too difficult to control. Thus, one premise is that it is better to no longer put all our collective efforts into on-site soil conservation but rather to focus on understanding the sediment and flow dynamics of the whole catchment and try to retard it along its sediment transfer pathways (Keesstra, 2007; Keesstra *et al.*, 2009b; Abedini *et al.*, 2012; Baartman *et al.*, 2012). The challenge is to create more sinks in the catchment where sediment can be trapped, preferably in a cost effective or even profitable way. Many semiarid slopes have patchy vegetation distribution that acts as sinks for sediment coming from the bare (source) areas (Cerdà, 1997a). This strategy helps to reduce the flow connectivity, which can reduce the soil and water losses.

Although many studies have assessed the effects of ST on an experimental basis, this information has not previously been applied holistically at a catchment scale. In this study, we split the ST measures into two categories: (i) those that promote sedimentation within farmers' fields ‘on-site’ measures and (ii) those outside the sphere of influence of individual farmers’ fields ‘off-site’ measures. On-site ST measures reduce overland flow velocity and thereby retard sediment transport, resulting in sediment deposition within fields before sediment can be discharged into streams (Fiener & Auerswald, 2003; Lee *et al.*, 2003; McKergow *et al.*, 2004; Edem *et al.*, 2012; Wanyama *et al.*, 2012). Off-site ST measures reduce concentrated runoff velocity within the (ephemeral) gully and river channel system thereby enhancing infiltration of water and deposition of sediment into ponds and behind check dams (Fiener *et al.*, 2005; Abedini et al., 2012) and into the riparian zone (Newson & Large, 2006; Keesstra *et al.*, 2012).

Besides distinguishing between on-and off-site, the ST measures are also grouped according to the methodology of sediment retardation: (i) vegetative, (ii) structural and (iii) combined vegetative and structural measures. Examples of on-site vegetative measures include grass strips, tree or shrub buffers, riparian vegetation and grassed waterways; terraces are on-site structural measures constructed on farmlands whereas sediment basins or ponds and check dams are off-site structural measures mostly located in (ephemeral) gullies and rivers.

The sediment trapping efficacy (STE) of various on- and off-site ST measures, defined as the percentage of sediment trapped compared to the amount of sediment that passed a control location, without the trapping measures, is explored for each type of ST measure used. STE is site and vegetation specific and can be affected by the combination of two or more ST measures (Fiener et al., 2005; Nyssen *et al.*, 2009a; Zhang *et al.*, 2010b).

## 3.2 Materials and methods

A critical review was carried out of 91 scientific journal articles, 6 case studies and 9 other publications (governmental reports, conference proceedings and book chapters). This review is further illustrated through participatory field observation (Figures 3.1-3.7) in the upper part of Blue Nile basin, Ethiopia, which included field work in 2013, consisting of interviewing stakeholders (government officials at Bureau of Agriculture), farmers, agricultural development agents and scientists (at Bahir Dar University), and measuring waterway, grass strip, terrace, check dam and pond characteristics including explanatory factors such as soil depth, land use/cover and average slope gradient.

## 3.3 vegetative sediment trapping measures

Vegetative ST measures can be grouped into grass strips, shrub and tree buffers, riparian vegetation and grassed waterways which can be established along contours, at the edge of fields or along streams or other water bodies to reduce runoff velocity and sediment transport and enhance sediment deposition (Dillaha *et al.*, 1989; Lee et al., 2003; Yuan *et al.*, 2009). Table 3.1 provides a summary of previous studies displaying the vegetative ST measures used, their location, STE and scale.

***Table 3.1*** *Studies of vegetative sediment trapping (ST) measures*

| Types | Scale | Duration (years) | Rainfall (mm) | Soil (texture) | Location | Sediment Trapping Efficacy (STE) % | References |
|---|---|---|---|---|---|---|---|
| **Grass strips** | | | | | | | |
| Lemon grass | Plot | 2 | 1050 | clay loam | Uganda | 72-92% (natural), 54-78% (simulated) | Wanyama et al., 2012 |
| Paspalum | Plot | 2 | 1050 | clay loam | Uganda | 65-88% (natural), 60-80% (simulated) | Wanyama et al., 2012 |
| Elephant grass | Plot | 2 | 1050 | clay loam | Uganda | 62-84% (natural), 48-70% (simulated) | Wanyama et al., 2012 |
| Sugarcane | Plot | 2 | 1050 | clay loam | Uganda | 56-82% (natural), 34-67% (simulated) | Wanyama et al., 2012 |
| Vetiver grass | - | 4 | 3585 | clay | Australia | 65% | McKergow et al., 2004 |
| Brome grass | Plot | 1 | - | silt loam | USA | 70-85% | Robinson et al., 1996 |
| Centipede grass | Plot | 3 | 1753 | - | Japan | 24-73% | Shiono et al., 2007 |
| Switchgrass + woody vegetation | Plot | - | - | loamy | USA | 92% and 97% (simulated) | Lee et al., 2003; 2000 |
| Switchgrass | plot | 2 | 805 | - | USA | 70% and 95% (natural ) | Lee et al., 2003; 2000 |
| Switchgrass + vetiver | Plot | - | - | - | - | 90% | Meyer et al., 1995 |
| **Shrub & tree buffers** | | | | | | | |
| Shrub | Plot | 1 | 530 | loess | China | 45-61% | Zhang et al., 2010a |
| Streamside management zones | Watershed | - | 203 | sandy loams | Georgia, USA | 71-99% | Ward & Jackson, 2004 |
| Streamside management zones | Watershed | 3 | 1020 | Loams, silt loam | Virginia, USA | 97% | Lakel et al. 2010 |
| Mixed deciduous forest buffer | Plot | 1 | - | Silt loam | USA | 76-86% | Schoonover et al., 2006 |
| Giant cane | Plot | 1 | 35 | Silt loam | USA | 94-100% | Schoonover et al., 2006 |
| Acacia tree belt | Plot | - | 35 | Chromic luvisol | Australia | 91-100% | Leguedois et al., 2008 |
| Remnant forests + grass | Watershed | 3 | 1020 | - | USA | 100% | Knight et al., 2010 |
| Remnant forests alone | Watershed | 3 | 1020 | - | USA | 80% | Knight et al., 2010 |
| Tree + grass | Cultivated field | 4 | 716 | - | Italy | 92% | Borin et al., 2005 |
| **Grassed waterway** | | | | | | | |
| Grassed waterways | Watershed | 8.5 | 804 | Loamy Inceptisol | Germany | 97% (with), 77% (without) waterway | Fiener & Auerswald, 2003 |
| Grassed waterways | Watershed | 2 | 890 | Silty clay loam | USA | 18% runoff, 65% sediment | Dermisis et al., 2010 |
| Grassed waterways | Watershed | 9 | 834 | Loamy Inceptisol | Germany | 87% runoff, 93% sediment | Fiener & Auerswald, 2006 |

***Grass Strips***

Grass strips are bands of grass mostly planted in agricultural fields along contours at specified vertical intervals (Figure 3.1). Grass strips reduce the velocity and sediment transport capacity of flowing water by retarding and spreading the concentrated surface runoff, which enhances sediment deposition within and upslope of the grass strip (Hurni, 1986). Through time, grass strips may develop into terraces and reduce the gradient of the field. This process is known as slow forming or progressive terracing (Kagabo *et al.*, 2013).

The STE of a grass strip depends on the grass species. Wanyama et al. (2012) evaluated the STE of four tropical grass species, lemon grass (*Cymbopogon citratus*), elephant grass (*Pennisetum purpureum*), paspalum (*Paspalum notatum*) and sugarcane (*Saccharum officinarum L.*) in croplands in Uganda, under natural and simulated rainfall conditions. Due to their spreading growth pattern and dense network of fine roots, lemon and paspalum grass showed significantly greater STE than elephant grass and sugarcane. The authors concluded that tropical grass strips provide a practical means for reducing sediment transport from croplands.

In the Johnstone River catchment in north Queensland, Australia, Vetiver grass strips planted on a steep and intensively cropped field under high annual natural rainfall condition (3585 mm), trapped >85% of the bedload and 25-65% of the suspended sediment (McKergow et al., 2004). In Nigeria, such grass strips trapped ~5 times more sediment than the control (Edem et al., 2012) on a runoff plot experiment. The mean total sediment yield was 29 kg $ha^{-1}$ from the control plot versus 6 kg $ha^{-1}$ from the Vetiver plots. Brome grass trapped 70-85% of the sediment at different buffer widths from cropland runoff on silty loam soil in Iowa, USA (Robinson *et al.*, 1996). Centipede grass (*Eremochloa ophiuroides (Munro) Hack*) trapped 24-73% of sediment in field plots under natural rainfall conditions in Japan (Shiono *et al.*, 2007).

In Iowa, USA the STE of switch grass (*Panicum virgatum L.*) alone and switch grass-woody vegetation buffers were studied (Lee *et al.*, 2000; Lee et al., 2003) under simulated and natural rainfall conditions on a 4.1 m by 22.1 m bare field with (a) no buffer, (b) a 7.1 m wide switch grass buffer and (c) a 16.3 m wide switch grass-woody vegetation buffer. The switch grass alone and switch grass-woody vegetation combination trapped 70% and 92% of the incoming sediment under natural rainfall, and 95% and 97% under simulated rainfall, respectively.

The physical characteristics of the different grass species are important in retarding runoff through upslope ponding. For example, hedges of switch grass and Vetiver (*Vetiveria zizanioides (L.) Nash*) caused backwater depths of up to 40 cm and trapped >90% of sediment coarser than 125 µm in areas of concentrated overland flow (Meyer *et al.*, 1995). The effect of grass litter and leaves on ST was also studied on the Loess Plateau, China (Pan *et al.*, 2010) where perennial local grazing grass, black rye (*Loliumperenne L.*) were tested on slopes of 3-$15^0$ applying three treatments: C- control with intact grass, NL- no litter i.e. without grass covering the soil surface and NLL - no litter or leaves i.e. only grass stems and roots. STE ranged from 42-69%; 41-72% and 37-59% for the C, NL and NLL treatments, respectively, and thus Pan et al. (2010) concluded that grass litter and leaves had no significant influence on STE of the local grass.

***Figure 3.1*** *Example of a vegetative sediment trapping measure: grass strip upper Blue Nile Basin, northwest Ethiopia (Photo by Mulatie Mekonnen)*

***Shrub and Tree Buffers***

Tree or shrub buffers are vegetative barriers established between farmlands and rivers, to trap transported sediment before reaching nearby streams and waterways (Figure 3.2). In Northern Shaanxi Province, China, on a $15^0$ slope and loess soil, native shrub species (*Caragana Korshinskii Kom*) reduced runoff rates by 22-32%, sediment concentration by 45-61% and sediment yield rates by 64-79% compared to the control plot (Zhang *et al.*, 2010a). Treatments were (i) bare soil as a control plot, without shrub cover, (ii) low shrub cover (30%) and (iii) high shrub cover (80%). Average sediment concentrations were 12.4 g $l^{-1}$, 6.8 g $l^{-1}$ and 4.8 g $l^{-1}$, for the control, low shrub and high shrub covers respectively. Near Booreowa, New South Wales, Australia on a $6^0$ slope and chromic luvisol soil a tree belt of Acacia was able to trap 94% of eroded sediment, with STE ranging from 91-100% (Leguedois *et al.*, 2008).

Ward and Jackson (2004) investigated the benefits of streamside management zones for two Georgia Piedmont clear cuts in the USA, in reducing sediment transport from concentrated overland flow, and recorded 15-49 t $ha^{-1}$ of accumulated sediment, with STE ranging between 71-99%. In Virginia, Upper James River basin, streamside management zones trapped an average of 24.8 t $ha^{-1}$ $y^{-1}$ of sediment (Lakel *et al.*, 2010), which is 38 times higher than the control treatment (0.65 t $ha^{-1}$ $y^{-1}$). With 97% of the sediment trapped, a streamside management zone represents an effective best management practice that should be included in most sediment harvest planning.

A buffer of giant cane (*Arundinaria gigantea (Walt.) Muhl.)* on a 1% slope with a silty loam soil, in southern Illinois, USA reduced incoming sediment by 94-100% while a mixed deciduous forest buffer reduced sediment by 76-86% (Schoonover *et al.*, 2006). On an annual and seasonal basis, the giant cane buffer consistently outperformed the forest buffer in significantly reducing sediment loads.

In the French Southern Alps, Burylo *et al.* (2012), investigated the buffering effects of morphologically contrasting woody species, i.e. (i) broadleaf species (*Buxus sempervirens and Lavandula angustifolia*) and (ii) coniferous species (*Juniperus communis and Pinus nigra*). They found that the broadleaf species *Lavandula* and *Buxus* trapped the highest amount of sediment per unit volume: 3.7 and 2.8 times more than *Juniperus*; and 1.9 and 1.5 times more than *Pinus*. Remnant forests with grass filters buffered 100% of the concentrated surface runoff, whereas remnant forests without adjacent grass filters buffered 80% of concentrated flow (Knight *et al.*, 2010). This suggests that even though natural remnant forests provide substantial buffering capacity, the addition of an adjacent grass filter further reduces sediment loads entering streams. In northeast Italy, on a 1.8% slope with Cambisol soil, a 6 m buffer strip, rows of trees with grass planted in the middle reduced runoff over a three year period by 78% and sediment by 92% compared to the control (Borin *et al.*, 2005).

***Figure 3.2*** *Example of a vegetative sediment trapping measure: riverside tree buffer upper Blue Nile Basin, Minizr catchment, northwest Ethiopia (Photo by Mulatie Mekonnen)*

***Grassed Waterways***

Waterways are either man-made or natural drainage lines channelling runoff from adjacent agricultural fields to local streams. Waterways can be either lined with stone or covered with grass (Figure 3.3) to help prevent soil erosion and gully formation. Grassed waterways are areas where runoff concentrates and are often planted with grasses to reduce runoff, enhance infiltration and reduce sediment transport and gully formation by decreasing flow velocity (Bracmort *et al.*, 2004; Fiener & Auerswald, 2006; Dermisis *et al.*, 2010).

***Figure 3.3*** *Example of a vegetative sediment trapping measure: grassed waterway upper Blue Nile Basin, northwest Ethiopia (Photo by Mulatie Mekonnen)*

Fiener and Auerswald (2003) studied the STE of grassed waterways and concluded that they exhibited great potential in reducing runoff and sediment from agricultural areas within a catchment. This is based on a 9 year experiment in two adjacent watersheds in southern Germany of 13.7 and 9.4 ha, respectively, with loamy inceptisols and slopes ranging from 3.6 to 5.3%. For the two watersheds with and without grassed waterways, runoff was reduced by 90% and 10%, and sediment load was reduced by 97% and 77%, respectively, due to reductions in runoff velocity, higher infiltration rates and increased surface storage capacity. Dermisis et al. (2010) obtained similar results for a watershed in Clear Creek (4% average slope), USA, where a 600 m long and 11.5 m wide grassed waterway reduced runoff volume by 18% and sediment yield by 65%.

(Fiener & Auerswald, 2006) evaluated the STE of grassed waterways at the watershed scale in Germany. In one of the sub-watersheds, in addition to other soil and water conservation (SWC) measures already in place, a 22-48 m wide and 290 m long grassed waterway was established. Runoff and sediment loads were reduced by 87% and 93% for the without and with grassed waterway treatments, respectively. Thus the potential of grassed waterways for reducing sediment transport from agricultural watersheds is more effective, if combined with other ST measures.

***Riparian Vegetation***

Riparian vegetation and channel form in headwater catchments play an important role in the resulting water and sediment dynamics of rivers further downstream (McKergow *et al.*, 2003; Wainwright *et al.*, 2003; Gao, 2008). Vegetation causes flow retardation within the channel and on the riverbanks due to increased roughness and flow obstruction.

Modelling results by Keesstra et al. (2012) in a Polish catchment showed an increase in the effect of riparian vegetation on catchment flow dynamics, with an increase in return period of the modelled peak discharge. On a 6 $km^2$ agricultural catchment in Western Australia with gentle slope, sandy soils and 799 mm average annual rainfall, suspended sediment concentration and loads were 90% lower after the riparian buffer was created due to reduced bank erosion and increased channel stability (McKergow et al., 2003). At Iowa's Loess Hills, riparian buffers trapped 4.8 t $ha^{-1}$ $y^{-1}$ of sediment from a 27.6 ha runoff contributing area on a loess soil at 5-20% slope (Tomer *et al.*, 2007). In a 77 ha watershed in southeast Brazil, with mean slopes of 10%, the riparian buffers were found to trap 54% of total sediment yield (12 t $ha^{-1}$ $y^{-1}$) (Sparovek *et al.*, 2002). At the catchment scale, integrating riparian buffers with other conservation measures that are more appropriate for reducing on-site soil erosion can help to reduce river sediment loads (Verstraeten *et al.*, 2006).

## 3.4 Structural sediment trapping measures

Structural ST measures are designed to intercept runoff, reduce sediment transport and trap sediments either from surface runoff or river flow. Examples of such measures include terraces, check dams, dams, basins and ponds. Structural ST measures can be grouped according to their location either as on-site or off-site. On-site measures mainly consist of terraces, which can be constructed from soil, stone or a combination. Off-site measures, such as check dams, are built from stone, sandbags, wood or gabions in the drainage channel, whereas ponds or basins are constructed using dikes or stone barriers. Dams can have a very dramatic effect on water and sediment transfer on the scale of a catchment. When runoff enters into the storage areas, its velocity reduces providing time for the suspended sediment and bed load to settle. Table 3.2 summarizes the studies that were used in this review of structural ST measures.

***Terraces***

Terraces are graded or level barriers built on sloping land along contours at specified vertical intervals either from soil, stone or other materials (Figure 3.4). They are structural measures designed to reduce runoff velocity, increase infiltration and to retard erosion and sediment transport. In the long term, terraces reduce slope gradient forming bench terraces due to the accumulated sediment (Bosshart, 1997; Gebremichael *et al.*, 2005).

Garbrecht and Starks (2009) assessed sediment yield reduction due to terraces, conservation tillage and gully reshaping at Fort Cobb, in West-Central Oklahoma. Based on suspended-sediment and discharge measurements on major tributaries within the watershed, the average annual suspended-sediment yield reduced from 760 t $y^{-1}$ $km^{-2}$ (pre-conservation) to 108 t $y^{-1}$ $km^{-2}$ (post-conservation), with targeted conservation efforts leading to a measurable reduction in watershed sediment yield.

Mekonen and Tesfahunegn (2011) investigated the STE of stone bunds in the Medego watershed, Ethiopia and found that sediment accumulated at a rate of 65.3 t $ha^{-1}$ $y^{-1}$. Also in Ethiopia, Gebremichael et al. (2005) determined that the annual rate of sediment accumulated behind stone bunds was 59 t $ha^{-1}$, while total soil loss was 77 t $ha^{-1}$. In central Java, Sukristiyonubowo *et al.* (2010) estimated that annually during wet and dry seasons, incoming sediment into paddy fields was 6.44 and 1.19 t $ha^{-1}$, while outgoing sediment was 1.89 and 0.14 t $ha^{-1}$, respectively.

Where agricultural land abandonment does occur and the abandoned terrace is rapidly re-vegetated, soil erosion diminishes whilst commensurately, STE increases (Grove & Rackham, 2001). Furthermore, soil properties such as organic matter content, soil structure and rate of infiltration all improve (Kosmas *et al.*, 2000). However if vegetation regeneration is slow or absent, abandoned terraced fields are vulnerable to erosion and gully formation due to terrace failure and crust formation, which increases runoff and reduces infiltration (Lesschen *et al.*, 2008). Possible mitigation measures include: (i) maintenance of terrace walls in combination with increasing vegetation cover on the terrace, and (ii) re-vegetation of runoff concentration areas with grass.

***Figure 3.4*** *Examples of structural sediment trapping measures: terraces northeast Ethiopia (Photo by Mulatie Mekonnen)*

***Basins and Ponds***

Sediment basins or ponds are defined as off-site surface water management structures, which capture runoff and sediment in an artificial impoundment and prevent sediment discharge into downstream lakes and reservoirs (Iqbal *et al.*, 2003; Fiener et al., 2005). Sediment ponds are built within channels or at the edge of fields to trap sediment from concentrated runoff and thus prevent off-site sedimentation (Figure 3.5). Sediment ponds constructed within channels can also trap sediment resulting in stream bank erosion, which is a major source of sediment to downstream rivers and dams (Ramos-Scharrón & MacDonald, 2007).

Fiener et al. (2005) monitored four ponds with a volume of 30-260 $m^3$ on a 22 ha field of arable land over 8 years in southern Germany, and found that the ponds trapped 54-85% (1.0-15.3 t $ha^{-1}$ $y^{-1}$) of incoming sediment and temporarily stored 200-500 $m^3$ of runoff. These ponds efficiently reduced off-site sedimentation and their efficacy was further improved when combined with on-site erosion control measures, which further reduced sediment and runoff. During the first year all ponds were silted (up to 0.5m) but the sediment input into the detention ponds decreased to less than 1.0 t $ha^{-1}$ $y^{-1}$ due to soil conservation measures and the storage volume of the ponds was not highly influenced by siltation after the first year. Markle (2009) demonstrated the efficacy of a sediment pond in a Californian almond orchard, which trapped 80-84% of the sediment. According to Verstraeten and Poesen (2001b), a typical pond of 1000 $m^3$ with a catchment area of 25 ha in Belgium, showed a short term STE of 58-100% and a long term (33 yrs.) STE of 68%. In Belgium, Verstraeten and Poesen (2002) tested the STE of 13 different sized ponds (50 $m^3$-5 mill. $m^3$) with a catchment area of 25-50 000 ha with alfisol soils, revealing a STE of 10-72%.

Halide *et al.* (2003) evaluated the STE of constructed vegetated and non-vegetated ponds in Indonesia and Australia. The average deposition rate in the vegetated pond (63 g $m^{-2}$ $h^{-1}$) was higher than in the non-vegetated pond (14 g $m^{-2}$ $h^{-1}$). While Hupp *et al.* (2008) assessed sediment deposition over a three year period from 20 transects in the Atchafalaya Basin, Louisiana, USA. Transect mean sedimentation rates ranged from 2-42 mm $y^{-1}$ while the basin trapped $6.72 \times 10^6$ t of sediment annually.

Construction sites (especially road construction) are areas where soil readily becomes unstable due to physical disturbance and thus are important sources of sediment (Anderson & Macdonald, 1998; Ramos Scharrón, 2010). Graded unpaved roads produce 5.7-580 t $ha^{-1}$ $y^{-1}$of sediment, which was 40% higher than ungraded roads in St. John, U.S. Virgin Islands (Ramos-Scharrón & MacDonald, 2007). Hence, construction sites required ST measures to intercept runoff and trap sediment before discharging runoff into downstream water bodies. In North Carolina, two sediment basins of different designs were evaluated within active construction sites (Markusic & McLaughlin, 2008). The trap (sized for a 10-year storm event) with a rock outlet, was found to have 35% STE while the basin (designed for a 25-year storm event with established vegetation), had an overall efficacy of 99%. McCaleb and McLaughlin (2008) monitored five ST basins on construction sites in North Carolina; STE at the three rock outlet basins was 40-73%, while a basin with surface outlets trapped > 99% of the sediment.

***Check Dams***

Gully and river bank erosion has been observed to contribute significantly to overall catchment scale sedimentation (Poesen et al., 2003; Ramos-Scharrón & MacDonald, 2007; Keesstra et al., 2009a). To counter this issue, check dams are mostly constructed within gullies and channels to help prevent gully erosion and trap sediment (Figure 3.6). A check dam can be classified as a structural measure established within ephemeral rivers and gullies. It is a fixed structure, constructed either from timber, sandbags, gabion, loose rock, masonry or concrete, to control concentrated water flow and trap sediment in an erodible channel (McGraw-Hill, 2003) and is an effective strategy for reducing sediment loss (Ran *et al.*, 2008; Sougnez *et al.*, 2011; Wang *et al.*, 2011).

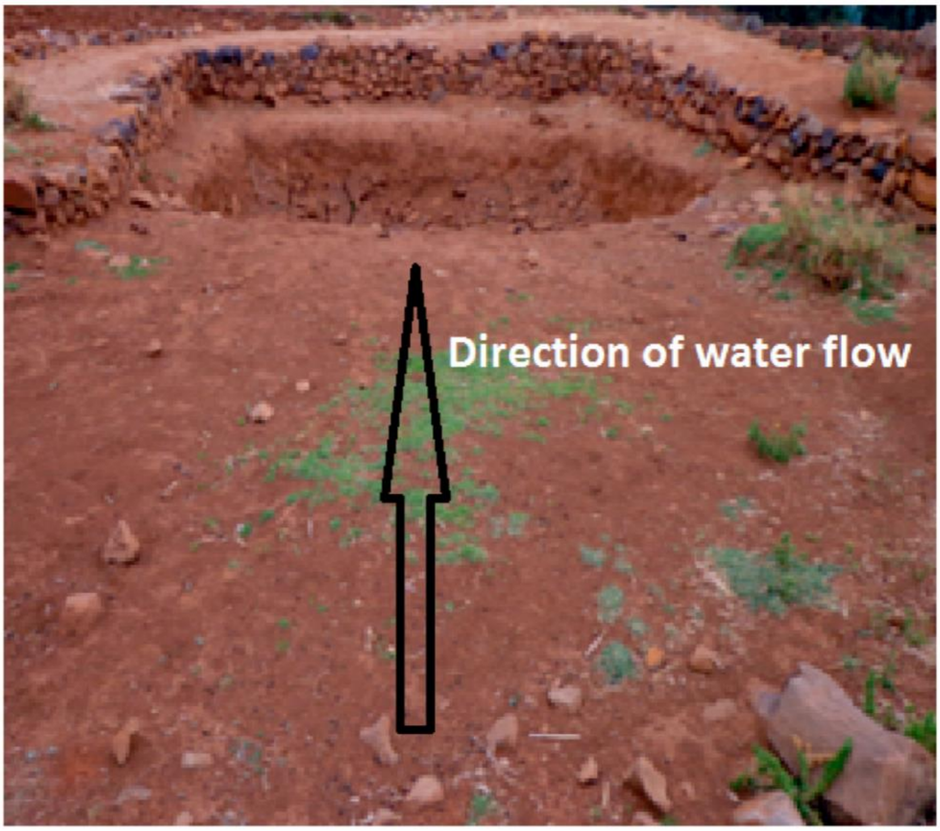


***Figure 3.5*** *Examples of structural sediment trapping measures: a sediment pond northwest Ethiopia (Photo by Mulatie Mekonnen)*

Wang et al. (2011) found that >100 000 check dams store 21 billion $m^3$ of sediment in the Loess Plateau of China in 50 years after construction. In Malaysia, Abedini et al. (2012) evaluated the STE of 3 check dams and their effectiveness in maintaining downstream reservoir storage capacity, which collectively trapped 6162 $m^3$ of sediment. Ran et al. (2008) found that the amount of sediment retained by check dams at the outlets of five catchments in China, was 4205, 2640, 15000, 1590 and 1360 ($10^3$ t) over 26 years, with reductions in sediment by check dams being 57.8%, 37.2%, 62.1%, 72.2%, and 64.7%, respectively, compared with other SWC measures. Sougnez et al. (2011) estimated the sediment volume trapped by 20 check dams in southern Spain as ranging from 4-920 $m^3$ for catchments with a drainage area varying from 1.5-317 ha.


