HAWASSA UNIVERSITY

ESTIMATION OF SEDIMENT YIELD AND EFFECTIVENESS OF LEVEL STONE BUNDS TO REDUCE SEDIMENT LOSS: IN GUMARA-MAKSEGNIT WATERSHED, NILE BASIN, ETHIOPIA.

M.Sc. Thesis

ATIKILT ABERA ALEMAYEHU

November, 2018

Hawassa, Ethiopia

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A THESIS SUBMITTED TO THE FACULITY OF BIOSYSTEMS AND WATER RESOURCES ENGINEERING

INSTITUTE OF TECHNOLOGY SCHOOL OF GRADUATE STUDIES,

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN SOIL AND WATER CONSERVATION ENGINEERING

MAJOR ADVISOR: ALEMAYEHU MULUNEH (PhD)

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November, 2018

Hawassa, Ethiopia

ADVISOR’S APPROVAL SHEET-I

This is to certify that the thesis entitled “***Estimation of sediment yield and effectiveness of level stone bunds to reduce sediment loss in Gumara-Maksegnit watershed, Nile Basin, Ethiopia***” submitted in partial fulfillment of the requirements for the degree of Master of Science in Bio-system and Water Resource Engineering, with specialization in soil and water conservation engineering, is a record of original research carried out by Atikilt Abera Alemayehu, under my supervision, and no part of thesis has been submitted for any other degree. The assistance and help received during the course of this investigation have been duly acknowledged. Therefore, I recommend that it be accepted as fulfilling the thesis requirements.

Alemayehu Muluneh (PhD) …………………….. …………………

Major Advisor Signature Date

Awdenegest Moges (PhD) …………………….. ……………………..

Co-Advisor Signature Date

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DEDICATION

This thesis manuscript is dedicated to my family who paved the way towards education and nursing me with affection and love in success of my life.

STATEMENT OF THE AUTHOR

First, I declared that this thesis is my original work and all sources of materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for M.Sc. degree in Soil and Water Conservation Engineering at Hawassa University and is deposited at the University Library to be made available to borrowers under the rules of the Library. I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

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ABBREVATIONS AND ACRONYMS

ARARI	Amhara Regional Agricultural Research Institute
C	Crop management factor
DEM	Digital Elevation Model
ERDAS	Earth Resource Development Application System
ETM^+	Enhanced Thematic Mapper Plus
FAO	Food and Agricultural Organization
ICARDA	International Center for Agricultural Research in Dry Areas
K	Soil Erodibilty factor
LS	Slope length and gradient factor
Mg	Mega gram
MUSLE	Modified Universal Soil Loss Equation
NASA	National Aeronautics Space Administration
NSE	Nash-Sutcliffe Efficiency
P	Conservation practice factor
R^2	Coefficient of Determination
RE	Relative Error
RMSE	Root Mean Square Error
RUSLE	Revised Universal Soil Loss Equation
SCRP	Soil Conservation Research Program
SLEMSA	Soil Loss Estimation Model for Southern Africa
SPSS	Statistical Package for the Social Science
SRTM	Shuttle Radar Topography Mission
STDEV	Standard Deviation
UK	United Kingdom
US	United States of America
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WFP	World Food Program

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ABSTRACT

The study was conducted in Gumara-Maksegnit watershed and it's sub-catchments to estimate event-based sediment yield and to evaluate the effectiveness of level stone bunds based on sediment loss reduction. Modified Universal Soil Loss Equation (MUSLE) was used for estimation of sediment yield. The model input parameters were collected from different sources and these are discretized and preprocessed with the help of various suitable software and tools. Finally, all six model factors were combined together using the raster calculator in map algebra to estimate the sediment yields of the study watersheds. The event-based mean observed and model estimated sediment yields were (0.5581, 0.4031 ton ha^{-1}*) for Gumara-Maksegnit watershed, (0.5125, 0.4194 ton* ha^{-1}*) for treated sub-catchment and (1.0694, 1.0150 ton* ha^{-1}*) for untreated sub-catchments respectively. The sediment losses between treated and untreated sub-catchments were highly significantly different when the sediment loss reduced by 58.8% as a result of level stone bund interventions. However, the observed and estimated sediment losses are not significantly different within a watershed. Hence, the model was well performed to estimate sediment yield in the study area with* R^2 *(0.62, 0.72 and 0.7) and NSE (0.53, 0.71 and 0.34) for treated, untreated and Gumara-Maksegnit watershed respectively. Hence, the result showed that the Modified Universal Soil Loss Equation (MUSLE) model was well suited for reliable applications of sediment yield estimation in the study area as well as similar agroecologies.*

Keywords: Runoff factor, Sub-catchments, Soil erosion, Sediment yield, MUSLE

1. INTRODUCTION

1.1 Background

Soil erosion is a widespread land degradation problem in many parts of the world (Arekhi *et al.*, 2011). Globally, more than 50% of pasture lands and about 80% of agricultural land suffers from soil erosion and six million hectares of fertile land is being lost every year due to soil erosion and related factors (Pimentel *et al.*, 1976). The worldwide annual rate of soil erosion from agricultural land ranges from 22 to 100 ton ha^{-1} and declines in the productivity as much as 15-30% annually (Morgan, 2005).

Soil erosion is continuous to be a global constraint to economic development, especially in developing countries, where soil erosion is becoming a limiting factor to increase or even sustaining agricultural production (Arekhi, 2008). Soil erosion is a principal degradation process, resulting in a negative impact on different soil functions and which is the ultimate causes of an irreversible effect on the poorly renewable soil resource (Addis *et al*., 2015).

Land degradation, in the form of soil erosion and nutrient depletion, threatens food security and the sustainability of agricultural production in Sub-Saharan Africa (Menale *et al*., 2007). Soil erosion is one of the major environmental problems in Ethiopia resulting in the reduction of productivity of arable lands through removals of the most productive portion of the soil that is a chemically active part such as organic matter and clay fractions (Woubet *et al.,* 2013; Kebede *et al*., 2011).

At the national level, the overall soil loss from the whole land is estimated about 1.5 billion tons per year (FAO, 1986), with a mean of 42 ton ha^{-1} accompanied with land loss of 25,000 ha yr^{-1} of which 45% initiated from cultivated land. However, the extent and severity of the problems are varied depending on a difference in relief, ecology, rainfall, land use, land cover and soil types. According to Adugnaw (2014), land degradation in Ethiopia is especially severe in the highlands where the average soil loss from farmland is estimated to be 100 ton ha^{-1}yr^{-1}.

The Ethiopian government responded with large-scale rehabilitation measures and the establishment of various soil and water conservation interventions across the country to counteract the ongoing soil erosion and land degradation. In order to extensively address the problem of natural resource degradation, conservation schemes were introduced especially after the occurrence of drought and famine in the 1970s (Tesfa and Sangharsh, 2015). However, the effectiveness of conservation measures was not sufficiently studied based on runoff discharged with a certain amount of sediment and its process results inadequate planning and design of soil and water conservation measures.

Therefore, understanding the state of soil erosion and environmental degradation with its root cause, nature, and consequence, as well as the previous management practice, is critical to look for options to mitigate the problem and its impact (Adugnaw, 2014). The most important consequence of erosion is sediment yield from the watershed, which causes siltation of canals, loss of storage volume in reservoirs, pollution, and flooding (Somnuck *et al*., 2010).

In order to reduce sediment yield and promote proper soil and water conservation and sustainable land use, a quantitative estimate of soil erosion and sediment yield with suitable modeling tools is a key component of land management plans. Therefore, accurately assess and predict soil erosion and sediment transport in the watershed becomes essential in different spatial and temporal scales to implement land use and soil management strategies as well as to protect and preserve technical constructions (Efthimiou *et al*., 2014).

At present, many models with a broad spectrum of concepts, which were classified as spatially lumped, spatially distributed, empirical, regression, semi-distributed eco-hydrological model and factorial scoring models are used for modeling the rainfall-runoff-soil erosion and sediment transport process at different scales.

Among available soil erosion and sediment yield empirical models, the Universal Soil Loss Equation (USLE), the revised version of it (RUSLE) and Modified Universal Soil Loss Equation (MUSLE) are used in hydrology and environmental engineering to predict the amount of potential soil erosion and sediment yield (Mizuyama *et al*., 2010; Arekhi *et al*., 2010). In this study, MUSLE was used to estimate event-based soil erosion and sediment yield in Gumara-Maksegnit watershed and it’s sub-catchments under different land management options.

1.2 Statement of the Problem

Soil erosion is one of the most significant environmental problems in Ethiopian highlands, more specifically in the Amhara Region (Lakew *et al.*, 2000). This is the principal problem, with a soil loss estimated to be eroding at very rapid rates of 16-50 ton $ha^{-1}yr^{-1}$. Likewise, the study watershed is affected by ongoing land degradation due to soil erosion as a result of human interventions, such as deforestation for agricultural food production, the cultivation of marginal lands, overgrazing and the exploitation of soil fertility accelerate soil erosion and subsequent soil depletion is accompanied with reduced crop productivity in Gumara-Maksegnit watershed(Addis *et al*., 2016).

On the other hand, the concurrence of intensive rainfall events at the start of the rainy season when the vegetation peak lags behind the rainfall and intensive cultivation of the soil to produce cereals exposes the soil for extreme erosion in the study area. In order to counteract, the ongoing land degradation as a result of soil erosion, level stone bunds were implemented through community mobilization. However, the effectiveness of conservation measures to reduce soil erosion and sediment transport at the watershed scale were not sufficiently studied.

Furthermore, studies on the impacts of soil and water conservation measures on erosion processes at plot scale were conducted in the study watershed (Rieder *et al*., 2014; Strohmeier *et al*., 2015; Klik *et al*. 2016). However, the plot level study may not able to capture the erosion processes when the result extrapolated at a large scale. Therefore, further assessment of the magnitude and intensity of runoff and sediment yield through modeling helps to provide reliable information for sound soil and water conservation planning.

For the present study, Modified Universal Soil Loss Equation (MUSLE) was used to estimate event-based sediment yield from Gumara Maksegnit watershed and its sub-catchments under different land management options. This model was preferred than others due to its simplicity, requirement of fewer data and direct consideration of runoff which is discharged with a certain amount of sediment.

1.3 Research and Development Efforts in the Study Area

In order to respond the ongoing land degradation as a result of soil erosion in the study area, there were an efforts to conduct multidisciplinary researches such as soil and water management, crop and livestock production, forest management and socio-economic researches. The researches were conducted with a collaboration of Amhara Regional Agricultural Research Institute (ARARI) and International Center for Agricultural Research in Dry Areas (ICARDA) to improve the livelihoods of the society by enhancing food security and alleviating poverty through research and partnerships.

Multidisciplinary researches were conducted in the study area from 2011 to 2016 under the frameworks of ICARDA and ARARI within two project phases. The first phase was "Unlocking the potential of rainfed agriculture in Ethiopia for improving rural livelihoods". The research focuses on baseline data collection and the establishment of the research facility. Under the frameworks of the first project phase, several watershed characteristics were sampled and analyzed to obtain input data for the development of the models and to provide a link between local watershed characteristics and generation of runoff and sediment losses.

Soil and water conservation measures in treated sub-catchment were implemented through community mobilization facilitated by Wereda office of agriculture to study the impacts of conservation interventions on soil erosion and its processes. Measuring structures and monitoring stations were installed in Gumara Maksegnit watershed and its treated and untreated sub-catchments that helps to measure surface runoff and sediment losses used for this study. Whereas, a detailed soil data were obtained from the databases of the first project phase which is used to determine soil erodibility factor for this study.

The second project phase was "Reducing land degradation and farmers' vulnerability to climate change in the highland dry areas of north-western Ethiopia". Overall, the project was given more emphasis for soil and water management issues and a number of studies were conducted in the study area more specifically, assessment of soil erosion and its processes at watershed scale (Klik *et al.*, 2015*;* Addis *et al*., 2016; Nigus *et al*., 2017) and the studies conducted at the plot level (Rieder *et al*., 2014; Strohmeier *et al*., 2015; Klik *et al*. 2016).

1.4 Objectives of the Study

1.4.1 General objective

The main objective of the study was to quantify the sediment yield using Modified Universal Soil Loss Equation (MUSLE) under different land management options with the aim of providing a tool for planning soil conservation and watershed development strategies.

1.4.2 Specific objectives

- To estimate event-based sediment yield in Gumara Maksegnit watershed using Modified Universal Soil Loss Equation (MUSLE) for the period of 2016.
- To assess the effectiveness of level stone bunds based on sediment loss from treated and untreated sub-catchments.
- To assess the sediment yield prediction efficiency of Modified Universal Soil Loss Equation (MUSLE).

1.5 Research Questions

- How much sediment lost in the study watersheds within an individual storm?
- Does the MUSLE model simulate sediment yield well?
- Are level stone bunds effective in reducing sediment loss?
- What are the most influential model parameters?

1.6 Significance of the Study

Soil erosion modeling is able to provide the information about soil erosion processes that helps effective planning and decision making to implement management interventions, such as watershed-based soil and water conservation and resource management. Watershed-based soil and water conservations are used to reduce the loss of the upper most fertile soil that supports crop production and downstream sedimentation problems more specifically Lake Tana.

Therefore, this study was initiated to estimate the amount of soil erosion and sediment yield under different land management options. Indeed, the model output could be influence planners and decision makers of land resource management to design and implement the most effective soil and water conservation interventions. Moreover, this study will be used as a reference for others who want to conduct similar research.

2. LITERATURE REVIEW

2.1 Soil Erosion Extent in the World

Soil erosion is the movement of soil from its origin mainly by water and wind and which is continuous to be a global constraint to economic development, especially in developing countries, where soil erosion is becoming a limiting factor to increase or even sustaining agricultural production (Arekhi, 2008). According to Morgan (2005), 38% of the world's agricultural land is degraded while in Africa and Central America, the share of degraded land in the total agricultural land is as high as 65 and 74% respectively.

The rate of soil erosion has dramatically increased during recent decades and globally has been reported as, 0.5, 0.75, 1 and 2.2 * 10^9 ton in 1951, 1961, 1971 and 1993 respectively (Sadeghi *et al*., 2013). Consequently, 65% of the soil in sub-Saharan Africa is said to have undergone degradation (Tadesse and Abebe, 2014). Soil erosion costs the US economy estimated at $30 billion-$44 billion, £90 million in the UK and $400 million in Indonesia (Morgan, 2005), and close to 1 billion birr for Ethiopia annually (Habtamu and Amare, 2016). These costs resulted from both on-site and off-site effects of soil erosion in order to reduce its negative impacts.

Nowadays, the adverse impact of widespread soil erosion has long been recognized as severe problems for human sustainability. In order to counteract soil erosion and land degradation, there were a lot of efforts for the last decades around the world through formulation and application of scientific methods that help to mitigate the problem and its impact (Adugnaw, 2014). Therefore, a better understanding of the global situation requires more information on the status of the earth's land resource and how fast soil is being lost by erosion (Morgan, 2005).

In recent decades, models have been built in order to represent and quantify the process of detachment, transport and deposition of eroded soil, with the aim of implementing assessment tools for educational, planning and legislative purpose (Lida *et al*., 2012). The needs to accurately assess and predict soil erosion and sediment transport in watersheds become essential in different temporal and spatial scales to implement land use soil management strategies as well as to protect and preserve technical constructions.

2.2 Soil Erosion in Ethiopia

Soil erosion is one of the most important environmental problems that pose serious challenges to food security and future development prospects of the country (Alemayehu, 2012). In Ethiopia, the overall soil loss from the whole land is estimated about 1.5 billion tons per year (FAO, 1986), with a mean of 42 ton $ha^{-1}yr^{-1}$ accompanied with land loss of 25,000 ha $yr.^{-1}$, of which 45% initiated from cultivated land.

According to Hurni *et al*., (2010), the long-term analysis soil erosion from SCRP stations showed that the amount of soil loss on cultivated lands ranges from a 1 ton $ha^{-1}yr^{-1}$ to more than 300 ton $ha^{-1}yr^{-1}$ and an average of approximately 40 ton $ha^{-1}yr^{-1}$ of soil loss was measured on cultivated land through plot experiment. Nationwide, the annual rate of soil loss (over 1.5 billion tons) is much higher than the rate of soil formation in annual basis with estimated cost close to one billion Ethiopian birr each year (Habtamu and Amare, 2016).

On the other hand, soil erosion is widely perceived to be a major problem, particularly in the highlands of Ethiopia, which is considered as a direct result of past agricultural practice in the highlands due to dissected terrain, intense rainfall and growing human and animal population that leads to accelerated erosion (Badege, 2009). Increased pressure on the land use of the hill slopes since the 1970s has resulted in degradation in the highlands of Ethiopia where agriculture is based on small-scale cereal production (Gizaw *et al*., 2009). Soil loss in the highlands of Ethiopia was estimated about 200–300 ton $ha^{-1}yr^{-1}$ (Habtamu and Amare, 2016; Tadesse and Abebe, 2014).

The effects of erosion on soil fertility, land degradation, agricultural productivity, environmental ecology and hydrological systems have been recognized as severe problems in every corner of the country (Tadesse and Abebe, 2014). The on-site effects are particularly important on agricultural land where the redistribution of soil within a field, the loss of soil from a field, deterioration of soil structure, decline in organic matter and nutrient, soil crusting, reducing infiltration and moisture holding capacity resulting in drought-prone conditions (Morgan, 2005). The off-site effects of erosion, such as reservoir sedimentation and water resource pollution are usually more costly and severe than on-site effects on land resources (Gebreyesus and Kirubel, 2009).

In response, Ethiopian governments and development agencies have invested substantial resources in order to extensively address the problem of natural resource degradation and to introduce conservation programs especially after the occurrence of drought and famines in the 1970s (Hurni *et al*., 2010). Starting from the 1970s and onward, huge areas have been taken under soil and water conservation activities, and millions of indigenous tree species were planted through community participation paid labors (Tesfa and Sangharsh, 2015). One of the underline principles of watershed management is the recognition of the interrelationships among land use, soil and water and the linkage between upland and downstream areas (Guangyu *et al*., 2016).

Hence, soil and water conservation measures have been implemented to alleviate both problems of erosion and drought. However, so far, little or no sufficient documented information has been available on the contribution of the different soil and water conservation measures implemented for soil loss reduction.

2.3 Measurement of Soil Erosion

Research on soil erosion and its effect on agricultural productivity started in the USA in the 1930s (Alemayehu, 2012). During 1940 and 1956, scientists began to develop a quantitative procedure for estimating soil loss. On the other hand research on the process of land use change, land degradation and sustainable land management were initiated since 1981 in Ethiopian highland by Soil Conservation Research Program (SCRP) in conjunction with the countrywide soil conservation Campaign (Hurni *et al*., 2010).

Very few estimates are available about the overall soil loss rates at regional and national scale. FAO (1986) estimated of gross annual soil loss at national level ranges 1.9×10^{9} ton of which 80% originates from cropland. Whereas, Hurni (1988) estimated a nationwide annual gross soil loss of 1.5×10^{9} ton through extrapolating data obtain from six SCRP research stations in which the highest loss is from croplands (42 ton $ha^{-1}yr^{-1}$).

According to Hurni *et al*., (2010), the long-term measurement and analysis from Soil Conservation Research Program (SCRP) stations showed that the amount of soil loss on cultivated land ranges from 1 ton $ha^{-1}yr^{-1}$to more than 300 ton $ha^{-1}yr^{-1}$and average soil loss measured on cropland ranges approximately 40 ton $ha^{-1}yr^{-1}$.

On the other hand, sediment yield analysis made at the regional scale, relying heavily on soil loss rates measured at plot scales that could lead to wrong conclusions because of the strong dependence of erosion process rates on the spatial scale with ignorance of gully erosion. Soil erosion can be measured either directly from runoff plot and gauging stations of watershed or estimated using models.

2.3.1 Field measurement of soil erosion

Field measurements of soil erosion are carried out at permanent research or experimental stations based on bounded runoff plots with a known area, slope gradient, slope length and soil type from which both runoff and soil loss are monitored. By using the data obtained from the field experiment, it is possible to estimate the average soil loss using different empirical models. On the other hand, the soil loss also measured at a specific monitoring point of river mouth through determination of sediment concentration of runoff.

However, direct measurement of soil loss is costly, labor-intensive and time-consuming and the variability in data caused by experimental errors can result in wrong conclusion and recommendations and that requires careful analysis when extrapolation of results from the field experiment to large scale. Modeling soil erosion simplifies the problems of direct measurement as a model is a representation of processes and their interactions with the aim of extracting, evaluating and simulating the relevant processes (Alemayehu, 2012).

