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# Soil erosion modeling and soil quality evaluation for catchment management strategies in northern Ethiopia

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## ABSTRACT

About 85% of the Ethiopian population is engaged primarily in agriculture. However, changing environmental factors have led to soil quality (SQ) degradation that poses a critical risk for food security. But, despite some alarming figures, there is no consistent information on the rate and extent of soil degradation in the country. This is due to the fact that the results of research on SQ degradation are more generalized to the country with its different environments and also based on empirical models or on runoff plot studies. It is problematic to extrapolate results from such case studies to other areas, and the resulting reports are thus inadequate to guide policy action on a large scale. Appropriate approaches that address such research gaps are thus needed for the country.

This study employs a participatory survey and scientific soil measurements, geo-statistics and erosion modeling to concurrently evaluate SQ degradation that can facilitate development of appropriate management strategies for the Mai-Negus catchment conditions in the northern Ethiopian highlands. A participatory SQ survey and group discussions with local farmers were conducted to identify SQ diagnosis indicators as well as the severity and determinants of SQ degradation. Soil samples were collected for analysis from the different SQ categories, land-use and soil management systems and erosion-status sites identified in the catchment. Data were subjected to statistical analysis. A soil erosion model (Soil and Water Assessment Tool; SWAT) interfaced in a GIS environment was evaluated and then applied to identify and prioritize erosion-hotspot sub-catchments. Finally, potential management strategies (scenarios) were simulated targeting prioritized areas to identify scenarios that can better reduce soil degradation caused by erosion.

The results of this study show that farmers used indicators such as crop yield, soil depth, soil color, soil erosion risk, sedimentation, for categorizing the catchment soils into high, medium and low SQ status (categories). The scientifically measured soil attributes were significantly different ($P \leq 0.05$) among these SQ categories. Using the soil attributes (cation exchange capacity, porosity, sand, total phosphorus, and Ca:Mg) retained in four component factors that explain about 88% of the SQ variability, discriminant analysis correctly classified the soils in the different SQ categories. Such SQ variability shows that farmer evaluation of SQ agrees well with the measured soil attributes. The maps of the interpolated soil properties show a well-defined trend of higher contents of fine soil particles and soil nutrients in the toe-slope and foot-slope areas in the catchment and those with better vegetation cover and soil management practices. The results of the soil erosion model show that > 45% of the catchment area has experienced soil losses through erosion of over 30 t $ha^{-1}$ $y^{-1}$, which is higher than the soil loss tolerance for Ethiopia (18 t $ha^{-1}$ $y^{-1}$). About 91% of the catchment experienced a soil erosion rate over 15 t $ha^{-1}$ $y^{-1}$, which is higher than the average African soil loss (10 t $ha^{-1}$ $y^{-1}$).

Land management scenarios that involve land-use redesign, terracing, grassed waterways and gully stabilization structures can reduce runoff, sediment yield and nutrient losses by up to 75% at catchment level and up to 90% in the hotspot sub-catchments (soil loss over 18 t $ha^{-1}$ $y^{-1}$) as compared to the baseline scenario. Generally, the results of this study confirm that the use of farmers` knowledge to evaluate SQ status and prioritize areas for implementing management intervention is useful as it is rapid, less expensive, has high reproducibility and is reasonably accurate as compared to scientific soil measurements and erosion modeling. This can thus support informed decision-making about SQ degradation in areas where professional experts and resources are limited, and where extrapolation of measured soil data is difficult. However, further research on catchments with contrasting environment is necessary to account for the heterogeneity of farmer knowledge of SQ degradation on a regional and national scale.

# Modellierung von Bodenerosion und Bewertung von Bodenqualität für Managementstrategien in NordÄthiopien

## KURZFASSUNG

Etwa 85% der äthiopischen Bevölkerung ist primär in der Landwirtschaft beschäftigt. Veränderte Umweltfaktoren haben jedoch zu einer Verschechterung der Bodenqualität (soil quality; SQ) geführt, die große Risiken für die Nahrungssicherheit darstellt. Aber trotz alarmierenden Zahlen gibt es kaum konsistente Information über Geschwindigkeit und Ausmaß der Bodendegradation im Lande. Dies liegt daran, dass die Forschungsergebnisse für das gesamte Land mit seinen verschiedenen Umweltbereichen generalisiert werden und auf empirischen Modellen oder Studien über Abflussflächen basieren. Es ist problematisch, die Ergebnisse solcher Fallstudien auf andere Gebiete zu übertragen; die Berichte sind daher als Grundlage für entsprechende Maßnahmen im großen Maßstab ungeeignet. Geeignete Ansätze, die solche Forschungslücken schließen könnten, sind daher notwendig.

In dieser Studie wurden partizipative Erhebung, wissenschaftliche Bodenuntersuchungen, Geostatistik, und Erosionsmodellierung eingesetzt, um die SQ-Degradation zu bewerten und damit die Entwicklung sinnvoller Managementstrategien für die Bedingungen im Mai-Negus Wassereinzugsgebiet im nördlichen Hochland Äthiopiens zu erleichtern. Eine partizipative SQ-Erhebung und Gruppendiskussionen mit örtlichen Farmern wurden durchgeführt, um Indikatoren für eine SQ-Diagnose sowie Ausmaß und Bestimmungsgrößen der SQ-Degradation zu bestimmen. Im Einzugsgebiet wurden zur Analyse Bodenproben aus den verschiedenen SQ-Kategorien, Landnutzung- bzw. Bodenbewirtschaftungssysteme und Bereichen mit unterschiedlichem Erosionsstatus genommen. Die Daten wurden einer statistischen Analyse unterzogen. Ein Boden-Erosionsmodell (Boden und Wasser Bewertungsinstrument; SWAT) innerhalb einer GIS-Umgebung wurde bewertet und anschließend eingesetzt, um die besonders stark von Erosion betroffenen Bereiche (hotspots) zu ermitteln und priorisieren. Schließlich wurden potentielle Managementstrategien (Szenarien) zielgerichtet auf die priorisierten Bereiche simuliert, um Szenarien zu ermitteln, die am besten erosionsbedingte Bodendegradation reduzieren können.

Die Ergebnisse dieser Studie zeigen, dass die Farmer Ertrag, Bodentiefe, Bodenfarbe, Erosionsrisiko und Bodenablagerungen als Indikatoren verwendeten, um die Böden in die Kategorien hohe, mittlere bzw. niedrige SQ einzuteilen. Die wissenschaftlich gemessenen Bodenattribute waren signifikant unterschiedlich ($P \leq 0.05$) zwischen diesen SQ-Kategorien. Die Bodenattribute (Kationenaustauschkapazität, Durchlässigkeit, Sandgehalt, Gesamtphosphor und Ca:Mg), die in vier Komponentenfaktoren verblieben, die circa 88% der SQ-Variabilität erklärten, wurden in der Diskriminanzanalyse verwendet und klassifizierten die Böden korrekt in die verschiedenen SQ-Kategorien. Eine solche SQ-Variabilität zeigt, dass die SQ-Bewertung der Farmer mit den gemessenen Bodenattributen gut übereinstimmt. Die Bodenkarten weisen einen klaren Trend mit feinkörnigeren Böden in den Hangfußbereichen sowie in den Bereichen mit höheren Vegetationsbedeckungsgraden und mit besseren Bewirtschaftungsmethoden auf. Die Ergebnisse des Erosionsmodels zeigen, dass > 45% des Gebiets erosionsbedingte Bodenverluste von über 30 t $ha^{-1}$ $y^{-1}$ erfahren hat, ein Wert höher als die Bodenverlusttoleranz für Äthiopien (18 t $ha^{-1}$ $y^{-1}$). Ungefähr 91% des Gebietes leidet unter Bodenverlusten von über 15 t $ha^{-1}$ $y^{-1}$, höher als der afrikanische Durchschnitt von 10 t $ha^{-1}$ $y^{-1}$.

Managementszenarien mit einer Neuausrichtung der Landnutzung sowie Terrassen, mit Gras bewachsenen Wasserwege sowie Strukturen zur Stabilisierung von Erosionsrinnen können Abfluss, Bodenablagerungen und Nährstoffverluste um bis zu 75% im gesamte Einzugsgebiet verringern und bis zu 90% in den hotspot Bereichen (Bodenverlusts über 18 t $ha^{-1}$ $y^{-1}$) verglichen mit dem Grundszenario. Die Ergebnisse dieser Studie bestätigen, dass der

Einsatz von Farmerwissen zur Bewertung der SQ und zur priorisieren von Bereichen für die Implementierung von Managementmaßnahmen von großem Nutzen sein kann, da die Methode schnell, weniger teuer, leicht reproduzierbar und verhältnismäßig genau ist verglichen mit Bodenanalysen und Erosionsmodellierung. Diese Methode kann daher Entscheidungen in Bezug auf SQ-Degradation in Gebieten unterstützen wo Experten und Ressourcen beschränkt sind und wo die Extrapolation von Bodendaten schwierig ist. Weitere Untersuchungen über Wassereinzugsgebiete mit unterschiedlichen Umweltbedingungen sind auf regionaler und nationaler Ebene notwendig, um die Heterogenität des Farmerwissens über SQ-Degradation zu berücksichtigen.

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# 1 INTRODUCTION

## 1.1 General

Agriculture is the mainstay of Ethiopia economy, which supports more than 85% of the population. This sector directly or indirectly forms an important component of the livelihoods of more than 70 million people (FDREPCC 2008). However, changing environmental factors have led to soil quality (SQ) degradation, which poses a critical risk of failure in agricultural productivity and food security (Bekele and Holden 1999; Krowntree and Fox 2008); on average, 1-3 million Ethiopians face the risk of food insecurity each year (USAID 2003). Soil degradation due to erosion and soil nutrients losses has become the most important problem constraining food security and environmental services (Sonneveld and Keyzer 2003). In addition, sedimentation reduces the capacity of reservoirs and drainage ditches and blocks irrigation canals, which is threatening irrigated crop production in the Ethiopian highlands (Oldeman 1994; Tamene 2005). Development of management strategies that effectively reduce degradation is thus fundamental to ensure food security and improve livelihoods.

Soil degradation in Ethiopa can be seen as a direct result of the historical development of agriculture and human settlement in the highlands because the highlands are the oldest settlement areas due to the favorable climatic conditions and fertile soil there (Huffnagel 1961). The high dependence on ´resource-poor´ agriculture characterized by uncertain rainfall, poor management and steep terrains, has resulted in high rates of deforestation and expansion of cultivation into steep fragile and marginal lands that aggravate SQ degradation due to soil erosion and soil nutrient depletion (Graaff 1993; Sonneveld and Keyzer 2003; Moges et al. 2007).

Severe soil degradation can be observed in about 50% of the Ethiopian highlands, whereas from the remaining areas about 54% are highly vulnerable to erosion (Kebede et al. 1996). A decline in land productivity due to erosion at the rate of 2.2% per year has also reported by FAO (1986). The problem of degradation is particularly escalating in the highlands, which account for ~45% of the country’s total area with its more than 88% of the human and 77% of the livestock population (McCann 1995). A severe soil degradation pressure is found in the northern Ethiopian highlands (Hakkeling 1989; Sonneveld 2003), and the effect is especially severe in the

Tigray region (Tamene 2005). A report by El-Swaify and Hurni (1996) also shows that the Ethiopian highlands, particularly the north, constitutes part of the most degraded lands in Africa.

Regardless of the great deal of efforts undertaken to reduce soil degradation in Ethiopia since the 1970s, soil erosion by water is recognized to be a severe threat to the national economy, as soil losses are estimated to amount to 1493 million t $y^{-1}$, of which 42 t $ha^{-1}$ $y^{-1}$ come from cultivated fields (Hurni 1990; 1993; Sutcliffe 1993). This is greater than the tolerable soil loss[1] (18 t $ha^{-1}$ $y^{-1}$) as well as the annual rate of soil formation (6 t $ha^{-1}$ $y^{-1}$) in the country (Hurni 1983; 1985). Bojo and Cassells (1995) reported an estimation of immediate gross financial losses due to degradation about USD 106 million per year, which was about 3-7% of the country's gross domestic production at that time. However, such studies do not consider the sediment delivery ratio, i.e., the estimation of the sediment delivered to the downstream area of interest. In addition, there is little research on a large scale in Ethiopia on soil erosion, which changes the physical, chemical and biological properties of a soil and ultimately reduces SQ and crop yields (Lal 1995). Reports show (e.g., Stoorvogel and Smaling 1990; UNDP 2002) that Ethiopia had among the highest rates of soil nutrient depletion for about 60 kg $ha^{-1}$ (30 kg $ha^{-1}$ nitrogen (N) and 15-20 kg $ha^{-1}$ phosphorous (P)) in Sub-Saharan Africa. However, there is limited understanding on the spatial variability of soil losses and other SQ indicators due to erosion at catchment scale in northern Ethiopia.

Many of the areas of greatest soil degradation concern in Ethiopia's highlands are located in the Tigray region (Hakkeling 1989; Hagos et al. 1999; Tamene 2005). Soil is being degraded on a large scale with respect to its rate and geographical extent due to natural and human factors (e.g., Valentin 1998; Tamene 2005). Previous studies in the region indicate a rate of soil erosion ranging from 7 t $ha^{-1}$ $y^{-1}$ (Nyssen 2001) to more than 24 t $ha^{-1}$ $y^{-1}$ (Tamene 2005) and 80 t $ha^{-1}$ $y^{-1}$ (Tekeste and Paul 1989). Erosion rates at 130 t $ha^{-1}$ $y^{-1}$ for cropland and a 35 t $ha^{-1}$ $y^{-1}$ average of all land-use types in the highlands of Ethiopia are also estimated (FAO 1986). Though the above figures highlight the significance of soil degradation, the discrepancies in the results of the studies are mainly due to differences in the methods employed and the scale of analysis.

[1]Tolerable soil loss indicates that the maximum rate of soil erosion that can occur and still allow crop productivity to be sustained economically (Renard et al. 1997; Shi et al. 2004).

Discrepancies in the rate of soil nutrient losses associated to sediment and runoff are also reported for Tigray, northern Ethiopia (e.g., Haregeweyn et al. 2006; Grimay et al. 2009). These indicate that area-specific research using a suitable methodology is needed for appropriate land management planning for the catchments in the region.

Predominantly, previous studies that illustrate SQ degradation are more generalized to the country with its different environmental and socio-economic settings, as the results are based on either qualitative or empirical models like USLE[2] or runoff plot studies (Hurni 1985; 1993; Nyssen 2001). Such approaches have limitations with respect to interpolation to an entire catchment or other similar areas. Past studies in the region also do not address well the SQ degradation aspect based on local farmer knowledge, scientific measurements and spatial variability of soil properties at catchment scale. In fact, information on physical soil degradation as conventionally reported by scientists as rates of soil erosion, extent of areas with particular degradation processes, tons of soil lost, etc., are not adequate to guide for policy action (UN-ESCWA 2007). It is difficult therefore to develop appropriate management strategies based on the previous research results to combat the existing SQ degradation processes using the limited resources at hand. Thus, the assessment of soil degradation must go beyond estimating soil erosion using simple erosion model or runoff plot studies, and this also should be preceded by SQ evaluation.

Despite the seriousness of soil degradation problem and its negative consequences on SQ and food security for individual households and the region at large, little is known about the application of process-based models that support decision-making at catchment scale. Past studies that show rates and hotspot areas of soil degradation through field SQ assessments and soil erosion modeling are also limited at the catchment scale in northern Ethiopia. In this study, local farmers´ knowledge, scientific measurements and soil erosion modeling are thus integrated to evaluate SQ status and spatial variability to identify critical areas of soil degradation and finally to suggest possible management strategies that can help to reduce the observed problem.

The results of this study could be useful for planners and decision-makers to

[2] In the 1970s, the Universal Soil Loss Equation (USLE) was developed to estimate soil erosion rates in temperate agriculture at small field (plots) (Wischmeier and Smith 1978). This model has been adapted for research and development actions in the tropical conditions. It is also widely applied at the catchment and even at national scales to estimate erosion, regardless of the criticism that it is often wrongly applied.

guide efficient land management strategies that reduce SQ degradation. As this study was conducted in a dryland region, the approaches and results could contribute to decision-making in other tropical environments where degradation and the associated problems remain a crucial concern. This study could also contribute scientific information to the scientific community for the development of alternative ways of assessment of the problem.

## 1.2 Main objectives

The main objectives of the study are to:

- Evaluate soil quality (SQ) based on farmers knowledge and using laboratory measurements as potential indicators of soil degradation for sustainable development decision-making;
- Assess variability of catchment-scale spatial soil properties (SQ indicators) and the implications for site-specific soil management;
- Evaluate and apply the Soil and Water Assessment Tool (SWAT) model to identify and prioritize soil degradation hotspots based on estimated runoff, sediment yield and soil nutrient losses and suggest suitable management options;
- Evaluate the effectiveness of alternative management strategies (scenarios) of land-use and cover redesign and conservation measures in reducing the existing soil degradation problem using the SWAT model in a GIS environment.

## 1.3 Thesis outline

The thesis is organized into nine chapters. Chapter 1 introduces the research relevance, problem and major objectives. Chapter 2 reviews the state-of-the-art on soil quality, soil degradation, and erosion models. Chapter 3 presents about the study area and general methodology employed. Chapter 4 deals with participatory SQ assessment and Chapter 5 evaluates the SQ identified by farmers using scientific soil measurements. Chapter 6 examines the catchment-scale spatial variability of selected SQ indicators. Chapter 7 evaluates and applies the SWAT model. Chapter 8 presents the simulation of alternative management strategies that reduce the effect of erosion. Finally, Chapter 9 summarizes the key findings of the research, concludes and presents policy and research implications for future research and development attention.

# 2 STATE OF THE ART

## 2.1 Soil quality concepts and definitions

Soil quality (SQ) is a holistic concept, which recognizes soil as a system related to management and ecosystem dynamics and diversification using soil attributes (Swift 1999; Karlen et al. 2001; Sanchez et al. 2003). These authors added that as a concept, it differs from conventional approaches that focus exclusively on production functions of soil. Other studies reported that the SQ concept cannot be viewed separately, but must be integrated with the land-use and other management systems (e.g., Karlen et al. 1998; Jijo 2005). Because of such conepts of soils in the farming system, a quantitative assessment of SQ is needed to determine the sustainability of land management systems related to agricultural production and practices, and to assist farmers, and scientists in the formulation of suitable strategies and resources evaluation systems (Mairura et al. 2007).

In literature, there are different and also sometimes inconsistent definitions of SQ (Jijo 2005). However, ´the capacity of soil to function´ is the simplest definition for SQ (Karlen et al. 1997). The word quality implies value judgment of the soil status to serve for a specific purpose (Jijo 2005). In addition to the anticipated function of a particular soil for the intended purpose, the specific definition of SQ is dependent on the soil inherent capabilities (Jijo 2005). Gregorich et al. (1994) define SQ as a composite measure of both a soil's potential to function and how well it functions relative to a specific use. Considering many factors, SQ is defined as the fitness of a specific soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Larson and Pierce 1994; Karlen et al. 1997; Kruse 2007). This definition was thought by Karlen et al. (1997) as a similar to that defined by Larson and Pierce (1991), Doran and Parkin (1994) and Acton and Gregorich (1995), and allows for quantification of SQ dynamics as well as for inherent differences among soils in assessing the intensity of soil degradation. Others have recommended that soil resilience should be considered in defining SQ (e.g., Singer and Ewing 2000).

Generally, to manage and maintain soils in an acceptable state for future generations, soil quality and health must be defined, and the definition must be broad enough to encompass the many functions of soil (Doran and Safley 1997; Nielsen and Winding 2002). The terms soil quality and soil health are often applied interchangeably in the popular press and scientific literature, but scientists in general prefer the term ´soil quality´ and producers ´soil health´ (Doran and Safley 1997). In this study, the terms soil quality and soil health are used synonymously.

## 2.2 Soil quality functions and indicators

The important functions of soil in an ecosystem as described by SQ includes physical support to plants, moderation of the hydrological cycle, disposal of wastes and dead organic matter, retention and delivery of water and solute (nutrients) to plants, renewal of soil fertility, and regulation of major element cycles (Daily et al. 1997). Larson and Pierce (1991) also noted that SQ functions describe how effectively soils respond to different sustainable soil management systems and degradation processes. The use of specified soil functions when defining SQ however is not universally accepted (Kruse 2007). A challenge in defining soil function is that soil that might be ´´good´´ for one function may be ´´poor´´ for another function (Kruse 2007). Efforts to quantitatively assess SQ should attempt to overcome such criticism by a prior determination of soil management goals or the soil functions to be evaluated (e.g., Andrews et al. 2004; Kruse 2007). In line with this, Kruse (2007) reviewed the example of lower nitrate levels in the soil as positive for soil functioning to protect the environmental services, but negative for soil functioning to enhance agricultural productivity. This illustrates that a device that assesses the changes in SQ indicators due to adoption of certain soil-crop management practices is a better approach than just identifiying soils in the order of their best soil function.

Soil quality indicators refer to measurable soil attributes that influence the capacity of soil to perform the intended functions. These can be measurable physical, chemical and biological soil attributes or morphological and visual features of soils and plants (Jijo 2005). Important indicators are those that can be described by qualitative or quantitative approaches, and which are easy to measure soil parameters and are able to evaluate changes in soil system (functions), correlate well with ecosystem processes, assessed in a reasonable period of time, meet management goals, are components of existing databases, and are sensitive to variations in climate and management systems on temporal and spatial point scale (Doran and Parkin 1996; Karlen et al. 2004; Murphy et al. 2004; Jijo 2005). Soil attributes that are most sensitive to management or erosion influencing factors are thus the most desirable soil indicators in this study. A system that contributes negatively to the SQ indicators could be considered potentially unsustainable and modified quickly in the system. On the contrary, strategies that improve the condition of the SQ indicators can be demonstrated and promoted to assure sustainability of soil resources (Arshad and Martin 2002). The existing literature contains an overlap of information concerning SQ indicators selection. The challenge is that literature shows that no scientific agreement exists on whether any one indicator measures or predicts changes in SQ better than the other (Kruse 2007). Similarly, Doran and Parkin (1994; 1996) and Seybold et al. (1998) stated that the selection of SQ indicators is based on indicators that considered reasonably useful to that particular area, and considering the purpose and financial situation.

Local farmers have a vast amount of practical knowledge about how the SQ indicators affect crop productivity and the environment at large (Birmingham 2003). The strengths of their knowledge can be an important contribution to SQ improvement currently. Such resource is greatly underutilized and should be much more vigorously pursued in developing world (NRC 1993). Farmers' criteria for SQ classifications are usually functionally related to visual observation of SQ indicators, similar to the morphologic categorizations derived by soil scientists (Birmingham 2003). Pawluk et al. (1992) reported that classifications resulting from state of observation of the local environment may lead to solutions for production related problems with reasonable costs. Despite the fact that the topic of farmer SQ indicators knowledge has been formally studied in many other settings elsewhere, limited information is documented on farmers' knowledge of SQ indicators that assess the consistency with the existing situation of science-based measurement in Ethiopia.

## 2.3 Soil erosion impact on soil quality and productivity

Soil erosion, i.e., the physical displacement of soil, can have severe adverse economic and environmental impacts. Such impacts can include SQ deterioration, crop damage by runoff and sediment deposition, introduction of weeds and pathogens, infrastructure and life destruction, siltation of water sources (reservoir) and irrigation channels (Holmes

1988). Erosion adversely affects on-site SQ by reducing infiltration rates, water-holding capacity, organic matter, nutrients, soil biota and soil depth, and in turn the SQ influences runoff and soil loss. Each of these factors influences on soil productivity individually and also interacts with each and other physical, environmental and human induced factors, making evaluation of the impacts of soil erosion more challenging (El-Swaify et al. 1985; Troeh et al. 1991; Pimentel et al. 1995).

Erosion rates are poor indicators of lossses in productivity, because soils may be redistributed within a catchment and not necessarily lost from production (Elliot et al. 1999). Soils also vary in tolerance level to erosion. For example, Andisols have a relatively higher water-holding capacity and natural fertility. Erosion may be severe on such sites, but declining in productivity may be little (Elliot et al. 1999). Conversely, Lithosols are shallow soils and are generally less productive, so a small rate of erosion can lead to a significant decline in overall soil fertility, water-holding capacity and thereby in productivity (Elliot et al. 1999). The effects of erosion are most severe in shallow soils or where there is a root-restrictive layer at shallow depth and on steep terrain (Wainwright et al. 2003). This indicates that erosion effect on SQ depends on the minimum soil depth required to sustain productivity and maintain the environmental regulatory capacity. The understanding of site-specific soil erosion impacts therefore has essential practical implications for successful soil degradation management.

The two most important processes that adversely affect SQ and hence contribute to soil degradation in Ethiopia are soil erosion and declining soil nutrient (fertility) (Badege 2001). The northern highlands of Ethiopia are particularly vulnerable to such soil degradation, given the inherent high population and historical tillage system, coupled with unreliable rainfall, steep terrains and improper land practices (Huffnagel 1961; McCann 1995; Badege 2001). Soil erosion also leads to the development of landforms over short and long time scales. For instance, in some cases the landscape can significantly modify in a matter of hours as a consequence of an extreme storm event that leads to high flooding (Wainwright et al. 2003). Erosion processes are highly variable over catchment hillside fields because the soils of some landscape units´ are more susceptible to erosion and erosion-induced degradation than others (Lal and Elliot 1994). In many cases, constantly high erosion rates can result in a total loss of productivity and ecosystems services, leading to desertification (soil degradation) (Desmet and Govers 1997). Understanding soil erosion at catchment level is therefore fundamental to explaining the SQ and geomorphology of an area and defining appropriate erosion protection measures. Testing tools (e.g., erosion models, interpolation SQ indicators maps, field survey) that can identify different risks of erosion and soil nutrient losses in a catchment are thus important for site-specific management planning.

Soil erosion incurs a substantial yield reduction in Sub-Saharan Africa, e.g., about 3.6 million tons of cereals, 6.5 million tons of roots and tubers, and 0.36 million tons of pulses were lost through erosion in 1989 (Lal 1995). The average yield loss was estimated to be 6% at that time, but if accelerated soil erosion continues, yield losses in Sub-Saharan Africa by the year 2020 could be 14.5% (Lal 1995). The effects of erosion on crop yields arise as a result of reduction in effective rooting depth, loss of plant nutrients, loss of plant (soil) available water, damage to seedlings, loss of cultivated land area due to gully initiation and expansion, and reduced efficiency of external inputs which impair productivity and environmental regulatory capacity (Letey 1985; Lal et al. 1999). The loss of soil nutrients and water can account for about 90% of the losses in land productivity (Pimentel et al. 1995). A ton of fertile topsoil can have 1-6 kg N, 1-3 kg P, and 2-30 kg of K whereas a severely eroded soil may have considerably lower levels of these nutrients (Troeh et al. 1991). Despite the above facts, the impact of soil erosion on SQ at catchment scale is not well documented in the Sub-Saharan Africa in general and Ethiopia in particular.

## 2.4 Severity of soil degradation

The extent of soil degradation is estimated to be between 5 and 7 million ha per year, which means that 0.3 to 0.5% of the world's arable land area is being lost every year through soil degradation (FAO/UNEP 1983). About 87% of the world's degraded soils are caused by erosion (Oldeman et al. 1991; UNEP 1992; Katyal and Vlek 2000). A soil degradation assessement by WRI (1990) reported that 10% of the world land surface has changed from forest and rangelands into desert, and another 25% is at a high risk. The report by Oldeman et al. (1991) shows that 7 and 1.5 million ha of agricultural land are degraded annually due to soil erosion and chemical degradation, respectively, of which more than 40% of the strongly degraded land is in Africa. Steiner (1998) also reported that in Africa alone, 12% of the potential agricultural land has been severely degraded, 18% has lost substantial productivity, and 0.5% has become unsuitable for cropping. Out of the estimated 60 million ha of agriculturally productive land in Ethiopia, about 27 million ha experienced erosion, 14 million ha are considered eroded and requiring rehabilitation, and 2 million ha are considered lost with an estimated total loss of 2 million $m^3$ of top soil per year with average annual soil loss from cultivated lands of 100 t $ha^{-1}$ (FAO 1986). The economic impact of soil erosion is more significant in developing countries due to lack of capacities to protect existing nutrients and to replace lost nutrients (Erenstein 1999). If the soil degradation continues at the present rates, the consequence will be a challenge for sustainable future productivity and food security of many developing countries.

Soil erosion is one of the physical degradation processes and is the most widespread form of soil degradation in Ethiopia. According to FAO (1986), about 50% of the land area in the highlands was significantly eroded, 25% was seriously eroded, 5% had reached the point of no return and the remaining 20% was considered to be rather free from serious erosion risks. Later studies also show that severe soil degradation due to soil erosion has occurred in Ethiopia (Tamene 2005; Tizale 2007). In some of the densely populated highlands of the country, entire hillsides have passed the threshold of degradation and entered the irreversible stage at which restoration is hardly possible. Such severely affected areas are mainly found in the northern highlands of the country (Tamene 2005). Literature on the state of soil degradation in Ethiopia indicates that the main contributing factors are diverse and related to the country's physiographical settings and socio-economic condition. Although there is evidence of declining soil productivity, especially in fragile ecosystems, quantitative information on the spatial variability of the severity of soil degradation is sketchy and fragmented (FAO 1994; Tizale 2007).

Soil erosion by water and its associated negative effects on productivity, food security and well being of the population are recognized to be the severe threats to the national economy of Ethiopia. As more than 85% of the country's population depends on agriculture for living; soil loss and the associated nutrient losses have contributed to food insecurity (Hurni 1993; Sutcliffe 1993; Bekele and Holden 1999). The highlands of Ethiopia in general and the Tigray region in particular experience severe soil erosion mainly due to steep terrain, poor surface cover, cultivation of sloppy areas, and degradation of grazing lands due to human and livestock pressure. In the region, erosion leaves stones and bare-rock on the surface of landscapes as it has been removed almost all topsoil in many places and in some cases the subsoil also (Tamene and Vlek 2008). It is assumed that some of the eroded soils have been deposited at the downstream, but the areas in the catchment that benefit from the depositions are quite small and in unfavorable position compared to the source areas where the soil was detached (Sonneveld and Keyzer 2003). In the region, the eventual delivery of sediment to streams and reservoirs is also high (Tamene 2005), indicating that this may reduce the possibility of soil redistribution within the catchment.

Previous studies related to soil degradation due to erosion in the Tigray region provide a quantitative picture of the magnitude of the problem. For instance, Hunting (1974) estimated the mean erosion rate in the highlands of central Tigray to be above 17 t $ha^{-1}$ $y^{-1}$. Other studies estimated soil loss rates higher than 80 t $ha^{-1}$ $y^{-1}$ (Tekeste and Paul 1989), 21 t $ha^{-1}$ $y^{-1}$ and 19 t $ha^{-1}$ $y^{-1}$ based on data from an in-filled dam and rainfall simulation, respectively, (Machado et al. 1996). Hurni and Perich (1992) also reported that the Tigray region has lost 30-50% of its productive capacity compared to the original state 500 years ago, which challenges the achievement of the goal of food security. The same report shows that the cost of rehabilitating the degraded areas is 10-50 times higher than that of preventing degradation in early stages. The different estimates of soil erosion rates indicate the dynamics of erosion processes and causes, and also the need for area-specific research using appropriate methodologies for the situation of such diversified environmental settings. Besides, from a policy standpoint, what matters most is not how much land has already been lost, but rather the current rates of degradation, and hence losses in the future (Tamene 2005). Such questions can not be answered unless degradation is measured and proper indicators of changes are identified to develop and suggest appropriate remedial measures.

Accurate information is needed by land managers and policy makers on the actual areas where severe soil degradation is taking place and where better soil management and improvement is necessary, and the nature of the effects on agricultural production (Scherr 1999; Tamene 2005). However, past studies of such data are insufficient to guide and prioritize areas for targeted rehabilitation policy action. As a result, more qualitative and quantitative information on SQ degradation is needed for many areas of the developing region, as extrapolations to those areas from previous studies will not be adequate. Integrating local knowledge, erosion rates, spatial patterns and controlling factors of SQ degradation is thus necessary in order to identify hotspot areas and then prioritize for deisigning intervention based on appropriate approaches.

### 2.5 Effect of management practices on soil quality degradation

Negative impacts of erosion can be masked by technological advances, e.g., using improved cultivars, chemicals, and soil-crop management practices, but the cost of production with these technologies rises on eroded soils. As a result, production in such condtions may not be sustainable due to an extra cost incurred to counteract the overall SQ decline due to continued soil erosion (Pagiola 1992). The low-input agricultural systems with little or no investment in conservation-effective measures, and removal of crop residues from farmlands are among the many management factors that aggravate SQ degradation. Other important factors include deforestation, over-exploitation and excessive grazing. Sound soil management is thus the most important factor that counteracts erosion-induced changes in SQ through judicious input and appropriate systems of soil and crop management (Doran and Parkin 1994; Lal 1999). The latter author also reported that subsistence agriculture, based on little or no input leads to deterioration in SQ, e.g., decreasing soil fertility and soil organic matter, poor soil structure, low crop stand and canopy cover, and increased soil susceptibility to erosion.
Therefore, the assessment of SQ would provide valuable information for the evaluation and recommendation of appropriate and sustainable soil and land management options.

Management schemes that maintain the SQ include conservation tillage practices, crop rotation, crop residue management, fertilizers, organic amendments, water conservation techniques, terracing, contour farming, improved drainage, and better management systems that match the respective cultivar to the soil and climatic conditions (Pagiola 1992; Lal 1998). Assessing SQ allows producers and educators to recognize the early warning signs of management effects and then make informed decisions about the sustainability of their management practices (Pagiola 1992; Karlen et al. 1997). Studies on SQ can thus make decision makers focus more on soil conservation rather than on erosion, on soil fertility enhancement rather than on nutrient depletion and imbalance, on soil restoration rather than on degradation and desertification, and on judicious use of input rather than on low input systems (Kruse 2007).

## 2.6 Modeling soil erosion: erosion and sediment transport models

The existing soil erosion assessment methods can be grouped into three main approaches: a runoff plot experiment that provides net soil loss (Hurni 1985; Herweg and Stillhardt 1999), a field survey that involves the measurement of visible soil erosion indicators and the combination of erosion-influencing factors (Whitlow 1986; Herweg 1996), and erosion modeling that involves the use of empirically derived equations or process-based models (Wischmeier and Smith 1978; Helldén 1987). The methods that measure or estimate soil erosion and sediment yield have various limitations for example, scale (spatial and temporal), representativeness, data requirement, cost and range of environments in application (Zapata 2003). In addition, erosion on a field scale is a result of interlinked erosion processes involving continuous and gradual removal of surface soil, which makes it complicated to quantify using conventional methods. The need for alternatives and complementary techniques that measure the past soil erosion compared to the existing situation has led to the use of radio nuclides such as the cesium-137 ($^{137}Cs$) (Higgitt 1995).

At present, a variety of erosion and sediment models exists focusing on different spatial scales (point to regional) and temporal scales (event to continuous) with different degrees of complexity and precision to address the practical implication of soil erosion at landscape level. However, researchers (e.g., Coppus 2002; Romero 2005) proved that there is no single erosion or sediment transport model that can be universally applied better to complex catchments. There is also no clear agreement in the scientific community on which kind of model is more appropriate for simulation purposes in a specific ecological condition (Tamene 2005), as several modeling alternatives exist all with potentials and limitations that need to be known. Therefore, when using soil erosion and hydrological models as a tool for understanding erosion-deposition processes at catchment scale or predicting sediment yield to rivers and reservoirs, the model user should be aware of the possibilities and limitations of the model beforehand and also understanding the basic considerations when choosing a model is crucial (Govers 1987; Desmet and Govers 1997; Wainwright et al. 2003).

Based on the nature of the basic algorithms, there are three main types of erosion models. These are: empirical, conceptual and physical models (Wheater et al. 1993; Argent et al. 2005). Empirical models are the simplest of the three model types. They are based on extensive experimental results (site-specific observations) and input-output relationships. The data and computational requirements for such models are usually less than for conceptual and physically-based models (Li et al. 1996). Empirical models have constraints of applicability to regions and ecological conditions other than from which data were used in their development (Merritt et al. 2003) but such models are simply calibrate a relationship between inputs and outputs without any effort to describe the condition caused by each processes (Argent et al. 2005). Examples of empirical models include the Universal Soil Loss Equation (USLE) and its derivatives.

Physical (process)-based models are based on the understanding of the physics of flow and sediment transport processes and their interaction using equations governing the transfer of mass, momentum and energy (Doe et al. 1999; Kandel et al. 2004). In principle, they can be applied outside the range of conditions used for calibration. This is because physical models are based on computation of erosion using mathematical representations by deeper understandings of the fundamental hydrologic and erosion processes (Argent et al. 2005). Such models can be applied across multiple landscape conditions, as the mathematical relationships are derived from physical laws of water flow over and through soil and vegetation that must be obeyed under all circumstances (Maidment 1996; Merritt et al. 2003). Physically-distributed models are commonly applied to small catchments represented by detailed data, e.g., Water Erosion Prediction Project (WEPP) (Flanagan and Nearing 1995), European Soil Erosion Model (EUROSEM) (Morgan et al. 1998). An important limitation of the physical models has been the need of intensive data for model parameterization, calibration and more particularly the lack of data for validating the spatial pattern of runoff, sediment and soil nutrients losses and redistribution within a catchment in order to apply a model to a wide range of field conditions. The other major limitation of these models is that they are too complex and also suffer from computational costs and from reliance on data to test and calibrate for assessment of performance before the model output is used for decision-making (Foster 1990; De Roo and Walling 1994; Mitasova et al. 1999; Argent et al. 2005). It is difficult to reliably apply most of the physical-based models developed in the data-rich regions to developing countries, where both data availability and quality are critically poor. Selection of appropriate model(s) that can suit the areas under study is therefore crucial and needs to be based on the objective at hand, resources available (e.g., access data, expertise, time and money, etc.) and scale of investigation required.

Placed somewhere in between empirical and physically-based models, conceptual models reflect the physical processes governing the system but describe them with empirical relationships, e.g., Agricultural Non-Point Source (AGNPS). Such models incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure, and are formulated to mimic the functional flow paths in the catchment as a series of storages, each requiring some characterization of its dynamic behavior (Viney and Sivapalan 1999; Viney et al. 2000; Merritt et al. 2003). These models have the inherent limitations of the empirical models and also require relatively detailed data for calibration.

In this study, following the literature review of different types of erosion models, the physical-based SWAT model was selected and evaluated based on the northern Ethiopian catchment conditions to assess the magnitude of SQ degradation and to identify erosion-hotspot areas. This was because the participatory approach that used local knowledge and was evaluated by a science-based approach shows the severity and general pattern of the SQ degradation, but not the rate and detailed spatial distribution of erosion-hotspot areas. Model description and the reasons for its selection are given in Chapter 7. Knowledge about the SQ degradation alone is not adequate. It is necessary to know ``what`` to do ``where`` to tackle SQ degradation in a catchment. In support of this, Mitasova et al. (2001) show that through model simulation the selection of appropriate management options that create a sustainable landscape is possible. In this study, therefore, model-based simulation of management strategies was done that enable reduction of soil degradation to less than a tolerable level as compared to the current conditions after identifying soil erosion-hotspot areas using the model and SQ evaluation results in the study catchment.

# 3 AREA DESCRIPTION AND GENERAL METHODOLOGY

## 3.1 Study area description

Ethiopia lies within the zone of Sub-Saharan Africa in the horn of Africa. The Tigray region is located in northern Ethiopia. The study was conducted in the Mai-Negus catchment in the highlands of the Tigray region (Figure 3.1). Brief description of the biophysical resources of the study area is given in the following sub-sections (section 3.1.1 to 3.1.3).

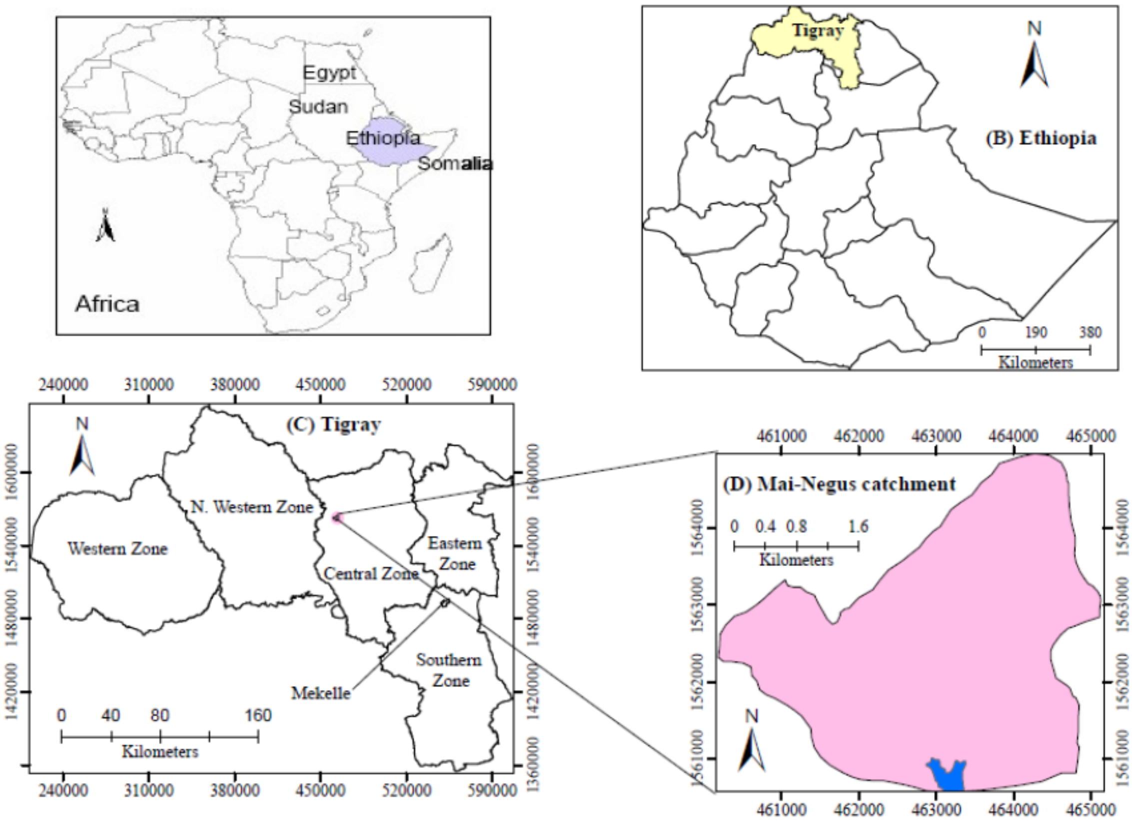



Figure 3.1: Location of the study area (A) Africa, (B) Ethiopia, (C) Tigray and (D) Mai-Negus catchment. Blue area is the reservoir

### 3.1.1 Ethiopia: biophysical description

Ethiopia is located in east Africa in the area referred as the Horn of Africa (32°42'-48°12' E longitude and 3°24'-15°00' N latitude). The country covers about 1.13 million km$^2$. The highlands > 1500 m above sea level (a.s.l.) constitute around 45% of the total area are inhabited by > 80% of the Ethiopian population (Gebeyehu 2002). In general, Ethiopia is a land of natural contrasts with landscapes ranging from the top of the rugged Siemens Mountains (4300 m a.s.l.) to high plateaus (above 2000 m a.s.l.), and lowlands (< 1500 m a.s.l.) to the depths of the Danakil Depression at 120 m below sea level, which is one of the lowest dryland points on earth (EMA 1988). The population in Ethiopia is more than 76 million (FDREPCC 2008).

Agriculture contributes to more than 50% of the gross domestic production and over 80% of the overall export revenue of the country (Sonneveld and Keyzer 2003; FDREPCC 2008). Agricultural production is mainly rain-fed, and harvests are determined by the vagaries of the climatic conditions in the country. The south-westerly monsoon is the most important moisture-bearing wind system (Daniel 1977; FAO 1984a). The highest mean annual rainfall (above 2700 mm) is in the south-western highlands, which gradually decreasing to 100 mm or less in the north-eastern lowlands. The mean annual temperature ranges between less than $0^{o}C$ at night in the highlands to 45°C in the Afar lowlands (Dallol Depression) (FAO 1984a; EPA 2003).

Vegetation types in Ethiopia are the direct reflections of altitude and climate (Gemechu 1977). The major vegetation types range from montane evergreen forest in the south-western areas and scattered bushes and shrubs in the lowlands to dominantly barren land in some of the coastal deserts (Gemechu 1977). The faunistic diversity of Ethiopia is high, reflecting the diversity in climate, vegetation and terrain. Such wide range resources have resulted in a high variability of soil types (FAO 1984b; Eweg et al. 1997). The main soil types are Lithosols, Nitosols, Cambisols and Regosols (FAO 1984b).

Soils are subjected to severe losses of nutrients through soil erosion. From the Ethiopian highlands, over 1.5 billion tons of topsoil per annum is lost through erosion (Taddese 2001). This could have added to the country's harvest a grain loss about 1-1.5 million tons (Taddese 2001). However, the soil formation rate for Ethiopia is less than 6 t $ha^{-1}$ (Hurni 1983), which is very low compared to the estimated soil erosion rates. About 60% of the highland areas in the country have a slope of more than 16% (Cloutier 1984), and cultivation on these steep slopes has accelerated severe soil erosion. Such losses will certainly cause biomass decrease and this will remain as environmental challenge unless appropriate measures are taken.

### 3.1.2 Tigray region: biophysical description

The Tigray region is located in the northernmost part of Ethiopia (12°00'-15°00' N latitude and 36°30'-41°30' E longitude) (Figure 3.1B-C). The region has a total population of 4.3 million, with an average population growth rate of 2.5%, occupaying an approximate area of 53,000 $km^2$ (FDREPCC 2008). The average population density in the region is about 80 persons $km^{-2}$ (FDREPCC 2008), which exceeds the country's average of 49 persons $km^{-2}$ (Elias 2002). The region has very rugged topography, which consists of both high mountains and incised deep gorges. Altitude varies from 500 m to 4000 m a.s.l. with a significant proportion of the region having an altitude of more than 2000 m a.s.l. Terrain slope generally ranges from more than 80% in the central and southern parts to less than 2% in the western lowlands of the region (Tamene 2005).

In Tigray, rainfall is highly variable in spatial as well as temporal scales. It increases from the eastern to the central, western and southern parts of the region (Figure 3.2). The main rainy season is from June-September, and the higher rainfall occurs in July and August. The average annual rainfall ranges between 250 mm and 1000 mm. The annual rainfall coefficient of variation in the region is 20-40% (CoSAERT 1994; Belay 1996) which is high as compared to 8% variability for the whole Ethiopia (Belay 1996). Rainfall intensity is generally very high, i.e., on average 60% falls at rates exceeding 25 mm $h^{-1}$ (Virgo and Munro 1978). In the region, the average annual temperature is about 18°C, but it varies mainly with altitude and seasons.

The geology of the Tigray region is composed of weakly metamorphosed rocks formed by a Precambrian basement complex, which are extremely folded and foliated (Tamene 2005). The common rocks include slates and phyllites of sedimentary origin and granites (igneous), but greenstones of basic volcanic origin are the predominant rock types in the region (Tamene et al. 2006a). The main soil types in the region can reflect the variability in altitude and geology. Generally, Leptosols are common on the step-slopes, Cambisols on intermediate positions and Vertisols on the lower slopes of the region (Tamene and Vlek 2007).

In Tigray region, agriculture is one of the most important activities. About 65% of the land is used for cultivation and the remaining is allocated for grazing/pasture, plantations/forests, wasteland, etc. In the region, smallholder farmers farmed over 95% of the cultivated area (BoANRD 1997). In this part of the country, agricultural crop cultivation has the oldest history (Tamene et al. 2006a). Tigray`s agriculture is based on the use of oxen-drawn plows of predominantly cereal production. Environmental deterioration that caused a decline in production together with the population increase has created a shortage of land. These processes have led to expand agricultural and grazing activities into marginal and steep-slope which has accelerated land degradation (Tamene et al. 2006b). The increasing losses of topsoil due to erosion and the exploitation of forests for fuelwood and cultivation have exposed the region to serious environmental and ecological dangers (Gebre-Egziabher 1989; CoSAERT 1994).

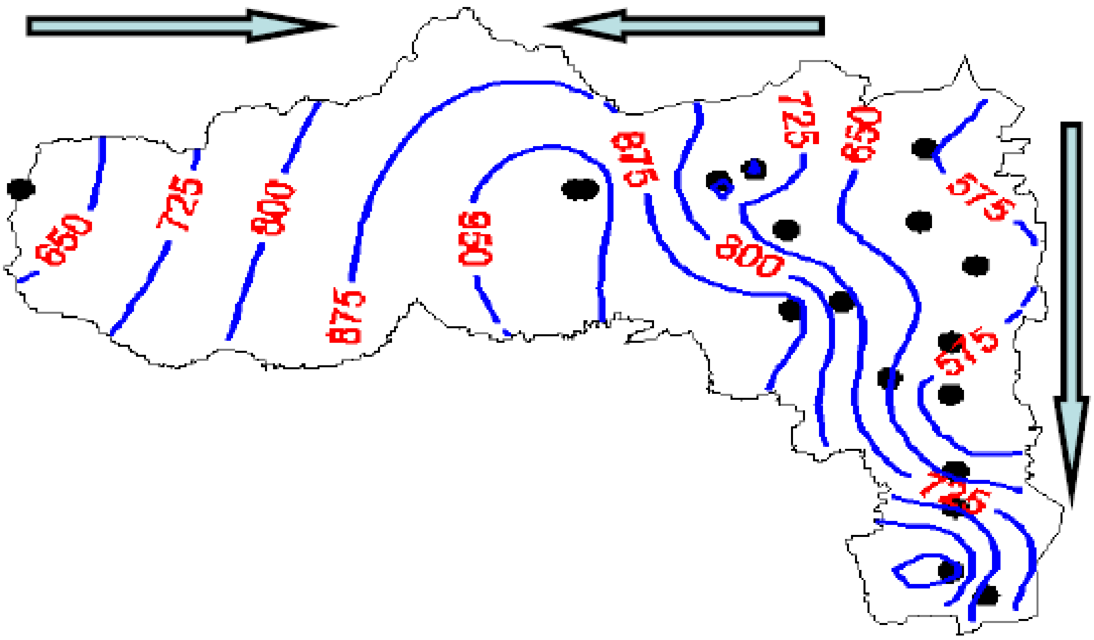



Figure 3.2: Isohyets showing mean annual rainfall distribution in the Tigray region. Arrows indicate the direction of rainfall increment

In the Tigray region, soil degradation is one of the highest in Ethiopia. Due to population growth, political instability, deforestation and repeated drought, the region has virtually lost its forest cover, and has been left with only a remnant vegetation of an estimated 0.3% (CoSaERT 1994). The existing vegetation cover includes sparse woodland of thorny acacia, bushes and scrubs spread between cultivated areas. The combination of rugged terrain, which is sensitive to erosion effects and also difficult for its utilization and management with the poor surface cover and the prominent gullies have led the region to be considered as one of the most degraded area in the Ethiopian highlands (Eweg et al. 1997). There have been efforts to cover the bare landscape with trees in the last 30 years. These were not able to reduce erosion and the consequent effects significantly because of limitations in scope and budget.

Regardless of the significant amounts of runoff and high irrigation potential in the highlands of Tigray (CoSAERT 1994), the economic conditions and complex topography make it difficult to implement the existing irrigation potential that is necessary for the food security of the growing population. Since the runoff originates from a higher topography with high flow energy and also the rivers flow in gorges, the use of the high runoff potential in the highlands of the region for irrigation is limited. Harvesting such high runoff potential is, therefore, considered an alternative to supplement the rain-fed agriculture using small-scale irrigation in the region. However, the risk of reservoir sedimentation due to high soil erosion challenges such irrigation option (Tamene 2005). Thus, efforts to rehabilitate degraded habitats and protect non-degraded ones should be the focus in the region using appropriate decision-support tools and techniques.

### 3.1.3 Study site: Mai-Negus catchment

The Mai-Negus catchment (14. 07 $^{o}$ N and 038. 39 $^{o}$ E) is situated 249 km south-west of Mekelle, the capital of the Tigray region (Figure 3.1C-D). Altitude varies over short distances and ranging between 2060 and 2650 m a.s.l. The catchment has a total area of 1240 ha. The mean annual temperature is 22$^{o}$C and precipitation 700 mm. Annual rainfalls is erratic in distribution and also highly variable over a single main rainy season (June to early September). About 70% of the annual rainfall is concentrated in July and August. In general, the seasonal rainfall is inadequate in amount, poor in distribution (erratic) and intensive mainly during July-August (Figure 3.3). Despite such weather variability and soil erosion and socio-economic constraints, agriculture is the leading economic sector for the farmers in the catchment. The catchment has a long time human settlement history which related to its agricultural activities.

The population density in the study catchment is 72 persons km$^{-2}$. This is relatively low compared to the regional average of 80 persons km$^{-2}$ (FDREPCC 2008). The average landholding by a household in the catchment is small (1.2 ha) with a range of 0.5 to 2.0 ha. The average number of household members is 6.5, ranging from 3 to 9 members. Land-use is mainly characterized by smallholder subsistence rainfed cereal agriculture.

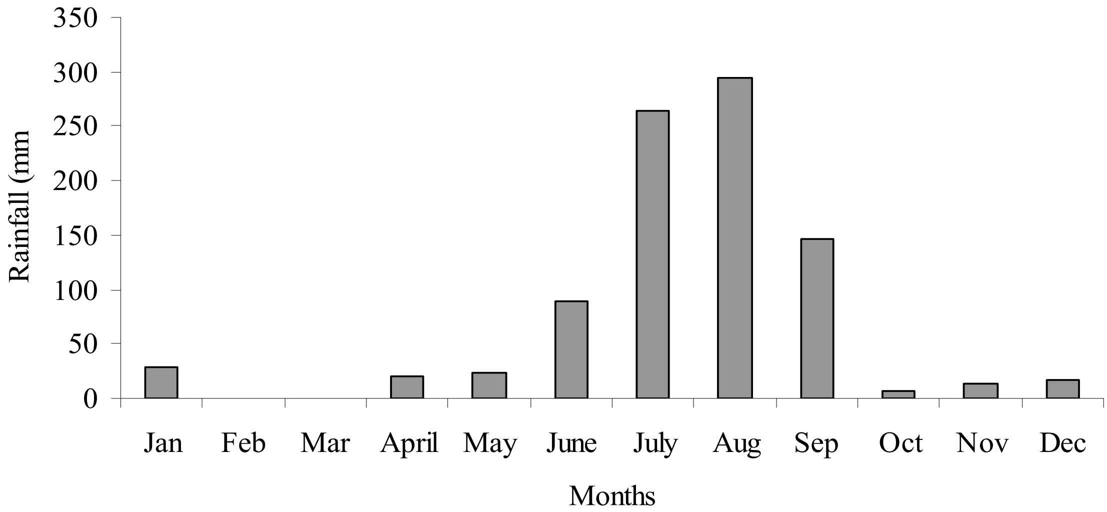



Figure 3.3: Mean monthly rainfall in Mai-Negus catchment, northern Ethiopia (1963-2009) (source: Meteorology Agency Mekelle branch)

The farming system in the catchment is a mixed crop-livestock system where livestock provide the draught power for the farming operations; crop residues are fed to the livestock. Teff *(Eragrostis tef*) cultivation, a cereal with very fine grains endemic to Ethiopia, is practiced on the majority of the arable land (above 80%). Teff has very fine seeds that require repeated plowing of fields to prepare fine seedbeds but the plow creates loose soil, which increases soil susceptibility to erosion (Bewket and Sterk 2003). The remaining land coverage is maize *(Zea mays)* and wheat *(Triticum vulgare)*. Other crops such as lentil *(Lens culinaris)*, faba bean *(Vicia faba)*, field pea *(Pisum sativum)*, chick pea *(Cicer arietinum)*, flax *(Linum usitatissimum),* barley *(Hordeum vulgare)* and sorghum (*Sorghum bicolor*) are also important crops but cover only a very small area. Livestock production is essential part of the farming system, although livestock numbers have decreased with time due to animal feed shortage. But a significant part of the study catchment is used as grazing land regardless of its potential in productivity. In the catchment, cattle are kept mostly for draught power and milking, goats and sheep for live sale and for their own meet demand, and equines for transportation. Despite the high agricultural diversification in the catchment, farmers are not able to feed their family throughout the year with what they produce. This indicates that the productivity of the catchment in particular and of northern Ethiopia in general needs to be improved.

Vegetation in most of the catchment is sparse and has been overexploited for a many years. The existing vegetation consists of some shrubs and bushes of little economic value and little patches of mixed forest. The frequently occurring tree species observed include seraw (*Acacia etbaica*), chea' (*Acacia abyssinica*), acacha (*Acacia decurrence*), Awhi (*Cordia africana*) momona (*Acacia albida*), tambock (*Croton machostachys*), bahrizaf (*Eucalyptus globulus*), tahsus, (*Dodonaea euquistifolia*), Awlie (*Olea europaea*), lahai (*Acacia lahai*), Kulkual (*Euphorbia candelabrum*) and Kulieo (*Dovyelis abyssinica*). Leucena (*Leuceana leucacephala*) and sesbania (*Sesbania sesban*) and some grass species also occur in the catchment. Tree species such as *Eucalyptus camaldulensis* have been introduced through reafforestation. Generally, the vegetation coverage is not good, which demands sound management practices.

## 3.2 Methodology

### 3.2.1 Study site selection

This study was conducted in the Mai-Negus catchment in the Tigray region in northern Ethiopia. The site is considered representative for the highland catchments in the region with respect to farming system, land-use and land -cover diversity, terrain complexity, soil degradation and presence of a water-harvesting reservoir in the downstream of the catchment and its sedimentation risk. When selecting this catchment as a study site, previous preliminary survey results of the Ministry of Water Resources (MWR 2002) and knowledge of the author in the region were used. The report of the MWR showed that the catchment has already been identified as a site with high soil degradation-related problem in the Tigray region. After site selection, field data were collected from May 2009 to June 2010. A brief description of the data collected and the approaches are described in the sub-sections 3.2.2 to 3.2.7.

### 3.2.2 Identification of geomorphic landforms

Having a landform map is crucial to show the variability of soil quality degradation across small units of the landscape. The geomorphic landform map (Figure 3.4A) was developed in ArcGIS software using a field survey in combination with the topographic map information. The topographic map (scale 1:50,000) was obtained from EMA (1997). It was used for field verification, delineation of boundaries, generation of a digital elevation model (DEM), and for capturing other vector features in the catchment. In addition, information from geological map was taken into account while developing the landforms. A report by MWR (2002) about the landforms in the study catchment was also reviewed to classify these. The study catchment is characterized by different landforms that range from flat plains to undulating and rolling land to steep mountains and escarpments. Considering elevation, slope, and geomorphologic character (surface and subsurface flows, alluvial and colluvial deposition), the catchment topography can be classified into six landforms. The landforms also vary in vegetation cover and most morphodynamic processes. The major geomorphic landforms (Figure 3.4A) are valley (covers 19% of the catchment area), plateau (8%), rolling-hills (9%), central-ridge (27%), escarpments (29%), and mountainous (6%) with an average slope of 4%, 13%, 18%, 22%, 36%, and 80%, respectively. The reservoir, which is considered as a separate landform, covers about 2% of the catchment area.

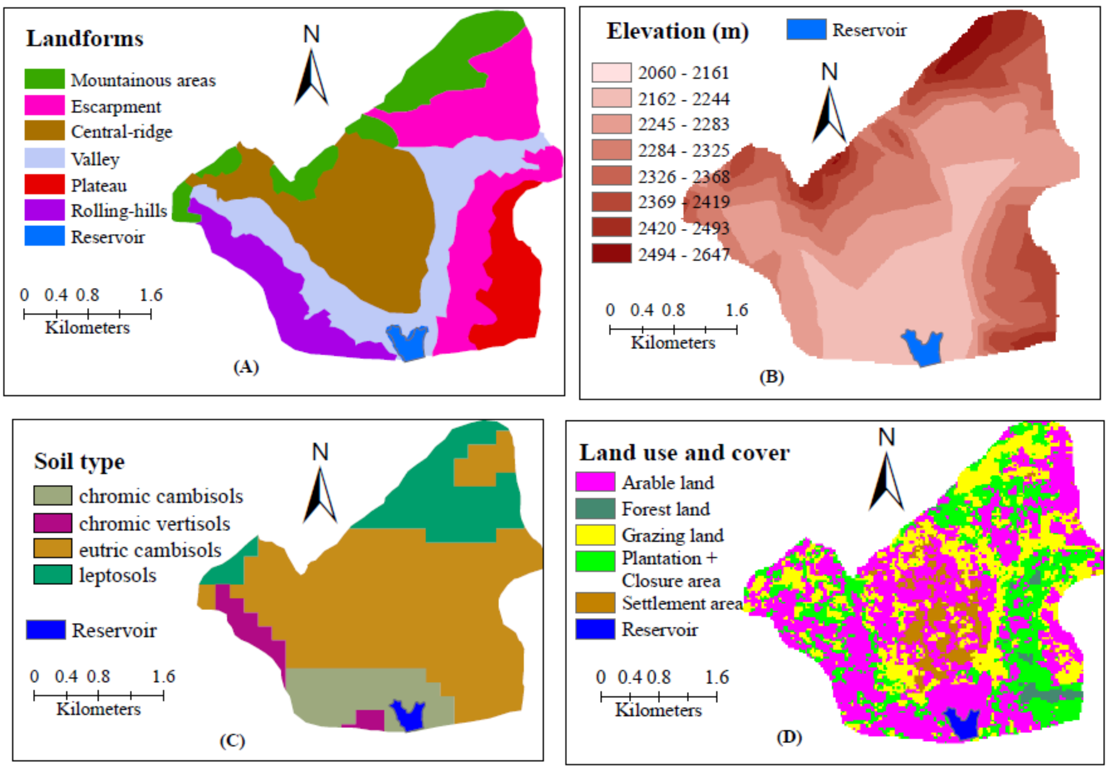



Figure 3.4: Geomorphic landform (A); digital elevation model (B); major soil types (C) and land-use and-cover (D) of the Mai-Negus catchment, northern Ethiopia

A brief description of the six landforms is given as follows. (i) Valley: the two big valleys with the extended alluvial accumulation zone join where the reservoir is located, (ii) central ridge: divides the drainages of the two valleys, and is composed of crystalline rocks possibly due to regional metamorphism of parent sediment rocks, (iii) plateau: at the eastern part of the catchment, covering an area of approximately 1 $km^2$, built of basic intrusive (gabbros) covered by sandstone showing only slightly undulating relief, (iv) escarpment: downhill from the plateau area at the eastern and below the mountainous margin of the drainage, (v) rolling hills: in the western margin of the catchment and composed of predominantly basic volcanic rock, and (vi) mountainous area: mountains with high relief in the northern margin of the catchment characterized not only by steep slopes but also by scarp faces with a height up to 20 m basic volcanic rock (MWR 2002). Generally, topography is best described using a digital elevation model (DEM) for erosion modeling, rather than using the landforms.