***Figure 3.6*** *Examples of structural sediment trapping measures: check dams northeast Ethiopia (Photo by Mulatie Mekonnen)*

***Table 3.2*** *Studies on structural sediment trapping measures (terrace, basins or ponds and check dam)*

| Types | Scale | Location | Duration (years) | Rainfall (mm) | STE (%) or trapped sediment ($m^3$, t, Mg) | References |
|---|---|---|---|---|---|---|
| **Terraces** | | | | | | |
| Terraces | Watershed | Oklahoma | 3 | - | 760 & 108 Mg $y^{-1}$ $km^{-2}$ (pre & post conservation) | Garbrecht & Starks, 2009 |
| Stone bunds | Watershed | Ethiopia | 1 | 700 | 65.3 t $ha^{-1}y^{-1}$ | Mekonen & Tesfahunegn, 2011 |
| Stone bunds | Plots | Ethiopia | - | 700 | 59 t $ha^{-1}$ $y^{-1}$ | Gebremichael et al., 2005 |
| Terraces | - | Java | 2 | - | 4.55 & 1.05 t $ha^{-1}$ | Sukristiyonubowo et al., 2010 |
| **Basins & ponds** | | | | | | |
| Ponds | Watershed | Munich | 8 | 834 | 54-85% | Fiener et al., 2005 |
| Pond | Watershed | California | - | - | 80-84 % | Markle , 2009 |
| Pond | Watershed | Belgium | - | - | 58-100 % | Verstraeten & Poesen, 2001b |
| Pond | Watershed | Belgium | - | 750 | 10-72% | Verstraeten & Poesen, 2002 |
| Basins | - | N. America | 3 | - | $6.72x10^6$ Mg $y^{-1}$ | Hupp et al., 2008 |
| Basins | - | USA | - | - | 35-99% | Markusic & McLaughlin, 2008 |
| **Check dams** | | | | | | |
| Check dams | Watershed | China | - | - | 21 billion $m^3$ | Wang et al., 2011 |
| Check dams | Watershed | Malaysia | - | 2500 | 6,162 $m^3$ | Abedini et al., 2012 |
| Check dams | Watershed | China | - | - | 10465 t $km^{-2}$ $y^{-1}$ | Ran et al., 2008 |
| Check dams | Watershed | Spain | - | 300 | 4-920 $m^3$ | Sougnez et al., 2011 |

* $m^3$-cubic meter, t-Metric tonnes, Mg-megagram

## 3.5 Combined measures

Vegetative measures can be used to stabilize structural measures and improve their STE. Several researchers argue that to effectively trap sediment and ensure the sustainability of ST measures, it is important to combine both vegetative and structural measures (Nyssen *et al.*, 2009b; Zhang et al., 2010b). In general, more sediment can be trapped using a combination rather than with single measures (Fiener et al., 2005; Zhang et al., 2010b). Figure 3.7 illustrates the combination of vegetative and structural measure; after the construction of terraces, grasses are planted on the bunds and on sandbag check dams.

In a 6.6 ha watershed in southwest Iowa, on a 2-16% slope with silt loam soils, the STE of switch grass (*Panicum Virgatum L.*) and bench terracing were evaluated (Rachman *et al.*, 2008). Bench terracing reduced runoff and sediment yield by 9% and 58%, respectively, but their combined effects gave the highest reduction in runoff (22%) and sediment yield (79%) compared to individual effects. According to Fisseha *et al.* (2011), a structural measure, *fanya juu*, trapped 64% of the sediment and its STE increased to 75% and 80% when combined with elephant grass and Vetiver grass, respectively, on a Eutric Cambisol soil, with 1167 mm average annual rainfall and 20-22% catchment slope in northwest Ethiopia.

***Figure 3.7*** *Examples of the combined application of vegetative and structural measures for sediment trapping northwest Ethiopia (photo by Mulatie Mekonnen): check dams combined with grass (left) and terrace combined with grass strip on top (right)*

## 3.6 Integrated measures

Integrated ST representing the application of all required ST measures on their specific location within the catchment is the most effective approach to manage and control sediment movement compared to individual and combined measures (Nyssen et al., 2009a; Nyssen et al., 2009b; Zhang et al., 2010b). For example, grasses can be planted in waterways and on terraces, tree or shrub buffers can be established along streams or rivers, infiltration trenches, terraces or grass strips can be raised in fields, controlled grazing can be used on grazing lands while area closure can be practiced on degraded lands. Check dams and sediment ponds can also be implemented within gullies or drainage channels. According to Zhang et al. (2010b), the integrated application of trees, grass, terrace and sediment dams reduced mean annual runoff by 3.16-3.42×$10^8$ $m^3$ $y^{-1}$ and mean annual sediment yield by 0.71-1.07×$10^8$ t $y^{-1}$ in the Wuding River basin, China. In Germany, SWC measures without grassed waterways reduced sediment by 87% but their efficacy increased to 93% when integrated with grassed waterways (Fiener & Auerswald, 2006).

The integrated impact of stone bunds, vegetation re-generation, controlled grazing and check dams was studied at a catchment scale in Ethiopia (Nyssen et al., 2009a). Results show that sediment yield decreased from 8.5 to 1.9 t $ha^{-1}$ $y^{-1}$ and sediment delivery ratio decreased from 0.6 to 0.21. The STE of SWC measures and reservoirs were evaluated by Peng *et al.* (2010) in the Yellow River Basin, China over 58 years and found that there was a 40% reduction in total sediment by SWC measures, 30% by reservoirs, 20% by precipitation reduction and 10% by other human activities.

Evrard *et al.* (2008) studied the effectiveness of a grassed waterway and three earthen dams in a 300 ha cultivated watershed in the Belgian loess belt. Runoff and sediment discharge was reduced by 69% and 93% between the grassed waterways inflow and outflow. Before the installation of the control measures, specific sediment yield of the catchment was 3.5 t $ha^{-1}$ $y^{-1}$ with ephemeral gullies observed each year. Since control measures have been installed, no (ephemeral) gullies have developed and the specific sediment yield of the watershed dropped to a mean of 0.5 t $ha^{-1}$ $y^{-1}$. Sediment budgets before and after the implementation of integrated sediment trapping measures were compared in a 187 ha catchment in Ethiopia (Nyssen et al., 2009b). The measures applied include the building of stone bunds, regrowth of vegetation on steep slopes and other marginal land, stubble grazing abandoned, and check dams built in gullies. Within six years, annual soil loss decreased from 14.3 to 9.0 t $ha^{-1}$ and sediment deposition increased from 5.8 to 7.1 t $ha^{-1}$. Thus implementing ST measures in an integrated way is an effective strategy to curtail and manage soil loss and represents an important way to combat land degradation in tropical mountainous areas.

### 3.7 Final considerations and future research agenda

From upstream to the outlet of a catchment, runoff and sediment passes numerous landscape sections that may be more or less connected to each other. Sedimentological connectivity, which refers to the physical transfer of sediment from its source to its sinks through the drainage basin (Bracken & Croke, 2007) or the transfer of sediment from one location to another (Hooke, 2003) is an important concept in understanding sediment dynamics. Moreover, identifying landscape connectivity, which refers to the physical coupling of landforms within a drainage basin, e.g. from agricultural plots to drainage channels (Bracken & Croke, 2007), the upslope sediment source areas, the sediment routing and potential sedimentation spots are needed (Keesstra et al., 2009a; Baartman et al., 2012; Keesstra et al., 2012). This provides essential insights for planning the implementation of ST measures at the most appropriate spatial location, in an integrated way within a catchment (Zhang et al., 2010b). On-site ST measures, for example, afforestation (Keesstra et al., 2009b), vegetative strips (Pan *et al.*, 2011), riparian vegetation (Keesstra et al., 2012; Poeppl *et al.*, 2012) and terraces (Gebremichael et al., 2005; Garbrecht & Starks, 2009) could be utilized in sediment source areas. While off-site ST measures for example, check dams (Abedini et al., 2012) and ponds (Fiener et al., 2005) could be implemented within drainage channels. Consequently, such on-and off-site ST measures could disconnect the sediment transfer linkage, which retards the transfer of sediment further downslope.

Although ST measures have significant advantages, as outlined in this review, they can also have unintended negative consequences downstream. One such impact, the ‘clean water effect’, occurs after the sediment has been trapped from the runoff, after which the increased erosive capacity and power of the now low sediment laden runoff can lead to scour and enhanced soil erosion, through rill and gully development (Nyssen *et al.*, 2007a). Poor construction and lack of regular maintenance of ST measures are also issues. To maximize the effectiveness of any ST measures, regular maintenance is needed to ensure the specific ST measure used meets the design criteria for its sustainable use and to avoid structural failure (Zhang et al., 2010b). For instance, when the drainage ditch behind a ST measure is filled with sediment, the STE quickly decreases with additional pressure being placed on the structure leading to possible structural failure (Gebremichael et al., 2005; Nyssen *et al.*, 2007b). It is important to ensure that ST measures are appropriately located as inadequately localized structure alignment can concentrate runoff at one location (Nyssen et al., 2007b) which creates large erosive potential and can generate major problems further down the landscape. Therefore, a thorough understanding of the hydrological and sediment dynamics of a catchment and its spatial alignments is needed during the design and siting of ST measures. Finally, it is also important to assess the sustainability of ST measures. Factors like subsidy and incentives were affecting ST measures sustainable use. For example, although subsidies and incentives like food-for-work or cash-for-work were used as means of short term food security and as instruments to stimulate farmers’ to build ST measures, even in their own fields (Steiner & Drechsel, 1998; Birhanu, 2003) they are affecting the measures sustainability. The ST measures dismantled in expectation of getting incentives (GTZ/IFSP, 2004). This indicates that temporary benefits are upsetting long-term and sustainable changes. Therefore, it could be important to consider such sustainability factors during measures implementation in addition to the design and siting of ST measures.

Most of the reviewed ST studies refer to research at the plot scale. However, much less is known about the integrated STE of measures at the catchment scale. Therefore, evaluating the integrated STE of ST measures at the catchment scale should be a priority for future research. Assessing the STE of all potential vegetative and structural measures, including their placement on a field-by-field basis and quantifying their integrated effect on the entire catchment is difficult both technically and financially. One method to achieve this could be by using appropriate modelling (Deletic, 2001; Verstraeten & Poesen, 2001b; Rachman et al., 2008). The outcome of such models could be a ST plan for the catchment, as indicated schematically in Figure 3.8, where on-site measures such as terraces, grassed waterways, grass strips, etc. can be established in fields, while tree buffers or streamside (riparian) measures can be located in and along streams to trap sediments from surface runoff before being discharged into the rivers. Off-site measures, for example, sediment ponds and check dams can be built in ephemeral gullies and drainage channels to trap sediment from concentrated runoff before re-joining downstream reservoirs and lakes. On-site ST measures can trap on-site sediments in fields and off-site ST measures can trap off-site sediments in drainage channels and gullies. Sediments transported from fields without being trapped by on-site ST measures can be trapped by off-site ST measures. The integrated effect of all on-and off-site ST measures can reduce sediment load at the outlet of the catchment to a minimum and can be evaluated by measuring the sediment budget 'before and after' at the catchment outlet. A further advantage of using a modelling approach is the ability to assess, *a-priori* (i.e. before actual implementation), the effect of different spatial configurations of the various ST measures in the landscape and chose the optimal design.

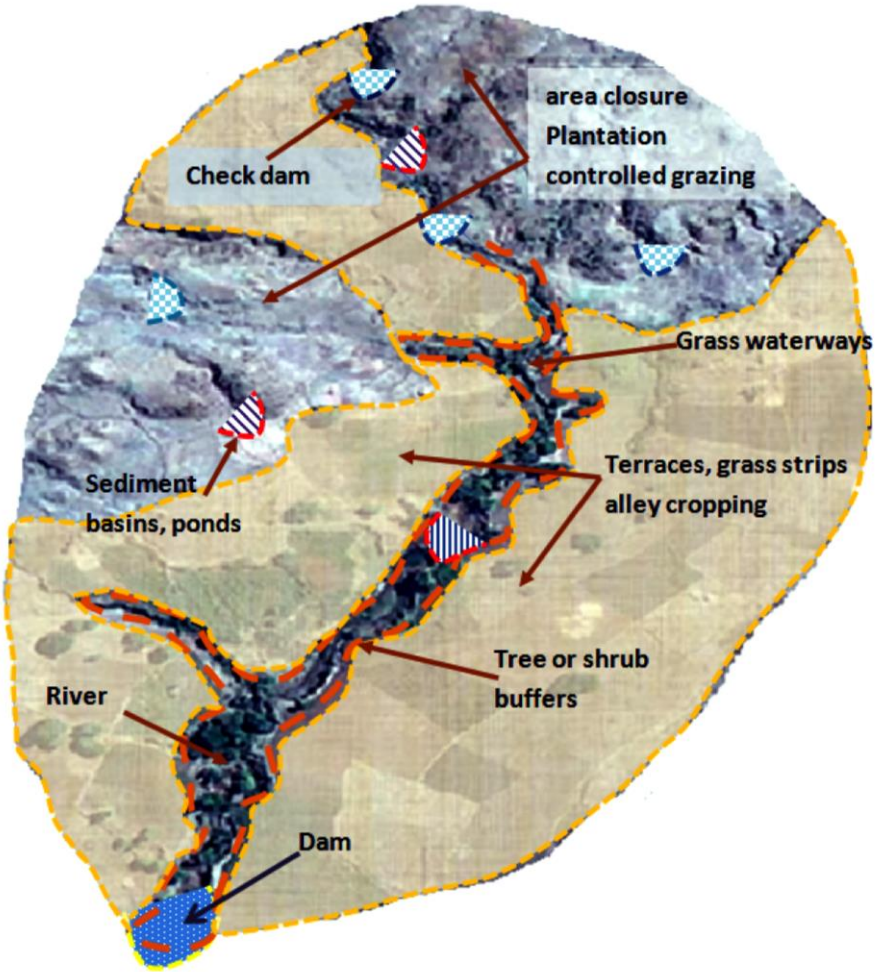


***Figure 3.8*** *Schematic representation of integrated sediment trapping measures at a catchment scale*

## 3.8 Conclusions

In this paper a large number of scientific journal articles were reviewed, field observations and stakeholder interviews were conducted in relation to on-site and off-site vegetative and structural sediment trapping (ST) measures with the results revealing that grassed waterways, terraces, grass strips, tree buffers and in-channel and riparian vegetation play an important role in reducing surface runoff velocity and in trapping sediment from agricultural fields. Check dams were found to be the preferred structural measures to reduce concentrated runoff and to trap sediment in gullies and drainage channels. Sediment ponds are also important runoff and ST measures in construction sites, drainage channels and at the edge of farmlands.

The reviewed studies also showed that vegetation type and combinations of two or more measures (vegetative and structural) are important factors influencing sediment trapping efficacy (STE). To evaluate the STE of ST measures three approaches were identified: (i) individual approach; evaluating the STE of individual measures; (ii) Combined approach; evaluating the STE of two or more types of ST measures implemented at the same location; and (iii) integrated approach; the application of all required ST measures on their specific location within the catchment and evaluating their integrated efficacy. Almost all studies evaluated ST measures using the individual approach, which revealed a lower efficacy than the combined approach. A few studies attempted to evaluate the STE of two or more measures using an integrated approach at the catchment scale, but they were not exclusively integrated. Therefore, there is a need for further research into the use of STE of measures in an integrated approach. The integrated approach, at the catchment scale is believed to be the most effective in helping to increase the STE of ST measures and thereby reducing sediment loads at the outlet of the catchment.

# Chapter 4

# Sediment trapping with indigenous grass species showing differences in plant traits in NW Ethiopia

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# Sediment trapping with indigenous grass species showing differences in plant traits in NW Ethiopia

*Abstract*

*Soil loss from an 8% sloping Teff field in north-western Ethiopia is significant (~70 t ha$^{-1}$ y$^{-1}$), and thus found to be an important source of sediment. Grass barriers showing sediment trapping efficacy (STE) are important measures in trapping sediment inside Teff fields and protecting downstream reservoirs and lakes from sedimentation. There are many indigenous grass species available that have the potential to act as sediment trapping measure when used in strips downstream of sloping crop fields. However, their STE and their key functional traits that determine their STE are not yet known. This negatively influence agricultural extension agents in disseminating conservation technology to farmers at larger scales. The indigenous grass species Desho (Pennisetum pedicellatum), Senbelet (Hyparrhenia rufa), Sebez (Pennisetum schimpri) and Akirma (Eleusine floccifolia) and one exotic species, Vetiver (Vetiveria zizanioides) were tested for two years (2013 and 2014) in 1.5 m wide strips below Teff fields at 8% slope in the Debre Mewi watershed, northwest Ethiopia. The average runoff during the study was 79, 64, 69, 71, 74 and 75 l m$^{-2}$, with 7.0, 1.7, 2.9, 3.6, 4.5 and 5.6 kg m$^{-2}$ y$^{-1}$ of sediment from the Control, Desho, Vetiver, Senbelet, Akirma and Sebez treatments, respectively. Differences in key functional traits affected the STE of the different grass barriers. Desho with the highest tiller number and density, and the second highest root length (depth) showed better STE (76%) than the other grass species, Vetiver (59%), Senbelet (49%), Akirma (36%) and Sebez (20%). This indicates that grass barriers can be used as a soil conservation measure replacing the costly and more maintenance demanding physical structures like trenches and ridges. As a co-benefit, grass barriers provided important fresh biomass for livestock, thereby helping to reduce the feed shortage. Thus we conclude that indigenous grass species provided a practical means to reduce soil loss from Teff fields (up to 8% slope) in the northwest Ethiopia and can be easily adopted by farmers due to their combined soil conservation and feed value.*

## 4.1 Introduction

Soil erosion by water is a global problem (Morgan, 2005), however, it is more severe in developing countries (Lal, 2001; Thomaz & Luiz, 2012), such as Ethiopia, where soil erosion of agricultural fields is leading to the loss of fertile top soil (Hurni, 1993; Zeleke, 2000) and significantly reducing crop yields (Hurni, 1993; Haileslassie *et al*., 2005). The problem is most critical in the Ethiopian highlands (> 1500 m a.s.l.) (FAO, 1986; Zeleke, 2000; Nyssen *et al*., 2004; Frankl *et al*., 2013) as 4% of the highlands is seriously eroded (Kruger *et al*., 1996). Plot scale measurements of soil loss in the cultivated fields of the Ethiopian highlands has been estimated to be 42 t ha$^{-1}$ y$^{-1}$ (Hurni, 1987).

Recent and more location specific studies at watershed scale estimated sheet and rill erosion losses between 19 and 79 t ha$^{-1}$ y$^{-1}$ at Chemoga watershed (Bewket & Sterk, 2003), and from 12.5 to 50 t ha$^{-1}$ y$^{-1}$ at Debre Mewi Watershed (Mekonnen & Melesse, 2011). Amare *et al*. (2014) also found from 26 to 71 t ha$^{-1}$ y$^{-1}$ at plot scale in Debre Mewi watershed. Erosive tropical rains, steep slopes, extensive deforestation for fuel wood collection, expansion of cultivation into steep land areas, overgrazing, long periods of inadapted agricultural practices and high population pressure are important causes of such high rates of soil erosion in the north-western Ethiopian highlands (Bewket, 2002; Nyssen et al., 2004; Amsalu *et al.*, 2007; Mekonnen *et al.*, 2015b).

To maintain sustainable crop cultivation about 75% of the highlands need soil conservation measures (FAO, 1986). The use of on-site sediment trapping measures can reduce soil loss by promoting sedimentation within farmers' fields (Verstraeten *et al.*, 2006; Wanyama *et al.*, 2012; Mekonnen *et al.*, 2014b). Vegetative measures, for example grass barriers, are among the on-site measures that play a significant role in trapping sediments from overland flow (Ritsema, 2003; Blanco-Canqui *et al.*, 2004; McKergow *et al.*, 2004; Stroosnijder, 2009; Wanyama et al., 2012). This is because of sediment filtration and deposition (Dillaha *et al.*, 1989), upslope ponding (Meyer *et al.*, 1995; Spaan *et al.*, 2005), and decreased flow velocity and increased surface roughness, which decreases sediment transport capacity of surface runoff (Borin *et al.*, 2005). Grass barriers also increase the efficacy of physical soil conservation structures in trapping sediment and reducing on-site soil loss when combined together (Rachman *et al.*, 2008; Zhang *et al.*, 2010b; Mekonnen et al., 2014b) and are less expensive and less labour intensive to implement than physical structures such as trenches and ridges. As a co-benefit, grass barriers provide livestock with feed and this can play an important role in controlling free grazing, encouraging a cut and carry system for soil conservation and in the adoption of the measures (MoA, 2001; MOARD, 2010).

The sediment trapping efficacy (STE) of many grass species is well known. For example; Lemon grass (72-92%), Elephant grass (62-84%), Paspalum (65-88%) and Sugarcane (56-82%) in Uganda (Wanyama *et al.*, 2012); Vetiver grass (65%) in Australia (McKergow *et al.*, 2004); Brome grass (70-85%) (Robinson *et al.*, 1996) and Switch grass (92%) (Lee *et al.*, 2000) in the USA; Centipede grass (24-73%) in Japan (Shiono *et al.*, 2007); Black rye (42-69%) in China (Pan *et al.*, 2010) and Vetiver (62%) and Desho (43%) in the lowland part of Ethiopia (Welle *et al.*, 2006). The STE of Desho grass was tested by Welle et al. (2006) in the lowland part of Ethiopia but not in the highlands where it performs best (MOARD, 2010). There are in fact many grass species that could potentially serve as vegetative barriers in the northwest Ethiopian highlands but have not been studied for their STE including locally used grass species Desho (*Pennisetum pedicellatum*), Senbelet (*Hyparrhenia rufa*), Sebez (*Pennisetum schimpri*) and Akirma (*Eleusine floccifolia*). Traditionally, these four grass species are being used by a majority of Ethiopian farmers by planting them on their lower field edges in 1-1.5 m wide strips.

Investigating the STE of these indigenous grass species in northwest Ethiopia will provide valuable information for local farmers, agricultural extension agents and researchers. To facilitate the extrapolation of results to other contexts and species, attention should be paid to key functional traits. Grass morphological characteristics such as number of tiller, density and root depth affect STE (Pearce *et al.*, 1997; Abu-Zreig *et al.*, 2004; Spaan et al., 2005; Montakhab & Yusuf, 2011; Burylo *et al.*, 2012; Wanyama et al., 2012) found that dense vegetation barriers promote sedimentation reducing flow velocity and building up backwater upslope. STE is influenced by the type and density (Abu-Zreig et al., 2004), and density and distribution (Montakhab & Yusuf, 2011) of the grass barrier. Plant roots increase the resistance of soils to erosion (Reubens *et al.*, 2007) and help improve soil permeability, increasing soil infiltration and thus decreasing runoff volume, thereby promoting sedimentation. Furthermore, a plant with deep roots can access water deep below the surface, which increases infiltration and reduce runoff, thus increasing sedimentation (Ohare *et al.*, 2016).

This study evaluated the STE of four indigenous grass species (Desho, Senbelet, Akirma and Sebez) and one exotic grass species (vetiver), to determine the differences in plant traits, in northwest Ethiopia. The objectives were to (i) evaluate the STE of these grass species at the field level, and (ii) determine the differences in STE through the key functional traits of these grasses (root depth, tiller number and density). Finally, an assessment of the chance of adoption of these plants by farmers in northwest Ethiopia, based on social and economic considerations, is presented.

## 4.2 Materials and methods

***Experimental site***

The study was conducted over a two year period using experimental plots located at an elevation of 2300 m a.s.l., with an average slope of 8% (ranging from 7-9%), in the Debre Mewi watershed, in the upper Blue Nile Basin, northwest Ethiopia (327865 m N and 1256370 m E; Adindan_UTM_Zone_37N; Figure 4.1). The average annual rainfall over these two years was 1080 mm (1105 mm in 2013 and 1055 mm in 2014). About 80-90% of the rainfall falls in the main rainy season (*Kiremt*), which starts in June and extends to September, but is preceded and followed by one month of low and dispersed rains. Mean annual minimum and maximum temperatures of the site are 8.7 $^{0}$C and 25.4 $^{0}$C, respectively.

The Nitosol soil type present has a predominantly clay texture (Mekonnen & Melesse, 2011; Mekonnen *et al.*, 2015c) containing 12% stoniness. According to Bationo *et al.* (2006), Nitosols are deep, well drained and red tropical soils with a clay-rich subsoil, characterized by good soil structure. They are general considered to be fertile soils and are found in ~200 million ha worldwide, with more than half of all Nitosols present in tropical Africa, especially in the highlands (>1000 m) of Ethiopia, Kenya, Zaire and Cameron.

***Field experiment***

The experiment was conducted during the 2013 and 2014 seasons on a natural slope, which was treated similarly as the surrounding farmland (Figure 4.2). Six runoff plots (6 m wide x 29.5 m: 177 m$^2$) were constructed according to the Soil Conservation Research Programme (SCRP) plots used in Ethiopia (Herweg & Ludi, 1999). Teff (*Eragrostis teff, E. abysainica*) is the dominant indigenous crop and used as the test crop. Teff is a staple crop in Ethiopia comprising >43% of the total crop production area in Amhara Regional State (CSA, 1999). Teff was planted in the first week of July and harvested in December. Broadcasting was applied to sow the crop (Teff), which is a common planting method in the area. To reduce sediment loss variability due to crop type, the same crop was used in both experimental years without rotation.

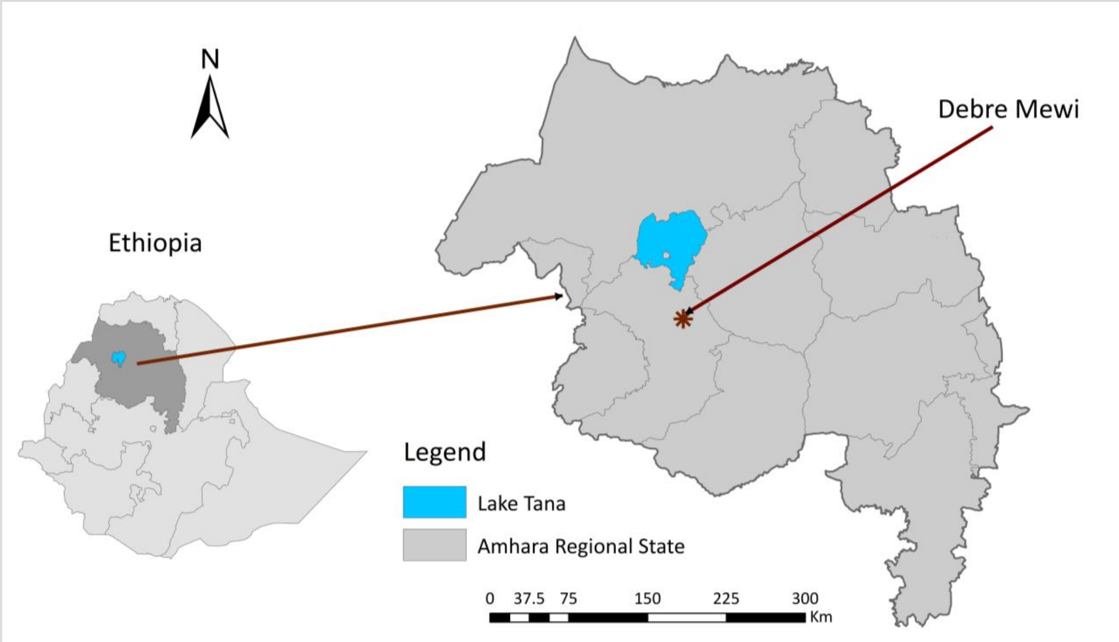


***Figure 4.1*** *The Debre Mewi watershed in Amhara Regional State of Ethiopia*

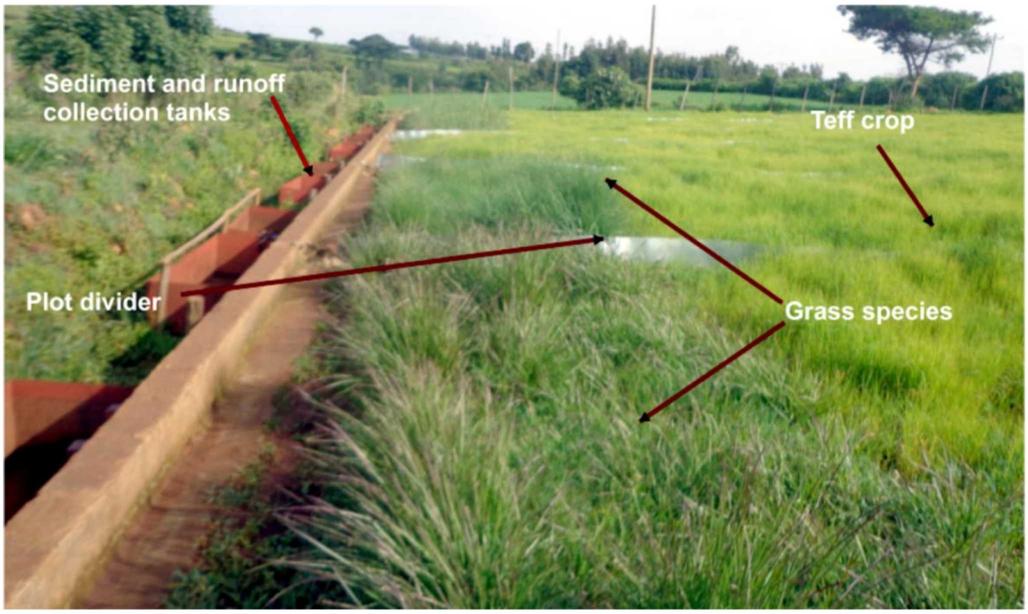


***Figure 4.2*** *Field experimental setup with Teff as food crop and 1.5 m wide grass barriers and runoff and sediment collection tanks, Debre Mewi watershed, Ethiopia*

Grass strips (1.5 m wide) were planted at the end of each plot except for the control. Most farmers in the area plant grass species with widths of 1.0-1.5 m on the edge of their fields. The maximum width (1.5 m) was used in our experiment assuming that wider strips can trap sediment more efficiently (Abu-Zreig et al., 2004; Wanyama et al., 2012).