2.3.2 Sediment yield estimation using models

Methods for estimating sediment yield were first developed for the analysis of the effect of agricultural practices using empirical models to evaluate soil erosion and sediment yield in the watershed without statistical data and information is inevitable (Lida *et al*., 2012). Since it is not possible to monitor the influence of every land-use practices in all ecosystems under all weather conditions, erosion predictions are used to rank alternative practices with regard to their likely impact on erosion (Rabin and Dushmanta, 2005).

Erosion prediction models can be used as predictive tools for soil loss assessment and inventories, conservation and project planning, decision making and policy development. Moreover, the models can be used as tools for understanding erosion processes and their impact (Habtamu *et al*., 2013). According to Renard (1997), soil loss equations were developed to enable conservation planners, environmental scientists and other concerned with soil erosion to extrapolate limited erosion data to the many localities and conditions that have not been directly in the research. Erosion prediction models are basically categorized into three types namely, empirical, conceptual and physical based (Rabin and Dushmanta, 2005; Habtamu *et al*., 2013; Umesh *et al*., 2002; Morgan, 2005).

Empirically based models tend to require fewer data and are easier to apply, particularly over large areas. However, the models suffer from a lack of specificity and do not incorporate mechanism. Despite this, the results of empirical models can be reasonably accurate and reflect the underlying processes generating the erosion and sediment yield without modeling for the actual processes.

Physically based models attempt to capture the physics of the system and if specified properly can be used to provide significant insight into the behavior of the system of interest. However, these models may be so complex that it is difficult to determine how to translate management practices into specific changes in the model parameter values or physical processes simulated by the mathematics in the model.

Based on the temporal and spatial scales of application, erosion models can be classified as Black-box, Grey-box and White-box. Black box models are primarily based on an observation and are usually statistical in nature. Whereas, the Grey box models are used, when some details of how the system works are known and the white box models are intended to represent the essential mechanisms and processes controlling erosion.

Estimation of soil erosion or its consequences, such as sediment yield can be realized by applying appropriate models. Empirical models have been and are still used in hydrology and environmental engineering for computing the amount of potential soil erosion and sediment yield (Ashish *et al.,* 2009). The most widely used empirical soil erosion models include, Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), Modified Universal Soil Loss Equation (MUSLE) and Soil Loss Estimation Model for Southern Africa (SLEMSA).

The USLE was originally applied to predict soil losses from agricultural land in the USA, in order to preserve soil resources, but has been extended for use in numerous countries (Sadeghi *et al*., 2013). Wischmeier (1978), was suggested that simple empirical models like Universal Soil Loss Equation (USLE) rather than complex model seems better for the tropics. Due to its dependence on easily available soil, topographic and vegetation data USLE has emerged as the most commonly used soil loss estimating model. Even though USLE is adequate to represent the first order effects of the factors that affect sheet and rill erosion, the model does not estimate deposition and sediment yield as a result of ephemeral gully erosions.

One problem with USLE and RUSLE models is that there is no direct consideration of runoff, that sediments being discharged with the flow, which varies with runoff and sediment concentration (Kinnell, 2005; Mizuyama *et al*., 2010; Arekhi *et al*., 2010). Storm event factor used by USLE often fails to account for the effective rainfall that generates surface runoff and sediment delivery ratio that varies with storms and adds other sources of errors to estimate sediment loss.

Predicted gross soil loss using USLE needs to be multiplied by a sediment delivery ratio to give sediment yield estimates. However, sediment delivery ratios for determining sediment yields from soil loss predictions suffer from uncertainty due to considerable variations in rainfall distributions with time (Arekhi, 2008). Whereas, RUSLE is the revised version of universal soil loss equation, intended to provide more accurate estimates of erosion through revision of equations to obtain erosion factor values. It can be applied to any land use where the soil material is exposed to raindrop impact and overland flow that generated by rainfall intensity exceeding infiltration rate (Renard *et al*., 1994).

RUSLE2 is a user-friendly computer program and a set of mathematical equations that able to predict long-term average annual erosion by water. The RUSLE2 program makes the prediction of soil erosion easy and it maintains the same basic six-factor structure as the original USLE. However, all of the algorithms used to derive the factors have been modified and enhanced to account for a variety of field conditions. The major fundamental difference between USLE, RUSLE1 and RUSLE2 is in the method used to solve governing equations (Renard *et al*., 1997). Accordingly, RUSLE2 uses a much more detailed and proper mathematical approach to integrate the underlying governing equations, which makes RUSLE2 more powerful and accurate for many conditions than either the USLE or RUSLE1.

Due to uncertainty in delivery ratio and the inability of USLE and RUSLE models to give direct sediment yield estimates, modified universal soil loss equation was proposed by Williams and Berndt (1977), Which has been generally used to predict sediment yields on a single storm base. An improved erosivity factor was therefore introduced by Williams (1975) and Foster *et al*. (1977) into account the runoff shear stress effect in terms of the product of runoff volume and peak discharge on soil detachment for single storms (Mizuyama *et al*., 2010; Sadeghi *et al*., 2013).

The approach of William and Berndt (1977) in developing the modified version of USLE was to drive a sediment yield estimation model based on runoff characteristics as the best single indicator for storm event sediment yield prediction at the watershed outlet and some factors affecting soil erosion. MUSLE increases sediment yield prediction accuracy and eliminates the need for sediment delivery ratio (Arekhi *et al*., 2010).

Presently, only the MUSLE model is applied in storm-wise sediment yield prediction due to lack of adequate data regarding rainfall, channel geometry and hydraulics of entire stream systems. In this case, the MUSLE model optimizes hydrologic model parameters to estimate sediment yield.

2.4 Modified Universal Soil Loss Equation Model Parameters

2.4.1 Runoff factor (R)

Runoff factor (R) is a major input for MUSLE model which is computed from volume (Q) and peak runoff rate (q_p). The streamflow is determined by converting the water level records based on an experimentally developed water level and discharge rating curves (equation 16, 17 and 18).

To calculate the runoff the flow depth and velocity data are required and the corresponding discharge can be calculated through the integration of channel cross-sectional area (Klik *et al*., 2015). The rating curve is a function of stage plotted against flow discharge to generate the scattered plots that are used to fit a squared polynomial curve. Hence, the fitted function is used as a rating curve, which enables continuous discharge calculation (Klik *et al*., 2015).

Flow channels are the overflow structures that alter the flow and in general, they can be classified as sharp and broad crested flow channels. During the establishment of gauging stations, it is important to consider the suitability of the structures to measure surface runoff. Hence, a broad crested weir with a rectangular control section weir is suitable to calculate the surface runoff through the application of a predefined equation. According to Bos (1989), the simplified equation used to estimate runoff for broad crested weir with a rectangular control section written as,

$$Q = Cd * Cv * \frac{2}{3}(\frac{2}{3}g)^{0.5}Bc * h^{1.50} \ldots\ldots\ldots (1)$$

The weir structures in the sub-catchments make possible an explicit calculation of the discharge based on water level data (Klik *et al*., 2015). The discharge of broad-crested weirs with truncated triangular control sections (Appendix Figure 1) can be calculated using two different equations (Bos, 1989). In this case, two head discharge equations have to be used: one for the conditions where flow is confined within the triangular section (Equation 2, if height of flow (h1) ≤ 1.25 height of triangular section (Hb)) and the second equation (Equation 3, if height of flow (h1) ≥ 1.25 height of triangular section (Hb)) is valid for higher stage/water level and written as,

$$Q = C_d C_v \frac{16}{25}\left[\frac{2}{5}g\right]^{0.5} \tan\frac{\theta}{2} h_1^{2.50} \ldots\ldots\ldots (2)$$

$$Q = C_d C_v \frac{2}{3}\left[\frac{2}{3}g\right]^{0.5} B_c\left(h_1 - 0.5H_b\right)^{1.50} \ldots\ldots\ldots (3)$$

Where, Q is flow rate (m^3/s), C_d is the discharge coefficient, which depends on shape and types of the measuring weir, C_v is the velocity coefficient, g is accelerated gravity (m/s) and Bc is the breadth of the crest (m).

The runoff is obviously discharged with a certain amount of suspended sediment in the stream as a result of soil erosion and transport within the drainage basin area. Continuous sediment concentration and runoff data enabled the sediment yield calculation. The sediment concentration can be determined in conjunction with runoff volume that arrives at a known confluence point of the upper catchment.

2.4.2 Soil erodibility factor (K)

Soil erodibility factor (K) is a measure of the inherent susceptibility of the soil to erosion at a particular site under standard experimental conditions. That implies, some soils erode more readily than others even when all other factors are the same (Wischmeier and Smith, 1978). This difference is caused by the physical and chemical properties of the soil that affects the soil infiltration rate and the extent to which particles can be detached and transported. The most crucial soil variables that control K factor include organic matter content, clay content, bulk density, particle size distribution, shape, size and stability of aggregates, shear strength, porosity and permeability and chemical composition.

Soil texture affects the susceptibility of soil to erosion, while sediments containing more clay area more resistant to erosion than sand or silt, because of their ability of binding soil particles together (Ibrahim, 2008). Whereas, soil containing high levels of organic materials are usually more resistant to erosion because it coagulates soil colloids and creates a more stable soil structure (Humberto *et al*., 2010). According to Hurni (1985) and Hellden (1987), soil erodibility factor value developed for Ethiopian condition by adopting different sources and proposed the K values of the soil based on their color and their value ranges from 0 to 1.

The soil erodibility factor can be calculated via the Universal Soil Loss Equation (USLE) nomograph, applied frequently to estimate soil erosion on the base of other factors obtained from (Wischmeier and Smith, 1978). Accordingly, for soils containing less than 70 percent silt and very fine sand, the USLE nomograph equation solves soil erodibility instead of soil color as follows,

$$\mathrm{K} = \frac{\mathbf{2.1*10^{-4}*}\boldsymbol{M}^{\mathbf{1.14}}\mathbf{(12-}\boldsymbol{a}\mathbf{)+3.25(}\boldsymbol{b}\mathbf{-2)+2.5(}\boldsymbol{c}\mathbf{-3)}}{\mathbf{100}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where M = [(100-C) (L+Armf)] ………………………………………………….... (5)

Where K is expressed in the international system of the unit as, (Mg h MJ^{-1} mm^{-1}), M is particle size parameter, C is % of clay (<0.002 mm), L is % of silt (0.002-0.05 mm) and Armf is % of very fine sand (0.05-0.1 mm). Whereas (a) is organic matter content (%), (b) is the soil structural class code, (c) is the soil permeability class code and they obtained from soil laboratory analysis result.

The structural code (s) was derived from the USLE nomograph (Wischmeier and Smith, 1978), based on the structural shape and size of each soil sample and assigned as (1, 2, 3 and 4) for very fine granular, fine granular, moderate or coarse granular and blocky or platy structural classes respectively. The soil sample textural class can be encoded from a USDA soil textural triangle to determine the permeability class code (p) based on corresponding textural classes.

2.4.3 Topographic factors (LS)

The slope length and gradient factor (LS) is defined as the ratio of soil loss from any slope length and gradient to soil loss from 22.13 m plot with 9% slope and same soil type and other conditions (Arekhi, 2008). The interaction of slope gradient and length has an effect on the magnitude of erosion. As a result of this interaction, the effect of slope gradient and slope length should be considered together (Edward, 1987). However, the soil loss is more sensitive to changes in slope gradient than to changes in slope length. Application of ArcGIS spatial analysis tool is helpful to compute the spatial variability of the slope length and steepness factors using the following Equation (Renard *et al.*, 1997).

$$L = \left(\frac{\lambda}{22.13}\right)^{m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where $m = \frac{\beta}{1+\beta}$ $\beta = \frac{\left(\frac{\sin\theta}{0.0896}\right)}{(3(\sin\theta)^{0.8}+0.5)}$……………………………………………..…..…..... (7)

Where λ is the horizontal projection (m) and ϴ is the slope angle.

The slope length can be calculated considering the watershed conditions with the standard slope steepness of 9% and the slope length of a 22.13m plot. The steepness factor derived from the slope map of the study area calculated for high (> 9 %) and low slope land (< 9%), as shown below (Wischmeier and Smith, 1978; Renard *et al.*, 1997)

S = 16:8sinϴ-0.5 (for slope angle ≥9%)……………….………………………………….…… (8)

S =10:8sinϴ + 0.3 (for slope angle ≤ 9%)…………………………….……………….…..... (9)

According to the original MUSLE model structure the, LS parameters can be used both as classic USLE and as (McCool *et al.*, 1987). The slope length and steepness (LS) factors of classic USLE can be calculated using the following equation,

LS = (L/22.13) ^{m} * (0.43 + 0.30s + 0.043s^{2})/6.574…………………………………….... (10)

Where, s is field slope in percent, L is the slope length in meters and m is the dimensionless exponential varies from 0.2 for slopes <1% to 0.6 for slopes >10% (Somnuck *et al*., 2010). However, McCool *et al*., (1987) improved the LS factor from classic USLE for use in terrain with steeper slopes and can be calculated by the following equation.

$LS = (L/22.13)^{m} * (16.8 * \sin\Theta - 0.5)$ ……………………..………………………………......(11)

Where L is slope length in meter and m is the dimensionless exponential calculated from the equation below,

$m = \frac{\sin\theta}{\sin\theta + 0.269(\sin\theta)0.8 + 0.5}$ ……………………………………………………..…. (12)

Where Θ is field slope in degrees = $\tan^{-1}$ (s/100) and s is field slope in length. The value of m is depends on slope steepness and which described as 0.2, 0.3, 0.4 and 0.5 for the slope steepness of <1%, 1-3%, 3-5% and >5% respectively.

Erosion would normally be expected to increase with an increase in slope steepness and slope length as a result of respective increases in velocity and volume of surface runoff. Hence, steeper terrain slope causes higher runoff velocities, more splashes downhill and faster flow and therefore contributes greater soil erosion.

The calculation of slope length and gradient factor can be optimally carried out using spatial analysis tools in ArcGIS Environment. Because, the conventional method of direct slope measurement is both expensive and time-consuming and is not feasible to estimate LS factor at large scale (Habtamu, 2017). Accordingly, deriving slope by Geographic Information System (GIS), benefits a wide range of environmental models because slope attributes are frequently needed as input for landslides, land planning and construction, and others.

2.4.4 Crop management factor (C)

Crop management factor (C) represents the ratio of soil loss from a land with specific cropping and management to that from tilled and fallow conditions generally varies from 1 for bare soil, 0.01 for grassland and 0.001 for forest land (Arekhi, 2008). The factor indicates the level of protection of a soil under a certain land cover.

Vegetation cover is one of the most crucial factors in reducing soil erosion by: protecting the soil against the action of falling raindrops, increasing the degree of infiltration of water into the soil, reducing the speed of the surface runoff, binding the soil mechanically, maintaining the roughness of the soil surface, and improving the physical; chemical and biological properties of the soil (Asis and Omasa, 2007). Once, the vegetation cover converted to agricultural land erosion rates could be increased because of the removal of the protection cover.

In order to identify the cover factor for soil erosion assessment, ArcGIS and remote sensing application play a great role to facilitate the data entry, analysis and presentation of the results. Application of remote sensing is used to preprocess digital images prior to classification, such as enhancement, geometric and radiometric correction. Image enhancement is a procedure applied to image data in order to make effectively displayed or recorded the data for subsequent visual interpretation. Then the process of classification involves translating the pixel values in a satellite image into meaningful categories.

The study watershed was classified into three major land uses, that area cultivated land, forest land and grassland and there cover management factor was adopted from Hurni (1985), and assigned as, 0.15, 0.05 and 0.01 respectively.

2.4.5 Erosion control practice factor (P)

Erosion control practice factor is the ratio between the soil losses expected for a certain soil conservation practice to that with up and downslope cultivation which has a value of one (Wischmeier and Smith, 1978). Erosion control practice typically affects erosion by redirecting runoff around the slope and slow down the runoff to cause deposition because of barriers such as contouring, strip cropping, concave slopes, terraces, grass hedges, silt fences, and subsurface drainage (Arekhi *et al*., 2010).

Efficient implementation of land management practices requires proper selection of soil and water conservation measures considering the agroecological zone, topography, soil type and land use in a given area. In Ethiopia, most of the soil and water conservation measures were implemented based on the recommendations given in the community based participatory watershed development guideline (Lakew *et al*., 2005).

2.5 Effectiveness of Soil and Water Conservation Measures

Soil erosion is one of the most important environmental problems in Ethiopia with overall losses estimated at about 1.5 billion tons annually (FAO, 1986). Nationwide, the annual rate of soil loss is much higher than the rate of soil formation. In order to respond the ongoing land degradation as a result of soil erosion, conservation measures were introduced through mass mobilization and paid labor financed by governmental and non-governmental organizations. However, the effectiveness of conservation measures has not been sufficiently studied based on soil erosion and sediment transport processes.

The efficiency of soil and water conservation measures to reduce soil erosion is different from one intervention to the other. The long-term plot-level measurements from Soil Conservation Research Project (SCRP) stations in Ethiopian highlands showed that the P factor value ranges from 0.2-0.37, 0.34-0.60, 0.12-0.25, 0.14-0.35 and 0.27-0.43 for graded fanyajuu, graded bund, level fanyajuu, level bund and grass stripes (SCRP, 2000). Whereas, Adimassu *et al.*, *(*2016) reported as, the average P factor values of the level bund, graded bund, drainage ditch and traditional bunds were 0.20, 0.60, 0.60 and 0.70 respectively.

On the other hand, the study conducted in the highlands of Ethiopia by (Desta *et al*., 2005), revealed that the efficiency of stone bunds was 0.32. The effect of stone bunds on runoff and soil erosion was initially assessed during the erosion plot experimental campaigns in 2002 and 2013, based on the comparison of treated and untreated basins located in the study watershed.

Based on the plot experiments conducted by (Rieder *et al*. 2014), stone bund structures were found to reduce surface runoff by approximately 0.6–0.8 and sediment yield between 0.4–0.8. Similarly, the plot experiment result reported by Adimassu *et al*., (2016), showed that stone bunds were able to reduced sediment yield by roughly 0.5 as compared to untreated plots.

3. MATERIALS AND METHODS

3.1 Description of the Study Area

3.1.1 Location and topography

The study was conducted at Gumara-Maksegnit watershed which is located at the upper parts of Lake Tana in Blue Nile Basin, Ethiopia. The watershed is found in Amhara Region, North Gondar Administrative Zone and located at about 45 km southeast of Gondar Town. It covers an area of 54 km^2 and which is geographically located between 12^0 23’ 53”N to 12^0 30’ 49”N and 37^0 33’ 39”E to 37^0 37’ 14”E (Figure 1).

In order to investigate the impact of soil and water conservation, two adjacent sub-catchments within Gumara Maksegnit watershed were selected and established based on similarity of topography, farming practice, and ecological characteristics. Namely, Ayaye which is treated by soil and water conservation measures mainly with level stone bund that covers an area of 23 ha and Abakaloye which is left without conservation measures and that covers an area of 34 ha. The two sub-catchments are neighboring each other at a distance of 1 km between the outlets.

