Application of SWAT and GeoWEPP model in predicting the impact of stone bunds on runoff and erosion processes in the Northern Ethiopian Highlands

Final report
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Table of contents

Summary of the Report

This report consists of two parts. The first part of this report contains the 'modeling impact of soil and water conservation structures on runoff and erosion processes using SWAT, GeoWEPP and WEPP models in the Northern Ethiopian highlands'. The modeling study was conducted in the Landscape based Environmental System Analysis and Modeling Laboratory (LESAM) in the University at Buffalo, New York, USA. From this study one article is published in peer reviewed journals and the second one is under revision. The publications acknowledged the Marshall Plan foundations for the finical support.

1. **Nigus DM,** Renschler CS, Holzmann H, Strohmeier S, Bayu W, Zucca C, Ziadat C, Klik A (2017). Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the Northern Ethiopian highlands. Journal of Soils and Sediments. DOI: 10.1007/s11368-017-1901-3.

2. **Nigus DM,** Renschler CS, Flagler J, Bayu W, Klik A (2017). Assessing the impact of soil and water conservation structures on runoff and erosion processes through measurements and modeling. (*In revision at CATENA journal.)*
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3. **Nigus DM,** Renschler CS, Flagler J, Klik A (2017). Hillslope Simulation of surface runoff and soil loss using WEPP model based on field measurements in the highlands of Ethiopia. (Manuscript)

The second part of the report contains the general impression of the research stay abroad, quality of the host institution contacts within the host institution inclusion in the organization and recommendations for future Marshall Plan students and fellows.

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1. Introduction

Degradation of agricultural land as a result of soil erosion is a worldwide phenomenon leading to loss of nutrient-rich surface soil and increased runoff from the more impermeable subsoil that leads to lowering agricultural productivity (Erkossa et al. 2015; Taguas et al. 2015; Ganasri and Ramesh 2015; Keesstra et al. 2016; Nigussie et al. 2017). Soil erosion is more severe in the Sub-Saharan African countries where the population livelihood is dependent on the soil (Sunny et al. 2012; Erkossa et al. 2015). In the Ethiopian highlands deforestation for crop production, cultivation of marginal lands and overgrazing are the major factors that dramatically increased the vulnerability of agricultural lands to rainfall-driven soil erosion (Nyssen et al. 2000;Vancampenhout et al. 2006; Belay et al.2013; Adimassu et al. 2014; Erkossa et al. 2015; Addis et al. 2016).Intensive rainfall during the rainy season (June to September) threatens the mountainous regions to severe land degradation especially on the steep sloped and unprotected areas (Addis et al. 2016).To tackle the soil erosion problem in the Ethiopian highlands, constructing soil and water conservation structures is considered to be a top priority in halting land degradation and thus to improve agricultural productivity.

Since 2010 a massive effort has been undertaken by the government of Ethiopia in constructing soil and water conservation structures on private owned and community lands through community mobilization (Kebede 2014; Dagnew et al. 2015; Teshome et al. 2016; Dagnew et al. 2017; Girum et al. 2017; Guzman et al. 2017;). Examples of soil and water conservation practices include stone bunds, soil bunds, percolation ditches, etc are constructed (Teshome et al. 2016). However, the effectiveness of these soil and water conservation measures on the dynamics of runoff and sediment loading has not been sufficiently studied and identified clearly for long and short-term effects in the Ethiopian highlands.

In the Northern highlands of Ethiopia, different studies have been carried out on the impacts of soil and water conservation structures on erosion process at field scale (Kaltenleithneret al. 2014; Rieder et al. 2014; Strohmeier et al. 2015; Klik et al. 2016; Obereder et al. 2016). These studies reported that the SWC structures are effective at plot scale in the Gumara-maksegnit watersheds. However, studies on the impacts of soil and water structures on erosion process at watershed scale are limited. As data from field experiments cannot be extrapolated to a watershed scale

(Verstraeten et al. 2006), the use of mathematical models for evaluating soil and water conservation measures is quite common.

Insufficient information on soil erosion and streamflow could lead to inefficient planning and inadequate design and operation of soil and water resource management projects (Poitras et al. 2011). Changes in the extent of seasonal precipitation, frequency and intensity of extreme precipitation events directly affect the amount of seasonal streamflow (Poitras et al. 2011). The prediction and assessment of streamflow and sediment yield using a watershed model are important for agricultural watershed management in the Ethiopian highlands as watershed models are crucial tools to illustrate hydrological processes and to scale up the model results.

SWAT (Soil and Water Assessment Tool) (Arnold et al.1998) is a continuous-time, semi-distributed, process-based river basin or watershed scale model. The model is one of the most comprehensive models able to evaluate hydrologic processes (Gassman et al. 2007). SWAT has been employed to simulate the discharge in the Ethiopian highlands (Setegn 2008; Setegn et al. 2009; Easton et al. 2010; Setegn et al. 2010; Betrie et al. 2011; Setegn et al, 2011; Yasir et al. 2014).

GeoWEPP, the Geospatial interface of the Water Erosion Prediction Project (GeoWEPP) model, was developed to integrate the advanced features of GIS (Geographical Information System) within the WEPP (Water Erosion Prediction Project) model, such as processing digital data sources and generating digital outputs (Renschler et al., 2002; Renschler, 2003). The current version of GeoWEPP allows users to process digital data such as Digital Elevation Models (DEM), soil surveys, land use maps, and precision farming data (Flanagan et al., 2013). Required input data include slope, land cover types, soil map, land use types, and climate. Based on the initial delineation of watersheds and channels (Renschler et al., 2002), these other inputs are integrated into the spatial database of WEPP and using the GIS functions to run WEPP to simulate runoff, soil loss and sediment yields (Renschler and Flanagan, 2008).

Hence, the objective of this study was 1) to calibrate and validate the SWAT and GeoWEPP model for two watersheds with and without soil and water conservation (SWC) structures, 2) to study the impact of these structures on runoff and erosion processes, and 3) to provide feedback on the efficiency of the structures in reducing soil erosion in the watersheds and to advise future up-scaling.

2. Materials and Methods

2.1. Description of the study area

The two study watersheds, TW and UW, are located in the Gumara-Maksegnit watershed in northwest Ethiopia (Figure 1). The watershed drains into the Gumara river, which finally drains into Lake Tana. The two watersheds are located at 12°25’24’’ and 12°25’54’’ latitude and at 37°34’56’’ and 37°35’38’’ longitude and at an altitude ranging from 1998 to 2150 meter above sea level (Figure 5.1). The two study watersheds are neighboring each other at a distance of about 1 km between the outlets which embrace an area of 31.7 ha for the TW and 27.1 ha for the UW. About 80% of the area of the watersheds have >10 % slope. The soil types found in the watershed are Cambisol and Leptosol which are found in the upper and central part of the watershed, while Vertisol is found in the lower catchment. The watershed has a long term (1997-2015) annual rainfall of 1157 mm with 8% raining from June to September and a mean minimum and maximum temperatures of 13.3 °C and 28.5 °C (Addis et al., 2016).

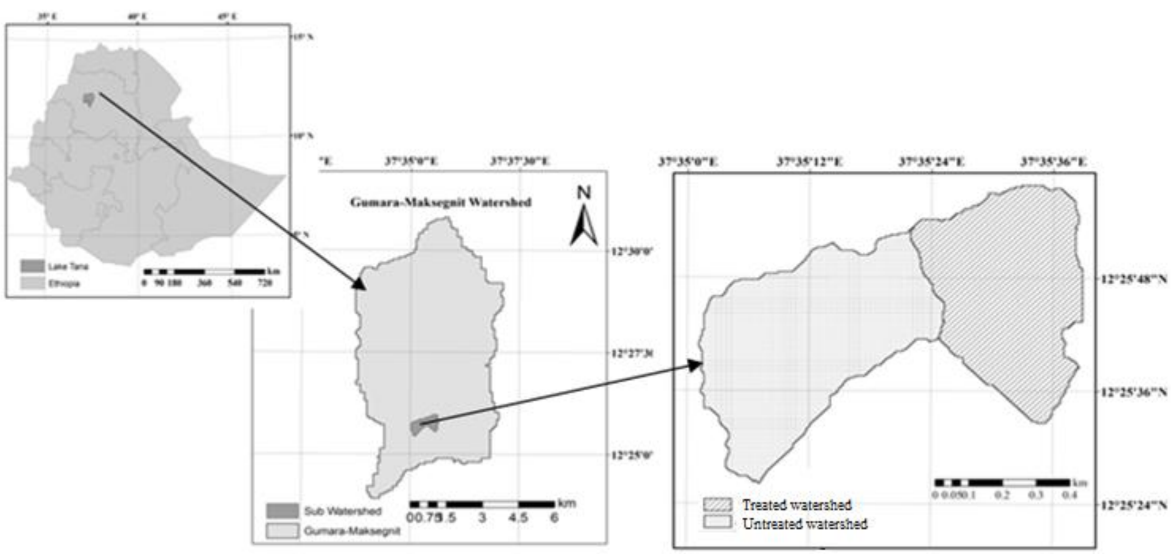


Figure 1 Maps of Ethiopia (left top), the larger Gumara-Maksegnit watershed (middle) and the two-paired watersheds (right)

In 2011 SWC structures mainly stone bunds were constructed in the first watershed (TW) (Figure 2). On farmlands 40 cm high stone bunds at distances ranging between 15 and 25 m depending on the steepness of the land were constructed. While in the gullies check dams at various intervals were constructed using gabions. The second watershed was used as a reference without SWC structures.

Figure 2 Erosion plot experiments (left) and SWC structures (right) at the treated watershed

2.2. SWAT model Application to predict the impact of SWC structures

Arc SWAT (Arnold *et al.,* 1998) was used to estimate the runoff and sediment yield in the TW and UW watersheds. Surface runoff was modified by the adjustment of the runoff ratio (Curve Number) while SWC structures impacts on sediment yield were adjusted through the support practice factor (P-factor) and/or the slope length factor (LS).

In this study, Curve Number values were modified by editing Management (.mgt) input table from the field experiment results (Klik *et al.,* 2016) while the SLSSUBSN value was modified by editing the HRU (.hru) input table. The model divides watersheds into a number of sub-basins during watershed delineation and adopts the concept of the Hydrologic Response Unit (HRU), which represents the unique property of each parameter. SWAT is able to simulate runoff based on separate HRUs, which are aggregated to generate output from each sub-basin. Model output results like surface runoff, sediment yield, soil moisture, nutrient dynamics, crop growth etc., are simulated for each HRU, aggregated and processed to sub-basin level results on a daily time step resolution. SWAT model requires input data, which can be supplemented with GIS data and the model interface (Di Luzio *et al.,* 2002).

For this study, SWAT offers finer spatial and temporal scales, which allows observing an output at a particular sub-basin on a daily base. It considers comprehensive hydrological processes, estimating surface runoff, sediment yield, nutrients, groundwater flow and channel processes within each sub-basin and at the watershed scale.