Tanks (0.5 m height x 1 m width x 1.5 m length) were positioned at the lower end of each experimental plot to collect sediment-laden runoff. Additional tanks were established connected to the first tank to collect the overflow runoff and sediment. To isolate the experimental treatments from each other and from the surrounding fields, 40 cm height corrugated iron fencing was installed around each plot.

Due to time and resource constraints this experiment was not replicated spatially. Therefore, great care was taken to select a site with uniform slope, soil type, texture, rainfall and land cover in order to have 6 similar plots to be arranged in sequence. Ellis *et al.* (2006), Shiono et al. (2007) and Leguedois *et al.* (2008) demonstrated that any likely error in the surface water budget due to spatial variation between treatment sequences was likely to be smaller than the measurement errors.

***Grass morphological traits***

Five grass species were selected for this study; four locally dominant indigenous grass species Desho (*Pennisetum pedicellatum*), Senbelet (*Hyparrhenia rufa*), Sebez (*Pennisetum schimpri*) and Akirma (*Eleusine floccifolia*) of the northwest Ethiopia and one exotic but well adapted grass species, Vetiver (*Vetiveria zizanioides*). All species are perennials, are suitable for the rainfall and altitude of the Debre Mewi watershed and are already known and used by farmers. The morphological characteristics and elevation and rainfall ranges to which these grass species are adapted, are presented in Table 4.1.

***Table 4.1*** *Available information of the selected barrier grass species used in the 2013-2014 trials at Debre Mewi, Ethiopia.*

| Grass species | Elevation | Rainfall | Height | Fodder | References |
|---|---|---|---|---|---|
| | m a s l | mm | cm | | |
| Desho | 1500-2800, (perform best 1700-2500) | 1000-1500 | 90-120 | +++ | Welle et al. (2006); MOARD (2010); NBDC (2013) |
| Senbelet | 0-2000 | 600-1400 | 60-240 | ++ | Skerman and Riveros. (1990) |
| Sebez | 1600-3100 | No data | Up to 120 | + | Skerman and Riveros. (1990) |
| Akirma | 1800-3100 | 900 | 120-150 | ++ | Dagnachew *et al.* (2014) |
| Vetiver | 1000-3000 | 750-2000 | Up to 200 | ++ | MOARD (2010); Truong and Loch (2004) |

*Palatability of the grass species from farmers experience; high palatability (+++); palatable (++); low palatability (+)*

The grasses, splits containing 3-5 tillers, were planted in rows with 30 cm between the rows and at 15 cm spacing within rows (MoA, 2001; Welle et al., 2006; Oshunsanya, 2013). There were five rows within the 1.5 m strip. Some of the grass species were collected in farmers' fields and some obtained from a local nursery. During the first year (2013), the grass species were planted at the end of April. Data collection started two months after planting at the beginning of July when the grasses were well established and ended at the end of September. The first years' data collection was finalized when the rainy season ended; grasses were harvested and they re-vegetated during the next rainy season (July, August and September) for the second year (2014) of data collection.

To evaluate the key plant functional traits root length, tiller number and density were determined in the field. To assess the average root length per split, 20 grass splits were taken, carefully dugout and measured from each species. To find the average number of tillers per split, 16 splits were sampled randomly from each species. To calculate tiller density (in $m^2$), the total number of tillers was divided by the total area covered by the grass barriers.

***Sediment data collection and sediment trapping efficacy (STE) calculation***

Daily rainfall data was collected using a rain gauge, while daily runoff was measured after each rainfall event. Daily runoff was summed up into annual runoff. To estimate sediment loads, one-litre runoff samples were collected from the sediment collection tanks after each runoff producing rainfall. Before taking samples, the trapped runoff and sediment in the tanks was stirred thoroughly to make the samples representative. Over the two years, 54 one-litre samples from each treatment, amounting to 324 samples being collected, dried and weighed. The dry sediment mass from the runoff sample (g $l^{-1}$) was used to quantify daily sediment loss using the daily total runoff volume. The sum of daily sediment losses provided the annual soil loss.

To estimate the sediment trapping efficacy (STE,) sediment measured at the outlet of the control treatment was considered as inflow into the grass strip, while sediment measured at the outlet of a grass barrier was considered as outflow sediment. STE was then calculated using Eq. 4.1 (Coyne *et al.*, 1995; Verstraeten & Poesen, 2000).

$$STE = \frac{(S_{inflow} - S_{outflow})}{S_{inflow}} * 100 \qquad 4.1$$

Where: $STE$ is sediment trapping efficacy (%); $S_{inflow}$ is total seasonal sediment mass measured at the outlet of the control plot (kg) and $S_{outflow}$ is total seasonal sediment mass measured at the outlets of each treated plot (kg).

## 4.3 Results

***Effect of grass barriers on runoff reduction and sediment trapping***

The average inflow and outflow runoff over the two years from the experimental plots for each species is given in Figure 4.3. While the control resulted in the overall highest runoff (14.0 $m^3$), the least runoff from the grassed plots was recorded from Desho (11.3 $m^3$) and the most runoff from Sebez (13.2 $m^3$). Overall, Desho, Vetiver, Senbelet, Akirma and Sebez reduced runoff by 2.7 $m^3$ (19%); 1.9 $m^2$ (14%); 1.4 $m^2$ (10%); 1.0 $m^3$ (7%) and 0.8 $m^3$ (6%), respectively.

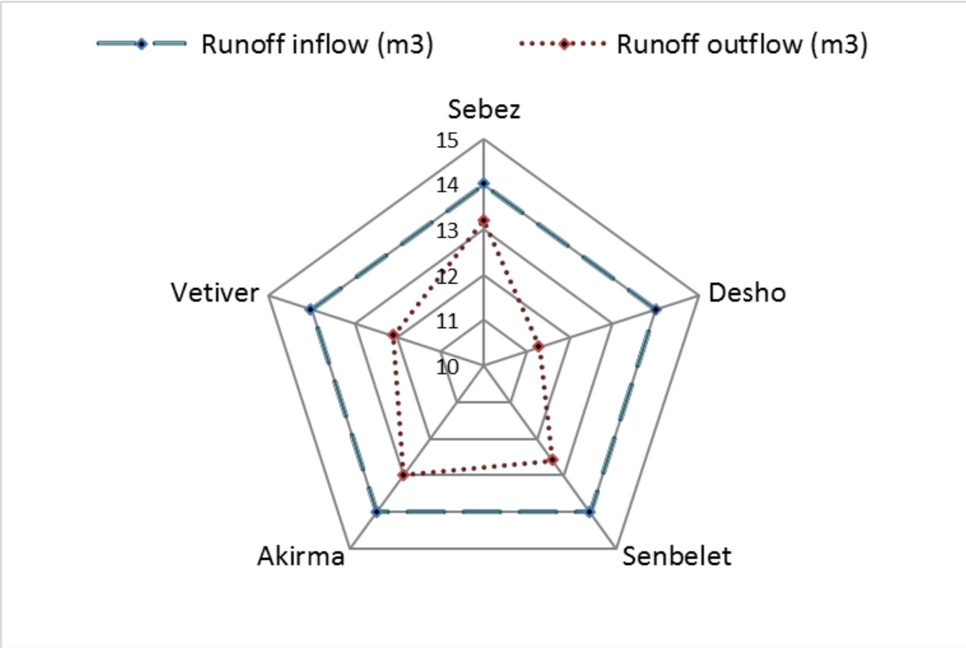


***Figure 4.3*** *Radar diagram showing inflow and outflow runoff records from each experimental plot*

Sediment concentration and the corresponding STE recorded over the two years is given in Figure 4.4. The lowest sediment concentrations were from the Desho (27 g $l^{-1}$) plot, which were three times lower than the control (93 g $l^{-1}$), while the highest was from the Sebez (71 g $l^{-1}$) plot. Sediment concentration from the Vetiver (42 g $l^{-1}$) was 2 times lower from the control readings. Given the rapid growth of the Teff crop, there is a large difference in sediment concentration at the beginning of the season and at the end. Comparing 10 sediment samples at the beginning with 10 at end of the rainy seasons for the Control plot, revealed high sediment concentrations (189 g $l^{-1}$) at the beginning of the season versus very low concentration (14 g $l^{-1}$) at the end.

The lowest sediment loss was recorded from Desho (306 kg) with most sediment loss recorded from Sebez (996 kg), while the Control (1251 kg) had the highest overall sediment loss (Figure 4.4). Sediment loss was 4 times lower in Desho plot and 2 times lower in Vetiver plot relative to the control. This implies that Desho grass trapped four and two times more sediment than Sebez and Akirma, respectively. Vetiver and Senbelet also trapped three and two times more sediment than Sebez and Akirma, respectively. The resulting average STE (in %) was 76, 59, 49, 36 and 20 for Desho, Vetiver, Senbelet, Akirma and Sebez, respectively (Figure 4.4).

***Functional traits of grass barrier species***

Figure 4.5 shows the four indigenous and one exotic barrier grass species used. The grass barriers revealed some distinct variations in the morphological characteristics in root length, tiller number and density (Table 4.2). Desho had the highest number of tillers and highest tiller density whereas Sebez displayed the lowest. Vetiver had the highest root length whereas Sebez had the lowest. Desho had a fast lateral spreading growth pattern compared to the other grass species and covered the free space between rows and within rows in a short period of time.

The functional traits of the grasses appear to influence the STE of the grass barriers (Figure 4.6). STE revealed strong correlation with tiller density ($R^2$ = 0.89), number of tillers ($R^2$ = 0.85) and root length ($R^2$ = 0.73).

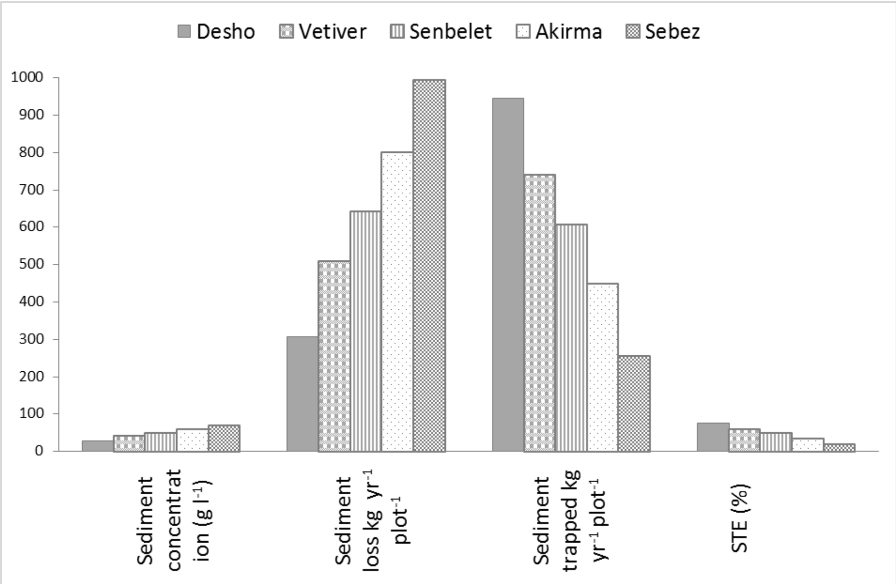


***Figure 4.4*** *Mean (2013-2014) annual sediment concentration; -loss; -trapped and STE of the grass barriers in Debre Mewi watershed, north-western Ethiopian highlands*

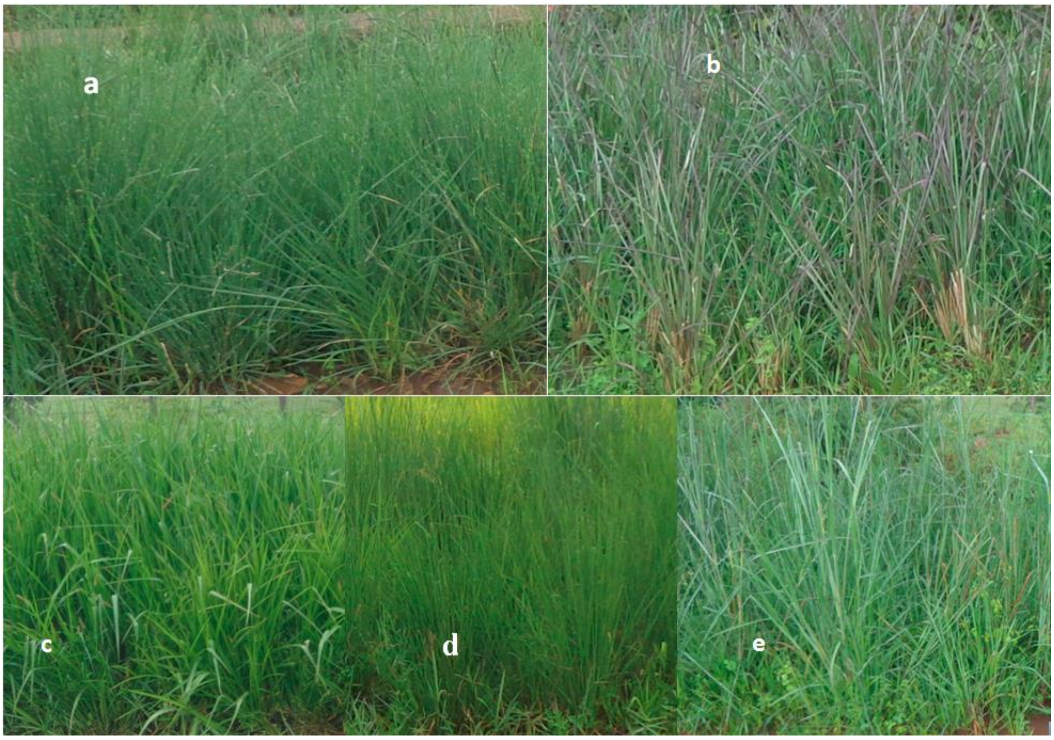


***Figure 4.5*** *Barrier grass species evaluated for their key plant functional traits for STE: Akirma (a), Vetiver (b), Desho (c), Sebez (d) and Senbelet (e) (Photos by Mulatie Mekonnen)*

***Table 4.2*** *Functional traits (average of 2013 and 2014 growing seasons) of tested barrier grass species, Debre Mewi watershed, Ethiopia*

| Grass barrier | Root length (cm) | Av. number of tillers (split$^{-1}$) | Tiller density (m$^{-2}$) |
|---|---|---|---|
| Desho | 61 | 41 | 92 |
| Vetiver | 64 | 35 | 78 |
| Senbelet | 51 | 36 | 81 |
| Akirma | 46 | 32 | 72 |
| Sebez | 39 | 30 | 67 |

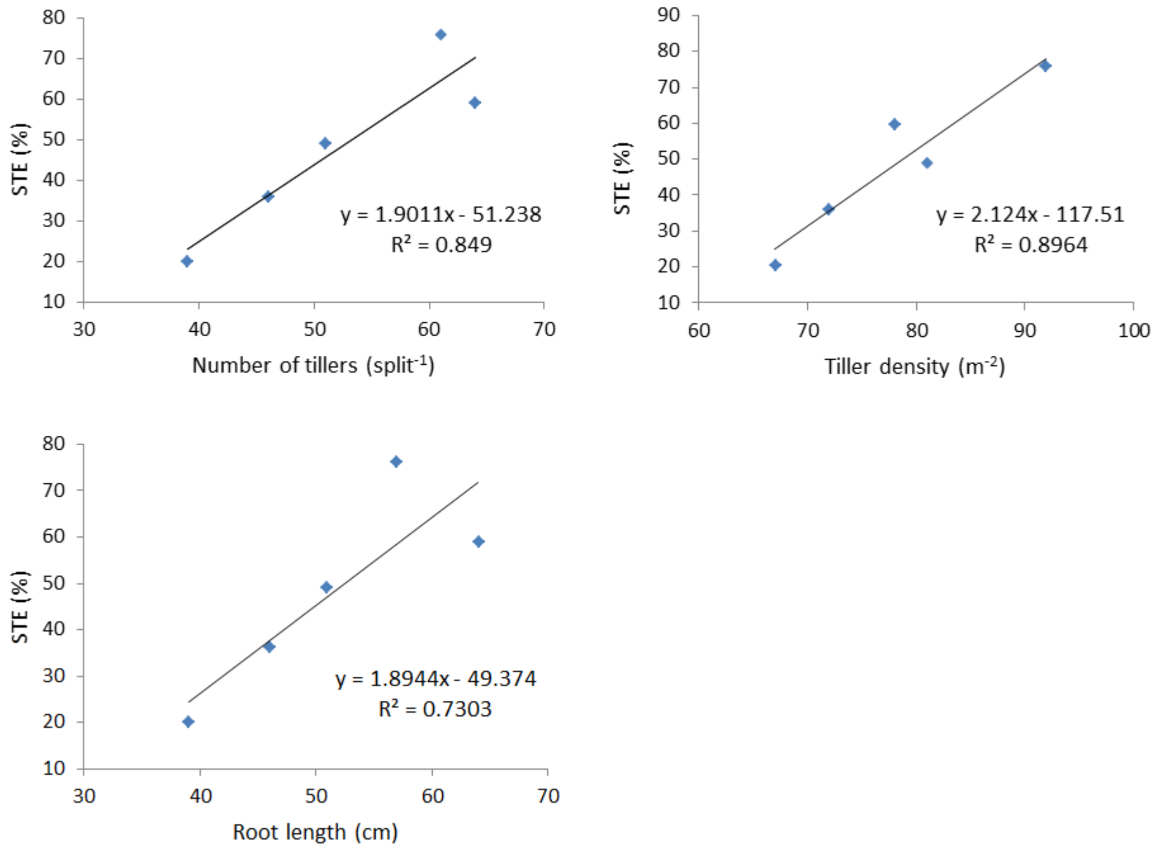


***Figure 4.6*** *Relations of STE with number of tiller (a), tiller density (b) and root length (c)*

## 4.4 Discussion

***Sediment trapping efficacy (STE)***

In this study, the STE of Desho (76%) was the highest followed by Vetiver (59%), Senbelet (49%), Akirma (36%) and Sebez (20%). Due to its fast lateral spreading growth pattern, large number of tillers and high tiller density, Desho covered the free space between rows and within rows rapidly, which contributed to its high STE compared with the other grass species. In line with this result, Wanyama et al. (2012), found lemon and paspalum grass revealed greater STE than elephant grass and sugar cane because of their spreading growth pattern. Because of their slow lateral spreading and more vertical growth pattern, which causes low coverage of the free space between rows and within rows that allows the sediment to pass, Vetiver and Senbelet revealed lower STEs than Desho. The slow growth nature of Akirma and Sebez influences their STE considerably.

Our finding for the STE of Desho (76%) was much higher than the 43% reported by Welle et al. (2006) for a low land area of Ethiopia at a lower altitude (1650 m a.s.l.) and lower annual rainfall (661 mm) than in this study. These difference in altitude and rainfall influence the growth and tillering capacity of the grass barrier. In our study, Desho grass performs best at the higher altitude and higher rainfall, which is in line with (MOARD, 2010). The STE of Vetiver grass was 59%, which is comparable with the 62% reported by Welle et al. (2006) in Ethiopia and the 65% reported by Mckergow et al. (2004) in Australia.

***Key functional traits of barrier grass and STE***

In this study, tiller density and STE showed a good relationship ($R^2$ = 0.89) with increasing tiller density STE increases; which agrees with Abu-Zreig et al. (2004) and Montakhab and Yusuf (2011). STE also showed a good correlation with the number of tiller ($R^2$ = 0.85), which is in line with Lambrechts *et al.* (2014) who found that STE increases with an increase in the tillering capacity of vegetative barriers.

In this study no backwater effects was observed upslope of the grass barriers and hence sedimentation was largely due to sediment filtration by, and deposition in, the grass barriers. This result agrees with Dillaha et al. (1989) who also found that grass barriers played a significant role in trapping sediment from surface runoff because of sediment filtration and deposition. In this study deep rooted grass species revealed a good positive correlation with STE ($R^2$ = 0.7), which is in line with Ohare et al. (2016) that deep rooted plants increase sedimentation.

***Importance of soil loss reduction by grass barriers***

On-site sediment trapping measures can trap sediment and thus limit sediment export from agricultural fields (Verstraeten et al., 2006; Lambrechts et al., 2014; Mekonnen et al., 2014b). Grass barriers are among the many on-site measures that play a significant role in trapping sediments from overland flow (Ritsema, 2003; Blanco-Canqui *et al.*, 2004; McKergow et al., 2004; Stroosnijder, 2009; Wanyama et al., 2012). In this study, grass barriers reduced sediment concentration on a Teff field considerably. Compared with the control plot (93 g $l^{-1}$), Desho, Vetiver, Senbelet, Akirma and Sebez reduced sediment concentration (in g $l^{-1}$) to 66; 51; 43; 33 and 22, respectively.

The average soil loss during the study due to sheet erosion from the un-grassed 8% sloping Teff field was found to be 70 t $ha^{-1}$ $y^{-1}$ (control treatment). Grass barriers trapped a lot of sediment and reduced soil loss substantially. Desho showed the highest reduction with 53 t $ha^{-1}$ $y^{-1}$ while Sebez had the lowest at 15 t $ha^{-1}$ $y^{-1}$. Vetiver, Senbelet and Akirma reduced 42; 34 and 26 t $ha^{-1}$ $y^{-1}$, respectively. This indicates that grass barriers can be used as an effective soil conservation measure in replacing the costly and more maintenance demanding physical structures like trenches and ridges, as also noted by (MOARD, 2005), for fields up to 8% slope. An important advantage of vegetative measures over physical structures is the use of grass as feed. Moreover, Desho and Vetiver grasses are not affected by nor harbour rats unlike the case in physical structures such as stone bunds.

Sediment trapping was found to be effective when structural and vegetative measures combined together (Mekonnen et al., 2014b). Erktan *et al.* (2013) investigated the role of morphological diversity of plant barriers in sediment trapping and found that grass barriers performed best in trapping sediment however, the morphological diversity was significantly impaired by STE. On the contrary, Lee et al. (2000) found that the combined STE of Switch grass-woody vegetation (92%) was higher than the switch grass alone (70%) and according to Knight *et al.* (2010), even though natural remnant forests showed substantial STE (80%), the addition of an adjacent grass barrier further reduced sediment load entering streams with a STE of 100%. In this study, grass barriers showed substantial STEs when evaluated in a monospecific (individual) test and further study has been recommended to evaluate the STE of the grass barriers in a plurispecific (combined) approach.

***Chances for adoption by farmers***

The biggest challenge for soil conservation experts is the adoption of conservation measures by farmers. Lack of feed for animals is an important problem in the north-western Ethiopian highlands. As a co-benefit, grass barriers can provide livestock feed and this can play an important role in adoption of the measure. Improved feed supply can help to control free grazing and encourage a cut and carry system for soil conservation (MoA, 2001; MOARD, 2010). According to Engdayehu *et al.* (2015), at Debre Mewi watershed the major source of fodder is crop residue and hay collected during harvesting. During the rainy season edible weed species from the crop fields and during the dry season crop residues (mainly teff and maize straws) and grass collected during October and December are the main sources of livestock feed. In our study, the evaluated grass species were found to be important sources of livestock feed in addition to trapping sediment and reducing soil loss. Desho, Senbelet, Akirma, Vetiver and Sebez provided 132, 106, 76, 69 and 51 t $ha^{-1}$ $y^{-1}$ fresh biomass, respectively. A field day was organized for farmers living around the study area and they visited the experiment and indicated Desho as their first priority for livestock feed. Leaf softness and biomass production were their most important criteria.

To reduce the bias that often results when using artificial rainfall, this study was conducted at field level with a considerable investment in collecting runoff and sediment data after each natural rainfall event during two growing seasons (2013 and 2014). Due to resource constraints, this experiment was not replicated spatially. Great care was therefore taken to select a site with similar conditions (soil type, slope, rainfall and land cover) and set the treatment in sequences. We therefore regard our measurements to be representative of the runoff and sediment processes observed during the experiment. Ellis et al. (2006) and Leguedois et al. (2008) demonstrated that any likely error in the surface water budget due to spatial variation between treatment sequences was likely to be smaller than the measurement errors.

## 4.5 Conclusions

Soil loss from an 8% slope Teff field was measured at 70 t $ha^{-1}$ $y^{-1}$. Erosion was high at the beginning of the rainy season as a result of repeated ploughing (fine seed bed preparation) and lack of a crop cover. The use of 1.5 m wide strips of local grasses showed promising results in trapping sediment. Desho grass performed best and reduced soil loss with 53 t $ha^{-1}$ $y^{-1}$ with a Sediment Trapping Efficacy (STE) of 76%. Differences in key functional traits affected the STE of the different grass barriers. Desho with the highest tiller number and density, and the second highest in root length revealed better STE than the other grass species, Vetiver (59%), Senbelet (49%), Akirma (36%) and Sebez (20%). The fast lateral spreading growth nature, leading to covering the free space between rows and within rows within a short period of time helps Desho grass to perform best. As a co-benefit, grass barriers provided fresh biomass for livestock helping to reduce the forage problem. Thus we conclude that Indigenous grass species provided a practical means to reduce soil loss from Teff fields (up to 8% slope) in the north-western highlands of Ethiopia and seemed to be easily adopted by farmers due to its feed value.

Determining the STE of grass barriers and evaluating key functional traits that influence STE is important, both for soil conservation experts to disseminate the technology with evidence, for researchers as a source of scientific information and for farmers to use the grass barriers as a sediment trapping measure. This study is the first to test the effectiveness of Desho, Senbelet, Akirma and Sebez under sheet erosion conditions and to give attention to their key functional traits in the north-western Ethiopian highlands. However, further study is recommended on higher slopes (> 8%) and under concentrated flow conditions with different strip widths.

# Chapter 5

# Evaluating sediment storage dams: structural off-site sediment trapping measures in NW Ethiopia

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# Evaluating sediment storage dams: structural off-site sediment trapping measures in NW Ethiopia

*Abstract*

*Reservoir and lake sedimentation is a vital problem in Ethiopia. Constructing small and medium size dams at the outlets of sub-catchments within the larger catchment helps to reduce the transport of sediment to downstream man-made reservoirs constructed at the outlet of the catchment or natural lakes. This study assessed the sediment trapping efficacy (STE) of sediment storage dams (SSDs) built at the outlets of eight small sub-catchments in northwest Ethiopia, as an off-site sediment trapping measure. Satellite imagery and topographic maps were used to assess land use/land cover and delineate the boundaries of sub-catchments. In the field, trapped sediment by SSDs was measured directly, as well as in- and outflow of suspended sediment with which the STE of each SSD was estimated. Sediment yield of each sub-catchment was calculated from the measured trapped sediment and estimated suspended sediment loss. Results show that SSDs trapped an average of 1584 t $y^{-1}$ of the inflow sediment and catchment specific sediment yield ranged from 8.6-55 t $ha^{-1}$ $y^{-1}$. Two representative SSDs constructed from gabion and stone were evaluated with regard to their STE. Results showed that their efficacy was 74% and 67% for the gabion and stone SSD, respectively. In general, although SSDs might be costly for small scale farmers and have a relatively short life span depending on their size, they are promising off-site structural measures to trap significant amounts of sediment at the outlets of sub-catchments and subsequently reducing sediment movement to downstream reservoir or lakes.*

## 5.1 Introduction

On-site soil erosion and off-site sedimentation are natural phenomena in landscape formation. However, human activities have accelerated natural erosion rates causing on- and off-site problems with soil degradation and sediment accumulation on undesirable locations (reservoirs, rivers, etc.) (Zeleke, 2000; Morgan, 2005; Amsalu et al., 2007; Mekonnen & Melesse, 2011). Reservoir sedimentation is the product of on-site soil erosion resulting either from point sources like mining and construction sites or non-point sources such as from agricultural areas and grazing lands. Gully and river bank erosion are also important sources of sediment (Wasson *et al.*, 2002; Ritsema, 2003; Keesstra et al., 2009b; Hughes & Prosser, 2012).