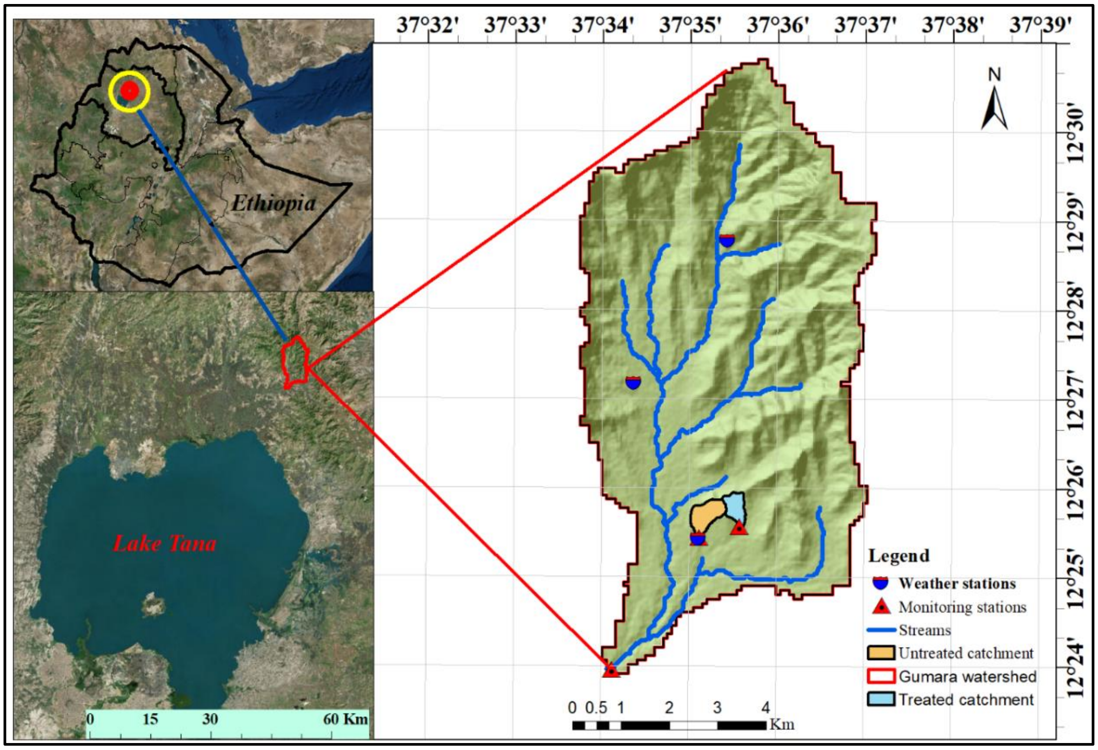

Figure 1. Map of Gumara Maksegnit watershed, sub-catchments and monitoring stations

The watershed elevation ranges from 1920 to 2850 m above sea level and the land slope ranges from nearly flat (<2%) to extremely steep (>70%). The northern part of the watershed, Denkeze mountain ridge, is the borders of Tekeze basin, while the Gumara-Maksegnit watershed is part of the Blue Nile Basin. The watershed geology dominated by a trap series of the tertiary volcanic eruption which is commonly described by their degree of oxidation as exemplified by the frequent dominance of ferric over ferrous iron and by the abundant water content (Addis, *et al*., 2016).

3.1.2 Climate

The climate of the watershed is characterized by Moist Woina Dega agroecological zone based on the classification of Hurni *et al*., (2016). Accordingly, the majority of the watershed elevation ranges between 1920 m to 2400 m above sea level that represents Moist Woina Dega and the Dega zone also found elevation more than 2400 m above sea level.

The climate is dominated by distinct wet and dry periods. The wet season typically occurs from June to September and the dry season occurs from November to April, while May and October are transition months (Addis *et al*., 2016). The study area is characterized by unimodal rainfall distribution with a mean annual rainfall in the watershed is 1052 mm of which more than 90% occurs during the rainy season (June to September). The average monthly maximum and minimum temperatures were recorded as 28.3^{0}C and 13.8 ^{0}C respectively.

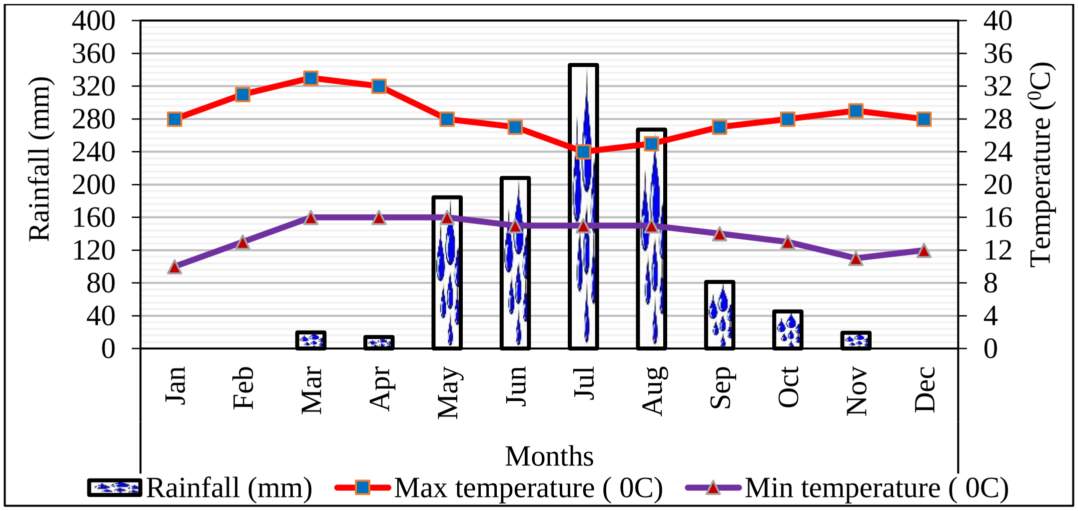

Figure 2. The rainfall and temperature information in the study area for 2016

3.1.3 Soil and water resources

The main soil types in the study area are cambisols and leptosols in the upper and central part of the watershed and vertisols in the lower part of the watershed. The soil resource in a given watershed suffered by water erosion because of poorly managed cultivated lands, overgrazing and continuous trampling that enhances the development of runoff instead of percolation (Worku, *et al*., 2015).

The main stream of the study watershed is Gumara-Maksegnit River, which is the parts of Lake Tana basin that discharges continuously throughout the year and is characterized by several flood events during the rainy season and decreased flow drastically during the dry season (Addis *et al*., 2016).

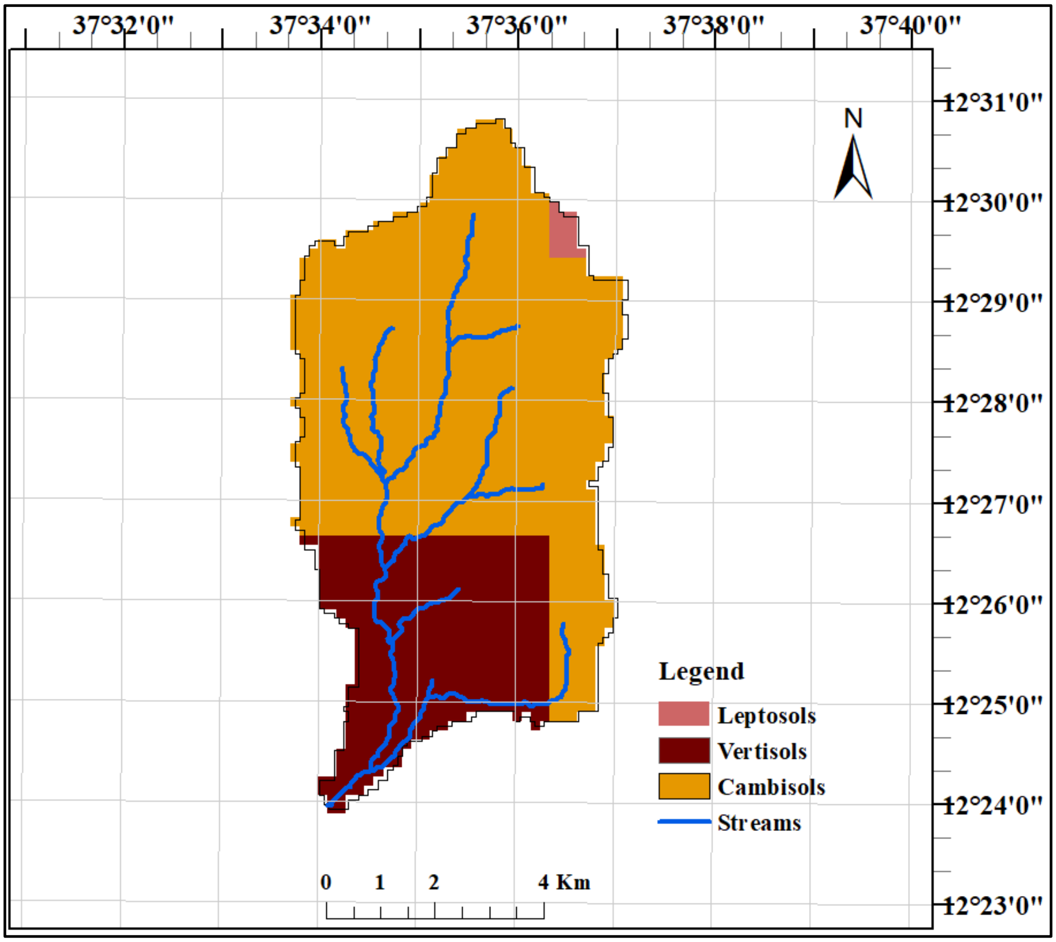

Figure 3. Map of major soil types and streams in Gumara Maksegnit watershed

3.1.4 Socio-economic characteristics

Population in the study area

The watershed is inhabited by a total of 4,246 individuals and 1,148 households with an average family size of four individuals and their settlement is spatially scattered (Worku *et al*., 2015). The rural household largely depends upon the products and services from forestry, pasture and agricultural lands of the watershed. Overexploitation and inappropraite uses of land resources in the study watershed resulted in the process of severe soil erosion, which is the major challenge to keep stable and productive ecosystems in the study area.

Land uses in the study area

The study watershed has three major land-use classes and is mainly covered by agricultural land (58.4%), followed by mixed forest (25.1%) and grazing land (16.5%). Most of the lower parts of the watershed are devoted to crop cultivation and most of the forest and grazing lands are found at the hillside. There are many villages that comprise from ten to fifteen households and the settlement in the watershed is scattered and the average landholding is 1.33 ha, which is characterized as small and fragmentedarable land due to population pressure and resulted ina conversion of forest and grassland land to arable lands.

Agricultural production and economy

The production system in the watershed is a mixed crop-livestock subsistence farming system with more emphasis on crop production (Worku *et al*., 2015). The farming practice is based on a mixed subsistence farming system including crop, horticulture, forestry and livestock activities. However, livestock production also plays a substantial role in supporting crop production.

Livestock is kept in the study area for multiple purposes, such as drawn agricultural implements and used as the source of income and important proteins. The lower part of the watershed is covered by vertisol with a depth up to 70 cm and the area is suitable for *teff*, sorghum and chickpea production mainly grown in the main season/rainfed with traditional crop management practice. Whereas, horticultural crops such as potato, garlic and pepper were grown using traditional irrigation practices (Worku *et al*., 2015).

3.2 Description of Modified Universal Soil Loss Equation (MUSLE)

Failure of the USLE/RUSLE models to include direct consideration of runoff leads to systematic errors in the prediction event erosion (Kinnell, 2005). By including the runoff as an independent factor in modeling erosion, MUSLE has an improved accuracy of sediment yield prediction over USLE and RUSLE (Rostamizad, 2010).

Modified Universal Soil Loss Equation (MUSLE) was developed as a watershed-based model to estimate the sediment yield produced by individual storm events (Somnuck *et al.*, 2010). William, (1975), was developed the following modified form of the USLE using 778 storm runoff events collected from 18 small watersheds, with areas varying from 15 to 1500 ha, slope angle ranges from 0.9 to 5.9% and the slope length of 78.64 to 173.74 m and called it the modified universal soil loss equation (MUSLE).

In the modified universal soil loss equation, the rainfall factor is replaced by hydrological storm runoff volume and peak runoff rate for sediment yield estimation. The MUSLE was then successfully developed with a correlation coefficient of 92% for estimation of sediment yield on a storm basis in the following general formulas.

$$A = R*K*L*S*C*P \quad \text{……………} \quad (13)$$

Where $R = a\,(Q*q_p)^{\,b}$ ……………… (14)

$$A = a\,(Qq_p)^{\,b} * KLSCP \quad \text{……………} \quad (15)$$

Where A is sediment yield (in ton) on storm basis for the entire study watershed, Q is volume of runoff (in m^3), q_p is the peak flow rate ($m^3\ s^{-1}$) and K, L, S, C and P, are soil erodibility (in Mg h $MJ^{-1}\ mm^{-1}$), slope length, slope steepness, crop management and soil erosion control practice factors respectively similar to the USLE model. Whereas, a and b are conceptual factors or location specific coefficients and their initial value was 11.8 and 0.56 respectively.

MUSLE has been applied to many different watersheds worldwide for a different purpose (Sadeghi *et al.*, 2013). Many types of research have been conducted to evaluate the MUSLE model under different conditions around the world (Ashish *et al.*, 2009; Petru, 2010; Habtamu *et al.*, 2013; Mizuyama *et al.*, 2010; Sundara *et al.*, 2015; Arekhi *et al.*, 2011; Arekhi *et al.*, 2010; Somnuck *et al.*, 2010; Sima and Sukeshni, 2014; Zhang *et al.*, 2008). Most of the studies were conducted in Asia, North America and Europe, with several studies also in Iran, especially during the last 10 years (Sadeghi *et al*., 2013). More than 90% of the studies were at the watershed scale and few studies have been done in experimental plots.

In Ethiopia Modified Universal Soil Loss Equation (MUSLE) was applied with integration of Soil and Water Assessment Tool (SWAT) and GIS and Remote Sensing to predict event-based sediment yield (Abdi *et al*., 2012; Habtamu *et al*., 2013; Addis *et al*., 2016; Hassen *et al*., 2015; Zelalem and Devendra, 2016).

3.3 Method of Data Collection

Three monitoring stations were established to monitor the meteorology and surface hydrology in the study watershed in 2011. The main outlet was used to monitor the erosion processes of Gumara Maksegnit watershed, Ayaye, which is the sub-catchment treated by physical soil and water conservation and Abakaloye, which is untreated sub-catchment. For the present study, the data required to compute MUSLE input parameters were collected from different sources.

Table 1. Source, description and purposes of the data used in this study

No	Types of data	Sources	Description	Purpose
1.	Runoff volume	Stage reading manually and automatically	Time series recording of head discharge	Determine runoff factor
2.	Peak runoff rate	Stage reading manually and automatically	Time series recording of head discharge	Determine runoff factor
3.	Soil data	ICARDA project database	Grid based soil samples were collected at 234 points	Soil erodibility factor
4.	DEM	USGS	SRTM 30m pixel resolution	Topographic factors
5.	Satellite image	USGS	Landsat LC08 ETM+ image with 15-meter pixel resolution	Cover factor
6.	Google earth image	Google earth	1m pixel resolution, acquired in March 11 2016.	Conservation practice factor
7.	Sediment loss	Manually collected runoff sample	Runoff-sediment concentration	Observed sediment loss
8.	Ground control points	GPS reading	160 ground control points at three land use classes	Accuracy checking

3.4.1 Runoff factor (R) and sediment yield

In Modified Universal Soil Loss Equation (MUSLE), the rainfall factor was replaced by runoff factor unlike Universal Soil Loss Equation (USLE) and the revised version of it (RUSLE). Rainfall and runoff data were collected using automatic devices and manually for the last 7 years from 2011 to 2017 at three monitoring stations of Gumara Maksegnit watershed and its treated and untreated sub-catchments. In this study, 16 storm events occurring from June to September 2016 were selected that have a daily rainfall depth more than 12.7 mm, which is a threshold value of daily rainfall developed by Wischmeier and Smith (1978).

To determine the runoff factor of the study area the runoff volume and peak discharge were recorded manually through stage reading with the help of 5 minutes interval time serious pictures of DOERR Digital Camera to prove the data at three monitoring stations. Total runoff volume (Q) and Peak discharge (q_p) were determined using the stage-discharge relationship rating curve from collected data at three gauging stations.

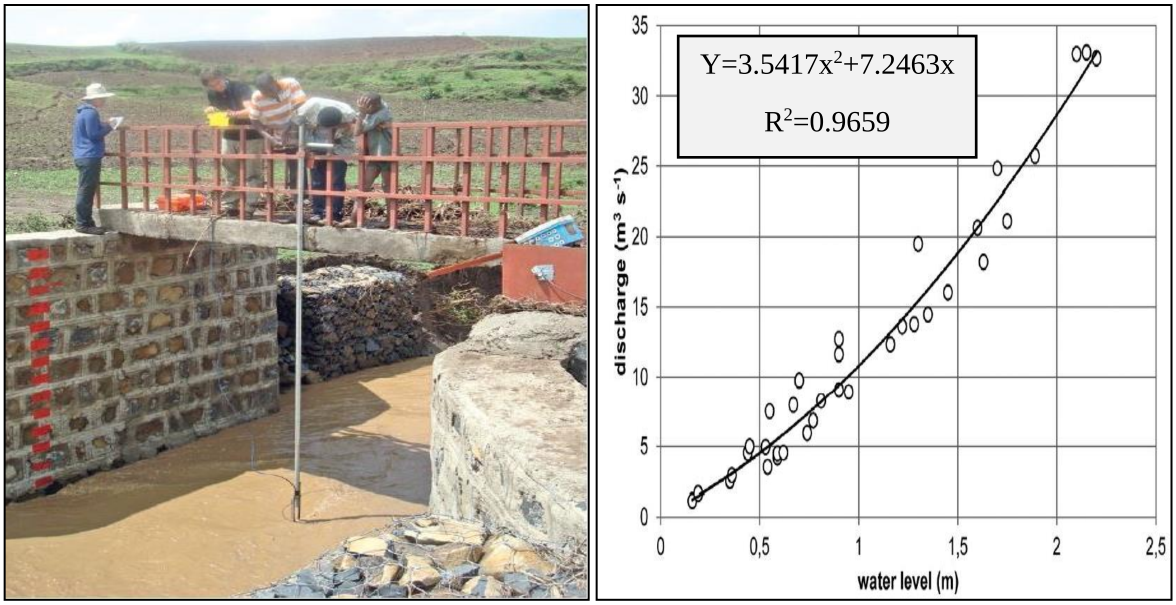

Figure 4. Flow velocity measurement and development of rating curve at Gumara Maksegnit watershed

Source: Klik *et al*., (2015).

The rating curve for Gumara-Maksegnit watershed was developed from frequent measurements of flow velocity and channel profile to calculate peak flow and runoff volume based on equation (1), which is recommended to broad crested weir with a rectangular control section (Klik *et al.*, 2015). Whereas, the rating curve for sub-catchments were developed based on equations (2 and 3), applied when the flow confined under and above v-notch respectively. After all, a graph of stage versus discharge represents the stage-discharge relationship with a line of polynomial regression fit equation known as the rating curve.

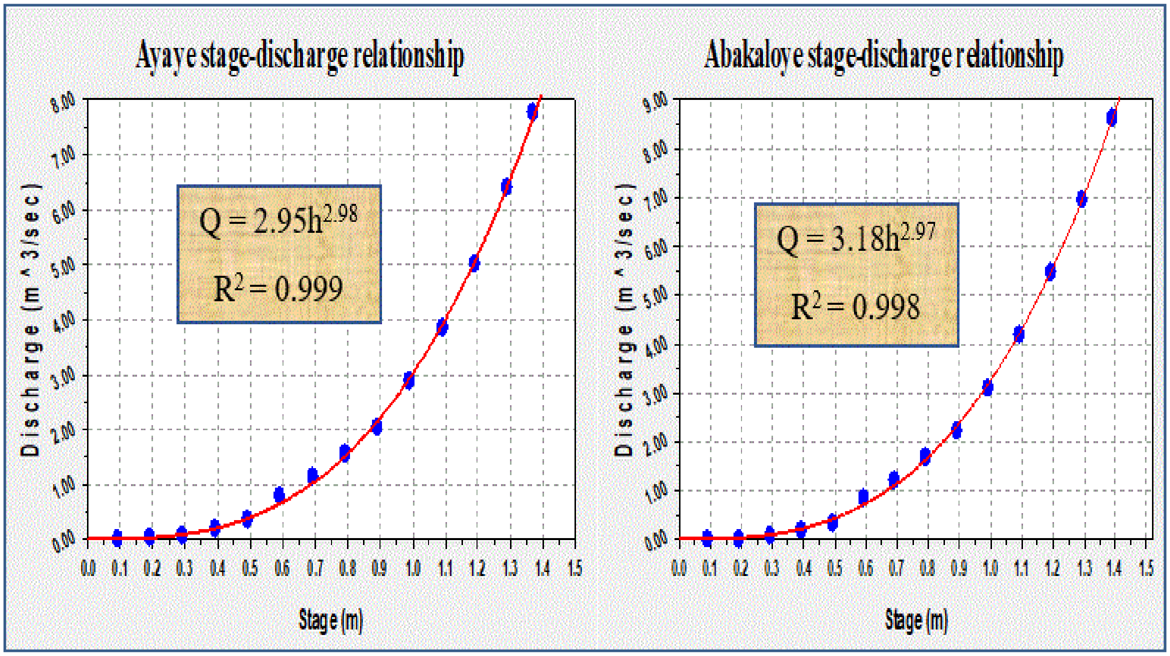

Figure 5. Flow rating curves of treated and untreated sub-catchments

The following equations were developed from the stage-discharge relationship in the study area and used to calculate flow rate and volume for each gauging stations as follows, Gumara-Maksegnit watershed (Figure 4 and Equation 16), treated (Figure 5 and Equation 17) and untreated (Figure 5 and Equation 18).