2.3. GeoWEPP model Application to assess the onsite and offsite soil loss and runoff

Daily precipitation and temperature data were collected from a weather station located at the outlet of the untreated watershed (UW). Daily solar radiation, relative humidity, and wind speed data were recorded from an automatic weather station installed at approximately 5 km away from the watersheds. The WEPP model was used to generate the climate file with the daily values of precipitation, temperature, solar radiation, and wind speed obtained from the weather stations. The WEPP model that uses CLIGEN was used to generate the climate input file (Zeleke et al., 1999).

2.4. WEPP Model application for Hillslope Simulation of surface runoff and soil loss

On farm plot experiment was conducted in 2012-2014 rainy season in the Gumara-maksegnit watershed, Ethiopia. Runoff monitoring system was established during the rainy season. 20 m long and 3 m wide erosion plots were established. Plots with an average slope of 9 % have been used for this study.

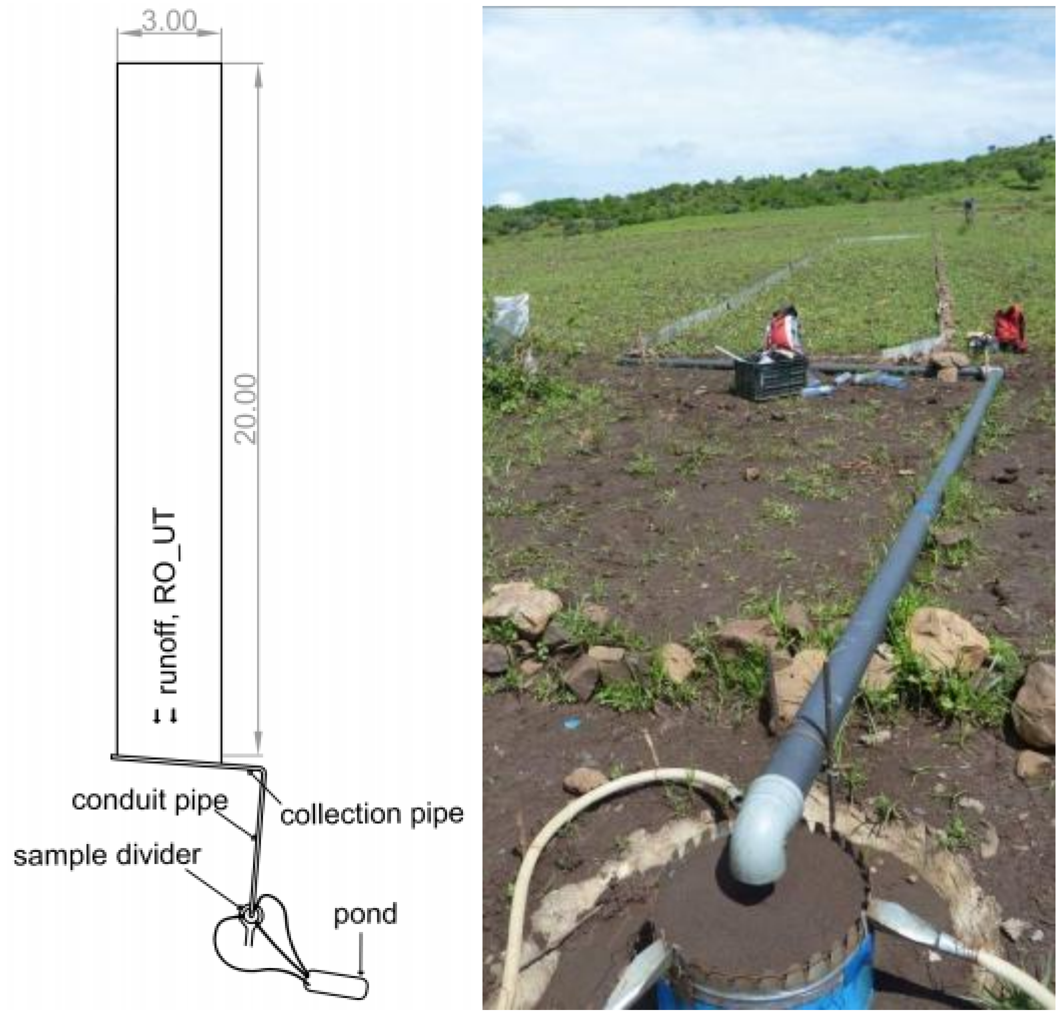


Figure 3 Experimental plot

The whole runoff generated on plot was directed to a system of collecting tanks with plastic tubes (Figure 3). Plastic tube with 10 cm of diameter was used to collect the whole surface runoff and to transfer to the sample dividers. Because of very high expected surface runoff, caused by high precipitation events, sample-dividers were used to divide the total runoff into 30 equal parts and transferred only about 10% of the total runoff into the collecting tanks. The collecting tanks were covered with plastic sheets and galvanized corrugated iron sheets to prevent raindrops and evaporation. To prevent runoff from adjacent fields, galvanized iron sheets was buried 10-15 cm deep in the ground around the perimeter of each plot. Protective nets/mesh wires were placed at the upstream gate of the plastic tubes to prevent leaves, branches, grasses and other residues.

The runoff volume and sediment yield was measured from the collection tanks in 2012-2014. Sediment samples were taken after the collected runoff stirred uniformly and the total sediment yield was determined in the laboratory. The whole runoff collected in the tanks was measured manually.

WEPP model was used to evaluate seasonal runoff and erosion data collected from an experiment comparing the management practices. The simulations were performed using WEPP for the period of 2012–2014, for which a comprehensive data set was available in terms of weather, soil properties and management practices. Model performance was assessed by comparing the model outputs to field measurements of annual runoff and erosion.

2.5. Model input

A DEM was developed based on conventional terrestrial surveying using total stations to obtain the topographic characteristics of the watersheds. The DEM was used to derive topographical parameters and automatically delineate watershed boundaries and channel networks. The -watersheds were divided into five slope steepness classes, namely: 0-10%, 10-20%, 20-30%, 30-40% and greater than 40% (Figure 4). The land use maps of both watersheds were evaluated based on the satellite image and ground truth data. A parcel as a polygon was developed containing a single land use using the Google earth imagery taken on 14/10/2011 and cross checking was done using the ground truth data. The study watersheds have nine land use classes (Figure 4). The land use percentages of each watershed are summarized in Table 1.

Table 1 Land use and land cover in the Untreated and treated watersheds

Land use type	Untreated watershed (UW)	Treated watershed (TW)
Barley	4.7%	2.3%
Lentils	6.2%	4.6%
Green Beans	5.9%	7.4%
Pasture	2.4%	6.9%
Corn	10.1%	5.1%
Mixed forest	33.2%	30.4%
Grain sorghum	28.4%	27.3%
Eragrostis teff	4.1%	9.1%
Wheat	5.0%	6.9%
Total	100%	100%

Intensive soil sampling was carried out to determine selected soil properties in a 100 meter by 100 meter grid in the two watersheds. At each location, about two kilograms of bulk soil were taken from different soil layers (0-25cm), (25-60cm) and (60-100cm) for physical and chemical analyses. Spatial distribution of soil textures and other soil properties were determined in the field and in the laboratory. The major soil textural classes in the UW are clay (3.7%), clay loam (52.9%), loam (36.3%), silty clay loam (4.7%) and silty loam (2.9 %). In TW, the major soil types are clay (12.4%), clay loam (50.7%), loam (23.4%), silty clay loam (0.16%) and silty loam (12.9 %) (Figure 4).

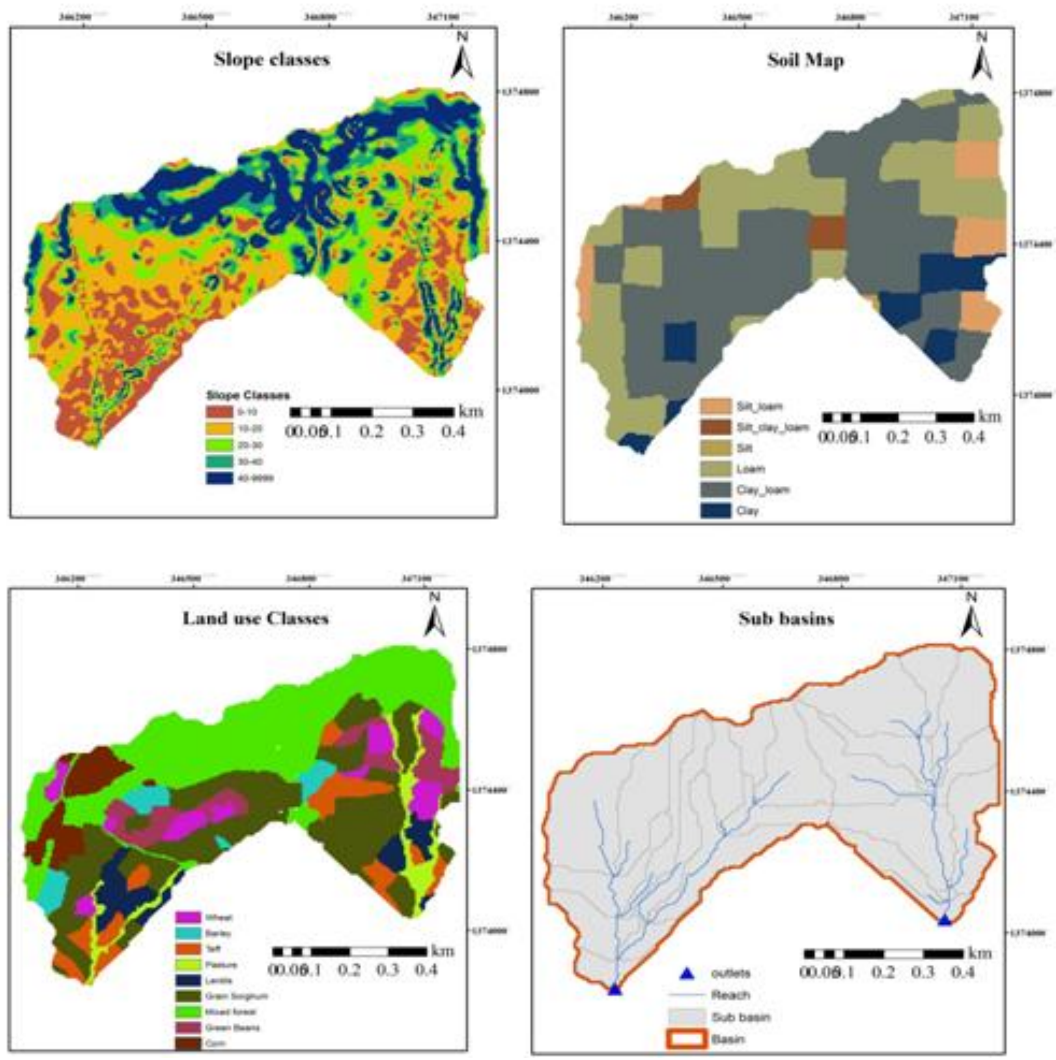


Figure 4 Slope classes, soil map, land use classes and sub-basins of both watersheds

The required daily precipitation and temperature data were collected from the weather station located at the UW outlet. Daily solar radiation, relative humidity, and wind speed data were recorded from an automatic metrological station located at approximately 5 km far from the watersheds. The SWAT weather generator was used for simulating missing daily weather data (Schuol and Abbaspour, 2007). Daily climatic data (January 1, 1997 to December 31, 2015) recorded at the weather stations were used to create the monthly weather statistics using the weather generator.