### 3.2.3 Generating digital elevation model

The digital elevation model (DEM) is a digital representation of the hight of a terrain over a given area, usually at a regularly spaced grid (Richardson 2000). It is often not readily available at an adequate resolution and quality at catchment scale. Topography can be modeled digitally from elevation data collected from a variety of sources (Maune 2001). The DEM is one of the data models required for erosion modeling and in disciplines such as climatology, geomorphology, hydrology, ecology and also for extracting drainage networks and topographic parameters at catchment scale (Moore et al. 1991; Sulebak 2000; Maune 2001). The knowledge of surface relief is of great importance for understanding and evaluating different topographic processes.

The DEM of the study area (Figure 3.4B) was prepared with a resolution of 10 m cell size after digitizing the topographic map (scale 1:50,000) with a contour spacing of 20 m (EMA 1997) in ArcGIS 9.2. The map was scanned, and contours and spot heights were digitized and tagged with elevation values in a GIS environment. The map was geo-referenced using ground control coordinate points collected in the field and taken from the map. The vector elevation map was converted to raster and projected using the Universal Transverse Mercator 37 North (UTM-37N) reference system. After the DEM was created, pits/sinks were filled before processing undertaken in order to

´route´ runoff to the catchment outlet. Flow tracing can be difficult if the DEM has low accuracy, insufficient vertical resolution and numerous pits that trap the flow lines (Martz and Garbrecht 1992). A grid cell resolution affects the routing of surface runoff and sediment movement across the catchment. Zhang and Montgomery (1994) suggested that a 10 m grid size can show the effect of increasing resolution of grid size and the data volume needed for hydrological and erosion modeling. A grid size of 10 m after comparing various grid sizes to validate a terrain-based hydrological model prediction was also suggested by Quinn et al. (1991), Maidment (1996) and Bundela (2004). Thus, a DEM with cell size of 10 m was generated in this study (Figure 3.4B).

### 3.2.4 Mapping major soil types

The soil data were obtained from the NEDECO database (NEDECO 1998). Additional soil physical, chemical and morphological properties were determined on-site to supplement the data gap in the database. According to the FAO-UNESCO (1974) Soil Classification System, the main soil types in the study catchment are Eutric cambisols (67%), Chromic cambisols (13%), Leptosols (15%) and Chromic vertisols (5%). Chromic cambisols and vertisols occupy almost flat areas, Eutric cambisols the undulating plains and rolling land and Leptosols steep to very steep lands (Figure 3.4C).

### 3.2.5 Driving land-use and land-cover (LULC)

Different LULC types were identified during the field survey in the study catchment. Ground truthing was conducted in the dry season between mid September and November 2009 using a Geographic Positioning System (GPS) (*Garmin III*). The GPS points were used to geo-reference the image and as training samples for supervised classification of the Landsat image of November 2007 for the study catchment. The LULC image was rubber sheeted to match ground control locations, and the area containing only the Mai-Negus catchment was extracted from the full scene. A root mean square error less than 5 m was achieved while geo-referenced. Sampling points ranging from 10 to 15 were selected for each land-use class. Maximum likelihood classifier was then applied for the land-use image data classification into six LULC classes (Figure 3.4D). About 55% of the land area in the catchment was allocated as arable land, 21% for grazing, and 14% as protected (enclosure) plantation. Dense bush and woodland with mixed forest accounted for about 2% of the catchment. The rest of the land was miscellaneous such as settlement, marginal area and reservoir (8%).

### 3.2.6 General methodological research framework

Figure 3.5 shows the general methodological framework employed in this study. Detailed descriptions of the data collection, analysis and interpretation methods are given in the respective chapters. This study was carried out in several stages with the aim to collect the required data in the catchment (Figure 3.5).

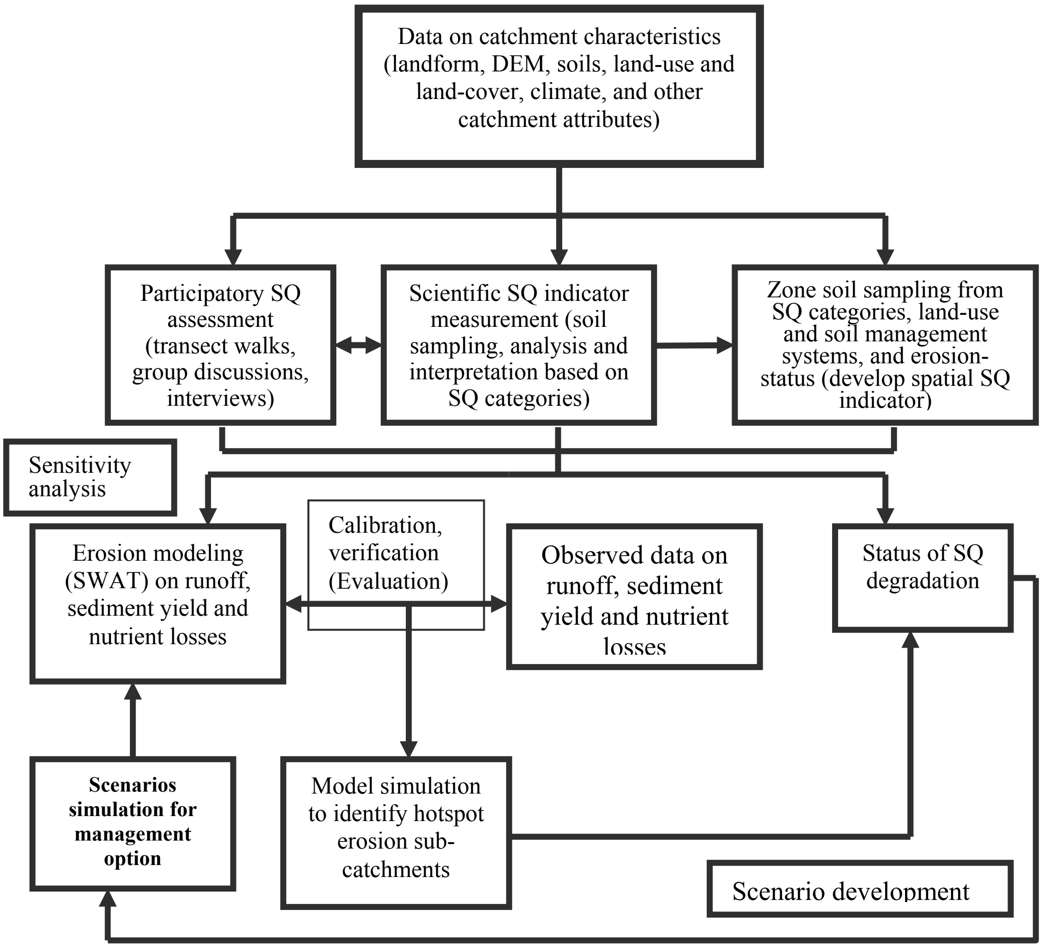



Figure 3.5: Methodological framework for evaluating soil quality (SQ) using farmer knowledge, scientifc measured soil data and soil erosion modeling so as to evaluate management strategies (scenarios) that reduce soil degradation

First, a reconnaissance survey was executed to get a general field impression about the landforms, land-use and land-cover, topography, geology and the soil types in the study catchment. In the second stage, data and information regarding land-use history, local knowledge on SQ as well as land and crop management practices were obtained through field transect walks and group discussions supplemented by interview. In the third stage, soil information was gathered from representative sampling zones in the catchment (see *section 3.2.7*) for laboratory analysis. In the fourth stage, field-based data for model calibration and verification (evaluation) were prepared and data for the SWAT model simulation at catchment scale were collected before model running. In the final stage, scenarios were developed and compared to the baseline condition to suggest management strategies that best reduce soil degradation.

### 3.2.7 Soil sampling design

Field surveys were employed to characterize the study catchment in terms of different attributes such as visual SQ indicators, SQ categories (high, medium low), long-term land-use and soil management systems, and erosion-status (stable, eroded, deposition) based on knowledge of farmers, extension agents and researcher field observations. On the basis of such soil sampling zones, soil samples were collected and then analyzed to acquire the intended soil parameters. The purpose of stratifying the catchment area into different sampling zones (Figure 3.6) was to ensure that the sampling points were well distributed across representative sampling units in the catchment. The soil samples were analyzed following the standard laboratory procedure and results interpreted to address the purpose of the study. The results of the soil analysis were also used as an input for SWAT model dataset (Chapter 7).

### 3.2.8 Data analysis

Data were subjected to different statistics such as descriptives, analysis of variance, correlation, regression, factor and discriminant analysis using SPSS 18.0 (SPSS 2010), and geo-statistical analysis by ArcGIS 9.2 software. Normality tests were conducted for the soil parameters and non-normal data were transformed to stabilize the variance. The SWAT model simulation performance between observed and simulated values was evaluated by the coefficient of determination ($R^2$) and Nash-Sutcliffe efficiency ($N_{SE}$) (Nash and Sutcliffe 1970).

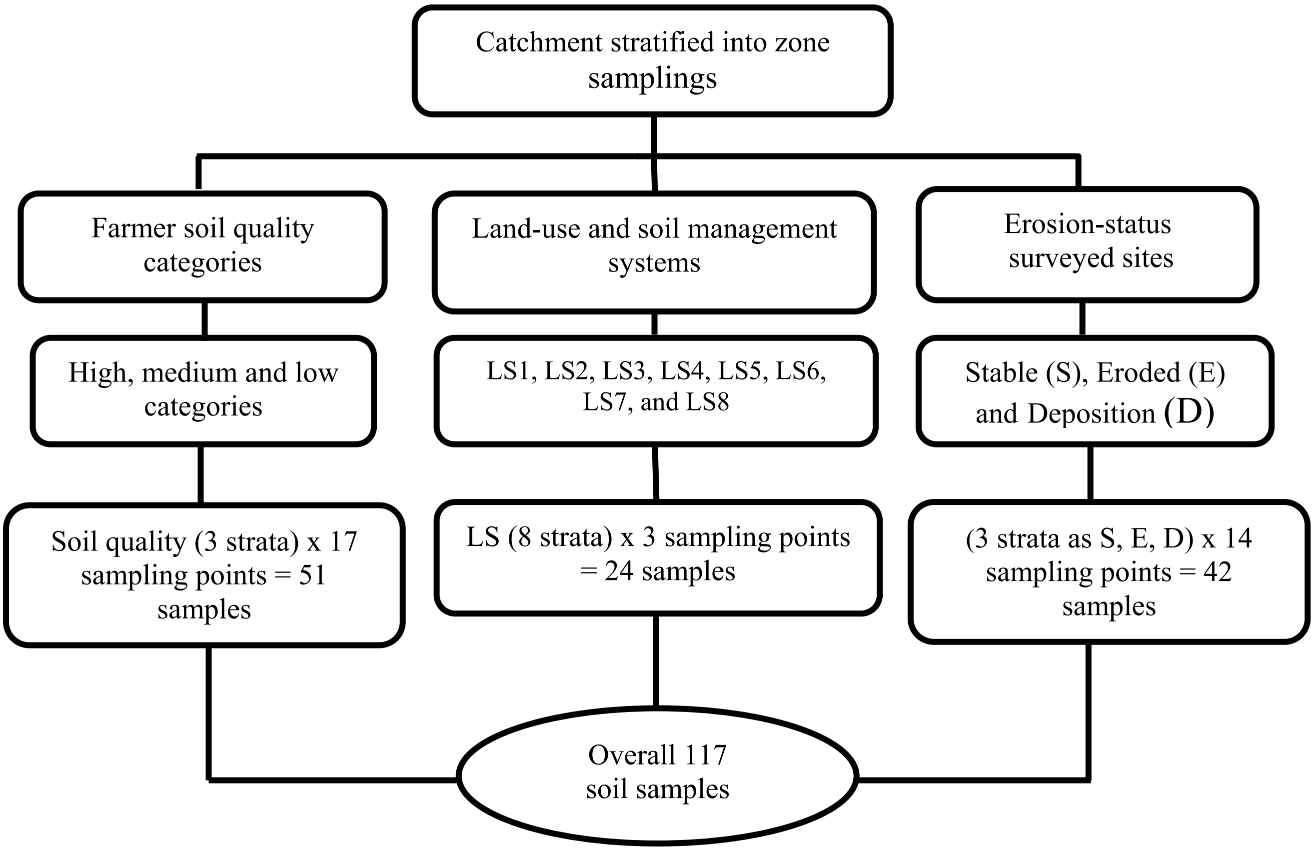



Figure 3.6: Soil sampling design employed in the Mai-Negus catchment, northern Ethiopia.

Note: LS1, natural forest; LS2, afforestation of protected area; LS3, grazed land; LS4, teff (*Eragrostis tef*)-faba bean (Vicia faba) rotation; LS5, teff-wheat (*Triticum vulgare*)/ Barley (*Hordeum vulgare*) rotation; LS6, teff mono-cropping; LS7, maize (*Zea mays*) mono-cropping; LS8, marginal land

# 4 PARTICIPATORY SOIL QUALITY ASSESSMENT IN MAI-NEGUS CATCHMENT, NORTHERN ETHIOPIA

## 4.1 Introduction

Agriculture is the mainstay of Ethiopia economy, providing the major source of employment and income. About 85% of the population in the country is primarily engaged in this sector (FDREPCC 2008). Thus, agriculture directly or indirectly forms an important component of the livelihoods of more than 70 million people in the country. However, changing environmental factors have led to soil quality degradation, which poses a critical risk of agricultural productivity and food security (Bekele and Holden 1999; Krowntree and Fox 2008). Soil quality is commonly defined as the capacity of the soil to function (Karlen et al. 1997).

Soil quality (SQ) degradation is often associated with interactions among land-use, soil management and local knowledge regarding agricultural production and with inherent soil forming and erosion factors (Karlen et al. 2001). Deforestation and accelerated soil erosion that causing SQ degradation are serious problems in Ethiopia (Badege 2001). Even though several impact assessment studies have demonstrated that investments in rehabilitating degraded landscapes in tropical regions do payoff in economic terms (Boyd and Turton 2000; Holden et al. 2005), the overall productivity of many areas in the country is often perceived to be so dramatically damaged by human impact that recovery is deemed impossible (Nyssen et al. 2009). Regardless of this, there has been a great deal of attempts to reduce soil degradation-related problems in Ethiopia, though success in reversing land degradation is minimal (Badege 2001; Nyssen et al. 2009). Among the main reason for the lack of success is that the introduced measures and technologies were not well-matched to the conditions local farmers face, and that local communities were often not involved in the technology selection processes (Kebrom 1999; Badege 2001).

An active involvement of communities under consideration is vital for successful implementation of introduced land management practices. Participation of local communities in evaluating SQ, its determining factors and possible management options is crucial, not only for the measures to be accepted and implemented, but also for sustaining those practices. Local knowledge also benefits our scientific understanding of the entire land management and decision-making processes (Sillitoe 2000; Barrera-Bassols et al. 2006).

Worldwide, traditional rural societies still encompass the majority of small farmers, and the result of conventional soil survey information often fails because it does not take into account or underestimates the importance of local knowledge (Barrera-Bassols et al. 2009). Local people and their cultures have substantial knowledge about soils and environments gained through experiences of many generations living close to the land. The environmental knowledge rooted in local communities provides a long-term perspective about land-use and management systems (WinklerPrins 1999; WinklerPrins and Sandor 2003). The long-term experience of local communities with natural resource use and management, including successes and failures, can help in evaluating SQ of the land-uses in relation to sustainable agriculture through a participatory approach (Romig et al. 1995; WinklerPrins and Sandor 2003).

Participatory processes are useful for providing persons with different backgrounds the opportunity to develop shared abilities for discourse and reflection, engage in an interactive dialogue, and communicate their perspectives (Röling 2002; Patel et al. 2007). There is also an increasing awareness and acceptance that information obtained from local people at the ´grassroots´ level can both provide feedback on and enrich decisions made at even the national or international level (Patel et al. 2007). Persons at the local level are usually those most affected by the issue at stake and are often the greatest experts on many aspects affecting their own situation (Patel et al. 2007). Farmer participation is thus for the most part valued as a means to enable and enhance democracy (Patel et al. 2007), and creates empowerment for implementing practical and effective decisions on the ground (Stave 2002; Mostert 2003).

Despite the aforementioned importance, previous SQ studies using participatory local communities are lacking in Ethiopia. Taking into account such benefits of participatory research and information gaps regarding SQ in the country, this study was designed to explore the experiences of local communities in the diagnosis of SQ and to assess the contribution of local knowledge as potential indicators of soil degradation for sustainable decision-making. The goal was to enhance our understanding of both the determining factors causing land degradation at the local level and the benefits of local participation in problem identification and solution prescription. If successful, the experience could also help redesign strategies, investment programs and projects that enhance SQ and thereby food security not only in the study area but also throughout the Ethiopian highlands.

## 4.2 Methodology

### 4.2.1 Study area

This study was conducted in Mai-Negus catchment in the Tigray region (12°00′-15°00′ N latitude and 36°30′-41°30′ E longitude) of northern Ethiopia (Figure 4.1). The catchment has an area of 1240 ha with a rugged terrain and altitude ranging from 2060 to 2650 m a.s.l. Land-use is predominantly arable with teff *(Eragrostis tef*) being the major crop along with different proportions of pasture and scattered patches of trees, bush and shrubs land.

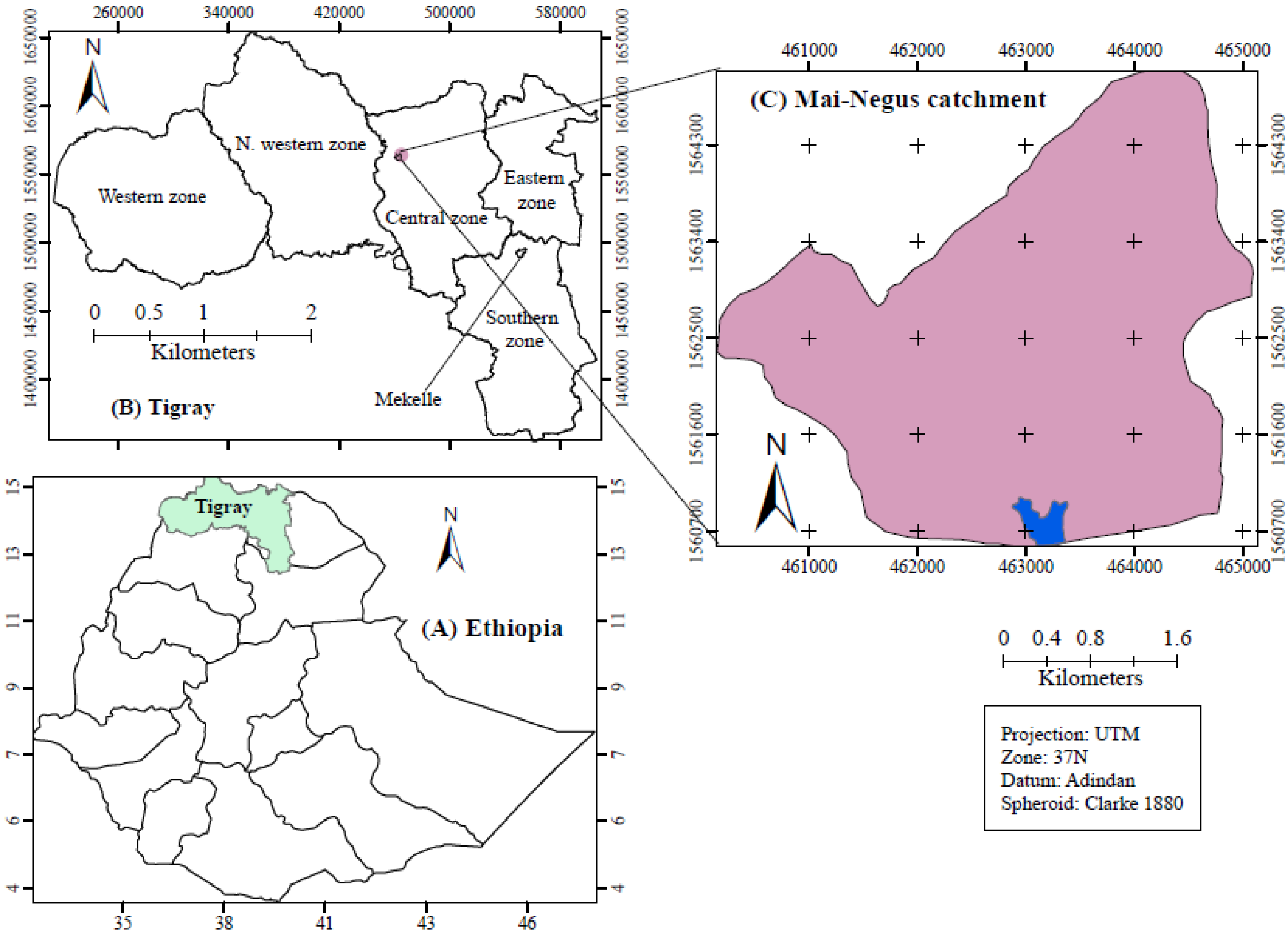



Figure 4.1: Location of Mai-Negus catchment in Tigray, northern Ethiopia. Blue area is the reservoir

The major rock types are lava pyroclastic and meta-volcanic. Soils are commonly Leptosols on the very steep positions, Cambisols on middle to steep slopes and Vertisols on the flat areas. Soils are highly eroded in most landscape positions and the overall terrain erosivity potential is high because the slope gradient often reaches 80% or more. Surface cover is also poor with high human disturbance often facilitating SQ degradation processes throughout the catchment.

### 4.2.2 Research approach and sampling strategy

A participatory field survey complemented by household head interviews was carried out to collect relevant information related to SQ within the catchment. The first field visit covered the whole catchment in June 2009 to provide a clear, overall impression about the area. Local farmers were then selected randomly from different wealth categories to be involved in transect walks. Finally, in addition to the participatory transect walks; arrangements were made to supplement the data from field observations by group and informal discussions with farmers and development agents (DAs).

Categorizing farmers into different socio-economic groups was done entirely by the farmers themselves using local criteria such as (1) food security status and (2) draught oxen ownership and the number of other livestock held by their household. The aim for differentiating farmers into groups was to include farmer knowledge associated with different levels of resources, as the respective farmers may also have different views on SQ degradation. Three farmer wealth groups were identified in the study catchment, i.e., poor, medium and rich.

Rich farmers were defined as those who are able to feed the household members throughout the year, medium farmers were those who sometimes have problems with their daily food supply, and poor farmers were those with no means of getting daily food and who were thus dependent on the sale of fuelwood, grass and wage labor for most months of the year. Physical assets such as the condition of the house, farm size and ownership of permanent trees and other crops were also considered as additional criteria for categorizing farmers into different wealth groups. Resource-rich farmers accounted for only 13% of the total households in the study area. Medium farmers constituted about 47% and the rest were poor farmers. Based on the list of farmers assigned to each wealth category, names of farmers were randomly drawn and these farmers were participated in the SQ assessment survey in the catchment.

### 4.2.3 Participatory transect walks and group discussions

Each field transect walk took place with a group consisting of five farmers from each of the three wealth categories (total of 15 farmers). The individuals were randomly selected to participate because it was impractical due to group size for all the household heads to participate. Doing so would have been problematic not only for the walks but also for the discussions and consensus building that were needed to extract accurate and representative information from all economic groups. The transect walks and discussions were guided by the author with two development agents serving as facilitators.

The participatory transect walks and field observations were conducted in two different months. The first was in June 2009 before planting and the second in September 2009 at the vegetative stages. In June it was easy to identify and differentiate SQ indicators such as erosion, texture, color, hard surfaces, and terrain factors. While the land was being prepared for planting, it was also very easy to visually identify management practices, soil conservation efforts and tillage effects resulting in both good and poor SQ conditions. Similarly, in September it was easy to observe differences in SQ across the landscape using biological indicators, e.g., weeds, grasses and crop performance at the vegetative and flowering stages.

Prior to the transect walks, the research goals and type of preliminary information that was to be obtained (i.e., the dominant soils and land-use practices in relation to SQ degradation indicators across the landscape) were explained to the farmers. Once awareness had been created, the participants in consultation with facilitators planned the route considering diversity of topography, soil types, land-uses and catchment-related degradation problems. In short, the transect was designed to cross several land-uses and soil types as much as possible, with at least part of it aligned perpendicular to the direction of the main drainage course. The route was neither a single straight line nor confined to the most accessible roads or paths, as such a strategy could give a false perception about the area. Once the route to be followed was agreed upon, the walk began at a point near the hydrological divide of the catchment and continued downhill toward the drainage line.

A specific checklist of issues that guided the discussions during the transect walks and field observations was developed. These included: (1) identifying observable SQ indicators of erosion such as rills, sheet wash, gullies, root exposure, pedestals, rock exposure, sedimentation or deposition and relative severity of the erosion indicators, and reasons for continued soil erosion processes. The frequency of rills, gullies and other soil erosion indicators on the surface was counted per 100 $m^2$ quadrants at several points along the transect to estimate the relative severity of erosion indicators on SQ; (2) observing soil color, texture, thickness of topsoil, workability, drainage, dominant landform, soil fertility and management requirements and practices across different soil quality soils; (3) observing crop and weed species SQ indicators in the landscape; (4) observing general land husbandry practices, and their relationship to SQ degradation; (5) categorizing SQ conditions and identifying hotspot degraded areas using the indicators; (6) determining the spatial variability of SQ based on field observation by the farmers participating in the transect walks. Geographical Positioning System (GPS) readings according to farmer understanding of SQ and hotspot degraded areas were taken during the walks.

During the transect walks, the author and development agents took note of indicators of SQ degradation associated with water erosion, soil fertility, weeds and crops, and management practices based on information given by the participant farmers. Occasionally, open-end interviews were also carried out with local farmers within the catchment along and after the transect walk. Group discussions were conducted after the walk focusing on the existing status of SQ and the diagnosis indicators employed in the catchment. Observations during the walk were presented to the household heads to discuss, review, and reach consensus about (sometimes to vote) by a designated presenter. The transect walks were implemented in the morning, whereas group discussions were held in the afternoon of the next day.

In order to have a common understanding about the SQ indicators (e.g., soil erosion, soil fertility, soil thickness, yield, etc.), assessment categories, and severity of the degradation and its main causes, the group discussion meeting was held among the 15 farmers involved in the transect walk and the other 52 household head farmers in the catchment. During this group discussion, the 15 farmers presented the common SQ indicators, SQ categories and general resource variability across the study catchment. These farmers also described the appearance of each of the indicators in the fields and their associated causes. The farmers who participated in the transect walks analyzed all the soil quality indicators during the group discussions to establish a final list of observable SQ indicators based on consensus using their defined criteria to categorize SQ into categories of high, medium or low soil SQ status in the catchment. Farmers used their experience to decide which of the listed indicators describes a relatively more severe SQ degradation than the others.

### 4.2.4 Household interviews

Forty-two household heads were chosen for the questionnaire interview at random among the farmers who had participated in the transect walks and group discussions (Appendix 1). The interview was carried out to complement the information collected during the transect walks and group discussions. This was done by collecting data on individual farmer knowledge of a range of SQ indicators that they used to identify the SQ categories. The interview thus addressed specific information not well covered during the transect walks and group discussions. This was done based on the assumption that each SQ indicator mentioned in a group discussion might not be representative for every farmer when categorizing the SQ categories. Having such information was helpful to identify the indicators most frequently used by the local farmers as diagnostic criteria for the SQ categories into high, medium or low. The interview also gave the chance to explore the status of the fields farmers possessed with respect to the SQ categories described in the transect walks and group discussions.

### 4.2.5 Data management and analysis

Data management was handled using a Microsoft Excel spreadsheet. All spatial data (point location using GPS) for each SQ category and source of runoff and sediment were identified based on the consensus of the participant farmers and entered into the spreadsheet. The data were then accessed by Geographical Information System (GIS) software and used to develop a SQ map that helped identify critical sources of runoff and sediment delivery. In addition, data analysis was carried out using SPSS release

18.0 software. Descriptive statistics such as frequencies and percentages were used. Chi-square ($\chi^2$) was applied to test whether a particular SQ indicator was significantly used by the interviewed farmers or not while categorizing the SQ.

## 4.3 Results and discussion

### 4.3.1 Participatory soil quality diagnosis

The results of the participatory SQ survey indicate that farmers have the experience and knowledge to assess SQ status and the severity and determinants of SQ degradation. The local farmers identified many SQ indicators in the transect walks and described the SQ status based on their own diagnostic criteria (Tables 4.1 and 4.2). Table 4.1 shows that the local farmers' SQ indicators ranged from physical (soil-related indicators) to biological (yield and yield components) while Table 4.2 shows how they categorized their soil in local terms without yield and yield component information.

Indicators related to crop yield and erosion (e.g., soil depth, color) were often used by the farmers to classify their soils into the SQ categories high, medium and low. Their classification was not limited to the soil nutrient status but also considered soil erosion, fertility, color, thickness, water-holding capacity, yield and crop performance indicators. Soil quality was seen as dynamic by the farmers, since a particular unit of land can have high or low SQ based on the type of management imposed or natural processes, including erosion, that were observed.

The farmers used popular local terms for good, medium and low SQ (Table 4.2). They stated that dark soils are fertile with high water-holding capacity and that they generally produce good crop yields. The local term *′Diqua′,* meaning fertile soil, was commonly used to describe good SQ. According to the farmers, medium soil depth, mixed red and dark color, and presence of some stone out-crop on the soil characterized medium SQ. Red, white and yellow colored soils were usually used by local farmers to describe poor SQ. The farmers thought that poor soils showed low fertility, a tendency to dry up quickly and to generally produce lower crop yields, particularly in low rainfall seasons. The farmers added that poor soil can be described by shallow depth, high weed infestations, a sandy texture, and a very loose surface that is easily detached by raindrops and runoff (Table 4.2).

Table 4.1: Diagnostic criteria of soil quality (SQ) indicators into high, medium and low SQ categories agreed on by farmers in Mai-Negus catchment, northern Ethiopia

| SQ indicator | Diagnostic criteria | | |
|---|---|---|---|
| | High soil quality | Medium soil quality | Low soil quality |
| Crop yield[a] | Teff (*Eragrostis tef*) yield more than 1.5 t $ha^{-1}$ | Teff (*Eragrostis tef*) yield 1.0 to 1.5 t $ha^{-1}$ | Teff *(Eragrostis tef)* yield less than 1.0 t $ha^{-1}$ |
| Crop appearance and vigour | Overall crop is dark green, large, tall, in a dense stand, even growth, matures on time | Overall crop is light green, small, thin stand, uneven growth and late to mature | Overall crop is poor, stunted, discolored, uneven stand, rarely matures |
| Weed infestation/ incidence[b] | Low weed biomass and incidence but high in diversity and demanding least labor | Some how high biomass and diversity, demanding relatively less labor | Higher biomass due to high weed infestation but low diversity, demand high labor |
| Soil fertility | Soil is high potential nutrient with little or no fertilizer need | Soil needs some inputs as its potential is decreasing | Very low, needs higher fertilizer inputs for production |
| Soil erosion | Little or no erosion evident and topsoil resists erosion | Signs of sheet and rill erosion and some topsoil blows away, moderate erosion level | Considerable topsoil moved, rills, gullies formed that resulted in severe erosion |
| Soil compaction | Soil stays loose, does not pack | Thin hardpan or plow layer | Soil is tight and compacted, thick hardpan |
| Moisture in dry season | Soils holds moisture well, and gives and takes water easily | Soil is drought prone in dry weather | Soils dries out very fast and resulted in wilted crops |
| Topsoil thickness | Soil is deep to a root or water-restricting layer | Topsoil is shallow (about plow depth) | Subsoil exposed or near surface |
| Earthworm population | Soil has numerous worm holes and castings, birds follow tillage | Few worm holes and castings | No worm casts holes or activity |
| Fertilizer response of soil | Soils are responsive to some fertilizer | Demanding high fertilizer input | Need higher fertilizer rate |
| Soil tilth/ workability | Soil is easy to work or soil flows and falls apart | Soils difficult to work or need extra passes | Plowing is hard or soil never works down |
| Soil color | Surface soil color is dark, dark brown, dark gray, black | It is brown, gray or reddish | It is light, light yellow, light gray, or orange white color |
| Soil texture | Texture is clay loam, loamy, loam clay | Texture is too light or too heavy but presents no or little problem | Texture is extremely sandy, or clayey rocky |
| Drainage | Water drains at good rate, no ponding, and moves through soil progressively, soil not too wet and not too dry | Soil drains gradually, slow to dry out, water remains on surface for short periods, eventually drains | Poor drainage as soil is often oversaturated or waterlogged for long periods, very wet ground for long time |

[a] *Teff is the most commonly grown crop in the catchment regardless of soil quality category. That is why farmers selected and used its grain yield to categorize soil quality.*
[b] *Farmers can identify weed species that grow on productive soils, heavily eroded surfaces and heavily degraded gullies, or that indicate extreme shortage of nutrients and moisture, and the trend in declining soil quality.*

Table 4.2: Consensus-based description of soil quality indicator terms used for classifying high, medium and low soil quality by local farmers in Mai-Negus catchment, northern Ethiopia

| Soil descriptor (local terms) | Translation |
|---|---|
| *Reguid* | High soil quality |
| *Tselimo hamed* | Darkish soil |
| *Aeman zeibilu* | Not stony out-cropped |
| *Diqua`* | Highly fertile soil |
| *Reguid hamed* | Deep soil |
| *Maekelay* | Medium soil quality |
| *Hawsi Walka / tselimo* | Mix of red and dark soil |
| *Maekelay* | Medium soil depth |
| *Kirub Aeman zelebo* | Some stone out-crops |
| *Rekik* | Low soil quality |
| *Keih, hamekushtay hamed* | Red soil, light yellow soil |
| *Aeman zelebo* | Stone out-crops dominate |
| *Enda-Tsihayay* | High weed infestation |
| *Hashewama* | Sandiness |
| *Teferkashay* | Loose soil |
| *Rekik hamed* | Shallow soil |

In addition, farmers reported that *reguid* (deep soil) has better water-holding capacity, is more fertile and therefore more productive. This is consistent with research findings by Haile (1995) and Corbeels et al. (2000) in reports that focus on soil fertility, which is just one indicator of SQ. Systematic studies using farmers' soil knowledge and their local soil classification system have been carried out in some developing countries, such as Nigeria (Osunade 1988), Indonesia (Grobben 1992), Zambia (Sikana 1993), Rwanda (Habarurema and Steiner 1997) and Kenya (Macharia and Ng'ang'a 2005). The present study adds to the scientific knowledge by incorporating the farmers' experience and understanding of SQ in northern Ethiopia.

The SQ indicators identified in this participatory survey reveal that the valley bottom of the catchment had medium to high SQ, whereas low SQ was widespread on the rolling-hills, central-ridge, and mountains landforms in the catchment. This is illustrated by the transect walk diagram (Figure 4.2) and spatial distribution of SQ categories (Figure 4.3). It is important to note that a wide range of criteria was used by the farmers to describe their field SQ. Farmers were not only concerned with factors such as soil fertility, depth, color etc., and its suitability for crop production but also took into account a broad range of other issues related to previous management and productivity history and the comparison with other nearby fields. In agreement with this, Elias (2000) reported that farmers´ soil description and other management decisions are based on a range of factors in southern Ethiopia. Such findings contrast with the classic approaches in evaluating soil, which only use the physical aspects to assess inherent or dynamic soil qualities in determining agricultural or environmental values (Beyene et al. 2001). Despite such knowledge of the local communities, the problem of SQ degradation still continues in many areas of Ethiopia. Therefore, to tackle this common problem, approaches that fully involve the local community should be designed in such away to address the concern of resource degradation in Ethiopia and other similar areas.

In general, this SQ study is rooted in field experiences of local farmers, which translate the descriptive indicators based on soil look, feel, smell, workability, productivity and presence of biota. That could be part of the reason why Pawluk et al. (1992) and Harris and Bezdicek (1994) remarked that farmer-derived descriptive soil indicators are valuable for describing SQ in meaningful terms. The present study also provides groundwork for validating an analytical assessment of SQ indicators that based on quantifiable laboratory results in order to be used as a tool for management and policy decisions at large scale. It is thus concluded that farmer knowledge regarding management of SQ throughout Ethiopia should be utilized and well documented.

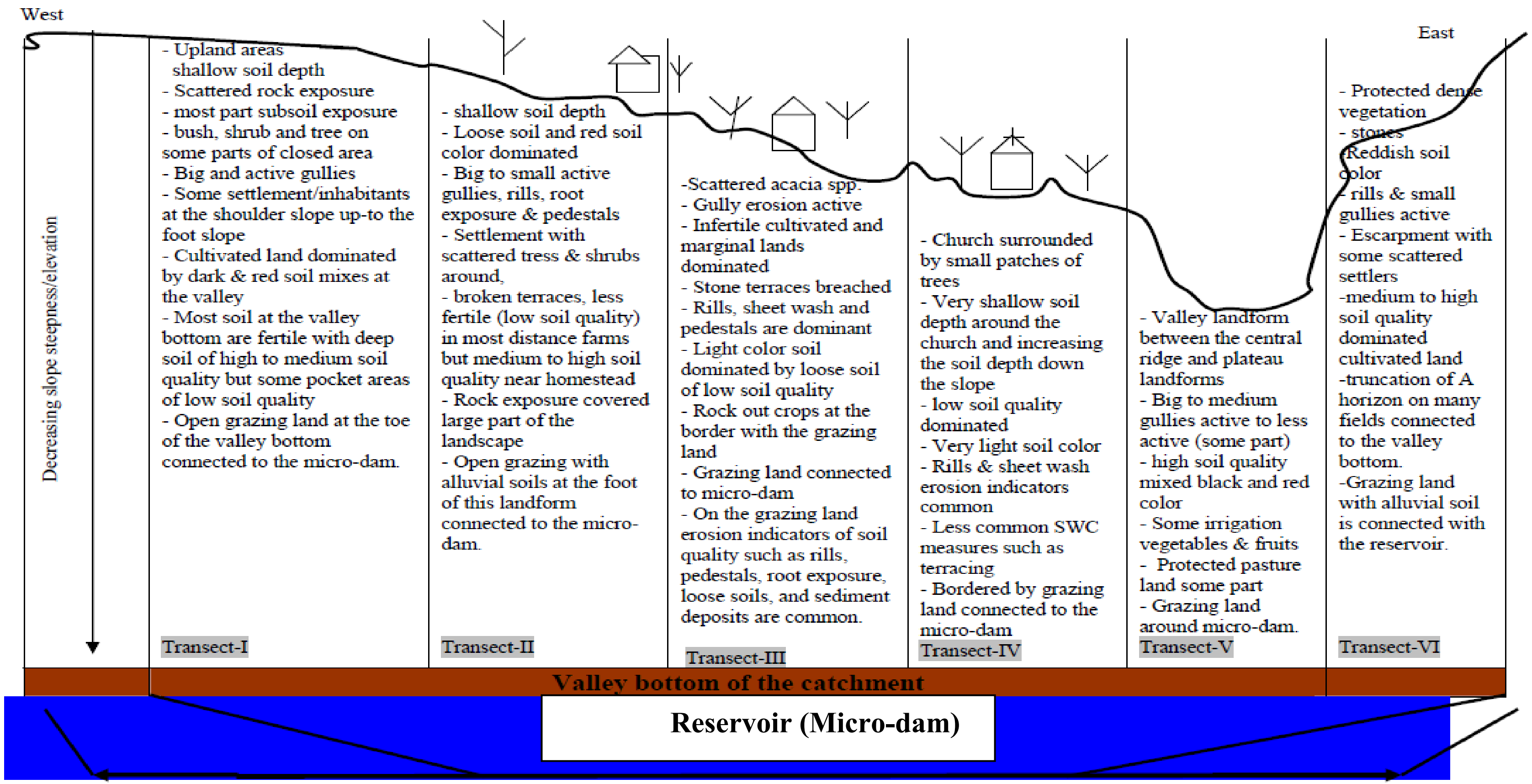



Figure 4.2: Transect walk diagram showing soil quality indicators and other resource variability across the landscape according to farmers' views in Mai-Negus catchment, northern Ethiopia. Each column designated by I-VI was subjected to each transect route in the catchment

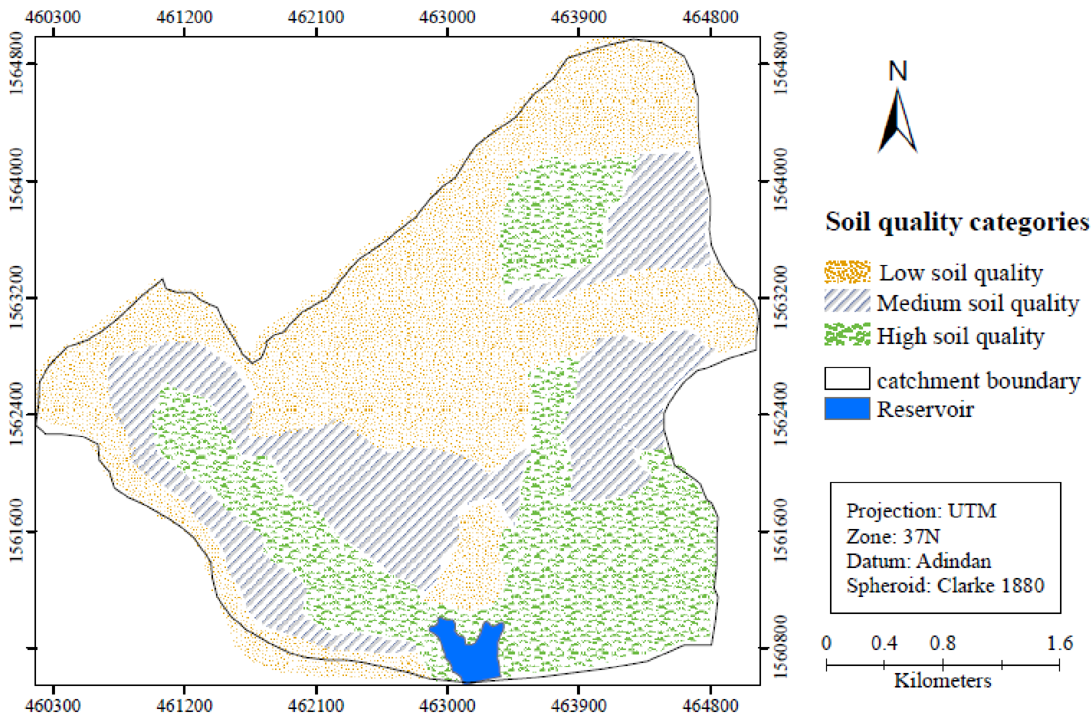



Figure 4.3:Spatial distribution of soil quality categories as identified during participatory farmer transect walks in a northern Ethiopia catchment. Pocket small fields were generalized during classification to each of the soil quality categories because tracing them manually would have been too time and labor consuming

### 4.3.2 Severity of degradation as soil quality indicators

For evaluation of SQ, it is desirable to select indicators that are suitably related to the intended soil function (Karlen et al. 1997). Thus, key indictors of SQ were identified and assessed during transect walks by a group of farmers (Figure 4.2 and 4. 3). During the transect walks, the group of farmers having different economic status identified SQ indicators that describe the severity of SQ degradation and then discussed these with other household head farmers in the study catchment. After the discussion, a consensus was reached on the list of SQ indicators. The frequency of rills, gullies and other SQ indicators that were counted at several points along the transect walk was summed to estimate the abundance of such indicators and then the severity of degradation with respect to the SQ indicators was ranked (Table 4.3). The SQ indicators identified by the farmers as the most important severity indicators in the study catchment were rills, followed by root and subsoil exposure (Table 4.3). Indicators of SQ in the form of erosion and sedimentation processes were easy to identify during the transect walks.

The process of achieving community consensus (involving above 60% of the land owners) on ranking SQ indicator in the form of erosion, soil depth and color led to a huge debate among the farmers in the meetings. In some cases, farmers had to visit the actual fields so that they could demonstrate the differences in the severity status of an indicator. In order to verify further whether the participants in the group discussion agreed with the farmer group participating in the transect walks, the overview of the SQ descriptors was discussed, which resulted in important reactions among all the participants. Final decisions on the common and relative severity of the SQ erosion indicators showing that the presence of active gullies, subsoil exposures and rills in the catchment soil surface (Table 4.3) indicated that the erosion position was severe, and soils in such conditions were believed to be not sustainable for crop production unless appropriate remedies are taken. In the study catchment where soil surfaces showed evidence of erosion indicators such as deposition, splash pedestal, sheet wash and soil structure becoming loose; it was understood by the farmers that SQ was deteriorating. Therefore, the order of erosion severity ranking reflects the scale of soil damage caused by widespread erosion features as shown by their higher frequencies (Table 4.3). This also helps in identifying possible causes and solutions from the farmers' point of view.

When farmers met, they actively participated in describing the status of the soils in the fields they possessed and identified production constraints and potentials. They were differentiated the SQ indicators that had evolved because of ongoing or past soil erosion effects and other related soil management practices (Table 4.3). This helped the farmers to appreciate the history of soil erosion in a segment of field or landscape profile, and to judge whether the soil erosion situation was high, moderate or low (Okoba et al. 2007). Many farmers could also evaluate the conditions of their own fields using changes in topsoil characteristics due to the effect of erosion. They were also able to link the changes in soil conditions due to erosion to crop productivity.

The evidence of the existing soil erosion as one SQ indicator was demonstrated by identification of many on-site erosion and soil fertility indicators and of off-site reservoir sedimentation indicators that were observed during the transect walks (Table 4.3). The most frequently observed erosion indicators were rills, root exposure, and subsoil exposure (Table 4.3; Figure 4.4). Even though the numbers of gullies are few as compared to the other indicators, their contribution to sedimentation and soil loss might be significant since most of the gullies were active. The severity of sheet wash and pedestals can be masked, as these are easily destroyed by human and animal activities.

Table 4.3: Consensus-based soil quality indicators, total frequency and relative severity as ranked by local farmers in Mai-Negus catchment, northern Ethiopia

| Soil quality descriptor | Total frequency count | Severity ranking [a] | Indicator due to [b], [c] | Measure |
|---|---|---|---|---|
| Rills | 89 | 1 | Ongoing soil losses | Presence of rills |
| Root exposure | 82 | 2 | Past soil losses | Soil depth differences |
| Subsoil exposure | 51 | 3 | Past soil losses | Soil depth differences |
| Soil color change | 43 | 4 | Ongoing soil losses | Direct observation |
| Sheet wash | 38 | 5 | Ongoing soil losses | Direct observation |
| Build-up of soil against barriers | 27 | 6 | Past soil losses | Soil accumulation depth |
| Sedimentation | 23 | 7 | Ongoing soil losses | Sediment thickness |
| Splash pedestals | 18 | 8 | Ongoing soil losses | Soil depth differences |
| Presence of gullies | 11 | 9 | Past and ongoing soil losses | Gully expansion or development |
| Rock exposure | 7 | 10 | Past soil losses | Direct observation rock out-crops |

[a] *Where severity ranks in the order 1 = severe degradation and 10 = low degradation. This ranking is based on the count made for each soil quality indicators using erosion features along the transect walks in 10 m x 10 m area. Farmers noticed the presence of few gullies as compared to the other indicators. But gullies may contribute to high soil loss as they are active in the study area, and this demands further investigation.*

[b] *Farmers described ongoing erosion indicators are those indicators that developed within a single or 2-3 rainfall events on the soil but where evidence of such indications were easily destroyed during tillage processes; they are thus considered as a reversible erosion indicators.*

[c] *Past erosion indicators were described as those indicators that had developed increasingly due to more severe erosion situations generally related to negligence of the recurring of ongoing indicators on time. These can either be or not be destroyed during tillage operations or any other restorative management.*

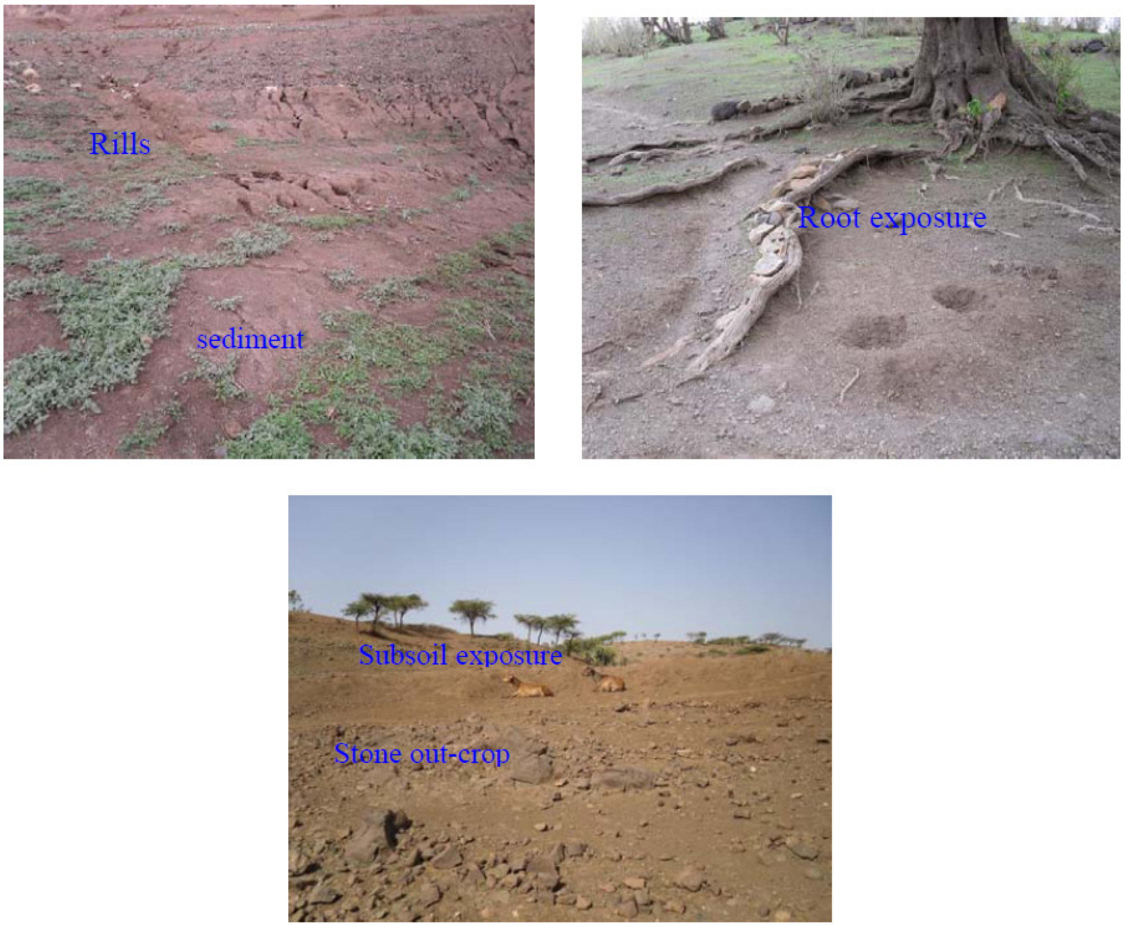



Figure 4.4: Most frequently observed soil quality indicators due to water erosion during transect walks with farmers in June 2009: rills, sediment deposition, root exposure, subsoil exposure and stone out-crop in Mai-Negus catchment, northern Ethiopia

Stone terraces were the most common structures designed to reduce soil loss in the study catchment. However, the failure or breaching of these soil and water conservation structures due to runoff force from upper slopes and human and livestock interference has resulted in subsequent erosion damage in the downhill fields by creating new gullies or changing the direction of the flow and breaking other conservation structures. Generally, the participatory survey confirmed that farmers have adequate knowledge related to factors determining SQ. However, they are not able to tackle the problem of SQ deterioration mainly because of lack of capital, labor and technical options in addition to their reluctance. They suggested that the food insecurity problem affects the interest of farmer to take proper measure against degradation, as they give priority to actions related to their immediate daily food requirements.

The SQ indicators identified by the farmers were also ranked as more problem[1], less problem[2], no problem[3] and don't know[4] (Figure 4.5) as compared to the status in the past 5-10 years. Soil erosion followed by soil fertility was considered by the majority of the farmer (about 80% in the group discussions) as a more problem. This was followed by soil dryness and compaction in decreasing order. On the other hand, soil workability followed by soil compaction was pointed as a less problem in the study catchment. The number of farmers who voted for no problem for soil workability was larger than for the other indicators, but the number of farmers who voted for no problem for soil fertility and erosion was very small. Most farmers in the catchment also understood that SQ was declining as evidenced by the high fertilizer demand of soils, and they thought that the problem might be getting worse through time. However, some farmers stated that the increasing demand for fertilizer is associated with the need to increase productivity. Considering the existence of such strength and limitation of local knowledge, appropriate strategies that involve and empower the local farmers should be designed to halt the SQ degradation problem.

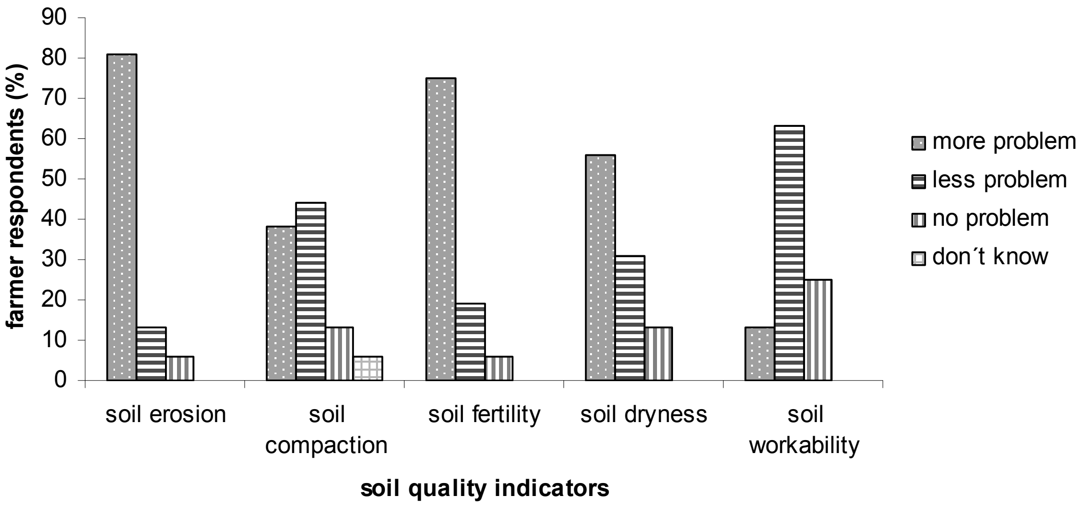



Figure 4.5: Severity of soil quality indicators from different levels of problem perspectives of local farmers in Mai-Negus catchment, northern Ethiopia

[1] Clearly visible erosion, poor soil fertility and water-holding capacity compared to productive soils. Soil is virtually lost and not suitable for agricultural systems; the original resources are largely degraded and need major investments and work to restore to full productivity.

[2] Fields that showed good productivity but strongly declining fertility as it has shown by some SQ indicators. These are still suitable for the local farming system. Inherent quality and biotic resources are partially destroyed and as a result soils demand major improvement efforts from the land users.

[3] Soil fullfills intended function and is suitable for local farming system; full productivity with some additional inputs.

[4] Not enough observations or knowledge whether the trend of a particular SQ indicator is changed or not.

Farmers participating in the transect walks identified that the steepest landscape parts are the source of large amounts of runoff and sediment (hotspots of degradation) (Figure 4.6). This confirms the findings of Hurni et al. (2005) who reported that degradation is not uniform, even in the same landscape. Farmers noticed that these source areas need first priority when introducing management practices. This is because as farmers underlined during the transect walks that the sediment sources such as the gullies at the lower part of the catchment are formed as a result of the runoff coming from the steeper areas. But cultivation close to the margin of the gullies and over grazing increases the collapsing of gully sides and development of wider gullies due to high runoff. These areas are thus the source of high sediment yield in the catchment. This was supported by the farmers during the group meetings, and they agreed that small areas of land be likely to be the source of disproportionately large amounts of runoff and sedimentation within the catchment. This indicates that confining mitigation to erosion source areas costs less than targeting wider areas in a resource-poor country such as Ethiopia using the local knowledge as input for decision making. The results of this study suggest that environmental programs should be focused on critical problem source areas within a hydrological unit instead of introducing large-scale measures.

Furthermore, when farmers were asked to suggest remedial actions and solutions to the problem of SQ degradation, they suggested more than one action. The most important management measures suggested were constructing terraces throughout the catchment integrated with planting economic trees and shrubs, enclosed low SQ areas, use of fertilizers and appropriate cropping systems and other related management practices. The assumption is that integration of such practices considering the land-use and terrain factor differences can rehabilitate degraded areas rapidly. Zero-grazing using a cut and carry system of grasses introduced recently in the study catchment was also appreciated by the farmers as part of the important approach to improve SQ degradation as compared to stocking the livestock for the whole year on the grazing land (Figure 4.7). But the area currently used as protected land for the cut and carry grass system was very small in proportion.

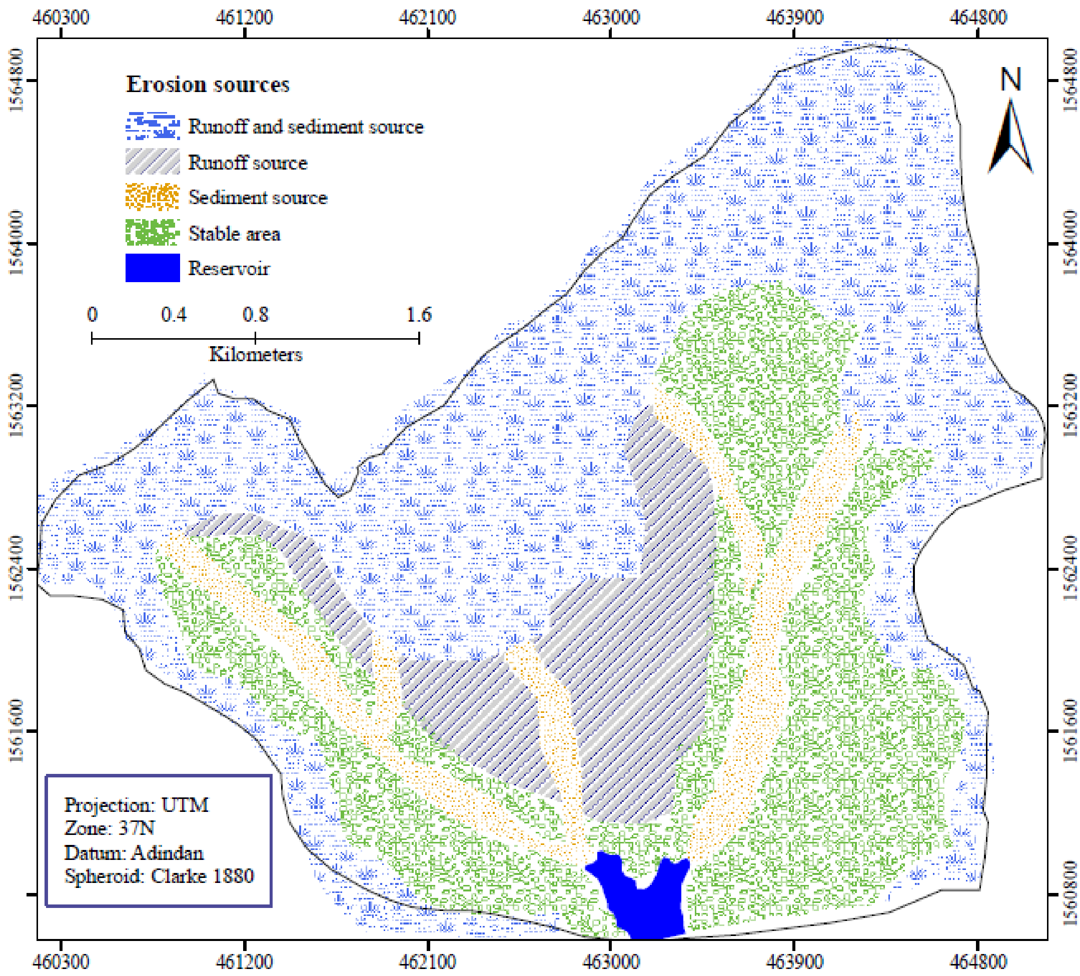



Figure 4.6: Overview of high runoff and sediment sources (hotspot) areas based on information from farmers who had participated in transect walks in Mai-Negus catchment, northern Ethiopia

Farmers also pointed out that in order to successfully rehabilitate degraded areas by enclosing, active involvement of the farmers within the catchments is needed, and potential conflicts of resources among land-users should be first resolved. Farmers whose land is to be enclosed should get compensation land or other equivalent incentives from the government or supporting agents. Strict local regulations should be setout by the farmers themselves to manage effectively any destruction or interferences by humans or livestock to enclosed areas. Strategies should also be designed to grow trees that increase income for the local farmers while improving SQ in the enclosures. In the long term, when using such an approach, resource exploitation from the enclosures can provide sustainable support for the farmers and the environment.