In Ethiopia, the rates of soil erosion are alarmingly high and sedimentation in reservoirs, lakes, and rivers is a serious problem (Haregeweyn et al., 2006; Tamene et al., 2006a). Many reservoirs which have been established for hydroelectric power, urban water supply and irrigation accumulate large amounts of sediment, resulting in shortage of water supply for these functions, decline in reservoirs water storage capacity and high costs to remove sediment from reservoirs. Some of the dams in the Amhara region of Ethiopia, like the dams of Adrako, Borkena and Dana (Amare, 2005; Kebede, 2012) have completely silted up before their design expectation period. Other dams in this region that have been constructed over the last decades are threatened by accelerated sedimentation.

Until recently, most studies and development activities that aim at reducing the sediment load in the reservoirs were focused on on-site physical soil and water conservation (SWC) measures on agricultural areas in the catchment. Off-site physical sediment trapping measures inside gullies and drainage channels are largely disregarded. Moreover, SWC measures are not designed to eliminate sediment loss and transport to a safe level. For instance, in the northern part of Ethiopia, SWC measures such as stone bunds and ex-closures trapped about 74% of the total soil eroded (Nyssen *et al.*, 2008). A structural measure, *Fanya juu*, trapped about 64% of the eroded soil at Debre Mewi watershed, northwest Ethiopia (Fisseha et al., 2011). Although on-site soil conservation measures result in reduced catchment sediment yields, sediment trapped by dams at the outlets of sub-catchments as an off-site measure represent the dominant cause of reduced catchment sediment yields (Walling, 2006).

The STE of many off-site sediment trapping measures is well known. For instance; Markle (2009) demonstrated the efficacy of a sediment pond in a Californian almond orchard, which trapped 80-84% of the sediment. According to Verstraeten and Poesen (2001b), a typical pond of 1000 $m^3$ in Belgium, showed a short term STE of 58-100% and a long term (33 yrs.) STE of 68%. In Belgium, Verstraeten and Poesen (2002) tested the STE of 13 different sized ponds (50 $m^3$-5 mill. $m^3$), which reveals a STE of 10-72%. Wang et al. (2011) found that >100 000 check dams store 21 billion $m^3$ of sediment in the Loess Plateau of China in 50 years after construction. In Malaysia, Abedini et al. (2012) evaluated the STE of 3 check dams and their effectiveness in maintaining downstream reservoir storage capacity, which collectively trapped 6162 $m^3$ of sediment. Sougnez et al. (2011) estimated the sediment volume trapped by 20 check dams in southern Spain as ranging from 4-920 $m^3$. There are structures like sediment storage dams that could potentially serve as off-site sediment trapping in Ethiopia but have not been studied for their STE.

One possible way to trap sediment in the sediment cascade is using sediment storage dams (SSDs) (MERET, 2008). SSDs are physical structures or barriers built of stone or gabion at the outlets of catchments with the objective to trap sediment. SSDs have similar functions as check dams, i.e. to trap sediment except that they are mostly constructed at the outlets of larger catchments than check dam. These dams have been implemented by the Ethiopian government in the Amhara region over the last decade (MERET, 2008).

Hence, to assess the functioning and effectiveness of this type of measure this study aims to (II) quantify the amount of sediment trapped by SSDs constructed at the outlets of small sub-catchments in northwest Ethiopia and determine the sub-catchments sediment yield from the trapped sediment mass, (II) estimate the sediment trapping efficacy (STE) of SSDs, and (III) assess the costs required to construct the SSDs and its applicability for small scale farmers, in northwest Ethiopia.

## 5.2 Materials and methods

*Study area description*

The study was conducted in Amhara Regional State, northwest Ethiopia. Eight SSDs constructed at the outlets of the small sub-catchments Shehena Borkena, Enchet Kab, Worka Wotu, Woybila, Segno Gebeya, Tigrie Mender, Dodota and Wuha Chale were studied (Figure 5.1). The size of the sub-catchments ranged from 34.6-104.5 ha. Table 5.1 summarizes the location, average annual rainfall, soil type (WBISPP, 2002), average slope and elevation characteristics of each study site. Farmland is the dominant land use type in each sub-catchment amounting to about 80% while the remaining 20% is used as grazing land, eucalyptus plantation and/or bush land. The slopes in the sub-catchments ranged from 0.4-31% with dominant average slopes of 11.6-24%.

***Table 5.1** Location, soil type, rainfall, slope and elevation characteristics of the studied sub-catchments*

| Study sites | X coordinate (m) | Y coordinate (m) | Soil type | Average slope (%) | Av. Annual rainfall (mm) | Elevation range (masl) |
|---|---|---|---|---|---|---|
| **Segno Gebeya** | 410030 | 1204435 | Nitosols | 12.7 | 1200 | 2653-2754 |
| **Woybila** | 410018 | 1206409 | Nitosols | 16.4 | 1200 | 2675-2846 |
| **Shehena Borkena** | 584808 | 1209121 | Cambisol | 24.0 | 850 | 1508-1872 |
| **Tigrie Mender** | 533579 | 1330784 | Cambisol | 23.9 | 870 | 2960-3094 |
| **Worka Wotu** | 531127 | 1329944 | Cambisol | 11.7 | 870 | 2822-2895 |
| **Dodota** | 607310 | 1238353 | Cambisol | 11.6 | 800 | 1621-1762 |
| **Enchet Kab** | 402452 | 1449577 | Leptosol | 11.9 | 1200 | 3088-3171 |
| **Wuha Chale** | 591772 | 1259992 | Regosol | 23.7 | 900 | 1989-2174 |

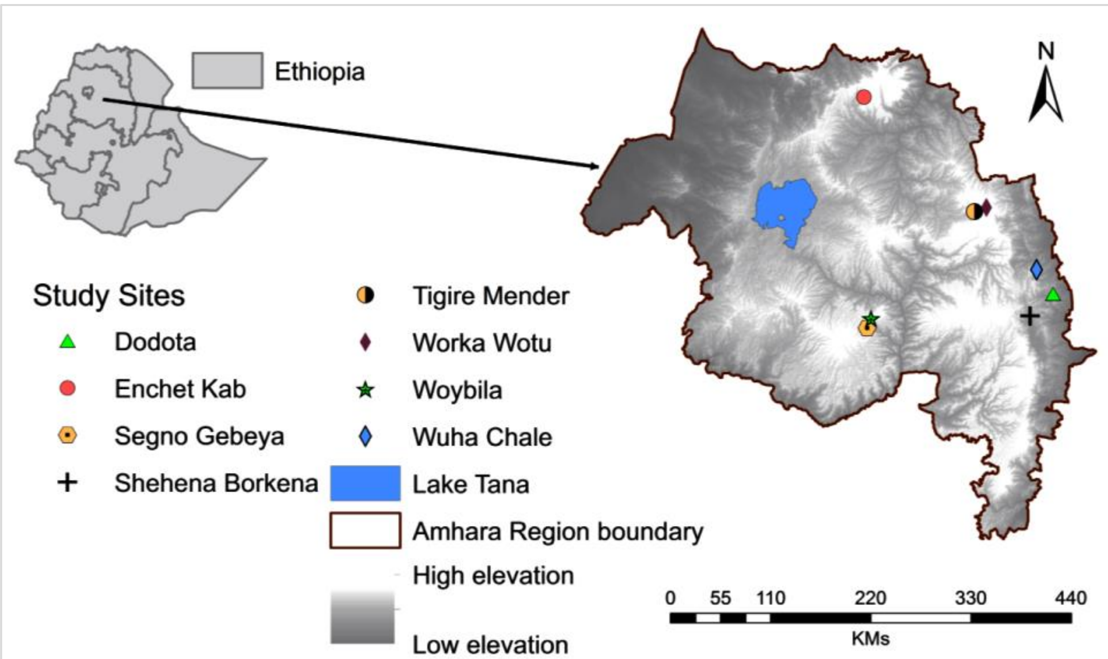


***Figure 5.1** Location of the study sites*

*Materials and datasets*

Land use / land cover was determined using satellite imagery (SPOT; 5 m resolution). A topographic map 1:50,000 scale (EMA, 1987) was used to delineate the boundary of each sub-catchment. A Digital Elevation Model (ASTER DEM 30 m; 2009) was used to derive the elevation and slope characteristics of each sub-catchment. Sub-catchments coordinates were taken in the field using a GPS device (Garmin GPS 60) and measurement tape was used to measure channel dimensions in each of the sub-catchments.

*Methods*

In order to quantify the amount of sediment trapped by sediment storage dams (SSDs), to determine the sediment trapping efficacy of the SSDs and to calculate sub-catchment sediment yield from the deposited sediment behind the dams the following methods were applied.

*Measuring trapped sediment in sediment storage dams*

To find multi-year data, SSDs with different ages (2-8 years old) in sub-catchments with different soil types, rainfall amounts and elevations were selected for this study. The amount of sediment trapped and stored behind each SSD was measured based on the geometric nature of the drainage channels, SSD dimensions and the surface area of the sediment using GPS and measuring tape. Some of the structures have trapezoidal shapes and others have rectangular shapes (see examples in Figure 5.2).


***Figure 5.2*** *Examples of SSDs constructed in the Amhara region, Ethiopia (a) Delanta, (b) Kobo, (c) Bati and (d) Kutaber (Photos by Mulatie Mekonnen)*

To calculate the volume (V; $m^3$) of the sediment accumulated behind the trapezoidal shaped dams, the cross-sectional area (A; $m^2$) of the sedimentation times the length (L; m) from the SSD to the end of sedimentation upstream was calculated (Eq. 5.1). The cross-sectional area (A) of the trapped sediment is the average of the top and bottom widths (b2 and b1; m) of the sediment times its height (h; m) measured from the base of the dam to the sediment surface (Eq. 5.2). For rectangular shape dams length times width times depth of the trapped sediment was used.

$$V = A * L \tag{5.1}$$

$$A = \frac{1}{2}(b1 + b2) * h \tag{5.2}$$

*Estimating the sediment trapping efficacy*

A proportion of the sediment entering into the SSDs, particularly the finest sediment fraction, is not trapped but passes the dam as suspended sediment. Therefore, the SSDs sediment trapping efficacy (STE) should be estimated to be able to include the un-trapped sediment into the overall sediment budget. STE is also an important indicator of the functioning of the dams in retaining and conserving sediments (Morgan, 2005; Sougnez et al., 2011). Two representative SSDs, one built from gabion to represent gabion SSDs and one built from stone to represent stone SSDs, which are not full of sediment yet, were evaluated for their STE. For that purpose, a total of 82 suspended sediment samples were collected from 21 rainfall events during the rainy season in 2013, 40 samples (20 inflows and 20 outflows) for the gabion SSD and 42 samples (21 inflows and 21 outflows) for the stone SSD. STE was calculated based on the inflow and outflow suspended sediment samples (Coyne et al., 1995; Verstraeten & Poesen, 2000) (Eq. 5.3).

$$STE = \frac{(S_{inflow} - S_{outflow})}{S_{inflow}} = 1 - \frac{S_{outflow}}{S_{inflow}} * 100 \tag{5.3}$$

Where: $STE$ is sediment trapping efficacy (%), $S_{inflow}$ is suspended sediment flowing into the SSD (g $l^{-1}$) and $S_{outflow}$ is suspended sediment flowing out of the SSD (g $l^{-1}$)

*Sediment yield measurement*

Sediment yield (SY) is the total sediment outflow from a catchment, to be measured at a point of reference and in a specified period of time either in absolute terms (e.g., t $y^{-1}$) or in area specific terms (e.g., t $ha^{-1}$ $y^{-1}$) (Vanoni, 1975; Verstraeten & Poesen, 2001a). Catchment sediment yield can be estimated by measuring the retained sediment in dams, reservoirs, check dams and ponds constructed at the outlet of a catchment (White *et al.*, 1997; Verstraeten & Poesen, 2002; Tamene *et al.*, 2006b; Haregeweyn *et al.*, 2008; Bellin *et al.*, 2011; Sougnez et al., 2011; Baade et al., 2012). In this study, SY generated from the sub-catchments was estimated by measuring the deposited or trapped sediment behind the SSDs built at the outlets of the sub-catchments and estimating the un-trapped sediment using the STE. The average annual SY transported from the catchments into the SSDs was calculated adding the trapped and un-trapped sediment and dividing it by the number of years involved to trap the sediment. Area specific sediment yield (SSY) was also calculated by dividing catchment sediment yield by catchment area.

*Deposited sediment density calculation*

To convert sediment volume, which was directly measured in the field to dry sediment mass and to calculate the catchments sediment yield in terms of mass, the density of the trapped sediment was estimated using the cylindrical core method (McKenzie *et al.*, 2002). In the middle of the deposited sediment a 1.5 m deep pit was dugout vertically downward and sampling was done at three depths (upper, middle and lower) pushing the cylindrical core sampler (5cm diameter * 7cm long) into the side wall at the desired depth. The collected samples were oven dried at 105 $^0$C in the laboratory and sediment density was calculated weighing the dried sediment and subtracting it from the wet sediment mass.

## 5.3 Results

*STE, trapped sediment and sediment yield*

The average sediment inflow, outflow and sediment trapped was 197.4 g $l^{-1}$, 51.2 g $l^{-1}$ and 146.2 g $l^{-1}$ at Segno Gebeya (gabion SSD) and 164.6 g $l^{-1}$, 53.7 g $l^{-1}$ and 110.9 g $l^{-1}$ at Shehena Borkena (stone SSD), respectively. Based on these inflow and outflow suspended sediment data, STEs were calculated to be 74% and 67% for the gabion and stone SSDs, respectively. These efficacy values were used as a proxy for the SSDs of the other sub-catchments to be able to calculate the un-trapped sediment. Table 5.2 shows the measured trapped and estimated un-trapped sediment of each SSD. The average volume of sediment trapped and accumulated behind the eight SSDs within 2-8 years was found to be 5500 $m^3$, but with high variation between sites (st. dev. of 4665 $m^3$) reflecting differences in catchment size and soil erosion factors.

Sediment bulk density values ranged from 1.33 g $cm^{-3}$ in heavy clay sediment deposits to 1.53 g $cm^{-3}$ in sandy loam dominated sediments. On average SSDs trapped about 1584 t of sediment annually. Figure 5.3 illustrates part of the sediment trapped and deposited behind the SSDs. Table 5.3 shows calculated annual sediment yield (SY) and area specific sediment yield (SSY) for all sub-catchments. SY and SSY show large variation between sub-catchments, ranging from 297-5759 t and 8.6 -55 t $ha^{-1}$ $y^{-1}$, respectively.

***Figure 5.3*** *Example SSDs and trapped sediment at Segno Gebeya (left) and Enchet Kab (right) (Photo by Mulatie Mekonnen)*

*Cost of sediment storage dams*

The cost of building an SSD is an important factor affecting its implementation by small scale farmers and it's up-scaling to other users. The most important inputs such as stone, gabion and human labour were evaluated and their costs were estimated (Table 5.4). On average € 8.74 and € 5.85 are required to construct 1m$^3$ gabion and stone SSDs, respectively. This means that to trap 1m$^3$ sediment about € 2.0 for a gabion and from € 0.4 to € 1.7 for a stone SSD was spent, which was calculated by dividing the dam costs by the volume of sediment trapped. The cost to trap 1m$^3$ sediment varies (€ 0.4 to € 1.7) although similar construction cost (€ 5.85) was financed for 1m$^3$ of all stone SSDs. This is because of difference in the amount of trapped sediment behind the constructed dams due to difference in shape of the reservoir in which sediment is deposited. The larger the reservoir behind the dam, the higher the amount of sediment trapped and the lower the cost per m$^3$ of sediment and vice-versa. In all studied SSDs labour costs were found to be higher than material costs.

***Table 5.2*** *Soil bulk density, volume and mass of sediment trapped and un-trapped by SSDs.*

| Catchments | type | trapped sediment (m$^3$) | bulk density (g cm$^{-3}$) | trapped sediment (t) | trapped sediment (t y$^{-1}$) | Un-trapped sediment (t) |
|---|---|---|---|---|---|---|
| Segno Gebeya | Gabion | 3240 | 1.33 | 4309.2 | 2154.6 | 1120.4 |
| Woybila | Stone | 15 920 | 1.36 | 21 651.2 | 4330.2 | 7144.9 |
| Shehena Borkena | Stone | 6156 | 1.53 | 6418.7 | 1069.8 | 2118.2 |
| Tigrie Mender | Stone | 1321 | 1.42 | 1875.8 | 468.9 | 619.0 |
| Worka Wotu | Stone | 1516 | 1.18 | 1788.9 | 223.6 | 590.3 |
| Dodota | Stone | 1085 | 1.31 | 1431.4 | 357.9 | 472.4 |
| Enchet Kab | Stone | 7593 | 1.40 | 10 630.2 | 2657.6 | 3508.0 |
| Wuha Chale | Stone | 7167 | 1.38 | 9890.5 | 1412.9 | 3263.9 |
| Average | | 5500 | 1.36 | 7249 | 1584.4 | 2355 |
| St. dev | | 4665 | 0.09 | 6400 | 1502.2 | 2132 |

***Table 5.3*** *Catchment area, SSDs age, sediment yield and area specific sediment yield of each catchment*

| Catchments | Area (ha) | SSDs age (y) | SY (t y$^{-1}$) | SSY (t ha$^{-1}$ y$^{-1}$) |
|---|---|---|---|---|
| Segno Gebeya | 56.0 | 2 | 2714.8 | 48.5 |
| Woybila | 104.5 | 5 | 5759.2 | 55.1 |
| Shehena Borkena | 66.9 | 6 | 1422.8 | 21.3 |
| Tigrie Mender | 41.8 | 4 | 623.7 | 14.9 |
| Worka Wotu | 34.6 | 8 | 297.4 | 8.6 |
| Dodota | 39.0 | 4 | 475.9 | 12.2 |
| Enchet Kab | 84.3 | 4 | 3534.5 | 41.9 |
| Wuha Chale | 71.8 | 7 | 1879.2 | 26.2 |

***Table 5.4*** *Type, size and costs of sediment storage dams*

| SSD sites | SSD type | SSD size ($m^3$) | Stone Cost | Gabion cost | Labour cost | Total cost | Cost per $m^3$ of sediment |
|---|---|---|---|---|---|---|---|
| Segno Gebeya | Gabion | 756 | 2063.9 | 2180 | 2358.7 | 6602.7 | 2.03 |
| Woybila | Stone | 972 | 2653.6 | - | 3032.6 | 5686.2 | 0.36 |
| Shehena Borkena | Stone | 483 | 1318.6 | - | 1507.0 | 2825.6 | 0.46 |
| Tigrie Mender | Stone | 325 | 887.3 | - | 1014.0 | 1901.3 | 1.44 |
| Worka Wotu | Stone | 437 | 1193.0 | - | 1363.4 | 2556.4 | 1.68 |
| Dodota | Stone | 306 | 835.4 | - | 954.7 | 1790.1 | 1.64 |
| Enchet Kab | Stone | 529 | 1444.2 | - | 1650.5 | 3094.7 | 0.39 |
| Wuha Chale | Stone | 617 | 1684.4 | - | 1925.0 | 3609.4 | 0.51 |

*Stone cost - 2.73 € $m^{-3}$, Gabion cost - 16.77 € $gabion^{-1}$, Labour cost - 1.56 € $0.5m^{-3}$ $person^{-1}$, Average costs are considered and all costs are in € (1 Ethiopian birr = 0.039 €)*

## 5.4 Discussion

*Sediment trapped by sediment storage dams and catchment sediment yield*

Rising rates of on-site soil erosion and off-site sedimentation in reservoirs and lakes emphasises the need to trap sediment along the sediment transfer pathways. Dam construction of both large and small sizes to trap sediment can reduce downstream sedimentation, flooding and other environmental problems. The world's registered 45,000 large dams can trap 4-5 billion t $y^{-1}$ of sediment (Vorosmarty *et al.*, 2003). In China >100 000 smaller check dams trapped 21 billion $m^3$ of sediment (Wang et al., 2011). Sougnez et al. (2011) estimated the sediment volume trapped by 20 check dams in southern Spain as ranging from 4-920 $m^3$. In this study, sediment storage dams (SSDs) built at the outlets of eight small sub-catchments in the Amhara region in Ethiopia trapped a total of about $58*10^3$ t ($44*10^3$ $m^3$) sediment. On average these SSDs trapped about 1584 t of sediment annually.

In addition to reducing downstream reservoirs sedimentation, SSDs contributed in conserving soil within the larger catchment and re-filling and stabilizing gullies. An SSD constructed at Woybila catchment within a gully, which is serving as a temporary drainage channel during the rainy seasons, trapped ~$22*10^3$ t of sediment and refilled an 8 m deep and 20 m wide gully in 5 years reducing the channel slope gradient by 12% on average, which can slow down the speed of runoff and give time for infiltration and sediment deposition.

Sediment trapped and stored behind sediment trapping measures can be used to estimate sediment yield produced by upper catchments (White et al., 1997; Verstraeten & Poesen, 2002; Bellin et al., 2011; Sougnez et al., 2011; Baade et al., 2012). In this study, the annual sediment yield of the investigated sub-catchments ranged from 8.6-55 t $ha^{-1}$, which is in line with other findings in Ethiopia. For example, in northwest Ethiopia, average annual sediment yield of 24.6 t $ha^{-1}$ at Anjeni catchment (Setegn et al., 2010) and 13.6 t $ha^{-1}$ at Angereb catchment (Amare, 2005) were reported. In the northern part of Ethiopia, the annual sediment yield of 10 catchments was estimated at 4-18 t $ha^{-1}$

(Haregeweyn et al., 2008) and 3.4-49 t $ha^{-1}$ (Tamene et al., 2006a) for another 11 catchments in the same region.

Catchment size is an important controlling factor for catchment sediment yield (Morgan, 2005). For example, a direct relationship between area specific sediment yield and catchment area has been reported in different studies (de Vente *et al.*, 2006; Haregeweyn et al., 2008) for small size catchments and a similar result was obtained in this study with $R^2$ = 0.66 (Figure 5.4). This is due to limited deposition of the transported sediment within such small sub-catchments.

According to Wasson et al. (2002), about 80% of the sediment in the Argyle reservoir, Australia has come from gully and channel erosions, and sediment yield in three small size gullied catchments (29, 52 and 510 ha) is at least one order of magnitude higher than that of un-gullied catchments (Armstrong & Mackenzie, 2002). In this study in the Segno Gebeya, Wuha Chale and Woybila sub-catchments foot paths, gullies and traditional ditches, and in the Enchet Kab and Shenena Borkena sub-catchments channel bank and gully erosions have some contribution for the estimated sediment yield.

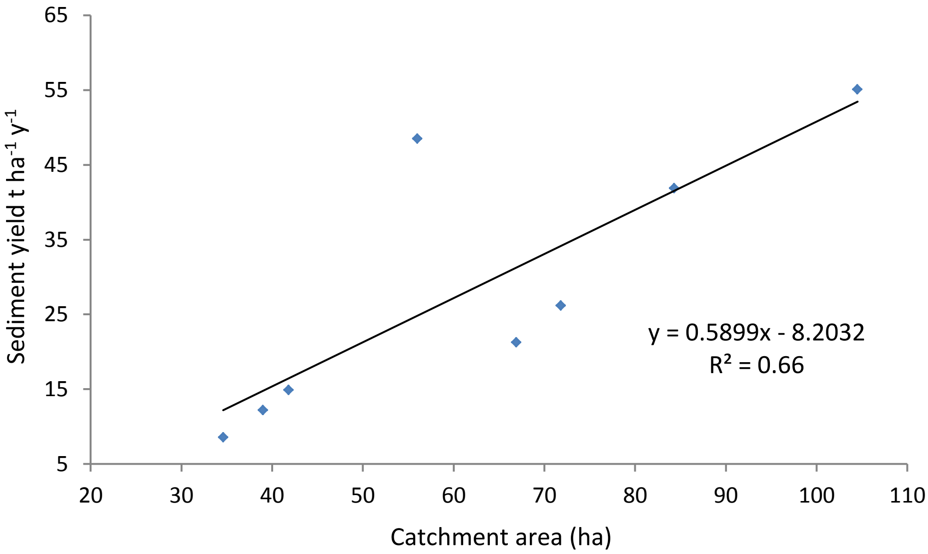


***Figure 5.4*** *The relationship between annual sediment yield (t $ha^{-1}$) and small size catchments*

*Sediment trapping efficacy*

Sediment trapping efficacy is an important factor to evaluate the effectiveness of sediment trapping measures. Markle (2009) demonstrated the efficacy of a sediment pond in a Californian almond orchard, which trapped 80-84% of the sediment. According to (Verstraeten & Poesen, 2001b), a typical pond of 1,000 $m^3$ with a catchment area of 25 ha in Belgium showed a short-term STE of 58-100% and a long-term (33 yr) STE of 68%. In northern Mississippi, the STE of small reservoirs was found to be 77% (Dendy & Cooper, 1984). In the northern part of Ethiopia Haregeweyn et al. (2006) estimated the STE of 10 reservoirs which ranged from 85-100% and Tamene et al. (2006a) found STEs ranging from 86-97% in 11 catchments. In this study the STE of gabion and stone SSDs were found to be 74% and 67%, respectively. This indicates that SSDs can trap and conserve up to ¾ of the inflow sediment coming from the upstream catchments in the form of surface erosion or concentrated through gullies, channel banks or foot path erosion and can be used as potential off-site sediment trapping measures.

The deposited sediment behind sediment trapping dams is an important indicator of soil loss in its upstream catchment provided the efficacy of the dams as a sediment trap is known (Morgan, 2005). For instance, the deposited sediment behind check dams was used to estimate soil loss from its upstream catchments (Bellin et al., 2011; Sougnez et al., 2011; Romero-Diaz *et al.*, 2012). In this study soil loss in the upstream catchments was estimated at 8.6-55 t $ha^{-1}$ $y^{-1}$. The soil loss value found in this study is within the same range of the study results conducted in northwest Ethiopia (Zegeye et al., 2010; Mekonnen & Melesse, 2011; Haile & Fetene, 2012). The total soil eroded within the catchments and transported into the SSDs was estimated by adding the trapped and un-trapped sediment. This method of estimating soil loss provides better results than for instance plot-scale measurement and catchment-scale river discharge sampling methods. This is because it represents the combined effects of soil erosion factors (soil type, land use/cover, slope, rainfall variability, etc.) at larger natural conditions, against plot-scale. Compared with data from suspended sediment concentrations, the data from sediment trapping dam survey incorporates materials transported as bed loads as well as suspended sediments which make the method more accurate.

Gullies and drainage channels are effective links to transfer runoff and sediment from upper parts of a catchment to their outlets (Poesen et al., 2003) and serve as important sediment source and transfer pathways. The main objective of constructing SSDs within drainage channels is therefore to disconnect such paths and trap the sediment (MERET, 2008). Disconnecting sediment transfer pathways through efficient sediment trapping measures could help to increase sediment deposition and reduce downstream sediment loads (Keesstra et al., 2009a; Baartman et al., 2013). In this study, SSDs were found as important structural measures in disconnecting the sediment transfer pathways and reducing the transport of sediment from upstream catchments to downstream water bodies (rivers, reservoirs or lakes).

Although SSDs played an important role in trapping sediments and reducing downstream sedimentation problems, they provide short term benefits (For example five out of the eight SSDs investigated have completely silted up in 4-8 years). After the dams are fully filled with sediment, the sediment transportation continues further downstream. To solve this problem sustainably, options are to (i) construct a series of dams within the drainage channel, which can increase the lifespan of each dam, and at the same time (ii) implementing on-site soil and water conservation measures (e.g. terraces and grass strips on farmlands, area closure on degraded lands, check dams inside gullies, etc.) to reduce erosion and trap the sediment within the sub-catchment before it reaches the SSDs. According to Mekonnen et al. (2014b) the integration of on-site and off-site sediment trapping measures at the catchment scale, is believed to be the most effective in helping to increase the STE of the measures and thereby reducing sediment loads at the outlet of the catchment.