$Q = 3.5417* (H)^2+7.2463H$………………………………………………..……..………... (16)

$Q = 2.95*h_1^{2.98}$……………………………………….……………………………….……..… (17)

$Q=3.18*h_1^{2.97}$……………….…………………………………….………………….………………. (18)

Where, Q discharge/flow rate (m^3/s), and H (m) is the height of flow in a given channel profile. Therefore, the volume of runoff was calculated using average flow rate multiplied by the time taken within an event and peak flow also was obtained from a maximum depth of event runoff within a given cross-sectional area of the channel. The data required and characteristics of the selected event are a date of data collection, rainfall, runoff volume, peak flow and observed sediment yield for each study catchments are depicted in (Appendix Table 1 and Table 2).

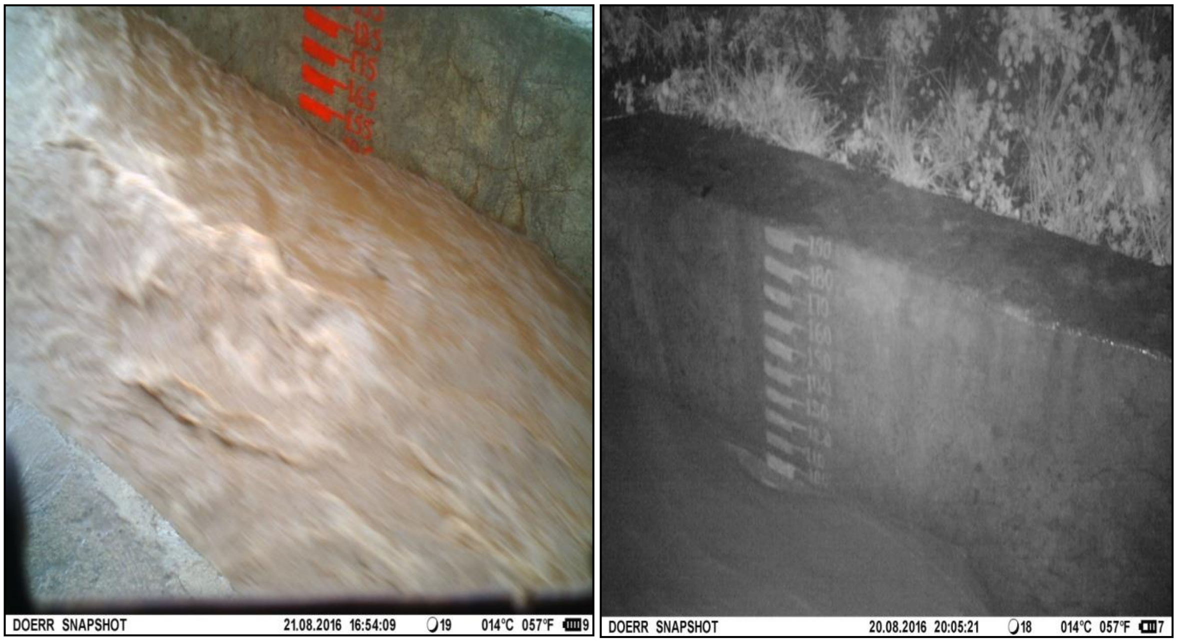

Figure 6. Event runoff taken by DOERR Digital Camera at day and night time

Source: ICARDA project database (2016)

The sediment yield was obtained from sediment concentration in conjunction with total event runoff volume. Whereas, sediment concentration was determined from manual runoff sample that was taken by assigned enumerators using 1 litter capacity plastic bottles, 3 bottles at the beginning of runoff, 3 bottles at the peak of runoff and 3 bottles at the recession time of runoff. Hence, a total of 9 bottles per event were collected and submitted to Gondar soil laboratory for sediment concentration analysis. Three groups of composite bottles were filtered using Whatman Ashless, Grade 42 filtration paper. Finally, the filtered sediment was dried at 105 ^{0}C for about 24 hours and weighed independently in the standard laboratory procedures to determine the sediment concentration.

3.4.2 Soil erodibility factor (K)

The soil data of the study area were obtained from ICARDA project databases, which is collected during the baseline survey of the watershed. The watershed was divided into 500meter by 500meter grid and approximately, at the center of each grid topsoil samples at a depth of 0.25meter were collected over 234 points to determine soil erodibility factor and other soil parameters (Addis *et al*., 2015). However, for this purpose 162 soil samples were used to determine soil erodibility factor through avoiding the soil samples having more than 4% organic matter content in order to standardize with universal soil loss equation nomograph.

Soil erodibility factor (K) was determined based on the observed physical and chemical properties of the soil, such as organic matter content, texture, structural and permeability class code. Analysis of physical and chemical properties of the soil samples were performed based on the standard laboratory procedures.

Particle size distribution was analyzed using hydrometer method. The hydrometer method of silt and clay measurement relies on the effects of particle size on the deferential settling velocities within a water. Whereas organic carbon and organic matter contents were determined by the wet combustion method of Walkley and Black as outlined by (Van Ranst *et al*., 1999).

Soil structure was identified under field condition with the help of soil structure assessment kit to determine soil structural class code. Soil structural class code was determined based on the observed shape and size of soil structure. In this case, the structural code (s) was adopted from the USLE nomograph (Wischmeier *et al*., 1978) and assigned as (1, 2, 3 and 4) for very fine granular, fine granular, moderate or coarse granular and blocky or platy structural classes respectively. Whereas, the permeability class code was obtained from soil textural classes which is encoded from textural triangle based on the observed soil texture.

According to Addis *et al*., (2015) and Somnuck *et al*., (2010), soil erodibility factor can be computed from the USLE nomograph when the silt content < 70%. The resulting silt content of the soil in the study area ranges from 9.84% to 49.84% (Addis *et al*., 2015). Indeed, USLE nomograph was applied to determine the soil erodibility factor in Gumara-Maksegnit watershed.

In this study, the soil erodibility factor was estimated based on USLE nomograph reported by (Wischmeier *et al*., 1971), then modified by (Foster *et al.*,1981), through regression analysis to define the soil erodibility factor in international system of unit as, (Mg h MJ^{-1} mm^{-1}), which is suggested by (Addis *et al*., 2015) for the study area.

$$K = 2.77*10^{-7}(12-a)*M^{1.14}+4.28*10^{-3}(b-2) +3.29*10^{-3}(c-3) \ldots\ldots (19)$$

Where M is the particle size parameter and determined based on equation (5), whereas (a) is organic matter content (%), (b) is soil structural class code and (c) is soil permeability class code. Soil textural classes were encoded from the USDA textural triangle (Appendix Figure 2) based on the laboratory results of particle size compositions.

Table 2. Permeability classes corresponding to the hydraulic conductivity

No	Textural class name	Profile Permeability Class Code	Permeability Class of 1951	Saturated hydraulic conductivity (in/hr.)
1	Clay, silty clay	6	Very slow	<0.04
2	Silty clay loam, sand clay	5	Slow	0.04-0.08
3	Sand clay loam, clay loam	4	Slow to Mod	0.08-0.2
4	Loam, silt loam	3	Moderate	0.2-0.8
5	Loamy sand, sandy loam	2	Mod. to Rapid	0.8-2.4
6	Sand	1	Rapid	>2.4

Source: (Renard *et al.*, 1997)

3.4.3 Slope length and gradient factor (LS)

Slope length and gradient factors were estimated by ArcGIS 10.3.1 spatial analysis of hydrology and terrain processing tools. First, the watershed and sub-catchments were digitally delineated from 30 meter spatial resolution DEM to determine watershed parameters such as slope length and gradient factor, drainage pattern and its characteristics and total watershed area.

The slope gradient was directly obtained from 30meter spatial resolution digital elevation model (DEM). Similarly, flow accumulation was derived from the DEM after conducting fill and flow direction processes in ArcGIS version 10.3.1. Flow accumulation operation is used to determine the number of grid cells that contributing to the downward movement of runoff. Finally, the combined LS factor was determined by multiplying L and S factor from the created map in a spatial analysis tool using raster calculator in map algebra.

In the GIS-based application of universal soil loss equation and the modified version of it, the slope length and steepness factors are quantified together as a product of LS factor value. Therefore, to create a combined raster layer for slope steepness and length (LS) factor, the following equation was proposed by (Moore and Burch, 1986a and 1986b).

$$LS = \text{Power}\left((\text{Flow accumulation}) * \frac{\text{Cell size}}{22.13}\right)^{0.5} * \text{Power}\left(\frac{(\text{Sin}(\text{Slope}*0.01745))}{0.0896}\right)^{1.3} \ldots\ldots\ldots (20)$$

The spatial resolution of the slope map was 30 meter that represent the cell value and the value of slope exponent (m) is depend on slope steepness and which described as 0.2, 0.3, 0.4 and 0.5 for the slope steepness of <1%, 1-3%, 3-5% and >5% respectively. The average slope steepness of the study area showed in (Figure 13) exceed 5%, thereby 0.5 was used as the slope exponent.

3.4.4 Crop management factor (C)

In this study, crop management factor for different land use was derived from satellite image-based land use and land cover maps and its attribute data analysis. The satellite images that acquired from the period of clear sky season in the region help to reduce atmospheric and radiometric problems. Therefore, for the purpose of this study, Landsat 08 ETM^+ image with 15-meter pixel resolution acquired on January 25, 2017, published by USGS on March 01, 2017, that obtained from (NASA, 2017) was used to generate crop management factors (C).

Landsat 08 ETM^+ provides 11 bands separately with different spatial and atmospheric resolutions. The bands that have high resolutions (2, 3, 4, 5, 7, 8 and 9) were selected and combined/stacked together using ERDAS Imagine 2014 raster processing. Other thermal and coastal bands were not used due to its low spatial and atmospheric resolution.

Satellite images were composed in false-color combination of RGB 432 as band 4 represents the Near-Infrared and band 3 belongs to red and band 2 to green. This combination gives better visualization in identifying vegetation which looks red in 432 combinations. Supervised digital image classification techniques were employed using ERDAS Imagine 2014 software complemented with a field visit to collect ground truth information for accuracy checking.

Classified land use and land cover maps from remotely sensed images may contain various types of errors. Hence, accuracy assessment in land use and land cover classification is important to check the compatibility of produced classification with what actually exists in reality. For this purpose, 160 ground control points were collected. To do so, the accuracy of the classified map has been assessed and compared with a ground control data using an error matrix. Overall accuracy is computed by dividing the total number of correctly classified pixels by the total number of reference pixels.

The study watershed was classified into three major land uses such as cultivated land, forest land and grassland and there cover management factors were adopted from Hurni (1985) and assigned as, 0.15, 0.05 and 0.01 respectively. Finally, the classified land use land cover map was converted to cover factor raster layer using ArcGIS conversion tools and the cover factor values were assigned and reclassified corresponding to each land uses classes.

3.4.5 Erosion control practice factor (P)

Different soil and water conservation measures have been applied in the study area through mass mobilization, more of physical structures such as level stone bund, check dam, trenches and semicircular bunds. The way of conservation practice and land management options in the watershed was identified through frequent field assessment combined with the help of high pixel resolution Google earth image. Among identified soil and water conservation measures, level stone bunds were selected during soil erosion modeling to evaluate the efficiency of soil and water conservation measures because of its large area covers approximately 50% of the watershed is treated with the stone bunds (Addis *et al*., 2016).

To generate conservation practices factor, the area which is covered by level stone bund was identified and digitized carefully from 1m by 1m pixel resolution image obtained from Google earth acquired on March 11, 2016. After on-screen digitization, the land use and land cover classes were reclassified into three major land management systems such as, all conserved land mainly treated by level stone bunds and the efficiency of level stone bund was assigned as, 0.32 which is adopted from (Desta *et al*., 2005). Second, non-conserved cultivated land managed by contour cultivation which is a common practice in the study area that has an efficiency of 0.9 adopted from (Hurni, 1985). The last category was all non-conserved land other than cultivated land and assigned as 1, which is also adopted from (Hurni, 1985).

Figure 7. Level stone bund at treated sub-catchment (Ayaye)

The efficiency of conservation measures was evaluated based on the two adjacent sub-catchments established as treated sub-catchments mainly with level stone bunds and untreated sub-catchment which is used as a reference.

3.5 Method of Data Analysis and Presentation

3.5.1 Pre-processing of Input Parameters

Runoff factor is a major input for MUSLE model that was computed from volume and peak runoff rate using respective weir equations (equation 16, 17 and 18), which are described in method section for each monitoring stations. The amount of total sediment yield was calculated from an observation based on the sediment concentration in conjunction with the total runoff volume.

Topographic factors (LS) were obtained from 30meter spatial resolution SRTM digital elevation model (DEM) after conducting fill, flow direction and flow accumulation processes and generate LS factor map using ArcGIS spatial analysis raster calculator function. Soil erodibility factor (K) was determined based on the methodology of (Foster *et al.*, 1981) that depends on the physical and chemical properties of the soil in the study area.

Land use and the land cover map was used to estimate cover management factor by converting the raster map to vector format and assign cover factor for each land use. Finally, the land use map was reclassified and converted from vector to raster to obtain cover factor map. Erosion control practice (P) factor was generated from satellite image-based land use land cover maps assisted by field assessment to identify the way of conservation practices in the study area.

In general, analyzing and processing spatial data such as digitizing, calculating and classifying the necessary information of each thematic layer was done using ERDAS Imagine 2014 and ArcGIS 10.3.1 software. After all, the amount of a total event-based sediment yield was estimated using MUSLE model and compared with observed sediment yields of individual storms.

3.5.2 Prediction of sediment yield using MUSLE

In the present study, Modified Universal Soil Loss Equation is used in conjunction with raster-based GIS applications to predict erosion potential on a cell-by-cell basis and to determine the catchment sediment yield. ArcGIS can be used for the discretization of the catchments into small grid cells and for the computation of such physical characteristics of these cells as slope, land use and soil type, all of which affect the processes of soil erosion and deposition in the different parts of a catchment.

The sediment yield is the amount of transported material passing through a given cross-section of a stream on a given interval of time located at the outlets of a catchment. Evaluating the applicability of soil erosion model on the watershed is not an easy task (Sadeghi, 2004). However, sediment yield models are easier to apply because of the data for these models can be measured at the watershed outlet. Hence, erosion modeling using MUSLE is more preferred than USLE and RUSLE models, because of its direct consideration of runoff and runoff factor, which is a major input into modified universal soil loss equation (Arekhi *et al*., 2010). Therefore, the simplified equation used for MUSLE model is formulated as follows.

$$A = 11.8\,(Q*q_p)^{0.56} * KLSCP \qquad (21)$$

A, Sediment yield for a single event in tons, Q is the total event runoff in m^3, q_p is the event peak discharge in m^3/s and KLSCP are similar to USLE equation.

3.5.3 Statistical techniques and model efficiency assessment

The sediment yields estimated by MUSLE for different events were essentially compared with the observed sediment yield data collected from the stream gauging station located at each outlet of the watersheds. The paired t-test parametric procedures were applied to test whether the means of event-based predicted and observed sediment yield values are different or not at a significant level of 5% (95% confidence interval).

Descriptive statistics such as standard deviation (STDEV) and relative error (RE) were analyzed using SPSS statistical software version 20 and Minitab version 18. Event-based sediment yield estimate potential of MULSE model on sub-catchments and whole watershed was evaluated in terms of overall mean relative errors and expressed as,

$$\text{RE (\%)} = \frac{S-O}{O} * 100 \qquad (22)$$

Where; RE is a relative error, S is MUSLE simulated sediment yield (ton) and O is observed sediment yield (ton). In the present study, the goodness of model fit related to sediment yield estimation was assessed based on Coefficient of determination (R^2), Root mean square error (RMSE) and Nash−Sutcliffe efficiency (NSE).

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Si-Oi)^2}{\sum_{i=1}^{N}(Oi-\tilde{O})^2} \qquad (23)$$

Where, Oi is observed sediment yield, Si is simulated sediment yield, Õ is the mean of observed sediment and N is the number of observation. NSE value ranges from -∞ to 1 that indicates the efficiency of the model. Whereas, the root mean square error (RMSE) has been used as a standard statistical metric to measure model prediction error in meteorology, air quality, and climate research studies; a smaller RMSE value indicates a better model performance (Chai *et al*., 2014). RMSE is calculated with the following equation,

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{N}} \qquad (24)$$

Where P_i is the predicted sediment yield, O_i is observed sediment yield and N is a number of events.

3.5.4 Software’s used

ArcGIS 10.3.1: this was used to complement the display and processing of the data. After computations of required model parameters in a MUSLE framework, the sediment yield was calculated using raster calculator under map algebra in ArcGIS environment.

ERDAS Imagine 2014: this was used for displaying and subsequent processing and enhancement of the image and used for the carving out of the study area from the whole scene imagery using the study area shape file. The land use and land cover map were derived through supervised image classification using this software.

SPSS Version 20: was used to compare the means of observed and predicted sediment yield statistically, that able to perform paired mean comparison with a paired t-statistics.

Minitab version 18: used for graphical presentation and comparison of observed and predicted sediment yield

Microsoft Word and Excel 2016: was used to preprocess and manage the raw data and the presentation of model outputs

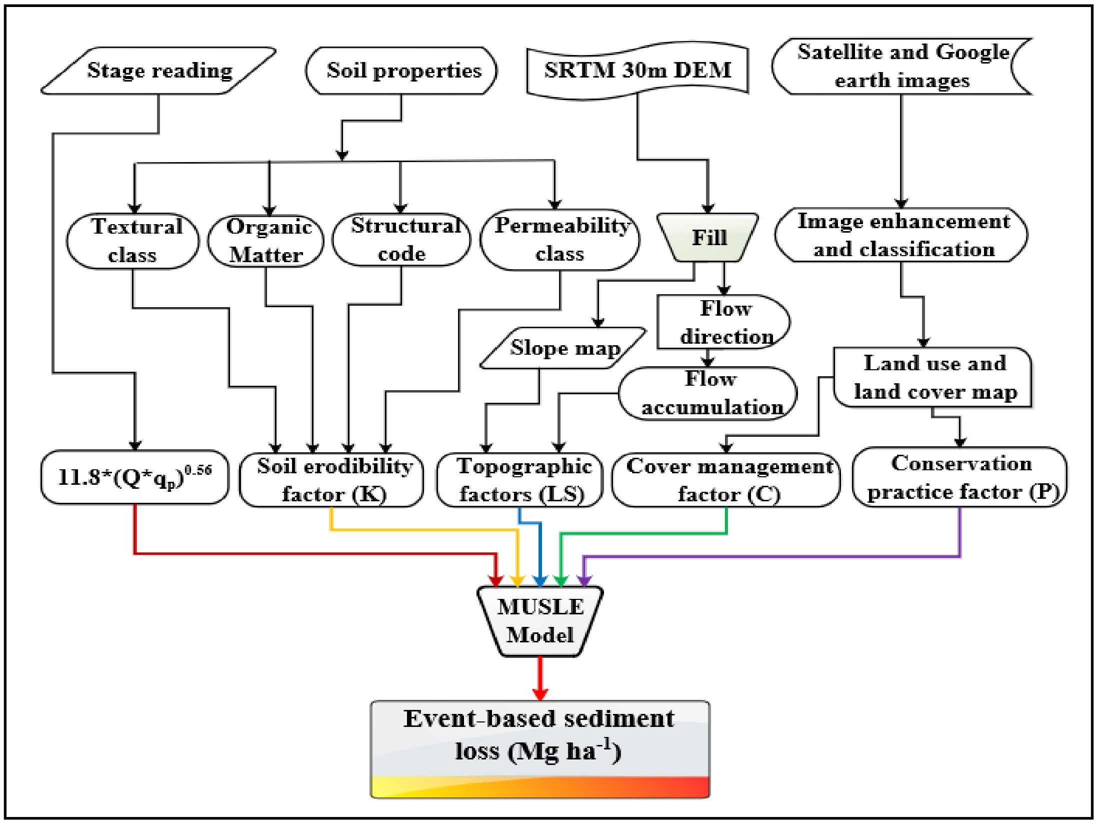

Figure 8. Conceptual framework of sediment yield estimation using MUSLE

4. RESULT AND DISCUSSION

4.1 Rainfall, Runoff and Sediment Concentration

In Modified Universal Soil Loss Equation (MUSLE), the rainfall factor was replaced by runoff factor unlike Universal Soil Loss Equation (USLE) and the revised version of it (RUSLE). Rainfall and runoff data were collected using automatic devices and manually for the last 7 years from 2011 to 2017 at three monitoring stations in Gumara Maksegnit watershed.