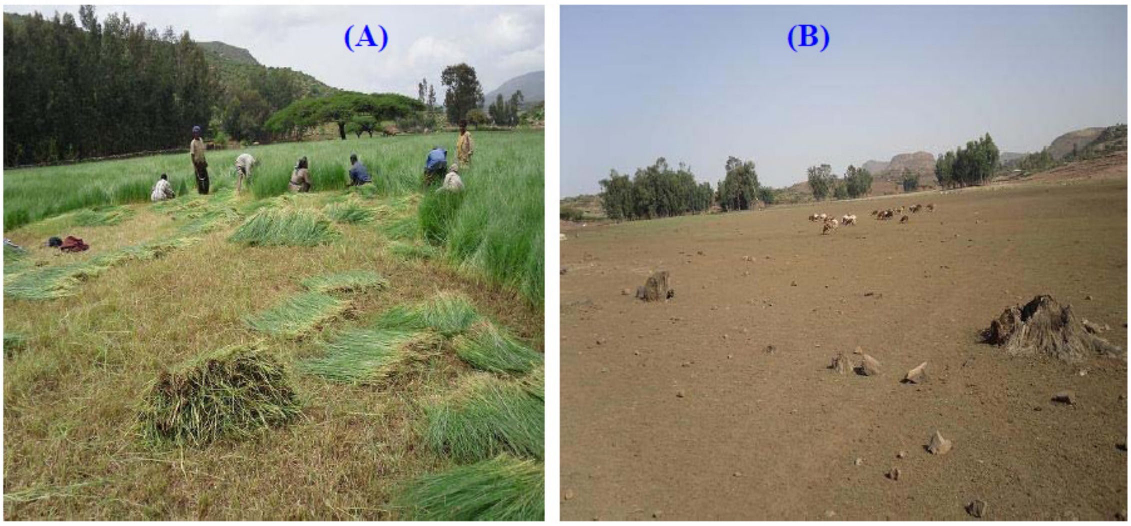



Figure 4.7: (A) Land rehabilitation after two years of enclosed pasture under cut and carry grass system; (B) livestock stocked throughout the year in Mai-Negus catchment, northern Ethiopia, July 2009

### 4.3.3 Farmers' understanding of causes for declining soil quality

The farmers´ group discussions based on the transect walk information as a brain storming indicated that erosion negatively impacted the SQ (crop production) and the overall environmental condition through sedimentation of reservoir and field borders. It also revealed that rainfall intensity is high, resulting in severe soil losses when the soils are bare. Soil erosion levels in the study catchment are still high due to the fact that farmers are not building much progress with respect to conservation measures and land-use redesign. This might be because many farmers are engaged in off-farm activities to maximize income regardless of the seriousness of the ongoing soil erosion. Besides, lack of full involvement of local community on problem identification and suggestion of remedies to problems before the implementation of new recommendations might make farmers reluctant to adopt the introduced soil and water conservation measures. By involving farmers from the beginning to the final stage of a new technology, the constraints of the recommended techniques from the soil productivity and environmental perspective can be understood better, and the farmers also feel ownership. Generally, the observations from the transect walks indicate that steep-slopes have a tendency to be relatively vulnerable to water erosion as indicated by widespread subsoil and root exposure, rills and shallow active gullies, and sediment deposition and formation of large gullies on flat to gentle slopes (Table 4.4).

Table 4.4: Observed soil quality indicators and their causes based on local farmers' consensus in meetings following transect walks in Mai-Negus catchment, northern Ethiopia

| Soil quality indicator | No. of observed indicators | Observable causes (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Poor soil cover | Steep slopes | Runoff | Poor terracing | Loose soils[m] | Others[n] |
| Rills [a] | 89 | 62 | 14 | 11 | 5 | 6 | 2 |
| Gullies [b] | 11 | 9 | 4 | 75 | 7 | 4 | 1 |
| Root exposure [c] | 82 | 4 | 6 | 56 | 3 | 7 | 24 |
| Red soil color [d] | 43 | 3 | 12 | 28 | 1 | 4 | 52 |
| Stoniness [e] | 8 | 7 | 16 | 37 | 6 | 1 | 23 |
| Rock out-crops [f] | 7 | 4 | 5 | 65 | 6 | 9 | 11 |
| Sedimentation [g] | 23 | 4 | 8 | 59 | 8 | 2 | 19 |
| Sheet-wash [h] | 38 | 5 | 3 | 62 | 4 | 16 | 10 |
| Splash pedestals [i] | 18 | 3 | 2 | 45 | 0 | 16 | 34 |
| Broken SWC structures [j] | 53 | 4 | 9 | 12 | 19 | 7 | 49 |
| Subsoil exposure [k] | 51 | 2 | 5 | 65 | 3 | 20 | 5 |
| Soil fertility loss [l] | 45 | 14 | 11 | 25 | 3 | 4 | 43 |

[a] *Continuous or discontinuous channels developed after an intensive rainfall event and started from a short distance that concentrate into channel; can be easily destroyed by tillage.*
[b] *Wider and deeper than rills and locally easily distinguished from rills that a 7-year-old child cannot jump across it.*
[c] *Exposure of roots after topsoil is removed by runoff and splash effect of raindrops. This indicates that topsoil had been removed thus weakening the nutrient-rich soils for crop stability.*
[d] *Indicates that topsoils rich in organic matter have been removed by runoff; also used as an indicator of severe erosion leaving unproductive shallow soils.*
[e] *Many stones out-cropped to the soil surface signified that the overlaying soil layers have been washed off by water erosion.*
[f] *Exposed rocks indicate that almost the whole part of the overlying soil layers have been removed by runoff flow.*
[g] *Identified by the the depth of soil accumulated that burying crops/grass indicators. Such effect is considered as fertile or infertile in a field depending on the intended soil functions. The deposited soils could be fine soil materials which are nutrient-rich or coarse sandy/stony deposits or a combination of these.*
[h] *Noticeable by its runoff flow path that leaving surfacse showing the removal of very small part of the topsoil in the direction of the flow.*
[i] *Describes the craters formed by raindrops and runoff detachment impact on soils which create soil column indicators as a result of stones, roots or crop residues etc.*
[j] *Noticeable of gaps or breaching in formerly continuous bunds of conservation measures*
[k] *Described by shallow soil depth and rock out-crop exposures. Thus, it used as an indicator of severely eroded soils.*
[l] *Fields marked by shallow soil depth and poor crop vegetative performance.*
[m] *Soils that are exposed to erosion and raindrop scouring effect as these have poor soil structure and poor water-holding capacity.*
[n] *Includes management practices such as tillage, fertilizer, removal of crop residues, grazing pressure, deforestation and human and livestock interference.*

Farmers were also asked to list and rank the main causes for declining SQ indicators (Table 4.4). They agreed that the main causes for the observed increasing soil erosion based SQ indicators were poor soil cover, steep slopes/terrain, high intensive rainfall, inappropriate spacing of terraces and untimely maintenance of conservation measures and the presence of loose soil in the fields (Table 4.4). The farmers also agreed that the number of observations of rills was highest as compared to the other indicators. The main cause for this indicator was identified as poor soil cover followed by steep slopes. The presence of poor soil cover and steep slopes in many parts of the catchment caused the formation of more rills by runoff. This is supported by Poesen (1984) and Herweg and Ludi (1999) who observed as slope-gradient increasing and in conditions with poor soil cover there is a tendency of rill formation as these increased the concentrated overland flow.

Farmers agreed that for the other indicators such as gullies, sheet-wash, red soil color, subsoil and root exposure and sedimentation, the main cause was excess runoff, which aggravated by high rainfall intensity, terrain, and poor soil cover (Table 4.4). The interference of human activities on steep terrain can aggravate the effect of runoff on SQ. Broken soil and water conservation structures coupled with wide spacing and inappropriate structure may also increase the runoff amount and its effect on SQ. The reasons for continued soil erosion processes in the study catchment are thus interrelated and call for a comprehensive approach that takes into account environmental variables such as slope, soil, crop cover and rainfall conditions, as well as the management practices. For example, regular bund maintenance mainly on terraces height increment is essential to maintain the effectiveness of bunds in allowing the continued reduction of slope-steepness and overland flows, in addition to the introduction of other appropriate techniques.

The soil thickness and vegetation cover observed in the field and informal discussions with farmers and experts indicated that SQ has been declining due to erosion, and that nutrients are also mined because of erosion effect and continuous cropping with minimal crop rotation and fertilizer inputs. Gullies have long been established and still continue to expand (Figure 4.8A), which in turn has increased the reduction in farm and grazing land size and therefore aggravated land fragmentation and land pressure. Rills and sheet erosion are also frequently visible on cultivated land mainly on teff (*Eragrostis tef*) fields and other croplands located on the hillside slopes of the study catchment and are a challenge for SQ maintenance.

The results of this study also suggest that to improve the SQ degradation in Ethiopia, limitations of the existing conservation measures and land-use systems should be assessed from the context of the local community in each catchment, besides the contribution of local communities to sustain the technologies. This assessment is based on field observations that indicated that past efforts on conservation measures did not greatly improve the situation of soil degradation in large parts of the study catchment, though some areas are getting substantially better. There was evidence supporting this, as many fields were not protected, terraces were destroyed and not regularly maintained, gullies continued to expand and develop, and there were highly degraded shallow marginal soils and poor soil cover in many parts of the catchment (Figure 4.8).

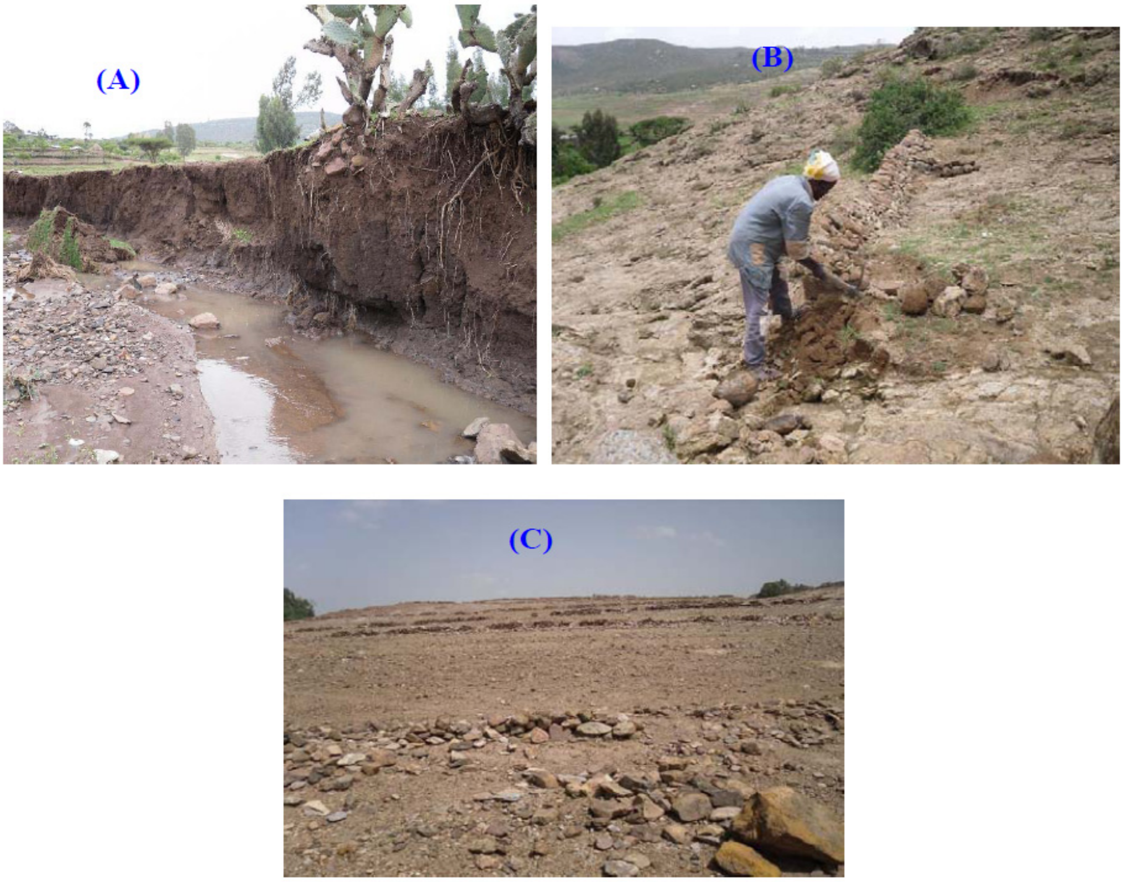



Figure 4.8 Continued gully development (A) rock out-crop exposure after topsoil has been removed by erosion (B) breached stone bunds without maintenance on shallow soil in marginal area (C) in Mai-Negus catchment, northern Ethiopia, July 2009

Therefore, designing solutions to the processes of SQ degradation in the study catchment and other similar areas should consider the landforms, potential erosion sources areas, appropriateness of the selected technology and full involvement of local farmers in all processes to ensure sustainable natural resource management.

Moreover, to clearly understand farmers` knowledge of SQ degradation and the effect of the technologies employed, different approaches need to be attempted. As a general remark, participatory assessment of SQ using the experience of local communities is crucial to rapidly monitor the adoptability of land management systems that sustained gricultural and environmental services. This can assist farmers, decision makers and scientists in formulating and evaluating agricultural soil management systems and land-use redesign against that prevent SQ degradation from end users´ perspectives.

### 4.3.4 Farmer´s use of indicators for diagnosis of soil quality

The Chi-square ($\chi^2$) test revealed that the percentage of the interviewed farmers that used the SQ indicators identified during the participatory group discussions to categorize SQ was significantly different from those who did not use it (Table 4.5 and 4.6). Statistically significant Chi-square values indicate a marked difference in rating between the farmers regarding the use or not use of each of the SQ indicators. The percentage of farmers who used crop yield (95%), top soil thickness (90%), crop vigour (86%), soil fertility (78%) and soil erosion (83%) indicators to categorize SQ significantly ($P = 0.000$) differed from those who did not use such indicators.

In addition, the Chi-square probability levels show significant differences between the proportions of respondents who used soil color, fertilizer response of soils, moisture in the dry season, weed infestation, texture, drainage conditions and earthworm population and those who did not use such indicators to categorize the SQ (Table 4.5). Even though the results of the test are significantly different, the number of farmers who used earthworms as a SQ indicator (14%) to classify the SQ was small compared to the farmers who did not (86%). The number of farmers who used indicators such as soil compaction or soil tilth and workability compared to those who did not use these to categorize SQ was not significantly different at $P \geq 0.05$ (Table 4.5). Those farmers who did not use soil compaction, and tilth and workability to categorize their field SQ might be confused with indicators such as temporal soil dryness, because they assumed that dry soils are compact and difficult to work and so this was not a SQ problem.

Table 4.5: Percentage of farmers that used soil quality (SQ) indicators to categorize their SQ in Mai-Negus catchment, northern Ethiopia (n = 42)

| | Farmers who used SQ indicators[a] | | |
|---|---|---|---|
| SQ indicator | Yes (%)[b] | No (%)[c] | $\chi^2$ probability |
| Crop yield | 40 (95) | 2(5) | 0.000 |
| Topsoil thickness | 38 (90) | 4 (10) | 0.000 |
| Crop performance/vigour | 36 (86) | 6 (14) | 0.000 |
| Soil fertility | 33 (78) | 9 (22) | 0.000 |
| Soil erosion | 35 (83) | 7 (17) | 0.000 |
| Soil color | 31 (74) | 11 (26) | 0.002 |
| Fertilizer response of soil | 30 (71) | 12 (29) | 0.005 |
| Moisture holding in dry season | 28 (67) | 14 (33) | 0.031 |
| Weed infestation/ abundance | 27 (64) | 15 (36) | 0.031 |
| Soil compaction | 16 (38) | 26 (62) | 0.123[ns] |
| Soil tilth and workability | 22 (52) | 20 (48) | 0.758[ns] |
| Earthworm population | 6 (14) | 36 (86) | 0.009 |
| Texture | 29 (69) | 13 (31) | 0.014 |
| Drainage condition | 28 (67) | 14 (33) | 0.031 |

[a] *Values in parentheses are percentages of respondents and without are counts. Percentage total is more than 100% because each respondent chose more than one SQ indicator;* $\chi^2$ *is Chi-squared, ns is non-significant at probability level > 0.05.*
[b] *Indicates farmers that used the SQ indicators to categorize their soils in the field into high, medium or low levels.*
[c] *Shows those farmers did not use indicators for such purposes.*

For all the local terms for SQ indicators, the Chi-square test shows a significant difference between the number of farmers who used these as criteria during SQ categorization and those who did not use (Table 4.6). For instance, the percentage of farmers who used the local term *Diqua`* (fertile soil) (98%) to indicate high SQ was high and significantly different (P = 0.000) from those who did not. The same holds true for all the other local indicator terms. Similarly, the terms *Maekelay hamed* (medium soil depth) for medium SQ, and *Rekik hamed* (shallow soil depth) for low SQ category were used by the highest percentage of farmers as compared to the other indicators in these categories (Table 4.6). The results of the Chi-square test also show that the proportion of farmers who had fields with high (12%), medium (40%) and low (48%) SQ in the study catchment was significantly different at P = 0.011. According to the farmers (88%), most soil in the catchment was in the range of low to medium quality. This reveals that much work has to be done to mitigate the existing SQ degradation.

Table 4.6: Percentage of interviewed farmers who used the local term for soil quality indicators for categorizing into high, medium and low SQ in Mai-Negus catchment, northern Ethiopia (n = 42)

| Soil quality indicator (in local terms) | Translation | Respondents (%)[a,b] | $\chi^2$ probability |
|---|---|---|---|
| *Reguid* | High soil quality | | |
| *Tselim hamed* | Dark soil | 86 (36) | 0.000 |
| *Aeman zeibilu* | No stone out-crop, pure soil | 76 (32) | 0.000 |
| *Diqua`* | Highly fertile soil | 98 (41) | 0.000 |
| *Reguid hamed* | Deep soil | 95 (40) | 0.000 |
| *Maekelay* | Medium soil quality | | |
| *Hawsi Walka/tselimo* | Mix of red and dark soil | 88 (37) | 0.000 |
| *Maekelay hamed* | Medium soil depth | 95 (40) | 0.000 |
| *Kirub Aeman zelebo* | Some stone-out crop | 86 (36) | 0.000 |
| *Rekik* | Low soil quality | | |
| *Keih, hamekushtay* | Red, white, yellow soil | 88 (37) | 0.000 |
| *Aeman zibeziho* | Stone out-crop | 81 (34) | 0.000 |
| *Enda-Tsihayay* | High weed infestation | 71 (30) | 0.005 |
| *Hashewama* | Sandy dominanted soil | 88 (37) | 0.000 |
| *Teferkashay* | Loose soil | 90 (38) | 0.000 |
| *Rekik hamed* | Shallow soil | 98 (41) | 0.000 |

*[a] Percentage total is more than 100% because each respondent used more than one indicator for each SQ category.*
*[b] Values in parentheses are percentage of respondents who used local term for SQ indicators, and without parenthese are the corresponding counts.*

In general, this study indicates that crop yield, top soil thickness, crop vigour, soil erosion and soil fertility were the most frequently cited SQ indicators by farmers, besides the local indicator terms used to describe the SQ. The reason for this frequency was due to their simple visual measurement or judgment compared to the other indicators. Romig et al. (1995) reported that crop growth and yield and erosion indicators were ranked first by farmers in the northern US as the most important properties for describing SQ, which is consistent with the present results.

A similar observation was reported by Saito et al. (2006) and Mairura et al. (2008) who stated soil colors as an important SQ indicator mentioned by farmers. The composition and abundance of weed species on agricultural soils is also a useful indicator of SQ frequently used by farmers, but the local knowledge of plant species has not been well documented. In addition, farmers reported that some weeds that grow in one season may not do so in the next season. In general, this study indicates that such visual approach for SQ classification is rapid, less expensive and is participatory in nature, which has important implications for practical decision-making. In line with this study, case studies elsewhere have shown a consistent rational ways to the need of local SQ indicators in decision-making processes (e.g., WinklerPrins 1999; Ramisch 2004).

### 4.4 Conclusions

This study shows that the assessment of SQ using a participatory survey is an important approach to sustain soil functions as it is quick, less costly and easily reproducible. Such an approach supports successful technology introduction and dissemination targeting the SQ problem areas. Generally, a well-structured local knowledge base on SQ exists in the study area, even though knowledge was not homogeneous among farmers. Many of them exhibited a refined and robust local knowledge and understanding of SQ that can support decision-making to minimize SQ degradation at catchment scale.

The local farmers used soil erosion, soil fertility and biological (crop and weed) indicators together to describe the SQ as high, medium or poor, but there was a significant difference between the number of farmers who used a certain SQ indicator compared with those who did not use it. Since SQ measurement using scientific techniques is expensive, time consuming and limited in upscaling to large areas and complex catchments, the participatory survey approach of assessing SQ can be useful in developing countries where resources are scarce. It can be thus noted that farmer-derived SQ indicators are important for providing the basis for sustainable management and policy decision making. However, for effectively implementing anti-degradation technologies, farmers should understand the issue of the technologies and be fully aware of SQ degradation especially of its nature, scope, and responsible factors. They should suggest possible solutions from the local perspective so that technologies can be implemented easily and adopted sustainably.

A participatory survey also promotes collaboration between local and external participants, and forms the basis for agreed land management planning, implementation and evaluation that can be part of a robust approach for sustainable management of natural resources. However, further research that verifies the SQ categories identified by the local communities using scientific soil measurement should be carried out so as to discover discrepancies and similarities between local and scientific approaches before extrapolation of results to similar environmental conditions.

# 5 EVALUATION OF SOIL QUALITY IDENTIFIED BY LOCAL FARMERS IN MAI-NEGUS CATCHMENT, NORTHERN ETHIOPIA

## 5.1 Introduction

A significant decline in soil quality (SQ) has occurred through worldwide due to adverse changes in physical, chemical and biological soil properties and contaminations by inorganic and organic chemicals (Arshad and Martin 2002). From 1950-2000, over 25% of the 8.7 billion ha of agricultural land, permanent pastures, and forests and woodlands have been degraded (Chadha 1996), with the largest share being from developing countries. Of the world's degraded lands, around 66% are found in Asia and Africa. However, human- induced degradation is most severe in Africa, where 30% of the agricultural land, pastures, forests, and woodlands are degraded, which are major sources of food, incomes, and employment (Sheikh and Soomro 2006). As a result, expansion of global grain production dropped from 3% in the 1970s to 1.3% in the period 1983-1993 (Arshad and Martin 2002).

In many areas of Sub-Saharan Africa, positive feedback dynamics between growing populations, land-cover and climate change have led to a rapid loss in the capacity of soils to deliver essential ecosystem services (Davidson et al. 2003). These changes are not easily reversible and represent major development costs. This challenges the prospects for a better future for Africans, and has potential for increased conflicts over land (Moseley 2001). Moreover, the population in the area is likely to double over the next 25-30 years, rising to an expected ~1.75 billion people (Hendrix and Glaser 2007), which will pose serious pressure on resources and their services. Thus, maintaining the levels of production or planing to increase output in order to meet the needs of the ever increasing number of people requires improvement of SQ (Alemu 2006). Such practical views have ignited the interest in the concept of SQ assessment for many researchers (e.g., Larson and Pierce 1994; Karlen et al. 2001; Barrios and Trejo 2003; Mairura et al. 2008).

In natural conditions, SQ tends to maintain an equilibrium between pedogenetic factors (Parr and Papendick 1997; Masto et al. 2007). According to Masto et al. (2007) however, this equilibrium is easily upset by human-induced activities (e.g., agriculture) and other soil related actions. Such effects are aggravated in arid and semi-arid developing countries such as Ethiopia with its poor technical and financial resources.

Knowledge of SQ is important for developing appropriate anti-degradation measures and designing management plans. However, acquiring SQ data based on field measurements and laboratory analysis is difficult, especially in developing regions. An alternative option for evaluating soil conditions to prioritize areas of intervention is thus necessary. Evidence indicates that assessing SQ degradation based on the knowledge of local farmers is rapid, less costly and has high reproducibility (Pretty 1995; Paytona et al. 2003). Local knowledge generally offers important long-term insights about human responses to environmental change, such as SQ degradation processes (e.g., Neef 2005). However, such a claim should be first assessed in the context of each region before employing the approach for effective soil resource management planning purposes. Measured data from representative locations can be used to evaluate farmers' knowledge of SQ so that results can be extrapolated to similar areas with reasonable accuracy. There is thus a need to evaluate the SQ issue under Ethiopian conditions by concurrently integrating the knowledge of farmers and measured soil parameters at catchment scale.

Assessment of SQ change from the perspective of farmers’ knowledge in combination with the technical knowledge is the primary concern of sustainable agriculture (Karlen et al. 1997). Integrating and harnessing knowledge from within and between scientific and local knowledge bases enables communities to fully realize their capacity and become involved in monitoring and responding to the challenges of soil degradation (Reed et al. 2007). This allows development and introduction of appropriate soil and crop management systems and also the improvement of technology adoption. The present study aims to evaluate the SQ status (categories) identified by local farmers using scientific soil measurements, and to assess their potential as indicators of soil degradation for decision-making processes in the Mai-Negus catchment, northern Ethiopia. The study will contribute to enhancing the synergies and discrepancies in scientific and local knowledge of SQ in the developing countries like Ethiopia.

## 5.2 Materials and methods

### 5.2.1 Study area

The study was conducted in the Mai-Negus catchment in the Tigray region, northern Ethiopia (Figure 5.1), which covers an area of 1240 ha. The landscape of the catchment is generally rugged terrain with altitudes ranging from 2060 to 2650 m a.s.l. Land-use is dominantly arable with a teff *(Eragrostis tef)* cropping system (> 80%) but with different percentages of pasture land, and scattered tree, bush and shrub covers. The dominant rock types are lava pyroclastic and meta-volcanic. Soils are mainly Leptosols on the very steep positions, Cambisols on the middle to steep slopes and Vertisols at locations around the flat areas. Soils are highly eroded in most parts of the landscape. Besides, terrain erosivity potential is high as slope gradients reach higher 85%. Surface cover is poor, and human disturbance is high, which facilitates SQ deterioration.

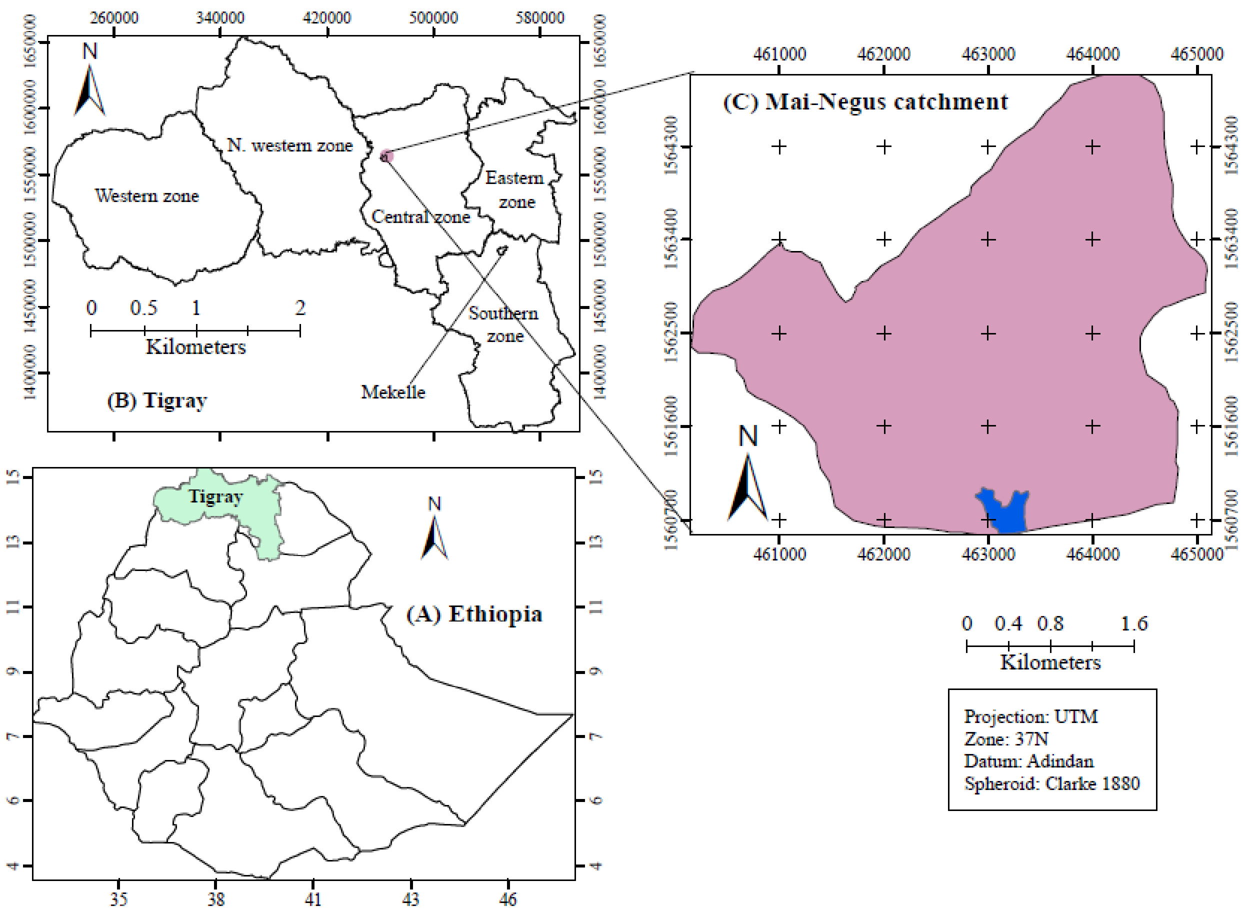



Figure 5.1: Map of Ethiopia (A), Tigray (B) and Mai-Negus catchment (study site) (C)

### 5.2.2 Research approach and soil sampling procedure

The study employed two approaches. The first deals with identification and categorization of SQ using knowledge of local farmers. In the second approach, SQ status is evaluated based on laboratory analysis of soil samples located in the different SQ status areas as identified by local farmers. In the first approach, participatory field transect walks with groups of 15 randomly selected farmers with different economic status were conducted to identify SQ indicators for categorizing soils of the catchment into low, medium and high SQ status. The collected information was supplemented by group meeting discussions with 52 household farmers in the catchment not involved in the walk (for details see Chapter 4).

In the second approach, soil samples were collected at 0-20 cm soil depth (plow layer) based on the SQ categories identified. The geographical positions of the soil sampling points in each SQ category were recorded using GPS and interpolated by ordinary kriging to show the spatial distribution of the SQ categories across the study catchment (Figure 5.2). Considering the analytical costs and soil variability, a total of 51 composite soil samples were collected to represent the SQ categories as low, medium and high, i.e., each SQ category had 17 soil sampling points. For each sampling point in each SQ category, six (n = 6) composite soil samples were collected in a grid of 20 m x 30 m. The samples were thoroughly mixed in a bucket, and a subsample was taken for analysis. Soil samples were air dried and sieved to pass 2 mm sieve before analysis.

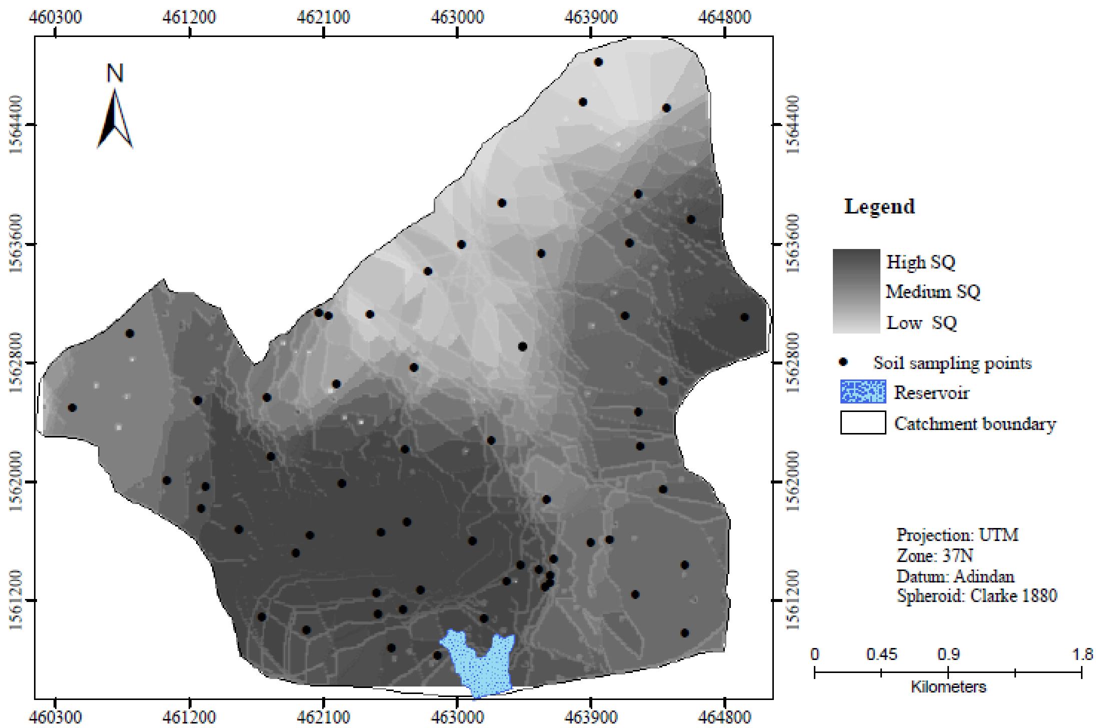



Figure 5.2: Spatial distribution of soil quality (SQ) categories and soil sampling points in Mai-Negus catchment, northern Ethiopia

### 5.2.3 Soil sample analysis

Soil samples were analyzed for texture, soil aggregate stability (SAS), dry bulk density (BD), pH, electrical conductivity (EC), exchangeable potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), available phosphorous ($P_{av}$), organic carbon (OC), total nitrogen (TN), total phosphorous (TP) and cation exchange capacity (CEC) following the standard laboratory procedures adopted by the Ethiopian National Soil Laboratory (MoNRDEP 1990). For certain soil parameters (e.g., OC, EC), samples were duplicated for quality monitoring of the laboratory results. The results were reported to the farmers and development agents in the study area in a half-day seminar, where similarities and differences between farmers' understanding and categorization of SQ in relation to field and laboratory results were discussed.

### 5.2.4 Data analysis

Data were subjected to statistical analysis using SPSS 18.0 (SPSS 2010). One-way analysis of variance (ANOVA) was used to test the differences in soil attributes among the SQ categories identified by local farmers. The SQ category was considered as a group variable. Normality and homogeneity assumptions of ANOVA were checked using the Kolmogorov-Smirnov and Levene tests (Zar 1996). The least significant difference (LSD) method at the probability level (P) of 0.05 was used to separate mean difference of the soil attributes among the SQ categories.

Correlations among the soil properties were checked by the Pearson product moment correlation test (2-tailed) in order to determine the strength of their association. Factor analyses (principal component analysis, PCA) were then used to extract high loading factors by statistically grouping soils attributes into major principal components (PCs). Four PCs with eigenvalues > 1 were selected for interpretation, as PC receiving high values best describe the variability in the factors (Brejda et al. 2000). Among well-correlated variables within the PC, the variable with the highest correlation coefficient (absolute value) was retained in the component factors. If highly weighted variables were not well correlated ($r < 0.60$), each was considered important and retained in the component factor.

Using the retained variables in the PCA, discriminant analysis was executed to identify the best discriminator among the SQ categories (group variables) and relationship between a group variable and scale-independent variables (soil attributes). Given a set of scale-independent and categorical dependent variables, discriminant analysis was used to determine linear combinations of those variables that best discriminate the group variables (Everitt and Dunn 1992). These combinations are called discriminant functions and are shown in the equation as:

$$f_{km} = u_0 + u_1 X_{1km} + u_2 X_{2km} + ... + u_p X_{pkm} \tag{5.1}$$

where $f_{km}$ is the value (score) of the discriminant function for case $m$ in the group $k$,, $X_{pkm}$ is the value of the discriminant variable $X_p$ for case $m$ in group $k$, and $u_p$ is standardized coefficient. The analysis automatically chooses the first function that separates the groups as much as possible. It then decides a second function which is uncorrelated with the first function and provides as much further separation as possible. The number of functions is one less the number of group variables (SPSS 2010).

Discriminant functions are interpreted by means of standardized coefficients. The larger the standardized coefficient, the greater is the contribution of the respective variable to discriminate between the groups of SQ categories (Everitt and Dunn 1992). The classification functions rate (%) in the discriminant analysis were also used to determine to which group each case most likely belonged in the original and cross-validation cases. In cross-validation, each case is classified by the functions derived from all cases other than that case (SPSS 2010).

## 5.3 Results and discussion

### 5.3.1 Evaluation of soil quality status using physical soil attributes

The physical SQ attributes differed significantly ($P \leq 0.05$) among the SQ categories (Table 5.1). The mean percentage of sand was significantly higher in the low SQ (55%) as compared to the medium SQ (36%) and high SQ (27%) category. The high sand content in the low SQ may be attributed to the selective behavior of erosion on soils with fine textures, as the low SQ fields are located commonly on steep slopes which are susceptible to erosion. Percentage silt was lower in the low SQ than in the medium and high SQ category, especially on fields where farmers indicated soil erosion as the main concern for agriculture production, and environmental rehabilitation. This observation confirms the basic principle that silt is the first soil component susceptible to erosion processes (Mairura et al. 2007). Besides, the effect of different management practices by farmers may influence soil texture and overall SQ in the long-term. The proportion of silt and clay content in the high and low SQ categories showed significant differences ($P \leq 0.05$), but no statistical difference ($P > 0.05$) between the high and medium SQ categories was observed. However, the clay content was higher in the high SQ than in the medium SQ category. Generally, the textural class of the high SQ category was clay loam, and that of the medium and low SQ was loamy sand and sandy loam, respectively (Table 5.1).

Table 5.1: Mean soil physical properties of soil quality categories at 0 - 20 cm soil depth in Mai-Negus catchment, northern Ethiopia

| | Farmers' soil quality category [a] | | |
|---|---|---|---|
| Soil parameter [b] | High ( n = 17) | Medium ( n = 17) | Low ( n = 17) |
| Sand (%) | 27b | 36b | 55a |
| Silt (%) | 42a | 40a | 27b |
| Clay (%) | 31a | 24ab | 18b |
| Textural class | Clay loam | Loamy sand | Sandy loam |
| Bulk density (Mg m$^{-3}$) | 1.37a | 1.49b | 1.63c |
| Total porosity (%) | 48a | 41b | 23c |
| Soil aggregate stability (%) | 51a | 41b | 24.8c |

*Means followed by different letters in the same row are significantly different at probability level, P ≤ 0.05.*
*[a]Number of representative sampling points used for soil analysis in each soil quality category.*
*[b]Corresponds well with farmer rating of SQ.*

The results of this study indicate that up to 70% of the soil texture was sand in the low SQ category as compared to the maximum sand content of 41% in the high and 50% in the medium SQ categories. The implication is that sand dominates over the active part of the soil in the low SQ category. As a result, farmers categorized sandy soils as low SQ because they perceived that such soils have low water-holding capacity and low soil nutrient contents, which agreed with the measured results. Among the popular descriptor of the high SQ category is the presence of a high soil clay content, which farmers describe as black soil. Such soils were evaluated by the farmers as being more fertile with a higher water-holding capacity than the sandy soils. The farmers' evaluation of SQ also corresponded well with measured bulk density (BD). An ideal BD for root growth in clay loam soil (< 1.37 Mg m$^{-3}$) and loamy sand (1.49 Mg m$^{-3}$) were found in the high and medium SQ categories, respectively, while a BD that negatively affects root growth was found in the sandy loam texture of the low SQ (1.63 Mg m$^{-3}$) category. The difference in BD in the SQ categories was described by farmers using the level of hard pans observed on the plow layer. They stated that low SQ soils are tight and difficult to get into. In support of this, Baruah and Barthakur (1999) and Doran (2002) reported that as bulk density increases, the circulation of air, water and plant nutrients and the root system are negatively affected.

Soil bulk density and porosity are influenced by soil aggregate (Hillel 1971). Increased soil looseness was cited by farmers to describe the decrease in soil aggregate stability (SAS), e.g., in the low SQ category. This is validated by the statistical difference among the SQ categories, which showed the lowest SAS in the low SQ (24.8%) compared to the medium (41%) and high SQ (51%) categories. This is probably due to lower levels of soil organic matter (SOM) and the fine-texture soils (silt, clay) in the low SQ. Significant movements of nutrients have been described in coarse soil textures such as soils in the low SQ category (Sojka and Upchurch 1999). Cultivation for many years without proper soil management also reduces the stability of soil aggregates and lowers carbon values (Mairura et al. 2007), which may account for the lower mean soil aggregates in the low SQ category. Besides this, inherent soil property is also a factor that influences the soil aggregate (Arshad et al. 1996; Baruah and Barthakur 1999). A decrease in SAS increases bulk density, which indicates an increase in physical soil degradation. In general, the physical soil attributes indicate that farmer categories of SQ as high, medium and low status agrees well with the trend of laboratory measurements.

### 5.3.2 Evaluation of soil quality status using chemical soil attributes

The SQ status classified by the local farmers in terms of high, medium and low was also evaluated using soil chemical attributes. A statistically significant difference ($p \leq 0.05$) was observed for many of the soil attributes among the SQ categories (Table 5.2). However, there was no statistically significant difference among the SQ categories regarding exchangeable sodium, exchangeable acidity, base saturation percentage (BSP), Mg:K, and Ca+Mg:K (Table 5.2). Irrespective of the statistical significance, the trend of the values of the indicators is well fitted with the direction of SQ categorization by the local farmers. This means that the value of soil chemical indicators based on laboratory measurement increased as we moved from low to medium, and then to high SQ fields in an ascending order, particularly for the soil nutrient indicators. For instance, the trend of nutrient stocks determined using nutrient concentrations shows that SOM, TN and Pav are higher in the high SQ than in the other SQ categories (Figure 5.3).

Table 5.2: Mean soil chemical attributes of soil quality categories at 0 - 20 cm depth in Mai-Negus catchment, northern Ethiopia

| | Farmers' soil quality category [a] | | |
|---|---|---|---|
| Soil parameter | High ( n = 17) | Medium ( n = 17) | Low ( n = 17) |
| pH | 6.9a | 6.4b | 6.3b |
| EC (dS $m^{-1}$) | 0.33a | 0.24ab | 0.16b |
| OC (%) | 2.56a | 1.57b | 0.98c |
| Pav (mg $kg^{-1}$) | 17.95a | 8.68b | 5.57b |
| TN (%) | 0.53a | 0.21b | 0.12c |
| TP (mg $kg^{-1}$) | 1050a | 361b | 465b |
| Ex. K ($cmol_c$ $kg^{-1}$) | 1.33a | 0.62b | 0.67b |
| Ex. Ca ($cmol_c$ $kg^{-1}$) | 22.4.0a | 15.0b | 9.3c |
| Ex. Mg ($cmol_c$ $kg^{-1}$) | 12.4a | 7.1b | 7.8b |
| Ex. Na ($cmol_c$ $kg^{-1}$) | 0.22a | 0.34a | 0.36a |
| Sum of cations ($cmol_c$ $kg^{-1}$) | 36.3a | 23.1b | 18.2c |
| CEC ($cmol_c$ $kg^{-1}$) | 40.5a | 23.7b | 19.3c |
| Ex. Acidity ($cmol_c$ $kg^{-1}$) | 4.19a | 1.05a | 0.62a |
| Base saturation % | 90a | 98a | 94a |
| ESP | 0.56b | 1.36ab | 1.90a |
| Ca : Mg ratio | 1.80b | 2.14a | 3.22c |
| Mg : K ratio | 9.38a | 12.00a | 17.62a |
| Ca + Mg : K ratio | 26a | 37a | 39a |

*Means followed by different letters in the same row are significantly different at $P \leq 0.05$.*
*BD, bulk density; pH, hydrogen ion concentration; EC, electrical conductivity; OC, organic carbon; TN, total nitrogen; Pav, available phosphorus; TP, total phosphorus; Ex., exchangeable; K, potassium; Ca, calcium; Mg, magnesium; Na, sodium; ESP, exchangeable sodium percentage.*
*[a] Nnumber of representative sampling sites used for soil analysis in each soil quality category.*

The soil nutrient measurements (Table 5.2) reveal that the soil in the high SQ category was characterized by high TN (0.53%) and Pav (17.95 mg $kg^{-1}$), and very high CEC (40 $cmol_c$ $kg^{-1}$), Ex K (1.2 $cmol_c$ $kg^{-1}$), Ex Mg (12.4 $cmol_c$ $kg^{-1}$), and Ex Ca (22.4 $cmol_c$ $kg^{-1}$) compared to the rate for African soils observed by Landon (1991). Exchangeable K was in the range of high for medium (0.62 $cmol_c$ $kg^{-1}$) and low SQ (0.67 $cmol_c$ $kg^{-1}$). This agrees well with other studies, which reported that K is not a limited soil nutrient in Ethiopia (Elias and Fantaye 2000). The soils in the medium SQ category contained medium levels of TN, Pav and CEC, while the soils in the low SQ showed low levels of TN, Pav, CEC and medium levels of Ex Ca and Mg. This indicates that SQ degradation of the soil attributes is higher in the medium and low SQ than in the high SQ category. In soils with high pH, Pav is the highest, as decreasing pH increases the solubility of iron and aluminum that results in the retention of phosphorus (Mairura et al. 2007). This might be another reason for the low Pav in the low SQ, besides the nutrients lost through erosion.

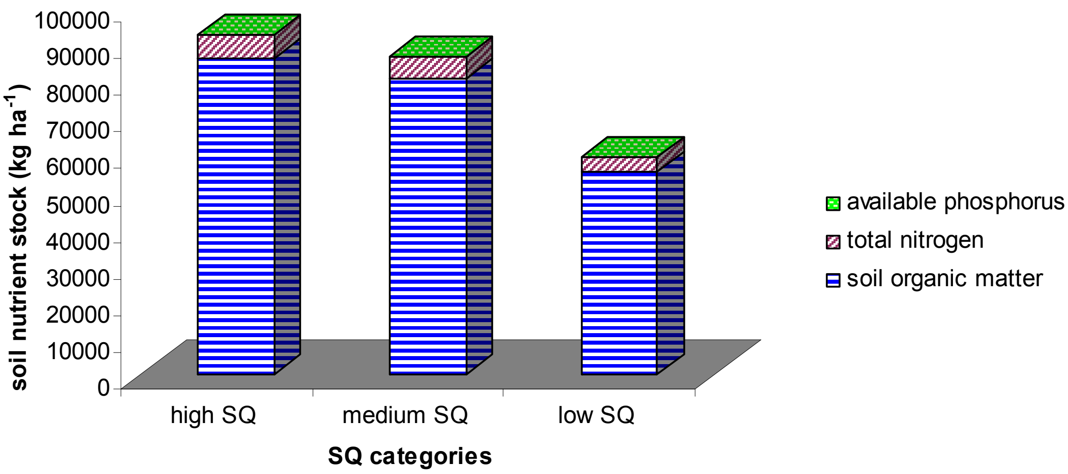



Figure 5.3: Mean (n = 17) soil nutrient stocks at 0-20 cm soil depth for the soil quality (SQ) categories identified by local farmers in Mai-Negus catchment, northern Ethiopia

In the high and medium SQ categories, SOM (SOM% = 1.72 * %OC (Landon 1991)) was 4.2 and 2.70%, respectively, which is rated as medium (2-4.2%), whereas in low SQ, it was 1.69%, i.e., rated as low (1-2%). However, the area coverage of the high SQ category is small, i.e., about 5-8% of the total arable land in the study catchment. Such high SQ farmlands are usually located near to homesteads that experience intensive soil and crop management. Thus, attention and support should be given to scale-up such promising practices to the low and medium SQ fields. Farmers recognized soils with higher SOM by color, as the soil looks darker in the high SQ, soil color is brown, gray or reddish in the medium SQ, and light, light yellow, orange white or light gray in the low SQ category. The overall biomass of vegetation is also used as an indicator of high SOM, as farmers expected this to be high in the high SQ status.

Farmers are also able to associate SQ status with plant growth and development conditions. According to the farmers, crops in the high SQ category are dark green, tall, in a dense stand and with even growth, in the medium SQ crops are light green, small, stands are thin and growth uneven, and in the low SQ category they are poor, stunted, discolored, and stands are uneven and never seem to mature. Farmers were also well acquainted with the SQ categories with respect to the fertilizer demand. Accordingly, they described soils in the high SQ category as having high potential nutrients needing little fertilizer, whereas in the low SQ more fertilizer needs to be applied. Farmers are well familiarized with N, P and SOM. They used general terms to describe the exchangeable bases including CEC, calling them simply other minerals. Farmers do not have clear information about the sources and effect of such minerals on productivity. Knowledge enhancement of farmers on overall integrated SQ management and its implication should be thus part of future attention.

### 5.3.3 Synthesis of soil quality variability based on soil attributes

The results of this study show that farmer evaluation of SQ status based on SQ indicators acquired through generations of trial and error agrees well with the measured physical and chemical soil attributes. Soils described as having high quality by the farmers using their own descriptors was confirmed by higher pH, SAS, TN, Pav, OC, CEC, base cations, silt and clay content, and lower sand content and bulk density than in the medium and low SQ categories. Similar results have been reported in other studies (e.g., Murage et al. 2000; Mairura et al. 2007; 2008) where productive soils (high SQ) had higher soil nutrients than unproductive soils (low SQ).

Scientific measurements of soils are expensive, and also results are not representative enough to interpolate or extrapolate to areas having complex catchments in many developing countries like Ethiopia. The results of this study thus indicate that the use of local SQ knowledge to categorize the differences in SQ status as low, medium and high can be very crucial from time, cost, reproducibility, and efficiency perspectives with regard to decision-making on where and which intervention to implement. The correspondence of such local soil knowledge with laboratory results can also help assess the status of soils and facilitate informed decisions about soil management in areas where no professional expertise is available and resources are limited, and also if extrapolation of measured data is difficult. Assessment of SQ attributes that appropriately link measured SQ levels to those of farmer-defined SQ levels is therefore essential before out-and up-scaling for decision-making processes to combat SQ degradation. However, even though the analyses confirm the consistency of farmer-defined SQ categories with the measured results, the key soil attributes that determine and control SQ variability in the catchment need to be examined using further analysis.

### 5.3.4 Soil variability using factor analysis

The correlation analysis revealed a moderate to strong correlation among many soil properties, which indicates the effect of multicollinearity (data not shown). The factor analysis can help reduce the dimension of soil attributes into factor components that best account for SQ variability by minimizing the effect of data redundancy. Among the 19 soil attributes initially analyzed, those that showed significant differences between SQ categories were subjected to factor analysis. As a result, soil attributes were grouped into four main PC factors using PCA to assess gradients in the data structure that best explain the variability in the SQ categories (Table 5.3). The communalities of the soil attributes (Table 5.3) indicate that the extracted four factors are explained by 70 to 98% of the variance of the soil attributes, which indicates that the extracted components are well represented by the soil variables. A high communality estimate suggests that a high portion of variance was explained by the factor; therefore, it gets higher preference over a low communality (Shukla et al. 2006). The first four PC factors with eigenvalue > 1 explain about 88% of the soil variability. The first two PC explain about 56% of the variance, which indicates that they are potential components to explain the SQ variability.

Table 5.3: Factor loadings and communalities of soil attributes in soil quality categories identified by local farmers in Mai-Negus catchment, northern Ethiopia

| Soil quality attribute | Principal Component, PC [a, b, c] | | | | Communalities |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Eigenvectors [d] | | | | | |
| Exchangeable sodium percentage, ESP | **-0.77** | -0.19 | -0.07 | -0.20 | 0.85 |
| Dry bulk density, BD | **-0.76** | -0.45 | -0.18 | -0.10 | 0.86 |
| Available phosphorus, $P_{av}$ | **0.75** | 0.19 | 0.41 | 0.21 | 0.86 |
| Cation exchangeable capacity, CEC | **<u>0.73</u>** | 0.33 | 0.54 | 0.14 | 0.95 |
| Total porosity, por | **<u>0.72</u>** | 0.33 | 0.42 | 0.47 | 0.97 |
| Soil aggregate stability, SAS | 0.69 | 0.42 | 0.29 | 0.46 | 0.94 |
| Sum of base forming cations, SBF | 0.68 | 0.44 | 0.54 | 0.18 | 0.98 |
| Exchangeable calcium, Ca | 0.67 | 0.41 | 0.46 | 0.38 | 0.96 |
| Exchangeable potassium, K | 0.60 | 0.11 | 0.57 | -0.01 | 0.70 |
| Exchangeable magnesium, Mg | 0.59 | 0.44 | 0.58 | -0.26 | 0.95 |
| Sand | -0.44 | **<u>-0.92</u>** | -0.18 | -0.12 | 0.98 |
| Clay | 0.05 | **0.85** | -0.13 | 0.03 | 0.83 |
| Total nitrogen, TN | 0.24 | 0.63 | 0.31 | 0.14 | 0.80 |
| Silt | 0.28 | 0.63 | 0.31 | 0.41 | 0.81 |
| Organic carbon, OC | 0.56 | 0.61 | 0.33 | 0.36 | 0.88 |
| Total phosphorus, TP | -0.01 | 0.25 | **<u>0.89</u>** | -0.25 | 0.91 |
| pH | 0.29 | -0.04 | **0.84** | 0.23 | 0.85 |
| Ca:Mg ratio | -0.04 | 0.11 | -0.14 | **<u>-0.96</u>** | 0.92 |
| Electrical conductivity, EC | 0.38 | 0.47 | 0.43 | 0.49 | 0.78 |
| Eigen values | 11.96 | 4.26 | 2.65 | 1.73 | n.a |
| % of variance | 30.95 | 25.35 | 19.98 | 12.00 | n.a |
| Cumulative variance (%) | 30.95 | 56.30 | 76.28 | 88.27 | n.a |

[a] *Rotation method: Varimax with Kaiser Normalization.*
[b] *Boldface factor loadings are considered highly weighted; underlined boldface factors correspond to the indicators included in the multiple discriminant analysis because each factor is mainly linked to these variables. n.a, not applicable.*
[c] *PC1 is soil nutrient and soil structure factor, PC2 is soil texture factor; PC3 is soil total phosphorus and reaction, and PC4 is Ca:Mg factor.*
[d] *Extraction method: principal component analysis.*

In the PC analysis, the first component factor is termed as the ***'soil nutrient and soil structure* factor'** due to the higher positive loading on Pav (0.75), CEC (0.73) porosity (0.72), and the higher negative loading on ESP (-0.77) and bulk density (-0.76). The variance represented by a combination of these variables is too complex to interpret, because all these high loading variables are strongly correlated with each other. To avoid repetition, the CEC (soil nutrient) with higher correlation coefficient (r > 0.90) than the other loadings was retained in PC1. The variable porosity (soil structure) with correlation coefficients of $r < 0.60$ which is the cutting point was also retained in PC1. This component factor is thus mainly linked to soil CEC and porosity. The second component factor is termed as the ***'soil texture factor'*** due to the high positive loading of clay (0.85) and high negative loading of sand (-0.92). Since the correlation ($r = -0.89$) between these two variables is strong, their communality was used to eliminate their redundancy. As a result, this factor is mainly linked to sand content because of the higher communality of sand (0.91) than clay (0.85).

The third component factor is termed as the ***'soil total phosphorus and reaction factor'***, because of the high positive loading in TP (0.89) and soil pH (0.84). These two variables correlated at $r = 0.87$, which indicates the need for selection of the variable contributing most to this factor. Thus, the third main component factor is mainly linked to TP due to its higher communality (0.91) and factor loading than soil pH (0.85). The fourth component factor is termed as the ***'Ca:Mg factor'*** due to its high negative loading (-0.96). The other variables in the fourth component factor had loading values below 0.49, which is much lower than the cutting point (±0.7). Farmers can use PC1 and PC2 to describe SQ variability in relation to soil physical properties, e.g., soil water-holding (sand), soil color (clay, SOM), soil drainage or high runoff and erosion (poor porosity), and hardpans that restrict root penetration (high bulk density). Component factors related to soil nutrients such as PC1 and PC3 make it easy for farmers to recognize the SQ variability using indicators such as crop growth and yield performance.

Generally, the PCA suggests that the variability of SQ categories identified by farmer knowledge is mainly linked to soil CEC, porosity, sand, TP, and Ca:Mg. As a result, the focus is on these variables in further multiple discriminant analysis to identify the best discriminator variable among the SQ categories (group variables) and also to assess the relationship with the group variables. However, first it is important to show and assess briefly how the factor analysis PC separates the SQ categories identified by the farmers by plotting the features using the PC on two-dimensional axes.

The best method to show the distribution of the n-variables with the corresponding PC factor would be to plot in n-dimensional space, which however is physically impossible for $n > 3$. Therefore, only two PC factors are used at a time, and the factor loadings are plotted on two-dimensional axes (Figure 5.4). Six combinations of the four rotated PC factor axes are plotted to separate the different SQ categories. Most of the factor loading points falls in the first quadrant, followed by the third and second quadrant in descending order in all the plots. This means that the first quadrant makes up the highest density clusters of loadings.

The SQ categories located within the first quadrant at the right side (high SQ) and third quadrant (low SQ) (Figure 5.4A) are based on the factor loadings Pav, CEC, porosity, OC, SAS, Ca, K, Mg for high SQ, and ESP and BD for low SQ with respect to PC1. The loading of sand in PC2 also contributes to the separation of low SQ in the third quadrant because low SQ has a higher sand content than medium and high SQ. The other soil attributes could not separate low SQ from medium and high SQ because no point falls in the third quadrant other than ESP, BD and sand for PC1 versus PC2 (Figure 5.4A). The medium SQ category is located mainly in the first quadrant, but a few points are distributed in the second and fourth quadrant due to variables such as clay, TN, silt, TP. Such wider scattering of points over different quadrant indicates that some of the points may be misclassified. Generally, the low SQ category loading points are separated at a higher distance than the other SQ categories, indicating a possible SQ disassociation. Similarly, the factor loadings of PC1 versus (vs.) PC3, PC1 vs. PC4, PC3 vs. PC2, PC4 vs. PC2 and PC4 vs. PC3 (Figure 5.4B-F) also indicate that the high SQ category is located on the right part of the first quadrant due to the higher positive loading values but medium SQ to the left of the first quadrant, and low SQ mainly in the third quadrant due to the high negative loadings of the PCs.

Generally, the plot PC1 vs. PC2 is likely more important in separating the different SQ categories than the other component factors because of the lower heterogeneity of the loadings in each SQ category group. The visual comparison with no statistical value of the separated group variables (SQ categories) using factor loadings on the two-dimensional axes suggests a high reliability of trends between measured soil properties and the SQ categories identified by the local farmers. However, without statistical measurement, it is difficult to judge the efficiency of the factor analysis in separating the group variables.

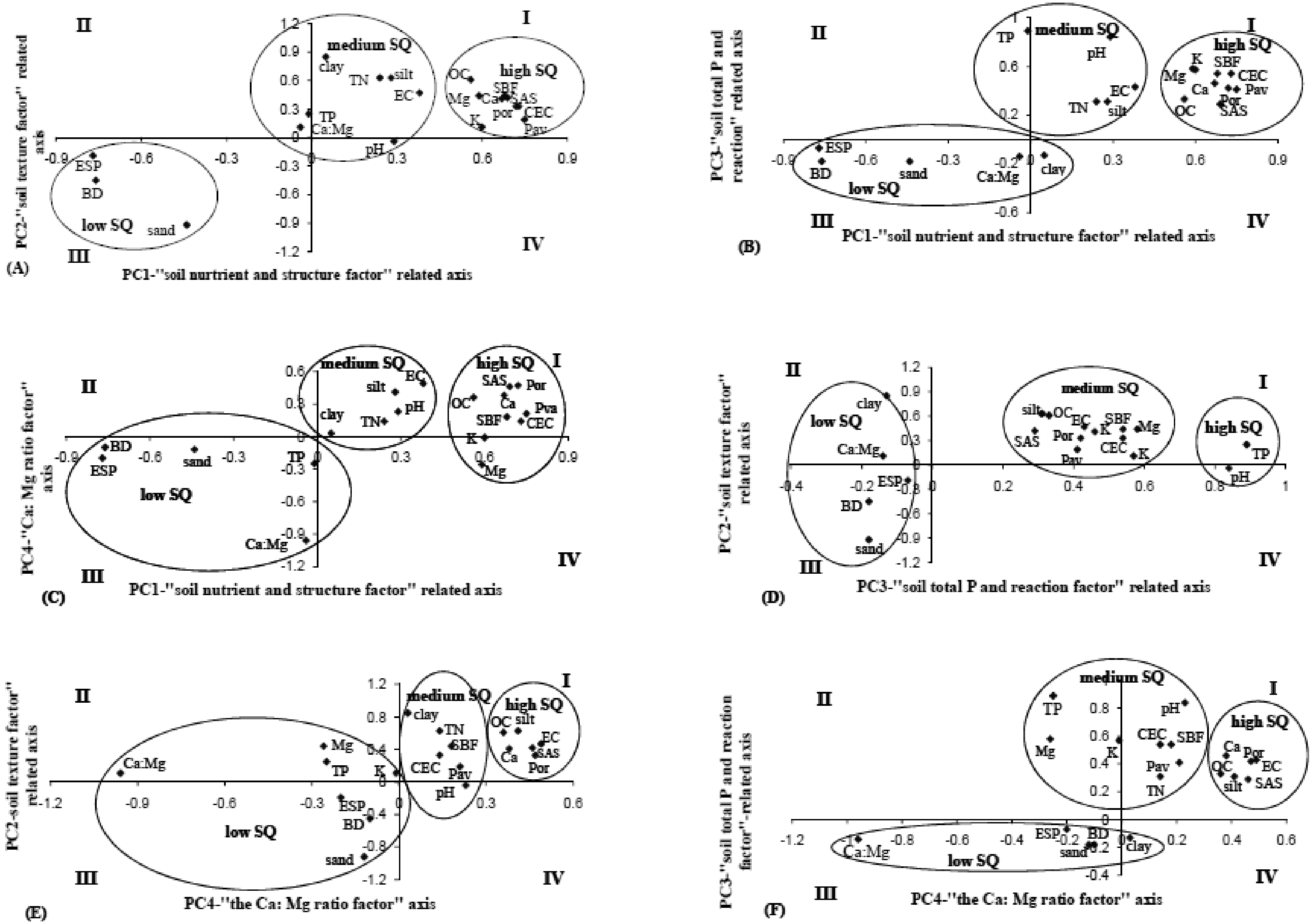



Figure 5.4: Series of two-dimensional plots using factor loadings to different pairs of principal components (PC) rotated factor axes. For details of variables see Table 5.3.