2.6. Runoff discharge and Sediment yield

Runoff and sediment yield were collected at the outlet of both watersheds where rectangular v-notch weirs with flow sensors and automatic cameras were installed to measure surface runoff. The automatic cameras were set to take pictures every 2 minutes (Figure 5). At each rainfall event, three runoff samples distributed over the whole runoff event were collected manually where subsequently sediment concentration of each sample was determined in the laboratory. Sediment yield was then calculated multiplying discharge by the mean sediment concentration. The data were used to calibrate and verify a distributed simulation model.

Figure 5 Pictures taken from the automatic camera at day (left) and nighttime (right)

2.7. SWAT Project set up

For each watershed a separate SWAT project was setup. The modeled period was from 2004 to 2015. Runoff and sediment yield data collected from the watersheds during 2011 to 2013 were used for model calibration while data from 2014 to 2015 were used for validation. Mean daily runoff and sediment data from both watersheds were used to calibrate the SWAT model. Some of the appropriate parameters were adjusted until the predicted daily runoff (Table 2) and sediment yield (Table 3) approximately matched the measured ones at the outlets of the watershed. Based on the given threshold areas and manual input data automatic sub-basin delineation was done for the UW and TW. The SWAT model divided the sub-basin into detailed HRUs. The model delineates each HRUs with a user defined threshold based on the percentage of the slope classes, soil type and land use (Arnold et al. 2011).

HRUs (Hydrologic Response Units) for this study were delineated using the soil type and the land use thresholds set at 5% area coverage. Any soil type and land use type each covering more than 5% of the sub-basin area was considered as an HRU. Based on the thresholds selected, there were a total of 760 HRUs in the UW and 658 HRUs in the TW. These HRUs were used for analyses on a particular land use, soil type and slope class.

Table 2 List of parameters adjusted for runoff during the calibration process

		Fitted value			
Parameter name	Description	UW[1]	TW[2]	Range	Rank
R__CN2.mgt	Curve number	-0.013	0.065	-0.25–0.25	1
V__RCHRG_DP.gw	Deep aquifer percolation fraction	0.19	0.1	0–0.2	2
V__SURLAG.bsn	Surface runoff lag coefficient	9.33	5.5	1–10	3
V__GW_DELAY.gw	Groundwater delay time (days)	262.5	250	0–500	4
R__SOL_K (1).sol	Saturated hydraulic conductivity	-0.16	-0.17	-0.25–0.25	5
V__REVAPMN.gw	Threshold depth of water in the shallow aquifer percolation to the deep aquifer to occur (mm H_2O)	337	250	0–500	6
V__GW_REVAP.gw	Groundwater “revap” coefficient	0.09	0.17	0–0.2	7
V__CH_N2.rte	Manning’s “n” value for the main channel	0.26	0.15	0–0.3	8
V__ALPHA_BF.gw	Base flow alpha factor (days)	0.23	0.5	0–1	9
V__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	875	833.3	0–5000	10
R__SOL_AWC (1).sol	Soil available water storage capacity	-0.11	-0.17	-0.25– 0.25	11
V__ESCO.hru	Plant uptake compensation factor	0.48	0.84	0.01 –1	12

[1]Untreated watershed
[2] Treated watershed

Table 3 List of parameters adjusted for sediment during the calibration process

Parameter name	Description	Fitted value UW	Fitted value TW	Range	Rank
R__USLE_K.sol	USLE soil erodibility factor	0.17	0.19	0.15–0.35	1
V__USLE_P.mgt	USLE support practice factor	0.79	0.72	-0.01–0.8	2
V__SPEXP.bsn	Exponent parameter for calculating sediment in channel routing.	1.2	1.06	1–1.4	3
V_SPCON.bsn	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing.	0.02	0.04	0–0.05	4
R__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	-0.08	-0.11	-0.2–0.2	5
V__CH_N2.rte	Manning's “n” value for the main channel	0.24	0.21	0–0.3	6
V_CH_COV1.rte	Channel erodibility factor	0.29	0.36	0.0–0.5	7
V__CH_COV2.rte	Channel cover factor	0.50	0.55	0.001–1	8

2.8. Watershed and channel delineation

For watershed delineation, WEPP uses the Topographic Parameterization (TOPAZ) method (Renschler and Lee, 2005; Renschler, 2003; Flanagan et al., 2013), described by Garbrecht and Martz (1999). The TOPAZ method of delineation is based on Digital Elevation Models (DEMs). The drainage network is determined by assessing each raster cell. TOPAZ employs the critical source area (CSA) concept that asserts the cells comprising the drainage network are those cells that have a drainage area of the CSA. For this study, 5 hectare CSA with 50-meter source channel length was used fitting the best with existing channels. Minimum Source Channel Length (MSCL) is required as an input for TOPAZ delineation, and this value determines the smallest size channel that will be represented. CSA and MSCL are the two most consequential parameters in the TOPAZ model, as the input of these two controls the number, density, and size of the drainage channels (Garbrecht and Martz, 1999).

2.9. Model Performance Evaluation

Graphical and statistical model evaluation techniques were used to see how well the model simulation matches the observed data. SWAT and SWAT-CUP calibration tools provide multiple model evaluation statistical criteria to be selected as an objective function for model calibration and validation based on the recommendations suggested by Santhi *et al.* (2001) and Moriasi *et al.* (2007). The algorism program SUFI-2 (Sequential Uncertainty Fitting 2) that is linked to SWAT-CUP2012 version 5.1.6.3 was used for a combined model sensitivity analysis, calibration and validation procedures (Abbaspour *et al.,* 2004; Abbaspour *et al.,* 2007).The SUFI-2 algorithm accounts for different sources of input data uncertainty, conceptual model uncertainty and parameter uncertainty (Gupta *et al.,* 2006). For this particular study coefficient of determination (R^2) (Krause *et al.,* 2005), Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and Percent bias (PBIAS) (Gupta *et al.,* 1999) evaluation statistics were used to see the goodness fit of the model related to runoff and sediment yield for the TW and UW watersheds (Santhi *et al*., 2001; Moriasi *et al.,* 2007).The equations used are:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(E_i - \bar{E})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(E_i - \bar{E})^2}}\right]^2 \quad (1)$$

where, n is the number of observations or samples; O_i is observed values; E_i is estimated values; $\bar{O}$ is mean of observed values; $\bar{E}$ is the mean of estimated values; I is counter for individual observed and predicted values. The R^2 ranges between 0 and 1, where 1 means that the predicted value is equal to the observed value and zero means that there is no correlation between the predicted and observed values.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (2)$$

The range of E lies between $-\infty$ and 1.0 with $E = 1$ describing a perfect fit. Values between 0-1.0 are generally viewed as acceptable levels of performance, whereas values <0 indicate that the mean observed value is a better predictor than the model.

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n}(O_i - E_i) * 100}{\sum_{i=1}^{n}(O_i)}\right] \quad (3)$$

The optimal value of PBIAS is 0, with low magnitude values indicating accurate model simulation (Moriasi *et al.,* 2007).

3. Results

3.1. SWAT Results

3.1.1 Model Calibration and Validation

Mean daily runoff discharge and sediment yield data from both watersheds were used to calibrate the SWAT model. Some of the appropriate parameters were adjusted until the predicted daily runoff (Table 2) and sediment yield (Table 3) were approximately matched the measured ones at the outlets of the watersheds.

3.1.2. Runoff Calibration and Validation

Results showed that the observed mean daily discharge was 0.03 m^3s^{-1} for the calibration period and 0.02 m^3s^{-1} for the validation period whereas the estimated mean daily discharge was 0.03 m^3s^{-1} for the calibrated period and validation period in the UW (Table 4). The simulation results showed that the coefficient of determination (R^2) and NSE values for the daily runoff in the UW were 0.77 and 0.75 for the calibration period and 0.72 and 0.56 for the validation period, respectively (Table 4). Percent bias (PBIAS) was -8.9 for the calibration and 14.8 for validation for the UW.

Similarly, the estimated and the observed daily discharge for the TW was 0.02 m^3s^{-1} for the calibration and validation periods (Table 4). The daily runoff simulation results showed better model efficiency with a coefficient of determination (R^2) value for the daily runoff 0.78 for the calibration period and 0.70 for the validation period (Table 4). The NSE values were 0.63 for calibration and 0.58 for validation periods (Table 4). The mean daily results give PBIAS of 29.2 for calibration and 24.3 for the validation periods (Table 4) indicating that the model performed well according to Moriasiet al. (2007).

Table 4 Mean daily discharge, sediment yield and summary statistics of treated and untreated watersheds

Parameter	Untreated watershed			
	Calibration		Validation	
	Observed (standard deviation)	Simulated (standard deviation)	Observed (standard deviation)	Simulated (standard deviation)
Mean daily discharge (m^3s^{-1})	0.03(0.02)	0.03(0.02)	0.03(0.02)	0.02(0.02)
Mean daily sediment yield (t ha^{-1})	4.19(4.05)	2.86(4.22)	3.71(2.46)	2.63(2.89)
Discharge				
R2	0.77		0.72	
NSE	0.75		0.56	
PBIAS	-8.9		14.2	
Sediment yield				
R2	0.69		0.65	
NSE	0.54		0.33	
PBIAS	29.2		24.3	
	Treated watershed			
Mean daily discharge (m^3s^{-1})	0.02(0.02)	0.01(0.02)	0.02(0.02)	0.02(0.03)
Mean daily sediment yield (t ha^{-1})	3.13(3.10)	2.21(3.22)	2.07(1.52)	1.55(1.69)
Discharge				
R2	0.78		0.70	
NSE	0.63		0.58	
PBIAS	29.2		24.3	
Sediment yield				
R2	0.65		0.55	
NSE	0.47		0.31	
PBIAS	25.4		33.8	

Results showed that there is good agreement between the observed and predicted daily runoff for both treated (TW) and untreated watershed (UW) during calibration and validation periods (Figure 5 and Figure 6) indicating that SWAT performs well. This indicates that the model predicts the daily discharge very well (Figure 5 and Figure 6).

