Soil and Water Assessment Tool (SWAT)-Based Runoff and Sediment Yield Modeling: A Case of the Gumera Watershed in Lake Tana Subbasin

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Abstract

Land degradation is a serious threat in the Gumera watershed which is reflected in the form of soil erosion. Erosion is a major watershed problem causing significant loss of soil fertility and productivity. Increased sediment loads that shorten the useful life of the reservoir, the lives of other water-related structures, and increase the cost of maintenance and sediment remediation are off-site impacts of erosion. To develop effective erosion control plans and to achieve reductions in sedimentation, it is important to quantify the sediment yield and identify areas that are vulnerable to erosion. In recent decades, several simulation models have been developed in order to estimate, quantify, enhance understanding of spatial and temporal variability of erosion, and identify areas which are high contributors of sediment at micro-watershed level and over large areas. We used SWAT (Soil and Water Assessment Tool) to predict sediment yield, runoff, identify spatial distribution of sediment, and to test the potential of watershed management interventions in reducing sediment load from 'hot spot' areas. The tool was calibrated and validated against measured flow and sediment data. Both, calibration and validation results, showed a good match between measured and simulated flow and suspended sediment. The model prediction results indicated that about 72% of the Gumera watershed is erosion potential area with an average annual sediment load ranging from 11 to 22 tonnes/ha/yr exceeding tolerable soil loss rates in the study area. The model was applied to evaluate the potential of filter strips with various widths to reduce sediment production from critical micro-watersheds. The investigation revealed that implementing vegetation filter strips can reduce sediment yield by 58 to 74%.

Introduction

Ethiopia has huge potential resources which includes total of 122 billion cubic meters of surface water, 2.6 billion cubic meters of groundwater resources and 3.7 million hectare of potentially irrigable land that can be used to improve agricultural production and productivity (Awulachew et al., 2007; MoWR, 2002).

Despite these potential resources base, agricultural production are lowest in some parts of the country attributed from unsustainable environmental degradation mainly reflected in the form of erosion and loss of soil fertility (Demel, 2004).Under the prevalent rainfed agricultural production system, the progressive degradation of the natural resource base, especially in highly vulnerable areas of the high lands coupled with climate variability have aggravated the incidence of poverty and food insecurity (Awulachew et al., 2007).

Sheet and rill erosion are by far the most widespread kinds of accelerated water erosion and principal cause of land degradation in the country and their combined effect significantly affect agricultural production and productivity (Contable, 1984).The loss of nutrient-rich top soil by water leads to loss of soil quality and hence reduced crop yield. Soil erosion by water and its associated effects are therefore recognized to be severe threats to the national economy of Ethiopia .Since more than 85% of the country's population depends on agriculture for living; physical soil and nutrient losses lead to food insecurity (Luelseged, 2005).

Rapidly increasing population, deforestation, over cultivation, expansion of cultivation at the expense of lands under communal use rights (grazing and woody biomass resources), cultivation of marginal and steep lands, overgrazing, and other social, economic and political factors have been the driving force to a series of soil erosion in the basin in general and in Gumara watershed in particular (BCEOM, 1998; MoARD, 2004).

One of the possible solutions to alleviate the problem of land degradation (soil erosion) is therefore, to understand the processes and cause of erosion at a micro watershed level and to implement watershed management interventions. Effective watershed planning requires understanding of runoff and erosion rates at the plot, on hill slopes, and at small watershed scale and how these vary across the landscape. Next we must have a means to identify areas that have the potential for high erosion so that corrective actions can be taken in advance to reduce sediment production from these areas.

In recent decades, several simulation models have been developed in order to estimate, analyze soil erosion and enhanced understanding of spatial and temporal aspects of the catchments and assessment of process over large area that enables priority management areas to be identified

The purpose of this study is therefore, to determine the spatial variability of sediment yield, to identify critical micro watersheds and evaluate various conservation scenarios in reducing sediment yield based on the simulation result of a physically based and spatially distributed SWAT (Soil and Water Assessment Tool) model.

Objective of the study

The overall objective of this study is to characterize the Gumara watershed, predict sediment yield and runoff and develop management options to control erosion and sedimentation problem in Gumara watershed.

The specific objectives of the study are:

- To characterize the Gumara watershed in terms sediment yield
- Assess and evaluate the spatial variability of sediment yield in the watershed
- To identify and prioritize hot spot areas for site specific management intervention
- To cite and recommend appropriate soil and water conservation measures.