As a result, PCA is suggested to be used as a pre-processing step to discriminant analysis and clustering (Everitt and Dunn 1992). In addition, literature suggests that the use of discriminant analysis is worthwhile to discriminate, classify and make predictions of categorical variables such as SQ categories (Everitt and Dunn 1992).

### 5.3.5 Multiple discriminant analysis

In the discriminant analysis, the actual values of the five soil attributes (CEC, porosity, sand, TP, and Ca:Mg ratio) with high factor loadings retained in the four PCs (Table 5.3) were used. The discriminant function coefficients (Table 5.4) show that soil porosity followed by CEC and sand content are the best discriminators in the first function between group 1 (low SQ) and the combination of group 2 (medium SQ) and group 3 (high SQ), but Ca:Mg was least effective in discriminating these groups. The trend of the discriminant coefficients of these independent variables is similar to that of function 1 in function 2 (Table 5.4). This is because in function 2 soil porosity, CEC and sand are the variables with the largest standardized coefficients that discriminate best between the medium and high SQ category. This indicates that soil porosity and CEC in the PC1 factor, followed by the sand content in PC2, offers the greatest potential for monitoring changes in SQ variability with changes in land-use and soil management practices at catchment scale, as these are the most important for group separation in the discriminant function.

About 95% of the variance explained by the discriminant model is due to the first discriminant function, and the remaining 5% to the second function. This indicates that the variability between the low SQ group and the combination of the medium and high SQ groups is higher than that between the medium and high SQ groups. In addition, the relation of each group variable (dependent variables) with the independent variable as indicated by a discriminant function coefficient shows that soil porosity followed by sand content and CEC is the most influential in all the group variables (Table 5.4). But the size of prediction by the same independent variable is not the same in all the group variables. As a result, the $R^2$ of the independent variables in the low, medium and high SQ status as group variables is explained by 94, 88 and 94%, respectively. This percentage is analogous to the $R^2$ in the multiple regression analysis. When we examine the relationship of the functions and the predictors, the coefficient of each independent variable defines the extent of the effect of that variable on the dependent variable and the sign of the coefficient the direction of the effect.

Table 5.4: Standardized and unstandardized coefficient functions of multiple discriminant analysis

| Function [a] | Constant | Porosity | CEC | Sand | TP | Ca:Mg | Model [b] |
|---|---|---|---|---|---|---|---|
| 1 | -5.004 | 0.516 | 0.491 | -0.435 | 0.341 | 0.086 | ($R^2$ = 95%), P = 0.000 |
| 2 | -5.622 | 0.991 | -0.689 | 0.548 | 0.102 | 0.178 | ($R^2$ = 5%), P = 0.008 |
| **Group** | **Constant** | **Porosity** | **CEC** | **Sand** | **TP** | **Ca:Mg** | **Model** |
| Low SQ | -32.843 | 1.029 | 0.289 | 0.561 | 0.204 | 0.112 | ($R^2$ = 94%), P = 0.000 |
| Medium SQ | -50.101 | 1.457 | 0.465 | 0.476 | 0.389 | 0.167 | ($R^2$ = 88%), P = 0.001 |
| High SQ | -53.973 | 1.503 | 1.503 | 0.352 | 0.524 | 0.219 | ($R^2$ = 94%), P = 0.000 |

[a] *Wilks'Lambda test of functions shows that the discriminant model was significant at probability P = 0.000 and 0.008, for function 1 and 2, respectively, indicating that these functions contributed more in the model.*
[b] *Coefficient of determination ($R^2$) is optimal combination of the variables so that the functions provide the best overall discrimination between groups and prediction within groups.*
*Sand (%); total porosity (%); TP, total phosphorous (mg $kg^{-1}$ soil); Ca, exchangeable calcium ($cmol_c$ $kg^{-1}$); Mg, magnesium ($cmol_c$ $kg^{-1}$); CEC, cation exchangeable capacity ($cmol_c$ $kg^{-1}$)*

In addition to the discrimination function coefficients, visualization of the functions that discriminate the group variables by plotting the individual scores of each case is crucial (Figure 5.5). In this figure, the first discriminant function is shown to discriminate mainly between the group of low SQ and the combined groups (medium and high SQ categories) because low SQ falls to the left of the centre line (0), but the combined groups to the right of the centre line in function 1. In the vertical direction (function 2), some of the low SQ category points fall above the center line (0). However, most medium SQ points are above the centre line of function 2. Most points of the high SQ category fall below the centre line (0) of function 2. The implication is that the second discrimination function discriminates between the medium and high SQ category (Figure 5.5).

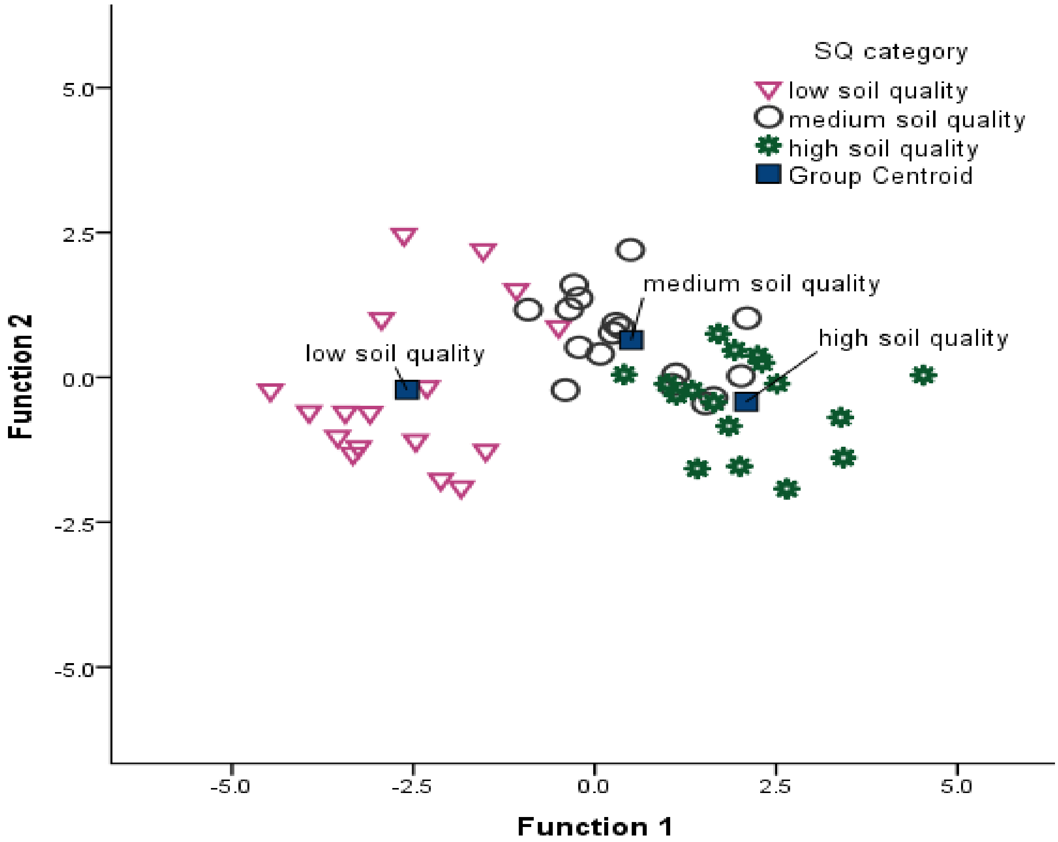



Figure 5.5: Discriminant functions separating the group variables as low, medium and high soil quality (SQ) category. Note: Group means are the centroids used as the cutting points for classifying cases to each group (SQ categories)

Figure 5.5 and Table 5.5 show that for the original grouped cases, the discriminant analysis correctly classified 16, 15 and 16 of the 17 in each group as low, medium and high SQ categories with a 94.1, 88.2 and 94.1% correct classification rate, respectively. In addition, in the cross-validated cases, 15 of the 17 cases in each group of the low and medium SQ category, the correct classification rate was 88.2%, which is similar in both groups. Of the 17 high SQ category group cases, 16 were correctly classified, i.e., a 94.1% correct classification rate in the cross-validated cases. Overall, about 92.1% of the original grouped cases and 90.2% of the cross-validated cases were correctly classified by the discriminant analysis method. This suggests that the overall prediction capability of the discriminant function analysis based on the independent variables can be accepted as more than 90% correct classification is adequate in discrimination of the SQ categories identified by the local farmers.

Table 5.5: Classification of soil quality (SQ) categories (group variables) by discriminant analysis method

| Case | Actual group [a] | Discriminant classification of predicted group membership [b] | | | |
|---|---|---|---|---|---|
| | | Low SQ | Medium SQ | High SQ | Group classification rate (%) |
| Original group | Low SQ | **16** | 1 | 0 | 94.1 |
| | Medium SQ | 0 | **15** | 2 | 88.2 |
| | High SQ | 0 | 1 | **16** | 94.1 |
| | Total | 16 | 17 | 18 | 92.1 [d] |
| Cross-validated [c] | Low SQ | **15** | 2 | 0 | 88.2 |
| | Medium SQ | 0 | **15** | 2 | 88.2 |
| | High SQ | 0 | 1 | **16** | 94.1 |
| | Total | 15 | 18 | 18 | 90.2 [e] |

[a] *17 weighted cases in each SQ category.*
[b] *Boldface figure in each group is number of cases correctly classified by the discriminant function analysis*
[c] *In cross-validation, each case is classified by the functions derived from all cases other than that case.*
[d] *Overall 92.1% of original grouped cases correctly classified.*
[e] *Overall 90.2% of cross-validated cases correctly classified.*

### 5.3.6 Implication of evaluating farmer knowledge with scientific measurements

In this study, farmers' knowledge of SQ was evaluated through comparison with measured soil attributes. The results show that farmer SQ knowledge can be used for decision-making processes (Figure 5.6) regarding technology development, introduction and dissemination with respect to SQ degradation. Similar to the present results, other studies have shown that there are significant similarities and complementarities between indigenous knowledge and scientific understanding of soils (e.g., Saito et al. 2006). These authors noted that such potential synergism is crucial especially for solving problems related to soil and land management. Many researchers also reported that the use of local knowledge facilitates soil surveys and evaluation of land resources for designing suitable agricultural development and also increases the probability of implementing research projects to meet local community demands and cultural values (e.g., Barrios and Trejo 2003; Saito et al. 2006; Mairura et al. 2007; 2008).

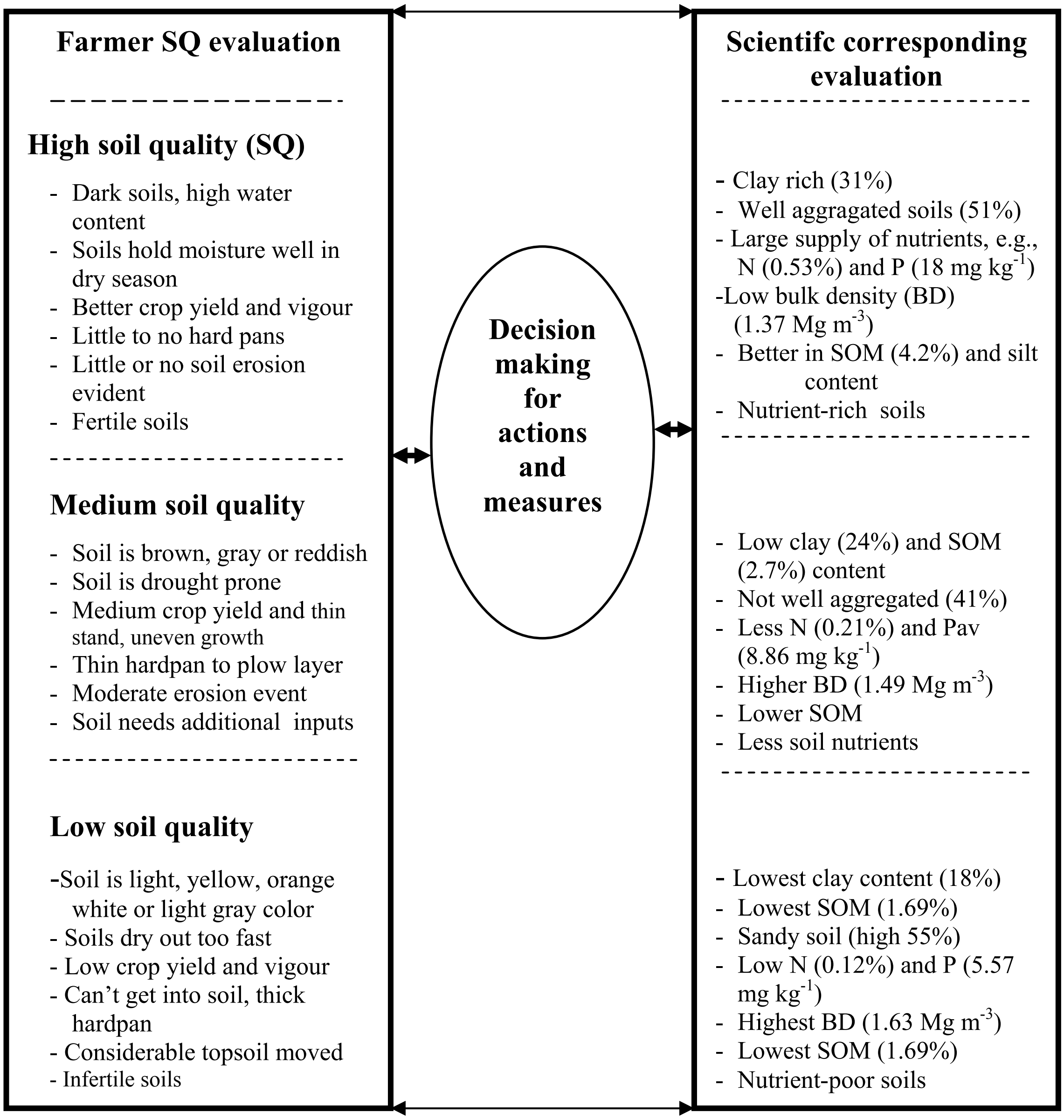



Figure 5.6: Conceptualization the similarities of local farmer soil quality categories with scientific measured indicators for decision-making process in Mai-Negus catchment, northern Ethiopia

Local farmers categorized SQ according to features that are easily visually recognizable and that are passed from generation to generation. The presentation of the results of the measured soil attributes in each SQ category in seminar to the local farmers (Figure 5.6) encouraged them to use their knowledge in characterizing and suggesting management related to soil resources, even in the absence of 'professionals'. This shows that farmers understood well the nature and condition of their SQ status. They used such knowledge in making farm and environmental management decisions based on the differences in SQ, but not in an organized approach. Thus, in low-input farming systems due to resource limitation, local knowledge is the key input in agricultural production and environmental management, and farmer involvement and empowerment is crucial to combat SQ degradation. Evaluation of farmers' knowledge with technical knowledge systems is thus decisive for achieving a more realistic assessment of SQ before out-scaling. Moreover, development recommendations are only relevant and successful if they take into account site-specific environmental factors and techniques based on local farmers' knowledge (Saito et al. 2006). Thus, considerations of farmers' experience and knowledge of SQ can improve the quality of technologies to be recommended and the chance for successful implementation and sustainable adoption. Such involvement of local communities also facilitates partnership between farmers, extension workers and researchers while working to achieve the goal of sustaining natural resources and enhancing productivity.

## 5.4 Conclusions

In this study, evaluation of farmer SQ knowledge using measurements of soil attributes of SQ categories identified as high, medium and low by the local farmers was carried out. Higher values of soil attributes such as CEC, OC, TN, Pav, exchangeable bases, porosity, and soil aggregate corresponded well to the high SQ category. Low sand content and bulk density also agreed well with the high SQ category. The soil attributes that differentiate the SQ categories were well described by the farmers in terms of low yield and crop performance for low soil nutrient-related parameters, hardpans for high bulk density, darker soil color for clay and organic matter dominated soils, water logging for conditions related to low porosity, soil looseness to low soil aggregate status, and low soil water-holding for sand dominated soils. Besides, the level of fertilizer demand (fertility status) is also an important aspect used by the farmers to categorize SQ. However, since all the soil attributes do not equally contribute to the differences in SQ status, factor analysis indicates that soil attributes such as soil porosity, CEC, sand, TP and Ca:Mg are the main variables that influence the SQ variability. In addition, the discriminant analysis shows that porosity, followed by CEC and sand content, is the most powerful soil attribute to group into different SQ categories. The overall implication of this study is that farmer evaluation of SQ based on experience acquired over generations agrees well with the physical and chemical properties determined scientifically. However, soil attribute measurements are expensive, time consuming, and also results are not representative enough to interpolate or extrapolate to areas having complex catchments in many developing countries like Ethiopia. This study indicates that the use of local SQ knowledge is thus feasible from time, cost, reproducibility, and efficiency perspectives to develop SQ management strategies that sustain soil resources to achieve the intended future production capacity. Therefore, alternative approaches should be developed for integrating farmer knowledge in soil science research and other development activities in the context of developing countries like Ethiopia in order to increase the chance of technology adoption by farmers that sustain soil resources.

# 6 CATCHMENT-SCALE SPATIAL VARIABILITY OF SOIL PROPERTIES AND IMPLICATIONS FOR SITE-SPECIFIC SOIL MANAGEMENT

## 6.1 Introduction

The most serious form of environmental degradation that threatens agriculture in many parts of the world such as Ethiopia is soil erosion (Haregeweyn et al. 2008). The impact of erosion is more serious in the Tigray highlands (northern Ethiopia) because average soil loss by erosion from cultivated land is about 49 t $ha^{-1}$ $y^{-1}$ in the region (Tamene, 2005) as compared to the 42 t $ha^{-1}$ $y^{-1}$ average soil loss estimated for cultivated land in Ethiopia (Hurni 1993). Stoorvogel and Smaling (1990) also reported a 60 kg $ha^{-1}$ nutrient outflow in Ethiopia, while inflow from fertilizers is very low (< 10 kg $ha^{-1}$).

Efforts to assess degradation by soil erosion often measures degradation in terms of erosion rate, rather than based on the soil properties spatial variability and redistribution (Pierce and Lal 1994; Haregeweyn et al. 2008). However, studies elsewhere have shown that erosion processes can contribute significantly to the soil properties variability and the associated nutrients within complex catchments (e.g., Kreznor et al. 1989). Similarly, Haregeweyn et al. (2008) reported that soil erosion and sediment delivery processes are responsible for high sediment transport and the associated export of sediment-bound nutrients to deposition areas in a catchment as influenced by landscape characteristics.

In addition, many studies on soil nutrient balance have indicated that more positive nutrient balance at farm level than plot level (Stoorvogel and Smaling 1990; Elias et al. 1998; Scoones 2001). This might be attributed to the fact that nutrient redistribution due to erosion-deposition processes and other input-output mechanisms counteracts positively at farm level as compared to plot level. Characterizing the spatial variability and distribution of soil properties at catchment scale is therefore essential for foreseeing rates of ecosystem processes (Schimel et al. 1991), and realizing how ecosystems and their services change with the effect of practices (Kosmas et al. 2000). Knowledge of soil spatial variability is also necessary to locate homogenous sites that need careful management for sustainable development (Schimel et al. 1991). This implies that accounting for the spatial variability of soil properties at catchment scale enhance site-specific decision-making processes related to soil management and other practices.

Geostatistics provide the basis for quantitative estimating spatial variations and distribution of soil properties (Webster 1985; Webster and Oliver 1990). Infact, geostatistical analysis has been used to study several soil properties, most of them physical and chemical (Cambardella et al. 1994). However, only few studies have been conducted that examine the spatial structure and variability of soil properties at catchment scale in many developing tropical regions in general and Ethiopia in particular. This has constrained the design of appropriate fertilizer recommendations and the planning of suitable land management decisions considering potentials and constraints. Understanding the spatial variability of soil properties at catchment scale in Ethiopia is therefore important for site-specific sustainable soil and crop management decisions. This study thus aims (1) to assess the variability of soil properties using a classical (exploratory) statistics approach, and (2) to examine the spatial dependence and variability of soil properties at catchment scale using a geostatistical method in the Mai-Negus catchment of northern Ethiopia. The two statistical approaches are used to explain soil properties variability (spatial vs. non-spatial) at catchment scale. The results of the study would enable the identification of sites where remediation such as management decision is needed to improve agricultural production and enhance environmental services. Therefore, a better understanding of the spatial variability and distribution of soil properties would be essential for refining agricultural and environmental management practices to improve sustainable soil and land-use, and provide a valuable basis for subsequent measurements (Cambardella et al. 1994).

## 6.2 Materials and methods

### 6.2.1 Study area

The study was conducted in the Mai-Negus catchment of the Tigray region, northern Ethiopia (Figure 6.1), which covers an area of 1240 ha. The landscape of the catchment is generally rugged terrain with altitude ranging from 2060 to 2650 m a.s.l. Land-use is dominantly arable with a teff *(Eragrostis tef)* cropping system (> 80%) but with different percentages of pasture land, and scattered tree, bush and shrub covers. The dominant rock types are lava pyroclastic and meta-volcanic. Soils are mainly Leptosols on the very steep positions, Cambisols on the middle to steep slopes and Vertisols at locations around the flat areas. Soils are highly eroded in most parts of the landscape. Besides, terrain erosivity potential is high, as slope gradients reach more than 85%. Surface cover is poor, and human disturbance is high, which facilitates soil quality deterioration.

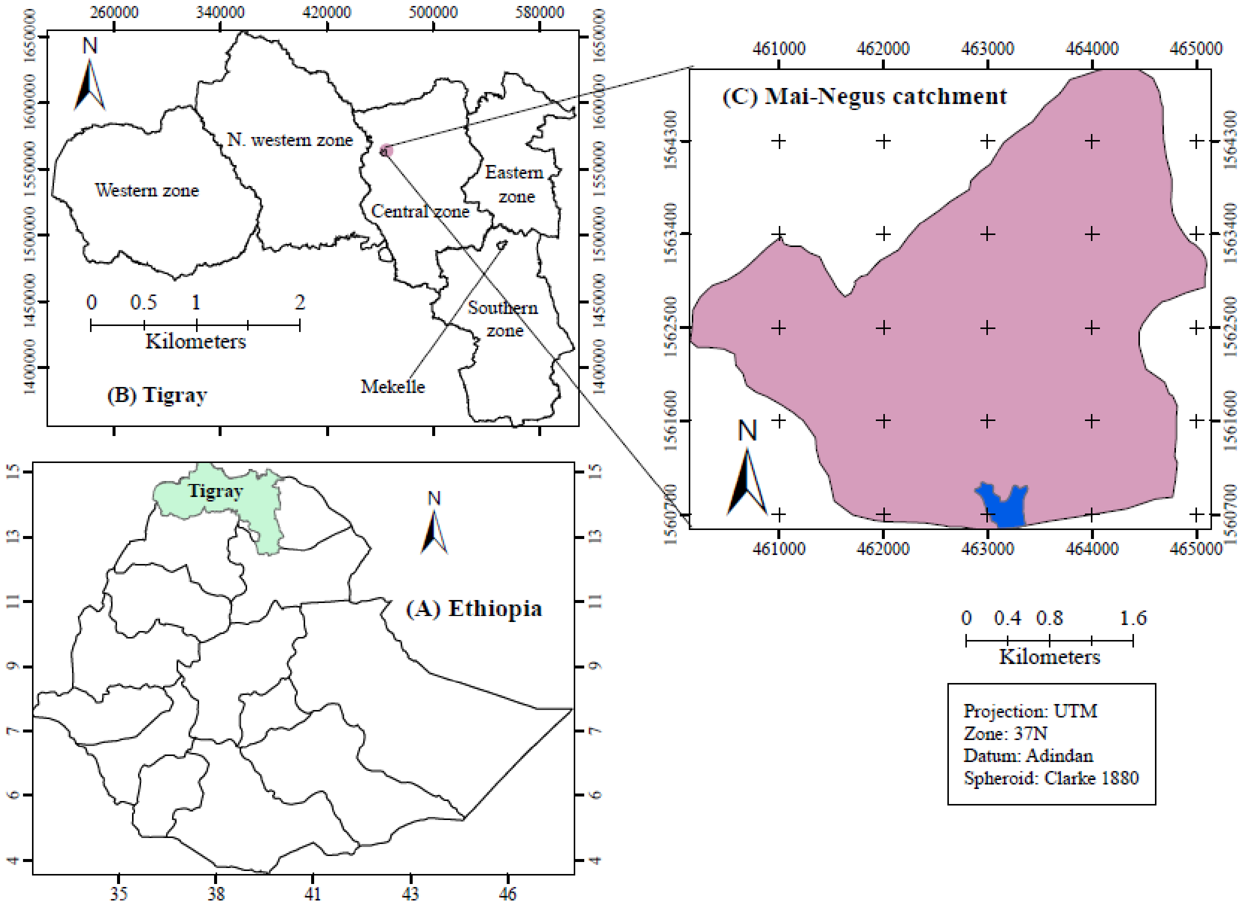



Figure 6.1: Map of Ethiopia (A), Tigray (B) and Mai-Negus catchment (study site) (C)

### 6.2.2 Soil sampling approach and soil sample analysis

Sampling approaches that divide a field into small units (zones of sampling) allow capturing variability and provide more information about soil-test levels compared with one-composite sample collected from an entire field or large sampling areas (Birrell et al. 1996). Zone sampling has been suggested to reduce the number of samples, and sampling and soil analysis costs, as it provides a way to group the spatial variability inherent to soils while maintaining acceptable level of information about the soil properties variances within fields (Franzen et al. 1998). Sampling by zone assumes that sampling areas can be grouped on the basis of specific criteria for the zones with different landscape characteristics such as soil, cropping system, elevation, aspect, management practices, where such zones are likely to remain temporally stable (Franzen et al. 1998).

In this study, zone sampling was employed to collect the soil samples based on prior and existing knowledge of the soils and land-use in the landscape of the whole study catchment. The influence of both natural and management factors on the spatial variability of soil properties was considered across the landscape while identifying soil sampling zones. Three representative soil sampling zones based on soil quality (SQ), long-term land-use and soil management systems, and erosion-status sites were identified in the study catchment, using farmers' opinions, and researcher and extension agents´ judgement. The information that divided the catchment into the soil sampling zones was derived mainly by informal discussions with local farmers, extension agents and field observation during the field reconnaissance surveys in June 2009. The SQ-based sampling zone was entirely covered by arable land whereas the other two sampling zones belonged to all the land-use systems in the catchment. These three sampling zones were further sub-divided into different sub-sampling zones considering the variability within each zone and analytical costs.

The SQ sampling zone was divided into three sub-zones, i.e., high, medium and low SQ status, by a group of farmers. They used indicators such as yield and yield components, soil depth, color, and fertility conditions to divide into such sub-zones (for details see Chapter 4). The sampling zone identified in the catchment based on long-term land-use systems included eight sub-zones based on farmers' historical and present information acquired in the catchment. These included: (i) natural forest, (ii) afforestation of protected area, (iii) grazing land, (iv) teff *(Eragrostis tef)*-faba bean *(Vicia faba)* rotation, (v) teff *(Eragrostis tef)*-wheat *(Triticum vulgare)*/ barley *(Hordeum vulgare)* rotation, (vi) teff *(Eragrostis tef)* mono-cropping, (vii) maize *(Zea mays)* mono-cropping, and (vii) uncultivated marginal land. The age of the systems varied from 5-6 years for *teff* mono-cropping and 20-30 years for maize mono-cropping. The average age of the other systems was about 10 years except for the afforested area, grazed land and uncultivated marginal land systems with more than 15 years.

The erosion-status-based sampling zone included three sub-zones, i.e., stable, eroded and deposition sites. Information from the local farmers, extension agents and researcher observation regarding the level of topsoil depth (A-horizon), deposition, rills, pedestals, root and sub-soil exposure and gullies was used to classify the catchment into these three sub-zones. Those areas with an A-horizon and the lowest number of erosion indicators were considered as stable sites, and those without an A-horizon and with the highest number of erosion indicators as eroded sites. Depositional sites were also easily identified, as they are mainly located in depression and flat areas with evidence of recent sediment deposition. In total, 14 sub-sampling zones across the catchment for the soil sample collection were located. The soil sampling points in each sub-zone were located at the center of each zone in order to reduce soil variability. Each sampling point was geo-referenced (Figure 6.2.) The sampling distance among the sampling points was not regular but ranged from 40 to 180 m.

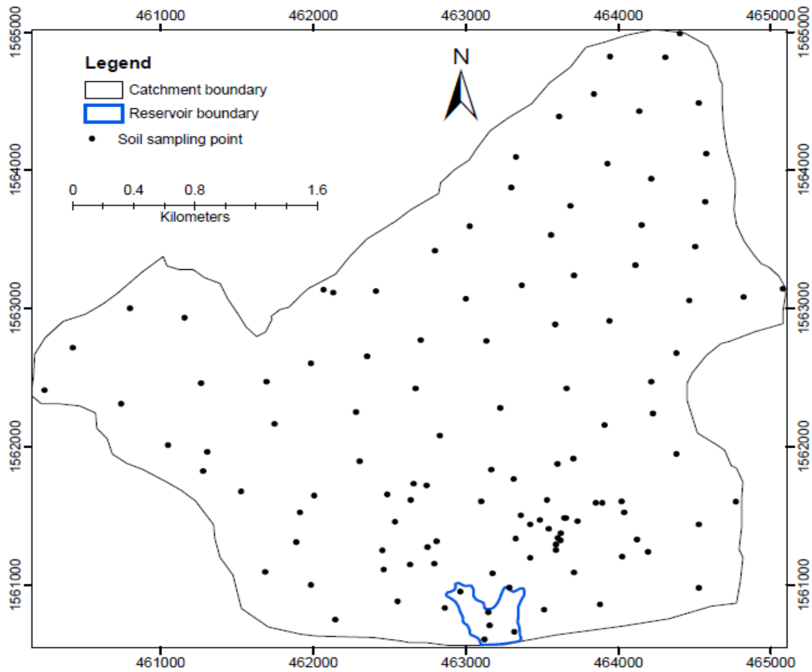



Figure 6.2: Distribution of representative soil sampling points in the study catchment

Soil samples were collected in June 2009. From the SQ-based sampling zone, a total of 51 soil samples (3 sub-zones x 17) were collected. A total of 24 soil samples (8 sub-zones x 3) from the long-term land-use systems, and of 42 soil samples (3 sub-zones x 14) from the three erosion-status-based sampling zones were collected. The grand total of the samples collected across the sampling sub-zones was 117. Each soil sample was collected using composite of 5-8 samples from each representative sub-sampling zone depending on the size and homogeneity of the sampling area. All soil samples were collected at a soil depth of 0-20 cm (plow depth), since this is where most changes are expected to occur due to erosion and the long-term land-use and soil management practices. The composites soil samples were pooled in a bucket and mixed thoroughly to homogenize and a sub-sample of 500 g was re-sampled. The samples were air dried and sieved to pass 2 mm sieve and then analyzed for texture, dry bulk density (BD), pH, total nitrogen (TN), available phosphorous (Pav), total Phosphorous (TP), organic carbon (OC), exchangeable calcium (Ca), magnesium (Mg) and potassium (K), cation exchange capacity (CEC), and available iron (Fe) following the standard soil analysis procedures adopted by Ethiopian National Soil Laboratory (MoNRDEP 1990).

### 6.2.3 Statistical analysis

**Exploratory statistical analysis**

Data were subjected to descriptive (classical) analysis using SPSS 18.0 release software. The mean, minimum and maximum, standard deviation, skewness, kurtosis, and coefficient of variation were computed for each soil parameter to describe the central trend and spread of the soil properties datasets. The coefficient of variation (CV) was mainly used to assess the variability of the different datasets averaged at catchment scale. Exploratory data analysis for outliers and normality tests were checked. Normal quantile-quantile (Q-Q) plots were used for identification of probability of obvious outliers (extreme values) (Fu et al. 2010). Non-normal data were transformed to stabilize the variance. The normality tests were recalculated using the transformed data, as asymmetry in the distribution of data has an important effect on the geostatistical analysis (Fu et al. 2010).

**Geostatistical analysis**

The semivariogram analysis and kriging interpolation were performed in ArcGIS 9.2. Prior to geostatistical analyses, the data were examined for the presence of trend (i.e., deterministic variation where properties vary as a function of their coordinates). Trend in the variation signals a departure from the intrinsic hypothesis in which the process is assumed to be random, and violates the assumptions on which geostatistics are based (McCormick et al. 2009). These authors also noted that the data can be examined for trend by fitting linear or quadratic function surfaces (polynomial line) to the coordinates of soil variables initially. Analysis using the trend removal could help to justify data an assumption of normality (Cressie 1993). By removing the trend, it will be possible to more accurately model the variation because the trend will not be influencing the spatial analysis (Kerry and Oliver 2007).

The semivariogram analyses were conducted before ordinary kriging interpolation of the soil data. This is because the semivariogram model determined the interpolation function. Each model was constructed by 12 lags for all continuous normalized data. The spatial variability of the different variables was described in terms of three main statistics of the perceptible distance of spatial dependence (range), process variance (sill), and the spatially independent or random error (nugget) in the semivariogram models. A semivariogram is defined by the following equation (Ayoubi et al. 2007) as:

$$\gamma(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} \left[ z(x_i + h) - z(x_i) \right]^2 \tag{6.1}$$

where γ(h) is experimental semivariogram value at a distance interval h, m(h) is the number of sample value pairs within the distance interval h, and $z(x_i)$, $z(x_i+h)$ are sample values at two points separated by the distance interval h (Ayoubi et al. 2007). Semivariogram functions were evaluated to decide the best fit with the data of this study. In this study, Spherical, Exponential or Gaussian models were fitted to the empirical semivariograms. The stationary models, i.e., Gaussian (Eq. (6.2)), Exponential (Eq. (6.3)) and Spherical model (Eqs. (6.4-6.5)), that fitted the semivariograms were defined in the following equations (Burgess and Webster 1980):

$$\gamma(h) = C_0 + C_1 \left[ 1 - \exp\left( -\frac{h^2}{a^2} \right) \right] \tag{6.2}$$

$$\gamma(h) = C_0 + C_1 \left[ 1 - \exp\left( -\frac{h}{a} \right) \right] \tag{6.3}$$

$$\gamma(h) = C_0 + C_1\left[\frac{3h}{2a} - \frac{h^3}{2a^3}\right] \quad \text{when } h \le a \qquad (6.4)$$

$$= C_0 + C_1 \text{ when } h > a \qquad (6.5)$$

where $C_0$ is the nugget, $C_1$ is the partial sill, and *a* is the range of spatial dependence to reach the sill ($C_0$ + $C_1$). The ratio $C_0/(C_0+C_1)$ and the range are the parameters that characterize the spatial structure of soil property. The $C_0/(C_0+C_1)$ relation is the proportion in the dependence zone, and the range defines the distance over which the soil property values are correlated with each other (Parfitt et al. 2009). A low value for the $C_0/(C_0+C_1)$ ratio and a high range generally indicate that high precision of the property can be obtained by kriging (Parfitt et al. 2009). The classification proposed by Cambardella et al. (1994) considers the degree of spatial dependence (DSD) as $C_0/(C_0+C_1)$ x 100. According to the authors, the DSD is strong when DSD ≤ 25 %, moderate when 25 < DSD ≤ 75 %, and weak when DSD > 75 %. Low ratios indicate a negligible nugget variance and therefore a relatively high spatial dependence and a more homogeneous distribution of the observed parameter, whereas high ratios point towards a higher small-scale variability and a more heterogeneous distribution.

The semivariogram models were selected by comparing the statistics of the cross-validation, which compared values predicted from the semivariogram models with actual values (Ayoubi et al. 2007). The prediction accuracy of models can be evaluated by the statistics of the mean square error (MSE) (Utset et al. 2000):

$$MSE = \frac{\sum_{i=1}^{n}\left[z(x_i, y_i) - z(x_i, y_i)\right]^2}{n} \qquad (6.6)$$

where *n* is number of observations for each case (soil parameter), $z(x_i, y_i)$ is estimated soil parameter value, $z(x_i, y_i)$ is observed soil parameter value, and $(x_i, y_i)$ are sampling coordinates. In addition to the MSE, the goodness-of-prediction criterium, *G* (Agterberg 1984), was used as criteria to check and compare interpolated map accuracies, and defined as:

$$G = (1\text{-}MSE/MSE_{average})100\% \quad (6.7)$$

where $MSE_{average}$ is the mean square error obtained from a catchment average value as an estimate of all test soil data (using exploratory statistics). Positive *G* values indicate that the map obtained by interpolating data from the samples is more accurate than a catchment average. Negative and close to zero *G* values indicate that the catchment-scale average predicts the values at unsampled locations as accurately as or even better than the sampling estimates (Parfitt et al. 2009).

Once the trend analysis of the soil data and the semivariogram models were evaluated, they were used in the construction of maps by ordinary kriging interpolation (Ayoubi et al. 2007). This interpolation method was used to estimate parameters over the landscape so that data could be obtained at all points over the surface. Ordinary kriging was selected as the preferred method for soil properties spatial interpolation because it is more reliable than the other interpolation methods based on the mean squared error, which compares the measured values with the predicted ones. Moreover, since the spacing of the measured soil sampling was relatively sparse and randomly chosen for each soil sub-sampling zone, ordinary kriging is the best unbiased predictor for conditions at specific unsampled locations (Cressie 1993). Ordinary kriging has an additional advantage of minimizing the influence of outliers (Triantafilis et al. 2001).

## 6.3 Results and discussion

### 6.3.1 Overall variability of soil properties in the catchment

The descriptive statistics of the soil properties in the study catchment show moderate to high skewness for part of the parameters (Table 6.1). The highly skewed soil parameters include BD, OC, TN, and TP whereas silt, Pav and Ex K are moderately skewed. This indicates that these highly skewed elements have a local distribution, i.e, high values were found for these elements at some points, but most values were low (Grego et al. 2006). The other soil parameters were approximately normally distributed in the catchment. The same tendency was observed for the coefficient of kurtosis, which ranged from -0.25 (Ex Mg) to 0.47 (silt) after transformation (Table 6.1). The underlying reason for normal or non-normal distribution of the soil parameters may be associated with differences in management practices, land-use and land-cover, topographic effects and soil erosion processes across the landscape of the catchment. Such factors can be the source of a large or very small concentration of materials in some of the samples that leads to the non-normal distribution. For the non-normally distributed soil parameters, data were transformed using appropriate transformation methods and then fitted to approximately normal distribution.

Table 6.1: Exploratory statistics of soil properties in 0-20 cm soil depth in Mai-Negus catchment, northern Ethiopia

| Variable | Min[a] | Max[b] | Mean | SD[c] | CV[d] (%) | Skewness[e] | Kurtosis |
|---|---|---|---|---|---|---|---|
| Sand | 14.7 | 70.3 | 50.0 | 11.98 | 24.9 | 0.06 | 0.17 |
| Silt[f] | 18.2 | 76.6 | 27.2 | 10.70 | 38.9 | 0.48 | 0.47 |
| Clay | 3.08 | 50.7 | 22.8 | 16.70 | 73.4 | -0.01 | 0.25 |
| BD[g] | 1.02 | 2.00 | 1.59 | 0.14 | 9.1 | -0.36 | 0.20 |
| OC[f] | 0.10 | 4.87 | 1.21 | 0.76 | 62.7 | 0.08 | 0.42 |
| TN[f] | 0.04 | 1.00 | 0.12 | 0.07 | 58.0 | 0.05 | 0.22 |
| Pav[h] | 0.87 | 26 | 7.80 | 5.02 | 64.4 | 0.18 | -0.03 |
| Ex K[g] | 0.20 | 1.3 | 0.77 | 0.11 | 14.2 | 0.23 | 0.45 |
| Ex Ca | 5.14 | 28 | 13.1 | 3.98 | 30.4 | 0.28 | 0.36 |
| Ex Mg | 1.62 | 15 | 6.90 | 1.65 | 23.9 | 0.37 | -0.25 |
| CEC | 8.09 | 51 | 23.4 | 13.42 | 57.3 | -0.13 | -0.16 |
| Fe | 3.4 | 45 | 19.7 | 6.74 | 34.2 | -0.16 | 0.19 |
| TP[f] | 118 | 2171 | 984 | 235 | 23.9 | 0.53 | 0.32 |
| pH | 5.60 | 7.54 | 6.61 | 0.57 | 8.6 | -0.03 | -0.06 |

*BD, dry bulk-density (Mg $m^{-3}$); Ex K, Exchangeable potassium ($cmol_c$ $kg^{-1}$); Ex Ca, Exchangeable calcium ($cmol_c$ $kg^{-1}$); Ex Mg, Exchangeable magnesium ($cmol_c$ $kg^{-1}$); CEC, cation exchange capacity ($cmol_c$ $kg^{-1}$); OC, soil organic carbon (%); TN, total nitrogen (%); Pav, available phosphorus (mg $kg^{-1}$); TP, total phosphorus (mg $kg^{-1}$); Fe, iron (mg $kg^{-1}$).*

*[a] Min, minimum; [b]Max, maximum; [c]SD, standard deviation; [d]CV, coefficient of variation; [e]Skewness provides an indication of symmetry, and a value of 0 indicates perfectly symmetrical distribution, and values between -1 and +1 are considered approximately symmetric (normally distributed) for field data (Ott 1977); [f]Log- transformed; [g]square- transformed and [h]square-root-transformed.*

A wide range of soil parameter values was observed at catchment scale (Table 6.1). For instance, the sand content ranged from 15-70%, silt from 18-77% and clay from 3-51%. The range of bulk density was 1.02 to 2.00 Mg $m^{-3}$. Soil OC, TN and Pav ranged from 0.61-4.87%, 0.04-1.00% and 0.87-26 mg $kg^{-1}$, respectively. The CEC of the soils ranged from 9-51 $cmol_c$ $kg^{-1}$. The maximum values of the soil chemical properties and fine (silt and clay) materials were found in areas where deposition and vegetation coverage is high and on cultivated land with intensive soil management practices. But the proportions of such areas are small in the study catchment. On the other hand, the low soil chemical and high physical properties such as sand content and BD were observed on soils prone to erosion, with poor vegetation cover and with intensive cultivation without proper management system (Table 6.1). The mean BD (1.59 Mg $m^{-3}$) for the catchment was high according to Arshad et al. (1996), who reported that BD higher than 1.4 Mg $m^{-3}$ impairs root growth. Such high BD may be associated with the low organic matter in the soils.

The mean value of OC (1.21%), TN (0.12%), and Pav (7.8 mg $kg^{-1}$) of the soils in the catchment were low, but that of Ex K (0.77 $cmol_c$ $kg^{-1}$) was high, and of CEC medium (23.4 $cmol_c$ $kg^{-1}$) compared to the rate for African soils observed by Landon (1991). This study agrees well with other studies, which reported that Ex K is not a limited nutrient in Ethiopia (Elias and Fantaye 2000). The mean TP of the soils had values higher than 200 mg $kg^{-1}$, which is the value indicated by Olsen and Engelstad (1972) as the maximum TP value for highly weathered tropical soils. The mean pH (6.61) of the soils was within the slightly acidic pH range. The mean Fe (19.7 mg $kg^{-}$1) was below the critical value set for crop production (50 mg $kg^{-1}$) (Jones et al. 1973).

The coefficient of variation (CV) of the soil properties ranged from 8.6% (pH) to 73.4% (clay) (Table 6.1). Regarding the small CV for pH, it should be noted that pH values were already transformed data of $H^+$ concentrations (Fu et al. 2010). The clay content had the highest CV amongst the different soil parameters, which may be difficult to capture by the sampling approach as it is susceptible to the erosion-deposition processes along the landscape. In line with this, previous studies showed that fine soil particles are susceptible to erosion (Stone et al. 1985). Similar to the soil clay, a higher CV of Pav (64.4%), followed by OC (62.7%) and TN (58.0%), was observed at the catchment scale. According to the classification proposed by Wilding and Drees (1983), BD, Ex K and pH in this study showed low variability compared to their mean (CV ≤ 15 %), whereas the sand, Ex Ca, Mg, Fe and Fe showed moderate variability compared to their mean (15 < CV ≤ 35 %). The silt, clay, OC, TN, Pav, and CEC soil datasets inturn showed high variability compared to their mean (CV > 35 %). In general, the use of the CV is a common procedure to assess the soil properties variability, since it allows a comparison among the samples with different units of measurement.

However, such classical statistics could not show the soil properties spatial variability in the study catchment. The geostatistical techniques must be thus carried out for understanding the spatial dependence and variability of the soil properties (Liu et al. 2006). However, before the geostatistical method is used, there is the need to determine the normal Q-Q plots to establish if the soil properties are normal distributed.

### 6.3.2 Normal Q-Q plots for row data

A Q-Q plot of selected variables shows the proportion of observed value against the expected normal value of the normal distribution. In general such plot is used to determine whether the distribution of the soil parametrs matches the normal distribution. If so, the points of a soil parameter row data cluster around a straight line (Wang et al. 2009). In this study, the normal Q-Q plots were produced for the raw data of selected soil parameters (Figure 6.3). Soil exchangeable Ca, Mg, sand and clay data followed a straight diagonal line with some exception of a very few points that slightly deviated from the majority at both ends, indicating approximately normal distribution. It was necessary to remove the few outliers, as the deviation was seen in the Q-Q plots. The soil Fe and pH expected normal values followed a near straight line.

A concave shape was displayed for soil BD, whereas a convex shape was displayed for the OC for some expected value. This indicates that some abnormally high and low values were observed in the dataset. The low values of soil nutrients and fine soil materials were located in the poor SQ and eroded and marginal part of the landscape, while the high values were in the high vegetative cover and high SQ sections and stable soils. Multiple small changes on the slope of the nearly normally distributed soil data were also detected and were probably attributed to differences in dataset sourced from multiple sites within the catchment. Similar normality testing was done using the normal Q-Q plot for the rest of the soil parameters (Figures not shown). Generally, the soil variables that are not normally distributed such as BD and OC were close to the straight line after transformation and can be used for further geostatistical analysis.

### 6.3.3 Trend analysis of soil properties

The trend of the soil properties was analyzed using the ´Geostatistical Analyst´ in ArcGIS 9.2. This is because global trend is an overriding process that affects all measurements in a deterministic way (nonrandom) (Cressie 1993). The trend analysis was achieved by plotting the soil sample locations on the *x,y* plane and the value of the soil property of each parameter on the *z* dimension. In addition, the values of the soil properties are projected onto the *x,z* and *y,z* planes as scattered plots (Figure 6.4).

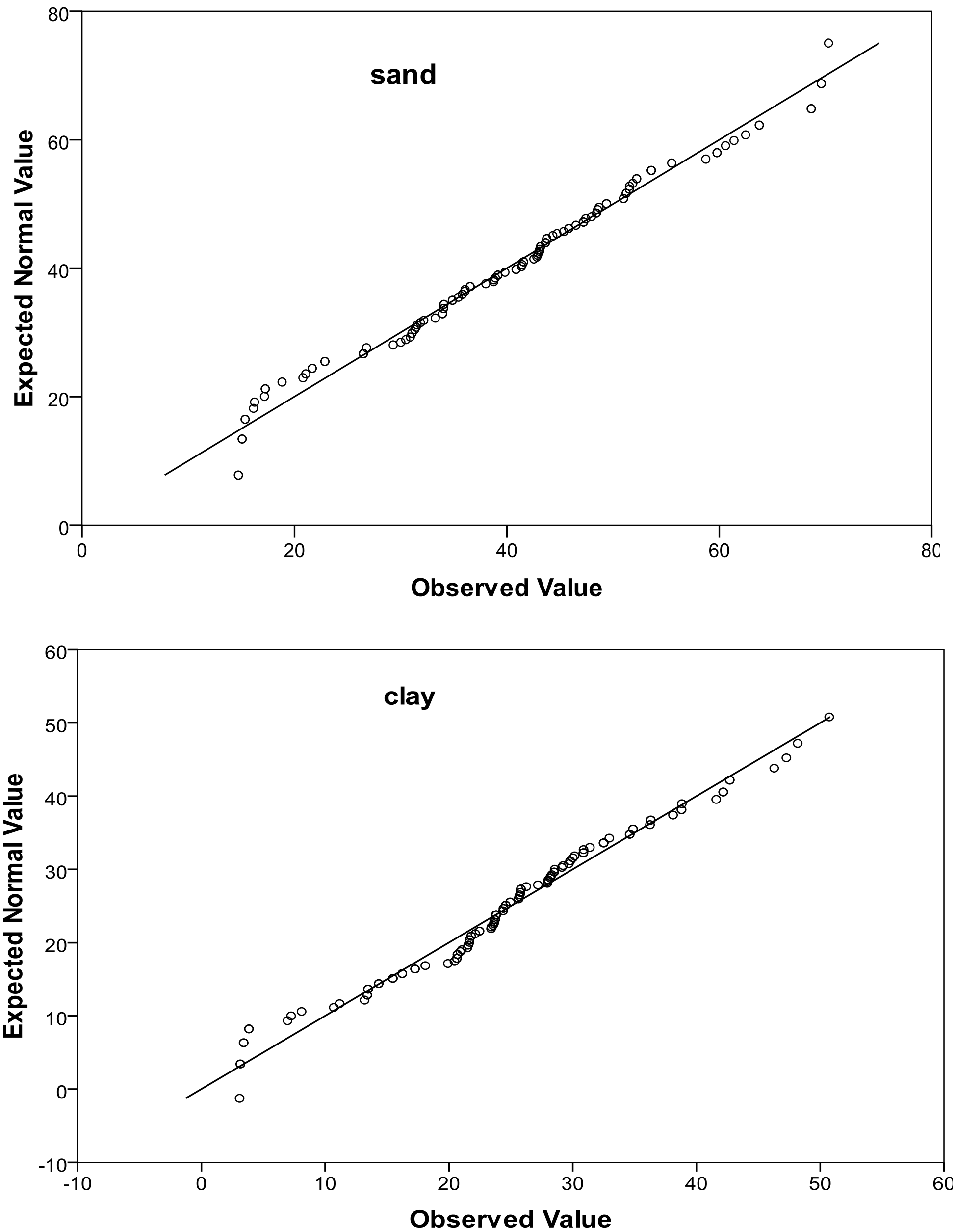
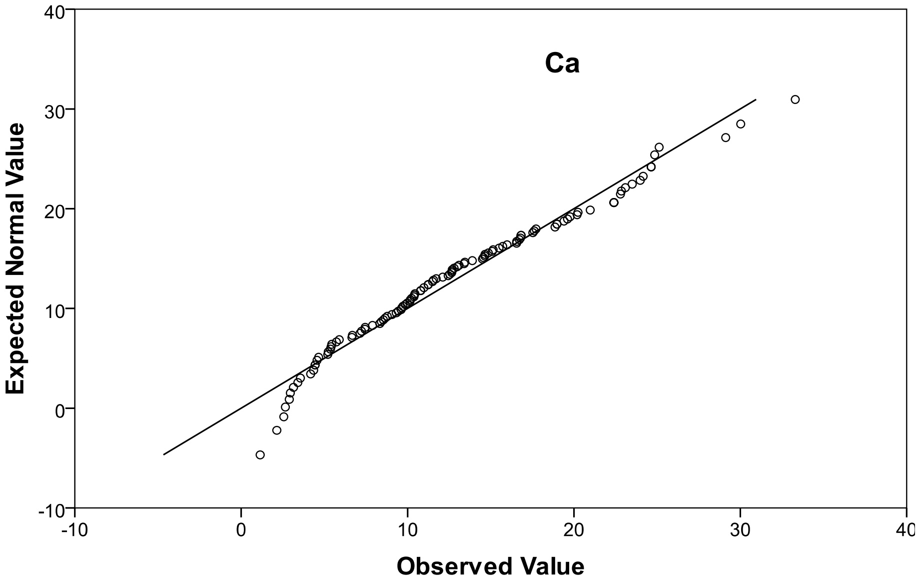
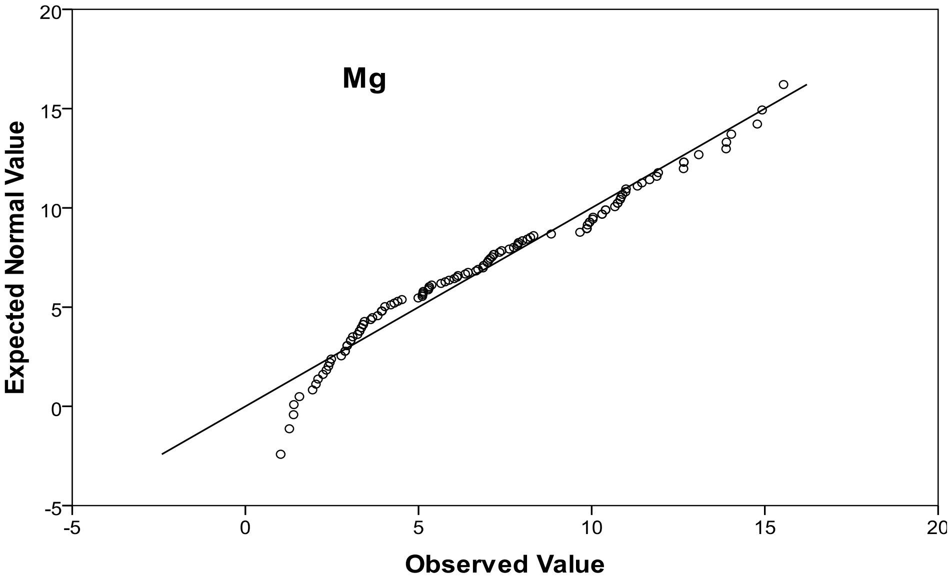



Figure 6.3: Normal Q-Q plots for selected soil parameter data



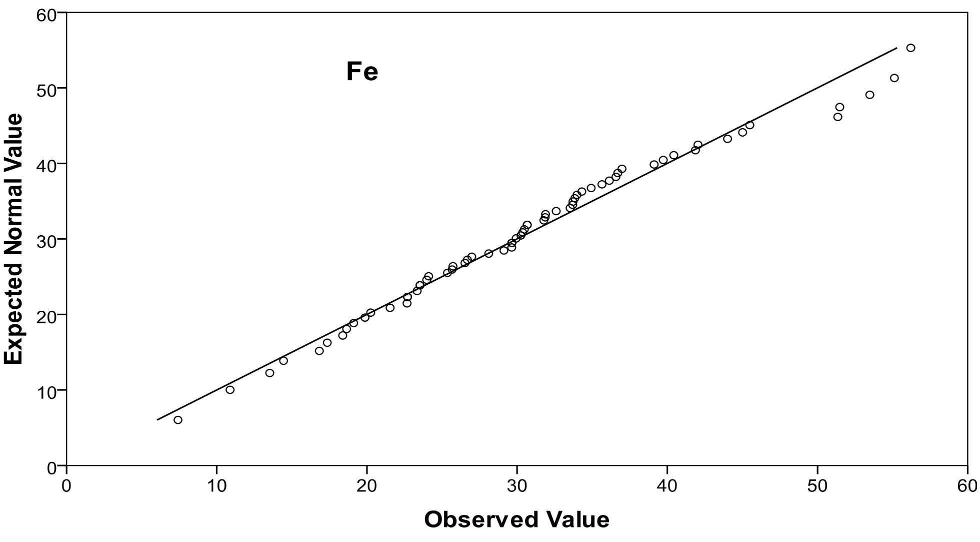




Figure 6.3 continued

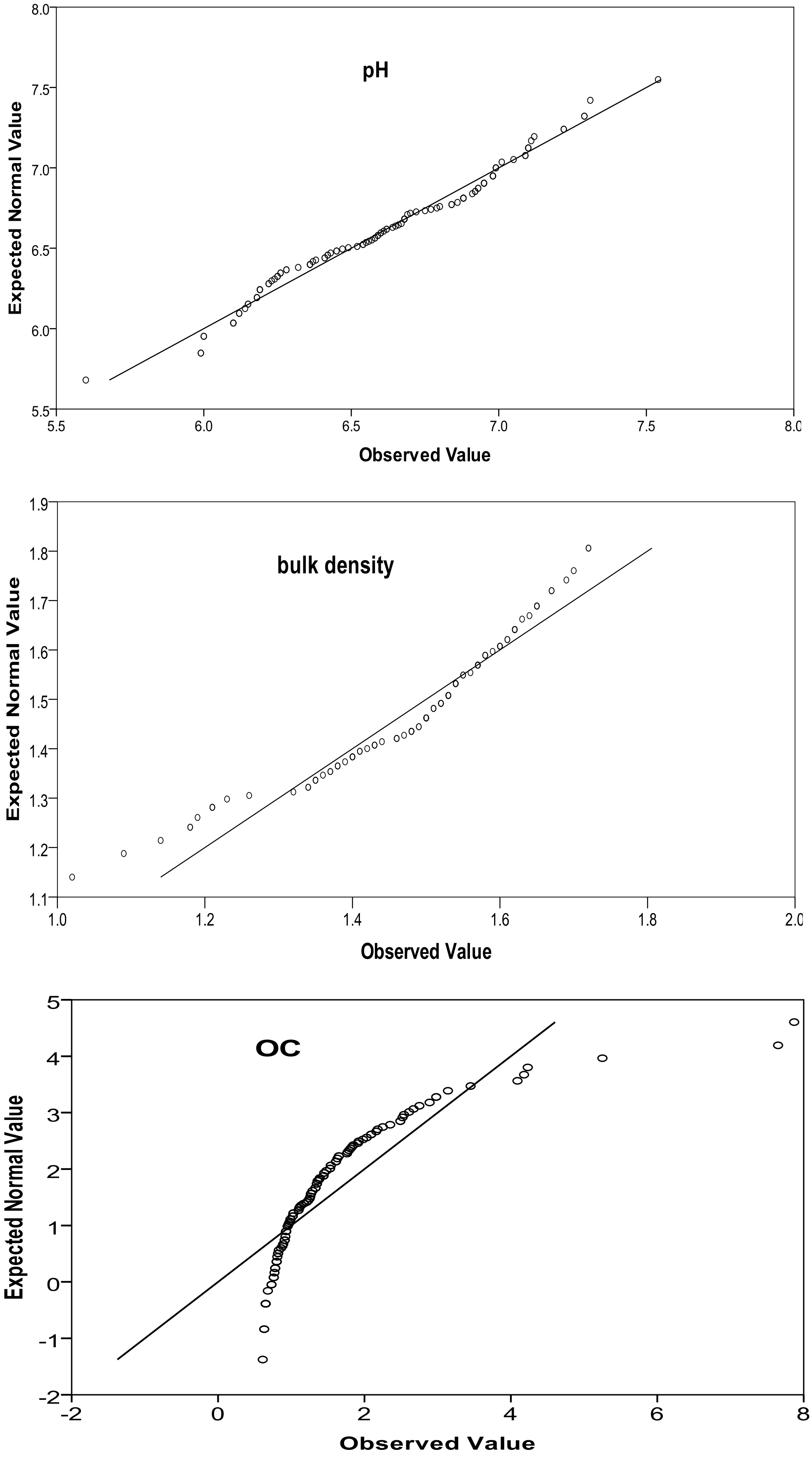



Figure 6.3 continued

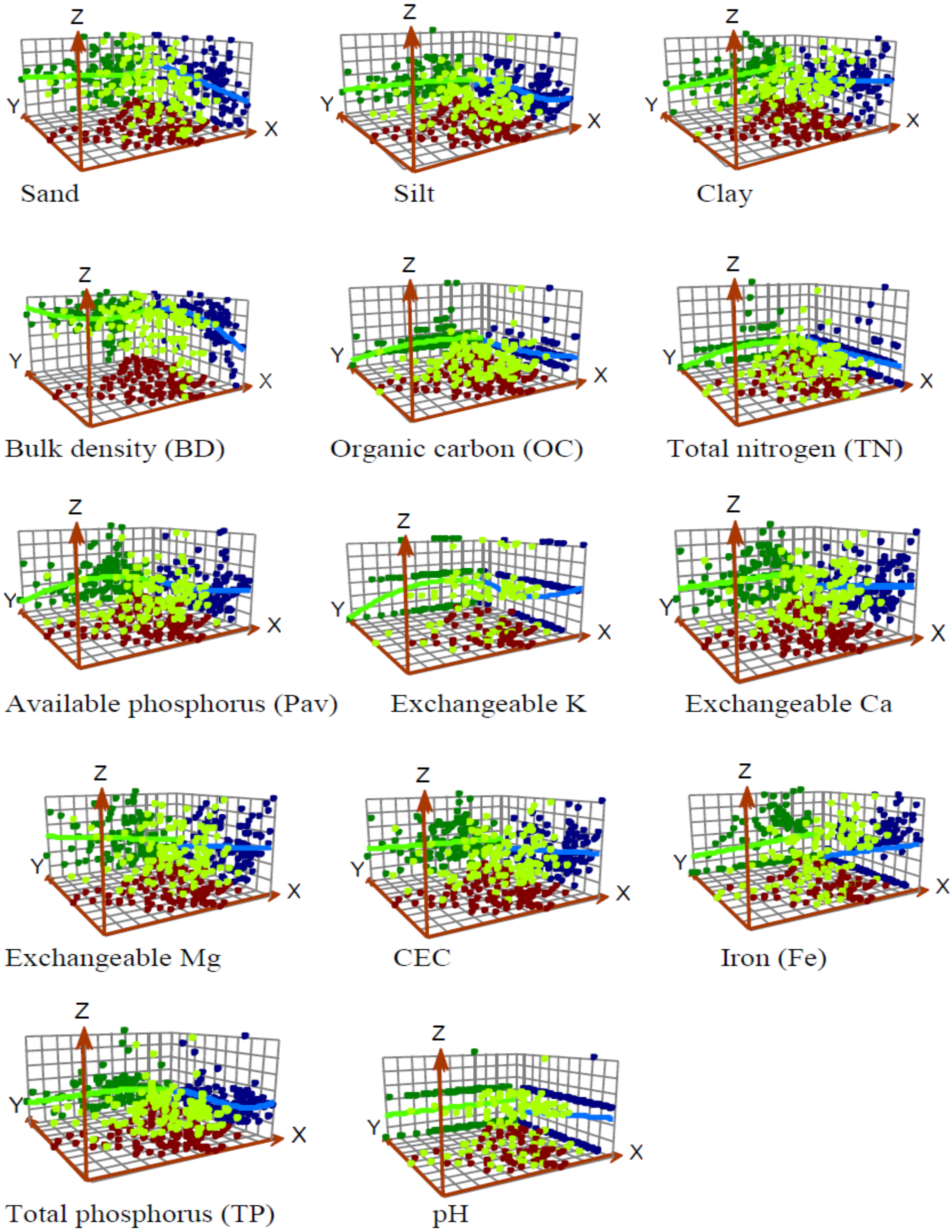



Figure 6.4: Trend analysis of soil properties in Mai-Negus catchment, northern Ethiopia

In Figure 6.4, the trend projection on the plane is shown by the green and blue lines. The yellow points are input data points, and the dark red, blue and green are projected data points. A global trend exists if a curve that is not flat (i.e., a polynomial equation) can be fitted when the data fluctuate. For the soil samples of the study catchment, the trend analysis shows that part of the soil properties had a trend while the rest did not (Figure 6.4). For silt, BD, OC, TN, Pav, Ex K, and TP, the strongest influence of a directional trend was identified from southeast to northwest. This can be associted to the geographic and land-cover characteristics of the catchment (valley surrounded by gentle to mountainous good vegetation cover landforms in the southeast to the mountainous area with poor vegetation cover in the northwest direction). Such trend can influence the spatial distribution of the measured soil properties. But this could not lead to a final remark that there is clear directional soil properties variability whereby the values increase or decrease differently in different directions (e.g., Pav with quadratic trend of the green line with values starting low, then rising and then dropping). The trend exhibited by the blue line appears to be more linear and gradual. In contrast, no directional trend was observed for sand, clay, Ex Ca, Mg, CEC, Fe and pH (Figure 6.4). However, the existence of a trend for part of the soil parameters indicates that trend analysis (removal) was required to create more accurate interpolation maps, as this could help to justify values an assumption of normality. The results of this study suggested that a second-order polynomial should be fitted to the data that have trend so as to normalize before they are used for further analysis.