The rainfall information was recorded within 5-minute intervals using Hobo tipping bucket device installed at three stations in different parts of watershed and Campbell Scientific Automatic Weather Station near to the main outlet. Whereas, the runoff data was determined through encoding manually recorded stage reading and a time serious pictures of DOERR automatic digital camera.

In this study, 16 storm events occurring from June to September in 2016 were selected that have a daily rainfall depth more than 12.7mm, which is a threshold value of daily rainfall developed by Wischmeier and Smith (1978), since the MUSLE model for sediment yield has been recommended for application to large storms and which is verified by (Sadeghi, 2004; Jaramillo, 2007).

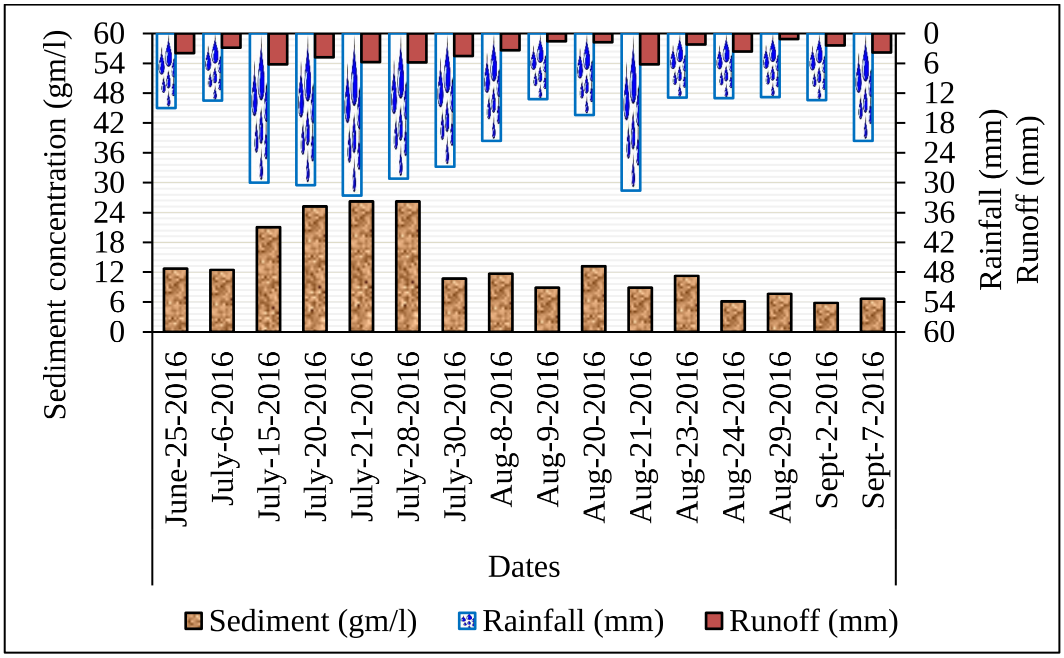

Figure 9. Event-based rainfall, runoff and sediment concentration in Gumara watershed

The amount of runoff volume and peak discharge was derived from a time serious data using the respective weir equations (equation 16, 17 and 18) for Gumara-Maksegnit watershed and its treated and untreated sub-catchments respectively. The mean depth of observed runoff volume for selected events were 3.37, 6.16 and 8.41 mm and the peak discharge were 38.58, 1.58 and 1.83m^3s^{-1} for Gumara Maksegnit watershed and its treated and untreated sub-catchments respectively.

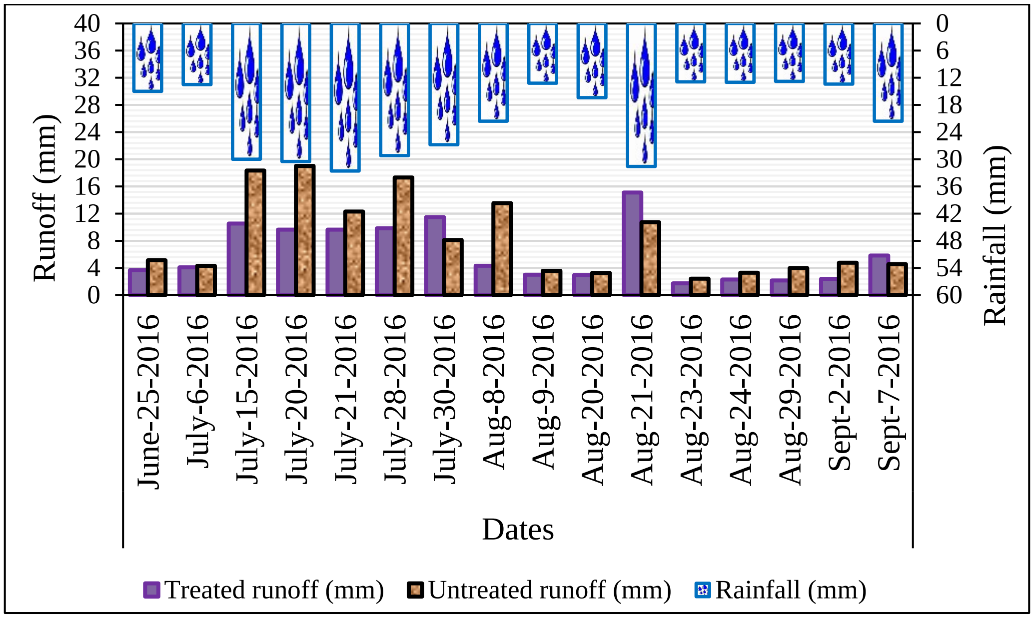

Figure 10. Event-based rainfall and runoff in treated and untreated sub-catchments

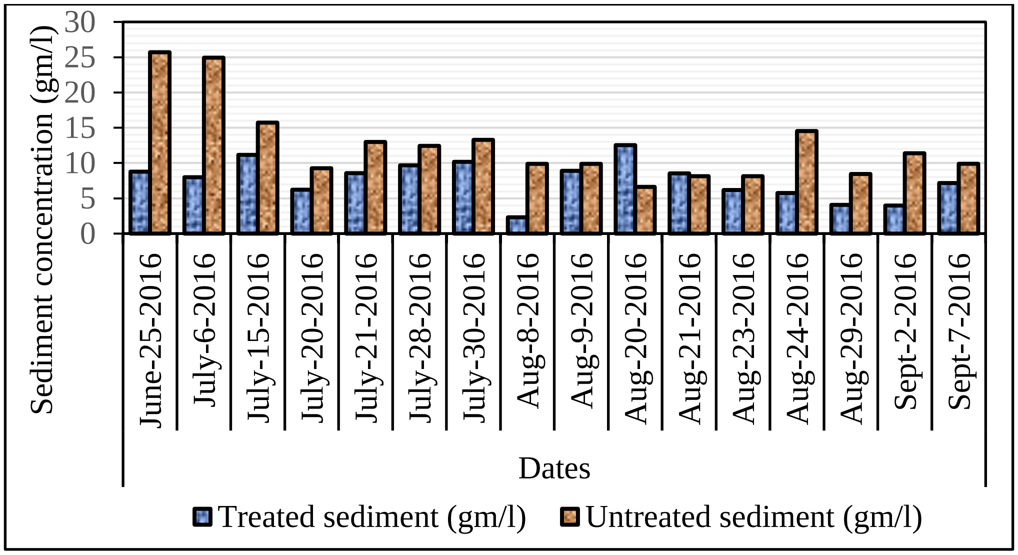

Figure 11. Event-based sediment concentration in treated and untreated sub-catchments

The runoff is usually being discharged with a certain amount of suspended sediment, which is determined by sediment concentration in conjunction with a total runoff volume that arrives at a defined confluence point. The sediment yield in the study area was extracted from the runoff volume based on corresponding sediment concentration for individual events and each catchment. The sediment concentration in the study watersheds was relatively high at the start of the rainy season as presented in (Figure 9 and Figure 11). It could be related to the seasonal variation of vegetation cover that lags behind the most intensive rainfall at the start of the rainy season.

4.2 MUSLE Model Parameter Estimation

4.2.1 Runoff factor

Event-based runoff factor was derived from a combination of runoff volume and peak discharge with conceptual factors (constant and power coefficient in the model general equation). The minimum, maximum and mean value of runoff factor in Gumara-Maksegnit watershed for 16 selected events of 2016 were 4.32, 25.61 and 15.88 MJ mm ha^{-1} h^{-1} respectively. Whereas, the minimum, maximum and mean values of runoff factor for treated and untreated sub-catchments were (8.44, 6.95), (117.51, 104.77) and (38.29, 42.73) MJ mm ha^{-1} h^{-1} respectively.

4.2.2 Soil erodibility

Soil erodibility was estimated based on soil samples physical and chemical properties such as soil structural class, textural characteristics, organic matter and permeability class. A point soil erodibility factors were determined based on the required soil parameters. Then, a point erodibility factors were converted to continuous data through extrapolation using ordinary kriging interpolation techniques in ArcGIS environment and the Gaussian model was suggested and preferred by (Addis *et al.*, 2015), due to its best performance to reproduce soil erodibility estimate using USLE nomograph.

In this study USLE nomograph was employed to estimate the soil erodibility factor when, the silt content < 70% (Wischmeier and Smith, 1978). The resulting silt content of the study area ranges from 9.84% to 49.84% (Addis *et al.*, 2015). The minimum, mean and maximum percentage of silt + very fine sand showed in (Table 3) was 9.48, 32.95 and 49.84% and for sand 14.56, 34.83 and 56.56% and the clay percentage of the soil in the study area was ranges from

13.6 to 67.76%. Whereas, the minimum, mean and maximum percentage of organic matter in the study area initially was about 0.21, 2.82 and 9.79 respectively.

Table 3. Statistical summary of selected soil parameters in the study watershed

No	Soil parameters	Minimum	Mean	Maximum	STDEV	CV
1	Clay	13.6%	32.21%	67.76%	13.43%	0.42
2	Silt +very fine sand	9.48%	32.95%	49.84%	7.83%	0.24
3	Organic matter	0.21%	1.97%	4%	0.98%	0.5
4	Sand	14.56%	34.83%	56.56%	9.11%	0.26

However, the soil samples having more than 4% organic matter was excluded from erodibility determination in order to standardize with USLE nomograph. After all, the selected soil sample organic matter percentage ranged from 0.21 to 4% with a mean value of 1.97%. Based on the above soil information the spatial prediction map of soil erodibility factor illustrated in (Figure 12) was created by ordinary kriging interpolation procedure using semivariogram coefficient of the Gaussian model.

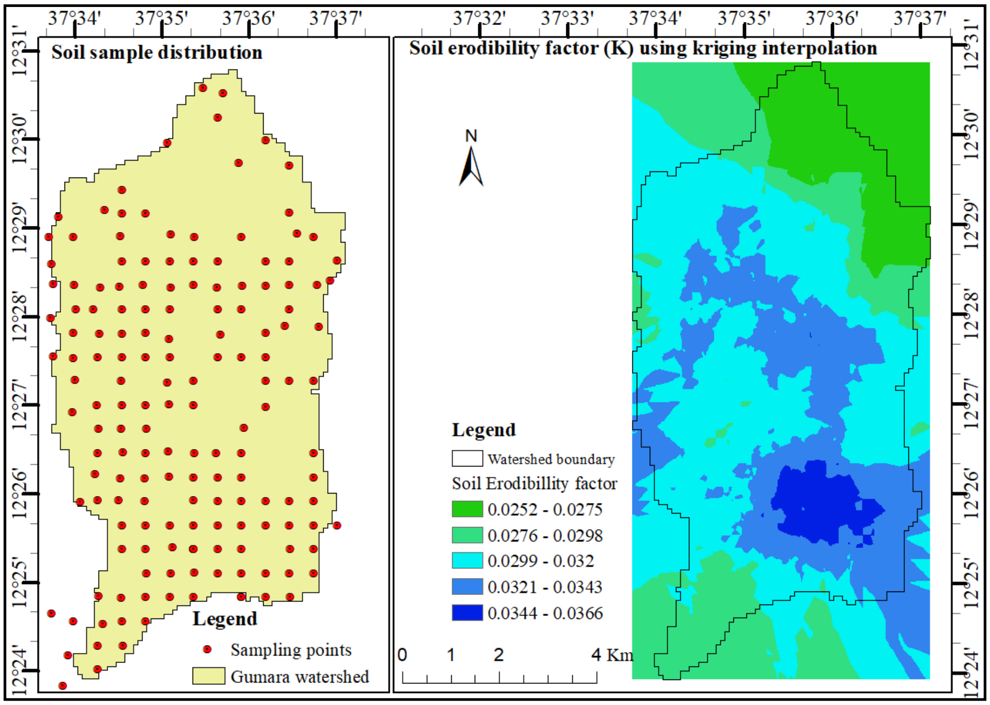

Figure 12. Soil sample distribution (left) and spatial prediction of soil erodibility factor (right)

Generally, the soil erodibility was smaller in northern and southern parts of the watershed ranges from 0.0252-0.0298 Mg h MJ^{-1} mm^{-1}. On the other hand, the soil erodibility tends to increase in central and southeastern parts of the watershed that ranges 0.0321-0.0366 Mg h MJ^{-1} mm^{-1} which is illustrated in (Figure 12). This result is in lined with the study conducted by (Addis *et al*., 2015) in the study watershed.

4.2.3 Topographic factor (LS)

Topographic characteristics have a significant impact on the spatial distribution of erosion and deposition (Moore and Burch, 1986b). Slope length and gradient factors have been derived from the SRTM 30meter spatial resolution DEM of the study area obtained in USGS earth explorer.

The elevation of the study area ranges from 1920 to 2850 meters above sea level. The highest and lowest aspect of elevations is found on the northern and southern parts of the study area respectively. Steeper slope causes higher runoff velocities, more splashes downhill and faster flow and therefore contributes greater soil erosion (Remortel *et al*., 2001).

The average slope of the study watersheds were 26.73, 15.98, and 17.35% for Gumara-Maksegnit watershed, treated and untreated sub-catchments respectively which is illustrated in (Figure 13). Therefore, the average slope gradient in the study areas is more than 5% and thereby, the slope exponent was 0.5 for all study catchments.

In the GIS-based application of Universal soil loss equation and Modified version of it, the slope length and steepness factors are quantified together as a product of LS factor value. To create a combined raster layer for slope steepness and length (LS) factors equation 20 was used which is proposed by (Moore and Burch, 1986a and 1986b).

The minimum, maximum and mean value of topographic factor for Gumara-Maksegnit watershed was (0, 1079 and 15.2) respectively with the standard deviation of 36.37. The result showed that the topographic factors (LS) range from 0 in plain areas to 1079 from hillsides and along a stream bank (Figure 17b). This is clearly showed that soil erosion increases potentially when the slope length and steepness of the land increases.

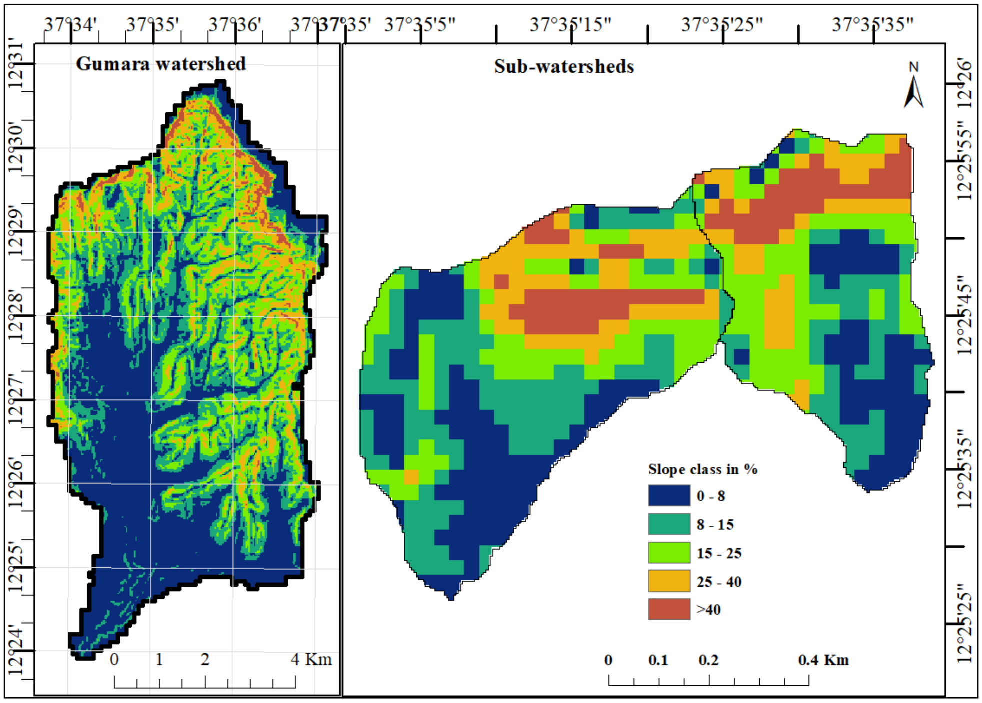

Figure 13. Slope classes in percent for the study watersheds

4.2.4 Cover and management factor (C)

The cover and management factor is defined as the ratio of soil loss from land with specific vegetation to the corresponding soil loss from continuous fallow with the same rainfall (Wischmeier and Smith, 1978). Remotely sensed data from Landsat 08 ETM$^+$ acquired on January 25, 2017 (NASA, 2017) was used to drive land use and land cover map.

Supervised digital image classification techniques were employed using ERDAS Imagine 2014 software complemented with a field visit to collect ground truth information for accuracy checking. The classified image was changed into vector format using conversion tool in ArcGIS environment and the corresponding cover factors obtained from (Hurni, 1985) were assigned and the cover factor map was produced through the vector to raster conversion.

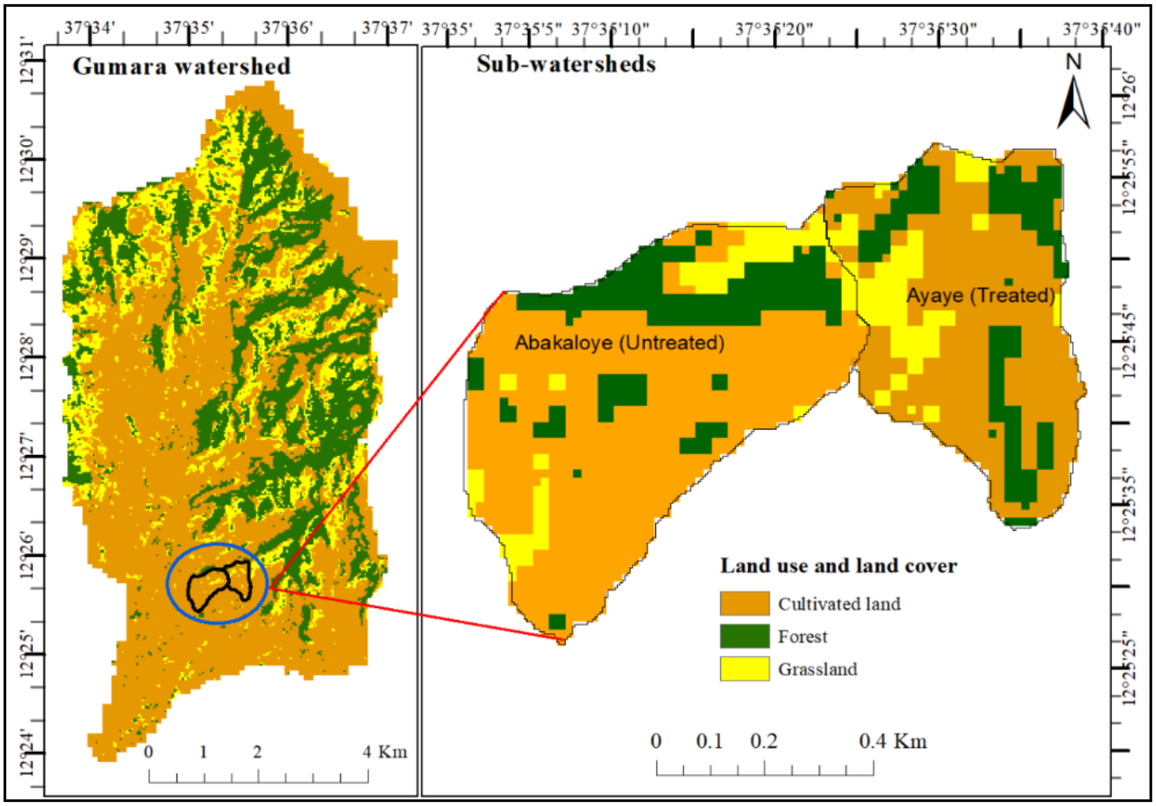

Figure 14. Land use and land cover classification map of the study watersheds

The type of land cover and cultural practices makes the greatest difference in the amount of erosion that occurs in a given area. From the supervised land use and land cover classification, three major land use and land covers were identified as, cultivated land, forest land and grassland.