According to Nyssen et al. (2007a) the increased erosive capacity and power of the low sediment-laden runoff can lead to scour and enhanced soil erosion. In this study, below the SSDs there were bottom and side scouring in some of the drainage channels, which might be due to the downstream effect of the clear water as a result of sediment accumulation behind the dams. Implementing vegetative measures, for example, planting grass and tree species and covering the bare land inside the temporary drainage channels where the SSDs have been built will be an option to minimize the problem.

*Cost required of construction of sediment storage dams*

In addition to sediment trapping efficacy (STE), the costs required to construct the sediment storage dam is an important factor affecting implementation of the sediment trapping measure at wider spatial scale and its adoption by farmers. Three most important inputs for SSD construction (human labour, gabion and stone) were assessed. Both stone and gabion SSDs are not affordable by the small scale farmers in northwest Ethiopia unless other alternatives are designed. For example: (i) a mass mobilization approach, which the Ethiopian government currently uses for soil and water conservation works. This forms a means to implement SSDs with free community participation to minimize at least the labour costs, which were found to be the largest part of the total construction costs; (ii) project support to cover at least the gabion (material) costs; and (iii) implementing SSDs where there is excess stone to reduce stone costs. These approaches could help to minimize the costs and up-scale the measures to wider spatial scales.

## 5.5 Conclusions

Sediment storage dams (SSDs), both gabion and stone, were found to be important off-site structural sediment trapping measures trapping sediment at the outlets of small sized catchments. The eight SSDs investigated, built from gabion and stone trapped a total of ~$44*10^3$ $m^3$ or ~$58*10^3$ t of sediment within 2-8 years with sediment trapping efficacies of 74% and 67%, respectively. In addition to evaluating the effectiveness of the dams, STE was used to estimate suspended sediment losses, and subsequently total (sub) catchment sediment yield. SSDs also reduce channel slope gradients and disconnect sediment transfer pathways inside drainage channels in addition to re-filling gullies. The lifespan of the investigated SSDs was relatively short, i.e. to be more effective and use the SSDs sustainably they should be integrated with on-site soil conservation measures. Also, due to high costs, SSDs are not affordable for small scale farmers, alternatives to minimize the cost like mass mobilization, project support and implementing the dams in areas of excess construction materials should be considered to be able to upscale these measures.

# Chapter 6

# Reducing sediment connectivity through man-made and natural sediment sinks in the Minizr catchment, NW Ethiopia

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# Reducing sediment connectivity through man-made and natural sediment sinks in the Minizr catchment, NW Ethiopia

*Abstract*

*Man-made and natural sediment sinks provide a practical means for reducing downstream reservoir sedimentation by decreasing soil erosion and enhancing the rate of sedimentation within a catchment. The Minizr catchment (20 km$^2$) in the northwest Ethiopian highlands contains numerous man-made soil and water conservation (SWC) structures (such as soil bunds (Erken), fanya juu ridge (Cab) and micro-trenches) and natural sediment sinks (wetlands, floodplains and grassed waterways). These sediment sinks reduce downstream sedimentation into the Koga reservoir, located at the catchment outlet, however, a large quantity of sediment is still reaching the reservoir. This study evaluates the function and effectiveness of both man-made SWC structures and natural sediment sinks in reducing sediment export from the Minizr catchment. SWC structures and natural sediment sinks were digitized using Google Earth Imagery. Sediment pins and vertical sampling through the deposit were used to quantify the amount of deposited sediment. In addition, inflow and outflow of suspended sediment data were used to calculate the sediment-trapping efficacies (STE) of man-made SWC structures (soil bunds and fanya juu ridges) and natural sediment sinks. Results reveal that 144 km soil bunds and fanya juu ridges trapped 7,920 Mg y$^{-1}$ (55 kg m$^{-1}$ y$^{-1}$) and micro-trenches trapped 13.26 Mg y$^{-1}$ (each micro-trench on average trapped 23 kg y$^{-1}$). The 17 ha floodplain located in the centre of the catchment trapped 9,970 Mg y$^{-1}$ (59 kg m$^{-2}$ y$^{-1}$), while a wetland with a surface area of 24 ha, located near the outlet of the catchment, trapped 8,715 Mg y$^{-1}$ (36 kg m$^{-2}$ y$^{-1}$). The STEs of soil bunds and fanya juu ridges, wetlands and floodplains were 54%, 85% and 77%, respectively. Substantial differences were observed between the STE of grassed and un-grassed waterways at 75% and 21%, respectively. Existing man-made and natural sediment sinks played an important role in trapping sediment, with 38% (26,600 Mg y$^{-1}$) of transported sediment being trapped, while 62% (43,000 Mg y$^{-1}$) is exported from the catchment and thus enters the Koga reservoir. Therefore, additional catchment treatment measures are required as an integrated catchment scale sediment trapping (ST) approach to help reduce sediment loads entering Koga reservoir. Moreover, to maximize the effectiveness of ST measures, avoid structural failure and ensure their sustainability, regular maintenance is needed.*

## 6.1 Introduction

Soil erosion by runoff water is a global land degradation problem (Dai *et al.*, 2015; Seutloali & Beckedahl, 2015; Stanchi *et al.*, 2015; Novara *et al.*, 2016; Ochoa *et al.*, 2016). However, it is more severe in developing countries like Ethiopia (Hurni, 2000; Nyssen *et al.*, 2004) and results in significant economic losses (Erkossa *et al.*, 2015). Currently, water erosion is the most serious land degradation threat to the upper part of the Blue Nile basin within the north-western highlands of Ethiopia (Adimassu *et al.*, 2014; Mekonnen *et al.*, 2015a; Ayele *et al.*, 2016). The main causes include erosive high intensity tropical rains, rugged steep topography, extensive deforestation for fuel wood, expansion of cultivation into unsuitable steeply sloping and erosion prone areas, high population pressure and the lack of integrated catchment management (Zeleke, 2000; Bewket, 2002; Nyssen et al., 2004; Amsalu *et al.*, 2007; Mekonnen & Melesse, 2011; Mekonnen *et al.*, 2014b).

Therefore, a holistic approach is needed to tackle soil erosion in the region (Mekonnen et al., 2014b; Lanckriet *et al.*, 2015; Nyssen *et al.*, 2015; Tesfaye *et al.*, 2015). Soil and water conservation (SWC) structures provide a practical means for reducing soil erosion, enhancing the rate of sedimentation and decreasing local slope gradient (Gebremichael *et al.*, 2005; Mekonnen *et al.*, 2015b). Various soil and water conservation measures have been implemented at large spatial scales by the Ethiopian government and international and national non-governmental organizations. For instance, 2.1 million ha of hillsides and farmlands were covered by SWC structures in the Amhara National Regional State from 2011 to 2013 (Engdayehu *et al.*, 2015), and a further 1.2 million ha in 2014-2015 (BOA, 2015).

Effective sediment trapping (ST) measures can disconnect landscape units from each other, resulting in a decrease in runoff velocity and sediment transport and, subsequently, reduced downstream flooding with fewer sedimentation impacts (Mekonnen et al., 2014b). This is enhanced by placing barriers and buffers in the catchment, which ultimately reduces sediment connectivity (Fryirs, 2012). According to (Baartman *et al.*, 2013), man-made structures such as terraces reduce sediment delivery to the catchment outlet. Research has shown that leaving mulch on the soil surface within the catchment can also reduce the amount of sediment being detached (Cerda *et al.*, 2015; Keesstra *et al.*, 2016; Prosdocimi *et al.*, 2016).

The Minizr catchment is an important source of water for the Koga reservoir in the northwest highlands of Ethiopia (Figure 6.1). To trap sediment within the catchment and reduce sediment loads reaching the reservoir, considerable effort was made to implement soil bund (Erken) and fanya juu ridge (Cab) and also micro-trench structures across large sections of the catchment. Over 144 km of soil/stone bunds and fanya juu ridges, and >576 micro-trenches were constructed within the catchment. In addition, existing natural sediment sinks such as wetlands and floodplains occur over large areas of the catchment, and are supplementing man-made structures in trapping sediment within the catchment (Figure 6.1).

Nevertheless, considerable soil is being eroded from the Minizr catchment and transported into the Koga reservoir: annually 43,000 Mg of suspended sediment enters the Koga reservoir (Mekonnen *et al.*, 2016c). In order to reduce the sediment load through improving the sediment trapping efficacy (STE) of the SWC structures, it is important to assess the functioning and effectiveness of existing SWC structures. According to (Yeshaneh *et al.*, 2014), there is a lack of in-depth studies quantifying the volume of sediment being deposited within SWC structures. Previous research demonstrates that terraces play a key role in trapping sediment and disconnecting sediment transfer pathways in a catchment, but very few have been measured (Marchamalo *et al.*, 2016).

Consequently, the objectives of this study in the Minizr catchment, northwest Ethiopia were to: (i) evaluate the functioning and effectiveness of both man-made structures (soil bund, fanya juu and micro-trenches) and natural sediment sinks (floodplain, wetland and waterways) and, (ii) quantify the amount of sediment trapped and stored in these man-made and natural sediment sinks.

## 6.2 Materials and methods

***Study area***

The study was conducted in the Minizr catchment in the North-western highlands of Ethiopia (UTM 1255891 - 1249499 N; 303559 - 310272 E; Adindan_UTM_Zone_37N, Figure 6.1) which is a source of water for the Koga reservoir. It covers an area of 20 $km^2$ with an elevation range of 2035 m at the outlet to 2283 m.a.s.l at its highest point on the watershed divide. Slopes in the catchment range from 0-51% (average of 8%), while >80% of the catchment has slopes between 0-8%.

Average rainfall (2013-2015) was 1215 mm $y^{-1}$, which falls mainly between June to September, and is preceded and followed by one month of sporadic, low intensity rain. Average minimum and maximum temperatures are $11^0C$ and $26^0C$, respectively. The dominant soil types are Nitosols (62%), Eutric Vertisols (30%), Lithic Leptosols (6%) and Chromic Cambisols (2%) (MNREP, 1995). Land use within the catchment area includes 71% cropping land, 18% grazing land, while plantation, bush land and settlement areas account for the remaining 11%.

Figure 6.1 shows the 144 km soil bund and fanya juu ridges implemented in Minizr catchment, a 24 ha wetland located near the outlet of the catchment and a small floodplain area of 17 ha located at the center of the catchment, which help to trap sediment and reduce sedimentation of Koga reservoir. In the wetland area, Chromic Cambisols dominate. They are developed from alluvial deposits. The soil is very deep, poorly drained with a dark gray to grayish brown, silty clay loam texture, while the floodplain soil is a Eutric Vertisol which is a very deep, poor to very poorly drained, cracking heavy clay textured soil. The floodplain is 696 m long and 243 m wide and is covered with grass, which serves as a grazing area during the dry season.

***Mapping***

All SWC structures, land use/cover, wetland and floodplain areas were digitized and mapped from Google Earth Imagery using ArcGIS 10.2.1. A Digital Elevation Model (ASTER DEM 30 m; 2009) was used to delineate the boundary of the Minizr catchment and for evaluating its elevation and slope characteristics. A GPS (Garmin 60; 2 m accuracy) helped to collect coordinate points and accurately geo-reference the location of rain gauges, sediment sampling sites and the catchment outlet.

***Measuring trapped sediment in SWC structures***

Three types of SWC structures soil bund (Erken), fanya juu ridge (Cab) and micro-trenches have been widely implemented throughout the Minizr catchment (Figure 6.2). Soil bund and fanya juu ridges were built on farmers' fields, whereas micro-trenches were constructed on degraded grazing lands and integrated with area closures. Figure 6.3 shows the detailed dimensions of the soil bund and fanya juu ridge (MOARD, 2005).

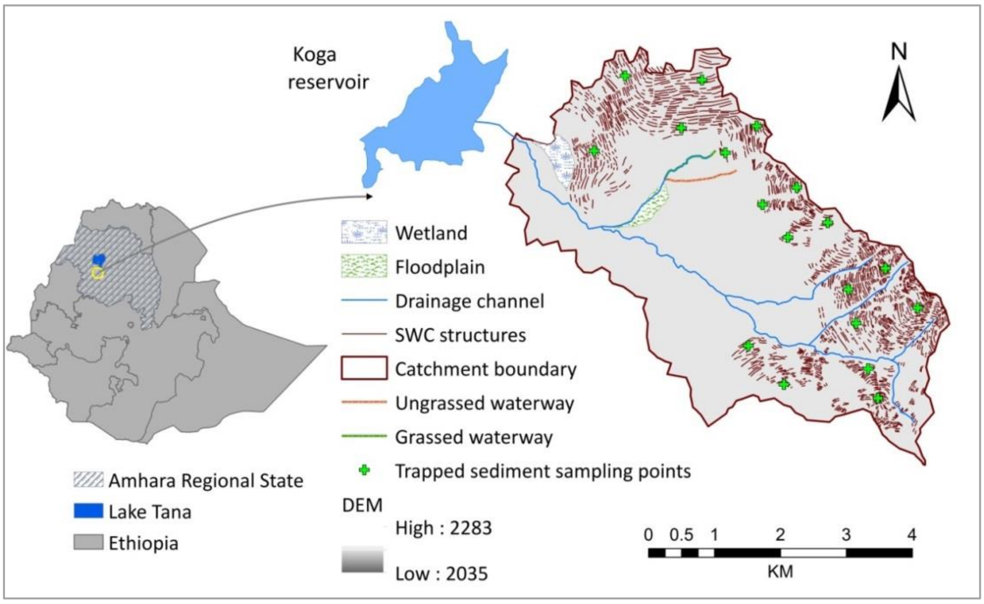



***Figure 6.1*** *Location map of the Minizr catchment, in the NW Ethiopian highlands of the Upper Blue Nile basin showing the SWC structures implemented to trap sediment (soil bunds and fanya juu ridges), natural sediment sinks (floodplain, wetland and grassed waterway); and trapped sediment sampling sites.*


***Figure 6.2*** *Sample pictures of a fanya juu (a), micro-trenches (b) and a soil bund (c) structures implemented for sediment trapping at Minizr catchment*

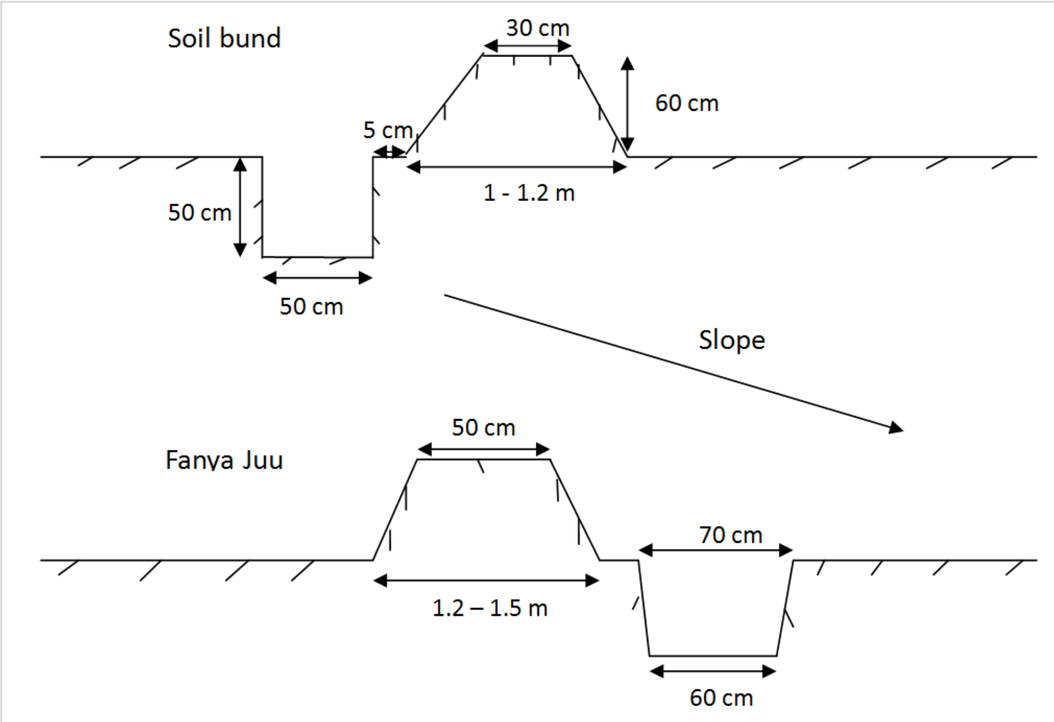



***Figure 6.3*** *Schematic diagram showing a soil bund (erken; upper) and fanya juu (cab; lower) operate to trap sediment from upslope. Both of them are positioned perpendicular to the slope and runoff direction, thereby maximizing sedimentation and infiltration of surface runoff*

According to Lakel *et al.* (2010) and Slattery *et al.* (2002), sediment pins and direct measurements of the sedimentary deposit can be used to quantify the amount of sediment in the sediment sinks. In this study, sediment pins and vertical cut measurements of the deposited sediment were used to measure the depth of sediment trapped by the SWC structures. Over a two-year period (2014 and 2015), a total of 214 depth measurements were recorded (72 from soil bunds; 72 from fanya juu and 70 from micro-trenches).

When selecting which soil bund and fanya juu ridge to sample, three slope classes were considered: <5% (lower), 5-7% (middle) and >7% (upper). Sampling sites were replicated three times for each of the three slope classes while three soil bunds and three fanya juu ridges were also evaluated.

The deposited sediment was measured for the nine 30 meter soil bunds. Sediment depth was recorded at four representative locations (every 10 m distance along each bund) resulting in 36 measurements in 2014 and 72 in 2015. Similarly, nine representative fanya juu ridges (30 m each) were selected. Before the rainy season, 36 sediment pins (10 m spacing, 4 sediment pins per ridge) were installed, with the depth of sediment measured at the end of the rainy season in 2014 and 2015. In total 72 depths were collected over the two years. Sedimentation width of fanya juu ridges ranged from 0.3-0.9 m with an average of 0.6 m. In addition to sediment pins, vertical cut measurements through the deposited sediment were taken upslope of the fanya juu ridge to increase the accuracy of the data. To calculate the total volume of the trapped sediment, the average depth and width of sedimentation of the two SWC structures (fanya juu and soil bunds) were multiplied by their total length within the catchment.

A sub-catchment containing SWC structures (soil bunds and fanya juu) was selected to evaluate the STE of the structures. Sediment outflow at the outlet of the sub-catchment was measured including sediment trapped by SWC structures within the sub-catchment, which was categorized as inflow sediment. STE was calculated (Eq. 6.1) based on sediment inflow and outflow (Verstraeten & Poesen, 2000; Mekonnen et al., 2015b) using,

$$STE = \frac{(S_{inflow} - S_{outflow})}{S_{inflow}} * 100 \tag{6.1}$$

where: $STE$ is sediment trapping efficacy (%); $S_{inflow}$ is the sum of the outflow sediment measured at the outlet of the sub-catchment and sediment trapped by SWC structures (kg) and $S_{outflow}$ is sediment measured at the outlet of the sub-catchment (kg)

Micro-trenches on average are 1.5 m long and 0.4 m wide. Thirty micro-trenches were selected with trapped sediment depth determined by measuring the depth of micro-trenches before and after the rainy seasons in 2014 and 2015. In addition, five sediment pins were used in five micro-trenches to measure trapped sediment depth more accurately resulting in 70 sediment depth measurements. To quantify the volume of trapped sediment in a micro-trench, the average measured sedimentation depth was multiplied by the width and length of the structure, which was multiplied by the total number of micro-trenches implemented in the study area.

***Measuring sediment trapped on the floodplain***

Sediment trapped on the floodplain was quantified using sediment pins and direct measurements of sediment depth (Riihimaki, 2011). Thirty sediment pins were installed inside the 17 ha floodplain area (Figure 6.1) before the rainy seasons and measured after the rainy seasons in 2014 and 2015. In addition eight vertical cut measurements of the deposited sediment were done every year. A total of 76 depth samples (16 direct samples and 60 buried pin depths) were taken over two years. To calculate the annual volume of trapped sediment, the average sedimentation depth was multiplied by the floodplain area.

To evaluate the STE of the floodplain, a total of 48 suspended sediment samples (24 composite inflows and 24 outflows in 2014 and 2015) were collected from 24 rainfall events (12 rainfall events each year). Two runoff inflow temporary streams through which the majority of the runoff enters onto the floodplain and one outflow/outlet were used to collect suspended sediment samples. The STE of the floodplain was calculated based on the measured inflow and outflow of sediment (Eq. 6.1).

***Measuring sediment trapped in the wetland***

Over three years (2013-2015), a total of 48 composite suspended sediment samples were collected at four inflow locations, while 48 samples were collected at the main outflow (16 samples each year). The reason being that runoff enters the wetland through four temporary drainage channels and exits the wetland through a single channel (Figure 6.4). Sediment trapping efficacy (STE) of the wetland was calculated based on the measured inflow and outflow of suspended sediment (Line *et al.*, 2008) (Eq. 6.1).

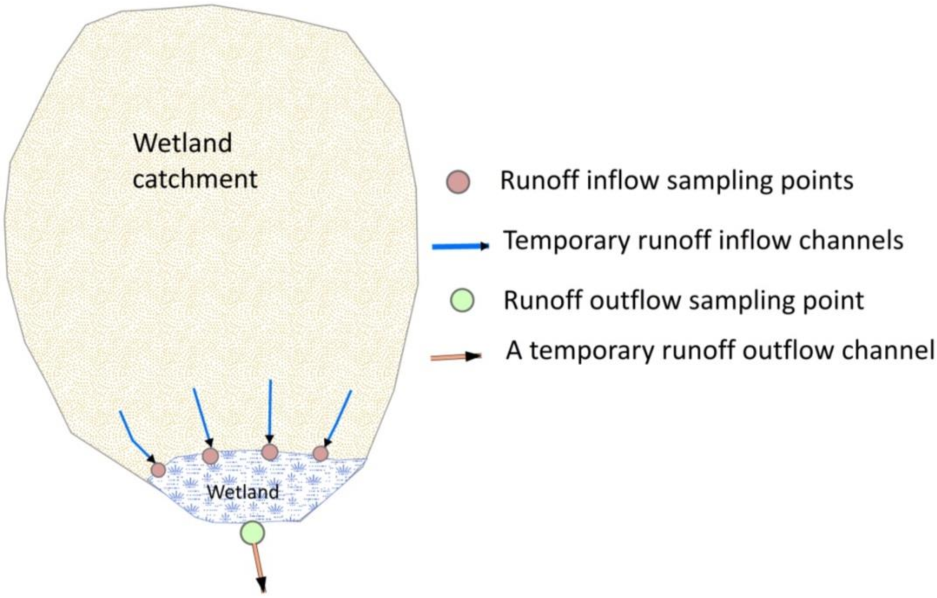



***Figure 6.4*** *Schematic diagram of the wetland area showing the inflow and outflow of runoff and the locations of the suspended sediment collection sites within the Minizr catchment.*

Although suspended sediment samples were collected at the inflow and outflow points of the wetland, it was not possible to estimate the total amount of sediment that enters into the wetland since it was difficult to accurately measure and quantify the inflow runoff entering the wetland through the four temporary inflow channels. Hence, the sediment trapping inefficacy (STI) and the un-trapped sediment that passed through the wetland were used to calculate the trapped sediment contribution using Eqs. 6.2 and 6.3,

$$STI\ (\%) = 100 - STE\ (\%) \tag{6.2}$$

$$TS = \frac{STE\ (\%) * UTS}{STI\ (\%)} \tag{6.3}$$

where: *TS* is the amount of wetland sediment trapped (t) and *UTS* is the amount of un-trapped sediment that passed through the wetland (t).

To quantify the un-trapped sediment that passed through the wetland, both runoff and suspended sediment data were collected at the outlet of the wetland. Runoff depth was measured using a pressure transducer (diver) while channel width was measured using a tape measure. Runoff velocity (m $s^{-1}$) was measured using the Valeport 'Braystoke' Model 001 current meter. The velocity/area method (FAO, 1993) was used to estimate total runoff discharge (Eq. 6.4), while sediment discharge was calculated from suspended sediment concentration samples (Blanchard *et al.*, 2011) (Eq. 6.5),

$$Q = A \times V \tag{6.4}$$

$$Q_s = Q * C_s * K \tag{6.5}$$

where: Q is runoff discharge in $m^3 s^{-1}$; A is channel cross sectional area ($m^2$) and V is flow velocity (m $s^{-1}$); $Q_s$ is sediment discharge (t $day^{-1}$); $C_s$ is concentration of suspended sediment (g $l^{-1}$) and K is 86.4, which is the conversion coefficient.

***Measuring suspended sediment in a grassed waterway***

Grassed waterways are areas where runoff concentrates over grassed areas rather than on bare erodible soil. Grasses enhance infiltration of the runoff and their roots bind the soil and help protect it from erosion. They also help to reduce sediment transport through decreasing flow velocity (Fiener & Auerswald, 2006; Dermisis *et al.*, 2010; Mekonnen et al., 2015a), and are very efficient at filtering runoff and contributing to nutrient and sediment deposition. Both grassed and un-grassed waterways discharge runoff within the Minizr catchment. Therefore, two natural waterways, one covered with grass (grassed waterway) and one devoid of grass cover (un-grassed waterway) were investigated for this study.

To evaluate the suspended sediment load reduction and STE of both waterways, 60 suspended sediment samples (30 inflow and 30 outflow) were collected in 2014 and 2015 in both the grassed and un-grassed waterways with their STEs calculated using Eq. 6.1. The grassed and un-grassed waterways were located at the outlet of two small adjacent catchments covering an area of 2.12 and 2.18 $km^2$, respectively. The catchments have similar rainfall, soil type, land use/cover and slope characteristics. The grassed waterway is 1023 m long while the un-grassed waterway has a length of 1016 m, both with an average width ranging from 2.6-3.0 m (Figure 6.1).

***Dry mass and sediment density calculation***

To convert the trapped (deposited) sediment volume to dry sediment mass, the density of the trapped sediment was estimated using the cylindrical core method (McKenzie *et al.*, 2002; Mekonnen et al., 2015b). Six samples from the floodplain, six from micro-trenches and 12 from SWC structures, each of 100 $cm^3$, were collected. The samples were oven dried at 105 $^0$C in the laboratory for 24 hours, with dry sediment calculated by weighing the dry sediment and subtracting it from the wet sediment mass. Dry mass of the collected suspended sediment samples at the inflow and outflow locations of the wetland, floodplain and waterways was determined in a similar manner. Density was calculated by dividing the dry sediment mass by volume.

***Statistical analysis***

Data analysis was done using Microsoft Excel and IBM SPSS statistics 22 software. ANOVA was run to evaluate differences in sedimentation rates for the different slope classes (upper, middle and lower) in the catchment and to compare the means of trapped sediment by soil bund and fanya juu ridges.

## 6.3 Results

***Sediment trapped by SWC structures***

In the Minizr catchment, there are 144 km of soil bunds and fanya juu ridges. Overall, the mean measured rate of sedimentation from the sampled soil bunds and fanya juu ridges was 0.053 $m^3\ m^{-1}\ y^{-1}$ or 55 $kg\ m^{-1}\ y^{-1}$, with an average depth of 0.09 m. Furthermore, the rate of sedimentation was not significantly different at $P<0.05$ in the upper, middle and lower parts of the catchment and between the soil bunds and fanya juu ridges (Table 6.1). The total annual sediment trapped was 7,620 $m^3$ or 7,922 Mg (using an average bulk density of 1.04 $g\ cm^{-3}$), resulting in a STE of 54%. All micro-trenches (576 in total) constructed on grazing lands trapped 13 $m^3\ y^{-1}$ or 13.26 $Mg\ y^{-1}$ (using an average bulk density of 1.02 $g\ cm^{-3}$), with each individual micro-trench trapping 23 kg of sediment annually.