### 6.3.4 Spatial dependence of soil properties

Knowledge of spatial dependency and distribution of soil properties is crucial for natural resource evaluation and environmental management on unsurveyed locations using known points. This section presents the spatial dependence and variability of selected soil properties. The results of the geostatistical analyses reveal that the soil parameters showed spatial dependence and fitted to different models (Table 6.2). Soil parameters such as TN and TP were best fitted with a Gaussian model, whereas clay, Pav, Ex Ca and Mg fitted best to an exponential model. The remaining soil parameters were fitted to the spherical model. Model selection for each soil parameter was based on the mean squared error, i.e., a model with low error values was preferred.

In geostatistical theory, the range of the semivariogram is the maximum distance between correlated measurements, and can be an effective criterion in evaluation sampling design for mapping soil properties (Fu et al. 2010). Table 6.2 shows that the spatial correlation (range) of the soil properties widely varied from 33 m (silt) to 223 m (Ex K). Beyond these ranges, there is no spatial dependence (autocorrelation). The soil sampling distance in the range of 40-180 m in this study was close to that of the models. The spatial dependence can indicate the level of similarity or disturbance of the soil condition.

Table 6.2: Model parameters values for the best fitted semivariogram model in the Mai-Negus catchment, northern Ethiopia

| Soil parameter | Model | $C_0$ | $(C_0+C_1)$ | Range | DSD (%) | MSE | G (%) |
|---|---|---|---|---|---|---|---|
| Sand | Spherical | 0.028 | 0.243 | 49 | 12 | 28.32 | 76 |
| Silt[a] | Spherical | 0.057 | 0.39 | 33 | 15 | 29.95 | 79 |
| Clay | Exponential | 0.201 | 0.427 | 41 | 47 | 69.63 | 71 |
| BD[b] | Spherical | 0.108 | 1.397 | 47 | 8 | 0.0066 | 65 |
| OC[a] | Spherical | 0.031 | 0.096 | 67 | 32 | 0.35 | 54 |
| TN[a] | Gaussian | 0.015 | 0.064 | 63 | 23 | 0.003 | 53 |
| Pav[c] | Exponential | 0.217 | 0.986 | 52 | 22 | 15.84 | 58 |
| Ex K[b] | Spherical | 0.048 | 0.267 | 223 | 18 | 0.0065 | 46 |
| Ex Ca | Exponential | 0.052 | 0.267 | 91 | 19 | 6.47 | 59 |
| Ex Mg | Exponential | 0.165 | 0.368 | 88 | 45 | 2.00 | 26 |
| CEC | Spherical | 0.103 | 0.437 | 76 | 24 | 53.91 | 55 |
| Fe | Spherical | 0.393 | 1.43 | 65 | 27 | 44.85 | 37 |
| TP[a] | Gaussian | 0.289 | 0.461 | 98 | 63 | 89.08 | 3 |
| pH | Exponential | 0.010 | 0.087 | 116 | 14 | 0.126 | 61 |

*$C_0$ = Nugget Effect; $C_0 + C_1$ = Sill; DSD = $C_0/(C_0 + C_1)$; DSD, degree of spatial dependence; strong DSD (DSD ≤ 25%); moderate DSD (25 < DSD ≤ 75%); weak DSD (DSD > 75%) according to Cambardella et al. (1994).*
*MSE, mean square error; G, goodness-of-prediction criterium; BD, dry bulk-density (Mg $m^{-3}$); Ex K, Exchangeable potassium ($cmol_c\ kg^{-1}$); Ex Ca, Exchangeable calcium ($cmol_c\ kg^{-1}$); Ex Mg, Exchangeable magnesium ($cmol_c\ kg^{-1}$); CEC, cation exchange capacity ($cmol_c\ kg^{-1}$); OC, soil organic carbon (%); TN, total nitrogen (%); Pav, available phosphorus (mg $kg^{-1}$); TP, total phosphorus (mg $kg^{-1}$); Fe, iron (mg $kg^{-1}$). [a] Log transformed; [b]square transformed and [c]square root transformed parameter.*

According to Ayoubi et al. (2007), a large range indicates that observed values of the soil variable are influenced by other values or factors over greater distances than soil variables that have smaller ranges. Thus, a range of about 223 m for Ex K can indicate that the measured Ex K value can be influenced the neighbouring values over greater distances as compared to the soil variables having a small range (Table 6.2). This means that soil variables with a smaller range such as silt are good indicators of the more disturbed soils. The different ranges of the spatial dependence among the soil properties may be attributed to differences in response to the erosion-deposition factors, land-use and land-cover, topography, parent material and human and livestock interferences in the study catchment. Consistent to this study, several studies have reported a large differences in the ranges of different soil properties, for instance, Weitz et al. (1993) found 30 to 100m, Doberman (1994) between 80 and 140 m, and Cambardella et al. (1994) about 80 m for total organic nitrogen.

The nugget, which is an indication of micro-variability, was higher for Fe followed by TP as compared to the other soil attributes. This may be due to the fact that the selected sampling distance could not capture their spatial dependence well. The lowest nugget was for soil pH (Table 6.2). This indicates that pH had low spatial micro-variability within small distances. As a rough guide, the sampling interval should be less than half the semivariogram range for most variables (Fu et al. 2010). According to Ayoubi et al. (2007), knowledge of the range of influence for various soil properties allows one to construct independent accurate datasets for similar areas in future soil sampling design to execute using both classical and geostatistical analysis. In addition, this helps to determine where to resample if necessary, and to design future field experiments that avoid spatial dependence (Ayoubi et al. 2007). Therefore, for future studies that aiming in characterizing the spatial dependency of the soil properties in the study catchment and/or a similar area, it is recommended that the soil properties should be sampled at distances shorter than the range found in this study. But the purpose and information required together with the cost of sample collection and analysis besides spatial dependence should be considered.

The resulting semivariograms indicate the existence of strong to moderate spatial dependence for all soil properties determined in this study. The degree of spatial dependence (DSD) that describes the characteristic of strength in soil spatial structure was between 8 and 63% (Table 6.2). Kravchenko (2003) stated that DSD values greater than 60% corresponded to a weak spatial structure, i.e., more than 60% of the data variability consisted of random, unexplainable, and short-distance variation. This is inconsistent with the results of a study by Cambardella et al. (1994) who established the classification of the DSD between adjacent observations of soil property >75% to correspond to weak spatial structure. In this study, the semivariograms indicate strong spatial dependence (DSD ≤ 25%) for soil properties such as sand, silt, BD, TN, Pav, Ex K, Ex Ca, CEC and pH, while the other soil properties show moderate (25 < DSD ≤ 75%) spatial dependence (Table 6.2). The strong spatial dependence of the soil properties may be restricted by intrinsic variability in soil characteristics (e.g., soil texture, mineralogy) whereas extrinsic variations (e.g., tillage, fertilizer conditions, conservation measures and management practices) may control the variability of the weakly to moderately spatially dependent parameters (Cambardella et al. 1994).

Kriging cross-validation was used to choose the semivariogram models that could give the most accurate spatial predictions of the unknown values of the field. The test was checked with the mean square error (MSE) values. The model with the lowest MSE value was chosen and applied in this study (Table 6.2). The MSE values for the respective models in Table 6.2 are low, indicating that kriging estimation of soil properties distribution are closer to field measured values. The accuracy of the kriged soil properties spatial maps was also assessed by the *G* value (Table 6.2). The *G* value for the soil parameters indicates that the prediction capacity of the datasets using kriging from the sample points as compared to catchment average values. For example, the G value for silt equals 79%, which indicates that the kriged silt map was 79% more accurate than that can be achieved using the average catchment scale values. A similar trend of accuracy of the kriged maps for sand, clay, BD, Ca, Pav, CEC, TN was achieved compared to the average catchment values. However, the *G* value was lower for the moderate spatial structure soil data, e.g., *G* equaled 3%, 26%, and 37% for TP, Ex Mg and Fe, respectively. Such soil properties had a DSD between 26 and 45%. These values are in a similar range with the observations reported in the literature for different soil datasets (e.g., Mueller et al. 2003). However, recent studies (e.g., Parfitt et al. 2009) reported that for a soil property with a weak spatial structure, an accurate map may be obtained at the expense of intensive sampling. For such soil properties, unless intensive sampling is an acceptable option, a catchment-scale average value could be used (Parfitt et al. 2009). However, as the values of *G* are higher than zero, kriging was more accurate than the catchment-scale average value for the study catchment conditions. Thus, the use of the interpolation technique was suitable for developing the soil properties spatial maps that can support for generation of site-specific soil management strategies.

### 6.3.5 Spatial distribution of soil properties

The semivariogram parameters were used for kriging that produced an interpolation map of the soil properties (Figure 6.5). High spatial distribution of sand (50-70%) in the north and north-western parts of the catchment, particularly in the mountainous and central-ridge landforms was observed (Figure 6.5A). However, spatial distribution of sand content decreases in the direction towards the valley and reservoir landforms (south part) to 20%. The reservoir, followed by the valley and plateau landforms thus showed the lowest sand content. The pattern of distribution of silt content showed the reverse of sand, as the highest silt content (48-77%) was in many parts of the valley, followed by the reservoir and some areas of the escarpment, and the lowest silt content (18%) on the central-ridge and mountainous landforms where some noisy trend was observed (Figure 6.5B). There was a comparatively high clay content (40-51%) spatial distribution along the toe-slope (e.g., reservoir, valley) and parts of the plateau landform in the south and south-east direction of the catchment (Figure 6.5C). The mountainous followed by the central-ridge landform showed the lowest clay content. This indicates that the content of finer soil materials increases towards the lower and flat area of the catchment, whereas the reverse is true for sand content. Saldana et al. (1998) found a similar trend of soil texture variability in their study that covered lower to higher river terraces in Spain.

The spatial distribution of soil bulk density (BD) was high (1.75-2.00 Mg $m^{-3}$) in the north and north-western part of the catchment (mountainous), followed by the central-ridge landform (center parts of the catchment). The lowest BD value was found in the reservoir (1.2 Mg $m^{-3}$), followed by the valley and to some extent in the landforms such as escarpment and plateau in the eastern part of the catchment (Figure 6.5D). This study indicates that a large part of the catchment (> 70%) shows high BD (> 1.60 Mg $m^{-3}$), which creates conducive conditions to increase erosion through runoff; because soil infiltration and soil water-holding capacity is reduced as BD increases (Ahmed et al. 1987). The low soil OC content could be partly responsible for the high BD, as the correlation between soil OC and BD was strong and significant ($r = -0.83$, $P = 0.001$).

From the spatial distribution map of the soil OC (Figure 6.5E), we can see that the OC values are higher (4.0-4.5%) in the south-eastern than in the western, central or northern parts of the study catchment. The north-western catchment includes the mountainous, central-ridge and parts of the escarpment landforms that show severe degradation in soil OC. In these landforms, the main reasons for low soil OC could be the relatively steep terrain (natural factor) and the anthropogenic factors (e.g., intensive tillage, cutting of trees, removal of plant and other organic sources, overgrazing), which enhance OC losses.

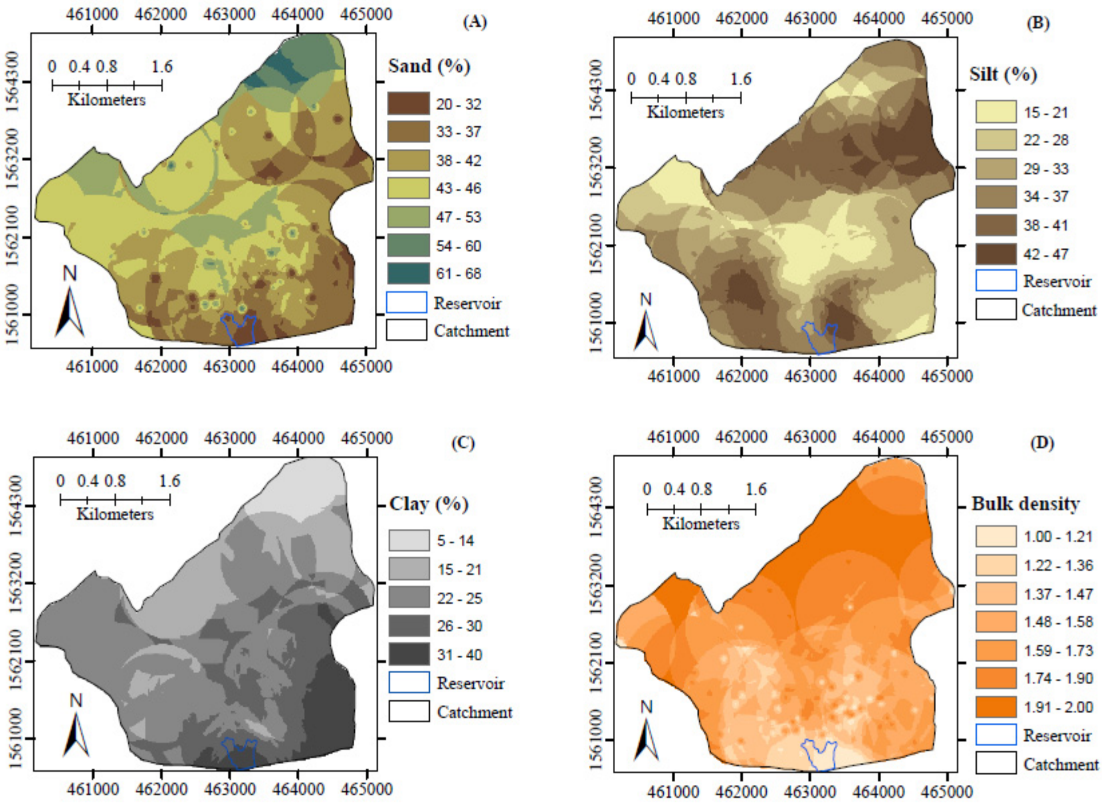



Figure 6.5: Spatial distribution of selected soil properties interpolated by ordinary kriging for Mai-Negus catchment: (A) sand (%), (B) silt (%), (C) clay (%), (D) dry bulk density (Mg $m^{-3}$), (E) OC, organic carbon (%), (F) TN (%), total nitrogen, (G) Pav, available phosphorous (gm $kg^{-1}$), (H) Ex K, exchangeable potassium ($cmol_c$ $kg^{-1}$), (I) Ex Ca, exchangeable calcium ($cmol_c$ $kg^{-1}$), (J) Ex Mg, exchangeable magnesium ($cmol_c$ $kg^{-1}$), (K) CEC, cation exchangeable capacity ($cmol_c$ $kg^{-1}$), and (L) Fe, iron (mg $kg^{-1}$).

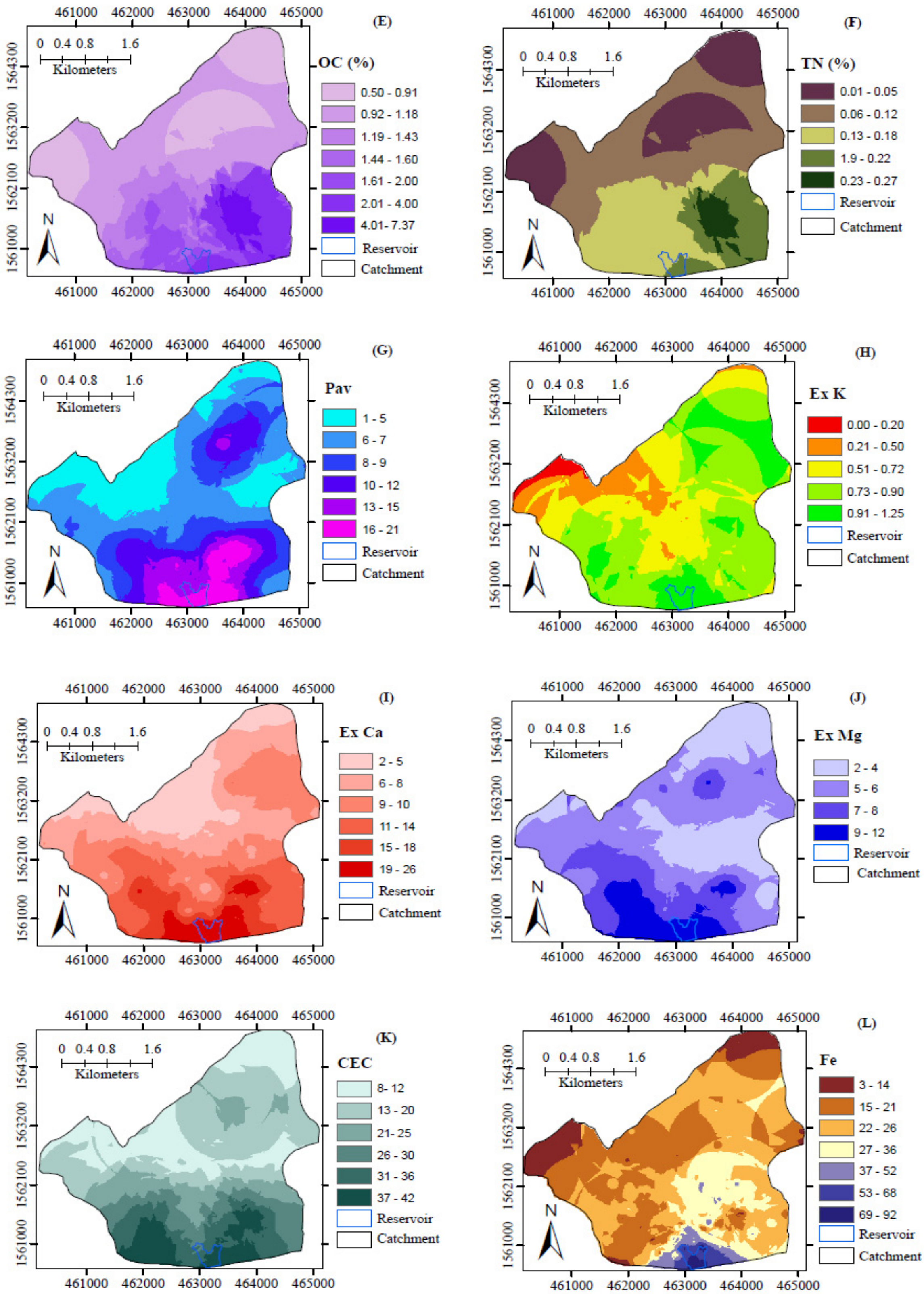



Figure 6.5: continued

The soil OC spatial pattern is approximately consistent with the spatial distribution of topography and land-use and land-cover in the catchment. The highest spatial distribution of OC (Figure 6.5E) was observed due to the mixed forest land-cover in the eastern part of the catchment (partly located on both the escarpment and plateau landforms). This is followed by the reservoir and valley and to some extent by the rolling-hills landforms. Similarly, Figure 6.5F shows a higher spatial distribution of TN in parts of the escarpment and plateau followed by the reservoir and part of the valley, whereas it was the lowest in the mountainous and central-ridge landforms. Such rating of the level of OC and TN is catchment specific. However, OC and TN were generally limited in the soils of the study catchment as compared to the standards used in rating for tropical soils.

The trend of the spatial distribution of Pav, Ex K, Ca, Mg, CEC and Fe (Figure 6.5G-L) show a similar spatial pattern. These figures show that the highest values were located in the reservoir and decreased towards the upper part (steep slopes in the north and west direction) of the catchment; although patterns were sometimes irregular. The valley in the north-east direction of the catchment also showed high rates of spatial distribution of Pav (18-26 mg $kg^{-1}$) similar to that of the reservoir. Such information and knowledge on the spatial distribution and variability of soil properties is beneficial for determining the trend and rate of soil nutrients in a landscape for future soil management planning. The spatial variability of soil properties may have several reasons, e.g., inherent soil conditions, marginal farming that use minimal inputs (Miller et al. 1988), tillage conditions and fertilizer practices (Sabbe and Marx 1987), cropping system, soil conservation measures and management practices (Ryan 1998). However, a better understanding of the main factors controlling the spatial variability of the soil properties in the study catchment demands further investigation.

Generally, spatial distribution of the soil properties showed a well-defined pattern of high contents of fine soil particles and soil nutrients in the reservoir (toe-slope) and valley (foot-slope) and in the sites with high vegetative cover. Due to its selective nature, soil erosion may cause such spatial variability of soil fine materials and the associted soil nutrients that are transported long distances towards depositional areas (Stone et al. 1985; Krogvang 1990). The soil parameters are also transported dissolved in runoff. Quantifying the rate of nutrient export to the deposition areas in the study catchment can show well the effect of erosion on the rate of spatial variability of the soil properties losses from a landscape units. For the purpose of site-specific soil management based on the maps of the spatial distribution of soil properties developed in this study, prioritization should be given to the north-west parts of the catchment (mountainous and central-ridge). This study indicates that the spatial distribution of topsoil properties can be used as an indicator for the spatial variability of soil degradation status at catchment scale.

## 6.4 Conclusions

The results of this study demonstrate that the use of classical statistics and geostatistical methods can simplify the soil sampling process without losing the quality of soil information. This is because both methods reveal the statistical variability of the soil properties across the study catchment. However, the geostatistical techniques are preferred to the classical statistics for estimation of the values of the soil parameters spatially and to show their variability in a catchment for site-specific decision-making. This indicates that the classical statistical techniques lack the necessary tools to identify the kind of systematic spatial variability of the soil properties at catchment scale.

The classical statistics of the soil properties show a coefficient of variation up to 73% for the soil parameters, but such values do not allow identification of the location of the sources of variability. Despite of this, the results of the semivariogram analysis show the presence of a strong to moderate spatial structure (dependence) of the selected soil properties within the catchment. Such understandings of the soils in the catchment provide new insights for site-specific management planning that can address the issues such as ``where to place the proper interventions``. The presence of spatial dependence also suggests that a composite or catchment average soil test is insufficient to provide information on soil properties under similar conditions.

The results of this study show that soil properties with a strong to moderate spatial structure can predict relatively accurate soil properties maps using the number of sampling locations in the study area than the catchment average value. In general, this study indicate a large range of soil properties variability, as the kriged maps show the lowest value of soil nutrients and fine soil particles in the mountainous (northwest) and central-ridge landforms, whereas the highest were in the reservoir followed by the valley (south direction). It can therefore be concluded that such spatial distribution of soil properties can be used for developing soil degradation indicator maps that can identify sites of prioritization within the study catchment for their management and reclamation requirements. Thus, introducing appropriate interventions (soil management practices) targeting the prioritized sites based on the kriged soil properties spatial variability in the study catchment is crucial for sustaining agricultural production and environmental services.

# 7 SOIL EROSION MODELING USING THE SWAT MODEL IN A SEMI-ARID NORTHERN ETHIOPIA CATCHMENT

## 7.1 Introduction

Soil erosion is one of the most serious land degradation problems all over the world. At the global scale, soil erosion is the dominant agent of soil degradation (Scherr 1999; Lal 2001; Morgan 2005), accounting for 70 to 90% of total soil degradation (Lal 2001; Zoebisch and DePauw 2002). Total land area affected by soil erosion all over the world is 1,094 Mha of which 43% suffer from deforestation and the removal of natural vegetation, 29% from overgrazing, 24% from improper management of the agricultural land and 4% from over-exploitation of natural vegetation (Walling and Fang 2003). Erosion has long-term impacts on soil quality, agricultural productivity, transportation of pollutants and ecological degradation (Lal 1998; Saha 2004). Erosion reduces not only topsoil but also organic matter, soil nutrients and soil moisture (Lal 1999). Moreover, sedimentation due to erosion reduces the capacity of reservoirs and drainage ditches and also poses a risk of flooding and blocking of the irrigation canals, which is frequently observed in the Ethiopian highlands (Oldeman 1994; Tamene 2005). Dejene (1990) and Admassie (1995) show that there is nowhere in the world where erosion is as destructive to the ecosystem as in the northern Ethiopian highlands.

The adverse influences of widespread soil erosion that causes severe soil degradation have long been documented as severe environmental and production problems for human sustainability (Lu et al. 2004). However, estimation of soil erosion loss is often difficult due to the complex interplay of many factors such as climate, land-cover, soil, topography, lithology and human activities (Lal 1998; Lu et al. 2004). In addition, social, economic, political, and scale and methodological components influence the estimated soil erosion rate (Ananda and Herath 2003). Reports on soil quality (SQ) degradation are thus generalized for the whole country though derived from sources with different environmental settings, and have limitations in scope. It is problematic to extrapolate results from such case studies to other areas, and the resulting reports are also inadequate to guide policy action. In support of the above facts, previous studies in the Tigray region, northern Ethiopia, indicate that the rate of soil erosion varies from 7 t $ha^{-1}$ $y^{-1}$ (Nyssen 2001) to more than 24 t $ha^{-1}$ $y^{-1}$ (Tamene 2005) and 80 t $ha^{-1}$ $y^{-1}$ (Tekeste and Paul 1989). Erosion rates are also estimated to be 130 t $ha^{-1}$ $y^{-1}$ from cropland and 35 t $ha^{-1}$ $y^{-1}$ averaged over all land-use types in the highlands of Ethiopia (FAO 1986). The discrepancies in the results of the above studies are mainly due to differences in the methods employed and their respective scale of analysis. Some of the soil loss estimates are derived from empirical models, and some are based on erosion plots while others employed reservoir surveys (e.g., Haregeweyn et al. 2006; Tamene et at. 2006a). Discrepancies on the rate of soil nutrient losses associated to sediment and runoff is also reported for Tigray, northern Ethiopia (e.g., Haregeweyn et al. 2006; Grimay et al. 2009).

Predominantly, past soil erosion estimates and extrapolations in Ethiopia are mainly based on plot level studies (Hurni 1985; 1993; Nyssen 2001). Although runoff plots provide good experimental insight into the relationships between soil loss under different cover, soils and slopes, results cannot be extrapolated to an entire catchment (Mutua et al. 2006). It also poses many limitations in terms of cost, representation, and reliability of the resulting data (Lu et al. 2004). Modeling soil erosion using physical models thus provides a sophisticated alternative tool for investigating the processes and mechanisms of soil erosion at catchment scales (Boggs et al. 2001).

To estimate soil erosion and develop suitable management plans, many erosion models such as the Annualized Agricultural Non-Point Source model (AnnAGNPS) (Bingner and Theurer 2001), European Soil Erosion Model (EUROSEM) (Morgan et al. 1998), Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), Water Erosion Prediction Project (WEPP) (Flanagan and Nearing 1995), and Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) have been developed. Among these models, the USLE has continued as the most practical approach for estimating field soil erosion potentials for more than 40 years, whereas the other process-based erosion models developed afterward have limitations in applicability due to intensive data and computation requirements (Lim et al. 2005). However, studies using the USLE do not consider the sediment delivery ratio to estimate the sediment delivered to the downstream point of interest (Lim et al. 2005). This could be part of the reason for developing other erosion and hydrological models that consider the sediment delivery process.

The application of these models is not always an easy task since they require large amounts of information which often is not available. However, physical models are the only current tools that enable an approximate quantification of soil erosion processes, facilitating the recognition of high-risk areas and consequently the development of efficient planning to prevent soil degradation at catchment scale (Santhi et al., 2001) though such models are rarely applied in Ethiopia for many reasons. Before applying any of the models developed elsewhere for natural resource management decision-making, evaluation of model performance from the context of the new environment is very crucial (Ndomba et al. 2005). In this study, following a literature review of different types of erosion models, the physical-based SWAT model interfaced in a geographical information system (GIS) environment was selected to be evaluated and then applied in a northern Ethiopian catchment so as to assess soil quality (SQ) degradation management. The SWAT model is based on extensive modeling experience and also incorporates the features of several other models (Neitsch et al., 2005). Recent advances in the use of GIS, remote sensing and digital elevation model have promoted the application of such models at catchment scale with reasonable costs and better accuracy (Lu et al. 2004; Mutua et al. 2006).

While the study area lacks some of the data needed for most physically-distributed models, it is possible to accommodate the requirements of SWAT by integrating field and literature survey. Despite this fact, little information is available that evaluate and apply SWAT model for catchment scale management planning in northern Ethiopia. The objectives of this study are to (1) evaluate the performance of the SWAT model by comparing predicted stream flow, sediment yield and soil nutrient loadings with the corresponding measured values at the study catchment, (2) apply the verified model in identification and prioritization of hotspot soil degradation sub-catchments on the basis of estimated runoff, sediment yield and nutrient losses, (3) assess the relationships among these losses and (4) suggest suitable management options that can help tackle the observed problem. Identification of erosion-hotspot areas using a physical model that estimates soil erosion rates with sufficient accuracy will have great importance for implementing appropriate erosion control practices (Shi et al. 2004). Evaluation of the model application to conditions in northern Ethiopia will also be a contribution to scientific community to expand research on soil degradation.

## 7.2 Materials and methods

### 7.2.1 Study area

This study was conducted in the Mai-Negus catchment, northern Ethiopia (Figure 7.1). The study catchment is located in the central zone of the Tigray region, 245 km west of Mekelle, the capital of the region. The catchment area is about 1240 ha. Altitude varies over short distances within the range of 2060 to 2650 m a.s.l. The catchment is part of the northern highlands of Ethiopia comprising high and low mountains, hilly lands, and valleys. The catchment has a mean annual temperature of 22$^{o}$C and precipitation of 700 mm, with a main rainy season from July to September. The dominant soil type in the catchment is Cambisols. Soils in the mountains, hilly land and piedmont areas are generally shallow and relatively deep in the valley. The farming system is principally crop-oriented, supplemented by livestock. The vegetation has been almost cleared due to deforestation. Forest covers a small area and is classified as a deciduous and dry forest with medium-sized and small trees as well as bushes, and some scattered trees showing evidence of former natural forest. Other land-use types include grazing land, and rainfed annual crops (*Zea mays*, *Eragrostis tef*, pulses, e.g., *Vicia faba*, etc.). However, *Eragrostis tef* covers the largest part (> 80%) of the cultivated land.

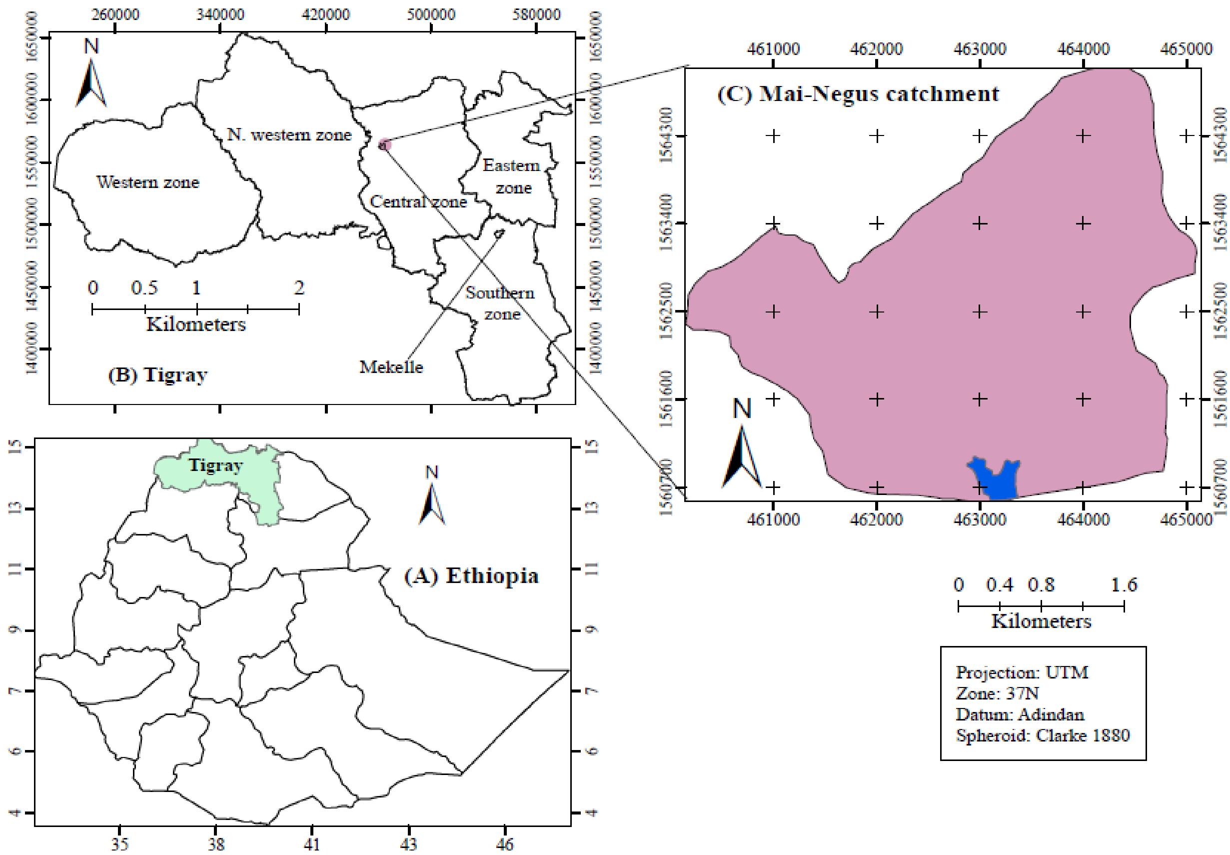



Figure 7.1: Location of the study area (A) Ethiopia, (B) Tigray, and (C) Mai-Negus catchment

### 7.2.2 SWAT model description

The Soil and Water Assessment Tool (SWAT) is a river-basin scale, continuous-time and spatially-distributed physically-based model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in complex catchments with varying soils, land-use and management conditions over long periods of time (Setegn et al. 2009). In this study, the ArcSWAT 2009 model version was applied to predict runoff, sediment yield and nutrient losses. The model was selected after hydrological models were reviewed using predefined criteria, i.e., meeting the objectives of the study, practical use in the area, data availability (DEM, land-use and land-cover, soil, weather), model sensitivity and uncertainty analysis, applicability in a complex catchment, spatial continuity, interface with GIS and its continuous review and improvements. The recently developed SWAT-CUP interfaced program for calibration and uncertainty analysis procedures (CUP) also made the SWAT model more attractive for this study.

As a physically-based model, the SWAT uses the spatial heterogeneity in terms of land-use and land-covers, soil types and slopes to divide catchment into sub-catchments and further subdivided into Hydrologic Response Units (HRUs). The water balance is the driving force for the simulation of hydrology from each HRU. The SWAT model uses two steps for the simulation: land phase and routing phase. The land phase controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. The routing phase of the model defines the movement of water, sediments and nutrients through the channel network of the catchment to the outlet (Lenhart et al. 2005). The SWAT model simulates the hydrological cycle based on the water balance equation in Setegn et al. (2009) defined as:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep}\ Q_{gw}) i \qquad (7.1)$$

where $SW_t$ is the final soil water content (mm), $SW_0$ is the initial soil soil water content on day i (mm), $t$ is the time (days), $R_{day}$ is the amount of precipitation on day i (mm), $Q_{surf}$ is the amount of surface runoff on day i (mm), $E_a$ is the amount of evaporation on day i (mm), $W_{seep}$ is the amount of water entering the vadose zone from the soil profile on day i (mm), and $Q_{gw}$ is the amount of return flow on day $i$ (mm). A comprehensive description of the SWAT model can be found in SWAT2005 theoretical documentation (Neitsch et al. 2005). But an overview of the model output calculation is given as follows.

**Runoff**

The SWAT model has two methods for estimating surface runoff: the Soil Conservation Service (SCS) curve-number (CN) (SCS 1972) and the Green and Ampt infiltration method (Green and Ampt 1911). Using daily or sub-daily rainfall amounts, the model estimates surface runoff volumes and peak runoff rates for each HRU. The SCS CN method is less data intensive than the Green and Ampt method (Fontaine et al. 2002). In this study, the SCS CN method was used to simulate surface runoff amount because sub-daily data for the Green and Ampt method was unavailabile for the study area. The SCS runoff equation is an empirical model that came into common use in the 1950s after more than 20 years of research of rainfall-runoff relationships from small watersheds across the U.S.A. The model was developed for quantifying runoff amount across various land-uses and soil types (Rallison and Miller 1981). The SCS curve-number runoff equation (SCS 1972) is:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \tag{7.2}$$

where $Q_{surf}$ is the daily accumulated surface runoff or rainfall excess (mm), $R_{day}$ is the rainfall depth for the day (mm), $I_a$ is the initial abstractions which include surface storage, interception and infiltration prior to runoff (mm), and $S$ is the retention parameter (mm). The retention parameter varies spatially due to changes in soils, land-use, management and slope, and temporally due to changes in soil water content. The retention parameter is defined in Xue and Xia (2007) as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{7.3}$$

where $CN$ is the curve-number for the day. Runoff will only occur when $R_{day} > I_a\ (=0.2S)$. The SWAT calculates the peak runoff rate using a modified rational method (Setegn et al. 2010). For further information on surface and subsurface runoff see SWAT2005 theoretical documentation (Neitsch et al. 2005).

**Sediment**

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) to calculate surface erosion due to rainfall and runoff for each HRU. The USLE predicts average annual gross erosion as a function of rainfall energy, whereas in the MUSLE the rainfall energy factor is replaced by a runoff factor to estimate soil loss (sediment yield) (Williams 1975). This improves the sediment yield prediction accuracy, eliminates the need for delivery ratios (the sediment yield at any point along the channel divided by the source erosion above that point), and single storm estimates of sediment yields can be calculated (Setegn et al. 2009). In MUSLE, sediment yield prediction is improved because runoff is a function of antecedent moisture condition and rainfall energy. The crop management factor is also recalculated every day when runoff occurs. It is a function of aboveground biomass, residue on the soil surface and the minimum C-factor for the plant (Setegn et al. 2009). In SWAT model, the MUSLE (Williams 1975) is:

$$Sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad (7.4)$$

where *sed* is the sediment yield on a given day (metric tons), $Q_{sur}$ *is the surface runoff volume* (mm $ha^{-1}$), $q_{peak}$ is the peak runoff rate ($m^3$ $s^{-1}$), $area_{hru}$ is the area of the HRU (ha), $K_{USLE}$ is the USLE soil erodibility factor (0.013 metric ton $m^2$ hr ($m^3$-metric ton cm$)^{-1}$), $C_{USLE}$ is the USLE cover and management factor, $P_{USLE}$ is the USLE support practice factor, $LS_{USLE}$ is the USLE topography factor, and *CFRG* is the coarse fragment factor. The hydrological model component estimates the runoff volume and peak runoff rate that are inturn used to calculate the runoff erosive energy variable (Setegn et al. 2009). The details of the USLE factors description and their respective equation components can be viewed in SWAT theoretical documentation (Neitsch et al. 2005).

In SWAT, the sediment routing model consists of two components that operate simultaneously to simulate the sediment transport in the channel network. These are the deposition and degradation processes (Neitsch et al. 2005). To decide such processes, the maximum sediment concentration in the reach is compared with that of sediment in the reach at the beginning of the time step. The maximum amount of sediment that can be transported from a reach segment is calculated as (Neitsch et al. 2005):

$$Conc_{sed,ch,mx} = C_{sp} \cdot v_{ch,pK}^{sp\exp} \qquad (7.5)$$

where $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton $m^{-3}$), $C_{sp}$ is a coefficient defined by the user, $v_{ch,pk}$ is the peak channel velocity (m $s^{-1}$), and *spexp* is exponent parameter for calculating sediment reentrained in channel sediment routing that is defined by the use and normally varies between 1.0 and 2.0. The maximum concentration of sediment calculated in equation 7.5 is compared with the concentration of sediment in the reach at the beginning of the time step, $conc_{sed,ch,i}$. If $conc_{sed,ch,i} > conc_{sed,ch,mx}$, deposition is the dominant process in the reach segment and the net amount of sediment deposited (Neitsch et al. 2005) is:

$$Sed_{dep} = (conc_{sed,ch,i} - conc_{sed,ch,mx}) \cdot V_{ch} \tag{7.6}$$

where $sed_{dep}$ is the amount of sediment deposited in the reach segment (metric tons), $conc_{sed,ch,i}$ is the initial sediment concentration in the reach (tons $m^{-3}$), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton $m^{-3}$), and $V_{ch}$ is the volume of water in the reach segment ($m^3$). Conversely, if $conc_{sed,ch,i} < conc_{sed,ch,mx}$, degradation is the dominat process in the reach segment and the net amount of sediment reentrained is calculated as ( Neitsch et al. 2005):

$$Sed_{\deg} = (conc_{sed,ch,mx} - conc_{sed,ch,i}) \cdot V_{ch} \cdot K_{CH} \cdot C_{CH} \tag{7.7}$$

where $sed_{deg}$ is the amount of sediment reentrained in the reach segment (metric tons), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (tons $m^{-3}$), $conc_{sed,ch,i}$ is the initial sediment concentration in the reach (tons $m^3$), $K_{CH}$ is the channel erodibility factor (cm $h^{-1}$ $Pa^{-1}$), and $C_{CH}$ is the cahnnel cover factor. Once the amount of degradation and deposition has been calculated, the final amount of sediment in the reach (basin´s outlet) is determined as:

$$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{\deg} \tag{7.8}$$

where $sed_{ch}$ is the amount of suspended sediment in the reach (metric tons), $sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period (metric tons), $sed_{dep}$, is the amount of sediment deposited (metric tons) and $sed_{deg}$ is the amount of sediment reentrained in the reach segment (metric tons).

**Soil nutrients**

The SWAT model also allows the computations of soil nutrient losses such as nitrogen (N) and phosphorus (P) through runoff flows and attached to sediment from the sub-basins to the basin outlet (Tripathi et al. 2003; Neitsch et al. 2005). Runoff transported

$NO_3$-N is estimated by considering the toplayer (10 mm) only. The total amount of water leaving the layer ($Q_T$, *mm*) is the sum of surface runoff, lateral subsurface flow, and percolation. Amounts of $NO_3$-N transported in runoff, lateral flow and percolation are estimated as the products of the volume of water lost and the average $NO_3$-N concentration (Tripathi et al. 2003) as:

$$V_{NO3} = Q_T \cdot C_{NO3} \cdot \beta_{NO3} \tag{7.9}$$

where $V_{NO3}$ is the amount of $NO_3$-N lost from the first layer (kg $ha^{-1}$), $Q_T$ is total amount of water leaving the layer (*mm*), $C_{NO3}$ is the concentration of $NO_3$-N in the first layer (Kg $mm^{-1}$ $H_2O$), and $\beta_{No3}$ is the nitrate percolation coefficient. Leaching and lateral subsurface flows in the lower layers are treated with the same approach as in the upper layer except that surface runoff is not included (Tripathi et al. 2003). The amount of organic N transported with sediment to the stream from the HRU for individual runoff events is calculated with the loading function (Tripathi et al. 2003; Neitsch et al. 2005) defined as:

$$orgN_{surf} = 0.001 \cdot conc_{orgN} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{N:sed} \tag{7.10}$$

where $orgN_{surf}$ is the amount of organic N transported to the main channel in surface runoff loss at the sub-basin outlet (kg $ha^{-1}$), $conc_{OrgN}$ is the concentration of organic N in the topsoil layer (g $ton^{-1}$), *sed* is the sediment yield on a given day (tons), $area_{rhu}$ is the HRU area (ha) and $\varepsilon_{N:sed}$ is the nitrogen enrichment ratio. The SWAT model uses the logarithmic relationship between enrichment ratios and sediment concentration to calculate organic N. The logarithmic equation estimating nitrogen enrichment ratio (Neitsch et al. 2005) is:

$$\varepsilon_{N:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \tag{7.11}$$

where $conc_{sed,surq}$ is the concentration of sediment in runoff (ton $m^{-3}$). Total nitrogen (TN) was considered as the sum of $NO_3$-N and organic N in this study. As P is commonly deependable on the sediment phase, the soluble P in runoff can be expressed (Tripathi et al. 2003; Neitsch et al. 2005) as:

$$P_{surf} = \frac{P_{solution,surf} \cdot Q_{surf}}{\rho b \cdot depth_{surf} \cdot K_{d,surf}} \quad (7.12)$$

where $P_{surf}$ is the amount of soluble P lost in surface runoff (kg ha$^{-1}$), $P_{solution,surf}$ is the amount of P in solution in the top 10 mm (kg ha$^{-1}$), $Q_{surf}$, is the amount of surface runoff on a given day (mm), $\rho_b$ is the bulk density of the top 10 mm (Mg m$^{-3}$) (assumed to be equivalent to bulk density of the first soil layer), $depth_{surf}$ is the depth of the surface layer (10 mm), and $k_{d,surf}$ is the P soil partitioning coefficient (m$^3$ Mg$^{-1}$) which is the ration of soluble P concentration in surface soil to the concentration of soluble P in surface runoff. The value of $k_{d,surf}$ used in SWAT is 175 (Tripathi et al. 2003).

The phosphrous (P) transported associated with sediment is simulated using the loading function described in Tripathi et al. (2003) as:

$$Y_p = 0.01(Y)(C_p)(ER) \quad (7.13)$$

where $Y_P$ is the amount of P transported with sediment to the main channel in runoff (kg ha$^{-1}$), $Y$ is the sediment yield (ton ha$^{-1}$), $C_p$ is the concentration of P in the topsoil layer (g ton$^{-1}$), and ER is the P enrichment ratio. Details about the processes of the soil nutrients and sediment routing by the SWAT model can be found in SWAT theoretical documentation (Neitsch et al. 2005).

### 7.2.3 Model inputs

The GIS input files needed for the SWAT model are the digital elevation model (DEM), land-use and land-cover, soils and daily observed weather data. The weather generator can be used to generate missed data. The data required for the SWAT model are determined following the information given in Neitsch et al. (2005). Digital Elevation Model (DEM): A 10 m by 10 m cell size DEM was developed from the topographical map of the area (Figure 7.2A). After the DEM was created, pits/sinks were filled before any processing was undertaken in order to route runoff to the catchment outlet. The DEM was used to delineate the catchment boundary and develop the drainage patterns of the catchment as well as estimate slope parameters.

Land-use and land-cover and soil data: Land-use is one of the most important factors that influences the model estimated outputs in a catchment. The SWAT model is capable of splitting the land-use and land-cover into different proportions based on the information from the user. The land-use and land-cover was derived from a Landsat Image of November 2007 (Figure 7.2B). These were changed into SWAT codes. The model requires soil map which was derived for the study catchment (Figure 7.2C). The SWAT model also requires soil physical and chemical properties such as available water content, soil texture, bulk density, hydraulic conductivity, organic carbon, etc., for different layers of each soil type (Neitsch et al. 2005; Setegn et al. 2009). These data were obtained from the NEDECO (1998) and field observation.

Weather data: In this study, the weather variables used for simulation the hydrological balance by the model were daily rainfall, minimum and maximum air temperature, solar radiation, wind speed and relative humidity obtained for the period of 1992-2009. These data were collected from Ethiopian National Meteorological Agency, Mekelle branch for the station located near the catchment. The weather generator in the SWAT model was used to estimate missed data for daily rainfall, temperature, solar radiation, wind speed and relative humidity.

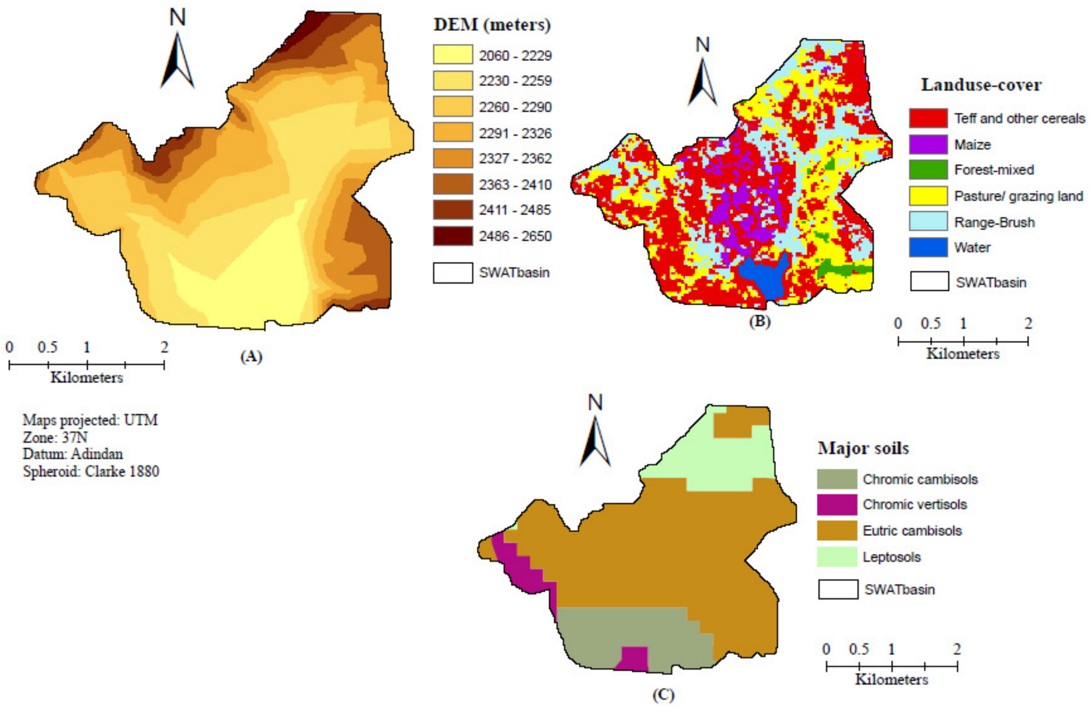



Figure 7.2: SWAT model inputs: (A) Digital elevation model (DEM), (B) land-use and land-cover and (C) major soils of Mai-Negus catchment, northern Ethiopia

### 7.2.4 Model setup

The SWAT model system embedded within GIS integrates the spatial environmental data inputs of soil, land-cover, topography and weather. The DEM was utilized by ArcSWAT to automatically delineate the basin (or catchment) into 16 sub-basin boundaries, calculate sub-basin average slopes and delineate the drainage networks. By overlaying the slope map along with the reclassified land-use and soil datasets, all the three map inputs were used to determine Hydrologic Response Units (HRUs) combinations that define the level of spatial detail to be included in the model. Within each sub-basin, the HRUs were created by ArcSWAT when the option to create multiple HRUs per sub-basin was enabled. The multiple slope option (an option for considering different slope classes for HRU definition) was used in this study. The land-use, soils and slope threshold values used in this application were 4%, 4% and 2%, respectively. These were selected in order to keep the HRUs to a reasonable number of 369. The model calculates unique runoff, sediment and nutrient transport to each HRU.

### 7.2.5 Preparation of observed data

The SWAT model does not use observed data values of flow, sediment and soil nutrients in calculations, but instead these are used for comparing the simulated values during model calibration and validation. Nevertheless, the SWAT model was originally developed to operate in ungauged basins with little or no calibration efforts (Shi et al. 2011). This is because the applicability of the model can be improved by *a priori* parameter estimation from the physical catchment characteristics (Atkinson et al. 2003; Shi et al. 2011). This implies that given appropriate spatial input data, SWAT can provide a satisfactory simulation output (Shi et al. 2011). To improve the simulation result in this study, first-hand catchment characteristics such as curve-number, Manning's coefficients, soil erodibility, management practices, land-cover, terrain and weather factors were collected and used as model input.

Model calibration and validation requires sufficiently long, quality observations of stream flow and the other variables, but observed data on both spatial and temporal scales of interest are very limited, especially in ungauged catchments such as the Mai-Negus catchment. In such situations, different methods have been used to build hydrologic modeling systems in ungauged basins, including the extrapolation of response information from gauged to ungauged basins, measurements by remote sensing, the application of process-based hydrological models in which climate inputs are measured, and the application of combined meteorological-hydrological models that do not require the user to specify precipitation inputs (Sivapalan et al. 2003).

In this study, the extrapolation of response information as a mean value from gauged to ungauged basins was adopted to prepare the observed data for model calibration and validation in the Mai-Negus catchment. In doing so, the measured (observed) runoff (Q) was determined through the runoff coefficient (RC) method described in Neitsch et al. (2005) (equation 7.14), which multiplies the daily rainfall of the period 1992-2009 (18 years) by the RC obtained from studies conducted in different parts of the Tigray region having a similar farming system (dominated by cereals), climate, topography and soil conditions (Appendix 2). This is because there are no short-and long-term measured stream flow or other hydrological parameters for the study catchment or other similar areas in this region. A mean RC of 0.20 was thus adopted in this study, which was assumed representative for the real situation of the study catchment, since it is an average of different sites having many aspects in common. Generally, reports for RC in the region are in the range of 15-30%.

$$Q = RC \cdot R_{day} \tag{7.14}$$

where Q is runoff (mm), RC is runoff coefficient (-), and $R_{day}$ is the rainfall for the day (mm).

The sediment thickness in the reservoir of the study catchment was collected using a pit-based survey in June 2009 when a large part of the reservoir bed was almost without water. The number of point (pit) samples depended on size and shape of the reservoir as well as on the pattern of sediment deposition based on judgment and visual observation. Then the Thiessen interpolation method was used to estimate sediment deposition in the reservoir (Tamene 2005). Soil total nitrogen (TN) and mineral phosphorus (P) were determined from the sediment exported to the reservoir following the standard laboratory procedures. In addition to the sediment and soil nutrients observed in the reservoir, data from past studies in the region with similar catchment characteristics were also used for model calibration and validation (Appendix 3).

### 7.2.6 Model sensitivity analysis, calibration and validation

The SWAT model is a complex catchment model relying on numerous parameters. This creates problems when attempting to calibrate the model to a specific study area due to the number of parameters and the possible correlations between each other (Vandenberghe et al. 2001). Therefore, a sensitivity analysis was performed before model calibration to identify the important input parameter sets on predicting stream flow, sediment, and N and P losses. Model sensitivity is defined as the change in model output per unit change in parameter input (Byne 2000). The analysis was conducted for the study catchment to determine the parameters needed to improve simulation results and thus to understand better the behavior of the hydrologic system, but it could also be useful to interpret results during the calibration phase (Kleijnen 2005). The parameters used in the sensitivity analysis were selected by reviewed previously used calibration parameters and the SWAT model documentation (e.g., Werner 1986; Zeleke 2000; Neitsch et al. 2005; Chekol 2006; Ashagre 2009).

The sensitivity analysis was carried out for flow, sediment and soil nutrients (N and P) using 29 parameters. The parameters were analyzed with a Latin Hypercube interval value of 10, and the sensitivity analysis thus required 290 simulations. Parameters with high sensitivity were chosen with care for this study, because small variations in their values can cause large variations in model output (Byne 2000). The analysis was run for the period 1992 to 1995. The year 1992 was used as a warm-up period for the model, and the other years (1993 to 1995) were considered in the sensitivity analysis. Relative sensitivity (absolute value) was categorized by Lenhart et al. (2002) as 0-0.05, 0.05-0.2, 0.2-1.0 and > 1 for small to negligible, medium, high and very high sensitivity, respectively, which was used to rank the sensitivity of model parameters.

Following the sensitivity analysis, the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) version 3.1.3 was applied to calibrate, validate, and assess model uncertainty (Abbaspour et al. 2007). The calibration and uncertainty analysis was performed using the SUFI-2 (sequential uncertainty fitting version 2) algorithm, which is a semi-automated inverse modeling procedure for a combined calibration-uncertainty analysis (Abbaspour et al. 2004; 2007).

In order to utilize any predictive catchment model for estimating the effectiveness of future potential management practices, the model must be first calibrated to measured data and should then be tested without further parameter adjustment against an independent set of measured data (model validation). Model calibration determines the best or at least a reasonable parameter set while validation ensures that the calibrated parameters set performs reasonably well under an independent dataset.

The SWAT was calibrated and validated based on daily, monthly and annual data basis for flow, whereas sediment yield and soil nutrients losses at the catchment outlet were calibrated only on an annual basis. The constraint to calibrate and validate sediment and soil nutrients on a daily and monthly basis is that no measured data existed for the catchment or similar areas. Flow data from 1992 to 2000 were used for calibration using the 1992 data as a warm-up period for the model. The 2001 to 2009 data were used for model validation using the 2000 year as the warm-up period. The model was next calibrated for sediment and then for soil nutrients. Observed sediment and nutrient data from 2001 to 2004 were used during calibration. The period 2001 was used for the model warm-up during calibration. For model validation of sediment and soil nutrients, the observed data from 2005 to 2009 were used, with the 2005 as the warm-up period.

### 7.2.7 Model evaluation

The efficiency of the SWAT model was evaluated using the coefficient of determination ($R^2$) and the Nash-Sutcliff coefficient ($N_{SE}$) (Nash and Sutcliffe 1970) between the observed data and the best simulation values. The $R^2$ is the square of the Pearson's correlation coefficient that describes the proportion of the total variance in the observed data that can be explained by the model. It ranges from 0.0 to 1.0 with higher $R^2$ values indicating better agreement (Kim et al. 2007). The range of $N_{SE}$ is between $-\infty$ and 1.0 (1 inclusive), with $N_{SE} = 1$ being the optimal value (Nash and Sutcliffe 1970). In general, values ranging between 0.0 and 1.0 are indicated better model efficiency than the mean observed values, but values of $N_{SE} > 0.50$ is accepted as satisfactory for the SWAT model. In contrast, $N_{SE}$ values < 0.0 indicate that the mean observed value is a better estimator than the model simulated value, which indicates poor performance of model (Santhi et al. 2001). The $R^2$ and $N_{SE}$ can be calculated as:

$$R^2 = \left[ \frac{\sum_{i=1}^{N} (O_i - \overline{O})(P_i - \overline{P})}{\left[\sum_{i=1}^{N} (O_i - \overline{O})^2\right]^{0.5} \left[\sum_{i=1}^{N} (P_i - \overline{P})^2\right]^{0.5}} \right]^2 \tag{7.15}$$

$$E_{NS} = 1.0 - \left[ \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \overline{O})^2} \right] \tag{7.16}$$

where $O_i$ is the measured data at time $i$, $\overline{O}$ is the mean of measured data, $P_i$ is the predicted data at time $i$, $\overline{P}$ is the mean of the predicted data, and $N$ is the number of compared values. Provided that the model predictive capability is demonstrated as being reasonable in the calibration and validation phase using such model evaluation criteria, the model can be used with confidence for future predictions under different management scenarios.