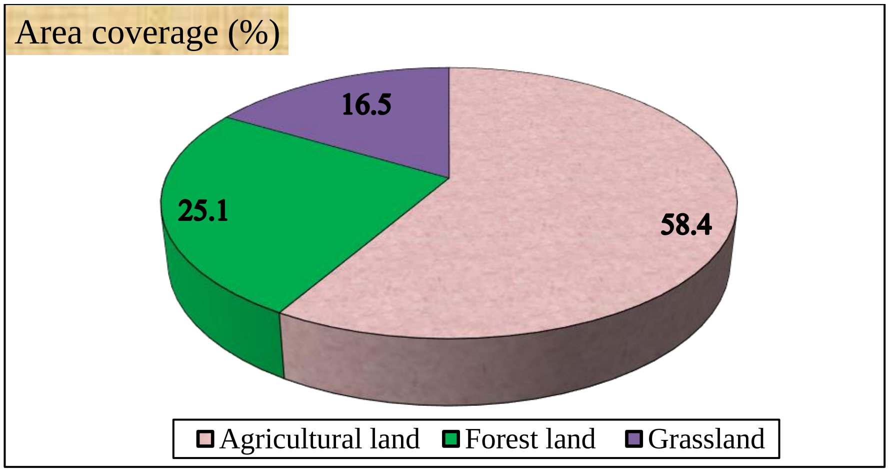

Figure 15. Area coverage of land use and land cover classes of Gumara-Maksegnit watershed

The area coverage for each land uses is defined in (Figure 15 and Table 5), showed that cultivated land constituted the largest proportion of the study watersheds, followed by forest land and grassland. The maximum cover factor was 0.15 assigned for cultivated land adopted from (Hurni, 1985) for cereal-based agriculture that requires intensive cultivation of the soil to grow them. The coincidence of intensive cultivation of the land to produce cereals and intensive rainfall especially at the start of rainy season exposes the soil for extreme erosion in the study area.

Classified land use and land cover maps from remotely sensed images may contain various types of errors. Hence, accuracy assessment in land use and land cover classification is important to check the compatibility of produced classification with what actually exists in reality. In this study, 160 ground control points were collected and the accuracy of the classified map has been assessed and compared with a ground control data using an error matrix based on users and procedures accuracy.

Table 4. Error matrix for accuracy assessment of land use and land cover

Class Name	**Agriculture**	**Forest**	**Grassland**	**Row Total**	**Users accuracy**
Agriculture	***73***	1	3	77	94.81%
Forest	4	***36***	5	45	80%
Grassland	3	3	***32***	38	84.21%
Column Total	80	40	40	160	
Producers accuracy	91.25%	90%	80%		
Overall classification accuracy					***88.13%***

The results of user's accuracy in this study showed in (Table 4) that the most accurately classified land use was agricultural land followed by grassland and the lowest accuracy of classification was observed in forest land. The lowest values of class accuracies were as a result of misclassified due to spectral property similarities among other land cover classes.

Moreover, the time of image acquisition has a great role in such misclassification problems. The overall accuracy results in this study were 88.13%, which is beyond the threshold value of overall accuracy mentioned by (Anderson *et al*., 1976), while the acceptable level of overall accuracy is above 85%.

Table 5. Land use, area coverage and cover management factor for the study areas

No	**Land use type**	**Gumara**		**Untreated**		**Treated**		**Cover factor**
		Area ha	**Area %**	**Area ha**	**Area %**	**Area ha**	**Area %**	
1	Agricultural land	3127.32	58.383	24.46	71	15.05	65.32	0.15
2	Grassland land	883.98	16.503	3.26	9.46	3.35	14.54	0.05
3	Mixed forest	1345.23	25.114	6.73	19.54	4.64	20.14	0.01
	Total	**5356.53**	**100**	**34.45**	**100**	**23.04**	**100**	

Source: Cover factor adopted from Hurni (1985)

The average value of cover management factor in Gumara-Maksegnit watershed was 0.098. On the other hand, the weighted mean value of cover management factors for treated and untreated sub-catchments were 0.1144 and 0.1133 respectively. The maximum cover factor was 0.15 assigned for cultivated land adopted from (Hurni, 1985) for cereal-based agriculture that requires intensive cultivation of the soil to grow them. This condition results in higher soil erosion where the agricultural land is the largest proportion of land use.

4.2.5 Conservation Practice factor (P)

The conservation practice factor refers to management practices such as terracing, mulching, strip cropping, contour plowing and other protective measures and its effect in reducing the amount and rate of runoff. In this case, the study watersheds were characterized as all lands treated mainly by level stone bunds, non-conserved cultivated land and non-conserved land other than cultivated land.

The way of conservation practice system in the study area was identified through frequent field assessment with the help of very high-spatial-resolution satellite image obtained from Google earth acquired on March 11, 2016. To generate conservation practices factor, the area which is covered by level stone bund was identified and digitized carefully. After onscreen digitization, the land use and land cover classes were reclassified into three major land management options.

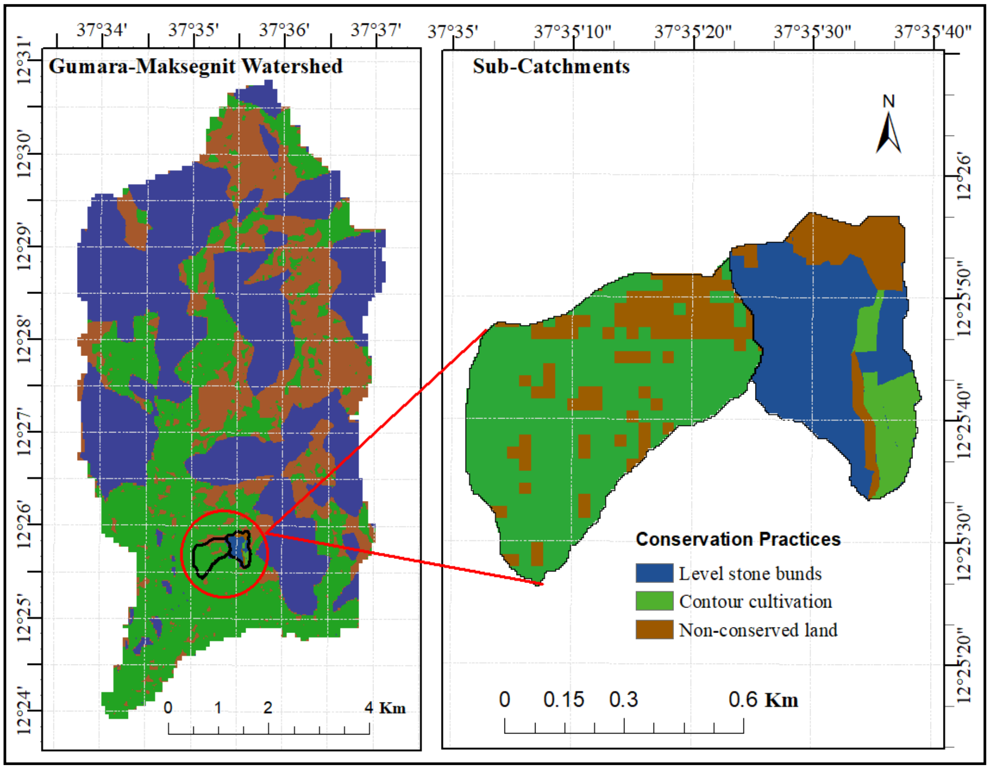

Figure 16. Conservation practice factor map of the study watersheds

Approximately 50% of the study watershed is treated by linear level stone bunds (Addis *et al*., 2016), which is considered during the determination of conservation practices factor. Hence, the efficiency of level stone bunds was 0.32 which is adopted after (Desta *et al*., 2005). Whereas, the non-conserved cultivated land was managed through contour cultivation which is the common practice of the study area and assigned as 0.9 adopted from (Hurni, 1985). The third category of land management system was non-conserved forest and grasslands combined together and assigned as 1 which is adopted from (Hurni, 1985).

After all, the appropriate values for each feature class were assigned according to the corresponding land management systems and converted to raster layer using practice factor field to drive raster based conservation practice factor (Figure 17d).Hence, the weighted mean values of conservation practice factor were 0.677, 0.551 and 0.924 for Gumara-Maksegnit watershed, treated and untreated sub-catchments respectively. The results showed that there is a significant difference that the highest value of practice factor was obtained at untreated sub-catchment as a result of the absences of conservation practices.

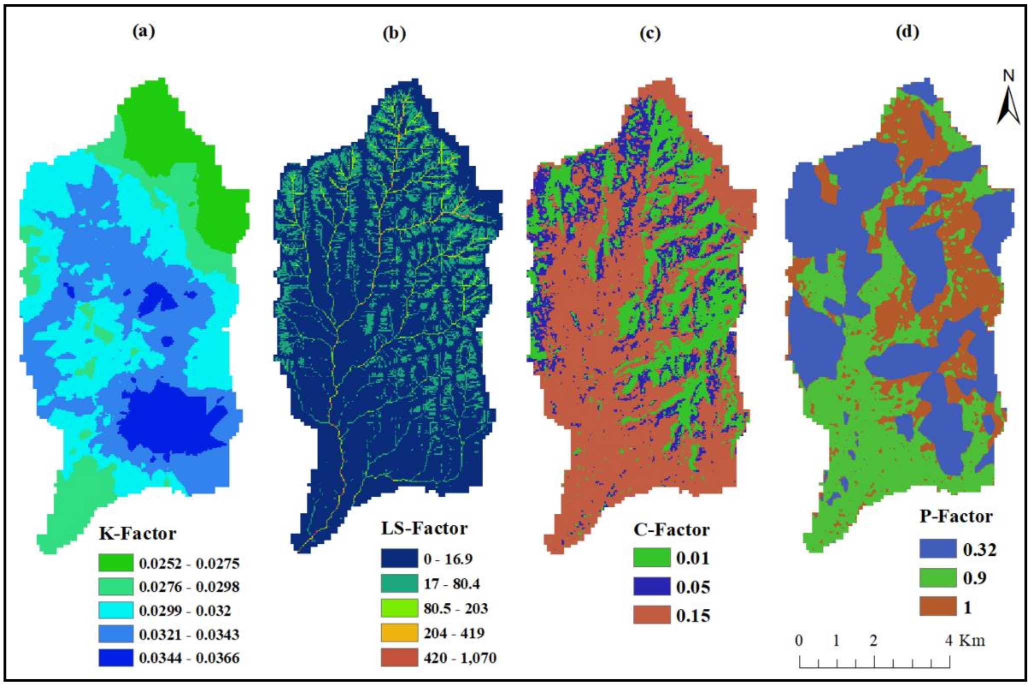

Figure 17. Model parameter map to estimate sediment yield in Gumara-Maksegnit watershed

All six factors of MUSLE, Runoff factor (R), Soil erodibility factor (K), Topographic factors (LS), Cover management factor (C) and Conservation practices factor (P) were combined together using raster calculator of map algebra in ArcGIS 10.3.1 environment to determine event-based sediment yield in the study watersheds.

ArcGIS 10.3.1 was used for the discretization of the catchment into small grid cells and to integrate layers of spatial information for the purpose of quantitative assessment of sediment yield. The derived spatial model input parameters were compiled into one coherent raster database for modeling and event-based sediment yield prediction.

Table 6. Summary of the mean values of model parameters for each study watersheds

Model parameters	**Unit**	**Gumara watershed**	**Untreated**	**Treated**
Runoff factor (R)	MJ mm ha^{-1}	15.88	42.73	38.29
Soil erodibility (K)	Mg $MJ^{-1}mm^{-1}$	0.0309	0.0332	0.0350
Slope length and gradient factor (LS)	Dimensionless	13.7614	6.0352	5.8245
Crop management factor (C)	Dimensionless	0.0983	0.1133	0.1144
Conservation practices factor (P)	Dimensionless	0.6770	0.9240	0.5509

4.3Application of MUSLE to Estimate Event Based Sediment Yield

4.3.1 Sediment yield estimation in Gumara-Maksegnit Watershed

The event-based sediment yield of the study area was estimated by multiplying the respective raster based MUSLE factors (Figure 17a-d) including runoff factor as an independent input factor. The sediment yield was computed by raster calculator of map algebra in spatial analysis tools of ArcGIS 10.3.1 using the original simplified equation (equation 21), adopted from (William, 1975). Whereas, the observed sediment yield was obtained from event runoff volume corresponding to its sediment concentration analyzed in Gondar soil laboratory.

Table 7. Observed and estimated sediment yield in Gumara-Maksegnit watershed

No	Event date	Observed sed. ton ha^{-1}	Predicted sed. ton ha^{-1}	Relative error (%)
1	June-25-2016	0.50	0.39	-22.00
2	July-6-2016	0.35	0.31	-11.43
3	July-15-2016	1.31	0.61	-53.44
4	July-20-2016	1.21	0.53	-56.20
5	July-21-2016	1.51	0.59	-60.93
6	July-28-2016	1.25	0.64	-48.80
7	July-30-2016	0.49	0.47	-4.08
8	Aug-8-2016	0.39	0.35	-10.26
9	Aug-9-2016	0.14	0.23	64.29
10	Aug-20-2016	0.23	0.27	17.39
11	Aug-21-2016	0.55	0.65	18.18
12	Aug-21-2016	0.25	0.26	4.00
13	Aug-24-2016	0.28	0.38	35.71
14	Aug-29-2016	0.06	0.11	83.33
15	Sept-2-2016	0.16	0.26	62.50
16	Sept-7-2016	0.25	0.4	60.00
	Mean	**0.5581**	**0.4031**	**-27.8**
	STDEV	**0.4768**	**0.1637**	

Results given in (Figure 18 and Table 7), showed that MUSLE was performed well in prediction of event-based sediment yield in the study area. The mean values of event-based observed and predicted sediment loss was 0.5581 ton ha^{-1} and 0.4031 ton ha^{-1} respectively. A paired means of observed and predicted sediment yields were compared statistically at 5% level of significant using SPSS version 20.

The difference between the mean values of observed and estimated sediment yield was not significant statistically at 5% level of significance, while the probability value from the paired sample t-test statistics was 0.099 (Table 8). The relative errors of observed and predicted sediment yields were ±27.8%, which is the acceptable level of error in natural phenomena (Das, 2000). However, the standard deviation (STDEV) of observed sediment yield showed in (Table 8) was too high as compared to predicted sediment yield that tells us the observed sediment yield was not consistence and more dispersed from the mean and which is visually inspected in (Figure 18).

Table 8. Paired mean comparison of observed and predicted sediment yield

Paired samples	**Mean**	**Mean difference**	**N**	**Std. Deviation**	**Std. Error**	**t**	**df**	**Sig. (2-tailed)**
Observed sediment (ton ha^{-1})	0.5581	0.155	16	0.4768	0.1192	1.757	15	0.099
Predicted sediment (ton ha^{-1})	0.4031		16	0.1637	0.0409			

Based on the model efficiency and goodness of fit assessment criteria's the following results were obtained. The R^2, RMSE and NSE values were 0.7, 152 and 0.34 respectively for Gumara Maksegnit watershed. These results confirmed that there was a strong association between observed and model estimated sediment yields in Gumara Maksegnit watershed.

On the other hand, there was a highly significant difference between a pair of individual storm observed and estimated sediment yield. This situation could be coming from a seasonal variation of vegetation cover and spatial and temporal variability of storms, as well as a change in the antecedent hydrological conditions. This is due to the variability of eroded sediment throughout the watershed is not taken in to account by the MUSLE as for many other lumped models (Sadeghi and Mizuyama, 2007).

A graph of event-based observed and estimated sediment loss in Gumara-Maksegnit watershed (Figure 18), revealed that the model tends to underestimate the sediment yields of the events that occurred in June and July and tends to overestimate the events occurred in August and September. It could be coming from the temporal variation of vegetation cover that lags behind the most erosive rainfall events at the start of the rainy season.

Overall the MUSLE model was tended to underestimate the sediment yield in the study area that depicted in (Figure 18 and Table 7), which is in lined with the study conducted in Ethiopian highland by (Habtamu *et al*., 2013) and similar results were obtained by (Ashish *et al*., 2009; Odongo *et al*., 2013). On the other hand, the result contradicts with the findings reported by (Sadeghi *et al*., 2004, Ma, 2006 and Jaramillo, 2007), reported as MUSLE tends to overestimate the sediment yield.

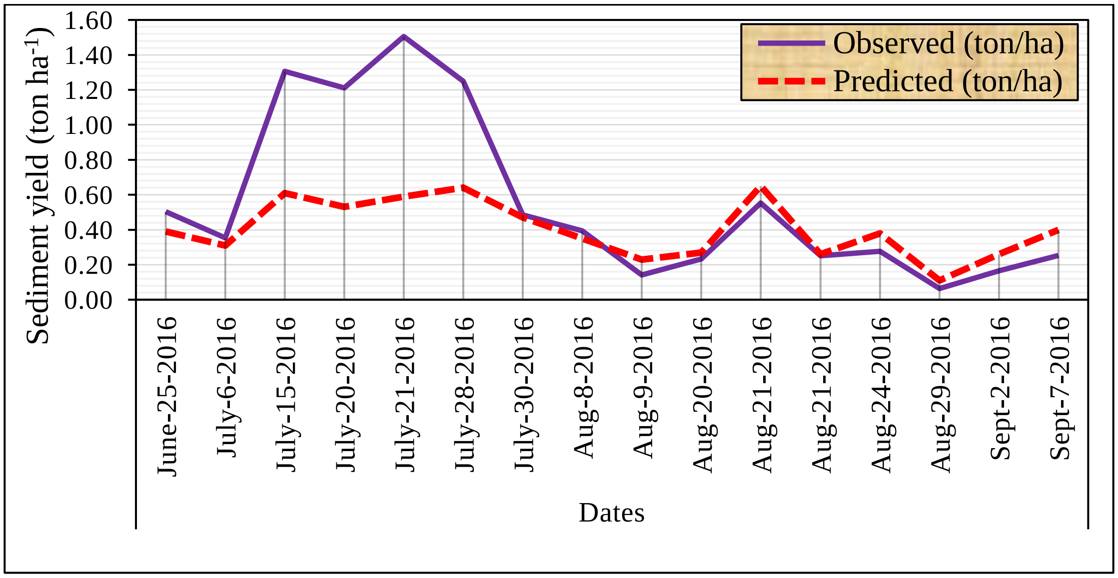

Figure 18. Event-based observed and predicted sediment yield in Gumara-Maksegnit

Indeed, soil erosion was assessed in the study area using soil and water assessment tool (SWAT) and water erosion prediction project (WEPP) models by (Addis *et al*., 2016; Nigus *et al*., 2017). The models provide a satisfactory prediction of runoff while sediment prediction was low in both models especially the sediment simulation using SWAT conducted by (Addis *et al*., 2016) in the study area does not give a satisfactory result.

4.3.2 Sediment yield estimation in treated and untreated sub-catchments

Treated and untreated sub-catchments are located in Gumara-Maksegnit watershed, established primarily to evaluate the impact of conservation measures on surface runoff and soil erosion processes. The treated sub-catchment was maintained mainly by level stone bunds and the untreated sub-catchment was considered as a reference watershed for comparison.