***Table 6.1*** *Catchment sedimentation within a sample of fanya juu and soil bund structures*

| Structure[A] | Position in the catchment[B] | Sediment depth[C] (m) | Total sedimentation[D] ($m^3$ 30 $m^{-1}$) | Rate of sedimentation[E] | |
|---|---|---|---|---|---|
| | | | | ($m^3\ m^{-1}\ y^{-1}$) | ($kg\ m^{-1}\ y^{-1}$) |
| Fanya juu | Upper | 0.11 | 1.92 | 0.064[a] | 65.28[a] |
| Fanya juu | Middle | 0.09 | 1.68 | 0.056[a] | 57.12[a] |
| Fanya juu | Lower | 0.10 | 1.74 | 0.058[a] | 59.16[a] |
| Soil bunds | Upper | 0.08 | 1.20 | 0.040[a] | 40.80[a] |
| Soil bunds | Middle | 0.10 | 1.50 | 0.050[a] | 51.00[a] |
| Soil bunds | Lower | 0.11 | 1.65 | 0.055[a] | 56.10[a] |
| Average | - | 0.09 | 1.60 | 0.053 | 55.00 |

[A] Average sedimentation width is 0.6 m (fanya juu); 0.5 m (soil bund) and ditch length is 30 m.

[B] Position and slopes in the catchment; Upper (>7%), Middle (5-7%) and Lower (<5%) slopes.

[C] Two years average deposited sediment depth.

[D] Two years average sediment deposited behind 30 m structures.

[E] Two years average rate of sedimentation.

[a] Significance test of mean difference among treatments at $P<0.05$, which shows a non-significant difference.

***Sediment trapped on the floodplain***

Over 2014 and 2015, the average inflow, outflow and sediment trapped by the floodplain were 15.9 $g\ l^{-1}$, 3.7 $g\ l^{-1}$ and 12.2 $g\ l^{-1}$, respectively, with STE calculated at 77%. Thus a total of 12,950 $Mg\ y^{-1}$ of soil was eroded from the upper catchment and transported onto the floodplain. On the 17 ha floodplain, 8,670 $m^3$ or 9,970 Mg of sediment (using a bulk density of 1.15 $g\ cm^{-3}$) was trapped at a sediment depth of 5.1 cm, and an average sedimentation rate of 59 $kg\ m^{-2}\ y^{-1}$. Although 77% of the inflow sediment was trapped, 23% was transported downstream through the floodplain, which amounts to 2,590 $m^3 y^{-1}$ or 2,980 Mg $y^{-1}$.

***Sediment trapped in the wetland***

In the wetland, over the three years (2013 - 2015), the average inflow, outflow and trapped sediment was 6.7 g $l^{-1}$, 1.0 g $l^{-1}$ and 5.7 g $l^{-1}$, respectively, with the STE of the wetland being 85%. The average annual volume of sediment trapped and accumulated in the wetland was 8,715 Mg with a sedimentation rate of 36 kg $m^{-2} y^{-1}$. The remaining 15% of the sediment or 1,540 Mg $y^{-1}$, was annually transported downstream through the wetland. Therefore, 10,250 Mg $y^{-1}$ of soil was eroded from the upper catchment and transported into the wetland.

***Sediment trapped in waterways***

The average inflow, outflow and trapped sediment over 2014 and 2015, respectively, was 5.6 g $l^{-1}$, 1.4 g $l^{-1}$ and 4.2 g $l^{-1}$ (grassed waterway) and 5.6 g $l^{-1}$, 4.4 g $l^{-1}$ and 1.2 g $l^{-1}$ (un-grassed waterway); with STEs of 75% and 21% for the grassed and un-grassed waterways, respectively. The grassed waterway reduced suspended sediment content of the runoff three times more than the un-grassed waterway. This is clearly evident in Figure 6.5 which shows the junction between low sediment-laden runoff at the end of the grassed waterway on the left (a), and the high sediment-laden runoff at the end of the un-grassed waterway (b) on the right.


***Figure 6.5*** *Difference in sediment content in the runoff is reflected in differences in sediment loads at the junction between the grassed (A) and un-grassed (B) waterways.*

## 6.4 Discussion

***Sediment trapping by man-made SWC structures***

In the Minizr catchment, the rate of sedimentation caused by soil bunds and fanya juu ridges, was on average 55 kg $m^{-1}$ $y^{-1}$ with STE 54%. This finding agrees with (Lecce *et al.*, 2006), who found drainage ditch sedimentation rates ranging from 12.5 to 88.8 kg $m^{-1}$ $y^{-1}$ in North Carolina.

However, according to (Gebremichael et al., 2005), in the northern part of Ethiopia (Dogua Tembien district), the rate of sedimentation behind stone bunds was 119 kg $m^{-1}$ $y^{-1}$, which is much higher than the results obtained in this study. Differences in the rate of on-site soil erosion can significantly affect the inflow of sediment into the structures. Soil erosion in the Dogua Tembien district was much higher (57 Mg $ha^{-1}$ $y^{-1}$) than in the Minizr catchment (21.5 Mg $ha^{-1}$ $y^{-1}$). In general, SWC structures constructed within fields were found to trap large amounts of sediment and made a major contribution to the reduction of sediment entering the Koga reservoir at the catchment outlet.

SWC structures reduce the slope gradient of farmland by forming bench terraces as a result of sediment accumulation (Gebremichael et al., 2005; Mekonnen et al., 2015b). In the study area, even though no statistically significant difference was found in the rate of sedimentation between soil bunds and fanya juu ridges at different slopes, 20 year old fanya juu form high sediment ridge lines because the trapped sediment have gradually converted them into bench terraces (Figure 6.2a). This decreased average slope gradients by 2.7%. However, soil bunds do not alter the slope gradient largely because the trapped sediment is buried inside the ditch instead of forming a sediment ridge in front of the structure.

***Sediment trapping - natural sediment sinks***

In the study area, natural sediment sinks played an important role in trapping sediment and reducing downstream reservoir sedimentation. The 24 ha wetland located near the outlet of the Minizr catchment (Figure 6.1) trapped 8,715 Mg of sediment annually at an average sedimentation rate of 36 kg $m^{-2}$ $y^{-1}$ with a STE of 85%. This result agrees well with the literature. Braskerud (2001) found for constructed wetlands in southeast Norway, sedimentation rates of 14-121 kg $m^{-2}$ $y^{-1}$. Elder and Goddard (1996) obtained a STE of 80% at the Jackson Creek wetland in Wisconsin, while the Imperial Valley wetland in California had a STE of 97% (Kadlec *et al.*, 2010). Other constructed wetlands revealed STEs of 71-90% in southern Brazil (Sezerino *et al.*, 2012), and 72-88% in North Carolina (Line et al., 2008). Variations in these ranges are largely due to the natural morphology and size of the wetlands and vegetation species composition and diversity, which all have an important influence on the STE of the wetland in reducing erosion and enhancing deposition (Braskerud, 2001; Berendse *et al.*, 2015; Mekonnen et al., 2015a).

According to Keesstra (2007) and Keesstra *et al.* (2009a), sediment deposition on a floodplain depends on the location of the floodplain within the catchment and also on the width and land cover of the floodplain. In addition, sediment influx from hillslopes and the intensity of rainfall, all play a role in governing the potential of a floodplain or wetland to trap incoming sediment. In this study, a 696 m long and 243 m wide floodplain, which was covered with grass, trapped 9,970 Mg of sediment annually with a STE of 77% and an average sedimentation rate of 59 kg $m^{-2}$ $y^{-1}$. This result is in line with Brunet and Astin (2008), who found sedimentation rates on floodplains in southwest France ranging from 0.02-75 kg $m^{-2}$ $y^{-1}$.

Sediment load reduction in grassed waterways ranged from 65% (Dermisis et al., 2010) to 97% (Fiener & Auerswald, 2003). In this study, sediment discharge decreased by 75% between the grassed waterway inflow and outflow. Sediment reduction was considerably higher in grassed waterways than in un-grassed waterways (21%). In addition to trapping sediment, grass cover decreased the propensity for scour, deepening and widening of the waterway by erosion, further reducing the sediment yield from the catchment area.

Although the wetland plays an important role in trapping sediment, floodwaters will inundate the wetland, which over time, will be converted into farmland due to the persistent sediment accumulation. According to Wang *et al.* (2014), watershed management designed to reduce sediment input into the wetland may aid in the conservation of natural wetlands. Therefore, emphasis should be given to man-made ST measures on fields in the upper catchment to help trap and reduce sediment input into the wetland.

Agricultural expansion has also strongly affected the existence of the wetland which has been given to landless youths to cultivate and grow crops. They are slowly converting the wetland into farmland by draining the wetland water and ploughing it. This will destroy the wetland and its ecosystem in a very short period of time. As an alternative, instead of cultivating the wetland area for crop production, the youths could use the grass growing on the wetland for livestock fattening, as a means of generating income without affecting the wetland. Therefore, awareness raising of policy makers, the surrounding farmers and youth associations is needed to sustainably conserve and manage the wetland.

***Disconnecting sediment transfer pathways***

Connectivity is an emerging issue of a catchment system (Bracken *et al.*, 2015; Parsons *et al.*, 2015), which indicates how well a system transfers substances, such as water and sediment, through it. The combined effect of ST measures both on- and off-site will reduce the connectivity of the landscape and sediment transfer pathways within the catchment (Mekonnen et al., 2014b).

The possibility for sediment to be trapped within the catchment is enhanced by the appropriate placement of barriers and buffers, which can reduce sediment connectivity (Fryirs, 2012). According to Baartman et al. (2013), man-made structures like terraces are reducing sediment delivery to the outlet. Cerda et al. (2015) and Keesstra et al. (2016) have shown that leaving mulch within the catchment can reduce the amount of sediment transported to the catchment outlet. Furthermore, reducing the input of sediment from roads as a significant sediment contributor (Pereira *et al.*, 2015) to the total sediment budget, is needed as part of an integrated approach to the whole catchment system. In addition, studies on the impact of plant species (Novara *et al.*, 2013; Mekonnen et al., 2015a) and plant species diversity (Berendse et al., 2015), reveal that by effectively managing plant cover, sediment can be trapped more effectively and that soil erosion can be further reduced.

By utilizing scientific agricultural practices, appropriate SWC measures, and the effective management of the land with suitable plant species, sediment yield at the catchment scale can be reduced. In this study, SWC measures and natural sediment sinks (floodplain and wetland) trapped considerable quantities of sediment by disconnecting the sediment transfer paths within the catchment. SWC structures such as Fanya juu, played an important role in disconnecting the landscape by forming ridges due to the accumulated sediment, which further reduced the slope gradient.

***Integrated sediment trapping***

According to Mekonnen et al. (2014b), an integrated ST approach at the catchment scale is believed to be the most effective way in helping to increase the STE of ST measures and thereby reducing sediment loads at the outlet of a catchment. On-site ST measures can help maintain sediments on agricultural field sites, while off-site ST measures trap sediments in drainage channels and gullies. Sediments transported from farmlands without being trapped by on-site ST measures can be trapped by off-site ST measures.

In the Minizr catchment, despite the presence of numerous man-made ST structures and natural sediment sinks trapping large quantities of sediment (26,600 Mg), this only amounts to 38% of the total sediment load, with the vast majority (62%) being deposited in the Koga reservoir (43,000 Mg). There are three reasons for this:

(i) more emphasis is given to managing on-site sediment sources when implementing SWC structures within fields, without addressing gully erosion or riverbank erosion, which are both important sediment sources in the catchment. According to Mekonnen *et al.* (2014a) and Rijkee *et al.* (2015), river bank and gully erosion are severe and represent an important source of sediment.

(ii) Structural SWC measures are not fully supported with vegetative measures such as grass species, which can help improve STE. To effectively trap sediment and ensure the sustainability of ST structures, it is important to combine both vegetative and structural measures (Nyssen *et al.*, 2009b; Mekonnen et al., 2014b).

(iii) Lack of regular maintenance and free grazing are causing SWC structural failures, which affect STE and reduce the sustainability of SWC structures.

To effectively trap sediment within the catchment and further reduce sediment entering the Koga reservoir, an integrated ST approach is needed. This includes:

(i) implementing off-site ST measures such as check dams and sediment storage dams (SSD) inside gullies and within drainage lines as SSDs constructed inside drainage lines and gullies can trap 67-74% of incoming sediment (Mekonnen et al., 2015b);

(ii) implementing riparian zone measures such as establishing buffer zones and planting trees along the river to reduce riverbank erosion, because vegetation causes flow retardation within the channel and on the riverbanks and thus enhances sedimentation (Keesstra *et al.*, 2012);

(iii) managing sediment access paths; and,

(iv) conducting regular maintenance of structures and avoiding free grazing.

***Using vegetative measures instead of physical structures***

In the Minizr catchment, 144 km of SWC structures (fanya juu and soil bund) have been constructed in farmlands to trap sediment and thus help reduce soil loss. To construct this length of structure 69, 000 $m^3$ soil was moved from its original location either upslope (fanya juu) or downslope (soil bunds), which involved 25, 000 human labour days (work norm: 175 person day per km; (MOARD, 2005)). This process increased soil instability and facilitated soil loss, in addition to consuming large amounts of labour. To avoid this problem, vegetative ST measures were seen as better alternatives. According to Mekonnen et al. (2015a), grass barriers can trap from 20-76% of the inflow sediment on an 8% slope. Moreover, grass barriers can solve livestock feed problems, which is a crucial issue in both the study area and in Ethiopia in general.

## 6.5 Conclusions

The STE of existing man-made structures and natural sediment sinks were evaluated in the Minizr catchment, northwest Ethiopia. They play a significant role in trapping sediment and disconnecting sediment transfer pathways. Rates of sedimentation were 55 kg $m^{-1}$ $y^{-1}$ for SWC structures (soil bunds and fanya juu), 59 kg $m^{-2}$ $y^{-1}$ on the floodplain and 36 kg $m^{-2}$ $y^{-1}$ in the wetland, while >576 individual micro-trenches can trap 23 kg of sediment annually. Over 20 years old, fanya juu ridges have reduced the average slope gradient by 2.7% forming lines of high sediment ridges. In soil bunds, trapped sediment is buried inside a ditch instead of forming lines of sediment ridges, which reduces its role in changing the gradient of the slope. Wetlands, floodplains, grassed waterways and SWC structures (soil bunds and fanya juu) were found to be effective sediment sinks with STEs of 85%, 77%, 75% and 54%, respectively. Despite 26,600 Mg (38%) of sediment being trapped by both the existing man-made structures (soil bunds, fanya juu and micro-trenches) and natural sediment sinks (wetland and floodplain), there is still 43,000 Mg (62%) leaving the catchment and entering Koga reservoir as suspended sediment. Soil eroded within a catchment is very rarely transported in its entirety to the outlet, as a portion of it will be trapped and re-deposited within the catchment either due to man-made SWC structures or by natural sediment sinks.

This study shows that large amounts of money and labour are being invested to implement ST measures aimed at reducing soil loss by enhancing sedimentation within a catchment. Still large amounts of sediment are leaving the catchment and entering Koga reservoir. This is also a great challenge to reservoirs, which are under construction for hydropower generation involving large investments such as the Ethiopian Grand Renaissance Dam, and natural reservoirs like Lake Tana. Therefore, additional catchment treatment measures are required with an integrated catchment scale ST approach to help reduce sediment loads into Koga reservoir.

# Chapter 7

# Adapting LAPSUS_D model to simulate runoff and sediment yield in Minizr catchment, NW Ethiopia

Mulatie Mekonnen Getahun

# Adapting LAPSUS_D model to simulate runoff and sediment yield in Minizr catchment, NW Ethiopia

*Abstract*

*Direct field measurements and model simulations can be used to determine catchment sediment yield. Estimating catchment runoff and sediment yields using model simulation helps to save resources compared with field data measurements. A further advantage of using a modelling approach is the ability to assess, a-priori (i.e. before actual implementation), the effect of different spatial configurations of the various sediment trapping measures in the catchment and chose the optimal design. Moreover, models help to simulate the effectiveness of sediment trapping measures at larger catchment scales, which cannot be feasibly achieved by field experiments. In this study, we tried to adapt the daily based model, which require low input data sets, LAPSUS_D, for the northwest highlands of Ethiopia. We used the three years runoff and sediment yield data (Chapter 2) collected at the outlet of the Minizr catchment, northwest Ethiopia, to calibrate and validate the model. However, the result was not promising. The most probably reasons of the poor representation of the data is the quality of the DEM. The resolution of 30 m does not able to represent the small scale variations in the catchment such as the large number of gullies. Furthermore, a large part of the catchment is very flat in terms of topography and therefore small errors in the DEM have a large influence on the representation of the hydrology in the catchment. As a result of this the water was not routed through the catchment as it is in reality. Further study is recommended with a DEM of better resolution.*

## 7.1 Introduction

Reservoir sedimentation resulting from upstream soil erosion is a critical problem affecting the water storage capacity of water reservoirs in Ethiopia. Many reservoirs are losing their water storage capacity (Haregeweyn *et al.*, 2006; Tamene *et al.*, 2006a). This risk is poorly addressed because of lack of sufficient data and appropriate methodologies to predict sediment yield (Haregeweyn et al., 2006) and lack of an integrated catchment scale sediment trapping approach (Mekonnen *et al.*, 2014b).

To overcome these problems to predict catchment sediment yield, attempts have been made to adapt and use process-based models in Ethiopia. Some examples of models that have been used to predict catchment sediment yield are: Water Erosion Prediction Project (Zeleke, 2000) and Soil and Water analysis Tool (Setegn *et al.*, 2010) at Anjeni catchment, northwest Ethiopia, and the Agricultural Non-Point Source Pollution model (Haregeweyn & Yohannes, 2003) at Augucho catchment, eastern Ethiopia. However, such models require large input datasets and if such models are applied in conditions where the necessary data are not available and, therefore, a proper calibration cannot be performed, the results may become unreliable (Nyssen *et al.*, 2006; Haregeweyn *et al.*, 2013). Consequently, such models may be accurate but their complexity and data demand may reduce their usability. Therefore, models requiring minimal and easily accessible input datasets are best alternatives in data scarce countries like Ethiopia.

Research on catchment sediment dynamics has generally focused on large or small scales both spatially and temporally, largely ignoring the intermediate scale (Gao & Josefson, 2012; Keesstra *et al.*, 2014a; Yeshaneh *et al.*, 2014). But from an applied (management) perspective, the intermediate scale (meso-scale) is the scale at which catchment managers most often take decisions (Aksoy & Kavvas, 2005) and the temporal (daily) scale is the one for which most hydrological data are recorded (Higgitt & Lu, 2001; Newham *et al.*, 2004; Keesstra et al., 2014a).

In a meso-scale catchment (20-200 $km^2$) overland flow was assumed to reach the outlet of the catchment in one day, which makes possible to estimate daily discharge. According to Keesstra et al. (2014a), daily discharge is better than annual discharge because of two reasons; (i) it is a good indication of the amount of overland flow in the catchment, and with that a good indication of sediment transport capacity, and (ii) daily discharge data are usually available for most catchments and can therefore be used in calibration and validation.

Compared to the average annual sediment yield values, monthly and daily based values could provide valuable detailed information about the temporal and spatial variations of catchment sediment yield (chapter 2). Annual sediment yield data (t $ha^{-1}$ $y^{-1}$) is not informative to where the sediment sources are located and at which moments in time the sediment is discharged from the catchment. Only a small part of the catchment (Mekonnen & Melesse, 2011) and only a few heavy rain storms on specific dates usually produce the bulk of annual sediment yield (Hagmann, 1996; Ziadat & Taimeh, 2013).

In addition to sediment yield data, information is required on the actual sediment source areas, areas where most soil erosion occurs and sediment sink areas, areas where most sediment deposition takes place. Identifying major sediment source areas will help to intervene the problem of soil erosion allocating the available resources to high risk areas instead of spreading it equally all over the catchment (Mekonnen & Melesse, 2011; Haregeweyn et al., 2013).

Spatially distributed models help to indicate where erosion and deposition occurs within a catchment. The LAPSUS (LAndscape ProcesS modelling at mUlti dimensions and scaleS) model has been previously tested in several field studies on erosion and sedimentation in varying climates (Schoorl *et al.*, 2002; Haileslassie *et al.*, 2005; Baartman *et al.*, 2013; Barreto *et al.*, 2013). These studies used the original LAPSUS model, based on yearly timesteps. To fill this scientific and management gap, the landscape evolution model LAPSUS was adapted as LAPSUS_D for a meso-scale catchment to model runoff and sediment yield on a daily resolution (Keesstra et al., 2014a). In this study, the LAPSUS_D model is used to assess hydrology and sediment dynamics for the Minizr catchment in northwest Ethiopia.

The specific objectives of this study were to, (I) adapt the LAPSUS_D model and predict daily runoff and sediment yield in the 20 $km^2$ Minizr catchment, in northwest Ethiopia, (II) to identify erosion hotspot (sediment source) areas for intervention measures, (III) assess, the effect of different spatial configurations of the various sediment trapping measures in the catchment and chose the optimal design by running scenarios using the model. The scenarios consist of a different combination of measures on various locations within the catchment, (IV) evaluate potential sediment yield reduction of an integrated sediment trapping approach.

## 7.2 Materials and methods

*Study area*

The study was conducted in the Minizr catchment, northwest highlands of Ethiopia (1255891 - 1249499 N and 310272 - 303559 E; Adindan_UTM_Zone_37N; Figure 7.1). It covers an area of about 20 km$^2$ with an elevation range of 2035 m at the outlet to 2283 m. a.s.l. at its highest point on the catchment divide. Slope in the catchment ranges from 0-51% with an average value of 8%. More than 80% of the catchment has a slope between 0-8% .

Within the catchment about 71% is farmland and 18% is grazing land, while plantation, bush land and settlement areas account for the remaining 11%. Average rainfall (2013-2015) is 1215 mm y$^{-1}$, which falls mainly from June to September, preceded and followed by one month with low and dispersed rains. Average yearly minimum and maximum temperature is 11$^0$C and 26$^0$C, respectively. Dominant soil types are Nitosols (62%), Eutric Vertisols (30%), Lithic Leptosols (6%) and Chromic Cambisols (2%) (MNREP, 1995).

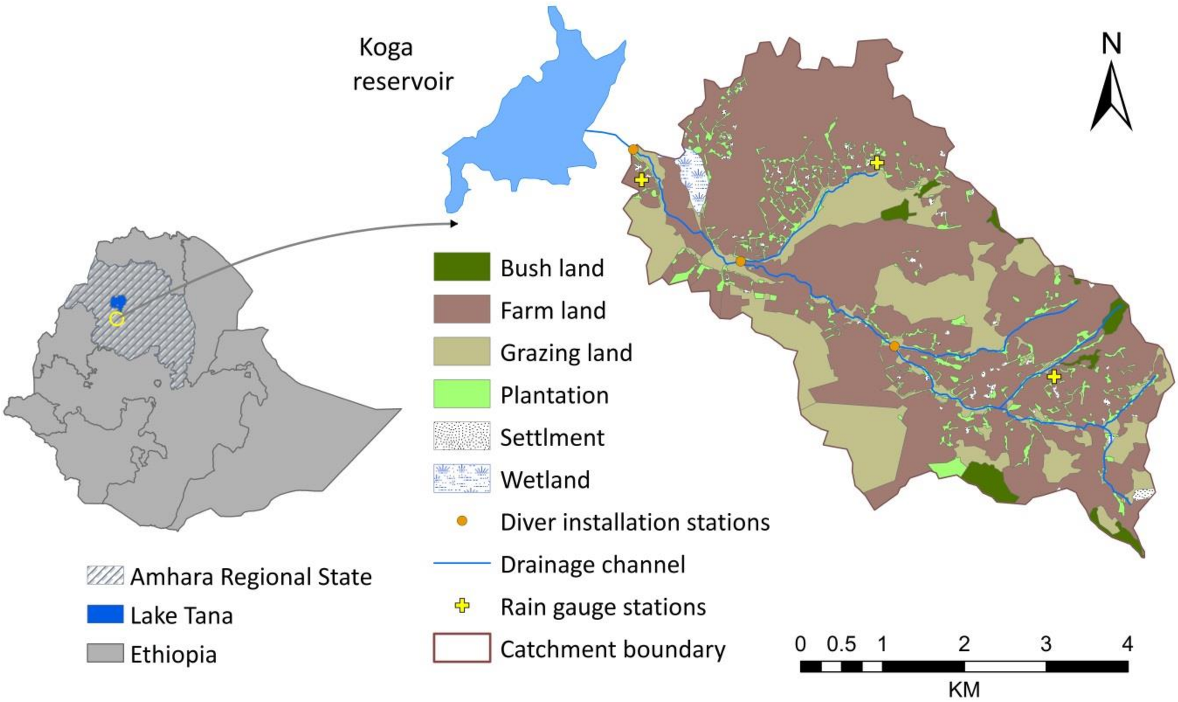



***Figure 7.1*** *Location map of Minizr with land use/cover, rain gauge and diver installation stations*

*The LAPSUS_D model*

In LAPSUS_D, LAPSUS is LAndscape ProcesS modelling at mUlti dimensions and scaleS, and D represents a daily resolution, Figures 7.2 and 7.3). LAPSUS_D is a daily based model that can simulate runoff, erosion and sediment yield based on a limited number of input datasets (Keesstra et al., 2014a). It is based on the LAPSUS model (Schoorl et al., 2002; Lesschen *et al.*, 2009; Baartman *et al.*, 2012; Barreto et al., 2013), which was originally created to use yearly timesteps and simulate long-term (decades – millennia) sediment dynamics. LAPSUS-D model can be used at a spatial resolution of a meso-scale catchment (20-200 $km^2$). The spatial data the model requires are: DEM, land use, soil depth, porosity and permeability, while the temporal data the model requires are daily precipitation and evaporation . The model output consists of daily discharge (both water and sediment) values and spatial maps of hydrology, erosion and deposition.

*Required input data*

The format in which the model requires the input data varies (Table 7.1). Some data are spatially distributed (e.g., permeability), others vary over time (precipitation, evaporation). The spatially variable data need to be in rasterised maps and temporal data in the form of tabularized series. Moreover, some parameters are variable in both time and space (land use). These data are delivered to the model as spatial maps. Lastly, the elevation changes as a result of the outputs of the model itself.

The DEM of the catchment has a resolution of 30 m (SRM DEM, 2009). All other maps (soil map and land-use/cover map) were polygon based and were transformed to the same raster size. The soil and texture maps (MNREP, 1995) were used and from it, soil porosity, soil permeability, the maximum infiltration rate and the capacity to hold moisture were estimated. For further confirmation, soil samples at a depth of 0-20 cm were collected from 20 locations and texture analysis was done in Bahir Dar soil laboratory using the hydrometer method (Sertu & Bekele, 2000). Soil depth was obtained from MNREP (1995). The land-use map was made from Google Earth images combined with ground truthing in 2014. Daily precipitation was measured at three locations at representative sites (Figure 7.1). The evapotranspiration was presented as a series of evapotranspiration values for each Julian day. Reference evapotranspiration (ETo) was calculated following the equation of Hargreaves (Allen *et al.*, 1998) using the latitude of the location and a general temperature record for a location near the research site.

At the outlet of the Minizr catchment, water height in the river was recorded with a pressure transducer. Daily runoff and sediment discharges were measured from end of May 2013 until September 2015 during the rainy seasons for three years (see chapter 2). For calibration we used runoff collected in 2013. For the validation we used the remainder of the data available (2014-2015). The Nash–Sutcliffe model efficiency factor (MEF) (Nash & Sutcliffe, 1970) was used to assess the runoff and sediment yield predictive power of the model (Eq. 7.1).

$$\text{MEF}= 1 - \left(\sqrt{\Sigma\,(Qm - Qp)^2}\,/\,\sqrt{\Sigma\,(Qm - Qm/n)^2}\right) \qquad \text{Eq. 7.1}$$

Where; *Qm* is measured discharge, *Qp* is modelled discharge and *n* is number of observations

A Digital Elevation Model (SRTM DEM 30 m; 2009) was used to delineate Minizr catchment and to derive its elevation, drainage network and slope characteristics. ArcGIS 10.2.1 software was used for mapping and GPS (Garmin 60, ~2 m accuracy) was used to collect ground control points for ground truthing during digitizing land cover/use from Google Map, to indicate locations of rain gauges, diver installation stations and catchment outlets.