### 7.2.8 SWAT for identification and prioritization of hotspot sub-catchments

The evaluated model was applied for identifying and prioritizing of hotspot runoff, sediment yield (soil loss) and soil nutrient losses in the study catchment. The categories of erosion (soil loss) rates suggested by Tamene (2005) were set as thresholds for identification of degradation hotspot sub-catchments. In identification such sub-catchments, average annual runoff, sediment yield and soil nutrient losses for the simulation period 1992-2009 were generally considered. The hotspot sub-catchments were then prioritized for the implementation of suitable interventions that reduce the runoff, sediment yield and soil nutrient losses. Priorities were targeted on the basis of rank assigned to each hotspot sub-catchment according to categories of soil erosion hazard zone described by Tamene (2005) (Table 7.1). For nutrient losses, a threshold value of 10 mg $l^{-1}$ for $NO_3$-N and 0.5 mg $l^{-1}$ for dissolved P as described by the US Environmental Protection Agency (Tripathi et al. 2003) were adopted as criteria for identifying the hotspot sub-catchments.

### 7.2.9 Data analysis and interpretation

In this study, descriptive, correlation and regression analysis were used to analyze SWAT model outputs. In addition, data were interpreted in relation to standards (soil loss severity classes, soil loss tolerance) for the study catchment condition. GIS maps in ArcGIS 9.2 were also developed to display the magnitude and spatial variability of model outputs for the sub-catchments in the study catchment.

Table 7.1: Classification of soil erosion based on soil loss rate

| Soil loss range (t $ha^{-1}$ $y^{-1}$) | Category |
|---|---|
| 0-5 | Very low |
| 5-15 | Low |
| 15-30 | Medium |
| 30-50 | High |
| > 50 | Very high |

*Source: Tamene (2005)*

## 7.3 Results and discussion

### 7.3.1 Model sensitivity analysis

The relative sensitivity value, category and rank of 12 parameters with respect to each variable were determined (Table 7.2). The 12 parameters were chosen to minimize calibration time and maximize model efficiency. Among the parameters used for the sensitivity analysis, the most sensitive in the range of medium to very high sensitivity during flow, sediment and soil nutrient simulation were ranked from first (most important) to the least. For example, the most sensitive parameters for flow simulation were CN2, slope, Esco, Sol_Awc, Gwqmn, Slsubbsn, Sol_k and Sol_BD. The CN2 determines the amount of precipitation that becomes runoff and the amount that infiltrates. The Esco is used for modifying the depth distribution for meeting soil evaporative demand to account mainly for the effect of capillary action, and the Gwqmn is used for regulating the return flow and groundwater storage. The effect of the other parameters on model outputs can be found in SWAT documentation (Neitsch et al. 2005).

The very high sensitive parameters for sediment included Usle_C, Spcon, Usle_P and slope. The soil nutrient N was highly sensitive to ErorgN, Surlag, Nperco and Usle_C, whereas P was highly sensitive to Usle_K, Usle_P, Usle_C and Erorgp. There are common parameters which show high sensitivity to flow, sediment and soil nutrients, regardless of the differences in the sensitivity values. An example of this is that Usle_K, Usle_C, Usle_P, slope, and Slsubbsn are sensitive to change these model outputs. In general, the obtained sensitivities show consistency with results determined in other studies for most of the parameters (e.g., Chekol 2006; Ashagre 2009).

Table 7.2: Most sensitive parameters for flow, sediment and soil nutrients simulation in Mai-Negus catchment, northern Ethiopia

| Flow | | | Sediment | | | Nitrogen (N) | | | Phosphorus (P) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameter | RS | category | parameter | RS | category | parameter | RS | category | parameter | RS | category | Rank[1] |
| CN2 | 2.02 | v. high | Usle_C | 2.34 | v. high | ErorgN | 0.89 | high | Usle_K | 1.32 | v. high | 1 |
| Slope | 1.33 | v. high | Spcon | 2.12 | v. high | Surlag | 0.87 | high | Usle_P | 1.10 | v. high | 2 |
| Esco | 0.84 | high | Usle_P | 1.84 | v. high | Nperco | 0.75 | high | Usle_C | 0.97 | high | 3 |
| Sol_Awc | 0.75 | high | Slope | 0.89 | high | Usle_C | 0.73 | high | Erorgp | 0.92 | high | 4 |
| Gwqmn | 0.56 | high | Ch_N2 | 0.68 | high | CN2 | 0.70 | high | Slope | 0.86 | high | 5 |
| Slsubbsn | 0.47 | high | Ch_Erod | 0.53 | high | Slope | 0.62 | high | Ch_N2 | 0.78 | high | 6 |
| Sol_K | 0.42 | high | Usle_K | 0.37 | high | Ubn | 0.57 | high | Ch_Erod | 0.73 | high | 7 |
| Sol_BD | 0.22 | high | Spexp | 0.33 | high | Epco | 0.18 | medium | Psp | 0.56 | high | 8 |
| Ch_K2 | 0.18 | medium | Ch_Cov | 0.28 | high | Usle_P | 0.15 | medium | Pperco | 0.49 | high | 9 |
| Surlag | 0.13 | medium | Canmx | 0.19 | medium | Sol_Z | 0.11 | medium | Slsubbsn | 0.17 | medium | 10 |
| Sol_Z | 0.10 | medium | Slsubbsn | 0.14 | medium | Slsubbsn | 0.08 | medium | Epco | 0.13 | medium | 11 |
| Alpha_Bf | 0.06 | medium | Prf | 0.10 | medium | GwNO3 | 0.06 | medium | Prf | 0.09 | medium | 12 |

[1] *Ranking of 1 is the highest relative sensitivity (RS) decreasing up to 12 for flow, sediment and soil nutrients simulation.*
*RS, relative sensitivity; CN2, Initial SCS curve-number II; Slope, Average slope steepness (m $m^{-1}$); Esco, Soil evaporation compensation factor; Sol_Awc, Available water capacity (mm $mm^{-1}$); Gwqmn, Threshold water depth in the shallow aquifer for flow (mm); Surlag, Surface runoff lag time (days); Sol_K, Saturated hydraulic conductivity (mm $hr^{-1}$); Sol_BD, soil moist bulk density (Mg $m^{-3}$); Ch_K2, Channel effective hydraulic conductivity (mm $hr^{-1}$); Ch_N2, Manning's n value for main channel; Ch_Cov, channel cover factor; Alpha_Bf, Base flow alpha factor (days); Sol_Z, Soil depth (mm); Spcon, maximum amount of sediment that can be re-entrained during channel sediment routing; Erorgp, P enrichment ratio with sediment loading; Usle_C, Universal soil loss equation cover factor; Usle_P, Universal soil loss equation management factor; Canmx, Maximum canopy storage (mm); Spexp, Sediment channel re-entrained exponent parameter; Slsubbsn, Prf, Sediment routing factor in main channels; Slsubsn, Average slope length (m); Usle_K, Universal soil loss equation soil factor; Ch_Erod, channel erodibility; Epco, plant uptake compensation factor; Nperco, Nitrate percolation coefficient(10 $m^3$ $Mg^{-1}$); Pperco, P percolation(10 $m^3$ $Mg^{-1}$); Ubn, N uptake distribution parameter; ErorgN, Organic N enrichment for sediment; Erorgp, Organic P enrichment for sediment; GwNO3, Concentration of $NO_3$ in groundwater; Psp, P availability index.*

### 7.3.2 Flow calibration and validation

After the sensitive parameters had been identified, the calibration process focused on adjusting the model-sensitive input parameters determined in the sensitivity analysis to obtain best fit between simulated and observed data. Model calibration is an important step in catchment modeling studies that helps to reduce uncertainties in model predictions (Setegn et al. 2010). During the model stream flow calibration process, the 12 sensitive parameters were considered. The final fitted values of these parameters were included in the SWAT model (Table 7.3) so as to fine tune the simulation with the observed data during validation. The effect of each parameter on model results is given in the SWAT documentation (Neitsch et al. 2005).

Table 7.3: Calibrated flow, sediment and soil nutrient parameter fitted values[a] for Mai-Negus catchment, northern Ethiopia

| Flow | | Sediment | | Total nitrogen (TN) | | Mineral phosphorus (P) | |
|---|---|---|---|---|---|---|---|
| Parameter | Value | Parameter | Value | Parameter | Value | Parameter | Value |
| CN2 | -0.2[b] | Usle_C | 0.27[c] | ErorgN | 2.35c | Usle_K | 0.15[b] |
| Slope | 1.50[b] | Spcon | 0.003[c] | Surlag | 0.10[c] | Usle_P | 0.8[c] |
| Esco | 0.53[c] | Usle_P | 0.8[v] | Nperco | 0.12[c] | Usle_C | 0.35[c] |
| Sol_Awc | -0.11[b] | Slope | 1.20[b] | Usle_C | 0.27[c] | Erorgp | 3.5[c] |
| Gwqmn | 53[c] | Usle_K | 0.12[b] | Ch_N2 | 0.03[c] | Slope | 1.20[b] |
| Slsubbsn | 0.25[b] | Ch_Erod | 0.42[c] | Slope | 1.20[b] | Ch_N2 | 0.03[c] |
| Sol_K | 0.15[b] | Ch_N2 | 0.03[c] | Ubn | 3[c] | Ch_Erod | 0.42 [c] |
| Sol_BD | 0.15[d] | Spexp | 1.25[c] | Epco | 0.03[c] | Epco | 0.14[c] |
| Ch_K2 | 1.2[c] | Ch_Cov | 0.45[c] | Usle_P | 0.6[c] | Pperco | -0.10[b] |
| Surlag | 0.10[c] | Canmx | 0.13[c] | Sol_Z | -0.10[b] | slsubbsn | 0.20[b] |
| Sol_Z | -0.10[b] | Slsubbsn | 0.20[b] | Slsubbsn | 0.20[b] | Psp | 0.20[c] |
| Alpha_Bf | 0.12[c] | Prf | 1.10[c] | GwNO3 | -0.10[b] | Prf | 1.1[c] |

*[a] Lower and upper parameter values are based on ranges recommended in the SWAT User's Manual (Neitsch et al. 2005).*
*[b] Relative change in the existing parameter where the current value is multiplied by 1 plus a given value.*
*[c] Substitution of the existing parameter value by the given value.*
*[d] Given value is added to the existing parameter value.*
*For description of parameters see Table 7.2.*

The calibration and validation results of the simulated stream flow on daily, monthly, and annual basis perform well for the Mai-Negus catchment as shown in the model goodness-of-fit of the SUFI-2 algorithm (Table 7.4). The $N_{SE}$ for stream flow calibration and validation on a daily basis was 0.55 and 0.53, respectively. An $R^2$ of 0.67 for daily flow calibration and 0.64 for daily flow validation was achieved. The model calibration efficiency value for monthly stream flow was $N_{SE}$ = 0.59 and $R^2$ = 0.72, whereas the monthly flow validation statistics was $N_{SE}$ = 0.61 and $R^2$ = 0.79. This indicates that model statistical values for daily flow validation were slightly lower than the calibration result while the opposite was found for the monthly value. But the model calibration and validation statistics are within the acceptable or satisfactory levels in both periods. On the other hand, the annual flow calibration ($N_{SE}$ = 0.67, $R^2$ = 0.81) and validation ($N_{SE}$ = 0.73, $R^2$ = 0.84) values of the model goodness-of-fit were higher than for the daily and monthly flow (Table 7.4).

Generally, efficiency values > 0.50 for $N_{SE}$ and > 0.60 for $R^2$ are considered adequate for SWAT model applications in management planning, as these values capture the variability of simulated and observed values reasonable well (Santhi et al. 2001). Considering such model statistics ($N_{SE}$ and $R^2$) for flow calibration and validation, the SWAT model was thus successfully calibrated and validated for the annual, monthly and daily stream flows. This indicates that the final values of the model-sensitive parameters selected during the calibration represent those parameters in the study area.

Table 7.4: Model evaluation statistics for stream flow calibration and validation at Mai-Negus catchment, northern Ethiopia

| | Nash-Sutcliffe model efficiency ($N_{SE}$) | | | Coefficient of determination ($R^2$) | | |
|---|---|---|---|---|---|---|
| | Daily | Monthly | Annual | Daily | Monthly | Annual |
| Cal | 0.55 | 0.59 | 0.67 | 0.67 | 0.72 | 0.81 |
| Val | 0.53 | 0.61 | 0.73 | 0.64 | 0.79 | 0.84 |

*Cal, calibration; Val, validation.*

In addition to the statistical measures ($R^2$, $N_{SE}$), the visual comparison of graphs also show model performance during calibration and validation of stream flows (Figure 7.3). This is used to identify differences in model bias in the timing and magnitude of peak flow simulation. The model underestimated daily peak flow for a number of days in the main rainy season (June to September) during calibration, but overestimated the daily peak flow for the validation period (Figure 7.3A-B). The same trend is also shown for the monthly peak stream flow during calibration and validation. The SWAT model underestimated high flows for 6 out of 8 peaks for monthly calibration, and overestimated flows for 6 out of 9 peak flows during monthly validation

(Figure 7.3C-D). Generally, the peak runoff value predicted by the model in the dry dates and months (Oct., Nov., Dec., Jan., Feb. and Mar.) during calibration and validation were slightly higher than those of the observed values. This could be associated with the sub-surface flows simulated by the model for such conditions. The SWAT model overestimated the high flows 5 out of 8 years during annual calibration, and overestimated 6 out of 9 years during validation (Figure 7.3E-F). Nevertheless, the SWAT model tracked most of the peak flow events well that occurred in the study catchment as indicated by the statistics values and Figure 7.3.

In general, the SWAT model in this study provides an acceptable and better prediction efficiency of stream flow that can use in further analysis to identify and prioritize critical runoff source sites and simulate alternative management strategies. In addition, the results show how well spatially distributed models are able to produce acceptable results using readily available, physically based input parameters in ungauged small catchments. Given further information about a catchment's characteristics and the availability of measured flow data using gauged stations, it can be expected that better simulation results than in this study could be obtained.

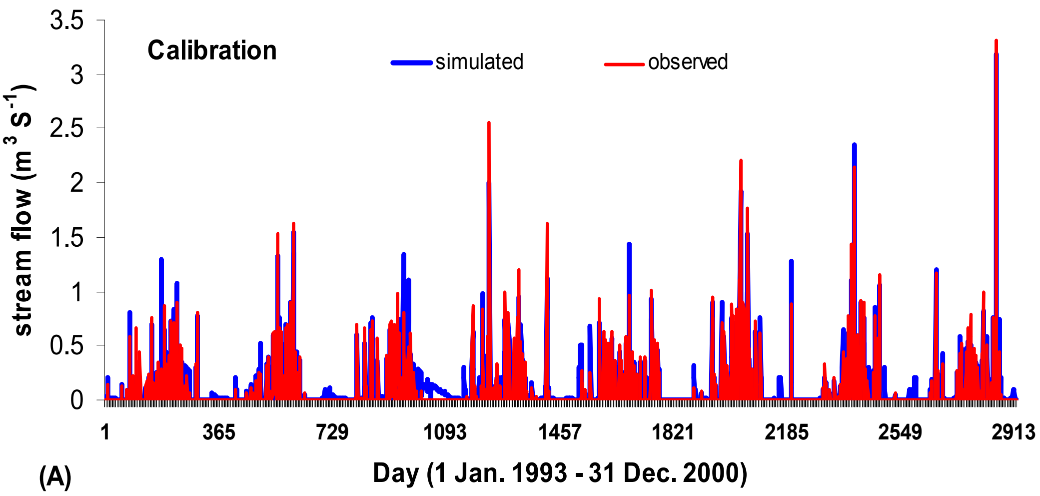



Figure 7.3: Model simulated and observed stream flow during (A) daily calibration, (B) daily validation, (C) monthly calibration, (D) monthly validation, (E) annual calibration, and (F) annual validation periods for Mai-Negus catchment, northern Ethiopia

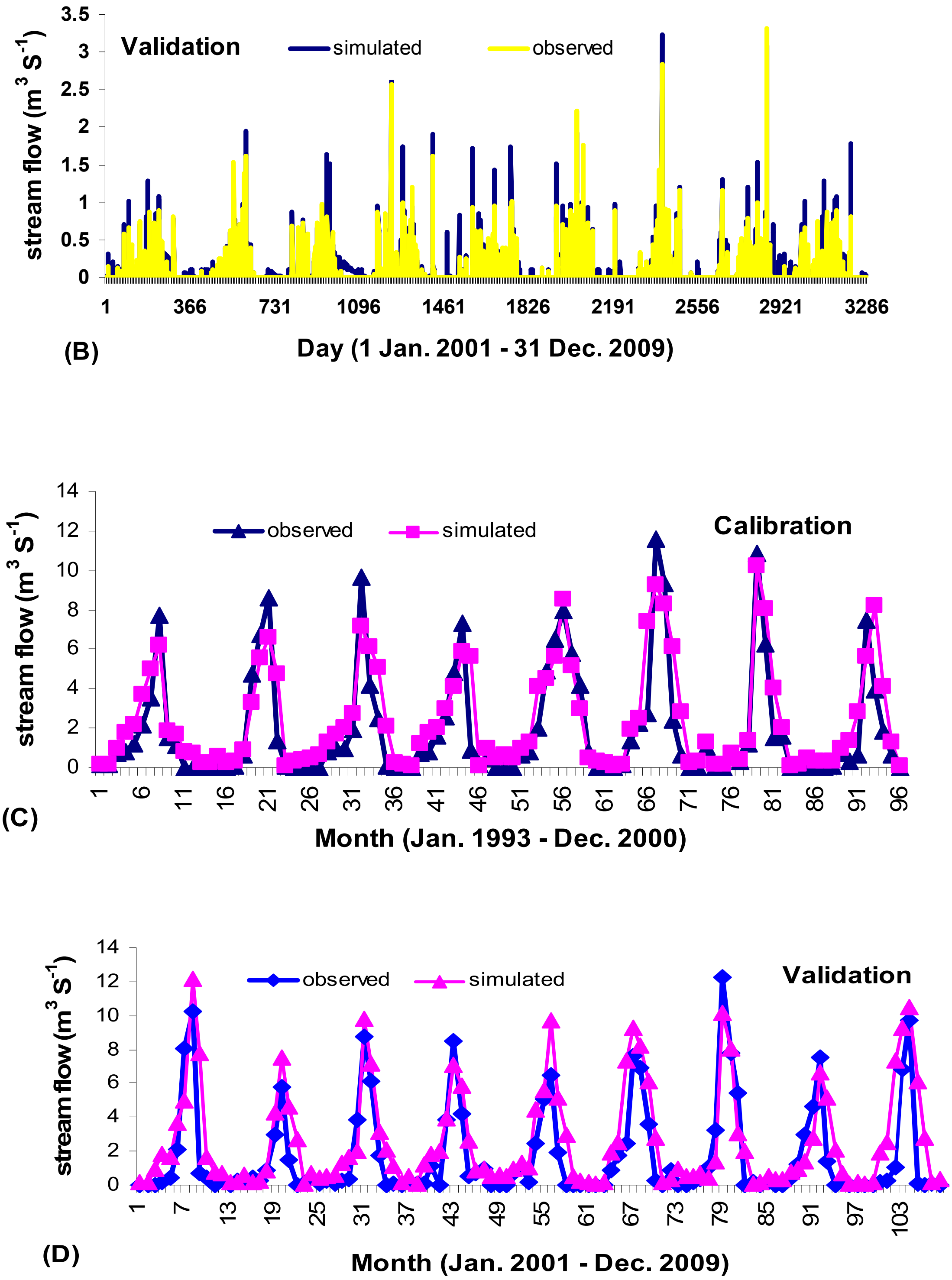
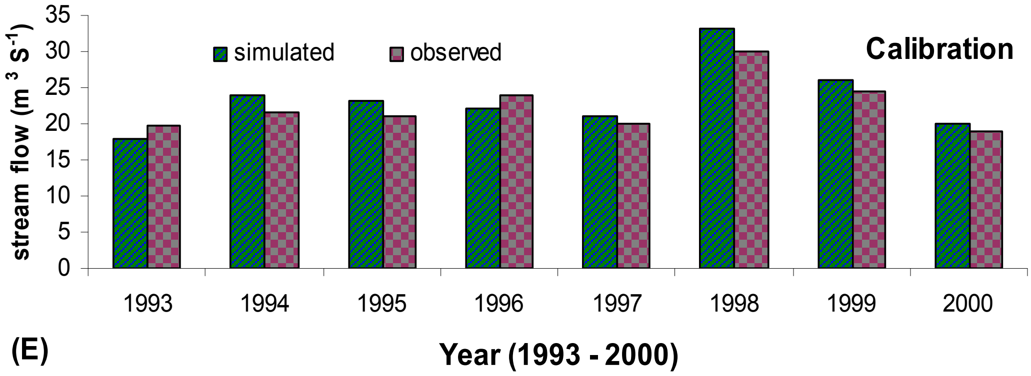
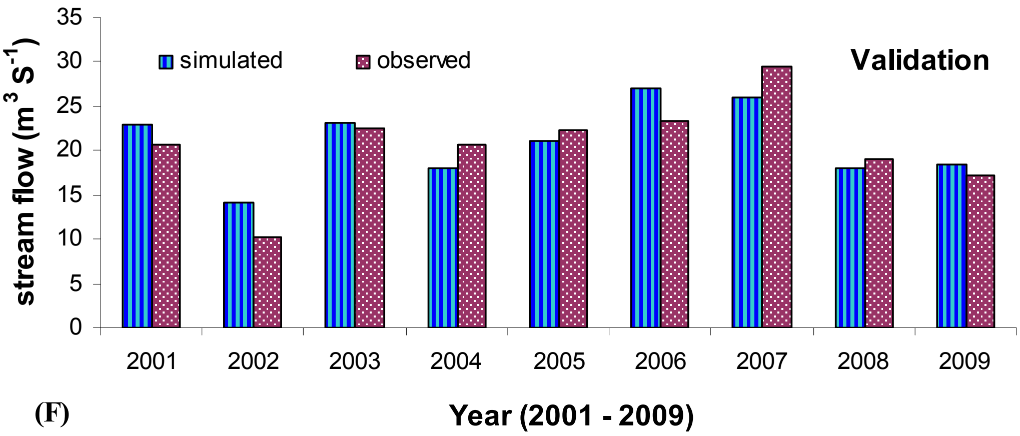



Figure 7.3: continued




(E)




(F)

Figure 7.3: continued

### 7.3.3 Calibration and validation of sediment and soil nutrients

The parameters and the fitted values considered during the sediment and soil nutrients model calibration are presented in Table 7.3 (section 7.3.2). The SWAT model calibration and validation statistics for the annual sediment yield and soil nutrients losses show an adequate level of accuracy (Table 7.5). The $R^2$ and $N_{SE}$ values computed between the simulated and observed annual sediment yields for the calibration period were 0.73 and 0.57, respectively. The validation of annual sediment yield showed a $R^2$ of 0.85 and $N_{SE}$ of 0.76, which is higher than the calibration values. The calibration of annual TN gave $R^2$ of 0.72 and $N_{SE}$ of 0.54, and of annual mineral phosphorus (P) calibration was 0.72 and 0.81, respectively. The efficiencies for P calibration are higher than for sediment and TN (Table 7.5). The reason may be attributed to the uncertainty in the observed data used, and also to the use of best-fit parameters during calibration. Similarly, in the model validation $R^2$ and $N_{SE}$ were higher for sediment and P than for

TN (Table 7.5). These model efficiencies improved during validation for sediment, TN and P as compared to calibration. The improvement for sediment was from 0.57 to 0.76 for $N_{SE}$ and from 0.73 to 0.85 for $R^2$, whereas for TN it was from 0.54 to 0.67 for $N_{SE}$ and from 0.72 to 0.83 for $R^2$. Phosphorus prediction efficiency also increased during validation from 0.72 to 0.76 and 0.81 to 0.87 for $N_{SE}$ and $R^2$, respectively.

The higher annual validation statistics for sediment yield and P than for TN indicates that the close agreement between measured and predicted values on an annual basis better explained by $N_{SE}$ and $R^2$ for P followed by sediment yield and TN. A better fit between simulated and measured values for P followed by sediment and TN is likely related to the quality of the input data used for the model. The sources of TN were included in the model; however, it was difficult to obtain all potential N sources and losses. Overall model prediction capacity for the sediment yield and soil nutrients is acceptable for the study catchment as it is greater than 0.50 for $N_{SE}$ and 0. 60 for $R^2$.

Table 7.5: Observed, simulated and model statistics during calibration and validation of annual sediment yield, total nitrogen (TN) and mineral phosphorus (P) at the outlet of the Mai-Negus catchment, northern Ethiopia

| | Calibration period (2002-2004) | | | | | | | Validation period (2006-2009) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sediment (ton) | | TN (kg) | | P (kg) | | | Sediment (ton) | | TN (kg) | | P (kg) | |
| Year | Obs | Sim | Obs | Sim | Obs | Sim | Year | Obs | Sim | Obs | Sim | Obs | Sim |
| 2002 | 17732 | 19540 | 22320 | 23460 | 109 | 110 | 2006 | 25048 | 28400 | 13640 | 17060 | 99 | 118 |
| 2003 | 22568 | 23500 | 26040 | 25010 | 115 | 115 | 2007 | 20708 | 24720 | 15748 | 15810 | 180 | 169 |
| 2004 | 19964 | 21080 | 24180 | 25072 | 113 | 111 | 2008 | 22940 | 25480 | 14694 | 14802 | 139 | 150 |
| $N_{SE}$ | 0.57 | | 0.54 | | 0.72 | | 2009 | 24304 | 26680 | 21998 | 23426 | 167 | 185 |
| $R^2$ | 0.73 | | 0.72 | | 0.81 | | $N_{SE}$ | 0.76 | | 0.67 | | 0.76 | |
| | | | | | | | $R^2$ | 0.85 | | 0.83 | | 0.87 | |

*Obs, observed; Sim, Simulated; $N_{SE}$, Nash-Sutcliffe model efficiency; $R^2$, coefficient of determination.*

With regard to the observed versus simulated data for sediment calibration and validation, results of this study reveal that the model overestimated in all the simulation years (Table 7.5). The overestimation of sediment yield ranged from 4-10% for calibration and 9-13% for validation. The model also overpredicted for TN and P by 5-15% during validation. However, during calibration TN was overestimated (5-8%) for two years (2002 and 2004) and underestimated in 2003 by about 5%. Similarly, P was overestimated in 2002 and 2003 and underestimated in 2004 within an acceptable range of deviation. It is, therefore, important to estimate soil erosion and soil nutrient losses using the calibrated SWAT model, which captured well the complex catchment characteristics for targeted land-use and conservation intervention after identifying and setting priorities to most vulnerable landscapes with the help of the model results.

### 7.3.4 Estimated runoff, sediment yield and soil nutrient at catchment level

After the SWAT model had been validated and evaluated, the model-fitted parameter values were used for simulation at catchment level. Average annual runoff, sediment yield, total N and P for the entire catchment were estimated as 168.0 mm, 34 t ha$^{-1}$ y$^{-1}$, 18.1 and 1.1 kg ha$^{-1}$ y$^{-1}$, respectively. The sediment yield estimated by SWAT indicates that soil loss at catchment level is high and above the soil loss tolerance level. The percentage of each soil loss category in the study catchment is presented in Table 7.6. The spatial pattern of the rate of sediment yield, runoff and soil nutrient losses are also shown in Figure 7.4. On the basis of the soil loss categories that corresponded with the annual sediment yield, the erosion spatial pattern was reclassified into five categories of soil erosion hazard zones, namely very low, low, medium, high and very high (Table 7.6; Figure 7.4A). The estimated sediment yield and the spatial patterns of the erosion categories are generally reasonable when compared to what has been observed in the study landscape.

Table 7.6: Soil loss categories and runoff in Mai-Negus catchment, northern Ethiopia

| Sediment yield | | | [a]Runoff | |
|---|---|---|---|---|
| Category | t ha$^{-1}$ yr$^{-1}$ | Area (%) | Range (mm) | Area (%) |
| Very low | 0-5 | 1.70 | 109-130 | 8.30 |
| Low | 5-15 | 6.60 | 130-150 | 23.1 |
| Medium | 15-30 | 46.3 | 150-180 | 11.2 |
| High | 30-50 | 13.1 | 180-210 | 18.0 |
| Very high | > 50 | 32.3 | 210-234 | 39.5 |

[a]*the sum of both surface and base flows*

The predicted sediment yield by the SWAT model shows that 13.1 and 32.3% of the catchment areas have a high and very high potential soil erosion rate, equivalent to average sediment yield of 30 to 50 and > 50 t ha$^{-1}$y$^{-1}$, respectively. It was estimated that 2% of the catchment experienced very low erosion rates, whereas 7% and 46%, respectively, is categorized as low and medium rates of soil erosion. In total, 45% of the catchment was considered to be affected by both high and very high sediment yield (soil loss) rates. The catchment areas with the highest and lowest runoff were 39.5 and 8.3%, respectively (Table 7.6). Generally, sediment yield was high in parts of the catchment where high runoff was observed (Figure 7.4A-B). The spatial patterns of the nutrient losses as TN and TP associated with runoff and sediment in the catchment are shown in Figure 7.4C-D. These figures also indicate that areas with high runoff and sediment yield are susceptible to high soil nutrient losses, despite the fact that they are below the threshold value set for environmental protection. Such below threshold losses of soil nutrients may be attributed to the low soil nutrient levels in the soils of the catchment.

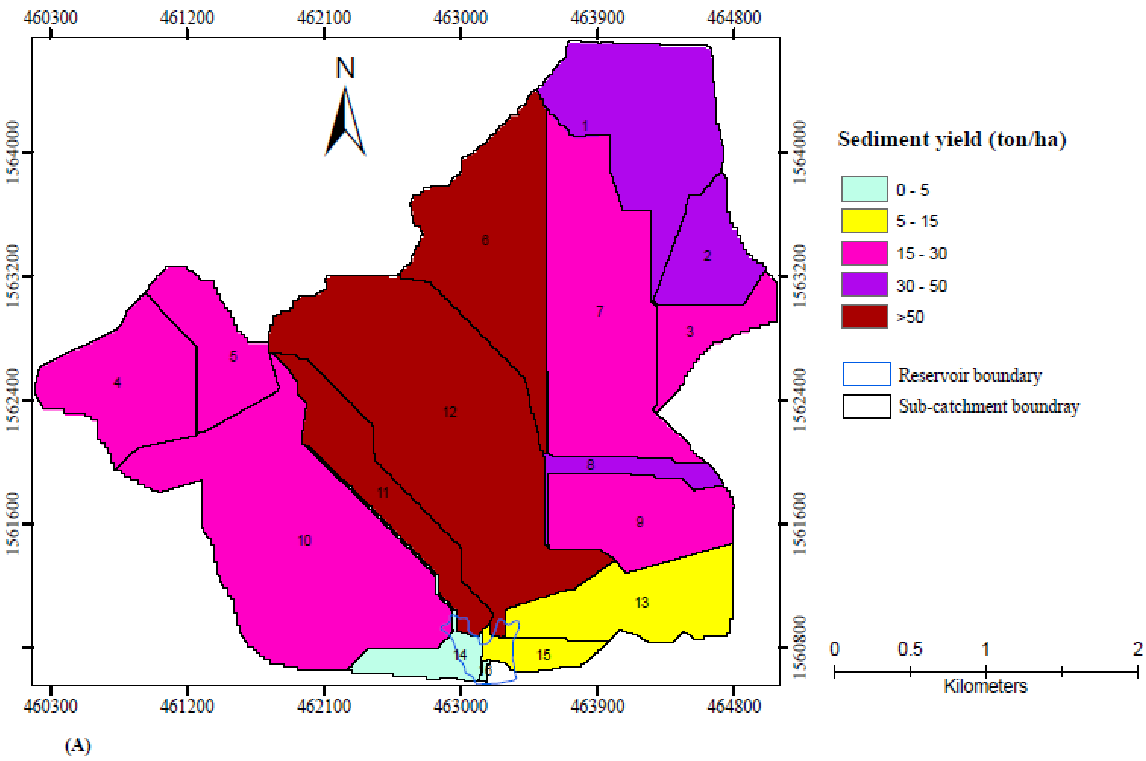
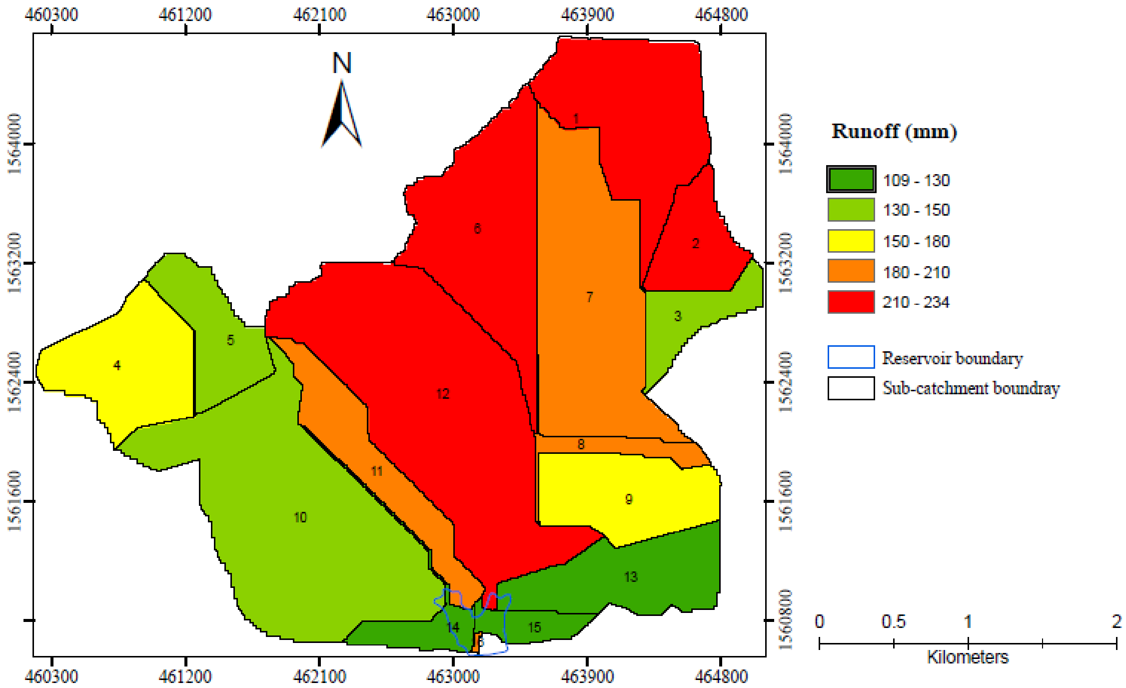
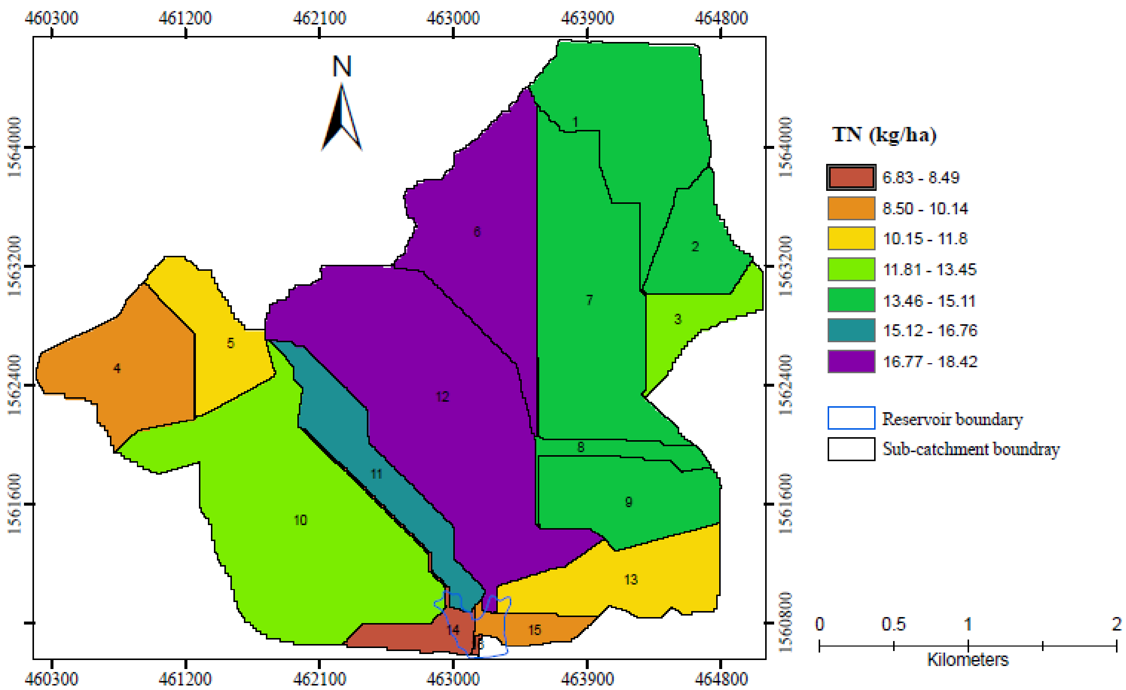



Figure 7.4: Variability in spatial pattern of annual losses as sediment yield (A), runoff (B), total nitrogen (TN) (C) and total phosphorus (TP) (D) in Mai-Negus catchment, northern Ethiopia. Sub-catchments are numbered 1 to 16.

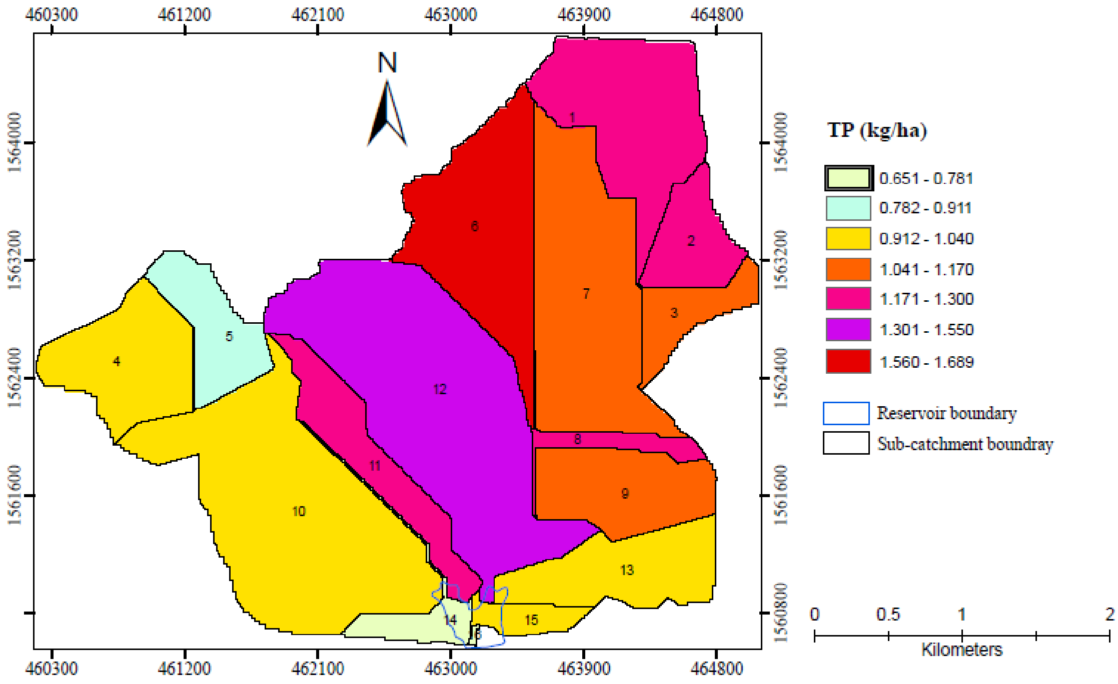



(B)




(C)

Figure 7.4: continued




(D)

Figure 7.4: continued

Field observation indicated that the parts of the catchment that produce high and very high sediment yields as indicated by the SWAT model output are dominated by cultivated land, steep slopes and active gully erosion development. Erosion on fields planted with small-seed cereals such as *Eragrostis tef* was found to be high as shown by the high cover-factor (C[1]) value. A comparison of the slopes with the spatial distribution of sediment yield and the associated soil nutrient losses across the catchment indicates that the sites on the steep-slopes are more at risk than the gentle to flat landscape provided that they have the same land-cover, management (P[2]) and erodibility factors. A relatively less severe erosion was also observed in the sites where vegetation cover is high, which agrees with (Hurni 1985) who reported using plot level study in forested areas soil loss rates are not commonly higher than 1 t $ha^{-1}$ $y^{-1}$.

[1] *Cover (C)-factor values for different cover types in Ethiopia were defined by Hurni (1985). These values include dense forest = 0.001; dense grass = 0.01; bush/shrub = 0.02; degraded grass = 0.05; sorghum/maize = 0.10; cereals/pulses = 0.15; Ethiopian Teff = 0.25 (Tamene and Vlek 2008).*

2 *Support practices (P)-factor values defined by Hurni (1985) and Eweg and Lammeren (1996) for Ethiopia are summarized in Tamene and Vlek (2008) as protected areas = 0.50; stone cover (80%) = 0.5; terraces = 0.6; stone cover (40%) = 0.8; strip cultivation = 0.80; plowing on contour = 0.9; plowing up and down = 1.0.*

### 7.3.5 Identification and prioritization of hotspot areas using SWAT modeling

After the SWAT model results have been used to categorize the erosion severity at catchment level, the model was also used to identify and prioritize erosion-hotspot sub-catchments. This is because substantial studies have demonstrated that for many catchments, a few erosion sensitive (prone) areas are the sources of higher amount of sediment yields and the associated soil nutrient losses (Mati et al. 2000; Tripathi et al. 2003; Tamene 2005). The mean annual runoff, sediment yield and soil nutrient losses estimated for each sub-catchment using the model are presented in Table 7.7. Priorities were given to erosion-hotspot sub-catchments based on the relative severity of the erosion hazard zones.

Table 7.7: Results of SWAT modeling (annual average) for identification of erosion-hotspot sub-catchments in the Mai-Negus catchment, northern Ethiopia

| Sub-catchment (SC) | Area (ha) | Runoff (mm) | Sediment yield (t ha$^{-1}$) | Organic N (kg ha$^{-1}$) | Organic P, (kg ha$^{-1}$) | NO3-N, (kg ha$^{-1}$) | Soluble P (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| SC1 | 101 | 230 | 46.8 | 12.8 | 1.14 | 2.26 | 0.09 |
| SC2 | 35.3 | 223 | 38.0 | 12.0 | 1.11 | 1.84 | 0.07 |
| SC3 | 28.0 | 143 | 28.4 | 10.1 | 1.04 | 1.88 | 0.10 |
| SC4 | 68.7 | 160 | 21.3 | 8.14 | 0.93 | 1.91 | 0.09 |
| SC5 | 42.3 | 133 | 23.0 | 9.17 | 0.82 | 2.40 | 0.08 |
| SC6 | 108.0 | 229 | 56.1 | 16.0 | 1.56 | 2.47 | 0.13 |
| SC7 | 140.8 | 210 | 16.2 | 11.6 | 1.01 | 2.28 | 0.15 |
| SC8 | 15.4 | 202 | 33.3 | 11.8 | 1.07 | 1.97 | 0.11 |
| SC9 | 61.1 | 176 | 19.9 | 11.3 | 1.04 | 2.30 | 0.10 |
| SC10 | 198.1 | 149 | 16.1 | 9.57 | 0.87 | 2.77 | 0.09 |
| SC11 | 53.3 | 185 | 65.3 | 13.3 | 1.17 | 2.88 | 0.08 |
| SC12 | 214.8 | 234 | 53.1 | 14.9 | 1.25 | 2.08 | 0.13 |
| SC13 | 62.0 | 111 | 10.3 | 8.75 | 0.96 | 2.79 | 0.08 |
| SC14 | 19.8 | 130 | 4.85 | 5.37 | 0.65 | 1.46 | 0.07 |
| SC15 | 14.3 | 109 | 7.47 | 6.91 | 0.87 | 2.33 | 0.09 |
| SC16 | 0.48 | 181 | 5.47 | 5.53 | 0.58 | 1.55 | 0.07 |

*N, nitrogen; P, phosphorus; organic N + $NO_3$-N = TN (total nitrogen); organic P + soluble P = TP (total phosphorus)*

The location of each sub-catchment (SC) with respect to the rate of erosion is given in Figure 7.4. Results show that out of the 16 sub-catchments, SC6, SC11 and SC12 were in the very high soil loss category (> 50 t ha$^{-1}$ y$^{-1}$). The sub-catchments SC1, SC2 and SC8 were in the high soil loss category (30-50 t $ha^{-1}$ $y^{-1}$). The sub-catchments in the medium soil erosion category (15-30 t $ha^{-1}$ $y^{-}1$) were SC3, SC4, SC5, SC7, SC9 and SC10, while SC15 and SC16 were in the low soil loss category (5-15 t $ha^{-1}$ $y^{-1}$) and SC14 was in the very low erosion category (0-5 t $ha^{-1}$ $y^{-1}$). The rates of soil loss in the sub-catchments were also examined with respect to the soil loss tolerance and soil regeneration condition for Ethiopia in order to indicate the state of sustainability. The model predicted higher sediment yields than the maximum tolerable soil loss rate (18 t $ha^{-1}$ $y^{-1}$) reported for the country by Hurni (1985), for all sub-catchments except SC7, SC10, SC13, SC14, SC15 and SC16. If an annual soil formation rate of 6 t $ha^{-1}$ $y^{-1}$ (Hurni 1983), is also considered, the soil loss rates estimated by the SWAT model in most of the sub-catchments could still be beyond the acceptable level. The only sub-catchments where soil loss rates predicted within the average soil generation rate for Ethiopia were SC14 and SC16.

The landscape positions of most of the sub-ctachments where erosion is above the tolerable soil loss limit are generally located on upslopes of greater than 15% and relatively low sediment yield potential are commonly located on slopes less than 15%. This is in agreement with the view of past studies that showed higher elevations and steep-slope areas with poor surface cover are more vulnerable to accelerated erosion compared to the lower slope areas with similar soil cover (e.g., Tamene and Vlek 2008). However, the widespread of collapsing gullies, which contribute higher amount of sediment, are located in the downstream parts of the catchment (e.g., SC11) where the slope gradients are not very steep but such areas are the source of high sediment yield and soil nutrient losses. This is well represented by the SWAT model as the model predicted high sediment yield values in such sub-catchments. Based on this study, it is possible therefore to suggest management strategies that can reduce the severity of erosion, such as increasing the soil cover (vegetation), terraces and gully stabilizing structures, land-use redesign or their combination. But to compare and select the most effective one, model simulation using the suggested manangement strategies is important after prioritizing erosion-hotspot sub-cathcments.

In addition to the soil loss rate, the runoff which is the driving force for sediment yield and soil nutrient losses, was highest in SC12 (234 mm) followed by SC1 (229 mm) and SC6 (228 mm), and the lowest in SC15 (109 mm) (Table 7.7). The model simulation results of the sub-catchments indicate that the dissolved soil nutrient losses with runoff that include $NO_3$-N and soluble P were below the maximum limit in this study (Table 7.7). As these values in the sub-catchments were below the threshold, the highest value was considered for prioritization for management planning. The highest $NO_3$-N loss was in SC8 followed by SC11 and SC13, while the lowest was in SC14 and SC16. The lowest soluble P loss was in SC14 and SC16 while the highest was in SC7 followed by SC12 and SC6. The average losses of nutrients associated with sediment yield (organic N and P) were highest in SC6 followed by SC12, SC11, SC1, SC2 and SC8 (Table 7.7). A similar trend can be observed for TN and TP (Figure 7.4C-D).

On the basis of the erosion severity (runoff, sediment yield and soil nutrient losses), the sub-catchments SC1, SC2, SC6, SC12, SC11, and SC8 were found to be critical hotspots of soil degradation, as they are the sources of higher runoff, sediment and soil nutrients losses. These sub-catchments were ranked as SC6, SC12, SC11, SC1, SC2 and SC8 in descending order for introducing appropriate land-use, management and conservation measures that reduce these losses. The other sub-catchments to be considered while designing best management practices in the study catchment next to the above highly prioritized areas are in the order of SC3, SC4, SC5 and SC9. This is because those sub-catchments show sediment yields more than the maximum soil loss tolerable limit for the country. Such identification and prioritization of erosion-hotspot areas will help for successfully plan and implement appropriate interventions with the available resources and capital. Finally, this study also confirms the applicability of the SWAT model for decision-making processes concerning management of small catchments using available data for the northern Ethiopian conditions.

Generally, the results indicate that the mount of soil nutrient losses does not necessarily depend on the amount of sediment yield or runoff. It may also be influenced by the nutrient concentration of the source sediment. The SWAT predicted soil nutrients (TN and TP) for the sub-catchments show consistency with those results reported by Haregeweyn et al. (2006) in the study of sediment-bound nutrients export using 13 reservoir catchments in Tigray, and of those of Girmay et al. (2009) from research at plot level for different land-use types in some sites in the region. However, as reservoirs are sinks of sediment coming from all parts of the catchment, reservoir sediment nutrient analysis could not show the contribution of the various upland sub-catchments and land-uses (Girmay et al. 2009). Besides, plot level erosion associated losses may not be representative if extrapolated to large scale areas. This study has thus contributed to filling such study gaps by showing the source areas and the rate of nutrient losses.

### 7.3.6 Relationships of runoff, sediment yield and soil nutrients

Assessing the relationship among the SWAT output variables that were used to prioritize the erosion-hotspot sub-catchments for management planning is crucial in order to target the nutrient losses due to either runoff or sediment transport, or their combinations. Even though the hotspot erosion areas in the catchment are assessed in section 7.3.4 and 7.3.5, further discussion is merited for the relationship of the soil nutrient losses with sediment yield and runoff so as to get a clear impression of their role to soil nutrient degradation in the sub-catchments. The correlation, regression and trend analysis results are presented in Table 7.8, Figure 7.5, and 7.6, respectively, to show the magnitude of the relationships.

A significatly ($P = 0.001$, 2-tailed) strong positive correlation between sediment yield with organic nitrogen (ON), TN, organic phosphorus (OP) and TP at r = 0.88, 0.87, 0.84 and 0.81, respectively was observed in the sub-catchments. A significantly ($P = 0.001$, 2-tailed) moderate positive correlation between these soil nutrients and runoff in the sub-catchments was observed (Table 7.8). The correlation between sediment yield with nitrate ($NO_3$-N) and soluble phosphorus (SP) was weak and non-significant ($P > 0.05$). However, SP shows moderately positive significant correlation with runoff whereas there was no correlation between $NO_3$-N with runoff (Table 7.8). The TN was strongly correlated with ON than $NO_3$-N. Similarly, a stronger correlation of TP with OP than SP was found. The implication of the weak or no correlation between the available soil nutrients with sediment yield and runoff is that the soluble soil nutrient condition in the catchment is highly degraded.

Table 7.8: Pearson correlation coefficients of runoff, sediment yield and soil nutrients predicted by SWAT model for the sub-catchments (n = 16) of Mai-Negus catchment, northern Ethiopia

| Parameter | Runoff | SY | ON | OP | $NO_3$-N | SP | TN | TP |
|---|---|---|---|---|---|---|---|---|
| Runoff | 1.00 | | | | | | | |
| SY | 0.69** | 1.00 | | | | | | |
| ON | 0.76** | 0.88** | 1.00 | | | | | |
| OP | 0.64* | 0.83** | 0.94** | 1.00 | | | | |
| $NO_3$-N | $-0.11^{ns}$ | $0.31^{ns}$ | $0.40^{ns}$ | $0.38^{ns}$ | 1.00 | | | |
| SP | 0.53* | $0.30^{ns}$ | 0.61* | 0.57* | $0.09^{ns}$ | 1.00 | | |
| TN | 0.70** | 0.87** | 0.99** | 0.94** | 0.51* | 0.58* | 1.00 | |
| TP | 0.65** | 0.81** | 0.94** | 0.99** | $0.38^{ns}$ | 0.63** | 0.94** | 1.00 |

** correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at 0.01 level (2-tailed); ns is non significant at > 0.05 level.*
*Runoff, runoff (mm); SY, sediment yield (t $ha^{-1}$ $y^{-1}$); ON, organic nitrogen (kg $ha^{-1}$ $y^{-1}$); OP, organic phosphorus (kg $ha^{-1}$ $y^{-1}$); NO3-N, nitrate nitrogen (kg $ha^{-1}$ $y^{-1}$); SP, soluble phosphorus (kg $ha^{-1}$ $y^{-1}$); TN, total nitrogen (kg $ha^{-1}$ $y^{-1}$); TP, total phosphorus (kg $ha^{-1}$ $y^{-1}$).*

In addition, the regression analysis showed a moderate relationship of TN and TP with sediment yield and a poor relationship with runoff coming from the sub-catchments (Figure 7.5A). About 75 and 66% of the variation in the TN and TP losses in the sub-catchments, respectively, can be explained by sediment yield coming from the sub-catchments. On the other hand, about 50 and 43% of the variation in TN and TP losses, respectively, can be explained by the runoff generated from the sub-catchments (Figure 7.5B). These relationships indicate that the variability in TN loss is higher than TP in both sediment and runoff, even though the variation of TN losses was more explained in sediment yield as compared to runoff in the sub-catchments. This implies the proportion of TN is mainly organic sources which demands further mineralization processes in order to be available for plant in the source soils. Approximately 48% of the variability in sediment yield can be explained by the runoff potential differences in the sub-catchments (Figure 7.5C). The remaining 52% of sediment yield variability in the sub-catchments can be explained by unknown and inherent catchment factors such as slope, land-cover.

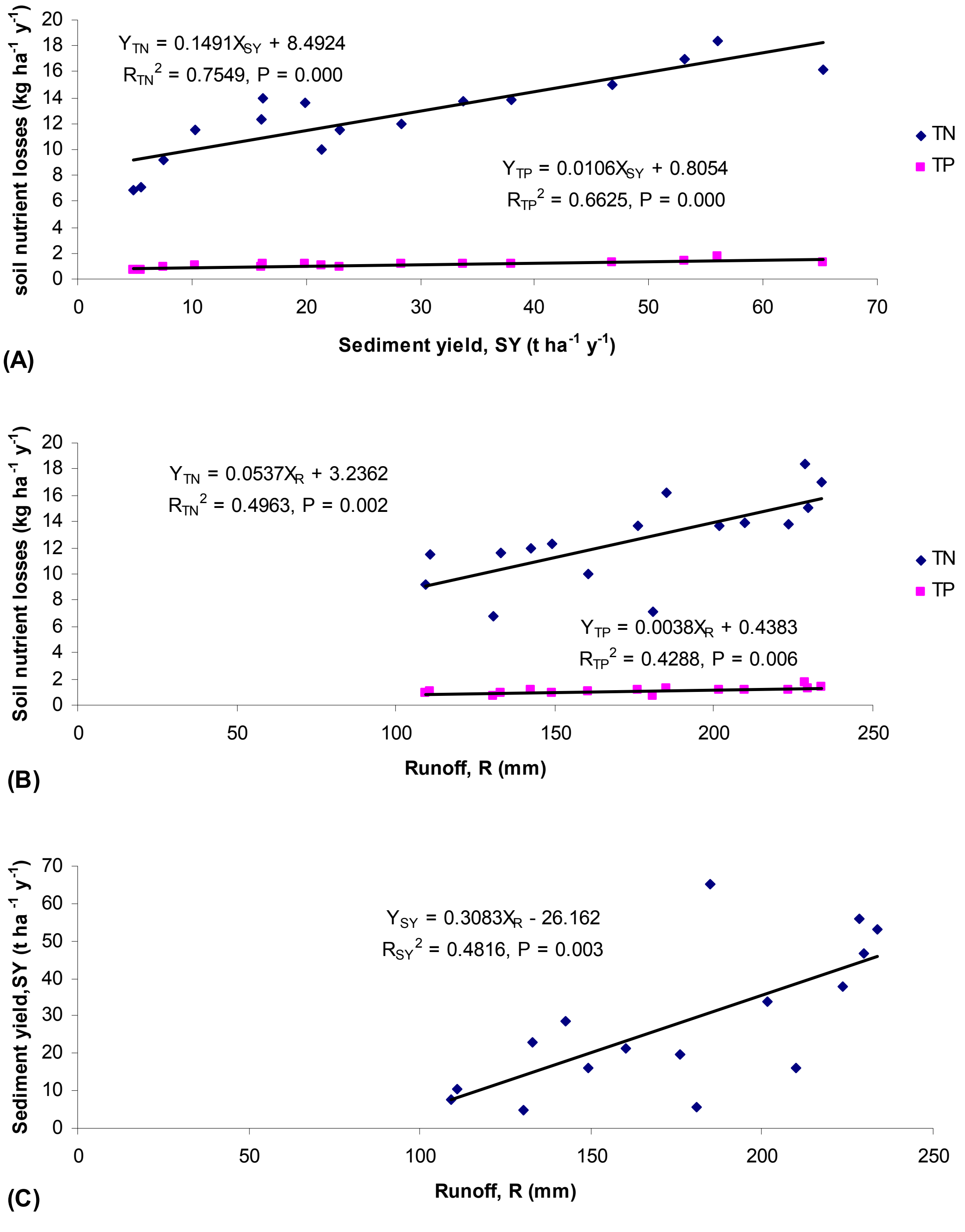



Figure 7.5: Scatter plot and best fitting regression lines that relating sediment yield with soil nutrients (A), runoff with soil nutrients (B) and runoff with sediment yield (C) for the sub-catchments of Mai-Negus catchment, northern Ethiopia. TN is total nitrogen; TP is total phosphorus; $R^2$ is coefficient of determination

The annual runoff and sediment yield variability have also shown similar trend to that of soil nutrient losses in the sub-catchments across the periods 1992-2008

(Figure 7.6). This indicates that as sediment yield or runoff increases, the associated soil nutrient losses is becoming high and vice-versa. The rate of soil nutrient losses across the simulation periods showed a slight decrease (but irregularly) with time which may be attributed to the effect of the intermittently introduced conservation measures, change in climate, and/or mixed up of sub-soil with low topsoil soil fertility that reduce the overall soil nutrient concentration in the eroded sediment (Palis et al. 1994). These are however, demanding further verification in the context of northern Ethiopia.

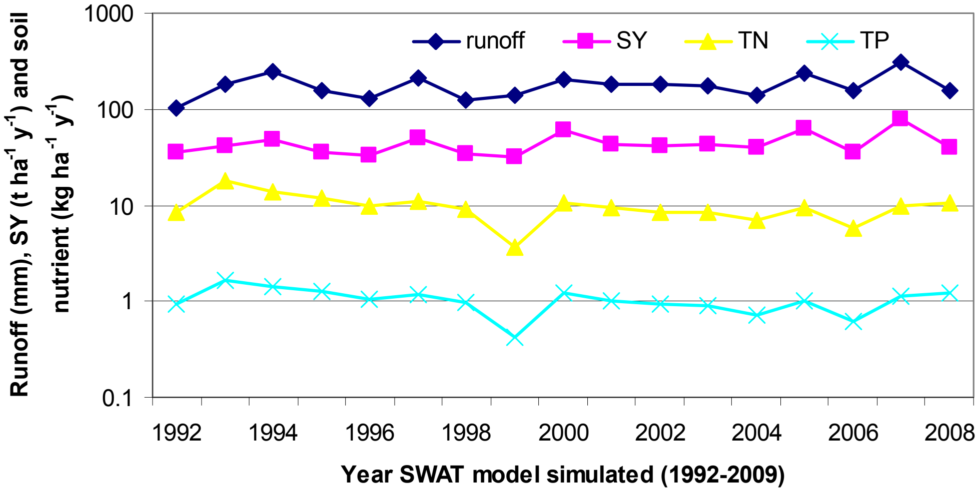



Figure 7.6: The trend of runoff, sediment yield (SY), total nitrogen (TN) and total phosphorus (TP) during the simulated periods for the study catchment

Generally, the significantly strong positive correlation and best linear fitting regression function between sediment yield and the soil nutrient losses from the sub-catchments reflect that nutrient losses are more strongly linked to sediment than runoff. This may be due to the low soil nutrient solubility or strongly bounded to soil particles. Therefore, management planning such as stone bunds and vegetative strips that target the sediment rather than runoff loss as a priority should be designed so as to decrease the nutrient losses from the erosion hotspot areas. This also increases the lifespan of the reservoir in the study catchment. In the study catchment condition, targeting to significantly reduce runoff can lead to other disadvantages such as reducing surface flow to the reservoir which badly hampering irrigation and domestic supplies.

## 7.4 Conclusions

The results of this study demonstrate that the SWAT model is a very useful tool for planning alternative catchment management strategies that reduce soil degradation cuased by soil erosion. However, the application of the model becomes more effective if it is calibrated and validated in the context of study catchment. Such model evaluation is an important issue in order to reduce model uncertainity and to increase model user confidence in its predicative abilities. A set of important parameters for calibration based on the sensitivity analysis of the model were identified during this study. The model was successfully calibrated and validated for flow, sediment yield, and soil nutrient losses with $N_{SE} > 0.5$ and $R^2 > 0.6$ in the Mai-Negus catchment, northern Ethiopia. The successful evaluation of SWAT as illustrated in this study can provide the opportunity for extending the model to other ungaged basins in the region. The results thus confirm that the model can be applied to simulate runoff, sediment yield and soil nutrient losses for similar catchments in northern Ethiopia.