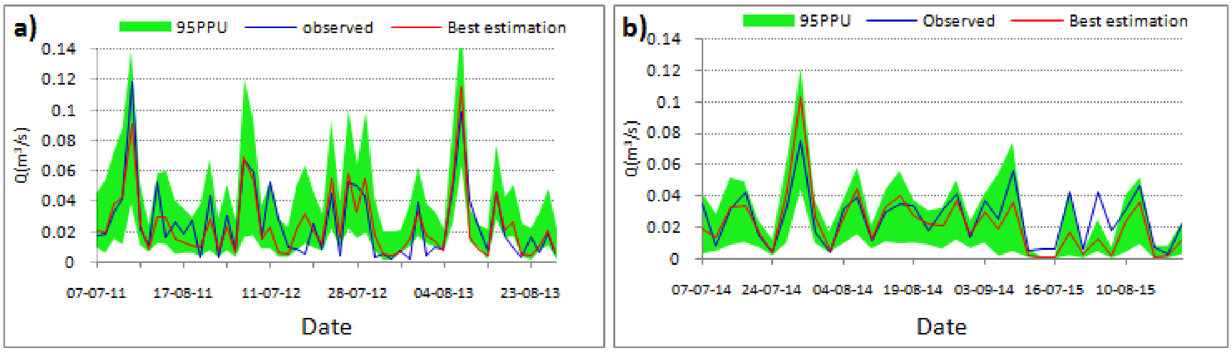


Figure 5 Observed and simulated daily runoff for calibration (a) and validation (b) period at the outlet of untreated watershed (UW)

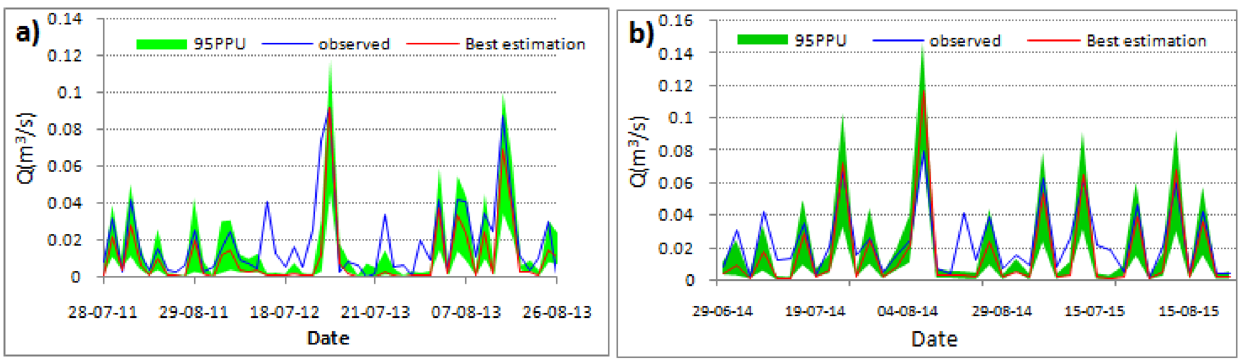


Figure 6 Observed and simulated daily runoff for calibration (a) and validation (b) period and at the outlet of the treated watershed (TW)

The observed runoff on the same day was often under predicted for the calibration period and for the validation period. Based on the model results the mean daily runoff from both watersheds shows better agreement with the measured runoff calibration and validation periods (Figure 7a and Figure 7b). The evaluation coefficients of the simulated daily runoff of different objective functions for both the TW and UW indicated satisfactory model fit according to the assessment criteria (Moriasi et al. 2007). Khelifa et al. (2016) reported daily runoff with NSE value of 0.64 for calibration and 0.68 for validation. Similar studies done are in better agreement with these results (Addis et al. 2016; Zimale et al. 2016). For a study in the Gumara watershed by Zimale et al. (2016), the NSE values for daily flows obtained were 0.70 for calibration and 0.77 for validation period.

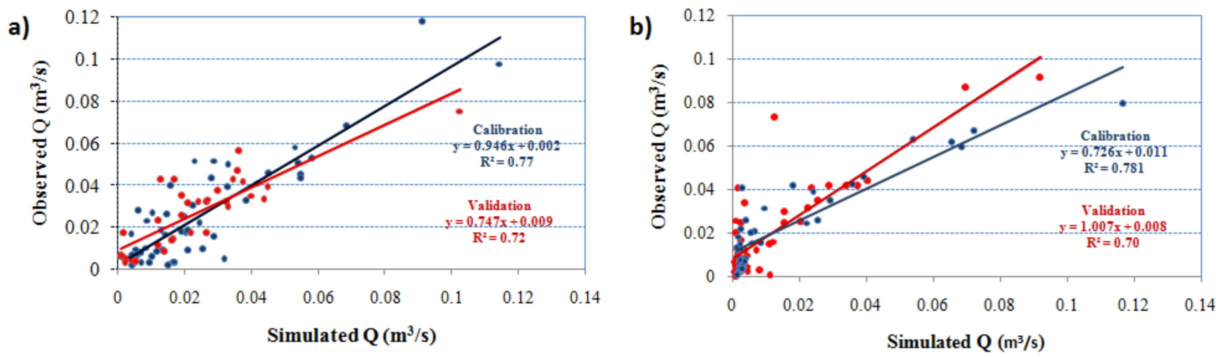


Figure 7 Observed and simulated daily discharge (Q) for calibration and validation period at UW (a) and TW (b)

3.1.3. Sediment Calibration and Validation

Daily sediment yield was calibrated and validated using the measured data from the two watersheds. Sediment yield prediction results gave a coefficient of determination (R^2) of 0.69 for calibration and 0.65 for validation period in the UW (Figure 8a) and a coefficient of determination (R^2) of 0.65 for calibration and 0.55 for validation period for the TW (Figure 8b).

Daily sediment yield calibration and calibration results showed NSE of 0.47 and 0.31, respectively for the TW and 0.54 and 0.33 for calibration and validation, respectively, for the UW (Table 4). Results showed that SWAT model under estimated the generated sediment yield. The model predicted about 33.5 t $ha^{-1}y^{-1}$ and 44.8 t $ha^{-1}y^{-1}$ sediment yield for the TW and UW, respectively. The observed sediment yield was 39.9 t $ha^{-1}y^{-1}$and 64.6 t $ha^{-1}y^{-1}$ in the TW and UW, respectively. The model under predict the annual sediment yield of the TW and the UW. This indicates that there is a potential impact of the SWC on sediment yield reduction on the treated watershed.

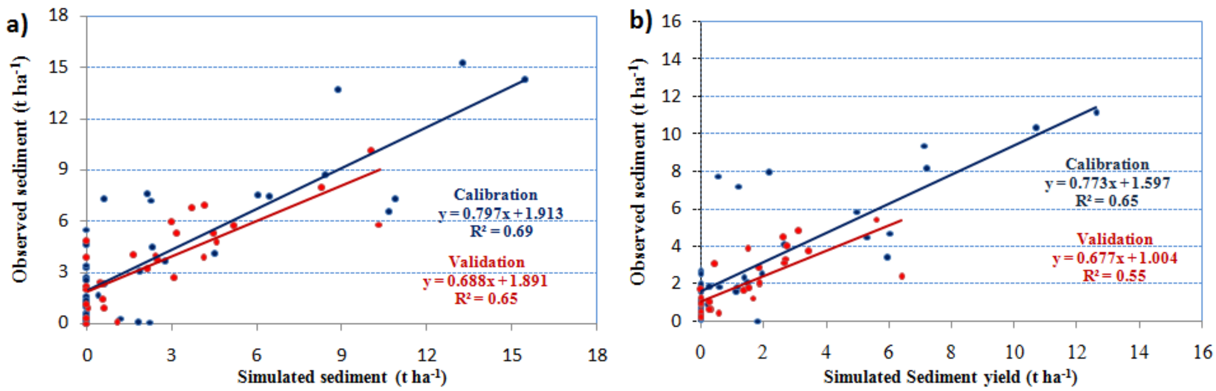


Figure 8 Observed and simulated daily sediment for calibration and validation period at UW (a) and TW (b)

3.2. GeoWEPP Results

3.2.1. Effects of SWC on slope gradient

The stone bunds change the inclination of the land, which changes the extent of slope gradient. Figure 9 illustrates the differences in slope gradient between the watersheds. Immediately after construction, stone and soil bunds reduced the slope length for surface runoff and provide retention space for runoff and sediments. On medium and long-term basis, sediments accumulate and fill up the retention space. The sediment accumulating on bunds gradually changes the original slope of the plot, making it more suitable for cultivation. Therefore, maintenance of stone and soil bunds are necessary to keep their efficiency.

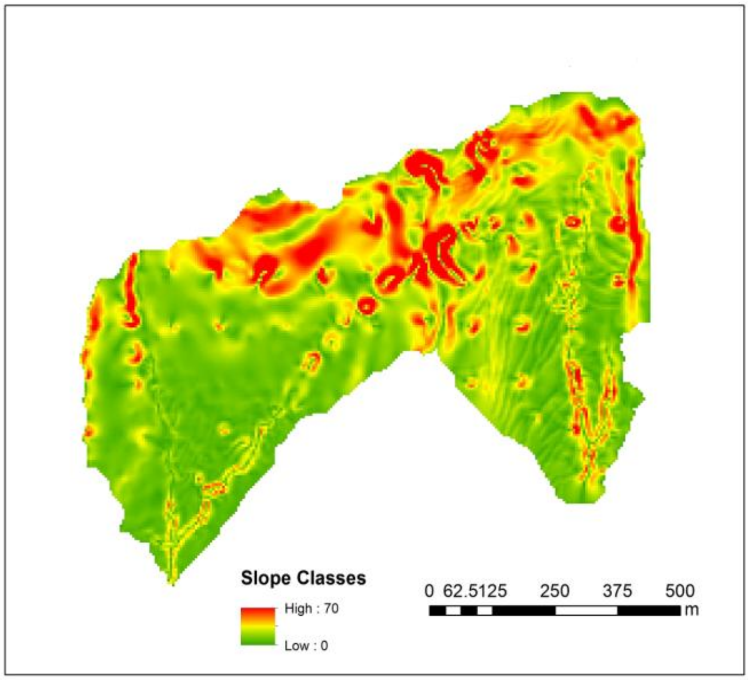


Figure 9 Slope of untreated watershed (left) and treated watershed with SWC (right)

In addition to slope gradient, the stone bunds change the flow accumulation and flow directions (Figure 10 and Figure 11). As shown below in the figures (circled by blue color) the slope change affects the drainage network in the treated watershed. The flow accumulation in the untreated watershed is more concentrated than the treated watershed. Similarly there is slight change of flow direction in the treated watershed as compared to the untreated watersheds.