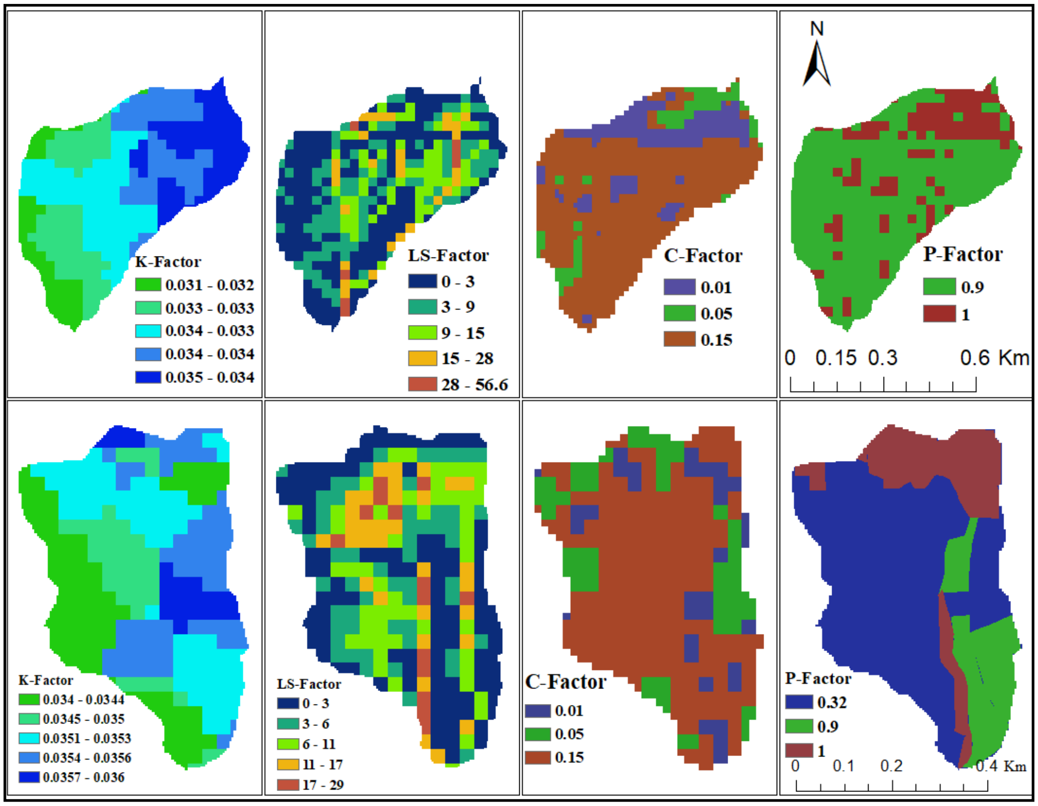

Figure 19. Model factor maps for untreated (top) and treated (bottom) sub- catchments

To estimate sediment yield using MUSLE, the model parameters were prepared and computed independently for treated and untreated sub-catchments. Similar procedures were followed as the entire watershed to compute and manage the model parameters.

Hence, the mean value of the model parameters was computed and depicted in (Table 6). The observed and predicted sediment yields were compared statistically and presented graphically in (Figure 20). It's clearly showed that MUSLE is able to estimate event-based sediment yield in the study sub-catchments.

Table 9. Observed and estimated sediment yield in untreated and treated sub-catchments

No	**Event date**	**Untreated catchment (ton ha^{-1})**			**Treated catchment (ton ha-1)**		
		Observed	**Predicted**	**RE (%)**	**Observed**	**Predicted**	**RE (%)**
1	June-25-2016	1.32	0.50	-62.12	0.68	0.43	-36.76
2	July-6-2016	1.07	0.45	-57.94	0.33	0.22	-33.33
3	July-15-2016	2.88	1.87	-35.07	1.17	0.77	-34.19
4	July-20-2016	1.76	2.16	22.73	0.60	0.52	-13.33
5	July-21-2016	1.59	1.32	-16.98	0.82	0.60	-26.83
6	July-28-2016	2.85	2.48	-12.98	0.95	0.66	-30.53
7	July-30-2016	1.24	1.21	-2.42	1.17	0.82	-29.91
8	Aug-8-2016	1.34	1.21	-9.70	0.40	0.30	-25.00
9	Aug-9-2016	0.35	0.34	-2.86	0.27	0.12	-55.56
10	Aug-20-2016	0.22	0.16	-27.27	0.37	0.13	-64.86
11	Aug-21-2016	0.87	1.54	77.01	0.69	1.29	86.96
12	Aug-21-2016	0.14	0.53	278.57	0.11	0.10	-9.09
13	Aug-24-2016	0.15	0.51	240.00	0.13	0.10	-23.08
14	Aug-29-2016	0.34	0.54	58.82	0.04	0.09	125.00
15	Sept-2-2016	0.54	0.74	37.04	0.17	0.14	-17.65
16	Sept-7-2016	0.45	0.68	51.11	0.30	0.42	40.00
	Mean	**1.0694**	**1.0150**	**-5.08**	**0.5125**	**0.4194**	**-18.16**
	STDEV	**0.8773**	**0.698**		**0.3685**	**0.3624**	

The mean value of observed and predicted sediment yield in both treated and untreated sub-catchments were not statistically significant at 5% level of significant while the probability value from paired sample test analysis was 0.133 and 0.649 respectively. The highest probability value for untreated catchment showed that the presence of a close relationship between observed and predicted sediment yields.

On the other hand, based on the model efficiency and goodness of fit assessment, the following results were obtained, R^2 (0.62, 0.72), RMSE (0.15, 0.23) and NSE (0.53, 0.71) for treated and untreated sub-catchments respectively. These results confirmed that there was a strong association between observed and estimated sediment yields in both treated and untreated sub-catchments. The RMSE is a measure of the error around the regression line that the smallest values of RMSE were obtained in both sub-catchments and that confirms MUSLE was performed well to estimate event-based sediment yield in the study area.

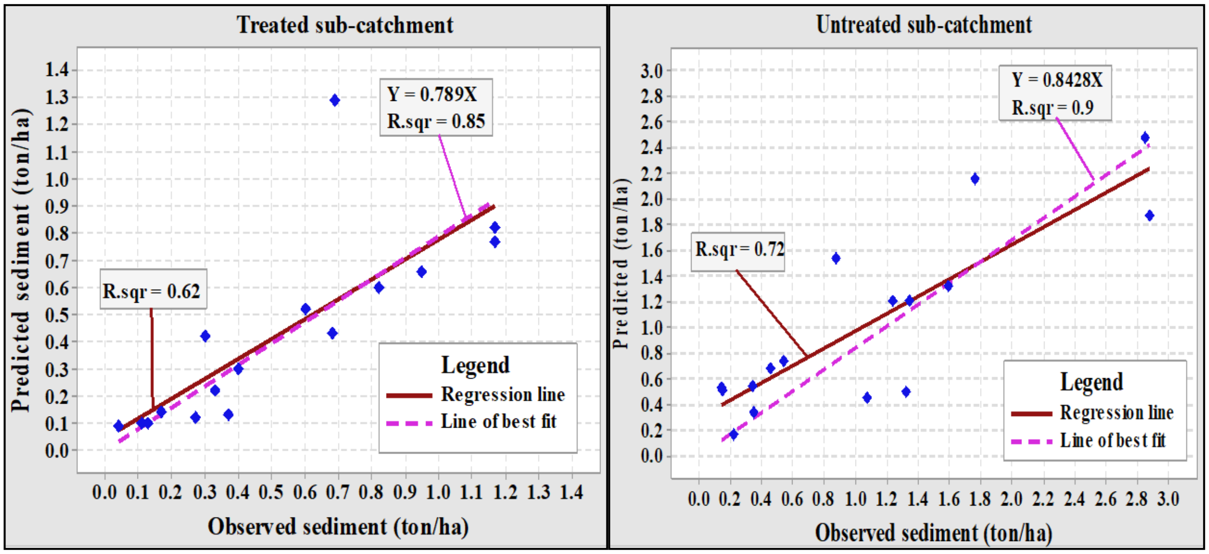

Figure 20. Comparison of event-based observed and estimated sediment yield

The regression as well as correlation coefficients close to one verified that there was a strong relationship between observed and predicted sediment yield in the study sub-catchments. However, there was a great variability of observed and predicted sediment yield within and between sub-catchments especially the events that occurred in June and July. It could be coming from storm characteristics and cover conditions.

The storms mostly occurred at the start of the rainy season are more intensive and thereby erosive in the study area when the vegetation cover lags behind the rainfall. In this situation, the absences of soil and water conservation measures could result in more soil erosion than conserved land.

4.4 The Effectiveness of Level Stone Bunds to Reduce Sediment Loss

Soil and water conservation measures are used to prevent the accelerated soil erosion by water through dissecting the slope length and gradient that helps to reduce the volume and velocity of runoff at the same time. Soil and water conservation measures are identified as the first line of defense that mostly acts as a barrier due to the creation of obstacles against surface runoff (Kebede, 2014).

Even though, the adjacent sub-catchments are similar in terms of topo-sequence and farming practice, the measured runoff depth in treated sub-catchment was reduced by 29.24% as compared to untreated sub-catchment which is consistent with the study conducted at a watershed level by (Addis *et al*., 2016), showed that the difference of measured runoff between treated and untreated sub-catchments was about 30%. Whereas, based on the plot experiment conducted by (Rieder *et al*. 2014; Klik *et al*., 2016), stone bunds were found to reduce surface runoff approximately by 60 to 80%.

Runoff is usually discharged with a certain amount of sediment from a given catchment. In this study, MUSLE was used to estimate the sediment losses from treated and untreated sub-catchments to evaluate the efficiency of conservation practices. Hence, a pair of estimated sediment losses from both catchments was statistically compared at 5% level of significance. The mean value of estimated sediment losses were 0.42 and 1.02 ton ha^{-1} for treated and untreated sub-catchments respectively and that referred us there was a highly significant difference between sub-catchments based on their sediment loss.

Table 10. Mean comparison of estimated sediment yield for treated and untreated catchments

Estimated sediment yield for paired sub-catchments	**Mean**	**Mean difference**	**N**	**Std. Deviation**	**Std. Error**	**t**	**df**	**Sig. (2-tailed)**
Untreated sediment (ton ha^{-1})	1.02	0.596	16	0.698	0.22	4.509	15	0.000
Treated sediment (ton ha^{-1})	0.42		16	0.343	0.086			

After comparison of a paired model parameters for treated and untreated sub-catchments, the most determinant model factors were identified. The mean values of model parameters presented in (Table 6) confirm that conservation practice and runoff factors are the most determinant factors of the model output with their mean values of (0.55 and 0.93) and (38.29 and 42.73 MJ mm ha^{-1} h^{-1}) for treated and untreated sub-catchments respectively. Hence, the combined effects of conservation practice and runoff factors on sediment loss prediction were about 51.2%.

Whereas, the other model parameters such as soil erodibility, topographic factors and cover management factor were not significantly different between treated and untreated sub-catchments. In this study, the estimated sediment loss in treated catchment was reduced by 58.8% as compared to untreated catchment and which is consistent with (Nigussie *et al*., 2015), confirms that conservation measures are able to reduce soil loss by 65% in average with a large regional variation. On the other hand, Adimassu *et al*., (2016) reported as, stone bunds can be reduced sediment loss by roughly 50% as compared to untreated plots.

The result was also in agreement with the research finding conducted at watershed level in the study area by (Nigus *et al*., 2017), verified that soil and water conservation structures were considerably reduced soil loss by as much as 25-38% in the treated sub-catchment. On the other hand, the plot level study conducted in sub-catchments of Gumara Maksegnit watershed showed that conservation measures able to reduce soil erosion by 33–41% (Rieder *et al*., 2014; Strohmeier *et al*., 2015; Klik *et al*., 2016). Therefore, successful implementation of stone bunds in the study area, as well as similar agroecologies, has a great benefit through enhancements of land productivity by reducing surface runoff and thereby sediment loss.

4.5 Sediment Yield Prediction Efficiency of MUSLE

The sediment yield prediction efficiency of the model was assessed based on the model efficiency and goodness of fit assessment criteria's and the following results were obtained.

The Coefficient of determination (R^2) is a measure of the functional relationship between two variables. Hence, the value of R^2 for observed and predicted sediment yield was (0.7, 0.62 and 0.72) for Gumara-Maksegnit watershed and its treated and untreated sub-catchments respectively. The result confirms that there was a close relationship between the estimated and observed sediment yield.

The result is in lined with the plot level study which is conducted by (Habtamu *et al*., 2013), in Ethiopian highland with an efficiency of 0.72. This was due to the direct consideration of runoff as an input factor for MUSLE model which is found to be a better indicator than rainfall for soil erosion prediction. Other similar findings were reported by (Sadeghi and Mizuyama, 2007; Ashish *et al*., 2009; Arekhi *et al*., 2010; Sundara *et al*., 2015), verified that MUSLE model is able to estimate sediment yield with a coefficient of determination values ranges from 0.77 to 0.99.

Root mean square error (RMSE) is a frequently used measure of the difference between values predicted by a model and the values actually observed from the environment that is being modeled. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power.

The resulting RMSE between observed and estimated sediment yield in the study watersheds were (0.152, 0.15 and 0.23) Gumara-Maksegnit watershed and its treated and untreated sub-catchments respectively. Hence the smallest value of RMSE indicates that the better model performance and inferred that MUSLE was well performed to estimate the sediment yield in the study watershed.

The Nash-Sutcliffe Efficiency (NSE) is commonly used to assess the predictive power of hydrological discharge models. The NSE value of Gumara-Maksegnit watershed was 0.34 and which is not satisfactory but acceptable for modeling processes in natural phenomena. Unlike RMSE the low value of NSE represents high deviation between observed and predicted sediment yield. Whereas, the NSE values of treated and untreated sub-catchments were (0.53 and 0.71) respectively and the result confirmed that there were a strong association between observed and estimated sediment yields in both treated and untreated sub-catchments.

Even though the model performs well in the prediction of sediment loss for all study watersheds, the degree of prediction was different across the watersheds under different land management options. The model was generally underestimated the sediment losses by (±27.8, ±18.16 and ±5.08%) for Gumara Maksegnit watershed and its treated and untreated sub-catchments. This variability is directly related to the conservation practices and runoff factors which are depicted in (Table 6) and that confirms, there was a significant difference of these factors across the study catchments under different land management options.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The study was conducted in Gumara-Maksegnit watershed and its sub-catchments, which is located in Lake Tana basin to estimate the sediment yield and to study the impacts of level stone bunds on soil erosion processes. In this study, MUSLE model was applied with the help of remote sensing and ArcGIS technologies to provide a tool for conservation planning. Remote sensing and GIS were used to detect, manage and preprocess the spatial data, as well as to combine the raster layers of model parameters together using raster calculator in map algebra to determine event-based sediment yield.

The event-based sediment yield in the study area was estimated by multiplying the respective raster-based model parameters including the runoff as an independent factor. The runoff factor was computed from a direct measurement of runoff volume and peak discharges in a combination of conceptual factors and the resulting mean values of runoff factors were 38.29, 42.73 and 15.88 MJ mm ha^{-1} h^{-1} for the treated, untreated and Gumara-Maksegnit watersheds.

Soil erodibility factor was estimated through interpolation of the point erodibility factors derived from the observed physical and chemical properties of the soil in the study area. Hence, the mean values of soil erodibility in the study watersheds were 0.0350, 0.0332 and 0.0309 ton $MJ^{-1}mm^{-1}$ for treated, untreated and Gumara-Maksegnit watershed respectively. On the other hand, the topographic factors were derived directly from 30meter spatial resolution DEM with the help GIS and the mean values were (5.8245, 6.0352 and 13.7614) for treated, untreated and Gumara-Maksegnit watershed.

Whereas, the cover management and conservation practice factor were determined from land use and land cover classes and identified conservation interventions in the study area. Accordingly, the mean values of cover management factors were (0.1114, 0.1113 and 0.0983) for treated, untreated and Gumara-Maksegnit watershed respectively. On the other hand, the mean values of conservation practice factors were (0.5509, 0.9240 and 0.6770) for treated, untreated and Gumara-Maksegnit watershed respectively.

Finally, all six MUSLE model factors were combined together to estimate the storm wise sediment yields using the raster calculator in map algebra. The resulting mean values of event-based observed and estimated sediment yields were (0.5125, 0.4194) Mg ha^{-1} for treated sub-catchment, (1.0694, 1.0150) Mg ha^{-1} for untreated sub-catchment and (0.5581, 0.4031) Mg ha^{-1} for Gumara-Maksegnit watershed respectively.

The paired mean comparison result in t-test statistics showed that the observed and estimated sediment yields were not significantly different at 5% level of significance within a watershed. Indeed, based on the model goodness of fit criteria the application of MUSLE was well performed to estimate the sediment yield in the study area with R^2 (0.62, 0.72 and 0.7) and NSE (0.53, 0.71 and 0.34) for treated, untreated and Gumara-Maksegnit watershed respectively. This result confirmed that there was a strong association between observed and estimated sediment yield in all study watersheds.

On the other hand, the sediment losses from treated and untreated sub-catchments were highly significantly different. Their difference obviously comes from the variation of input parameters of the model across sub-catchments. The results from parameter computation showed that conservation practice and runoff factors were the most influential factors of the model output with their combined effects on sediment loss ranges about 51.2%. In general, the results of conservation impact modeling showed that modification of the land with soil and water conservation has a capacity of reducing sediment loss by 58.8% as compared to untreated sub-catchments.

Generally, the result revealed that the model tends to underestimate for the events that occurred in June and July and overestimate for the events that occurred in August and September. The instability of model prediction could be coming from a seasonal variation of vegetation cover dynamics that lags behind the most intensive storm events occurred at the start of the rainy season.

5.2 Recommendations

The result showed that the most determinant factor that strongly affects the model output was conservation practices factor after comparison of a paired model factor values of treated and untreated sub-catchments. Indeed, level stone bunds are able to reduce the amount of runoff through dissecting the slope length and gradient. Therefore, the intervention of soil and water conservation measures in the study area and similar agroecologies is important to modify and dissect the slope length and gradient thereby the runoff discharged with the sediment could be reduced.

The model tends to underestimate at the start of the rainy season and overestimate at the end of the rainy season that could be related to the temporal variation of sediment concentration as a result of the vegetation cover lags behind the rainfall. Therefore, the study of the seasonal dynamics of vegetation cover is required to get more consistent model outputs.

In genral, MUSLE was performed well to estimate sediment loss without any modifications and inferred that recommended for reliable application of better soil and water conservation planning in the study area as well as similar agroecologies. To regionalize the results of the study a number of case studies in different parts of the country to be considered by the researchers.