The results of the model demonstrate that all sub-catchments within a catchment do not equally contribute to stream flow, sediment yield and soil nutrient losses. Within a catchment, small areas of land (e.g., gullies, steep slopes, poor soil cover) are likely to be the sources of higher erosion. The SWAT model predicted sediment yield from the sub-catchments ranging from 0-5 t $ha^{-1}$ $y^{-1}$ to more than 50 t $ha^{-1}$ $y^{-1}$. The model identified and ranked six sub-catchments that highly need management interventions due to their excessive runoff, sediment and soil nutrients losses. This indicates that the model is effective for identification and prioritization of erosion-hotspot sub-catchments to develop management strategies that reduce these losses. Therefore, the model can be used to confine mitigation to erosion source areas, which costs less than targeting wider areas. The output of this study can support decision-makers and planners by answering *where* the management strategies should be implemented to achieve the best benefit through reducing soil degradation. After knowing *where* to place the interventions, the completely verified SWAT model should be used to evaluate *which* alternative management strategies (scenarios) can reduce the existing consequences of erosion better. However, it is recommended that a wider validation effort is needed before adopting the model for decision-making purpose throughout the Tigray region (northern Ethiopia), which has a diverse environment.

# 8 EVALUATION OF CATCHMENT MANAGEMENT STRATEGIES THROUGH SWAT MODELING IN A GIS ENVIRONMENT

## 8.1 Introduction

At global scale, soil erosion is the dominant form of soil degradation (Scherr 1999; Lal 2001; Morgan 2005), which accounts for 70 - 90% of total soil degradation (Zoebisch and DePauw, 2002). The total land area affected by soil erosion worldwide is 1,094 Mha (Walling and Fang 2003). Soil degradation by erosion is thus a serious problem and will remain so as a major global issue during the twenty-first century, especially in developing world (Lal 1998; Saha 2004). The importance of soil degradation among global issues is enhanced because of its impact on world food security and environmental quality (Eswaran et al. 2001). Erosion has long-term impacts on soil quality, agricultural productivity, pollutants, and ecological degradation (Lal 1998; Saha 2004).

Deforestation, overgrazing, expansion of cropland to marginal and steep-slope areas with poor soil management practices, and unsustainable use of natural resources are the major causes for the alarming rate of soil degradation in the Ethiopian highlands (Nyssen et al. 2004; Tamene 2005). Such practices accelerate erosion, and this leads to the exhaustion of soil resources, deterioration in soil quality, and eventually to a decline in land productivity. Although soil erosion may not be perceived to be an immediate major problem in farmers' fields, degradation can result in a huge impact on soil productivity in the long term (Lal 1998; Scherr 2002). Substantial studies have demonstrated that erosion can significantly contribute to variability in soil properties and the associated nutrients losses (e.g., Stone et al. 1985; Kreznor et al. 1989).

Evidence in the Ethiopian highlands indicates that erosion has degraded the soil resources on which agricultural production and food for the people are entirely based (Hurni 1986**).** In such situation, the resource-poor small-scale farmers, who are predominantly subsistence oriented, will be seriously affected by long-term consequences on land productivity (Lal 1998; Scherr 2002). The highlands of northern Ethiopian that include the Tigray highlands are thus at a high risk of soil degradation unless appropriate correction measures are implemented (Nyssen et al. 2004; Tamene 2005). The degradation severity makes large areas unsuitable for agriculture, because the topsoil and part of the sub-soil in some areas have been removed, and only stones or bare rock remain at the surface (Gebrermichael et al. 2005; Tamene 2005).

There have been great efforts to address soil degradation problems in Ethiopia since the 1970s, though success in reversing land degradation is minimal. One reason for this is that the introduced interventions and technologies may not be well suited to the local conditions. Such a situation demands an integrated approach of catchment management that addresses both technical and non-technical issues. Alternative land-use redesign and conservation measures that consider local farmers' active involvement should be developed targeting the sources areas of runoff, sediment yield and nutrients losses in a catchment. This would answer questions such as what measures are necessary and where these should be implemented to reduce the severity of soil degradation.

According to Tamene and Vlek (2007), the effectiveness of land management to minimize the impacts of soil erosion in a complex landscape can be improved by detailed prediction of erosion rates of proposed management strategies. Optimization of measures aiming at forming stable landscapes is possible through simulation alternative management strategies that offer remedial solution for the existing erosion-related problems (Tamene and Vlek 2007). However, only a limited number of studies have been conducted on the application of hydrology models to simulate the impact of management strategies on runoff, sediment yield and soil nutrient losses under the conditions in northern Ethiopia catchment.

Soil conservation and sediment control measures are effective when combating a specific soil erosion or sediment delivery process in the source areas (Verstraeten et al. 2002; Tamene 2005). The impact of soil erosion and sediment delivery processes vary spatially with operating at various source locations. Therefore, implementation of a single conservation measure throughout a catchment will not be as effective as targeting such measures at those locations where they are most suited (Verstraeten et al. 2002). Management strategies (scenarios) should therefore be designed to integrate a variety of techniques into a catchment management plan. Such scenarios need to be possible, credible, and relevant to be useful in decision-making processes. In this study, the SWAT model in a GIS environment (Arnold et al. 1998), which supports identification of erosion-hotspot sub-catchments, and can simulate different management strategies (scenarios), was applied. This model can take into account many of the complex factors and interactions that affect rates of erosion and other hydrological variables. The aim of this study is to evaluate the effectiveness of different catchment management scenarios in reducing soil degradation as runoff, sediment yield and soil nutrients losses using SWAT model and then suggest suitable management options for the Mai-Negus catchment in northern Ethiopia.

## 8.2 Methodology

### 8.2.1 Study area

The study was conducted in the Mai-Negus catchment in the Tigray region, northern Ethiopia (Figure 8.1), which covers an area of 1240 ha. The landscape of the catchment is generally rugged terrain with altitude ranging from 2060 to 2650 m a.s.l. Land-use is dominantly arable with a teff *(Eragrostis tef*) cropping system (> 80%) but with different percentages of pasture land, and scattered tree, bush and shrub covers. The dominant rock types are lava pyroclastic and meta-volcanic. Soils are mainly Leptosols on the very steep positions, Cambisols on the middle to steep slopes, and Vertisols in the flat areas. Soils are highly eroded in most parts of the landscape. Terrain erosivity potential is high, as slope gradients can reach more than 85%. Surface cover is poor, and human disturbance is high, which has facilitated soil quality deterioration.

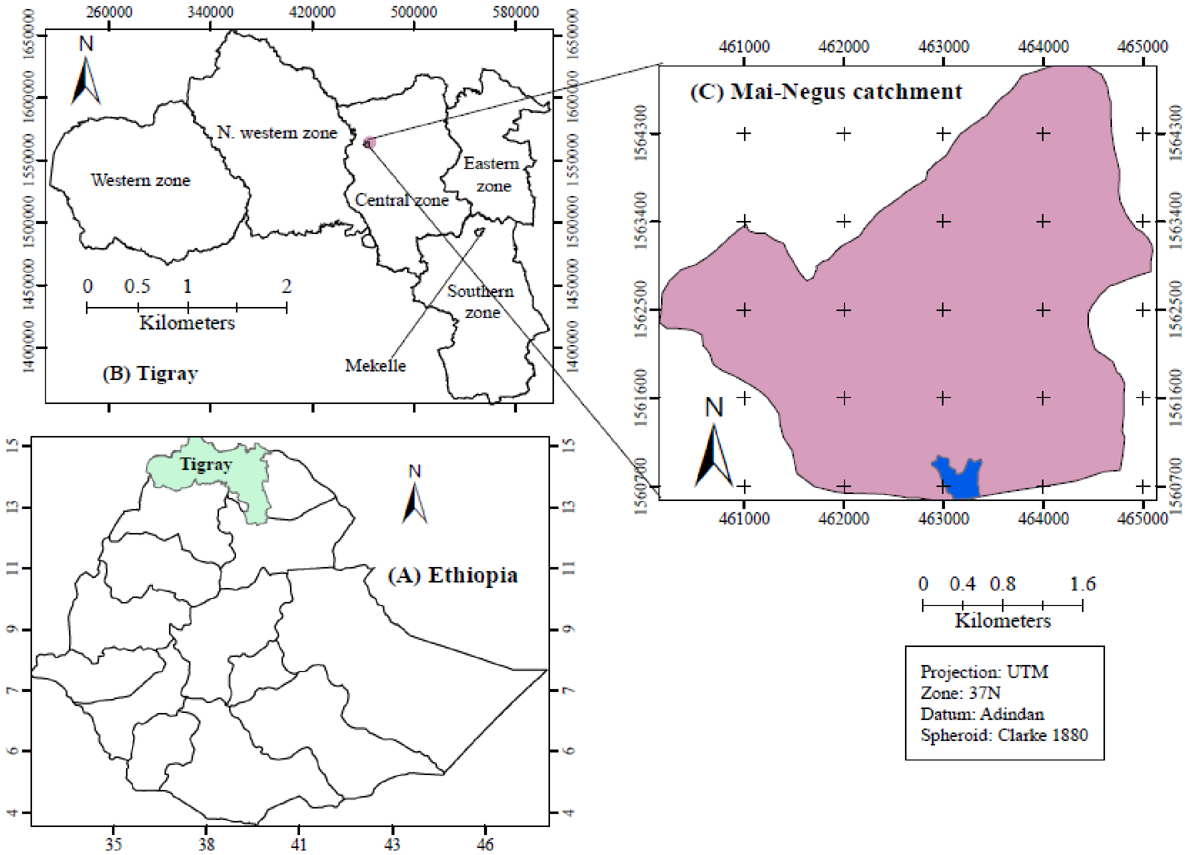



Figure 8.1: Study area in Ethiopia (A), Tigray (B) and Mai-Negus catchment (C). Blue area is the reservoir

### 8.2.2 The SWAT model

The Soil and Water Assessment Tool (SWAT) is a river-basin scale, continuous-time and spatially-distributed physically-based model developed to simulate the impact of land management practices on water, sediment and agricultural-chemical yields in complex catchments with varying soils, land-use and management conditions over long periods of time (Setegn et al. 2009). As a physically-based model, the SWAT uses the spatial heterogeneity in terms of land-use and land-covers, soil types and slopes to divide catchment into sub-catchments and further subdivided into Hydrologic Response Units (HRUs). Weather data are also needed for the model on a daily basis. In this study, the ArcSWAT 2009 version of the SWAT model was applied after it had been calibrated and validated to have an acceptable level of performance efficiency for the study catchment. For additional information on model description and application see

Chapter 7 of this thesis. Moreover, a detailed description of the SWAT model can be found in the SWAT2005 theoretical documentation (Neitsch et al. 2005).
After the SWAT model had been calibrated and validated successfully, it was then used to identify and prioritize erosion-hotspot sub-catchments for introducing appropriate management strategies (Figure 8.2A). The SWAT model was run with the actual land-use and land-cover, management and terrain characteristics to identify critical soil erosion areas. The SWAT model`s discretized 16 sub-catchments (SC) are numbered 1 to 16 in this Figure. The soil loss rate in the prioritized sub-catchments (SC) of SC3, SC4 and SC5 ranged from 20-30 t $ha^{-1}$ $y^{-1}$ and those of SC1, SC2, SC6, SC8, SC11 and SC12 from 30-66 t $ha^{-1}$ $y^{-1}$. The model is also capable of predicting sediment sourced from waterways and gullies as a higher sediment yield was estimated from the sub-catchments having active gullies and dense waterways (Figure 8.2B).

### 8.2.3 Scenario development and description

Given the spatial variability of the extent and intensity of erosion and delivery processes, land-use redesign, conservation or management measures, in general, should be applied at appropriate sites of the catchment so as to use resources efficiently. The modeled mean annual soil erosion eastimated for each sub-catchment was considered in developing the management strategies (scenarios), as well as for the mean losses at the outlet of the entire catchment and the knowledge of local farmers on sources of erosion. In order to compare the effectiveness of alternative management strategies that may reduce soil degradation due to soil erosion, it is necessary to develop and describe the relevance of the scenarios. Scenario development is a process of evaluating possible alternative outcomes based on the current or baseline situation.

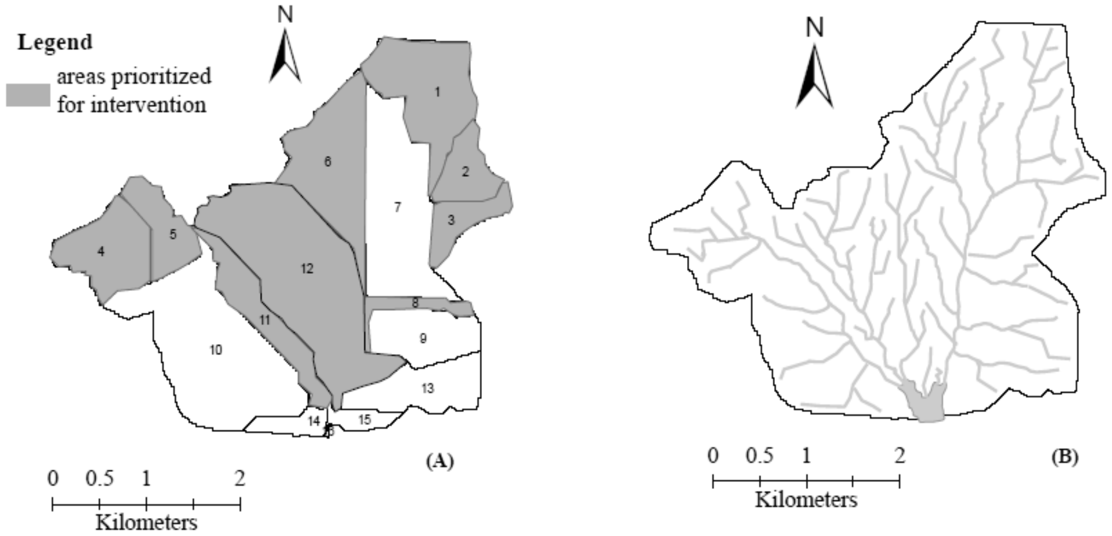



Figure 8.2: Spatial distribution of areas needing intervention (A) Prioritized areas by integrating farmers´ knowledge of soil quality degradation and erosion rate predicted by the SWAT model, (B) Waterways and gullies in Mai-Negus catchment, northern Ethiopia

Different scenarios were developed (Table 8.1) based on the current (baseline) condition of the study catchment. When developing the scenarios, the severity of the erosion rate/sediment yield, runoff and soil nutrient losses (hotspot areas), and the most strongly influencing (sensitive) factors and their relevance were considered. Scenario simulation and analysis can be used to select the most effective strategies for reducing soil degradation. The details of the scenarios (management strategies) developed in this study are described below.

**Scenario 1: Baseline scenario**

The baseline scenario corresponds to the current catchment land-use and land-cover, terrain, management and other factors. This includes cultivated land dominated by the *teff* crop cover-factor (C = 0.25), a conventional tillage system (Ethiopian *maresha*) of contoured plowing (P factor = 0.9), and degraded grazed lands (C-factor = 0.05). In such poor hydrologic conditions, the curve-number (CN) values are high and ranging from 79-88; values depend on the hydrologic soil groups. This indicates that the runoff flow that derives the loss of sediment yield and soil nutrients is high in this scenario. Runoff, sediment yield, and soil nutrient losses were determined using existing catchment factors. The baseline scenario was used as a benchmark against which the results of the other scenarios were rated.

**Scenario 2: Afforesting hotspot areas of erosion**

Afforesting all cultivated fields in the study catchment is impractical for many reasons. Instead, afforesting hotspot areas of degradation due to erosion is feasible (Figure 8.2A). Such areas in the catchment were identified by the local farmers´ defined indicators of degradation and model-estimated erosion rates. Dialogue with local stakeholders about the physical conditions and management practices in the catchment was used for obtaining reliable information for the location of degraded land by erosion to be afforested. Besides, on the basis of the results of the baseline scenario, sub-catchments with erosion rates > 18 t $ha^{-1}$ $y^{-1}$ were taken into account for the simulation of the afforestation scenario. This threshold was set based on the maximum tolerable soil loss of 18 t $ha^{-1}$ $y^{-1}$ for Ethiopia soils reported by Hurni (1985). This scenario afforested only the prioritized sub-catchments that comprised of cultivated land (35%), grazing and marginal land (55%), and others (10%). This area covers about 57% of the catchment. The scenario 2 changes the C-factor to 0.001 in the long-term and to 0.01 (dense grass) when simulated as pasture area in the short-term. The curve-number (CN) values for this scenario ranging from 40-60 on the basis of the hydrological soil groups, and were lower than in scenario 1. The CN determines the separation of precipitation between surface runoff and infiltration as a function of soil hydrologic group, land-use, and antecedent moisture condition (Mishra and Singh 2003). These areas were simulated with dense grass covers that reduce CN and the USLE's C-factor values but increase the Manning's n-value as given in Table 8.1.

**Scenario 3: Parallel terraces/conservation measures**

In a catchment vulnerable to erosion, there is a need for conservation measures such as terraces that reduce further soil degradation. Wherever soil loss rates exceed 16-18 t $ha^{-1}$ $y^{-1}$ in Ethiopia, soil conservation measures are recommended (WAPCOS 1990). This is therefore the reason for scenario 3 targeting vulnerable sub-catchments that are shown in Figure 8.2A. Terraces act as a barrier to runoff, increasing infiltration and decreasing flow volumes and speed, and ultimately reduce the transport capacity and encouraging sediment deposition (Tamene and Vlek 2007). Erosion computation of the SWAT model is most sensitive to the curve-number (CN) and slope, as these influence the rate of runoff, sediment and soil nutrients losses. The CN and the consequent simulated surface runoff amount can be expected to decrease significantly under terraced scenario. The sensitivity analysis (Chapter 7) indicated that simulations of the SWAT model are very sensitive to the USLE_P. The expected slope length and steepness reduction due to scenario 3 was 50% and 25%, respectively, as compared to in the baseline scenario. During the calibration for the baseline scenario the USEL_P was 0.9. This value was changed to 0.6 for the targeted sub-catchments in scenario 3. Additional information is provided in Table 8.1.

**Scenario 4: Grassed waterways**

Grassed waterways are used to cover a stream or gully channels, and act as a barrier for sediment and also filter some of the nutrient loadings carried in the surface runoff (Borin et al. 2005). Grassed waterways reduce runoff and soil loss using the grasses in the channels. In the SWAT model, three parameters that represent grassed waterways were modified. These were the channel cover-factor (Ch_Cov), the channel erodibility factor (Ch_Erod), and the channel Manning's ''n'' value (Ch_N2) (Table 8.1). The SWAT model uses Manning's equation to compute the velocity of flow in the channel segments (EPA 2004). Runoff (flow) velocity decreases with an increase in Ch_N2. The SWAT model default value for Ch_N2 is 0.014 whereas during calibration it was 0.030. These values were modified to 0.24 for the channel segment with grassed waterways (EPA 2004). Such channel segments were considered fully protected by the vegetation cover (Ch_Cov = 0) and thus to be non-erosive (Ch_Erod = 0). The simulation was targeted to the rehabilitation of the waterways in the study catchment by covering these areas with grass (Figure 8.2B).

Table 8.1: Scenarios and representation as the SWAT model parameters

| Scenario | | | Representing SWAT parameter | | Value when scenario simulated |
|---|---|---|---|---|---|
| No. | Description | Function | Variable | Range | |
| 1 | Baseline | Used as bench mark | - | - | - |
| 2 | Afforesting | Reduce rill-sheet erosion | USLE_C | 0-0.5 | 0.01[a] |
| | hotspot areas | Reduce overland flow | CN2 | 0-100 | 40-60[b] |
| | of erosion | Increase surface roughness | n-value | 0.17-0.3 | 0.24 |
| 3 | Parallel | Reduce overland flow | CN2 | 0-100 | 70-80[b] |
| | terraces | Reduce rill-sheet erosion | USLE_P | 0-1 | 0.6 |
| | | Reduce slope length | SLSUBBSN | 10-150 | maximum 75 m[c] |
| | | Reduce slope gradient | Slope (S) | 0.0-475 | Reduced by 25% for S >5% |
| 4 | Grassed | Increase channel cover | Ch_Cov | 0-1 | 0.0 (completely protected) |
| | waterways | Reduce channel erodibility | Ch_Erod | 0-1 | 0.0 (non-erosive channel) |
| | | Increase channel roughness | Ch_N2 | 0-0.3 | 0.24 |
| 5 | Gully/grade | Reduce gully erosion | Ch_Erod | 0-1 | 0.0 (non-erosive channel) |
| | stabilization | Reduce slope steepness | Ch_S2 | 0.006 | 0.0015[d] |
| | structures | Reduce rill-sheet erosion | USLE_P | 0-1 | 0.6 |
| 6a | 2 and 3[e] | Combination of the above | - | - | - |
| 6b | 2, 4 and 5[e] | Combination of the above | - | - | - |
| 6c | 2, 3, 4 and 5[e] | Combination of the above | - | - | - |

[a] *In the long-term, the USLE_C factor value will be changed to 0.001, but 0.01 for dense grass was taken as a short-term effect of the scenario 2.*
[b] *Determined based on the land-use and hydrologic soil group conditions of the HRU.*
[c] *Slope length was expected to be 50% less than in the baseline scenario.*
[d] *SWAT calibrated value reduced by 75% due to the structures.*
[e] *Combined scenario; USLE, Universal Soil Loss Equation; C, soil cover; CN2, runoff curve- number for antecedent moisture condition II; n, Manning's roughness coefficient; P, support practices; SLSUBBSN, sub-basin slope length; Ch_Cov, channel cover factor; Ch_Erod, channel erodibility factor; Ch_N2, Manning's 'n' value for tributary channels; Ch_S2, channel slope*

**Scenario 5: Gully/grade stabilization structure**

The grade stabilization structure scenario was developed on the basis that it can stabilize the channel grade so as to control erosion and prevent the formation or advance of gullies. Such structures can be vertical drop structures, check dam, concrete, earth or riprap chutes, gabions, or pipe drop structures which are physical conservation measures (GSWCC 2000). Permanent ponds or detention basins can also be part of a grade stabilization structures. Check dams built across an existing gully reduce water flow and the associated sediment yield and soil nutrient losses through gully erosion (Borin et al. 2005). Field observation of active gullies (Figure 8.2B; 8.3), as well as the simulated

SWAT erosion rates, and the discussion with farmers and extension agents in the study catchment confirmed that gullies can greatly contribute to high sediment yield. Before implementation of scenario 5, these areas with steep-slopes in the natural water course caused bank collapse and gully erosion advancement. Hence, in the baseline scenario, areas along the streams/gullies with degraded grass, steep-slope land and high C-factor in the MUSLE in the SWAT model accounted for bank sloughing and gully erosion. In scenario 5, the assumption is that building small earthen structures such as check dams can stabilize channel grade that reduce gully erosion. As a result, USLE_P = 0.6 was used for this scenario along the streams/gullies in the catchment. In addition, the slope and channel erodibility factors were modified in the SWAT model to values presented in Table 8.1.



Figure 8.3: Gully head and side collapses in Mai-Negus catchment, northern Ethiopia (July 2009)

**Scenario 6: Combined scenarios**

Catchment management should not focus on single soil conservation or sediment control measures or land-use redesign strategies. Therefore, integrated land-use redesign and conservation measures were evaluated through scenarios 6a-6c. Scenario 6a was the combination of scenarios 2 and 3, and 6b the combination of scenarios 2, 4 and 5. Scenario 6c combined scenarios 2, 3, 4, and 5. Such scenarios assume that it is possible for more parameters in the SWAT model to be modified at the same time (Table 8.1).

### 8.2.4 Scenario simulation

After the types of scenarios were defined and described, the parameters were modified in the appropriate SWAT input files such as management file, crop database file, channel input data and other HRU related files. First, the runoff, sediment yield and soil nutrient losses were simulated based on the baseline scenario to determine the reference conditions. The model was run using 18-year daily weather data (1992-2009) from a single gauge nearest to the catchment. The same simulation was performed using each of the alternative scenarios after modifying the parameter inputs. Average annual values of the alternative scenarios were compared with the baseline to compute percent change in average values for the simulation period. A comparison of model simulations of different scenarios enables the determination of the long-term impacts of the alternative management strategies on runoff, sediment yield and nutrient losses at the outlet of the catchment and the prioritized sub-catchments.

## 8.3 Results

### 8.3.1 Reductions by individual scenarios at catchment level

Results of the simulations at catchment level are presented in Table 8.2 and Figure 8.4. The figure shows the relative reduction of water, sediment yield (soil loss) and nutrient losses in the alternative scenarios simulated as compared to the baseline. In general, the simulation results indicate that land-cover change (afforestation) and the introduction of conservation measures can significantly change the hydrologic response of the catchment. The highest soil erosion rate as sediment yield (41900 t $y^{-1}$) was simulated in scenario 1 (baseline condition) followed by scenario 4 (36900 t $y^{-1}$). However, the lowest sediment yield at the catchment level was simulated in scenario 6c (9200 t $y^{-1}$) followed by scenario 6a (14700 t $y^{-1}$). A similar trend in runoff and the associated soil nutrients losses were also simulated in these scenarios (Table 8.2). The percentage reduction in these losses due to the interventions in the simulated scenarios as compared to the baseline scenario is given in Figure 8.4. A detailed description of the result of each scenario is given below.

**Scenario 1: Baseline scenario**

Mean sediment yield in the baseline scenario was nearly 41900 t $y^{-1}$, runoff was about 168 mm, TN was 22400 kg $y^{-1}$, and TP was 1360 kg $y^{-1}$ at catchment level. In general, most of the sediment source areas are located on steep-slopes, cultivated and open grazed fields, whereas lower slope positions show low soil loss despite the poor surface cover and inappropriate management pracitces that increase the hydrological losses due to gully expansion and initiation.

Table 8.2: Results of scenarios for runoff, sediment yield, total nitrogen (TN) and total phosphorus (TP) at catchment outlet level in northern Ethiopia

| Scenario | Runoff (mm) | Sediment (t $y^{-1}$) | TN (kg $y^{-1}$) | TP (kg $y^{-1}$) |
|---|---|---|---|---|
| 1 | 168 | 41900 | 22400 | 1360 |
| 2 | 77.6 | 20500 | 15700 | 740 |
| 3 | 109 | 28100 | 18000 | 900 |
| 4 | 156 | 36900 | 16600 | 800 |
| 5 | 151 | 35600 | 18600 | 970 |
| 6a | 63.9 | 14700 | 10550 | 570 |
| 6b | 70.6 | 17600 | 7900 | 420 |
| 6c | 50.4 | 9200 | 6300 | 340 |

*1, base line; 2, afforested hotspot areas of erosion; 3, parallel terraces; 4, grassed waterways; 5, gully stabilization structure; 6a, combined scenarios 2 and 3; 6b, combined scenarios 2, 4 and 5; 6c, combined scenarios 2, 3, 4, and 5.*

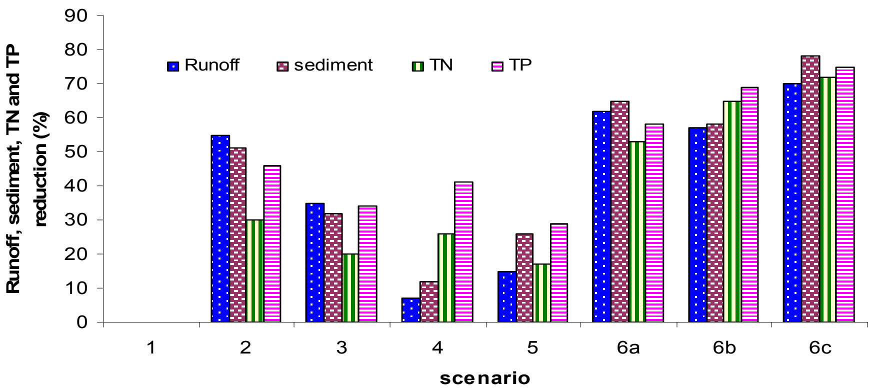



Figure 8.4: Percentage reduction in runoff, sediment yield, total nitrogen (TN) and total phosphorus (TP) losses as compared to the baseline scenario at catchment level in northern Ethiopia. For description of scenarios see Table 8.2

**Scenario 2: Afforesting hotspot areas of erosion**

When parts of the catchment considered as degraded by the local farmers and confirmed with the SWAT model to have soil erosion rates of > 18 t $ha^{-1}$ $y^{-1}$ were afforested, runoff, sediment yield, TN and TP losses could be reduced by about 55, 51, 30 and 46%, respectively (Table 8.2). Scenario 2 showed the highest reduction in runoff and followed by sediment yield and TP and TN losses (Table 8.2; Figure 8.4).

**Scenario 3: Parallel terraces targeting hotspot areas**

The use of parallel terraces on the prioritized areas can reduce the potential of runoff (35%), sediment yield (34%), TN (32%) and TP (20%) losses at catchment level (Table 8.2; Figure 8.4).

**Scenario 4: Grassed waterways**

This scenario of biological conservation measures targeted to waterways and gullies in the catchment. Reductions in TP, TN, sediment yield and runoff by 41, 26, 12 and 7%, respectively, were achieved as compared to the baseline scenario (Table 8.2; Figure 8.4). The reduction is higher for TP followed by TN, sediment yield and runoff. The lowest runoff and sediment yield reduction was simulated in this scenario (Figure 8.4).

**Scenario 5: Gully/grade stabilization structures**

This scenario involved stabilization of gullies in the catchment which reduced TP losses by 29%, sediment yield by 26%, TN losses by 17% and runoff by 15% (Table 8.2; Figure 8.4). This indicates that when gullies are stabilized through appropriate structures, losses can be reduced to a certain extent. Further reductions could be achieved through introducing additional support structures in the upstream parts of a catchment. Thus, adequate soil conservation practices are needed in the upstream of the catchment for gully stabilization structures to effectively reduce excess runoff and sediment that come from gully initiation and expansion.

**Scenario 6: Combined scenarios**

Combination of measures yielded the lowest hydrological losses (Table 8.2). Combining scenarios 2 and 3 (= scenario 6a) reduced the sediment yield, runoff, and TP and TN losses by 65, 62, 58 and 53%, respectively. The combination of scenarios 2, 4 and 5 (= scenario 6b) resulted in the reduction of TP and TN losses, sediment yield and runoff by 69, 65, 58 and 57%, respectively. A reduction of sediment yield, TP and TN losses and runoff by 78, 75, 72 and 70%, respectively, was achieved by integrating scenarios 2, 3, 4, and 5 (= scenario 6c) (Figure 8.4), leading to higher reductions than the other scenarios. The rate of reduction in sediment yield, runoff and nutrient losses is lower in scenario 4 and 5 than in scenarios 2, 3 and 6 (Figure 8.4). This is due to the fact that additional conservation and management measures are needed in the upper hotspot areas for scenario 4 and 5 to be effective across the catchment. Thus, the integration of conservation measures with land-use redesign such as afforestation can conserve soil quality, which inturn decreases the runoff that drives sediment yield and soil nutrient losses. Such approach is more effective than application of individual management strategy such as afforestation or conservation measures.

### 8.3.2 Reductions by individual scenarios at prioritized sub-catchments level

Results of sediment yields for the scenarios simulated while targeting the prioritized areas at the sub-catchment level are given in Table 8.3. All the scenarios can contribute to the reduction of soil degradation as reductions in sediment yield from 5-95% were achieved when compared to the baseline scenario. However, the general trend for the effectiveness of the simulated scenarios in reducing sediment yield at the outlet of the prioritized sub-catchments are scenario 6c > 6a > 6b > 2 > 3 > 5 > 4 > 1. In addition, for all the prioritized sub-catchments, the sediment yield in scenario 6c was less than the maximum tolerable soil loss (18 t $ha^{-1}$ $y^{-1}$) established for Ethiopian soils (Hurni 1985). This scenario also resulted in sediment yields below the maximum soil regeneration rate (6 t $ha^{-1}$ $y^{-1}$) (Hurni 1983) for SC6, SC8, SC11 and SC12. The sediment yield due to scenario 6a followed by 6b also fall for most of the sub-catchments below the tolerable soil loss level for the country. In general, the impacts of the scenarios vary with the condition of the sub-catchments. For example, scenario 4 and 5 perform better in sediment reduction for areas dominated by streams and gullies than scenarios 1 to 3, and vice-versa. A similar trend as that of sediment yield was observed in the effectiveness of the different scenarios in reducing runoff and soil nutrient losses in the prioritized sub-catchments (data not shown).

The ranges of sediment yield (soil loss) rates and their severity categories suggested by Tamene (2005) were also used for identification of critical hotspot soil degradation sub-catchments based on the simulation result of the baseline scenario. According to this author, soil losses 0-5, 5-15, 15-30, 30-50 and > 50 t $ha^{-1}$ $y^{-1}$ are rated as very low, low, medium, high and very high erosion categories, respectively. In this study, the sub-catchments (SC) with > 30 t $ha^{-1}$ $y^{-1}$ erosion rates were identified and ranked as SC6, SC12, SC11, SC1, SC2 and SC8 in descending order. These prioritized areas covered about 45% of the catchment area. Generally, the simulation of the alternative scenarios in these sub-catchments resulted in ´very low to medium´ erosion classes except for scenario 4 and 5.

Table 8.3: Model simulated sediment yield (t $ha^{-1}$ $y^{-1}$) of the different scenarios for the sub-catchment (SC) in the Mai-Negus catchment, northern Ethiopia

| | | Scenario | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sub-catchment | Area, ha | 1 | 2 | 3 | 4 | 5 | 6a | 6b | 6c |
| SC1 | 101 | 46.80 | 22.9 | 32.3 | 42.1 | 38.8 | 19.2 | 21.1 | 13.1 |
| SC2 | 35.3 | 37.98 | 19.4 | 24.7 | 35.0 | 30.8 | 14.1 | 16.3 | 9.50 |
| SC3 | 28.0 | 28.39 | 18.5 | 21.9 | 25.8 | 27.6 | 17.3 | 18.2 | 15.6 |
| SC4 | 68.7 | 21.32 | 15.8 | 17.0 | 18.7 | 20.6 | 13.0 | 14.1 | 11.5 |
| SC5 | 42.3 | 23.00 | 16.7 | 18.9 | 19.8 | 21.3 | 14.7 | 15.7 | 13.9 |
| SC6 | 108 | 56.05 | 21.9 | 34.8 | 47.7 | 39.8 | 14.6 | 17.4 | 3.93 |
| SC8 | 15.4 | 33.72 | 17.5 | 24.3 | 30.0 | 25.9 | 11.9 | 16.2 | 6.07 |
| SC11 | 53.3 | 65.30 | 35.8 | 43.8 | 53.5 | 34.4 | 21.5 | 19.6 | 3.27 |
| SC12 | 215 | 53.13 | 22.8 | 33.5 | 44.6 | 38.2 | 13.3 | 17.5 | 4.78 |

*1, base line scenario; 2, afforest hotspot areas of erosion; 3, parallel terraces; 4, grassed waterways; 5, gully stabilization structures; 6a, combined scenarios of 2 and 3; 6b, combined scenarios of 2, 4 and 5; 6c; combined scenarios of 2, 3, 4, and 5*

The percentage reductions of sediment yield and nutrient losses due to the scenarios 2-6 were compared with the baseline scenario for the six erosion-hotspot sub-catchments (Figure 8.5). The estimated average annual reductions in sediment yields varied from 8% to 95% across these sub-catchments (Figure 8.5A). The highest percentage reduction was predicted in the sub-catchments SC6, SC11 and SC12 due to the integrated land-use redesign and erosion control measures (scenario 6c), followed by scenario 6a and 6b. The lowest reduction was predicted for scenario 4 followed by scenario 5. However, the impact of sediment reduction due to scenario 4 and 5 was higher for SC11, which is characterized by active gullies and dense drainage network.

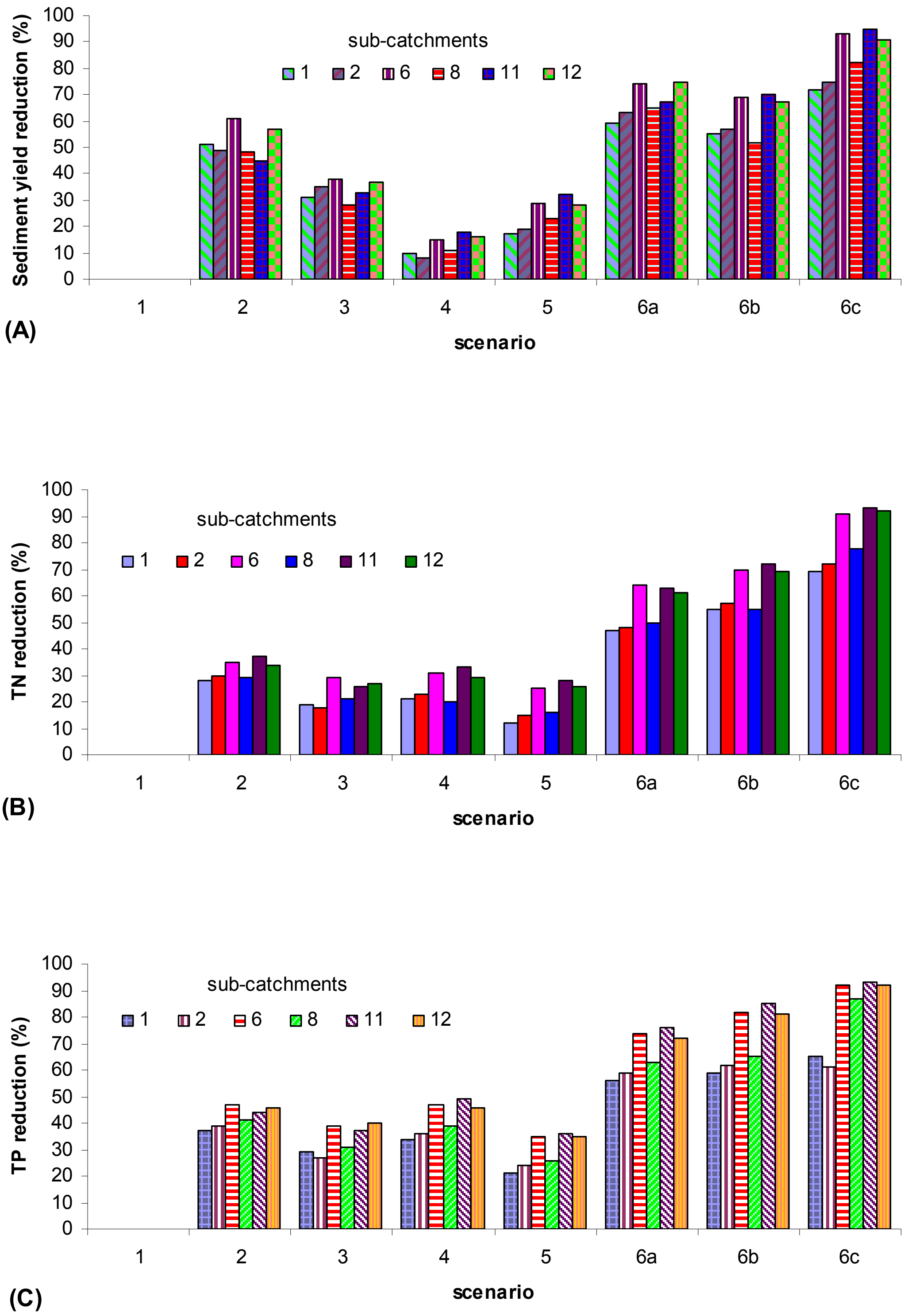



Figure 8.5: Sub-catchment level percentage reduction in sediment yield (A), total nitrogen (TN) loss (B), and total phosphorus (TP) loss (C) in Mai-Negus catchment, northern Ethiopia. For description of scenarios see Table 8.3

The predicted average annual TN loading reductions in the sub-catchments varied from 12% to 93% (Figure 8.5B). Highest reductions of TN losses were observed in scenario 6c, followed by 6a and 6b for SC6, SC11 and SC12. This study shows that scenario 2 can effectively reduce the effect of overland flow and sheet erosion, but its integration with erosion control measures can further reduce TN losses by both runoff and sediment yield from the sub-catchments. Similarly, reductions in TP losses varied from 21% to 92% across the sub-catchments (Figure 8.5C). The reductions varied as a function of the gully stabilization structure (scenario 5) and the integration of land-use and conservation measures (scenario 6c). The estimated reductions in sediment yield, TN and TP suggest that significant benefits can be expected in maintaining the soil resources by the application of integrated management strategies (scenarios) (Figure 8.5A-C).

## 8.4 Discussion

In this study, scenarios of land-use redesign, conservation measures and their integration were simulated for targeted erosion-hotspot areas. The scenarios assessed increasing soil cover, infiltration, and surface roughness, and decreasing raindrop and runoff detachment impact, channel erodibility, slope length and steepness through afforestation, grassed waterways, and conservation measures. The study indicates that afforestation (scenario 2) of erosion-hotspot areas (degraded lands) alone would be less effective in reducing soil erosion rate at catchment and sub-catchment level if other catchment management measures are not applied.

Similarly, the application of soil conservation measures individually such as terracing (scenario 3), grassed waterways (scenario 4) or gully stabilization structures (scenario 5) in such erosion-hotspot lands can reduce soil loss, but this is not as effective as the combination of these scenarios with each and other measures (e.g., scenarios 6a-6c). Of the tested scenarios, scenario 6c followed by scenario 6a reduced sediment yield at the catchment level by about 78% and 65%, respectively. In the erosion-hotspot sub-catchments, the reduction of sediment and nutrient loadings by scenario 6c was more than 90%. Thus, scenario 6c provides the most effective potential management option for reducing soil degradation by erosion at both catchment and sub-catchment level (Figure 8.4 and 8.5).

Based on the SWAT model scenario simulations, grassed waterways (scenario 4) and gully/grade stabilization structures (scenario 5) reduced nutrient losses at the outlet of the catchment and at the sub-catchments level more effectively than it reduced sediment yield. However, the construction of terraces (scenario 3) showed higher reductions in sediment yield than grassed waterways or grade stabilization structures. This indicates that application of management strategies such as parallel terraces would be more successful for catchments such as in the case of the study catchment where upland areas are the dominant sources of sediments and nutrient losses as stated by EPA (2004). On the other hand, if scenario 4 and 5 are to effectively reduce both sediment yield and nutrient losses, the erosion source areas should be targeted by different management measures that reduce the velocity and volume of runoff at its origin and prevent undercutting, piping or scouring of erosion channels (Chow 1964; Goldman et al. 1986). This is because without decreasing the runoff speed and volume in the source area, the erosion route may be diverted in a new direction in scenario 4 and 5, which could be more destructive than the current condition.

Generally, the reductions in soil nutrient loads were consistent with the trend of sediment yield at the outlet of the catchment and sub-catchments level for all the scenarios. This indicates that the impact of management scenarios in reducing nutrient losses was a consequence of the reduction of sediment yield. It can thus be argued that nutrient losses are closely associated with (dependable on) the sediment yield within the study catchment.

A concern is the feasibility (cost effectiveness) of the scenarios presented in this study in larger catchments given the limited resources available (e.g., capital). Part of the solution could be in defining priority sub-catchments. Generally, cost-benefit analyses for the different scenarios are necessary to assess the economic feasibility of the proposed measures. Even for the the relatively effective scenarios regarding reduction in runoff, sediment yield and soil nutrient losses, decisions would depend on the financial efficiency of the measures and resource availability. However, previous studies have not provided standardized soil-erosion-related costs (e.g., Pimentel et al. 1995; Pretty et al. 2000). Further research on cost effectiveness of the scenarios is important to support for decision-making.

In the sub-catchments with high soil erosion rates, the land-use types are either cultivated but not properly managed, over-grazed or marginalized steep-slopes. Such areas currently do not offer a high production potential for the farmers. Excluding these areas from cultivation (35% of cultivation) or grazing (55% from grazing land) by afforesting may not have a considerable immediate effect on the overall livelihoods of the farmers. In order to avoid conflicts among land-users, consensus should be built on which land is to be selected to be afforested and what benefits can be shared. The benefits could be through increasing productivity by improving farm management of cultivated lands at other locations, incentives, sharing downstream irrigation and resource use in the afforested areas (e.g., firewood, grass in a cut-and-carry system, fruits, bee forage). Training farmers in off-farm activities and ecologically friendly farm activities (apiculture, poultry production) would reduce their dependence on the unproductive and fragile cultivated lands, and would help to avoid conflicts when implementing a catchment management strategy.

## 8.5 Conclusions

In this study, the SWAT model was used to simulate the effectiveness of a variety of ‘‘what if’’ scenarios in reducing runoff, sediment yield, and total nitrogen (TN) and total phosphorus (TP) losses in the Mai-Negus catchment, northern Ethiopia. The simulation results demonstrate that compared to the baseline scenario, the alternative scenarios could reduce runoff by about 7-73%, sediment yield by 12-78%, TN losses by 17-72% and TP losses by 29-75% at the catchment level. Similarly, at the erosion-hotspot prioritized sub-catchments level, a reduction of 5-95%, 12-93% and 21-92% in sediment yield, and TN and TP losses, respectively, was achieved.

The highest reductions in runoff, sediment yield and soil nutrient losses were achieved when integrated management strategies that combined land-use redesign and conservation measures (scenario 6c) was applied, whereas the lowest reduction in sediment yield was found in scenario 4 (grassed waterways only) and in soil nutrient losses in scenario 5 (gully/grade stabilization structure). The scenario 6c reduced the sediment yield to 9200 t $y^{-1}$ as compared to the current rate of 41900 t $y^{-1}$ at catchment level. A similar and consistent reduction trend to that of sediment yield was also simulated by the model for runoff, TN and TP losses when scenario 6c was applied.

Thus, scenario 6c appears to be effective as a potential management strategy in reducing the soil degradation at both catchment and sub-catchment level. The results of the SWAT model need to be extended to similar environmental conditions to support decision-making processes in a catchment management plan.

The current erosion modeling approach can be very useful for decision-makers to evaluate the benefits of individual and integrated management strategies that best reduce the soil degradation interms of runoff, sediment yield and soil nutrient losses at the catchment and sub-catchment level. This should be helpful to identify suitable scenarios for implementation in a catchment and sub-catchment or to quantify the benefits of the management practices where they have been already implemented in a catchment. Generally, this study demonstrates that the SWAT model is a potentially powerful tool for land managers, allowing them to select the technically most effective management strategies for reducing soil degradation due to soil erosion at the catchment scale. However, further cost-benefit analyses are required of the respective management strategies.

# 9 SUMMARY AND CONCLUSIONS

This chapter synthesizes and concludes the major findings of this study with respect to the main objectives. The summary of the results focuses on answering the general research question how severe is the existing soil quality degradation problem, and what management strategies can reduce the problem more efficiently in the Mai-Negus catchment, northern Ethiopia. Figure 9.1 summarizes the research framework of the major approaches, tasks and implication of the study results. Understanding the severity (magnitude) of the soil degradation problem is an important step for prioritization catchment areas for introducing appropriate intervention by planners and decision makers. The following sections summarize how the existing soil quality (SQ) degradation is severe, as described in the view of SQ evaluation and erosion model results, and the role of the simulated management strategies in reducing soil degradation in the study catchment.

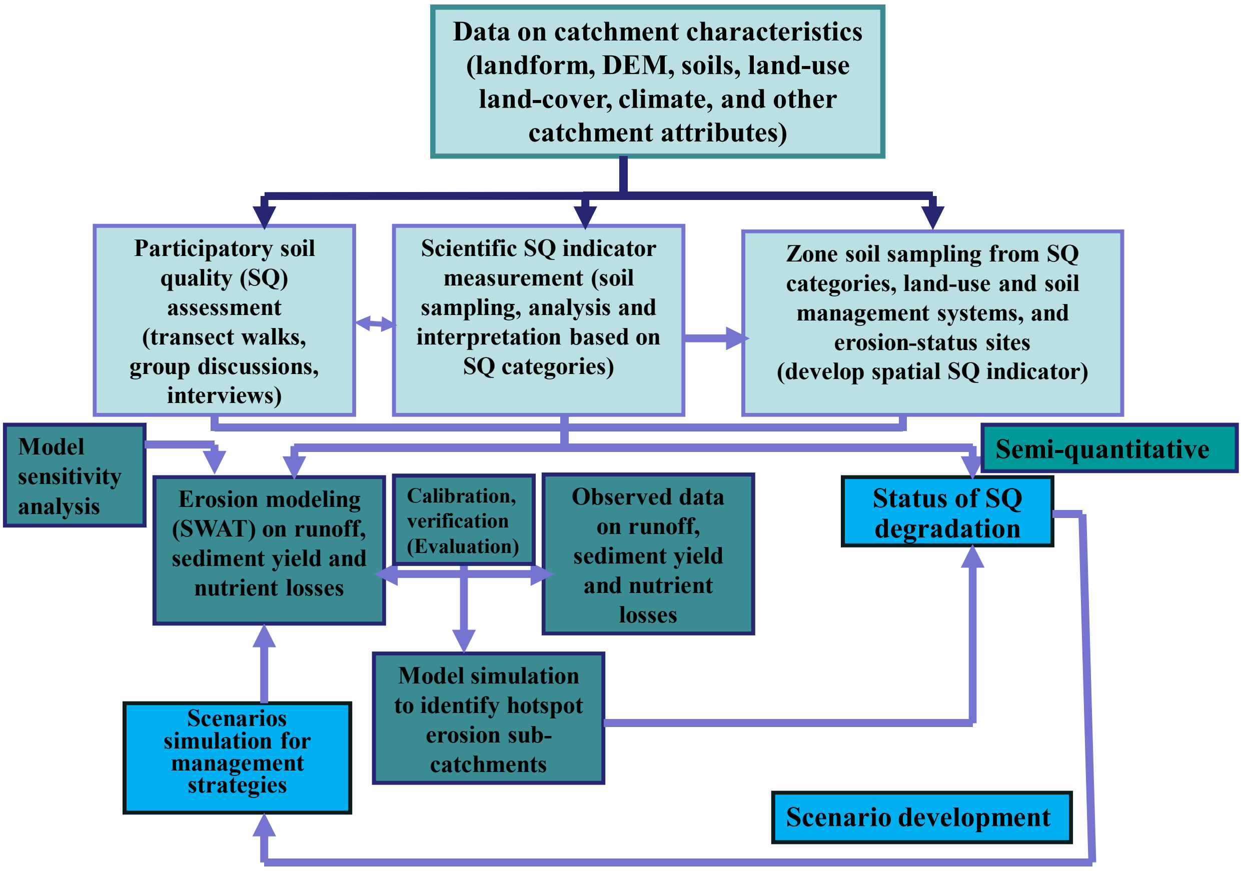



Figure 9.1: Research framework employed to fulfil the objectives of the study

## 9.1 What are the indicators and how severe is the problem?

***(a) How can farmer soil quality knowledge contribute as a potential indicator of soil degradation to sustainable development decision-making?***

In this study, a participatory SQ assessment was carried out to assess the contribution of local farmer knowledge of soil quality as potential SQ degradation indicators. Participation of local communities in evaluating SQ degradation, its determining factors and possible management options is crucial, not only for the measures to be accepted and implemented, but also to sustain those practices. The results of the participatory SQ survey indicate that farmers have the experience and knowledge to assess SQ status as well as the severity and determinants of SQ degradation. They have the knowledge to diagnose the status of SQ degradation and to identify erosion source areas and the main driving forces (terrain, poor surface cover, high runoff, inappropriate practices) for the degradation processes. The SQ diagnostic indicators related to crop yield and erosion (e.g., soil depth, color) were often used by the farmers to classify their soils to three SQ categories: high, medium and low. Their classification was not limited to the soils' nutrient status but also considered soil erosion, fertility, color, thickness, water-holding capacity, and yield and crop performance indicators. The local farmers reported that high SQ soils are dark, fertile and with high water-holding capacity, and that they generally produce good crop yields. The farmers thought that poor SQ soils had low fertility, were light in color, had a tendency to dry-up quickly and generally lower crop yields production potential. The farmers added that poor soil can also be described by shallow depth, high weed infestation, sandy texture, and a very loose surface that is easily eroded. The medium SQ category soil shows an intermediate character in between the high and low SQ categories, and has medium soil depth, and a mixed red-dark color. Despite such knowledge of the local communities, the problem of SQ degradation still continues in many areas of Ethiopia. Therefore, for addressing the concern of SQ degradation in Ethiopia and other similar areas, approaches that fully involve the indigenous community should be designed.

***(b) How does the scientific soil measurement evaluation compare with the SQ categories identified by the local farmers?***

Evaluation of measured soil data from representative locations of the SQ categories identified by farmers' knowledge is crucial to test whether the participatory SQ assessment approach is within a reasonable accuracy for developing appropriate management plans to combat SQ degradation. Soil attributes in the respective SQ categories determined following the standard soil sampling and analysis procedures corresponded well with the SQ classification made by the farmers. For instance, low SQ is characterized by significantly ($P \leq 0.05$) higher sand content and bulk density, and has lower soil nutrients (TN, Pav, CEC, organic matter), pH, SAS and clay content than the medium and high SQ categories. Farmers' categorized sand-dominated soils as low SQ because they perceived that such soils have low water-holding capacity and low soil nutrients, which agreed with laboratory results. Farmers are also able to associate SQ nutrient status with plant growth and development conditions. In addition, most soil nutrient attributes determined in the low and medium SQ categories were rated as low following the standard ratings for tropical soils. This indicates that SQ degradation is higher in the medium and low SQ than in the high SQ category. However, even though the analyses confirm the consistency of farmer-defined SQ categories with the measured indicators, the key soil attributes that determine and control SQ variability need to be examined using further analysis.

Among the 19 soil attributes initially analyzed, those that showed significant differences between SQ categories were subjected to factor analysis. As a result, soil attributes were grouped into four main PC factors using PCA (eigenvalues > 1) in assessing gradients in the data structure that explain about 88% of the SQ variability in the SQ categories. Generally, the PCA suggests that the variability of SQ categories identified by farmer knowledge is mainly linked to soil CEC, porosity, sand, TP, and Ca:Mg. Focus is thus given on these variables in the multiple discriminant analysis to identify the best discriminator variable among the SQ categories (group variables) and also to assess the relations with the group variables. In the discriminant analysis, the actual values of the five soil attributes (CEC, porosity, sand, TP, and Ca:Mg ratio) with high factor loadings retained in the four PCs were used. The discriminant function coefficients show that soil porosity, followed by CEC and sand content are the best discriminators in the first function between group 1 (low SQ) and the combination of group 2 (medium SQ) and group 3 (high SQ), but that Ca:Mg was least effective in discriminating these groups. The trend of the discriminant coefficients of these independent variables was similar in function 2 to that in function 1. This study indicates that the discriminant analysis correctly classified (> 90%) for the cases in the SQ categories, indicating statistically that the SQ categories identified by the farmers are correct. Generally, this shows that the measured soil data corresponded well with those of farmer identified SQ categories. As a result, local SQ knowledge can be used for decision-making processes regarding SQ degradation.

**(*c) What do catchment-scale spatial soil properties imply for site-specific soil degradation and its management?***

Understanding the variability of soil properties at catchment scale is important for site-specific sustainable soil and crop management decisions. Soil saamples were collected using zone sampling as SQ categories, land-use and soil management systems and erosion-status sites. The descriptive statistics results in this study show a wide range of the soil parameters values at catchment scale, e.g., 15-70% sand, 18-77% silt, and 3-51% clay. The mean BD (1.59 Mg $cm^{-3}$) was high. The mean OC (1.21%), TN (0.12%), and Pav (7.8 mg $kg^{-1}$) of the soils in the catchment were low, while values were high for Ex K (0.77 $cmol_c$ $kg^{-1}$), and medium for CEC (23.4 $cmol_c$ $kg^{-1}$) compared to the rate for African soils observed by Landon (1991). The coefficient of variation of the soil properties ranged from 8.6% (pH) to 73.4% (clay). However, such classical statistics information could not show the soil parameters′ spatial variability in the study catchment. The geostatistical technique was thus applied to determine spatial dependence and variability of the soil parameters after testing for normal distribution.

The results of the geostatistical analyses indicate that the soil parameters showed spatial dependence and fitted to different semivariogram models. The range of the soil properties varied from 33 m (silt) to 223 m (Ex K). The degree of spatial dependence was between 8% (strong) and 63% (moderate). The accuracy of the maps of the kriging interpolation soil properties was also assessed by goodness-of-prediction criterion (G) value. The values of G higher than zero indicate that kriging was more accurate than the average catchment values of descriptive statistics.

A higher sand (50-70%) and bulk density (1.75-2.00 Mg $m^{-3}$) spatial distribution in the north and north-west of the catchment, particularly in the mountainous and central-ridge landforms, was observed. The maps of the soil properties also showed well-defined patterns of higher fine soil particles and soil nutrients in the reservoir (toe-slope) and valley (foot-slope) landforms and on high vegetation cover sites in the catchment. The spatial maps indicate that the mountainous, central-ridge and part of the escarpment landforms had severe degradation with respect to soil nutrients. For the purpose of site-specific soil management, prioritization should be given to these areas. The spatial distribution of topsoil properties could be used as an indicator for the spatial variability of soil degradation, and thus support site-specific soil management decisions at catchment scale. This part of the study thus answered the question which landscape positions require prior attention from soil nutrient degradation perspective.

***(d) Where are the major erosion sources (severe soil degradation) in the catchment?***

Knowledge of the SQ status and the respective spatial distribution may not be adequate to tackle the SQ degradation problem unless the source and rates of soil erosion in the catchment is properly identified. This is demanding a model that identifies the location of hotspot areas i.e., important sources of runoff, sediment yield and nutrient losses. This is a necessary step as all areas of the catchments can not be conserved for financial and practical reasons. The GIS-interfaced SWAT model was used to show the spatial patterns of soil degradation and identify erosion-hotspot sub-catchments within the catchment so as to prioritize areas with a high risk of soil erosion. To do so, the model was first evaluated in the context of the study catchment. Model efficiency values > 0.50 for $N_{SE}$ and > 0.60 for $R^2$ were obtained for flow, sediment yield and nutrient losses during calibration and validation, which is adequate for SWAT model to apply for management planning regarding the most vulnerable landscapes.

The spatial patterns in the sediment yield map were used to classify into different soil loss categories, and sub-catchments experiencing soil loss rates higher than the acceptable threshold (18 t $ha^{-1}$ $y^{-1}$) were identified as those requiring prior attention for intervention. The SWAT model predicted sediment yield of the catchment ranged from 0-5 t ha $y^{-1}$ to more than 50 t ha $y^{-1}$. Priorities were given according to ranks assigned to each hotspot sub-catchments on the basis of erosion hazard categorie and the associated soil nutrient losses. Generally, the sub-catchments characterized by high elevation and steep slopes, poor surface cover, poor SQ and with a dense network of active gullies experienced higher rates of runoff, soil loss and nutrient losses than others. Thus, out of 16 sub-catchments, the model prioritized nine sub-catchments experiencing soil erosion rates higher than 18 t $ha^{-1}$ $y^{-1}$. Doing this can answer the question: *where* should the appropriate interventions to be located to tackle soil degradation in the study catchment?

## 9.2 What is a robust solution for the existing severe soil degradation?

After having scientific evidences on the status of SQ degradation from the context of local knowledge, scientific soil measurements, spatial variability of soil indicators and erosion modeling, alternative management strategies that reduce the existing soil degradation can be evaluated for the prioritized areas. The management strategies targeting hotspot areas should, therefore, reduce upstream erosion and the associated losses and the downstream effect on gully expansion and development and the related-problems.

In this study, different management strategies (8 scenarios) were simulated to assess their effectiveness in reducing soil degradation at catchment level and the targeted hotspot soil degradation sub-catchments. The highest soil erosion rate as sediment yield (41900 t $y^{-1}$) was simulated in scenario 1 (baseline scenario) followed by scenario 4 (36900 t $y^{-1}$). However, the lowest sediment yield was simulated in scenario 6c (9200 t $y^{-1}$) followed by scenario 6a (14700 t $y^{-1}$). A similar trend in runoff and the associated soil nutrients losses was also simulated in these scenarios. Some of the scenarios targeting the hotspot sub-catchments show the suitablity in reducing soil degradation to an acceptable level. The simulation results show that reductions of sediment yield, TP and TN losses and runoff by 78, 75, 72 and 70%, respectively, can be achieved at catchment level by introducing the integration of afforestation, terracing, grassed waterways, and gully stabilization (scenario 6c) in the hotspot-erosion areas, as compared to the baseline condition. A higher reduction in sediment yield, runoff, and soil nutrient losses was observed for the prioritized sub-catchments than at the catchment level due to the scenarios effect. This demonstrates the importance of introducing appropriate management strategies to sustain the productivity of soil resources by reducing the severity of soil degradation. Such scenario analysis can therefore make it possible to answer the question: Which management strategies placed where are more efficient?

## 9.3 Overall conclusions

The results of this study show that the use of local farmer knowledge of soil quality (SQ) can be used to indicate the status of SQ degradation at catchment scale. The SQ status identified by local farmers corresponded well with scientific measured soil data, interpolated spatial soil properties, and the hotspot-erosion sites identified by the erosion modeling. Areas identified by the farmers as a poor SQ showed low soil nutrients and low fine soil particle contents in the laboratory results, and were also identified as the sources of severe soil erosion by the SWAT model. This shows that farmers understood well the nature and condition of the SQ degradation. However, they are not able to tackle the problem of SQ deterioration mainly because of lack of capital, organized labor, technical skills, and immediate food requirements (food insecurity problems), besides their reluctance and not fully involved on related issues. Generally, this study confirms that the evaluation of SQ degradation status to prioritize areas of attention for decision-making using the knowledge of local farmers is rapid, less expensive, has high reproducibility and is participatory in nature, and is reasonably accurate when compared to scientific soil data measurement and erosion modeling. This can thus facilitate informed decision making on SQ management in areas where no professional experts are available and resources are limited, and if extrapolation of measured soil data is also difficult. Further efforts that address the issue of up-scaling of the knowledge and approaches acquired in this study are also important for researchers and decion-makers to implement successfully the best management strategies that reduce soil degradation in a similar condition. A higher reduction in runoff, sediment yield and soil nutrient losses can be achieved when management strategies such as land-use redesign and conservation measures are integrated during implementation.