***Table 7.1*** *Inputs and outputs of the LAPSUS_D model*

| Input and output data sets | Spatial resolution | Temporal resolution |
|---|---|---|
| *Inputs* | | |
| Daily precipitation ( measured) | 3 sites | Daily |
| Daily discharge at outlet (measured) | none | Daily measurement |
| DEM | 30 m x 30 m | Not applicable |
| Soil information | | |
| ▪ Porosity (soil map/soil characteristics a derivative) | 30 m x 30 m | Varies with land use |
| ▪ Permeability (soil map/soil characteristics a derivative) | 30 m x 30 m | Changes with land use |
| ▪ Maximum infiltration capacity (soil map/characteristics a derivative) | 30 m x 30 m | Changes with land use |
| ▪ Soil depth | 30 m x 30 m | No temporal resolution |
| ETo per Julian day (calculated with Hargreaves) | none | daily |
| Land-use map (digitized from Google earth imagery) | 30 m x 30 m | Changes with Julian day |
| *Outputs* | | |
| Maps of soil moisture per day | 30 m x 30 m | Daily |
| Maps of flow paths | 30 m x 30 m | Daily |
| Water discharge at outlet | None | Daily |
| Sediment yield at outlet | None | Daily |
| Maps of erosion and deposition in the catchment | 30 m x 30 m | Daily |

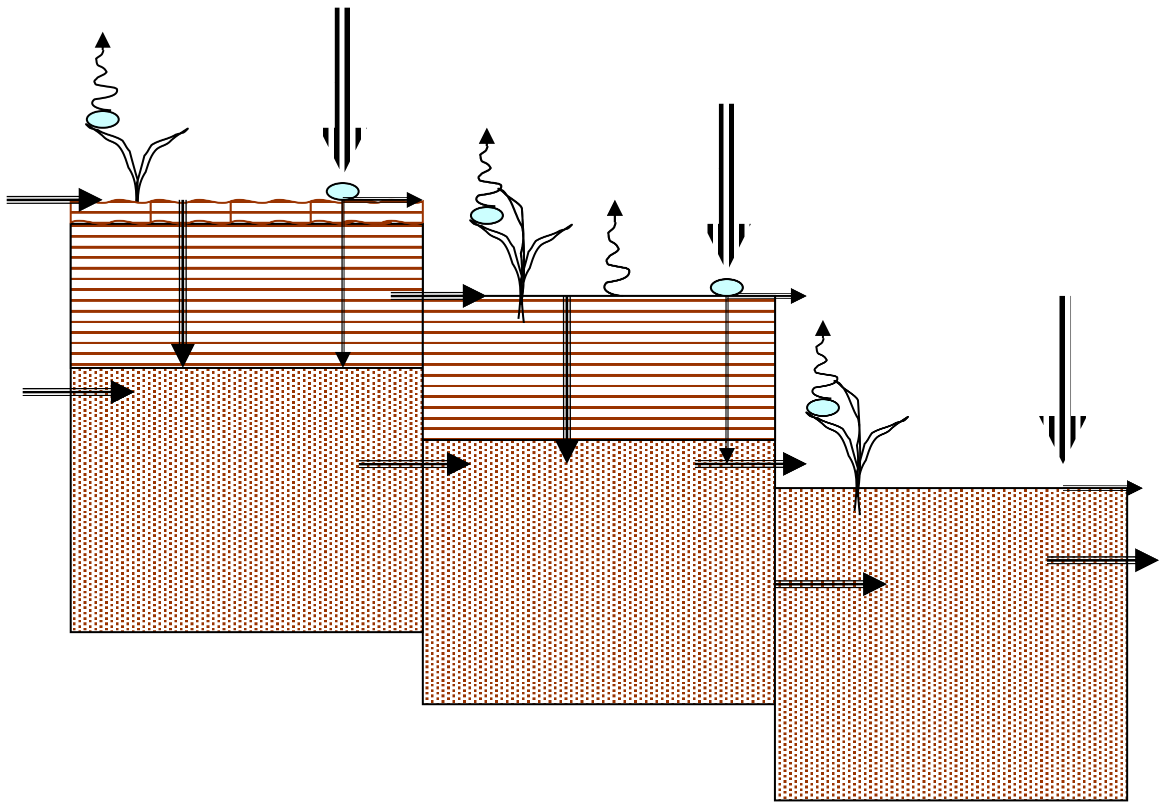


***Figure 7.2*** *Graphical representation of the LAPSUS_D model (Keesstra et al., 2014ab)*

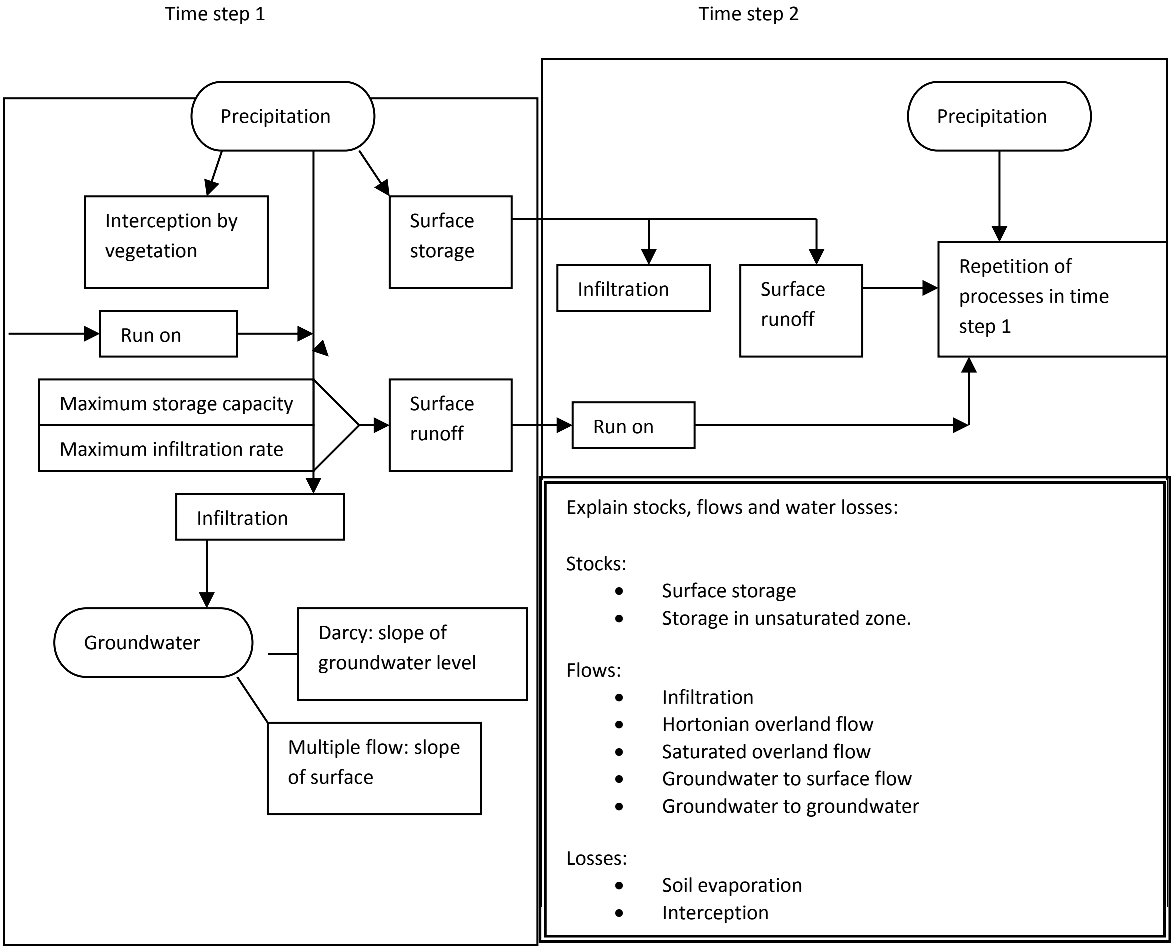



***Figure 7.3*** *Flow chart of the LAPSUS_D model (Keesstra et al., 2014ab)*

## 7.3 Results

*Calibration and validation*

After preparing the input data sets the LAPSUS_D model was run for calibration and validation. The calibration for daily runoff was promising except a few days after the start of the rainfall (Figure 7.4). The calibration values used were 1.9; 1.5; 15; 0.5 and 4.3 for porosity, permeability in (vertical permeability; infiltration), permeability through (horizontal permeability), initial storage and evaporation factors, respectively, which resulted in a model efficiency factor (MEF) of 0.322. Subsequently, the same values were applied to years 2014 and 2015 for validation. Unfortunately, results were not satisfactory for these years (MEF of -0.119 and 0.138, respectively). According to Nash and Sutcliffe (1970), MEF can range from −∞ to 1. An efficiency of 1 corresponds to a perfect match of modelled discharge to the observed data and the closer the model efficiency is to 1, the more accurate the model is. In this case, however, the MEF was 0.322 for the calibration (year 2013) and -0.119 (year 2014) and 0.138 (year 2015) for the validations.

The most probably reasons of the poor representation of the data is the quality of the DEM. The resolution of 30 m does not able to represent the small scale variations in the landscape such as the large number of gullies. Furthermore, a large part of the catchment is very flat in terms of topography and therefore small errors in the DEM have a large influence on the representation of the hydrology in the catchment. As a result of this the water was not routed through the catchment as it is in reality. Obviously, since the calibration and validation results of the runoff were not good, the sediment simulation was not feasible to do. we did not go for sediment simulation. Because the model evaluates the rate of sediment transport by calculating the transport capacity of water flowing downslope from one grid cell to another as a function of discharge and slope gradient.

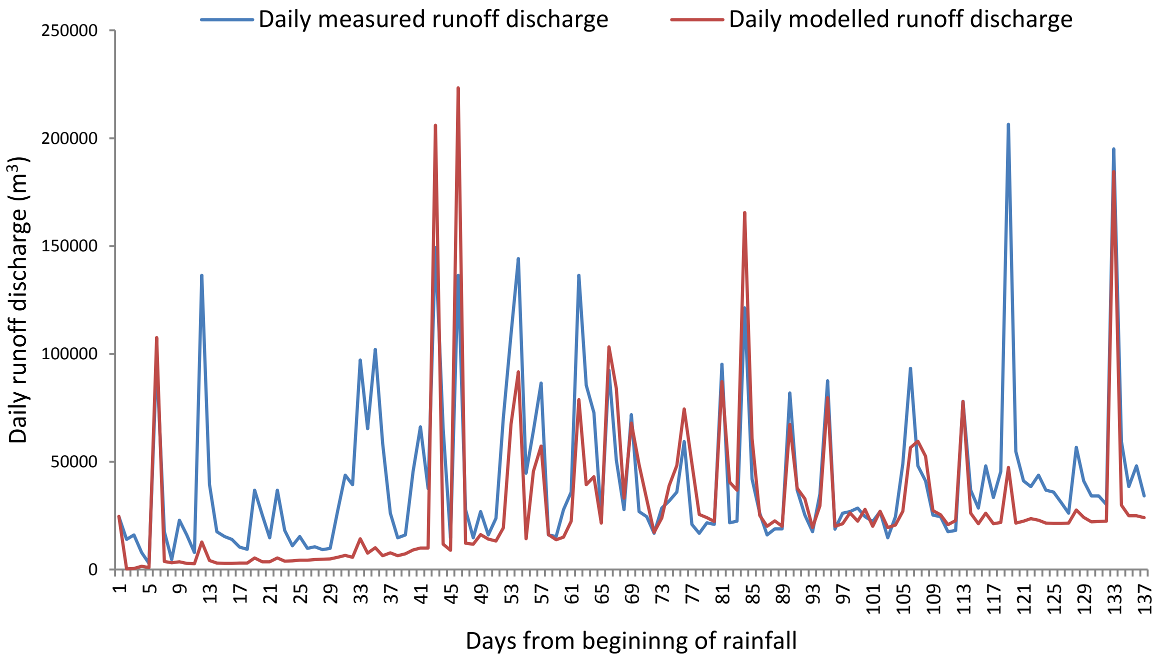



***Figure 7.4*** *Daily measured and modelled runoff discharges during calibration*

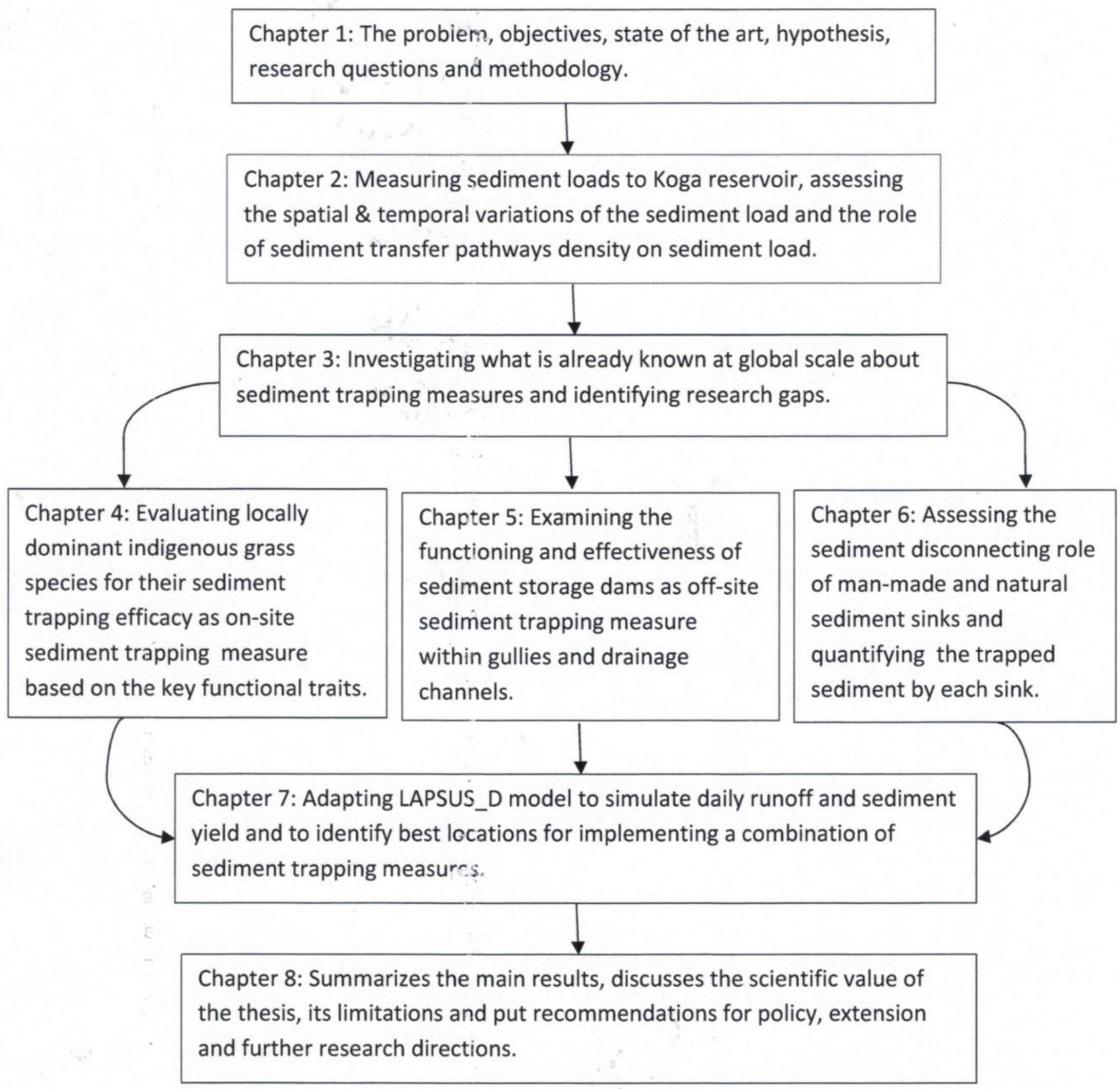
Because of the fact that the model did not give the desired calibration and validation outputs, the scenario runs could not be executed as planned. The planned scenarios were aimed at identifying best sites for the different ST measures and evaluate their integrated role in trapping sediment at catchment scale. But this objective could not be met. Due to time limitation we did not go further to solve the problem and thus further research is recommended.

## 7.4 Conclusions

Estimating catchment runoff and sediment yields using model simulation helps to save resources compared with field data measurements. Moreover, models have been increasingly used as valuable alternatives since model simulations can be run to test various implementation scenarios and help to simulate the effectiveness of sediment trapping  measures at larger catchment scales, which cannot be feasibly achieved by field experiments. In this study, we tried to adapt the daily based LAPSUS_D model for the northwest highlands of Ethiopia using the three years (2013-2015) runoff yield data collected at the outlet of the Minizr catchment. However, the result was not promising. The most probably reasons of the poor representation of the data is the quality of the DEM. The resolution of 30 m does not able to represent the small scale variations in the catchment such as the large number of gullies. Furthermore, a large part of the catchment is very flat in terms of topography and therefore small errors in the DEM have a large influence on the representation of the hydrology in the catchment. As a result of this the water was not routed through the catchment as it is in reality. Further study is recommended with a DEM of better resolution.

# Chapter 8

# Synthesis



# Synthesis

## 8.1 Problem and research themes

The title of this scientific research is "Sustaining reservoir use through sediment trapping in NW Ethiopia", which focused on Koga reservoir as a case study. In spite of massive investments in sediment trapping measures in the runoff contributing catchment, the life time of Koga reservoir is threatened by sedimentation. Rapid water storage loss due to sedimentation is becoming an important factor undermining the sustainable use of the reservoir.

This thesis covers four main themes of research: (I) Soil erosion within the runoff contributing catchment; (II) Sediment transfer pathways (STPs) serving as a route of runoff and sediment (III) Sedimentation in Koga reservoir; and (IV) Sediment trapping (ST) measures, which help to disconnect the STPs and thus trap sediment within the catchment.

The first theme is soil erosion within the runoff contributing catchment. Soil erosion by water is a priority problem in the upstream runoff contributing catchment of Koga reservoir resulting considerable sediment yield at the outlet of the catchment. Different studies estimated the sediment yield. For example; 3.7 t $ha^{-1}$ $y^{-1}$ (MoWR, 2008); 6.2 t $ha^{-1}$ $y^{-1}$ (Assefa *et al.*, 2015); 25.6 t $ha^{-1}$ $y^{-1}$ (Yeshaneh *et al.*, 2014) and 55 t $ha^{-1}$ $y^{-1}$ (Reynolds, 2013).

The second theme is sediment transfer pathways (STPs). STPs serve as a route of runoff and sediment from uplands to lowlands. Although any slope, and any place where water flows is potentially a STP, rivers, gullies and roads are the most important STPs (Poesen *et al.*, 2003; Morgan, 2005; Bracken *et al.*, 2015). An increase in the density of STPs is an indication of increased sediment transport while disconnecting STPs reduces the sediment in transport and increases sedimentability (Fryirs, 2012; Thompson *et al.*, 2016). To study these processes the concept of connectivity was used (Bracken et al., 2015; Parsons *et al.*, 2015; Masselink *et al.*, 2016), which allows studying catchment scale processes in a holistic way. Identifying the STPs within a catchment helps to implement ST measures where they can disconnect the STPs to enhance sedimentation within the catchment (Lloyd *et al.*, 2016).

The third theme is reservoir sedimentation at the outlet of the runoff contributing catchment. Large amounts of sediment are entering Koga reservoir. The estimated amount, however, is different in different studies. For exemple : 48,000 $m^3$ $y^{-1}$ (MoWR, 2008), 269,000 $m^3$ $y^{-1}$ (Yeshaneh et al., 2014), 84,800 $m^3$ $y^{-1}$ (Assefa et al., 2015) and 714,000 $m^3$ $y^{-1}$ (Reynolds, 2013).

The fourth theme is catchment treatment with ST measures. Treating an upstream catchment is treating a downstream reservoir. To this end, part of the Koga catchment has received a lot of assistance in on-site physical soil conservation measures like *fanya juu*, soil bund and micro-trenches. For example the Minizr catchment was treated with 144 km of soil bunds and *fanya juu* ridges, and with more than 576 micro-trenches. In addition, Minizr catchment contains a wetland and a floodplain but we know very little on their function in relation to ST. Therefore, this study was conducted to estimate the sediment loads to Koga reservoir to reduce its uncertainty, to evaluate the functioning and effectiveness of the existing man-made ST measures and natural sediment sinks, and to assess and identify limitations of the existing ST approach for improvement, which help to reduce the sediment load to Koga reservoir.

Our study was conducted in the Minizr catchment which is one of the sources of water for the Koga reservoir. It covers an area of 20 $km^2$ with a slope range of 0-51% (average of 8%), while >80% of the catchment has slopes between 0-8%.

## 8.2 Research questions and answers

Our hypothesis was that erosion both on-and off-site can never be stopped sufficiently in NW Ethiopia and will continue becoming an important factor affecting the water storage capacity of reservoirs. Therefore on- and off-site ST measures are needed to reduce the sediment load into valuable reservoirs till a safe level. In other words, not all efforts should focus on on-site soil conservation, but also on the safe routing of sediment-laden flows and on creating sites and conditions where sediment can be trapped, preferably in a cost effective or even profitable way. Hence research questions with respective answers were as follows.

***Is the Minizr catchment an important source of sediment for the Koga reservoir? If so, how much is the sediment load? Is there spatial and temporal variation in sediment yield?***

Chapter 2 attempts to quantify the amount of sediment entering Koga reservoir from the Minizr catchment, to identify potential sediment source areas at sub-catchment scale, to assess temporal variation in sediment production on daily, monthly and yearly basis. In addition the role of sediment transfer pathways (STPs) on catchment sediment yield has been assessed.

Results show that on average 43,000 t (21.5 t $ha^{-1}$ ) sediment entered Koga reservoir annually from Minizr catchment. The result agrees well with 25.6 t $ha^{-1}$ $y^{-1}$ in the upper part of Koga catchment (Yeshaneh et al., 2014) and 24.6 t $ha^{-1}$ $y^{-1}$ in the nearby catchment, Anjeni, NW highlands of Ethiopia (Setegn *et al.*, 2010). Spatially, Midre-Genet sub-catchment had the highest density of STPs (4.7 km $km^{-2}$) and gullies, contributed most to the total sediment measured (19,400 t $y^{-1}$) followed by Adibera sub-catchment (13,100 t $y^{-1}$). Tume-Shafrie sub-catchment with the lowest STPs density and without gullies, contributed the least to the total sediment measured (6,700 t $y^{-1}$). Temporally; daily and monthly sediment discharges were highest in July and August. From the total sediment entering Koga reservoir, 63% was transported in July and August. Drainage channels, gullies and footpaths were found to be the main STPs enhancing sediment connectivity and transport.

The annual sediment entering Koga reservoir from the total runoff contributing catchment was found to be 278,000 $m^3$, which agreed well with 269,000 $m^3$ (Yeshaneh et al., 2014). This indicates that large amounts of sediment are entering Koga reservoir, which considerably compromise its water holding capacity.

***What is the best method or approach to be used while implementing ST measures within a catchment, which helps to reduce sediment in transport to downstream reservoirs?***

Chapter 3 investigates what is already known about sediment trapping (ST) measures. It presents an overview of the sediment trapping efficacy (STE) of physical and vegetative ST measures at global scale, reviewing more than 90 scientific journal articles, case studies, government reports, conference proceedings and book chapters. In addition, there are participatory field observations and stakeholders' interviews in the upper part of the Blue Nile basin, Ethiopia.

The STE of physical and vegetative ST measures were evaluated using three implementation approaches: (I) individual approach; (II) combined approach; and (III) integrated approach. Almost all studies evaluated ST measures using the individual approach, which revealed a lower efficacy than the combined approach. Few studies attempted to evaluate the STE of two or more measures using an integrated approach at the catchment scale. This review leads to three promising directions of research put into the next three research questions. An integrated sediment trapping approach was found to be a best approach and is subject to the final research question.

***Are the locally dominant indigenous grass species in northwest Ethiopia (Desho, Senbelet, Akirma and Sebez) effective in trapping sediment from agricultural fields? What are the key functional traits, which will play a great role for ST? How much of the inflow sediment trapped by the grass barriers, with what STE?***

The sediment trapping efficacy (STE) of many grass species is well known. For example; Lemon grass (72-92%), Elephant grass (62-84%), Paspalum (65-88%) and Sugarcane (56-82%) in Uganda (Wanyama *et al.*, 2012); Vetiver grass (65%) in Australia (McKergow *et al.*, 2004); Switch grass (92%) (Lee *et al.*, 2000) in the USA; Centipede grass (24-73%) in Japan (Shiono *et al.*, 2007); Black rye (42-69%) in China (Pan *et al.*, 2010) and Vetiver (62%) and Desho (43%) in the lowland part of Ethiopia (Welle *et al.*, 2006). However, still many grass species that could potentially serve as vegetative barriers have not been studied for their STE, including the locally used grass species in the north-western Ethiopian highlands, Desho (*Pennisetum pedicellatum*), Senbelet (*Hyparrhenia rufa*), Sebez (*Pennisetum schimpri*) and Akirma (*Eleusine floccifolia*).

Chapter 4 evaluated the STE of such indigenous grass species and one exotic grass species, Vetiver (*Vetiveria zizanioides*) at 8% slope Teff field based on the key functional traits that influence the STE of the grass species. Desho with the highest tiller number and density, and the second highest in root length showed better STE (76%) than the other grass species, Vetiver (59%), Senbelet (49%), Akirma (36%) and Sebez (20%). The fast lateral spreading growth nature, leading to covering the free space between rows and within rows within a short period of time helps Desho grass to perform best.

The grass barriers trapped large amount of sediment and reduced on-site soil loss between 15 and 53 t $ha^{-1}$ $y^{-1}$. Desho, Vetiver, Senbelet, Akirma and Sebez reduced 53; 42; 34; 26 and 15 t $ha^{-1}$ $y^{-1}$, respectively, compared with the control plot without a grass barrier. This indicates that grass barriers can be used as an effective soil conservation measure in replacing the costly and more maintenance demanding physical structures like trenches and ridges, as also noted by (MOARD, 2005), for fields up to 8% slope. An important advantage of vegetative measures over physical structures is the use of grass as feed. Moreover, Desho and Vetiver grasses are not affected by nor harbour rats unlike the case in physical structures such as stone bunds.

***How much sediment can be trapped by sediment storage dams, with what STE? Are they economically feasible for the small-scale farmers' in Ethiopia?***

Since we found that drainage channels and gullies are main sediment transfer pathways (STPs) sediment storage dams (SSDs) are considered an interesting sediment trapping option which we investigated in Chapter 5. Results show that SSD constructed from stone and gabion trapped considerable amount of sediment and they are found to be important off-site ST measures. On average SSDs trapped about 1,584 t of sediment annually with STE ranging from 67-74%. SSDs also played an important role in disconnecting the STPs, refilling deep gully areas with sediment and reducing the channel gradient. Although SSDs trapped such a large amount of sediment inside temporary drainage channels and gullies, they are not affordable for small scale farmers in Ethiopia due to high construction costs. As an alternative mass mobilization to reduce labour cost, project support to buy gabion and implementing the dams in areas with ample construction materials (for example stones) should be considered to minimize the cost.

***How much sediment is trapped by the existing physical ST measures, with what STE? How much sediment is trapped by natural sediment sinks, with what STE? Are man-made and natural sediment sinks reducing the sediment load to Koga reservoir?***

After three years of intensive data collection and field survey, the sediment trapped behind man-made ST measures such as soil bunds (*Erken*), *fanya Juu* (*Kab*) and micro-trenches, and natural sediment sinks such as a wetland and floodplain were quantified at the Minizr catchment (Chapter 6). Existing man-made and natural sediment sinks played an important role in trapping sediment, with 38% (26,600 t $y^{-1}$) of transported sediment being trapped, while 62% (43,000 t $y^{-1}$) is exported from the catchment and thus enters the Koga reservoir. About 144 km soil bunds and *fanya juu* ridges trapped 7,920 t annually with an average sedimentation rate of 55 kg $m^{-1}$ $y^{-1}$ and a STE of 54%, which was within the range of 12.5 to 88.8 kg $m^{-1}$ $y^{-1}$ (Lecce *et al.*, 2006)). However, our result was much lower compared with Gebremichael *et al.* (2005), which was 119 kg $m^{-1}$ $y^{-1}$, in an area with high soil erosion in their catchment.