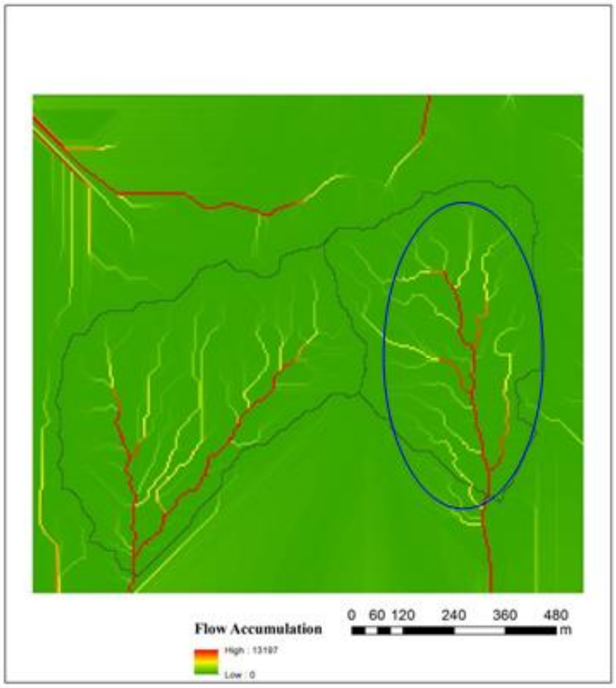


Figure 10 Flow accumulation of both watersheds without SWC

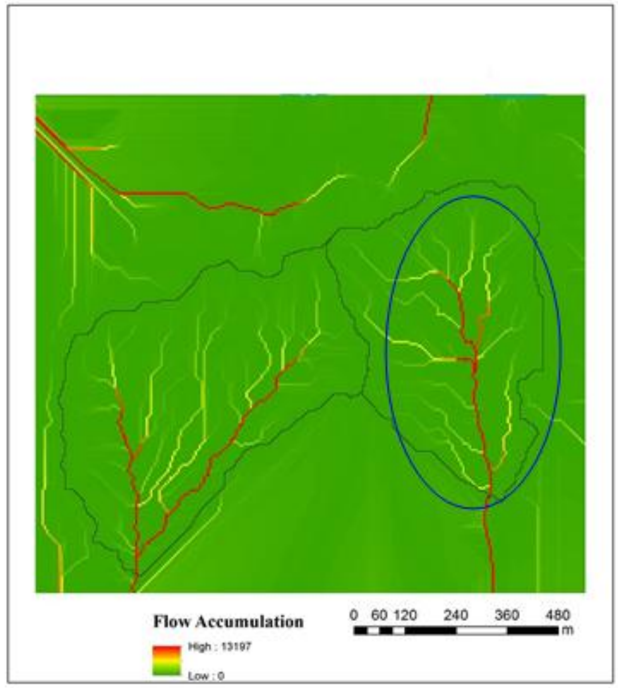


Figure 11 Flow accumulation of untreated watershed (left) and treated watershed (right)

3.2.2. Effects of SWC on Runoff

The results of the study showed that the observed runoff recorded was 441.l mm while the WEPP predicted 394.9 mm of surface runoff at the untreated watershed (Figure 12). Similarly, the model estimated 322.4 mm while the measured was 358.4 mm at the treated watershed (Figure 13). The treated watershed generates 18.8% less runoff as compared to the untreated watershed. This indicates the contribution of SWC structures in reducing surface runoff.

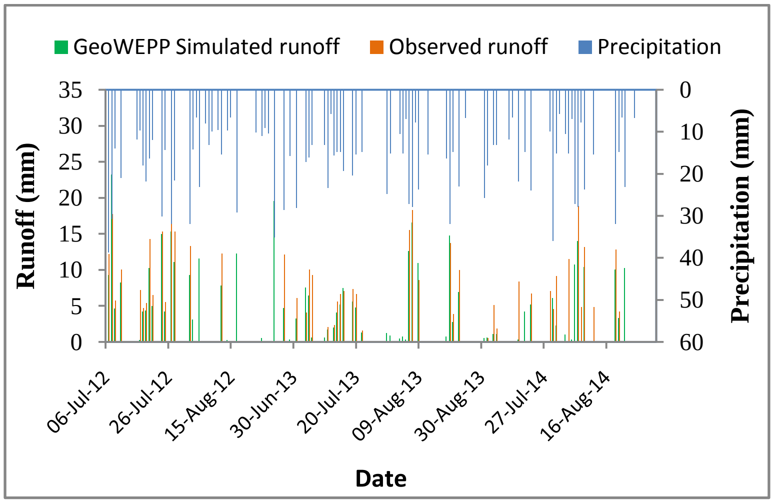


Figure 12 Simulated, measured runoff and precipitation (2012-2014) at untreated watershed

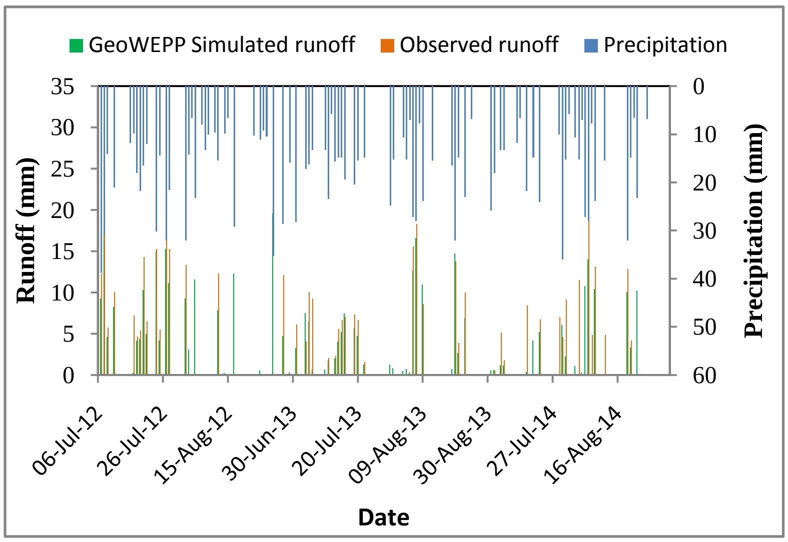


Figure 13 Simulated, measured runoff and precipitation (2012-2014) at treated watershed

3.2.3. Effects of SWC on soil loss

Onsite Soil loss assessment

GeoWEPP generated soil loss map indicates areas with tolerable (from dark to light green) and above tolerable soil loss (from light red to dark red). The onsite soil loss prediction was done for both watersheds using 10 t ha^{-1} y^{-1} as the soil loss Target (T) value (Figure 14 and Figure 15). According to Hurni (1985), Mwendera et al. (1997) and Tadesse (2001) the mean soil loss tolerable soil loss Target value (T) for this region is 10 t $ha^{-1}y^{-1}$.

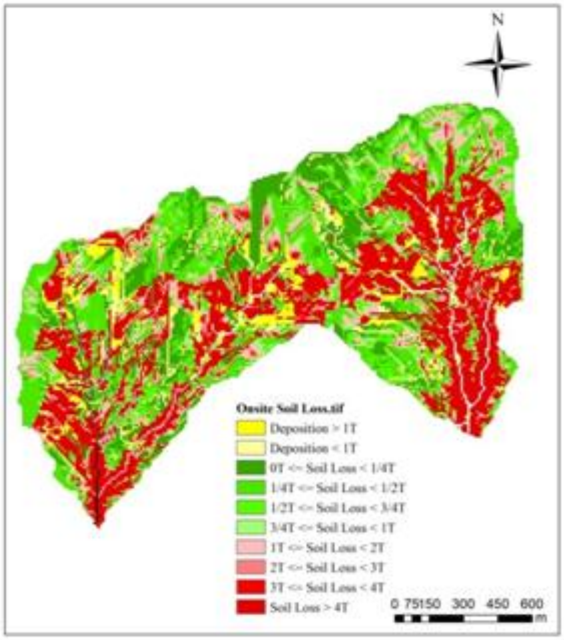


Figure 14 Onsite soil loses of both watersheds without SWC

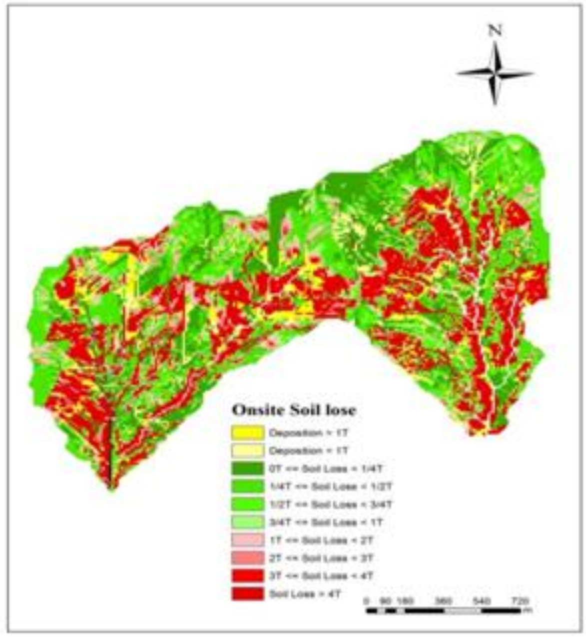


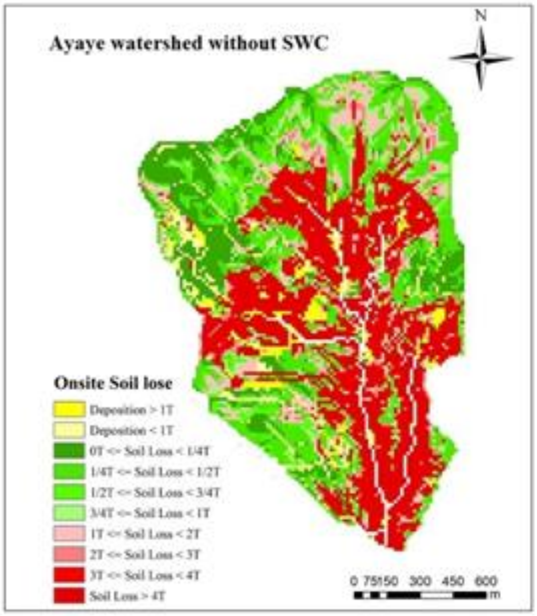
Figure 15 Onsite Soil losses untreated watershed (left) and treated watershed (right)

GeoWEPP predicts that about 52.4% of the watershed area generates more than 10 t $ha^{-1}y^{-1}$ at the untreated watershed (UW) (Table 6, Figure 16). Similarly, the model also predicted that 49.1% of the area generated more than 10 t $ha^{-1}y^{-1}$ at the treated watershed (TW) without SWC (Table 6, Figure 16).

Table 6 Textural classes of the watersheds

	Watershed	
Soil textural classes	Untreated watershed	Treated watershed
Clay	3.7%	12.4%
Clay loam	52.9%	50.7%
Loam	36.3%	23.4%
Silty clay loam	4.2%	0.6%
Silty loam	2.9%	12.9%

According to the model estimation, the SWC structures constructed in the TW reduced the total area that generates soil loss above the tolerable limit 11.3 to 37.8% (Table 6.3). Figure 11 and Figure 6.12 show the differences in severity of soil erosion and the impacts of SWC structures on soil erosion.