## 9.4 Research and policy implications

The erosion modeling and SQ evaluation conducted in this study provide relevant scientific information for planners and decision-makers. The study also serves the scientific community as a basis for further study. The main research and policy implications are outlined below.

1) A participatory SQ degradation assessment is crucial to monitor the impact of soil and other management systems on the sustainability of agricultural production and environmental services at large scale. Attention must be paid to the broader systems of policy-making and governance and the ways in which participatory SQ degradation assessments can be institutionalized. However, research on additional catchments with contrasting environmental conditions is necessary to account for the heterogeneity of farmer knowledge of SQ degradation before the result of this study is used for decision-making with respect to anti-degradation measures at regional or nation scales. Development recommendations at large scale are only successful if they take into consideration site-specific factors based on local farmers' knowledge perspectives.
2) The scientific soil attributes measured to evaluate the SQ status identified by local farmers were determined from the topsoil (plow depth) of 0-20 cm depth. The results indicate that the laboratory results agree well with the farmers´ classification of SQ status at the given soil depth. However, further research needs to be assessed the soil attributes in the sub-soil depths of the different SQ categories. Generally, as the soil surface can be easily assessed by the farmers, interpolation or extrapolation of the study results to similar areas would reduce resource wastage in conducting research of the same purpose.
3) Currently, many interpolation methods are available in geostatistical techniques. However, kriging interpolation showed that maps of soil properties are more accurate than average values at catchment scale. It is suggested that further investigation of the effect of soil sampling spacing across different slopes/elevations on the efficiency of the interpolation methods is crucial for the northern Ethiopia condition. In addition, the results of geostatistically determined soil properties can be used by planners and decision-makers to focus on site-specific soil management practices, e.g., variable fertilizer rate recommendations considering within field spatial soil nutrient variability.
4) The SWAT model applied in this study was calibrated and validated for conditions in the study catchment. Regardless of the data demand, the model identified erosion

hotspot sub-catchments and thereby the severity of soil degradation. Planners and decision-makers can use such models in order to quantitatively describe the rate and spatial pattern of soil erosion at catchment scale. However, it is recognized that a wider validation effort is needed before adopting the model for decision-making purposes throughout the Tigray region, which has a diverse environment. This model may need to be evaluated across different agro-ecological zones to see how it works under different governing factors in the region.

5) The scenarios simulated in this study demonstrate that an integrated catchment management strategy, e.g., afforestation with conservation measures on the major erosion sources sub-catchments could significantly reduce runoff, sediment yield and nutrient losses. The immediate problem for afforested areas that have been already used for cultivation and free grazing for many years is the resistance of the farmers to accept such decisions. Therefore, thorough discussions with the farmers about the necessity and benefits of such measures in the short-and long-term are necessary for successful implementation of the intended management strategies. Incentives for farmers who manage and protect their fields from severe soil degradation should also be considered by policy-makers to encourage sustainable land-use based on farmer innovation knowledge. Such involvement of local communities also facilitates partnership between farmers, extension workers and researchers while working to achieve the goal of sustaining natural resources and enhancing soil productivity. Consideration of farmers' experiences and knowledge of SQ can improve the quality of technologies to be recommended and the chance for successful implementation and sustainable adoption. Further efforts that address the issue of up-scaling of the knowledge and approaches acquired in this study to similar conditions should be given due attention by researchers, planners and decision-makers.

## 10 REFERENCES

Abbaspour KC, Johnson A, Van Genuchten MTh (2004) Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure Vadose Zone J 3: 1340-1352

Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R (2007) Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J Hydrol 333: 413-430

Acton DF, Gregorich LJ (1995) Understanding soil health. In: Acton DF, Gregorich LJ (eds) The Health of our soils: toward sustainable agriculture in Canada, Centre for Land and Biol. Resour. Res., Res. Branch, Agric. and Agri-Food, Ottawa, ON, p 5-10

Admassie Y (1995) Twenty year to no where. Property rights, land management and conservation in Ethiopia. PhD Thesis, Uppsala University

Agterberg FP (1984) Trend surface analysis. In: Gaile GL, Willmott CJ (eds) Spatial statistics and models, Reidel, Dordrecht, The Netherlands, p 174-171

Ahmed HA, Gerald ES, Richard HH (1987) Soil bulk density and water infiltration as affected by grazing systems. J Range Manage 40: 307-309

Alemu T (2006) The land issue and environmental change in Ethiopia. In: Rahmato D, Assefa T (eds) Land and the challenge of sustainable development in Ethiopia, Conference proceedings, Forum for Social Studies, Addis Ababa, Ethiopia, p 129

Ananda J, Herath G (2003) Soil erosion in developing countries: a socio-economic appraisal. J Environ Manage 68: 343-353

Andrews SS, Karlen DL, Cambardella CA (2004) The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci Soc Am J 68: 1945-1962

Araya A, Stroosnijder L (2010) Effects of tied ridges and mulch on barley (Hordeum vulgare) rainwater use efficiency and production in Northern Ethiopia. Agric Water Manage 97: 841-847

Argent RM, Grayson RB, Rahman JM (2005) Model selection and the catchment modelling toolkit proceedings, 29th Hydrology and Water Resources Symposium, 21-23 February 2005, Canberra, Engineers Australia

Arnold JG, Sirinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modelling and assessment, Part 1: Model development. J Am Water Resour Assoc 34: 73-89

Arshad MA, Lowery B, Grossman B (1996) Physical tests for monitoring soil quality. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality, SSSA Spec. Pub. 49. SSSA, Madison, WI, p 123-142

Arshad MA, Martin S (2002) Identifying critical limits for soil quality indicators in agro-ecosystems. Agric Ecosyst Environ 88: 153-160

Ashagre BB (2009) SWAT to identify watershed management options: (Anjeni watershed, Blue Nile basin, Ethiopia). MSc Thesis, Cornell University

Atkinson S, Sivapalan M, Viney NR, Woods, RA (2003) Predicting space-ime variability of hourly streamflows and the role of climate seasonality: Mahurangi catchment, New Zealand. Hydrol Process 17: 2171-2193

Ayoubi Sh, Zamani SMb, Khormali F (2007) Spatial variability of some soil properties for site specific farming in northern Iran. Int J Plant Prod 2: 225-236

Badege B (2001) Deforestation and land degradation in the Ethiopian highlands: a strategy for physical recovery. Northeast African Studies 8: 7-25

Barrera-Bassols N, Zinck JA, Ranst EV (2006) Symbolism, knowledge and management of soil and land resources in indigenous communities: ethnopedology at global, regional and local scales. Catena 65: 118-137

Barrera-Bassols N, Zinck JA, Ranst EV (2009) Participatory soil survey: experience in working with a Mesoamerican indigenous community. Soil Use manage 25: 43-56

Barrios E, Trejo MT (2003) Implications of local soil knowledge for integrated soil fertility management in Latin America. Geoderma 111: 217-231

Baruah TC, Barthakur HP (1999) A Text Book of Soil Analysis. Vikas Publishing House Pvt. Ltd., New Delhi

Bekele S, Holden S (1999) Soil erosion and smallholders' conservation decisions in the highlands of Ethiopia. World Dev 27: 739-752

Belay A (1996) Climatic resources, major agro-ecological zones and farming systems in Tigray, a paper presented in the Extension Intervention Program Workshop, Mekelle, Ethiopia

Bewket W, Sterk G (2003) Assessment of soil erosion in cultivated fields using a survey methodology for rills in the Chemoga watershed, Ethiopia. Agric Ecosyst Environ 97: 81-93

Beyene A, Gibbon D, Haile M (2001) Understanding diversity in farming practices in Tigray, Ethiopia. Managing Africa's Soils No. 24

Bingner RL, Theurer FD (2001) AnnAGNPS: estimating sediment yield by particle size for sheet & rill erosion. In: Proceedings of sedimentation: monitoring, modeling, and managing, 7th Federal Interagency Sedimentation Conference, vol 1, Reno, NV, 25-29 March 2001, p 1-7

Birmingham DM (2003) Local knowledge of soils: the case of contract in Côte d'Ivoire. Geoderma 111: 481-502

Birrell SJ, Sudduth KA, Kitchen NR (1996) Nutrient mapping implications of short-range variability. In: Robert PC, Rust RH, Larson, WE (eds) Proceedings of the 3rd international conference on precision agriculture, ASA-CSSA-SSSA, WI, p 206-216

Boggs G, Devonport C, Evans K, Puig P (2001) GIS-based rapid assessment of erosion risk in a small catchment in a wet/dry tropics of Australia. Land Degrad Dev 12: 417-434

Bojo J, Cassells D (1995) Land degradation and rehabilitation in Ethiopia. A reassessment. World Bank

Borin M, Vianello M, Morari F, Zanin G (2005) Effectiveness of buffer strips in removing pollutants in runoff from cultivated field in North-East Italy. Agric Ecosyst Environ 105: 101-114

Boyd C, Turton C (eds) (2000) The Contribution of soil and water conservation to sustainable livelihoods in semi-arid areas of Sub-Saharan Africa. Network Paper 102, The Agricultural Research and Extension Network, London

Brejda JJ, Karlen DL, Smith JL, Allan DL (2000) Identification of regional soil quality factors and indicators: II. Northern Mississippi Loess Hills and Palouse Prairie Soil. Soil Sci Soc Am J 64: 2125-2135

Bundela DS (2004) Influence of digital elevation models derived from remote sensing on spatio-temporal modelling of hydrologic and erosion processes. PhD Thesis, Cranfield University

Bureau of Agriculture and Natural Resources Development (BoANRD) (1997) Tigray soil and water conservation action programme, draft main report, Mekelle, Ethiopia

Burgess TM, Webster R (1980) Optimal interpolation and isarithmic mapping of soil properties: I. The variogram and punctual kriging. J Soil Sci 31: 315-331

Byne W (2000) Predicting sediment detachment and channel scour in the process-based planning model ANSWERS-2000. MSc Thesis, Virginia Polytechnic Institute and State University,

Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF, Konopka AE (1994) Field-scale variability of soil properties in central Iowa soils. Soil Sci Soc Am J 58: 1501-1511

Chadha GK (1996) Wastelands in rural India: Policy initiatives and programmes for their development. Occasional Paper 2, National Bank for Agriculture and Rural Development, Mumbai, p 97

Chekol AD (2006**)** Modeling of hydrology and soil erosion of upper Awash river basin, Ethiopia. Pub. PhD Thesis, University Bonn

Chow VT (1964) Handbook of Applied Hydrology. McGraw-Hill Book Company, New York

Cloutier PE (1984) Assessment of the present situation in agriculture. EHRS Working Paper 11, FAO, Rome

Commission for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CoSART) (1994) Sustainable agriculture and environmental rehabilitation in Tigray. Basic Text, Unpub. Document, SAERT, Mekelle, Ethiopia

Coppus R (2002) Landscape sensitivity in three semi-arid Central Andean Geo-ecosystems. PhD Dissertation, Universiteit Van Amsterdam

Corbeels M, Shiferaw A, Haile M (2000) Farmers' knowledge of soil fertility and local management strategies in Tigray, Ethiopia. Managing Africa's Soils, No. 10

Cressie NAC (1993) Statistics for spatial data, revised ed. New York: John Wiley

Daily GC, Matson PA, Vitousek PM (1997) Ecosystem services supplied by soil. In: Daily GC (ed) Nature's services: societal dependence on natural ecosystems, Washington, DC: Island Press, p 113-132

Daniel G (1977) Aspects of climate and water budget in Ethiopia. Addis Ababa University Press

Davidson O, Halsnaes K, Huq S, Kok M, Metz B, Sokona Y, Verhagen J (2003) The development and climate nexus: the case of Sub-Saharan Africa. Climate Policy 3: 97-113

Dejene A (1990) Environment, famine, and politics in Ethiopia: A view from the village. Lynne Rienner Publishers, Inc.

De Roo APJ, Walling DE (1994) Validating the ANSWERS soil erosion model using $^{137}Cs$. In: Rickson RJ (ed) Conserving soil resources: European perspective, Wallingford, UK, pp 246-263

Descheemaeker K, Nyssen J, Poesen J, Mitiku H, Muys B, Raes D, Moeyersons J, Deckers J (2006) Soil and water conservation through forest restoration in exclosures of the Tigray highlands. Journal of the Drylands 1:118-133

Desmet PJJ, Govers G (1997) Two dimensional modelling of the within-field variation in rill & gully geometry and location related to topography. Catena 29:283-306

Doberman A (1994) Factors causing field variation of direct-seeded flooded rice. Geoderma 62: 125-150

Doe WW, Jones DS, Warren SD (1999) The soil erosion model guide for the military land managers: analysis of erosion models for natural and cultural resources applications. Center for Ecological Management of Military Lands, Colorado State University, Colorado, USA

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart, BA (eds) Defining soil quality for a sustainable environment, SSSA spec. pub. 35. SSSA, Madison, WI, p 3-22

Doran JW, Parkin TB (1996) Quantitative indicators of soil quality: a minimum data set. In: Doran JW, Jones, AJ (eds) Methods for assessing soil quality, SSSA spec. pub. 49. SSSA, Madison, WI, p 25-38

Doran JW, Safley M (1997) Defining and assessing soil health and sustainable productivity. In: Pankhurst CE, Doube BM, Gupta VVSR (eds) Biological indicators of soil health, CAB International, p 1-28

Doran JW (2002) Soil health and global sustainability: translating science into practice. Agric Ecosyst Environ 88: 119-127

Elias E, Morse S, Belshaw DG R (1998) Nitrogen and phosphorus balance of Kindo Koisha farms in southern Ethiopia. Agric Ecosyst Environ 71: 93-113.

Elias E (2000) Soil enrichment and depletion in southern Ethiopia, In: Hilhorst T, Muchena FM (eds) Nutrient on the move-soil fertility dynamics in African farming systems, llED, London, UK, p 65-82

Elias E, Fantaye D (2000) Managing fragile soils: a case study from north Wollo, Ethiopia. Managing Africa’s Soils, No. 13

Elias E (2002) Farmers’ perception of soil fertility change and management. SOS Sahel and ISD, Addis Ababa, Ethiopia

Elliot WJ, Dumroese DP, Robichaud PR (1999) The effects of forest management on erosion and soil productivity. In: Lal R (ed) Soil quality and soil erosion, Boca Raton, FL: CRC press, p 195-209

El-Swaify ES, Pathak P, Rego TJ, Singh S (1985) Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. Stewart BA, (ed) Advances in soil science No 1, Springer-Verlag, New York, p 1-64

El-Swafiy SA, Hurni H (1996) Transboundary effects of soil erosion and conservation in the Nile basin. Land Husbandry 1: 6-21

Environmental Protection Authority (EPA) (2003) The Federal Democratic Republic of Ethiopia-state of environment report for Ethiopia. August 2003, Addis Ababa

Environmental Protection Agency (EPA) (2004) Impact of best management practices on water quality of two small watersheds in Indiana: role of spatial scale. United States Environmental Protection Agency http://www.epa.gov/nrmrl/pubs/600r05080/600r05080.pdf. Cited March 2011

Erenstein OCA (1999) The Economics of soil conservation in developing countries: the case of crop residue mulching. unpub. PhD Thesis, Wageningen University

Eswaran H, Lal R, Reich PF (2001) Land degradation: an overview. In: Bridges EM, Hannam ID, Oldeman LR, Penning de Vries FWT, Scherr JS, Sombatpanit S (eds) Response to land degradation, Science Publisher, Inc.: Enfield, NH, p 20-35

Ethiopian Mapping Agency (EMA) (1988) National atlas of Ethiopia. Ethiopian Mapping Authority, Addis Ababa, Ethiopia

Ethiopian Mapping Agency (EMA) (1997) Ethiopia 1:50000 topographic maps. Aksum Sheet

Everitt BS, Dunn G (1992) Applied multivariate data analysis. Oxford University Press, New York

Eweg H, Van Lammeren R (1996) The application of a Geographical Information System to the rehabilitation of degraded and degrading areas. a case study in the highlands of Tigray, Ethiopia. Centre for Geographical Information Processing, Agricultural University of Wageningen

Eweg HPA, Van Lammeren R, Fikru Y (1997) The GIS implementation. In: Feoli E (ed) Rehabilitation of degraded and degrading areas of Tigray, northern Ethiopia, Final Report. Commission of the European Communities, STD3 Project No. TS3-CT92-0049, 1992-1996. University of Trieste, Italy

FAO (1984a) Agroclimatological data for Africa, vol 1: countries north of equator. Plant Production and Protection Series 22, FAO, Rome

FAO (1984b) Geo-morphology and soils. Assistance to land use-planning project. Field document 2, AG: DP/ETH/781003, Addis Ababa, Ethiopia

FAO (1986) Ethiopian highland reclamation study. Final report, vol 1-2. FAO, Rome

FAO (1994) Land degradation in south Asia: its severity, causes and effects upon the people. World Soil Resources Report No. 78, FAO, Rome

FAO/UNEP (1983) Guidelines for the control of soil degradation, FAO, Rome

FAO - UNESCO (1974) Soil map of the world. vol 1, Legend, FAO, Rome

Federal Democratic Republic of Ethiopia Population Census Commission (FDREPCC) (2008) Summary of statistical report of the 2007 population and housing census. Addis Ababa, Ethiopia

Flanagan DC, Nearing MA (1995) USDA-Water Erosion Prediction Project (WEPP) - technical documentation, National Soil Erosion Research Laboratory, Report No. 10, USDA-ARS-MWA, West Lafayette, IN

Fontaine TA, Cruickshank TS, Arnold JG, Hotchkiss RH (2002) Development of a snowfall-snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT). J Hydrol 262: 209-223

Foster GR (1990) Process-based modelling of soil erosion by water on agricultural land. In: Boardman J, Foster IDL, Dearing JA (eds) Soil erosion on agricultural land, John Wiley & Sons Ltd. p 429-446

Franzen DW, Halvorson AD, Krupinsky J, Hofman VL, Cihacek LJ (1998) Directed sampling using topography as a logical basis. In: Robert PC, Rust RH, Larson WE (eds) Proceedings of the 4$^{th}$ international conference on precision agriculture, ASA, CSSA, and SSSA, WI, p 1559-1568

Fu W, Tunney H, Zhang C (2010) Spatial variation of soil nutrients in a dairy farm and its implications for site-specific fertilizer application. Soil Till Res 106: 185-193

Gebeyehu A (2002) Research and development in land and water resources. In: McCornick PG, Kamara AB, Girma T (eds) Integrated water and land management research and capacity building priorities for Ethiopia. Proceedings of a MoWR/EARO/IWMI/ILRI international workshop held at ILRI, Addis Ababa, Ethiopia, 2-4 December 2002, p 2-10

Gebre-Egziabher TB (1989) The Environmental variables which led to the ecological crisis in Ethiopia. Coenoses 4: 61-67

Gebreegziabher T, Nyssen J, Govaerts B, Fekadu G, Mintesinot B, Mitiku H, Deckers, J (2009) Contour furrows for in situ soil and water conservation, Tigray, northern Ethiopia. Soil Till Res 103: 257-264

Gebremichael D, Nyssen J, Poesen J, Deckers J, Haile M, Govers G, Moeyersons J (2005) Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray highlands, northern Ethiopia. Soil Use Manage 21: 287-297

Gemechu D (1977) Aspects of climate and water budget in Ethiopia. Technical Monograph, Addis Ababa University press, Addis Ababa, p71

Georgia Soil and Water Conservation Commission (GSWCC) (2000) Manual for erosion and sediment in Georgia. 5th ed. Athens, GA

Girmay G, Singh BR, Nyssen J, Borrosen T (2009) Runoff and sediment-associated nutrient losses under different land uses in Tigray, northern Ethiopia. J Hydrol 376: 70-80

Goldman, S J, Jackson K, Bursztyusky TA (1986) Erosion and sediment control. Handbook, McGraw Hill

Govers G (1987) Spatial and temporal variation in rill development processes at the Huldenberg experimental site. In: Bryan R (ed) Rill erosion: processes and significance. Catena supplement 8, p 17-34

Graaff J (1993) Soil conservation and sustainable land use: an economic approach. Royal Tropical Institute, Amsterdam

Green WH, Ampt GA (1911) Studies on soil physics, 1. The flow of air and water through soils. J Agric Sci 4: 11-24

Grego CR, Vieira SR, Lourenção AL (2006) Spatial distribution of Pseudaletia sequax Franclemlont in triticale under no-till management. Sci Agric 63: 321-327

Gregorich EG, Carter MR, Angers DA, Monreal CM, Ellert BH (1994) Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can J Soil Sci 74: 367-386

Grobben P (1992) Using farmers' knowledge about soil. a case study of a farming systems research project in Java. AT-source, no. 3/92, Wageningen

Habarurema E, Steiner KG (1997) Soil suitability classification by farmers in southern Rwanda. Geoderma 75: 75-87

Hagos F, Penden J, Gebresilassie N (1999) Land degradation in the highlands of Tigray, and strategies for sustainable land management. Socio-economic and Policy Research Working Paper No. 25. International Livestock Research Institute

Haile M (1995) Indigenous knowledge and agricultural practices in Central Tigray. Proceedings of the workshop on agro-ecological and health studies in the Central Zone of Tigray, (Unpublished), March 1995, Mekelle, Ethiopia

Hakkeling RTA (1989) Global Assessment of soil degradation-Eastern and Southern Africa. vol 1: main report, vol 2: Matrix Tables/Mapping Unit Descriptions. Netherlands Soil Survey Institute, Wageningen

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

Haregeweyn N, Poesen J, Deckers J, Nyssen J, Haile M, Govers G, Verstraeten G, Moeyersons J (2008) Sediment-bound nutrient export from micro-dam catchments in northern Ethiopia. Land Degrad Dev 19: 136-152

Harris RF, Bezdicek DF (1994) Descriptive aspects of soil quality/health. In: Doran J W, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment, SSSA Spec. Pub. 35, SSSA, Madison, WI, p 23-35

Helldén U (1987) An assessment of woody biomass, community forests, land use and soil erosion in Ethiopia. Lund University Press, Sweden

Hendrix CS, Glaser SM (2007) Trends and triggers: climate, climate change and civil conflict in Sub-Saharan Africa. Polit Geogr 26: 695-715

Herweg K (1996) Field manual for assessment of current erosion damage. Soil Conservation Research Programme (SCRP), Ethiopia and Centre for Development and Environment (CDE), University of Berne, Switzerland

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

Herweg K, Stillhardt B (1999) The variability of soil erosion in the highlands of Ethiopia and Eritrea: average and extreme erosion patterns. Soil Conservation Research Report 33, University of Bern, Switzerland

Higgitt DL (1995) The development and application of caesium-137 measurement in erosion investigations. In: Forster IDL, Gurnell AMB, Webb BW (eds) Sediment and water quality in river catchments, Wiley: Chichester, p 287-305

Hillel D (1971) Soil and water: Physical principles and processes. Academic Press, New York.

Holden S, Shiferaw B, Pender J (2005) Policy analysis for sustainable land management and food security in Ethiopia-a bioeconomic model with market imperfections. Research Report 140, International Food Policy Research Institute, Washington DC

Holmes TP (1988) The offsite impact of soil erosion on the water treatment industry. Land Econ 64: 356-366

Huffnagel HP (1961) Agriculture in Ethiopia. FAO, Rome

Hunting (1974) Central Tigre development study. Working Paper 1, Soils and Land Classification. Hemel Hempstead, Hunting Technical Services

Hurni H (1983). Soil formation rates in Ethiopia. Working Paper 2, Ethiopian Highlands Reclamation Studies, Addis Ababa

Hurni H (1985) Erosion - productivity - conservation systems in Ethiopia. In: Sentis IP (ed) Soil conservation and productivity, Proceedings 4th international conference on soil conservation, Maracay, Venezuela p 654-674

Hurni H (1986) Guidelines for development agents on soil conservation in Ethiopia. Soil Conservation Research Project, Community Forests and Soil Conservation Development Department, Ministry of Agriculture, Addis Ababa, Ethiopia

Hurni H (1990) Degradation and conservation of soil resources in the Ethiopian highlands. Mt Res Dev 8: 123-130

Hurni H, Perich I (1992) Towards a Tigray regional environmental and economic strategy (TREES): a contribution to the symposium on combating environmental degradation in Tigray, Ethiopia. Group for Development and Environment, Institute of Geography, University Bern, Switzerland

Hurni H (1993) Land degradation, famine, and land resource scenarios in Ethiopia. In: Pimentel D (ed) World soil erosion and conservation, Cambridge Univ. Press, p 27-62

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

Jijo TE (2005) Land preparation methods and soil quality of a vertisol area in the Central Highlands of Ethiopia. PhD Thesis, Universität Hohenheim

Jones J, Jr B, Eck HV (1973) Plant analysis as an aid in fertilizing corn and grain sorghum. In: Walsh LM, Beaton JD (eds) Soil testing and plant analysis and revised, SSSA, Madison, WI, p 349-364

Kandel DD, Western AW, Grayson RB, Turral HN (2004) Process parameterization and temporal scaling in surface runoff and erosion modelling. Hydrol Process 18: 1423-1446

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1997) Soil quality: a concept, definition, and framework for evaluation. Soil Sci Soc Am J 61: 4-10

Karlen DL, Gardner JC, Rosek MJ (1998) A soil quality framework for evaluating the impact of CRP. J Prod Agric 11: 56-60

Karlen DL, Andrews SS, Doran JW (2001) Soil quality: current concepts and applications. Adv Agron 74: 1-40

Karlen DL (2004) Soil quality as an indicator of sustainable tillage practices. Soil Till Res 78: 129-130

Katyal JC, Vlek PLG (2000) Desertification-concept, causes and amelioration, ZEF Discussion Papers on Development Policy 33, Center for Development Research, Bonn, Germany

Kebede A, Kederalah I, Mesfin S (1996) The flexibility of indigenous soil and water conservation techniques: a case study of the Harerge highlands, Ethiopia. In: Reij C, Scoons I, Toulmin C (eds) Sustaining the soil- indigenous soil and water conservation in Africa, Earthscan Publishers, London, p 156-162

Kebrom T (1999) Land degradation problems and their implications for food shortage in south Welo, Ethiopia. J Environ Manage 23: 419-427

Kerry R, Oliver MA (2007) Comparing sampling needs for variograms of soil properties computed by the method of moments and residual maximum likelihood. Geoderma 140: 383-396.

Kim SM, Brian L Benham BL, Brannan KM, Zeckoski RW, Doherty J (2007) Comparison of hydrologic calibration of HSPF using automatic and manual methods. Water Resour Res vol. 43, W01402, doi:10.1029/2006WR004883

Kleijnen JPC (2005) An overview of the design and analysis of simulation experiments for sensitivity analysis. Eur J Oper Res 164: 287-300

Kosmas C, Gerontidis S, Marathianou M (2000) The effect of land use change on soils and vegetation over various lithological formations on Lesvos (Greece). Catena 40: 51-68

Kravchenko AN (2003) Influence of spatial structure on accuracy of interpolation methods. Soil Sci Soc Am J 67: 1564-1571

Kreznor WR, Olson KR, Banwart WL, Johnson DL (1989) Soil, landscape, and erosion relationships in a northwest Illinois watershed. Soil Sci Soc Am J 53: 1763-1771

Krogvang B (1990) Sediment associated phosphorus transport from two intensively farmed catchments areas. In: Boardman J, Foster ILD, Dearing JA (eds) Soil erosion on agricultural land, John Wiley and Sons: Chichester, p 313-330

Krowntree KM, Fox RC (2008) Active learning for understanding land degradation: African catchment game and risk map. Geogr Res 46: 39-50

Kruse JS (2007) Framework for sustainable soil management-Literature review and synthesis. Soil Water Conserv Soc spec. pub. Ankeny, USA. http://www.swcs.org/documents/filelibrary/BeyondTliteraturereview.pdf. Cited 22 Oct 2010

Lal R, Elliot W (1994) Erodibility and erosivity. In: Lal R (ed) Soil erosion research and methods, 2nd edition. Soil Water Conserv Soc and St. Lucie Press, Ankeny, USA, p 181-208

Lal R (1995) Erosion-crop productivity relationship for soils in Africa. Soil Sci Soc Am J 59: 661-667

Lal R (1998) Soil quality and sustainability. In: Lal R, Blum WH, Valentine C, Stewart BA (eds) Methods for assessment of soil degradation, Boca Raton, FL: CRC Press, p 17-30

Lal R (1999) Erosion impact on soil quality in the tropics. In Lal R (ed) Soil quality and soil erosion, Boca Raton, FL, CRC press, p 285-317

Lal R, Hassan HM, Dumanski J (1999) Desertification control to sequester carbon and mitigate the greenhouse effect. In: Rosenberg N, Izaurralde RC, Malone EL (eds) Carbon sequestration in soils: Science, monitoring and beyond, Columbus, USA, Malone Battelle Press, p 83-149

Lal R (2001) Soil degradation by erosion. Land Degrad Dev 12: 519-539

Landon JR (1991) A booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Booker Tate, Thame, Oxon, UK

Larson WE, Pierce FJ (1991) Conservation and enhancement of soil quality. In: Dumanski J, Pushparajah E, Latham M, Myers R (eds) Evaluation for sustainable land management in the developing world, Proceedings of the international workshop, Chiang Rai, Thailand, September 1991. Technical Paper, vol 2. International Board for Soil Research and Management, Bangkok, Thailand, p 175-203

Larson WE, Pierce FJ (1994) The dynamics of soil quality as a measure of sustainable management. In: Doran JW, Coleman DG, Bezddick DF, Stewart BA. (eds) Defining soil quality for sustainable environment, SSSA Special Pub. 35. SSSA, Madison, WI, p 37-52

Lenhart T, Eckhardt K, Fohrer N, Frede HG (2002) Comparison of two different approaches of sensitivity analysis. Phys Chem Earth 27: 645-654

Lenhart T, Rompaey AV, Steegen A, Fohrer N, Frede H, Govers G (2005) Considering spatial distribution and deposition of sediment in lumped and semi-distributed models. Hydrol Process 19: 785–794

Letey J (1985) Relationship between soil physical properties and crop production. Adv Soil Sci 1: 277-294

Li Z, O'Neill AL, Lacey S (1996) Modelling approaches to the prediction of soil erosion in catchments. Environ Softw 11: 123-133

Lim KJ, Sagong M, Engel BA, Tang Z, Choi J, Kim K, (2005) GIS-based sediment assessment tool. Catena 64: 61-80

Liu TL, Juang KW, LEE DY (2006) Interpolating soil properties using kriging combined with categorical information of soil maps. Soil Sci Soc Am J 70: 1200-1209

Lu D, Li G, Valladares GS, Batistella M (2004) Mapping soil erosion risk in Rondoˆnia, Brazilian Amazonia: using RUSLE, remote sensing and GIS. Land Degrad Dev 15: 499–512

Machado MJ, Perez-Gonzalez A, Benito G (1996) Assessment of soil erosion using a predictive model. In: Feoli E (ed) Rehabilitation of degrading and degraded areas of Tigray, northern Ethiopia, University of Trieste, Trieste, p 237-248

Macharia PN, Ng'ang'a LW (2005) Integrating indigenous soil and land classification systems in the identification of soil management constraints in the tropics: a Kenya case study. Trop Subtrop Agroecosyst 5: 67-73

Maidment DR (1996) GIS and hydrologic modelling- an assessment of progress, Plenary Speech at the 3rd international conference on GIS and environmental modelling, Santa Fe, New Mexico, 23 January 1996

Mairura FS, Mugendi DN, Mwanje JI, Ramisch JJ, Mbugua PK, Chianu JN (2007) Integrating scientific and farmers' evaluation of soil quality indicators in Central Kenya. Geoderma 139: 134-143

Mairura FS, Mugendi DN, Mwanje JI, Ramisch JJ, Mbugua PK, Chianu JN (2008) Scientific evaluation of smallholder land use knowledge in Central Kenya. Land Degrad Dev 19: 77-90

Martz LW, Garbrecht J (1992) Numerical definition of drainage network and sub-catchment areas from digital elevation models. Comput Geosci 18: 747-761

Masto RE, Chhonkar PK, Singh D, Patra AK (2007) Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. Agric Ecosyst Environ 118: 130-142.

Mati BM, Morgan RPC, Gichuki FN, Quinton JN, Brewer TR, Liniger HP (2000) Assessment of erosion hazard with the USLE and GIS: a case study of the upper Ewaso Ng'iro north basin of Kenya. Int J Appl Earth Obs 2:1-9

Maune DF (2001) Digital elevation model technologies and applications: The DEM users manual. Bethesda: American Society of Photogrammetry and Remote Sensing Publication

McCann J (1995) People of the plow: An agricultural history of Ethiopia, 1800-1900. University of Wiconsin press, Madison, USA

McCormick S, Jordan C, Bailey JS. (2009) Within and between-field spatial variation in soil phosphorus in permanent grassland. Precis Agric 10: 262-276

Merritt WS, Letcher RA, Jakemna AJ (2003) A review of erosion and sediment transport models. Environ Modell Softw 18: 761-799

Miller MP, Singer MJ, Nielsen DR (1988) Spatial variability of wheat yield and soil properties on complex hills. Soil Sci Soc Am J 52: 1133-1141

Ministry of Natural Resources Development and Environmental Protection (MoNRDEP) (1990) Soil analysis laboratory manual. Soil Laboratory, MoNRDEP, Addis Ababa, Ethiopia

Ministry of Water Resources (MWR) (2002) Assessment and monitoring of erosion and sedimentation problems in Ethiopia. Final Report, RODECO Consulting, GmbH. Hydrology Studies Department, Addis Ababa, Ethiopia

Mishra SK, Singh VP (2003) Soil sonservation service curve number (SCS-CN) methodology. Kluwer Academic Publishers, Dordrecht, The Netherlands

Mitasova H, Mitas L, Brown WM, Johnston DM (1999) Terrain modelling and soil erosion simulations for Fort Hood and Fort Polk test areas. Geographic Modelling and Systems Laboratory, Annual report, University of Illinois at Urbana-Champaign, Urbana, Illions

Mitasova H, Mitas L, Brown M (2001) Multiscale simulation of land use impact on soil erosion and deposition patterns. In: Stott DE, Montar RH, Steinhardt GC (eds) Sustaining the global farm, Selected papers from the 10th international soil conservation organization meeting, Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, 24-29 May 1999

Moges A, Holden NM (2007) Farmers' perceptions of soil erosion and soil fertility Loss in southern Ethiopia. Land Degrad Dev 18: 543-554

Moore ID, Grayson RB, Ladson AR (1991) Digital terrain modelling: a review of hydrological, geomorphological & biological applications. Hydrol Process 5: 3-30

Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME (1998) The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. Earth Surf Proc Land 23: 527-544

Morgan RPC (2005) Soil Erosion and Conservation, 3rd edition. Blackwell: Malden

Moseley WG (2001) African evidence on the relation of poverty, time preference and the environment. Ecol Econ 38: 317-326

Mostert E (2003) The challenge of public participation. Water Policy 5: 179-197

Mueller TG, Hartsock NJ, Stombaugh TS, Shearer SA, Cornelius PL, Barnhise RI (2003). Soil electrical conductivity map variability in limestone soil overlain by loess. J Agron 95: 496-507

Murage WE, Karanja KN, Smithson CP, Woomer PL (2000) Diagnostic indicators of soil quality in productive and non-productive smallholder's fields of Kenya's Central Highlands. Agric Ecosyst Environ 79: 1-8

Murphy JM, Sexton DMH, Barnett DN, Jones GS, Webb MJ, Collins M, Stainforth DA (2004) Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature 430: 768-72

Mutua BM, Klik A, Loiskandl W (2006) Modelling soil erosion and sediment yield at a catchment scale: the case of Masinga catchment. Land Degrad Dev 17: 557-570

Nash J, Sutcliffe J (1970) River flow forecasting through conceptual models part 1- a discussion of principles. J Hydrol 10: 282-290

National Research Council (NRC) (1993) Soil and water quality: an agenda for agriculture. National Academy Press, Washington, DC

Ndomba PM, Mtalo F, Killingtveit A (2005) The suitability of SWAT model in sediment yield modelling for ungauged catchments. A case of Simiyu subcatchment, Tanzania. In: Proceedings of the 3rd international SWAT conference, EAWAG-Zurich, Switzerland, 11-15 July 2005, p 61-69

Neef A (2005) Participatory approaches for sustainable land use in Southeast Asia. White Lotus Co., Ltd, Thailand

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2005) Soil and water assessment tool, theoretical documentation: Version 2005. Temple, TX. USDA Agricultural Research Service and Texas A & M Blackland Research Center

Netherlands Engineering Consultants, NEDECO (1998) Tekeze river basin integrated master plan development project. Natural Resource, Soils and Terrain, vol xiv, Addis Ababa, Ethiopia

Nielsen MN, Winding A (2002) Microorganisms as indicators of soil health. NERI Technical Report No. 388, National Environmental Research Institute, Denmark

Nyssen J (2001) Erosion processes and soil conservation in a tropical mountain catchment under threat of anthropogenic desertification- a case study from northern Ethiopia. PhD Thesis, Katholieke University Leuven

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

Nyssen J, Poesen J, Deckers J (2009) Land degradation and soil and water conservation in Tropical highlands. Soil Till Res 103: 197-202

Nyssen J, Clymans W, Descheemaeker K, Poesen J, Vandecasteele I, Vanmaercke M, Amanuel Z, Van Camp M, Mitiku H, Nigussie H, Moeyersons J, Martens K, Tesfamichael G, Jozef D, Walraevens K (2010) Impact of soil and water conservation measures on catchment hydrological response- a case in north Ethiopia. Hydrol Process 24: 1880-1895

Okoba BO, Tenge AJM, Sterk G, Stroosnijder L (2007) Participatory soil and water conservation planning using an erosion mapping tool in the central highlands of Kenya. Land Degrad Dev 18: 303–319

Oldeman LR, Hakkeling RTA, Sombroek WG (1991) World map of the status of human-induced soil degradation. An explanatory note. ISRIC: Wageningen

Oldeman LR (1994) The global extent of soil degradation. In: Greenland DJ, Szabolcs I (eds) Soil resilience and sustainable land use. Wallingford: CABI, p 99-118

Olsen RA, Engelstad OP (1972) Soil phosphorus and sulfur. In: Soils of the humid tropics. National Academy of Sciences, Washington DC, p 82-101

Osunade AMA (1988) Soil suitability classification by small farmers. Prof Geogr 40: 194-201

Ott L (1977) An introduction to statistical methods and data analysis. Duxbury Press, Belmont, CA

Pagiola S (1992) Estimating the yield effect of soil degradation. J Soil Water Conserv 47: 486-490

Palis RG, Ueno Y, Reyes ER, Rojales JB (1994) Soil and nutrient loss from small catchment under various land uses in the Ultisol. In: Bhusan LS, Abrol IP, Ramamohan Rao MS (eds) Soil and water conservation challenges and opportunities, 8$^{th}$ ISCO conference, New delhi, India, pp 1450-1457

Parfitt JMB, Timm LC, Pauletto EA, Sousa RO, Castilhos DD, de Ávila CL, Reckziegel NL (2009) Spatial variability of the chemical, physical and biological properties in lowland cultivated with irrigated rice. R Bras Ci Solo 33: 819-830

Parr JF, Papendick RI (1997) Soil quality- relationships and strategies for sustainable dryland farming systems. Ann Arid Zone 36: 181-191

Patel M, Kok K, Rothman DS (2007) Participatory scenario construction in land use analysis: an insight into the experiences created by stakeholder involvement in the northern Mediterranean. Land Use Policy 24: 546-561

Pawluk RR, Sandor AJ, Tabor JA (1992) The role of indigenous soil knowledge in agricultural development. J Soil Water Conserv 47: 298-302

Paytona RW, Barra JJF, Martinb A, Sillitoec P, Deckersd JF, Gowinga JW, Hatibue N, Naseemf SB, Tenywag M, Zuberih MI (2003) Contrasting approaches to integrating indigenous knowledge about soils and scientific soil survey in East Africa and Bangladesh. Geoderma 111: 355-386

Pierce FJ, Lal R (1994) Monitoring the impact of soil erosion on crop productivity. In: Lal R (ed) Soil erosion research methods, 2nd ed. Soil Water Conserv Soc, p 235-263

Pimentel DC, Harvey P, Resosudarmo K, Sinclair D, Kurz M, McNair S, Crist L, Shpritz L, Fitton R, Saffouri, Blair R (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 267: 1117-1123

Poesen J (1984) The influence of slope angle on infiltration rate and Hortonian overland flow volume. Z Geomorphology 49: 117-131

Pretty JN (1995) Participatory learning for sustainable agriculture. World Dev 23: 1247-1263

Pretty JN, Brett C, Gee D, Hine RE, Mason CF, Morison JIL, Raven H, Rayment MD, Van Der Bijl G (2000) An assessment of the total external costs of UK agriculture. Agric Syst 65: 113-136

Quinn PF, Beven KJ, Chevallier P, Planchon O (1991)The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. Hydrol Process 5: 59-80

Rallison RE, Miller N (1981) Past, present, and future SCS runoff Procedure. In: Singh VP (ed) Rainfall-runoff relationship. Proceedings of the international symposium on rainfall-runoff modelling, Water Resources Publications, Mississippi, USA, p 353-364

Ramisch JJ (2004) Understanding soil fertility in its social context: integrating social and natural science research within AFNET. In: Bationo A (ed) Managing nutrient cycles to sustain soil fertility in Sub-Saharan Africa. ASP, Nairobi, p 501-522

Reed MS, Dougill AJ, Taylor MJ (2007) Integrating local and scientific knowledge for adaptation to land degradation: Kalahari rangeland management options. Land Degrad Dev 18: 249-268

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agricultural Handbook No. 703, US Department of Agriculture, Washington, DC

Richardson LM (2000) Errors in digital elevation models derived from airborne geophysical survey data. Australian Geological Survey Organisation, Canberra City, ACT, http://www.ga.gov.au/image_cache/GA2080.pdf. Cited 27 July 2011

Röling N (2002) Beyond the aggregation of individual preferences-moving from multiple to distributed cognition in resource dilemma. In: Leeuwis C, Pyburn R (eds) Wheelbarrows full of frogs, Royal Van Gorcum, Assen, p 25-47

Romero CC (2005) A multi-scale approach for erosion assessment in the Andes. Pub. PhD Dissertation, Tropical Resource Management Papers, no. 61, Wageningen, The Netherlands

Romig DE, Garlynd MJ, Harris RF, McSweeney K (1995) How farmers assess soil health and quality. Journal Soil Water Conserv 50: 229-236

Ryan J (1998) Changes in organic carbon in long-term rotation and tillage trials in northern Syria. In: Lal R, Kimble JM, Follett RF, Stewart BA (eds) Management of carbon sequestration in soil. CRS, Boca Raton, p 285-296

Sabbe WE, Marx DB (1987) Soil sampling: spatial and temporal variability. In: Brown JR(ed) Soil testing: Sampling, correlation, calibration, and interpretation, SSSA, Madison, WI, p 1-14

Saha SK (2004) Water and wind induced soil erosion assessment and monitoring using remote sensing and GIS. Agriculture and Soils Division, Indian Institute of Remote Sensing, Dehra Dun

Saito K, Linquist B, Keobualapha B, Shiraiwa T, Horie T (2006) Farmers' knowledge of soils in relation to cropping practices: a case study of farmers in upland rice based slash-and-burn systems of northern Laos. Geoderma 136: 64-74

Saldana A, Stein A, Zinck JA (1998) Spatial variability of soil properties at different scales within three terraces of the Henare River (Spain). Catena 33: 139-153

Sanchez PA, Palm CA, Buol SW (2003) Fertility capability soil classification: a tool to help assess soil quality in the tropics. In: Sposito G, Zabel A (eds) The assessment of soil quality, Spe. issue, An Int J Soil Sci, 114: 157-186

Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasan R, Hauck LM (2001) Validation of the SWAT model on a large river basin with point and nonpoint sources: J Am Water Resour Assoc 37: 1169-1188

Scherr SJ (1999) Soil degradation: a threat to developing-country food security by 2020? Food, Agriculture, and Environment Discussion Paper 27, International Food Policy Research Institute, Washington, DC

Scherr SJ (2002) Degradation and food security on a local/eco-regional scale. In: Lal R (ed) Encyclopedia of soil science, Marcel Dekker Inc. p 287-291

Schimel DS, Kittel TGF, Knapp AK, Seastedt TR, Parton WJ, Brown VB (1991) Physiological interactions along resource gradients in tallgrass prairie. Ecology 72: 672-684

Scoones I (ed) (2001) Dynamics and diversity. Soil fertility and farming livelihoods in Africa. Case studies from Ethiopia, Mali and Zimbabwe. Earthscan Publications Ltd, London and Sterling VA, p 45-77

Setegn SG, Srinivasan R, Dargahi B, Melesse AM (2009) Spatial delineation of soil erosion vulnerability in the Lake Tana Basin, Ethiopia. Hydrol Process *23:* 3738-3750

Setegn SG, Dargahi B, Srinivasan R, Melesse AM (2010) Modeling of sediment yield from Anjeni-gauged watershed, Ethiopia using SWAT model. J Am Water Resour Assoc 46: 514-526

Seybold CA, Mausbach MJ, Karlen DL, Rogers HH (1998) Quantification of soil quality. In: Lal R, Kimble JM, Follett RF, Stewart BA (eds) Soil processes and the carbon cycle, CRC Press, Washington, DC, p 387-404

Sheikh BA, Soomro GH (2006) Desertification: causes, consequences and remedies. Pak J Agri, Agril Engg, Vet Sc 22: 44-51

Shi ZH, Cai SF, Ding SW, Wang TW, Chow TL (2004) Soil conservation planning at the small watershed level using RUSLE with GIS: a case study in the Three Gorge area of China. Catena 55: 33-48

Shi P, Chen C, Srinivasan R, Zhang X, Cai T, Fang X, Qu S, Chen X, Li Q (2011)

Evaluating the SWAT model for hydrological modeling in the Xixian watershed and a comparison with the XAJ Model. Water Resour Manage 25: 2595-2612

Shukla MK, Lal R, Ebinger M (2006) Determining soil quality indicators by factor analysis. Soil Till Res 87: 194-204

Sikana P (1993) Mismatched models. How farmers and scientists see soils. ILEIA Newsletter l/93, Leusden, Netherlands

Sillitoe P (2000) Let them eat cake. Indigenous knowledge, science and 'the poorest of the poor'. Anthropol Today 16: 3-7

Singer MJ, Ewing SA (2000) Soil quality. In: Sumner ME (ed) Handbook of soil science, Boca Raton, FL: CRC Press. p 271-298

Sivapalan M, Takeuchi K, Franks SW, Gupta VK, Karambiri H, Lakshmi V, Liang X, McDonnell JJ, Mendiondo EM, O'Connell PE, Oki T, Pomeroy JW, Schertzer D, Uhlenbrook S, Zehe E (2003) IAHS decade on predictions in ungauged basins (PUB), 2003-2012: shaping an exciting future for the hydrological sciences. Hydrol Sci J 48: 857-880

Soil Conservation Service (SCS) (1972) National engineering handbook. Section 4. U.S. Department of Agriculture, Washington, DC

Sojka RE, Upchurch DR (1999) Reservations regarding the soil quality concept. Soil Sci Soc Am J 63: 1039-1054

Sonneveld BGJS (2003) Formalizing expert judgments in land degradation assessment:a case study for Ethiopia. Land Degrad Dev 14: 347-361

Sonneveld BGJS, Keyzer MA (2003) Land under pressure: soil conservation concerns and opportunities for Ethiopia. Land Degrad Dev 14: 5-23.

SPSS (2010) Statistical package for social sciences. Release 18.0, SPSS inc

Stave KA (2002) Using system dynamics to improve public participation in environmental decisions. Syst Dynam Rev 18: 139-167

Steiner KG (1998) Using farmers' knowledge of soils in making research results more relevant to field practice: experiences from Rwanda. Agric Ecosyst Environ 69: 191-200

Stone JR, Gilliam JW, Cassel DK, Daniels RB, Nelson LA, Kleiss HJ (1985) Effect of erosion and landscape position on the productivity of piedmont soils. Soil Sci Soc Am J 49: 987-991

Stoorvogel JJ, Smaling EM A (1990) Assessment of soil nutrient depletion in sub-Saharan Africa, 1983-2000. Report 28. DLO Winand Staring Center for Integrated Land, Soil and Water Research, Wageningen, the Netherlands

Sulebak JR (2000) Applications of digital elevation models DYNAMAP white paper. SINTEF Institute of Applied Mathematics, Department of Geographic Information Technology, Oslo

Sutcliffe JP (1993) Economic assessment of land degradation in the Ethiopian highlands: a case study. National Conservation Strategy Secretariat, Ministry of Planning and Economic development, Addis Ababa

Swift MJ (1999) Integrating soils, systems and society: plenary lecture 16th world congress soil science, Montpellier. Nat Resour 35: 12-20

Taddese G (2001) Land degradation: a challenge to Ethiopia. Environ Manage 27: 815-824

Tamene L (2005) Reservoir siltation in the drylands of northern Ethiopia: causes, source areas and management options. pub. PhD Thesis, University Bonn

Tamene L, Park SJ, Dikau R, Vlek PLG (2006a) Reservoir siltation in the semi-arid highlands of northern Ethiopia: sediment yield-catchment area relationship and a semi-quantitative approach for predicting sediment yield. Earth Surf Proc Land 31:1364-1383

Tamene L, Park SJ, Dikau R, Vlek PLG (2006b) Analysis of factors determining sediment yield variability in the highlands of northern Ethiopia. Geomorphology 76: 76-91

Tamene L, Vlek PLG (2007) Assessing the potential of changing land use for reducing soil erosion and sediment yield of catchments: a case study in the highlands of northern Ethiopia. Soil Use Manage 23: 82-91

Tamene L, Vlek PLG (2008) Soil erosion studies in northern Ethiopia. In: Braimoh AK, Vlek PLG (eds) Land use and soil resources, Springer Science 7 Business Media B.V. Dordrecht, The Netherlands p73-100

Tekeste G, Paul DS (1989) Soil and water conservation in Tigray, Ethiopia. Report of a consultancy visit to Tigray, University of Wageningen

Tizale CY (2007) The dynamics of soil degradation and incentives for optimum management in the Central hihglands of Ethiopia. PhD Thesis, University of Pretoria

Triantafilis J, Odeh IOA, McBratney AB (2001) Five geostatistical models to predict soil salinity from electromagnetic induction data across irrigated cotton. Soil Sci Soc Am J 65: 869-878

Tripathi MP, Panda RK, Raghuwanshi NS (2003) Identification and prioritization of critical sub-watersheds for soil conservation management using the SWAT model. Biosyst Eng 85: 365-379

Troeh FR, Hobbs JA, Donahue RL (1991) Soil and water conservation, 2nd ed. Englewood Cliffs (NJ): Prentice Hall

United Nations Development Programme (UNDP) (2002) Technical note on the environment. DCGE. Addis Ababa, Ethiopia

United Nations-Economic and Social Commission for Western Asia (UN-ESCWA) (2007) Promoting regional cooperation in reversing land degradation in the ESCWA region: A Working Paper. Regional Conference on Land Degradation Issues in the Arab Region, Cairo, 30 Oct.-1Nov. 2007, p 36

United Nations Environment Program (UNEP) (1992) Desertification, land degradation (definitions). Desertification Control Bulletin 21, New York

United States Agency for International Development (USAID) (2003) Food security crisis in Ethiopia and Eritrea, USAID Fact Sheet, Washington, DC. http://www.usaid.gov/press/factsheets/2003/fs030108.html. Cited 5 July 2011

Utset A, Lopez T, Diaz M (2000) A comparison of soil maps, kriging and a combined method for spatially prediction bulk density and field capacity of Ferralsols in the Havana-Matanaz Plain. Geoderma 96: 199-213

Valentin C (1998) Towards an improved predictive capability for soil erosion under global change. In: Boardman J, Favis-Mortlock D (eds) Modelling soil erosion by water, vol 55. NATO Series: Ser 1 Global Environmental Change, p 7-16

Vandenberghe V, Van Griensven A, Bauwens W (2001). Sensitivity analysis and calibration of the parameters of ESWAT: application to the river Dender, Water Sci Tech 43:295-301

Verstraeten G, Van Oost K, Van Rompaey A, Poesen J, Govers G (2002) Evaluating an integrated approach to catchment management to reduce soil loss and sediment pollution through modelling. Soil Use Manage 19: 386-394

Viney NR, Sivapalan M (1999) A conceptual model of sediment transport: application to the Avon River Basin in Western Australia. Hydrol Process 13: 727-743

Viney NR, Sivapalan M, Deeley D (2000) A conceptual model of nutrient mobilisation and transport applicable at large catchment scales. J Hydrol 240: 23-44

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

Wainwright J, Parsons AJ, Michaelides K, Powell DM, Brazier RE (2003) Linking short and long term soil erosion modelling. In: Lang A, Hennrich K, Dikau R (eds) Long term hillslope and fluvial system modelling - concepts and case studies from the Rhine river catchment, Lecture Notes in Earth Sciences, Springer Verlag: Berlin, p 37-52

Walling DE, Fang D (2003) Recent trends in the suspended sediment loads of the world's rivers. Global Planet Change 39: 111-126

Wang ZM, Song KS, Zhang B, Liu DW, Li XY, Ren CY, Zhang SM, Luo L, Zhang CH (2009) Spatial variability and affecting factors of soil nutrients in croplands of Northeast China: a case study in Dehui County. Plant Soil Environ 55:110-120

Water and Power Consultancy Services (WAPCOS) (1990) Water resources development master plan for Ethiopia. WAPCOS Ltd, India

Webster R (1985) Quantitative spatial analysis of soil in the field. In: Stewart BA (ed) Advances in soil Sciences, vol 3. Springer, New York, p 1-70

Webster R, Oliver MA (1990) Statistical methods in soil and land resource survey. Oxford University Press, Oxford, UK

Weitz A, Bunte D, Hersemann H (1993) Application of nested sampling technique to determine the scale of variation in soil physical and chemical properties. Catena 20: 207-214

Werner C (1986) Soil conservation experiment in the Anjeni area. Gojam Research Unit (Ethiopia). University of Berne, Switzerland: Soil Conservation Research Project 13

Wheater HS, Jakeman AJ, Beven KJ (1993) Progress and directions in rainfall-runoff modelling. In: Jakeman AJ, Beck MB, McAleer MJ (eds) Modelling change in environmental systems, John Wiley and Sons, Chichester, p 101-132

Whitlow R (1986) Mapping erosion in Zimbabwe: a methodology for rapid survey using aerial photographs. Appl Geogr 6: 149-162

Wilding LP, Drees LR (1983) Spatial variability and pedology. In: Wilding LP, Smeck NE, Hall GF (eds) Pedogenesis and soil taxonomy: concepts and interactions, New York, Elsevier, p 83-116

Williams JR (1975) Sediment-yield prediction with universal equation using runoff energy factor. In: Present and prospective technology for predicting sediment yield and sources, Proceedings of the sediment yield workshop, USDA Sedimentation Lab., Oxford, MS, ARS-S-40, 28-30 Nov 1972, p 244-252

WinklerPrins AMGA (1999) Local soil knowledge: a tool for sustainable land management. Soc Nat Resour 12: 151-161

WinklerPrins AMGA, Sandor JA (2003) Local soil knowledge: insight, application, and challenges. Geoderma 111: 165-170

Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses- a guide to conservation. Agricultural Handbook No. 537. USDA, Washington, DC

World Resources Institute (WRI) (1990) World Resources 1990-1991: A Guide to the global environment. World Resources Institute in collaboration with the United Nations Environment Programme and the United Nations Development Programme. Oxford University Press, New York, Oxford

Xue J, Xia J (2007) Research on runoff sub-model of non-point source pollution model. Water Int 32: 428-438

Zapata F (2003) The use of environmental radionuclides as tracers in soil erosion and sedimentation investigations: recent advances and future developments. Soil Till Res 69: 3-13

Zar JH (1996) Biostatistical analysis. Prentice Hall, New Jersey

Zeleke G (2000) Landscape dynamics and soil erosion process modeling in the North western Ethiopian highlands. African Studies Series A16. Geographica Bernensia, Berne

Zhang WH and Montgomery DR (1994) Digital elevation model grid size, landscape representation and hydrologic simulation. Water Resour Res 30: 1019-1028

Zoebisch MA, DePauw E (2002) Degradation and food security on a global scale. In: Lal R (ed) Encyclopedia of soil science, Marcel Dekker Inc. p 281-286

# 11 APPENDICES

**Appendix 1:** Semi structure questionnaire

1. Do you use the following soil quality indicators to categorize the soils of the arable fields in the study catchment into different soil quality status? Tick in the appropriate column below.

| SQ indicator | Yes (%) | No (%) |
|---|---|---|
| Crop yield | | |
| Top soil thickness | | |
| Crop performance/vigour | | |
| Soil fertility | | |
| Soil erosion | | |
| Soil color | | |
| Fertilizer response of soil | | |
| Moisture holding in dry season | | |
| Weed infestation/ abundance | | |
| Soil compaction | | |
| Soil tilth and Workability | | |
| Earthworm population | | |
| Texture | | |
| Drainage condition | | |

2. Which soil quality indicators from the above table are most frequently used to categorize your soils? List them in the order of their importance from most to least.

____________________________________________________________

____________________________________________________________

3. What soil quality descriptors (local terms) do you commonly use to describe each of the soil quality status as high, medium and low?

____________________________________________________________

____________________________________________________________

4. Could you arrange according to their popularity from the most to the least applicable local terms of SQ indicators in question no. 3?

____________________________________________________________

____________________________________________________________

5. Which soil quality category can describe your farm plot soils?

1. Low soil quality 2. Medium soil quality 3. High soil quality

**Appendix 2:** Annual rainfall (P) and runoff (R) measured data for selected catchments and experimental plots within different catchments in Tigray region, northern Ethiopia (Note: SG, slope gradient; A, area; n, replication; P, rainfall; RC, runoff coefficient; years = duration)

| Location /catchment | ºN | ºE | SG (%) | Elevation (m) | A($km^2$) | n | years | P (mm) | R (mm) | RC (%) | Land use | source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adi Gudum | 13º14` | 39º32` | 3 | 2000-2500 | 9.5 x$10^{-5}$ | 2 | | 422 | 65.3 | 15.5 | cultivation | Gebreegziabher et al. 2009 |
| May Zeg Zeg (before catchment management) | 13º39` | 39º11` | Flat to > 30 | 2100–2650 | 1.65 | | 1 | 629 | 95 | 15 | Cultivated, grazing, exclosure | Nyssen et al. 2010 |
| May Zeg Zeg (after catchment management) | 13º39` | 39º11` | Flat to > 30 | 2100–2650 | 1.65 | | 1 | 629 | 51 | 8.1 | Cultivated, grazing, exclosure | Nyssen et al. 2010 |
| Giba (with out soil conservation) | 13º30` | 39º29` | 2 | 2550 | 2 x$10^{-5}$ | 3 | 4 | 600 | 96-180 | 16-30 | cultivation | Araya and Stroosnijder 2010 |
| Giba (with soil conservation) | 13º30` | 39º29` | 2 | | 2.4 x$10^{-5}$ | 3 | 4 | 600 | 30-45 | 5-9 | cultivation | Araya and Stroosnijder 2010 |
| Maileba | 13º14` | 39º15` | Flat to 470 | 2300-2935 | 17.3 | 8 | 2 | 588 | 188 | 32 | Cultivated | Grimay et al. 2009 |
| | | | | | | 4 | 2 | 588 | 106 | 18 | Grazing | |
| | | | | | | 4 | 2 | 588 | 53 | 9 | Plantation | |
| | | | | | | 3 | 2 | 588 | 47 | 8 | Exclosure | |
| Gum Selasa | 13º15` | 39º32` | Flat to 80 | 2000-2500 | 23.5 | 8 | 2 | 452 | 136 | 30 | cultivated | Grimay et al. 2009 |
| | | | | | | 4 | 2 | | 81 | 18 | Grazing | |
| | | | | | | | | 52 | | | | |
| Hagere Selam | 13º39` | 39º10` | 15-110 | 2650 | 1 x$10^{-5}$ | 28 | 2 | 700 | 12-245 | 1.7-35 | Degraded grazing, young to old exclosure | Descheemaeker et al. 2006 |
| Mean | | | | | | | | 650 | 130 | 20 | | |

**Appendix 3:** Measured sediment, total nitrogen (TN) and Phosphorus (P) at the outlet of the study catchment and other similar areas in Tigray region, northern Ethiopia

| Sediment yield ($t\ ha^{-1}\ Y^{-1}$) | Total nitrogen ($kg\ ha^{-1}\ y^{-1}$) | Mineral Phosphorus ($kg\ ha^{-1}\ y^{-1}$) | Year | source |
|---|---|---|---|---|
| **14.3** | **18** | **0.094** | **2002** | **Haregeweyn et al. (2006)** |
| **18.2** | **21** | **0.099** | **2003** | **Haregeweyn et al. (2006)** |
| **16.1** | **19.5** | **0.097** | **2004** | **Mean of 2002 and 2003** |
| **20.2** | **11.0** | **0.08** | **2006** | **Girmay et al. (2009)** |
| **16.7** | **12.7** | **0.145** | **2007** | **Girmay et al. (2009)** |
| **18.5** | **11.85** | **0.112** | **2008** | **Mean of 2006 and 2007** |
| **19.6** | **17.74** | **0.135** | **2009** | **Author (from the study area)** |

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