The 24 ha wetland located near the outlet of the Minizr catchment trapped 8,715 t of sediment annually at an average sedimentation rate of 36 kg $m^{-2}$ $y^{-1}$ and with a STE of 85%. This result agrees well with the literature. For example, 14-121 kg $m^{-2}$ $y^{-1}$ (Braskerud, 2001) and STEs of 80% (Elder & Goddard, 1996), 71-90% (Sezerino *et al.*, 2012) and 72-88% (Line *et al.*, 2008). The 17 ha floodplain trapped 9,970 t of sediment annually with a STE of 77% and an average sedimentation rate of 59 kg $m^{-2}$ $y^{-1}$. This result is in line with Brunet and Astin (2008), who found sedimentation rates ranging from 0.02-75 kg $m^{-2}$ $y^{-1}$. Substantial differences were observed between the STE of grassed and un-grassed waterways at 75% and 21%, respectively.

***Is it possible to use a landscape model (LAPSUS_D) in the northwest Ethiopian highlands to help with integrated sediment trapping at catchment scale by optimizing the use of ST measures?***

Chapter 7 tried to calibrate and validate the daily based LAPSUS_D model for runoff and sediment yield simulation. We used the three years data collected from 2013-2015 (Chapter 2). Data collected in 2013 was used for calibration and data collected in 2014 and 2015 were used for validation. The daily runoff calibration result was promising, however, the two years validation results were not sufficient. Because of the fact that the model did not give the desired calibration and validation outputs, scenario runs for a more integrated ST approach could not be executed as planned. The planned scenarios were aimed at identifying best sites for the different ST measures and evaluate their integrated role in trapping sediment at catchment scale. But this objective could not be met. Due to time limitation we did not go further to solve the problem and thus further research is recommended.

The most probably reasons of the poor reproduction of the observed data is the quality of the DEM. The resolution of 30 m does not able to represent the small scale variations in the landscape such as the large number of gullies. Furthermore, a large part of the catchment is very flat in terms of topography and therefore small errors in the DEM have a large influence on the representation of the hydrology in the catchment. As a result, water was not routed through the catchment as it is in reality. The model evaluates the rate of sediment transport by calculating the transport capacity of water flowing downslope from one grid cell to another as a function of discharge and slope gradient. Obviously, since the calibration and validation results of the runoff were not good, sediment simulation was not feasible. Thus, further study to further develop this daily based model is recommended.

## 8.3 Scientific and societal contributions

The findings of this study make an important contribution to the scientific community, the society and the final users of the research findings, farmers.

Different studies estimated the sediment loads of Koga reservoir. However, the result showed considerable difference ranging from 48,000 $m^3$ to 714,000 $m^3$ $y^{-1}$ (3.7 to 55 t $ha^{-1}$ $y^{-1}$) which creates uncertainty for SWC practitioners, decision makers and researchers. This study tried to solve this uncertainty collecting field data for three years, conducting intensive field survey focusing on the sub-catchment, Minizr, and finding comparable result, which agreed well with literature.

This thesis assessed the sediment trapping efficacy (STE) of physical and vegetative ST measures at global scale, reviewing more than 90 scientific journal articles, case studies, government reports, conference proceedings and book chapters and making participatory field observations and stakeholders' interviews in the upper part of the Blue Nile basin, Ethiopia. This is an important input to experts, researchers, decision and policy makers to have an understanding on the existing situation at global scale.

Almost all previous studies evaluated the sediment trapping effectiveness of physical ST measures through measuring sediment yield at the outlet of the study catchment and comparing annual differences. This method was unable to provide information of the effectiveness of each individual measure implemented within the catchment rather is shows the collective effectiveness. This thesis evaluated the sediment trapping effectiveness of physical ST measures such as soil bunds and *fanya juu* ridges involving linear measurement in one direction pertaining to length (kg $m^{-1}$ $y^{-1}$); micro-trenches measuring the amount of sediment trapped by a single micro-trench (kg $y^{-1}$). This will help to know the effectiveness as well as the weakness of individual measures for further improvements.

This research is the first to test and scientifically proof the STE of the dominant indigenous grass species (Desho, Senbelet, Akirma and Sebez) in the NW Ethiopian highlands as on-site ST measure giving attention to their key functional traits. As a result best vegetative ST measures have been identified to be used by farmers, which helps them trap sediment within their farmlands and reduce soil loss. This added generic scientific knowledge to researchers working on the influence of grass barriers on ST processes, as well as practitioners dealing with erosion and runoff control on croplands

This study also assessed the STE of sediment storage dams and natural sediment sinks such as a floodplain and wetland (in kg $m^{-2}$ $y^{-1}$) to evaluate their effectiveness in trapping sediment in addition to quantifying the amount of sediment trapped by each measure. This helps to know the STEs of the measures, which were not well known before in the Ethiopia conditions.

Integrated catchment management approach (in the sense of integrating sectors, systems, technologies and resources) was started before decades in Ethiopia. Integrated sediment trapping is part of this approach, which focuses on technological integration. However, it does not reduce catchment sediment yield to a safe level. Therefore, this thesis tried to show the limitations of this approach. The existing approach focuses too much on on-site treatments largely disregarding off-site treatments. To trap sediment within the catchment and reduce sediment yield at the outlet of the catchment, both on- and off-site ST measures should be integrated at catchment scale.

In this study, the amount of sediment entering Koga reservoir, spatial (sub-catchment scale) and temporal (daily and monthly) variation in sediment discharge and the role of sediment transfer pathways density in connecting the landscape and enhancing sediment transport were assessed for the Minizr catchment. All of these will help to plan, design and implement appropriate ST measures within the catchment. This will contribute a vital role for SWC practitioners and decision makers.

### 8.4 Extension and policy issues

Reservoir construction requires a large investment. For example, the Ethiopian government invested more than 405 million Ethiopian Birr (25 ET = 1 €) to construct the Koga dam, which is designed to irrigate about 7,000 ha of land and is expected to benefit about 14,000 farmers living downstream of the reservoir. However, sedimentation is undermining its sustainable use.

Therefore, it is highly advisable to treat the upstream catchment and reduce the sediment load to a safe level. To this end, the government can issue a special policy that supports “Upstream catchment management using an integrated sediment trapping approach before reservoir construction for sustainable reservoir use”. This means “catchment treatment before reservoir construction”. This will help to use sustainably the large number of reservoirs, which are under construction and planned for construction by the Ethiopian government, including the Grand Ethiopia Renaissance Dam, designed to generate 6,000 MW hydro-electric power investing more than 90 Billion Ethiopia Birr.

The Amhara national Regional State, especially the Bureau of Agriculture (BOA), is working hard on SWC throughout the region including the Minizr catchment, following an integrated catchment management approach. Although successes have been reported, overall catchment scale sediment yield reduction is still low. For example, only 38% of the transported sediment was trapped and reduced at Minizr catchment and 62% was leaving the catchment and entering Koga reservoir. This is because the ST approach within the catchment is not enough integrated. Attention was given to on-site treatments largely ignoring the off-site treatments. Therefore, off-site measures should be implemented at the most appropriate spatial locations to further reduce the sediment entering Koga reservoirs (Mekonnen *et al.*, 2014b), which includes: (I) Implementing check dams and sediment storage dams (SSD) inside gullies and temporary drainage channels, because SSDs can trap 3/4 of the incoming sediment with the STE of 67-74 % (Mekonnen *et al.*, 2015b); (II) Identifying a buffer zone around the reservoir and planting grass (or other vegetative measures) to trap the sediment coming from the surrounding farmlands. According to Mekonnen *et al.* (2016b) indigenous grass species can trap up to 76% of the inflowing sediment; (III) Protecting and expanding the already established wetlands around the reservoir because wetlands can trap up to 85% of the inflowing sediment Mekonnen *et al.* (2016a); (IV) Establishing a buffer zone and planting trees along the river to reduce riverbank erosion since vegetation causes flow retardation within the channel and on the riverbanks and enhance sedimentation (Keesstra *et al.*, 2012); and (V) Disconnecting major sediment transfer pathways since they enhance sediment connectivity and transport.

Wetlands help to maintain good water quality in rivers, recharge groundwater, stabilise climatic conditions and control sedimentation in lakes and reservoirs. However, they are at risk. For example, at Minizr catchment, agricultural expansion strongly affected the sparsely existing wetland around the Koga reservoir and along river sides. Part of the wetland area is given to the landless youths to cultivate and produce crops. They are trying to convert the wetland into farmland by draining the wetland and ploughing it. This will totally destroy the wetland and its ecosystem in a short period of time. As an alternative, instead of cultivating the wetland area for crop production, the youths could use the grass growing on the wetland for livestock fattening, as a means of income without affecting the wetland. This is a win-win benefit between nature and human beings. Therefore, awareness creation to policy makers, the surrounding farmers and youth associations should be done to conserve, manage and use the wetland sustainably.

There is a promising start on riverside plantation near the Minizr catchment outlet. This should be strengthened and continued to the upstream ends of both temporary and permanent streams/rivers. Similarly, in the outlet part of the catchment farmers are using cut and carry system and reduced free grazing, which will serve as a lesson for the farmers living in the upper part of the catchment, especially in the Adibera sub-catchment where serious overgrazing was observed. It would be also important to up-scale these practices to other areas in the region.

## 8.5 Challenges and future research recommendations

This study estimated the amount of sediment entering Koga reservoir; provided the spatial (sub-catchment scale) and temporal (daily and monthly) variation of sediment load, assessed the role of sediment transfer pathways density on landscape connectivity and sediment yield and evaluated the sediment trapping efficacy (STE) of existing man-made SWC structures and natural sediment sinks. All of these help to trap sediment within the catchment and reduce sediment loads to Koga reservoir. However, a number of issues remain to be assessed in greater detail, which help to strengthen the findings.

- In this thesis, the STE of the locally dominant grass species was evaluated under 8% slope farmland, at 1.5 m strip width and under sheet erosion conditions, hence further study is recommended to evaluate their efficacy at higher slopes (> 8%), under concentrated flow conditions as well as at different strip widths.
- In this study, only suspended sediment was measured to estimate the sediment load of Koga reservoir. Hence, further study is recommended to estimate the bed load and know its contribution to the sediment load of Koga reservoir.
- In this thesis, the total suspended sediment load was measured at the outlet of the Minizr catchment and its sub-catchments. However, the sediment load share of agricultural lands, gullies, river banks and roads is not evaluated separately, which help to know their specific influence for targeted treatments, thus further study is recommended.
- Spatial variation in sediment production was assessed at sub-catchment scale, however to know specific locations of sediment source areas, cell-based studies are recommended at higher spatial resolution.
- The sediment load of Koga reservoir from its total runoff contributing catchment was estimated from the sediment yield of Minizr catchment. Therefore, either large scale studies of the total catchment or up-scaling from small catchments is recommended as it was believed to provide better estimates.
- A daily resolution LAPSUS_D model was run to simulate runoff and sediment yield and to identify best sites for the different ST measures and evaluate their integrated role in trapping sediment at catchment scale at Minizr catchment. However it does not provide promising results yet. Therefore, further study is highly recommended to further develop this model, run scenarios for optimizing the spatial integration of ST measures.

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# Summary

# Summary

Rainfed agriculture can increase agricultural production and improve food self-sufficiency when supplemented with irrigated agriculture. The Ethiopian government is following this strategy and constructed many reservoirs and still a large number of reservoirs are under construction. Koga reservoir is one of the largest reservoirs in northwest Ethiopia and is a key project for the Ethiopian government. However, rapid water storage loss due to sedimentation is becoming an important factor undermining its sustainable use. This is because of serious soil erosion both on-site and off-site, and lack of an integrated sediment trapping (ST) approach within the water contributing catchments.

To tackle the problem, the Ethiopian government is working hard following a catchment based ST approach. Various soil and water conservation measures have been implemented at large spatial scales in the Amhara region by the Bureau of Agriculture and international and national non-governmental organizations. For instance, over 144 km of soil/stone bunds and *fanya juu* ridges, and >576 micro-trenches were constructed within the 20 $km^2$ Minizr catchment in NW Ethiopia. In addition, existing natural sediment sinks such as wetlands and floodplains occur over large areas, and are supplementing man-made structures in trapping sediment.

In spite of massive investments in ST measures, catchment sediment yield at the outlet of Minizr catchment is still large. The sediment trapping efficacy (STE), which is a means to assess the effectiveness of ST measures, is not well known for most of the ST measures. Therefore, there is a need to assess the functioning and effectiveness of the existing ST measures and to design a more effective approach to reduce sediment yield at the outlets of catchments and manage reservoir sedimentation to a safe level.

**Chapter 2** attempts to quantify the amount of sediment entering Koga reservoir, to assess spatial and temporal variation in sediment production and to identify sediment transfer pathways (STPs), which enhance sediment connectivity and facilitate sediment transport. Insight herein could help to design improved ST strategies and reduce the siltation problem of the reservoir. From Minizr catchment annually 43,000 t of sediment is entering Koga reservoir with a sediment yield of 21.5 t $ha^{-1}$ $y^{-1}$. Using this sediment yield, the annual sediment entering Koga reservoir from the whole runoff contributing catchment was found to be 350,000 t (278,000 $m^3$). This reduces the uncertainty of sediment loads to Koga reservoir estimated by different studies showing large variations that ranged from 48,000 - 700,000 $m^3$ (3 - 55 t $ha^{-1}$ $y^{-1}$). Out of the total sediment entering Koga reservoir, 63% was transported in July and August. This was due to high gully and river bank erosions in July and August. STPs density shows a good relation ($R^2$=0.88) with catchment sediment production.

**Chapter 3** investigates what is already known about sediment trapping measures. It presents an overview on the sediment trapping efficacy (STE) of physical and vegetative sediment trapping (ST) measures at global scale, reviewing more than 90 scientific journal articles, case studies, government reports, conference proceedings and book chapters. In addition, there are participatory field

observations and stakeholders' interviews in the upper part of the Blue Nile basin, Ethiopia. Three ST approaches individual, combined and integrated were identified. Of these, the integrated approach at the catchment scale, is believed to be the most effective in helping to increase the STE of ST measures and thereby reducing sediment load at the outlet of the catchment.

This review leads to three promising directions of research. Since we can expect effective sediment trapping using grass strips we evaluated a number of species in a field trial described in Chapter 4. Since we found that drainage channels, gullies and footpaths are main sediment transfer pathways, sediment dams are also considered an interesting option which we investigated in Chapter 5. Finally it is worthwhile to know the trapping efficiency of existing man-made soil and water conservation structures in the catchment such as soil bunds, *fanya juu* and micro-trenches (Chapter 6). The same holds for the existing natural sediment sinks like the floodplain, the wetland and different waterways.

**Chapter 4** evaluated the STE of four locally dominant indigenous grass species, Desho (*Pennisetum pedicellatum*), Senbelet (*Hyparrhenia rufa*), Sebez (*Pennisetum schimpri*) and Akirma (*Eleusine floccifolia*) and one exotic but well adapted and locally used grass species, Vetiver (*Vetiveria zizanioides*) at Debre Mewi catchment, in northwest Ethiopia, based on the key functional traits that influence their STE. These grass species reduced soil loss up to 53 t $ha^{-1}$ $y^{-1}$ with the STE ranging from 20-76%. STE showed a good correlation with key functional traits such as tiller density, number of tillers and root length. Desho with the highest tiller number and density, highest root length (depth) and fast lateral spreading growth pattern showed better STE (76%) compared with other grass species. This indicates that such grass barriers can be used as a soil conservation measure replacing the more costly and more maintenance demanding physical structures like trenches and ridges up to 8% slope, with an additional advantage of livestock feed as a co-benefit.

**Chapter 5** examines the functioning and effectiveness of sediment storage dams (SSDs) as an off-site ST measure within gullies and drainage channels. The amount of sediment trapped behind the structures was estimated and their STEs calculated. SSDs constructed from gabion and stone trapped an average of 1,584 t $y^{-1}$ of the inflowing sediment with a STE of 74% and 67%, respectively. SSDs reduce sediment connectivity through disconnecting sediment transfer pathways inside drainage channels and gullies. SSDs also reduce channel slope gradients in addition to re-filling gullies. In general, although SSDs might be costly for small scale farmers and have a relatively short life span depending on their size, they are promising off-site structural measures to trap significant amounts of sediment at the outlets of sub-catchments and subsequently reducing sediment movement to downstream water bodies or reservoirs.

**Chapter 6** presents the sediment disconnecting role of man-made and natural sediment sinks and enables to quantify the trapped sediment behind man-made structures and within natural sediment sinks. It also enables to know the STE of man-made (Soil bund and *fanya Juu*) and natural sediment sinks (a wetland, a floodplain and grassed waterways). Results reveal that soil bunds and *fanya juu* ridges, a floodplain and a wetland trapped sediment at the rate of 55 kg $m^{-1}$ $y^{-1}$; 59 kg $m^{-2}$ $y^{-1}$ and 36 kg $m^{-2}$ $y^{-1}$ with STEs of 54%, 77% and 85%, respectively. A micro-trench on average trapped 23 kg $y^{-1}$ of sediment annually and substantial differences were observed between the STE of grassed and un-grassed waterways at 75% and 21%, respectively. Over 20 years old, *fanya juu* ridges have reduced the average slope gradient by 2.7% forming lines of high sediment ridges unlike the soil bunds, in which the trapped sediment is buried inside the ditch instead of forming lines of sediment ridges, which reduces its role in changing the gradient of the slope.

Although existing man-made and natural sediment sinks trapped 38% (26,600 t) of the transported sediment, 62% (43,000 t) is still leaving the catchment and entering Koga reservoir (Chapter 2). Lack of an integrated ST approach, in which emphasis is given to both on-site sediment sources and off-site sediment sources, is an important cause for such a large sediment export from the catchment.

**Chapter 7** tries to identify the best approach for implementing a combination of sediment trapping measures within the Minizr catchment. We tried to adapt an existing spatial model (LAPSUS_D model) for runoff and sediment prediction. Unfortunately, the calibration and validation results were not promising. Our objective to evaluate the integrated ST role of sediment trapping measures at catchment scale was not put into action. Therefore, further study is recommended to adapt a daily resolution model and run scenarios for a more integrated approach.

The final chapter is a **synthesis** of previous chapters. It not only summarizes the main results but also discusses the scientific value of the thesis and its limitations. Furthermore, attention is given to recommendations for policy, extension and further research.

Netherlands Research School for the
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# D I P L O M A

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KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

The SENSE Research School declares that **Mr Mulatie Mekonnen Getahun** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 44.6 EC, including the following activities:

## SENSE PhD Courses

- Environmental research in context (2014)
- Research in context activity: 'Organising a field visit with farmers participating on the subject of sediment trapping efficacy of indigenous grass species, Debre Mewi watershed, NW Ethiopia' (2014)

## Other PhD and Advanced MSc Courses

- Information literacy including EndNote introduction, Wageningen University (2012)
- Techniques for writing and presenting a scientific paper, Wageningen University (2013)
- Erosion processes and modelling, Wageningen University (2013)
- Project and time management, Wageningen University (2014)
- Training course on soil mapping, classification and assessment for soil and environmental scientists, Hands-on Global Soil Information Facilities (GSIF), organised by ISRIC - World Soil Information, Wageningen (2016)

## Management and Didactic Skills Training

- Supervising MSc student with thesis entitled 'Low-land gully formation in the Amhara region, Ethiopia' (2014)

## Oral Presentations

- *Sediment storage dam: A structural gully erosion control and sediment trapping measure, NW Ethiopia.* European Geoscience Union (EGU) General Assembly, 27 April-2 May 2014, Vienna, Austria
- *GIS and remote sensing based forest resource assessment, quantification and mapping in Amhara region, Ethiopia.* Ethiopian Forestry Society (EFS) 3rd Annual Conference, 22-24 December 2014, Bahir Dar, Ethiopia
- *Evaluating the sediment trapping efficacy of indigenous grass species, NW Ethiopian highlands.* TropiLakes 2015 Conference: Tropical lakes in a changing environment, 23-29 September 2015, Bahir Dar, Ethiopia

SENSE Coordinator PhD Education

Dr. ing. Monique Gulickx

# Curriculum vitae and author's publications

Mulatie Mekonnen Getahun was born on September 2, 1977 in Gojam, Ethiopia. He finished his secondary education from Adet, in 1990. Mulatie has obtained his Diploma in Agricultural Engineering from Awassa College of Agriculture in 1992 and his Bachelor Degree in Geography and Pedagogical Science from Bahir Dar University in 2004. He started the MSc program at Bahir Dar university in collaboration with TFH University of Applied Science, Germany and specialized in Geo-Information Science (GIS) from September 2007 to June 2009. Mulatie has been involved both in research and development programs: He was a regional watershed management and development expert in MERET (Managing Environmental Resources to Enable Transition) project; and GIS specialist in the Amhara National Regional State Bureau of Agriculture; Research Technical Assistant (RTA) in natural resource conservation and management research department at Adet Agricultural research center; and Soil and Water Conservation expert in the Ministry Natural Resources Conservation and Environmental Protection. He also served as a focal person for Amhara Micro-enterprise development, Agricultural Research, Extension and Watershed Management (AMAREW) Project in the Bureau of Agriculture.

Mulatie followed short term trainings on: GIS based database management; application of GIS and Remote Sensing for integrated water resource management (IWRM); Remote Sensing and Image Analysis; land rehabilitation, productivity improvement and income generating technologies; Local Level Participatory Planning Approach (LLPPA) for natural resource conservation at watershed scale; Water harvesting technologies and spring development techniques; community based participatory watershed development planning for productive safety net.

Mulatie provided many skill oriented trainings on: (i) Applications of GIS, topographic map, DEM, Satellite Imagery and GPS for watershed delineation, natural resource mapping, integrated watershed conservation and management planning to regional, zonal and district level soil and water conservation professionals working in Sustainable Water harvesting and Institutional Strengthening in Amhara (SWHISA) project; Sustainable Land Management (SLM) project; Productive Safety Net Program (PSNP) and the Bureau of Agriculture (BoA).

In September 2012, Mulatie started his Sandwich PhD at Wageningen University, Soil Physics and Land management (SLM) Group with NUFFIC sponsorship and finalized in August 2016. His PhD research focused on 'Sustaining reservoir use through sediment trapping in NW Ethiopia'. During this period, he has published a number of peer reviewed articles and made a number of oral and poster presentations in national and international meetings.

Mulatie Mekonnen married Ethiopia Abesha in 1993 and have two daughters (Nardos Mulatie, and Mahilet Mulatie) and one son (Kaleab Mulatie). He would like to continue in research on soil conservation and watershed management, sediment dynamics, land-scape connectivity, GIS and Remote Sensing.

Email: mulatiemekonneng@gmail.com

## Publications

*Peer reviewed Journal papers*

**Mekonnen**, M., Keesstra, S.D., Ritsema, C.J., Stroosnijder, L., Baartman, J.E.M. 2016. Sediment trapping with indigenous grass species showing differences in plant traits in northwest Ethiopia. Accepted, *CATENA Journal*.

**Mekonnen**, M., Keesstra, S.D., Baartman, J.E.M., Stroosnijder, L., Maroulis, J. 2016. Reducing sediment connectivity through man-made and natural sediment sinks in Minizr catchment, nothwest Ethiopia. *Accepted, Land Degrad Dev.Journal.*

**Mekonnen, M.**, Keesstra, S.D., Baartman, J.E.M., Ritsema, C.J., Melesse, A.M. 2015. Evaluating sediment storage dams: Structural off-site sediment trapping measures in northwest Ethiopia. Cuadernos de Investigacion Geografica 41: 7-22. DOI: 10.18172/cig.2643

**Mekonnen, M.**, Keesstra, S.D., Stroosnijder, L., Baartman, J.E.M., Maroulis, J. 2014. Soil conservation through sediment trapping: a review. Land Degradation and Development 26, 544-556. DOI: 10.1002/ldr.2308

*Book Chapters*

**Mekonnen,** M., Sewunet,T., Gebeyeh, M., Azene, B., Melesse, A.M. 2015. GIS and Remote Sensing-Based Forest Resource Assessment, Quantification and Mapping in Amhara Region, Ethiopia. Melesse A.M. and Abtew W. (Eds.), *Landscape Dynamics, Soil and Hydrological Processes in Varied Climates, Springer Geography. Springer International Publishing, Switzerland, 9-29*.

**Mekonnen**, M., Melesse, A.M., Kesstra, S.D. 2015. Spatial Runoff Estimation and Mapping of Potential Water Harvesting Sites: A GIS and Remote Sensing perspective, northwest Ethiopia. Melesse A.M. and Abtew W. (Eds.), *Landscape Dynamics, Soil and Hydrological Processes in Varied Climates, Springer Geography. Springer International Publishing, Switzerland 565-584.*

Engdayehu, G., Fisseha, G., **Mekonnen, M.,** Melesse, A.M. 2015. Evaluating Technical Standards of Physical Soil and water Conservation practices and their Role in Soil Loss Reduction: The case of Debre Mewi Watershed, north-west Ethiopia. *Melesse A.M. and Abtew W. (Eds.), Landscape Dynamics, Soil and Hydrological Processes in Varied Climates, Springer Geography. Springer International Publishing, Switzerland* 789-818.

**Mekonnen, M.**, Melesse, A.M. 2011. Soil Erosion Mapping and Hotspot area identification using GIS and Remote Sensing in Northwest Ethiopian Highlands, near Lake Tana. in: Melesse AM. editor. Nile River Basin hydrology climate & water use. Switzerland Springer: 207-224.

*Conference presentations /posters*

**Mekonnen**, M., Keesstra, S.D., Ritsema, C.J., Stroosnijder, L., Baartman, J.E.M. 2016. Evaluating indigenous grass species as on-site sediment trapping measures, northwest Ethiopian highlands. European Geoscience Union General Assembly 2016, April 17-22, 2016, Austria Vienna.

**Mekonnen,** M., Keesstra, S.D., Ritsema, C.J., Stroosnijder, L., Baartman, J.E.M. 2016. Assessing the integrated sediment trapping role of man-made and natural sediment sinks, Minizr catchment, Ethiopia. European Geoscience Union General Assembly 2016, April 17-22, 2016, Austria Vienna.

**Mekonnen**, M., Keesstra, S.D., Ritsema, C.J., Stroosnijder, L., Baartman, J.E.M. 2015. Evaluating the sediment trapping efficacy of indigenous grass species, north-west Ethiopian highlands. International Conference on TROPILAKES2015, Tropical lakes in a changing environment: Water, Land, Biology, Climate and Humans, Sept 23-29, 2015, Bahir Dar, Ethiopia.

**Mekonnen**, M., Keesstra, S.D., Baartman, J.E.M., Ritsema, C.J. 2014. Sediment Storage Dam-A structural gully erosion control and sediment trapping measure NW Ethiopia. European Geoscience Union General Assembly 2014, 27 April-02 May 2014, Austria, Vienna.

**Mekonnen**, m., Keesstra, S.D., Baartman, J.E.M., Stroosnijder, L., Maroulis, J. 2014. Soil Conservation Through Sediment Trapping: A review. European Geoscience Union General Assembly 2014, 27 April-02 May 2014, Austria Vienna.

**Mekonnen**, M., Sewunet, T., Gebeyehu, M., Azene, B., Melesse, A.M. 2014. GIS and Remote Sensing Based Forest Resource Assessment, Quantification and Mapping in Amhara Region, Ethiopia. Ethiopian Forestry Society 3$^{rd}$ National Conference. December 22-24, 2014, Bahir Dar, Ethiopia.

**Mekonnen, M.,** Melesse, A.M. 2010. Spatial Runoff and Mapping of Potential Water Harvesting Areas: A GIS and Remote Sensing Perspective, Debre Mewi, Ethiopia. International Conference of Water Resources in Ethiopia. 12-16 January, 2010, Addis Ababa, Ethiopia.

*Master Thesis*

**Mekonnen, M.** Soil Erosion Assessment, Runoff Estimation and Water Harvesting Site Selection using GIS and Remote Sensing at Debre Mewi Watershed, Amhara Region, Ethiopia. Master thesis. Bahir Dar University, Bahir Dar, Ethiopia. p96.

*Submitted paper*

**Mekonnen**, M., Keesstra, S.D., Baartman, J.E.M., Stroosnijder, L., Masselink, R.J.H. 2016. Spatial and temporal variations of sediment entering Koga reservoir, NW Ethiopia. Earth Surface Processes and Landforms.