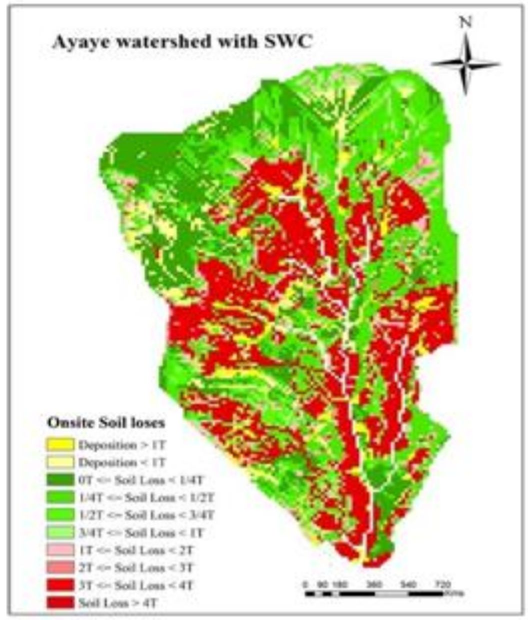


Figure 16 Watershed without SWC

Figure 17 Treated watershed with SWC

The model prediction clearly shows that largeproportions of both watersheds havea soil loss of greater than 40 t $ha^{-1}y^{-1}$. 33.8% of UW contributed a soil loss of above 40 t $ha^{-1}y^{-1}$ without any soil and water conservation structures (Table 7). On the other hand 26% of TWcontributes more than 40 t $ha^{-1}y^{-1}$of soil loss (Table 7).

Table 7 Onsite soil loss and area coverage of untreated and treated watersheds

Onsite soil loss ($t\ ha^{-1}$)	Watershed Area coverage (%)	
	Untreated without SWC	Treated with SWC
Deposition > 10	6.1	4.1
Deposition < 10	3.9	5.2
0<= Soil Loss <2.5	10.0	17.6
2.5 <= Soil Loss < 5	16.6	23.5
5<= Soil Loss <7.5	6.6	7.5
7.5<= Soil Loss < 10	4.5	4.1
10<= Soil Loss < 20	9.5	6.7
20<= Soil Loss < 30	4.8	2.9
30<= Soil Loss < 40	4.3	2.2
Soil Loss > 40	33.8	26.0

Offsite Soil loss assessment

The GeoWEPP model predicted 64.1 t $ha^{-1}y^{-1}$ sediment yields for the UW. The offsite soil loss assessment shows that 46.0 t $ha^{-1}y^{-1}$was observed in the TW. The results revealed that the SWC structure reduced soil loss by 25.5 % at the TW. The observed sediment yield was 64.6 t $ha^{-1}y^{-1}$ for the UW and 39.9 t $ha^{-1}y^{-1}$ in the TW. In both the predicted and the observed results the sediment yield is higher in the UW as compared to the TW (Figure 6.13 and 6.14). This indicates that the SWC has an impact on sediment yield reduction on the TW.

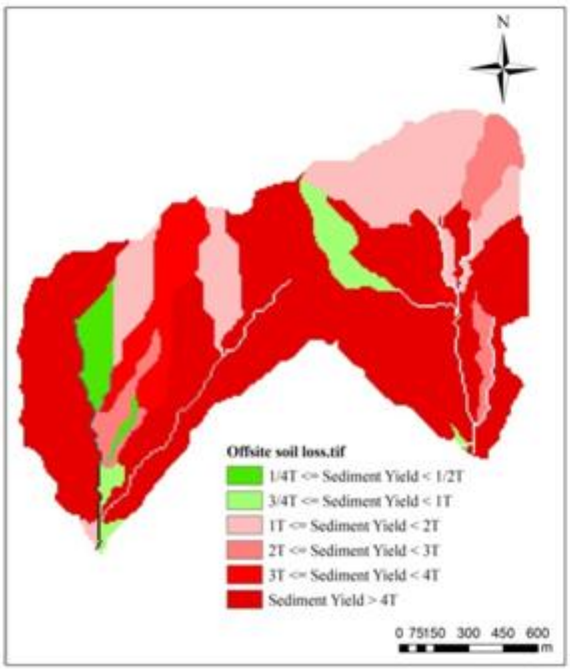


Figure 18 Offsite Soil loss both untreated watersheds without SWC

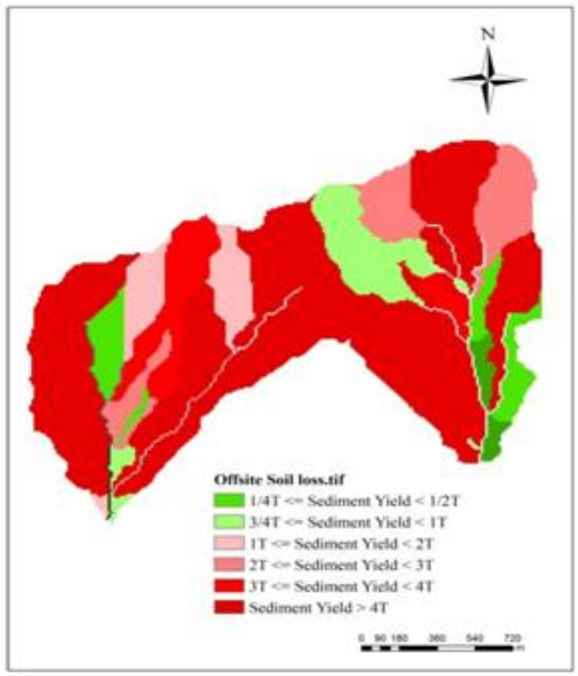


Figure 19 Offsite Soil loss untreated watershed (left) and treated watershed (right)

The observed and simulated daily runoff, peak runoff, and sediment yield of both watersheds were compared graphically (Figure 20 and 21). Figure 20 demonstrates that the simulated daily runoff and peak runoff values are distributed well to the 1:1 line of observed daily runoff and peak runoff in both the UW and TW. The GeoWEPP model simulation results predict the daily runoff and the peak runoff well with R^2 values of 0.68 and 0.81 for UW and 0.61 and 0.92 for TW, respectively. For higher values the model under predicts runoff volume. Similarly, daily-predicted sediment yield values are plotted against the measured values (Figure 20 and 21). The simulated sediment yields are predicted satisfactorily for both watersheds with R^2 values of 0.61 and 0.57 for UW and TW, respectively (Figure 20 and 21).

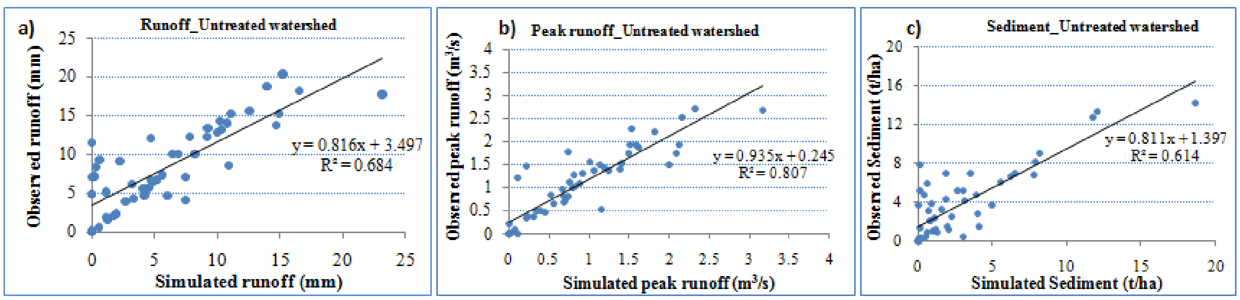


Figure 20 Runoff volume, peak runoff and sediment yield at the untreated watershed

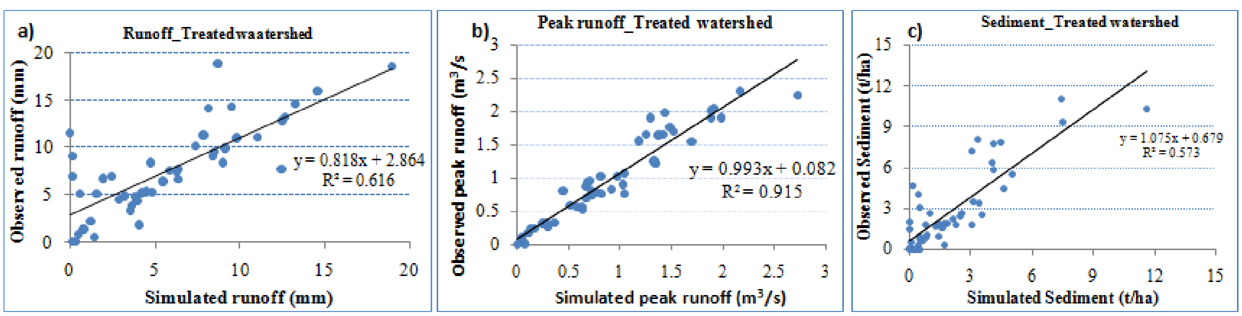


Figure 21 Runoff volume, peak runoff and sediment yield at the treated watershed

The NSE value of runoff at UW (NSE=0.43) shows lower results as compared to TW (NSE=0.84) (Table 8). The statistical comparison of the simulated sediment yield against the observed sediment yield relvealed NSE value of 0.59 and 0.81 for UW and TW, respectively (Table 8). Table 4shows reasonably higher NSE values for sediment yield at both watersheds. Similarly, the NSE value of the runoff at the TW indicated higher values. However, at the UW the value is relatively lower than the TW. The higher NSE values indicate that the GeoWEPP model performs satisfactorily for both watersheds. The model under predicts the amount of runoff generated in both watersheds.

In addition, a t-test is done to compare the simulated and the observed runoff and sediment yield for both UW and TW. The results of the t-test showed that there were not statistically significant differences (P > 0.05) between the observed and the simulated runoff and sediment yield (Table 8).

Table 8 Summary statistics runoff and sediment yield at Untreated and Treated watersheds

Parameter	Untreated		Treated	
	Simulated	Observed	Simulated	Observed
Runoff (mm)	394.9	441.l	322.4	358.4
Sediment yield (t $ha^{-1}y^{-1}$)	64.1	64.6	46.0	39.9
Runoff				
R^2	0.68		0.61	
NSE	0.43		0.84	
t-cal at 95% level	0.73		0.31	
Sediment yield				
R^2	0.61		0.57	
NSE	0.59		0.81	
t-cal at 95% level	0.89		0.93	

3.3. WEPP Results

The limited precipitation mainly occurs from June to end of August in the form of intense and localized rainstorms in the observation period (2012-2014) creates runoff and higher sediment yield in the watershed. The mean annual rainfall for the period (2012-2014) was 807.5 mm (Table 1). The mean annual amount of runoff recorded from 2012 to 2014 was 242.0 mm (Table 1). The plot experimental results showed higher runoff in the three rainy seasons. The annual runoff amount generated in 2013 (288.3 mm) was higher than 2012 (203.9 mm) and 2014 (198.7 mm) rainy seasons. Similarly, the results of the analysis showed higher soil erosion in the Gumara-maksegnit watershed. The sediment yield recorded in 2012, 2013 and 2014 were 47.1 t ha^{-1}, 36.6 t ha^{-1} and 24.9 t ha^{-1}, respectively (Table 9).