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Appendix

Appendix Table 1. Characteristics of selected storms in Gumara-Maksegnit watershed

No.	Date of events	Rainfall (mm)	Peak flow (m^3 s^{-1})	Runoff volume (m^3)	Observed sediment (Mg ha^{-1})
1	25-06-2016	15	34.44	212,027.88	0.50
2	06-07-2016	13.5	32.27	151,997.88	0.35
3	15-07-2016	30	48.33	332,525.63	1.31
4	20-07-2016	30.5	48.23	257,258.96	1.21
5	21-0.7-2016	32.6	49.83	307,504.53	1.51
6	28-07-2016	29.2	56.33	310,501.89	1.25
7	30-07-2016	26.8	42.45	242,953.40	0.49
8	08-08-2016	21.6	33.62	180,751.77	0.39
9	09-08-2016	13.2	33.03	84,786.37	0.14
10	20-08-2016	16.4	40.81	94,710.18	0.23
11	21-08-2016	31.6	54.43	334,011.72	0.55
12	23-08-2016	12.9	30.62	119,174.80	0.25
13	24-08-2016	13	35.95	194,613.00	0.28
14	29-08-2016	12.8	12.89	58,693.04	0.06
15	25-06-2016	13.4	26.77	130,581.87	0.16
16	06-07-2016	21.6	37.34	203,536.02	0.25

Appendix Table 2. Characteristics of selected storms in treated and untreated catchments

No.	Date of events	Rainfall (mm)	Untreated			Treated		
			Peak flow (m^3 s^{-1})	Runoff (m^3)	Observed Sed.(Mg ha^{-1})	Peak flow (m^3 s^{-1})	Runoff (m^3)	Observed Sed.(Mg ha^{-1})
1	25-06-2016	15	0.85	1,637.58	1.32	2.85	873.18	0.68
2	06-07-2016	13.5	0.66	1,378.53	1.07	0.80	976.82	0.33
3	15-07-2016	30	2.47	5,868.22	2.88	2.80	2,526.82	1.17
4	20-07-2016	30.5	3.09	6,085.15	1.76	1.50	2,308.93	0.60
5	21-0.7-2016	32.6	1.98	3,935.86	1.59	1.95	2,308.93	0.82
6	28-07-2016	29.2	4.34	5,540.32	2.85	2.25	2,362.38	0.95
7	30-07-2016	26.8	2.56	2,593.52	1.24	2.86	2,755.13	1.17
8	08-08-2016	21.6	1.54	4,328.35	1.34	1.27	1,039.50	0.40
9	09-08-2016	13.2	0.62	1,141.53	0.35	0.36	716.45	0.27
10	20-08-2016	16.4	0.18	1,044.06	0.22	0.44	709.93	0.37
11	21-08-2016	31.6	2.99	3,429.62	0.87	4.88	3,619.96	0.69
12	23-08-2016	12.9	1.96	771.70	0.14	0.44	413.07	0.11
13	24-08-2016	13	1.35	1,052.21	0.15	0.32	547.23	0.13
14	29-08-2016	12.8	1.25	1,268.95	0.34	0.31	513.38	0.04
15	02-09-2016	13.4	1.82	1,524.14	0.54	0.59	575.73	0.17
16	07-09-2016	21.6	1.64	1,452.34	0.45	1.72	1,399.07	0.30

Appendix Table 3. Sampling locations and soil physical and chemical properties

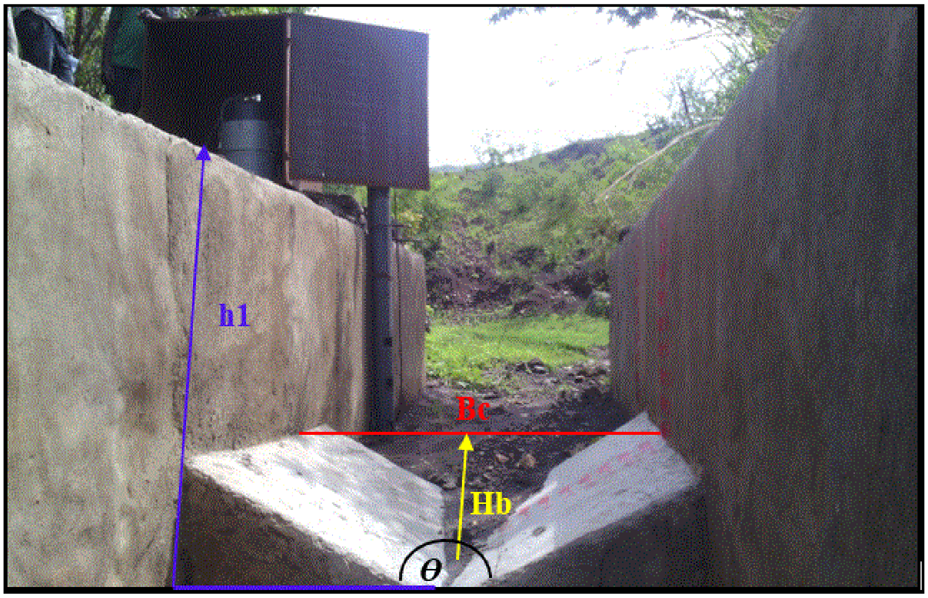
No	Sampling location		Soil structure			Soil texture (%)			Textural class	OM (%)
	Easting	**Northing**	**Shape**	**Size**	**Grade**	**Sand**	**Silt**	**Clay**		
1	346950	1383358	crumb	coarse	Weak	28.2	37.48	34.32	clay loam	2.46
2	347367	1383250	Granular	Fine	Weak	26.2	29.48	44.32	clay	3.16
3	347249	1382738	Granular	Fine	Weak	56.56	9.48	33.6	sandy clay loam	2.67
4	346200	1382210	Granular	fine	Weak	38.56	33.84	27.6	clay loam	3.23
5	348252	1382259	Blocky	Coarse	Weak	20.56	17.84	61.6	clay	2.25
6	347681	1381800	Granular	Fine	Weak	38.56	41.84	19.6	loam	3.72
7	348750	1381746	Granular	Fine	Weak	14.56	39.84	45.6	silty clay	2.88
8	345259	1381225	Blocky	Medium	Moderate	16.56	29.84	53.6	clay	2.39
9	343938	1380663	Granular	Very fine	Weak	38.56	43.84	17.6	loam	2.67
10	344899	1380807	Blocky	Medium	Weak	50.56	33.84	15.6	loam	3.37
11	345250	1380750	Granular	Medium	Moderate	44.56	37.84	17.6	loam	2.81
12	345743	1380746	Prismatic	Medium	Moderate	36.56	39.84	23.6	loam	4
13	348749	1380751	Granular	Fine	Weak	42.92	35.48	21.6	loam	4
14	343732	1380245	Granular	Fine	Weak	34.56	41.84	23.6	loam	2.88
15	344249	1380250	Granular	Medium	Moderate	36.56	39.84	23.6	loam	3.09
16	345217	1380262	Granular	Medium	Weak	44.56	35.84	19.6	loam	4
17	346282	1380307	Granular	Fine	Weak	32.92	35.48	31.6	clay loam	3.51
18	346767	1380256	Granular	Fine	Weak	38.92	37.48	23.6	loam	0.49
19	347750	1380252	Granular	Fine	Weak	32.92	39.48	27.6	clay loam	3.02
20	348905	1380319	Granular	Fine	Weak	44.92	31.48	23.6	loam	2.25
21	349249	1380251	Granular	Fine	Weak	44.92	27.48	27.6	clay loam	3.16
22	343784	1379692	Granular	Fine	Weak	46.56	29.84	23.6	loam	2.25
23	345249	1379750	Blocky	Medium	Moderate	46.92	31.48	21.6	loam	2.11
24	345749	1379750	Granular	Medium	Moderate	42.92	37.48	19.6	loam	3.3
25	346249	1379750	Granular	Medium	Moderate	38.92	35.48	25.6	loam	1.26
26	346750	1379750	Blocky	Medium	Moderate	34.92	33.48	31.6	clay loam	1.97
27	347250	1379738	Blocky	Medium	Moderate	30.92	39.48	29.6	clay loam	1.97
28	348249	1379747	Granular	Fine	Weak	44.92	35.48	19.6	loam	3.65
29	348748	1379748	Prismatic	Medium	Weak	34.92	41.48	23.6	loam	1.61
30	349738	1379755	Granular	Fine	Weak	38.92	27.48	33.6	clay loam	2.67
31	343819	1379274	Granular	Fine	Weak	46.56	31.84	21.6	sandy clay loam	3.37
32	344252	1379254	Granular	Fine	Weak	34.56	39.84	25.6	loam	3.37
33	344812	1379200	Granular	Fine	Weak	36.92	37.48	25.6	loam	3.37
34	345210	1379218	Granular	Medium	Moderate	38.92	35.48	25.6	loam	1.33
35	345691	1379247	Granular	Fine	Weak	43.28	33.84	22.88	loam	1.97
36	346270	1379193	Granular	Medium	Moderate	27.28	39.84	32.88	clay loam	2.53
37	346751	1379250	Granular	Fine	Weak	29.28	43.84	26.88	clay loam	2.67

38	347227	1379194	Granular	Fine	Weak	47.28	33.84	18.88	loam	1.61
39	347754	1379242	Granular	Very fine	Weak	45.28	33.84	20.88	loam	1.9
40	348257	1379243	Granular	Very fine	Weak	33.28	43.84	22.88	loam	3.02
41	348749	1379249	Granular	Very fine	Weak	45.28	35.84	18.88	loam	1.33
42	349314	1379245	Granular	Very fine	Weak	31.28	43.84	24.88	loam	3.51
43	349600	1379336	Granular	Very fine	Weak	41.28	39.84	18.88	loam	3.37
44	343768	1378561	Granular	Very fine	Weak	36.56	37.84	25.6	loam	2.95
45	344300	1378743	Granular	Medium	Moderate	56.56	29.84	13.6	sandy loam	3.72
46	344650	1378751	Granular	coarse	Strong	27.28	49.84	22.88	loam	2.81
47	345256	1378748	Prismatic	Medium	Weak	37.28	39.84	22.88	loam	1.33
48	345749	1378750	Platy	Medium	Moderate	49.28	33.84	16.88	loam	3.02
49	346250	1378751	prismatic	Medium	Strong	17.25	31.84	50.88	clay	1.12
50	347250	1378748	Platy	Medium	Weak	37.28	35.84	26.88	loam	2.04
51	347750	1378750	Columnar	Medium	-	27.28	43.84	28.88	clay loam	2.39
52	348750	1378747	Granular	fine	Weak	33.28	45.84	20.88	loam	3.51
53	344249	1378249	Granular	Medium	Weak	30.56	41.84	27.6	clay loam	1.54
54	344777	1378239	Blocky	Medium	Moderate	29.28	35.84	34.88	clay loam	1.68
55	345260	1378246	Granular	Medium	Moderate	33.28	33.84	32.88	clay loam	1.97
56	345746	1378254	Granular	Medium	Weak	43.28	22.88	33.84	clay loam	1.26
57	346232	1378130	Granular	Medium	Weak	35.28	39.84	24.88	loam	1.82
58	347302	1378224	Granular	Medium	Moderate	31.28	39.84	28.88	clay loam	1.4
59	348244	1378255	Granular	very fine	Weak	45.28	35.84	18.88	loam	1.26
60	348650	1378397	Granular	very fine	Moderate	37.28	41.84	20.88	loam	1.97
61	349350	1378380	Granular	fine	Weak	35.28	41.84	22.88	loam	0.7
62	343829	1377761	Granular	very fine	Weak	44.56	33.12	22.32	loam	3.51
63	344243	1377726	Granular	very fine	Weak	48.56	37.12	14.32	loam	0.98
64	344750	1377751	prismatic	coarse	Strong	30.56	41.12	28.32	clay loam	2.04
65	345253	1377748	Granular	coarse	Strong	24.56	27.12	48.32	clay	2.74
66	345753	1377750	Granular	Medium	Moderate	43.28	33.84	22.88	loam	1.12
67	346250	1377751	Granular	Medium	Moderate	26.56	25.12	48.32	clay	2.74
68	347250	1377747	Granular	Medium	Moderate	41.28	35.84	22.88	loam	0.98
69	347749	1377749	Granular	fine	Weak	34.56	45.12	20.32	loam	0.84
70	348251	1377751	Blocky	Medium	Moderate	38.56	41.12	20.32	loam	0.91
71	344283	1377275	Granular	very fine	Weak	44.56	35.12	20.32	loam	1.68
72	345237	1377260	Blocky	coarse	Moderate	34.56	27.12	38.32	clay loam	0.21
73	346198	1377217	prismatic	coarse	Strong	34.56	37.84	27.6	loam	3.09
74	346750	1377252	Granular	Medium	Moderate	36.56	43.12	20.32	loam	2.11
75	347749	1372750	Blocky	coarse	Strong	42.56	33.12	24.32	loam	1.82
76	348249	1377252	Granular	Fine	Weak	36.56	39.12	24.32	loam	0.98
77	348750	1377253	Granular	Medium	Weak	42.56	39.12	18.32	loam	2.53
78	349249	1377250	Granular	Fine	Weak	38.56	35.12	26.32	loam	0.42

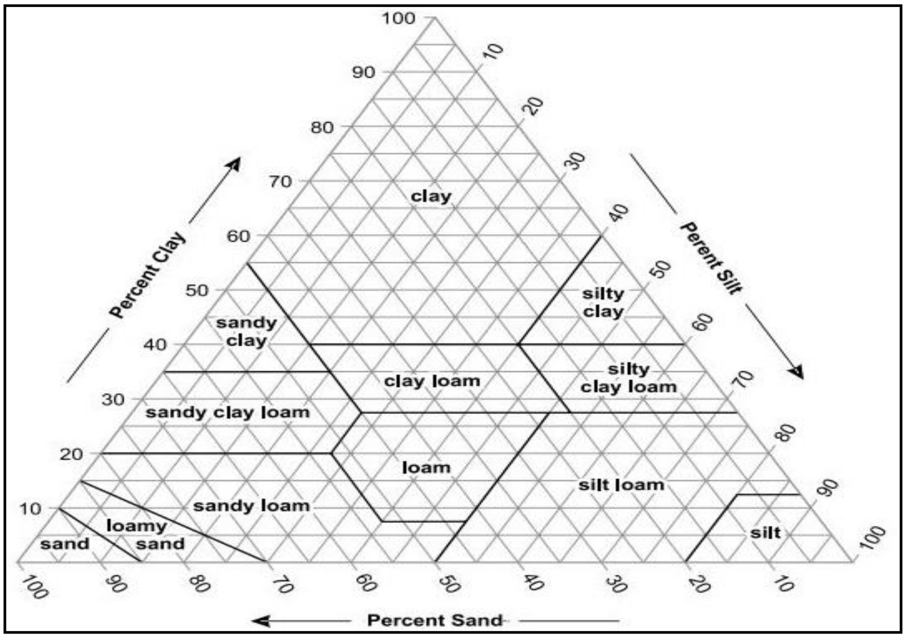
79	344215	1376605	Granular	very fine	Weak	48.56	33.12	18.32	loam	2.39
80	344735	1376746	Granular	fine	Weak	42.56	35.12	22.32	loam	1.68
81	345262	1376755	Blocky	coarse	Moderate	36.56	23.68	39.76	clay loam	2.18
82	345748	1376752	Blocky	coarse	Strong	25.64	27.48	46.88	clay	1.82
83	346241	1376762	Granular	fine	Weak	40.56	43.12	16.32	loam	4
84	346752	1376749	Granular	Medium	Moderate	32.56	43.12	24.32	loam	1.47
85	348253	1376714	Granular	very fine	Weak	42.56	37.12	20.32	loam	3.58
86	344774	1376259	Granular	Medium	Weak	42.56	35.12	22.32	loam	2.39
87	345235	1376259	Granular	coarse	Moderate	19.28	27.12	53.6	clay	1.12
88	345757	1376256	Blocky	coarse	Strong	19.64	25.48	54.88	clay	1.12
89	343187	1376279	Blocky	coarse	Strong	27.64	29.48	42.88	clay	1.33
90	347794	1376280	Granular	very fine	Weak	34.56	41.12	24.32	loam	2.95
91	344753	1375753	Granular	Medium	Moderate	27.64	41.48	30	clay loam	3.02
92	345284	1375775	Platy	Medium	Moderate	39.28	29.12	31.6	clay loam	0.42
93	345744	1375747	Blocky	coarse	Strong	17.64	37.48	44.88	clay	2.25
94	346227	1375782	Granular	Fine	Weak	39.28	31.12	29.6	clay loam	2.95
95	346771	1375751	Granular	Medium	Moderate	44.56	35.12	20.32	loam	0.7
96	347225	1375746	Granular	fine	Weak	40.56	37.12	22.32	loam	0.98
97	347751	1375750	Granular	Fine	Weak	38.56	41.12	20.32	loam	3.09
98	349249	1375751	Granular	Medium	Moderate	34.56	41.12	24.32	loam	3.93
99	344690	1375314	Granular	fine	weak	44.56	37.12	18.32	loam	2.75
100	345225	1375229	Granular	Coarse	strong	27.28	29.12	43.6	clay	0.91
101	345738	1375220	Blocky	Coarse	strong	20.2	25.48	54.32	clay	1.82
102	346238	1375259	Granular	fine	weak	46.56	33.12	20.32	loam	0.63
103	346748	1375249	Blocky	Medium	Moderate	31.28	35.12	33.6	clay loam	3.93
104	347250	1375251	Granular	fine	weak	35.28	45.12	19.6	loam	0.98
105	347752	1375250	Granular	fine	weak	44.56	41.12	14.32	loam	3.09
106	349257	1375250	Granular	fine	Moderate	37.64	39.48	22.88	loam	2.88
107	344380	1374735	Granular	Medium	Moderate	42.56	35.12	22.32	loam	1.47
108	344751	1374773	Granular	Medium	Moderate	31.84	32.4	35.76	clay loam	0.91
109	345188	1374774	Granular	Medium	Moderate	34.4	41.76	23.84	loam	1.12
110	345734	1374759	Blocky	Coarse	strong	25.64	19.48	54.88	clay	1.12
111	346748	1374766	Granular	Medium	Moderate	42.56	29.12	28.32	clay loam	1.33
112	347249	1374750	Granular	Medium	weak	48.56	33.12	18.32	loam	0.98
113	347752	1374750	Granular	fine	weak	42.56	39.12	18.32	loam	0.42
114	348252	1374750	Granular	Medium	Moderate	50.56	29.12	20.32	loam	0.28
115	348750	1374750	Prismatic	Medium	strong	27.28	23.12	49.6	clay	0.7
116	349247	1374750	Granular	fine	weak	30.56	45.12	24.32	loam	1.97
117	345250	1374253	Blocky	Medium	strong	19.64	25.48	54.88	clay	0.98
118	345751	1374251	Blocky	very course	strong	25.64	29.48	44.88	clay	1.4
119	346250	1374250	Blocky	Coarse	Moderate	29.84	32.4	37.76	clay loam	1.68

120	346750	1374250	Granular	Medium	Moderate	40.56	39.12	20.34	loam	0.84
121	347248	1374248	Blocky	Medium	Moderate	43.28	23.12	33.6	clay loam	2.18
122	347752	1374247	Granular	Medium	weak	47.28	33.32	19.6	loam	2.18
123	348251	1374248	Blocky	Coarse	weak	51.64	29.48	18.88	loam	3.23
124	348750	1374250	Blocky	Coarse	strong	33.28	23.12	43.6	clay	1.12
125	349250	1374248	Blocky	Coarse	weak	43.28	31.12	25.6	loam	0.42
126	349748	1374250	Granular	fine	Moderate	34.56	27.12	38.32	clay loam	0.42
127	345254	1373751	platy	Coarse	Moderate	26.56	19.68	53.76	clay	1.47
128	345754	1373753	Blocky	Coarse	strong	30.56	11.68	57.76	clay	1.54
129	346305	1373790	Blocky	Coarse	strong	23.84	22.4	53.76	clay	1.4
130	346749	1373749	Blocky	Coarse	strong	26.2	27.48	46.32	clay	0.98
131	347251	1373751	Blocky	Coarse	Strong	28.2	27.48	44.32	clay	2.32
132	347749	1373750	Granular	Medium	Moderate	25.64	25.48	48.88	clay	1.12
133	346751	1373751	columnar	fine	weak	43.28	33.12	23.6	loam	3.44
134	348762	1373749	Blocky	Medium	Moderate	38.56	23.68	37.76	clay loam	2.53
135	349250	1373750	Granular	Medium	weak	49.64	33.48	16.88	loam	1.82
136	346750	1373750	Granular	fine	weak	42.56	43.12	14.32	loam	0.49
137	345774	1373247	Blocky	Coarse	strong	30.56	29.68	39.76	clay loam	2.11
138	346265	1373253	Blocky	Coarse	strong	28.56	25.68	45.76	clay	1.4
139	346755	1373257	columnar	Coarse	strong	27.84	24.4	47.76	clay	1.47
140	347250	1373250	Blocky	Coarse	strong	32.56	25.68	41.76	clay	1.4
141	347750	1373250	Blocky	Coarse	strong	25.84	22.4	51.76	clay	1.12
142	348246	1373244	Granular	Medium	Moderate	21.84	45.76	32.4	clay loam	1.33
143	348750	1373250	platy	Medium	Moderate	22.2	25.48	52.32	clay	0.98
144	349253	1373250	Granular	Medium	Moderate	38.56	33.12	28.32	clay loam	2.25
145	344764	1372773	Blocky	Coarse	strong	28.56	19.68	51.76	clay	1.47
146	345236	1372747	Blocky	Coarse	strong	20.56	13.68	65.76	clay	1.68
147	345750	1372750	platy	Medium	strong	19.84	30.4	49.76	clay	1.82
148	346250	1372750	platy	Medium	strong	18.56	19.68	61.76	clay	1.47
149	346750	1372750	Blocky	Coarse	strong	20.56	11.68	67.76	clay	1.97
150	347749	1372750	Blocky	Coarse	strong	16.2	19.48	64.32	clay	1.33
151	348249	1372750	platy	Coarse	strong	20.2	23.48	56.32	clay	1.4
152	348751	1372751	platy	Coarse	strong	23.84	22.4	53.76	clay	1.4
153	343782	1372408	Blocky	very course	strong	30.56	13.68	55.76	clay	1.68
154	344250	1372250	Blocky	very course	strong	31.84	24.4	43.76	clay	1.68
155	344858	1372203	Blocky	Coarse	Moderate	32.56	33.12	34.32	clay loam	0.56
156	345250	1372250	Blocky	Coarse	Moderate	27.84	30.4	41.76	clay loam	1.68
157	345750	1372250	Granular	Medium	strong	27.84	26.4	45.76	clay	0.42
158	344132	1371540	Granular	very course	strong	24.2	23.48	52.32	clay	1.33
159	344750	1371750	Granular	Medium	Moderate	27.28	31.12	41.6	clay loam	0.56
160	345268	1371735	Granular	Coarse	strong	31.64	23.48	44.88	clay	0.63

161	344024	1370905	columnar	Medium	Moderate	18.2	33.48	48.32	clay	1.33
162	344750	1371250	Blocky	Coarse	strong	22.2	21.48	56.32	clay	1.61



Appendix Figure 1. Broad-crested weir with truncated triangular control section



Appendix Figure 2. USDA textural triangle used to identify basic textural classes

Source: USDA Handbook 18, *(2017)*