The WEPP simulation results showed good model fit with NSE value of 0.79 for annual runoff and 0.85 for sediment yield. Similarly, the model showed good results of R^2 for surface runoff and sediment yield at the Gumara-maksegnit watershed (Table 9). The model predicted 268.0 mm surface runoff in 2012, 284.7 mm in 2013 and 210.0 mm in 2014.

Table 9 Annual observed precipitation, observed runoff and simulated runoff (2012-2014)

Year	Precipitation (mm)	Observed Runoff (mm)	Simulated Runoff (mm)	Observed Sediment yield (t ha^{-1})	Simulated Sediment yield (t ha^{-1})
2012	766.6	241.9	268.0	47.1	46.3
2013	910.0	288.3	284.7	33.3	37.3
2014	745.8	195.7	210.0	24.9	29.4
Mean	807.5	242.0	254.2	35.1	37.7
*SD	89.4	46.3	39.2	11.2	8.5
NSE		0.79		0.85	
R^2		0.83		0.94	

***SD**: Standard Deviation

The monthly results showed higher runoff amount in July and August in all the three years. Similarly, higher monthly soil losses were recorded in July and August. The highest monthly runoff was observed in August 2013 followed by June 2012 (Table 10). However, the amount of soil loss was higher in July in all the seasons. This is the fact that most tillage practices are done in the last week of June to mid of July in the watershed.

WEPP model predicts the monthly runoff amount satisfactory while the model gave good model fit on monthly soil losses with NSE value of 0.69 and 0.88, respectively. However, the model under predicts the amount of monthly runoff in August 2013 and slight over prediction was observed in June 2012.

Table 10 Monthly observed precipitation, observed runoff and simulated runoff (2012-2014)

Year	Observed Runoff (mm)	Simulated Runoff (mm)	Observed Sediment yield (t ha^{-1})	Simulated Sediment yield (t ha^{-1})
June 2012	0	3.5	0	1.5
July 2012	157.6	165.97	25.4	27.1
August 2012	83.6	96.45	21.7	17.0
September 2012	0	1.2	0	0.0
June 2013	0	68.59	0	8.3
July 2013	104.5	112.87	22.4	16.7
August 2013	167.02	79.07	13.12	11.3
September 2013	16.82	23.59	1.3	0.9
June 2014	0	0	0	0.0
July 2014	74.5	81.3	13.6	11.5
August 2014	68.7	71.53	11.3	9.4
September 2014	0	25.29	0	0.1
Mean	56.1	60.78	11.6	9.5
*SD	62.9	51.5	10.1	8.7
NSE	0.69		0.88	
R^2	0.71		0.89	

*SD: Standard Deviation

The relative soil erosion increases across the hilslope. WEPP model predicts 8.11 kg m^{-2} was observed at 20 m in the hillslope (Figure 22). The annual rainfall of 807.47 mm generates 254.24 mm of runoff and 37.7 t ha^{-1} sediment yield (Figure 22). The results showed that the soil losses increase along the hillslope.

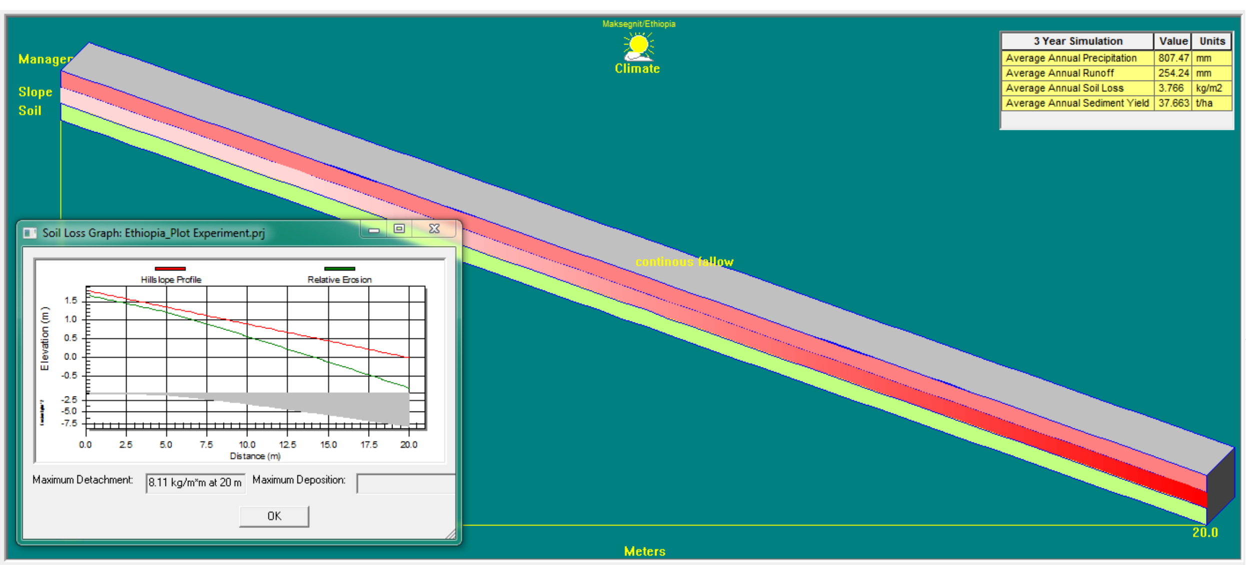


Figure 22 Hillslope Soil erosion

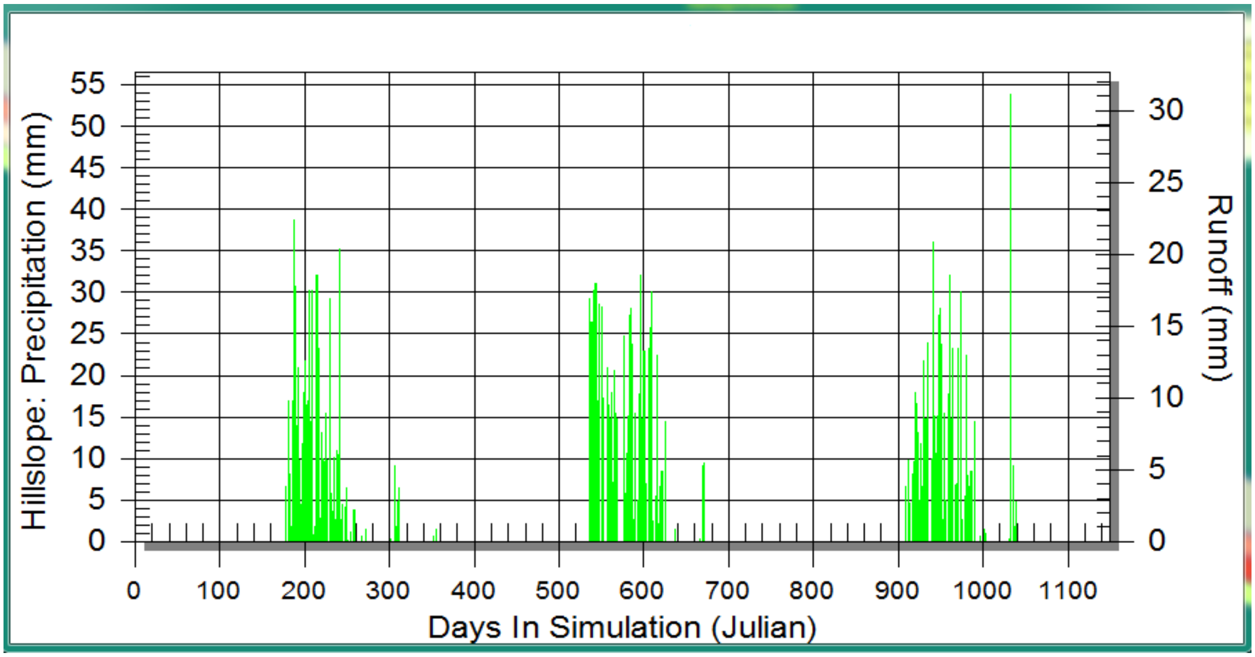


Figure 23 Simulated runoff and precipitation in the Gumara-maksegnit watershed (2012-2014)

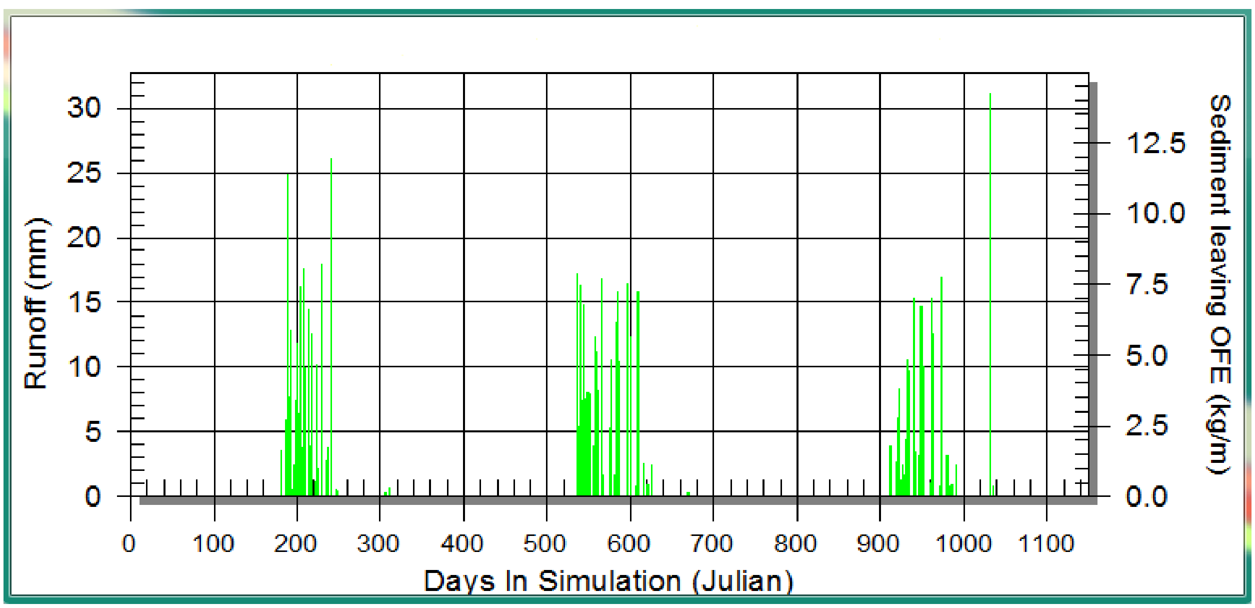


Figure 24 Simulated runoff and sediment yield in the Gumara-maksegnit watershed (2012-2014)

4. Discussion

4.1. SWAT Model

The results of the UW (Untreated Watershed) and TW (Treated Watershed) show that the soil and water conservation structures constructed by the farmers reduce the surface runoff and soil losses in the Highlands of Ethiopia. The results show that the untreated watershed had higher sediment and runoff losses than a treated watershed, given similar climatic and land use patterns. The intervention of SWC measures by the mobilization of the community has a significant soil loss reduction to protect their land from the rainfall driven soil erosion. The effectiveness of SWC on runoff and sediment yield reduction has been reported in other studies in the Northern Ethiopia (Desta et al 2005;Nigussie et al. 2005; Descheemaeker et al. 2006c; Mitiku et al. 2006; Nyssen et al. 2007, 2009; Dagnew et al. 2015, 2017).

In this study, SWAT was used to assess the impacts of SWC on runoff and erosion processes, and the model has been found a useful tool for understanding the hydrologic processes and the sediment dynamic in the study area in both watersheds. The evaluation coefficients of the simulated daily runoff of the different objective functions for both the TW and UW indicated satisfactory model fit according to the assessment criteria (Moriasi et al. 2007). The NSE values found in the UW and the TW agreed with Khelifa et al. (2016) findings of a daily runoff with NSE value of 0.64 for calibration and 0.68 for validation who has studied the impact of SWC on runoff and sediment yield. In another study in the Gumara watershed by Zimale et al. (2016), the NSE values for daily flows obtained were 0.70 for calibration and 0.77 for validation period, which is comparable with the UW and TW NSE values in the Gumara-maksegnit watersheds. Similar studies done are in better agreement with these results (Addis et al. 2016).

However, the model tends to underestimate sediment yield during calibration and validation period for both watersheds. The NSE for sediment yield in both watersheds showed lower values in the calibration and validation periods. The under estimation of the sediment yield by the model is because, there are parts of the watershed severely eroded which created gully erosion in both watersheds that led to higher soil losses beyond the estimated sediment load. This is substantiated by the photo taken in figure 25 which shows the development of deep gully in the upper parts of the watershed that contributes higher soil erosion losses that generate higher sediment load in the outlets.

Figure 25 Gully development in the upper part of the watershed (left) runoff with high sediment concentration at the outlets (right)

The model result indicated that SWC structures considerably reduced soil loss by 24.8-38.2% in the Gumara-Maksegnit watershed. A plot level experiment conducted on the effects of stone bunds showed that stone bunds can reduce soil erosion by 33-41% (Riederet al. 2014; Klik et al. 2016) in the TW which is close to the current finding of the soil loss reduction level due to SWC. Similarly, Strohmeier et al. (2015) reported that at plot scale stone bunds reduced soil loss by 40% in the Gumara-Maksegnit watershed. In another study conducted in Northern Tunisia on the effects of soil and water conservation structures on sediment load, Khelifa et al. (2016) reported 22% reduction in sediment yield at the watershed scale. Similar studies by Abouabdillah et al. (2014), Yesuf et al. (2015), Addis et al. (2016) and Licciardello et al. (2016) are in agreement with our findings. Betrie et al. (2011) also reported 41% reduction sediment yield in the Blue Nile Basin due to stone bunds. The soil loss reduction (24.8-38.%) in this study due to SWC structures at watershed scale agreed with the findings of Abdouabbdilah et al. (2014) who estimated an overall soil loss reduction by 25%.

The sediment yield estimated by SWAT model for the UW (44.8 t $ha^{-1}y^{-1}$) and TW (33.5t $ha^{-1}y^{-1}$) was in agreement with other studies. Setegn et al. (2010) reported sediment loads of 30-60 t $ha^{-1}y^{-1}$ were exported from the Lake Tana watersheds while Easton et al. (2010) predicted a maximum soil loss of 84 t $ha^{-1}y^{-1}$ in the Gumara watershed. Similarly, Zimale et al. (2016) reported an average sediment yield of 49 t $ha^{-1}y^{-1}$ from Gumara watershed. There are also a number of simulation studies on sediment loads prediction at the gauging stations near Lake Tana (Easton et al. 2010; Setegn et al. 2010; Kaba et al. 2014; Zimale et al. 2016) which confirmed the results of the current study conducted in the Gumara-Maksegnit watershed.

4.2. GeoWEPP Model

In general, GeoWEPP model performed satisfactorily in both surface runoff and sediment yield simulations in the UW and TW. The GeoWEPP model simulation results predict the daily runoff and the sediment yield well with R^2 values of 0.68 and 0.61 for UW and 0.61 and 0.57 for TW, respectively. The results agreed with other findings that confirmed GeoWEPP predicts surface runoff successfully (Pandy et al., 2008; Peri et al., 2014; Zhang et al., 2015). Yakusel et al.(2008) reported that GeoWEPP predicts the runoff and sediment yield with higher precision(R^2= 0.93 for runoff and R^2= 0.94 for sediment yield). Similarly, Kirnak (2002) reported that GeoWEPP can better estimate runoff amount and sediment yield in comparison with the observed result (R^2= 0.91 for runoff and R^2= 0.94 for sediment yield).

In this study the prediction of daily runoff, peak runoff, and sediment show lower accuracy compared to other studies done by Yakusel et al. (2008) and Kirnak (2002). The main reason is that there are areas of the watershed where have severe gully erosion generate higher sediment yield during intense storms. The stone bunds form a barrier that slows down runoff, allowing rainwater to seep into the soil and spread more evenly over the land. The slowing down of runoff helps with building up a layer of fine soil and manure particles, rich in nutrients. The layers have an impact on slope, flow direction, and flow accumulation changes.

The model results indicated that SWC structures considerably reduced soil loss by 28.2% in the simulated results, and38.2% in the observed results in the Gumara-Maksegnit watershed. A plot level experiment conducted on the effects of stone bunds showed that stone bunds can reduce soil erosion by 33 to 41% (Rieder et al., 2014; Klik et al., 2016) in the TW. Similarly, Strohmeier et al. (2015) reported that at plot scale stone bunds reduced soil loss by 40% in the Gumara-Maksegnit watershed. In another study conducted in Northern Tunisia on the effects of SWC structures on sediment load, Khelifa et al. (2016) reported 22% reduction in sediment yield at the watershed scale. Similar studies by Abouabdillah et al. (2014), Yesuf et al. (2015), Addis et al.

(2016), and Licciardello et al. (2016) are consistent with our findings. Betrie et al. (2011) also reported 41% reduction sediment yield in the Blue Nile Basin due to stone bunds. The soil loss reduction in this study due to SWC structures at watershed scale agreed with the findings of Abdouabbdilah et al. (2014) who estimated an overall soil loss reduction by 25%.

The sediment yield estimated by GeoWEPP model for the UW (64.1 t $ha^{-1}y^{-1}$) and treated watershed (39.9 t $ha^{-1}y^{-1}$) is consistent with other studies. Setegn et al. (2010) reported that sediment loads of 30-60 t $ha^{-1}y^{-1}$were exported from the Lake Tana watersheds while Easton et al. (2010) predicted a maximum soil loss of 84 t $ha^{-1}y^{-1}$ in the Gumara watershed. Similarly, Zimale et al. (2016) reported an average sediment yield of 49 t $ha^{-1}y^{-1}$ from Gumara watershed. There are also a number of simulation studies on sediment loads prediction at the gauging stations near Lake Tana (Easton et al., 2010; Setegn et al., 2010; Kaba et al., 2014; Zimale et al., 2016), which confirmed the results of the current study conducted in the Gumara-Maksegnit watershed.

4.3. WEPP Model

The limited precipitation in the Ethiopian highlands often occurs in the form of intense and localized rainstorms from mid June to end of August which can cause severe soil and nutrient losses (Addis et al., 2016; Melaku et al., 2017).

Comparison between WEPP simulated and field measured sediment yields indicates that WEPP prediction gave good results of the soil loss. The observed annual sediment yield showed 24.9-47.1 t ha^{-1} for the observed period of 2012-2014. Similarly, the simulations results indicates that WEPP predicts annual soil loss of 29.4-46.3 t ha^{-1} for the period from 2012-2014. Both the observed and simulated results indicate that the soil erosion is so critical and above the tolerable limit in the Gumara-maksegnit watersheds. The results from the monthly predictions showed higher accuracy in sediment yields and a slight lower accuracy in runoff predictions even though the values are within the acceptable range.

Goodness-of-fit statistics for simulation of annual runoff and sediment yield confirmed that WEPP model predicts both runoff and sediment yield very well. The higher the coefficient of determination values of 0.71 and 0.89, respectively for runoff and sediment yield indicate the good relationship between the measured and simulated values. Further, reasonably high values of Nash–Sutcliffe model efficiency, 0.69 and 0.88 runoff and sediment yield, respectively shows satisfactory performance of the model.

5. Conclusion

Soil resources are finite in extent, unequally distributed geographically, prone to degradation by land misuse and mismanagement, but essential to all terrestrial life and human wellbeing. Reducing soil erosion and fertility management are among the key factors for sustainability of soil ecosystem.

In this dissertation, Soil and Water Assessment Tool (SWAT) and GeoWEPP models have been used to predict the impacts of SWC interventions on runoff and soil loss for two adjacent watersheds in the highlands of Ethiopia. In addition, the effect of rate and timing of nitrogen fertilizer application on the possibility to shorten the maturity period and the productivity of sorghum of has been assessed in the same watershed.

In this chapter 5 and 6, SWAT and GeoWEPP models were used to assess the impacts of SWC on runoff and erosion processes the untreated (UW) and treated watersheds (TW). The results of the SWAT simulation study showed good model performance for daily runoff prediction at each watershed with acceptable R^2, NSE and PBIAS values. However, the model performance was poor in terms of predicting sediment loss with lower NSE values. Similarly, the results of GeoWEPP simulation study showed satisfactory model performance for daily runoff prediction at each watershed with acceptable R^2 and NSE values. Overall, the watershed modeling results indicated that soil and water conservation structures can reduce runoff and soil loss in the Gumara-Maksegnit watershed. The SWC structures reduced soil losses by 28.2% in the simulated results and 38.2% in the observed results in the TW as compared to the UW. Both the SWAT and GeoWEPP simulated and the observed results showed that soil erosion is still severe and above the soil loss Target value T (10 t $ha^{-1}y^{-1}$). Therefore, land management strategies and SWC structures should be improved to achieve more sustainable soil erosion protection for sustainable agriculture for food security in the area. Generally, this study found that SWAT and

GeoWEPP can be used as a tool in other watersheds in the Ethiopian highlands to predict the impact of soil and water conservation structure (SWC) on runoff and soil erosion processes.

In general, these studies concluded that land management strategies and SWC structures should be improved to achieve more sustainable soil erosion protection for sustainable agriculture for food security in the area.

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