Description of Gumara Watershed

The study area is found in North West part of Ethiopia in Amhara Regional State, south Gondar Zone (Figure 1). The watershed covers partly four woredas (administrative units) namely, farta, Fogera, Dera, Iste. It is situated in the south east of Lake Tana and covers a drainage area of about 1464 km^2 .

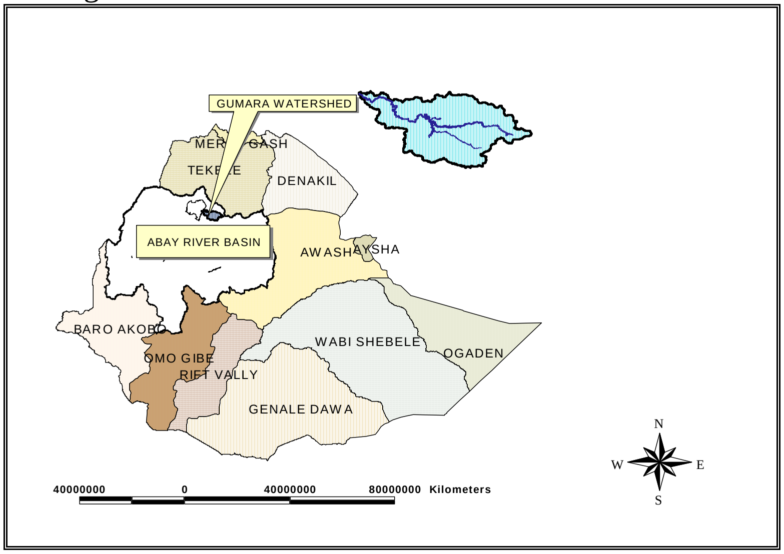

Figure 1: Major River Basins in Ethiopia and Location Map of Gumara Watershed

The major land form of the watershed includes flat, gently sloping to undulating plains, hills and mountains. The upper and middle parts of the catchment are characterized by mountainous, highly rugged and dissected topography with steep slopes and the lower part is characterized by valley floor with flat to gentle slopes. Elevation in the watershed varies from 1780 to 3678 meter above sea level with a mean elevation of 2200 meter above sea level.

More than three quarter of the watershed is intensively cultivated land and teff, maize, Barley, and Wheat are the major crops grown in the watershed. Bush or shrub land, grazing land, forest/wood land and wetland/swap are other land cover types in the watershed (WWDSE, 2007).
Based on FAO classification system, six soil types namely, Haplic luvisol, chromic luvisol, Lithic leptosol, Eutric vrtisol, Eutric Fluvisol and Chromic Cambisol are common soil types in Gumara Watershed (BCEOM, 1998; MoARD, 2004; WWDSE, 2007).

Rainfall over the Gumara watershed is mono-modal and most of the rainfall is concentrated in the season June to September and with virtual drought from November through April. The four wettest months cover 85 percent of the total annual rainfall. The dry season, being from October to May has a total rainfall of about 15% of the mean annual rainfall (WWDSE, 2007).

Methodology

SWAT 2005 (Soil and Water Assessment Tool) model integrated with GIS techniques is used to simulate runoff and sediment yield of this study. SWAT is a physically based and computationally efficient hydrological model, which uses readily available inputs .It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch, et al., 2005).

Digital elevation model (DEM) data, polygon Coverage' of soils and land use, and point coverage of weather stations were used as basic input to the model. Other inputs used include daily rain fall, minimum and maximum temperature, relative humidity, solar radiation, and wind speed. We delineated the watershed using a using a 90mx90 m resolution digital elevation model (DEM) and digitized stream networks of the study area.

After watershed delineation, the watershed was partitioned in to hydrologic response units (HRU), which are unique soil and land use combinations within in the watershed to be modeled.
In this study, multiple HRU with 20 percent land use threshold and a 10 percent soil threshold were adopted.

For modeling surface runoff and sediment yield we used the SCS curve number method (SCS, 1972) and modified universal soil loss equation respectively. In order to identify the most important or sensitive model parameters before calibration, model sensitivity analysis was carried out using a built-in SWAT sensitivity analysis tool that uses the Latin Hypercube One-factor-At-a-Time (LH-OAT) (Van Griensven, 2005).

We used the manual calibration procedure and the model was calibrated and validated using flow and suspended sediment data measured at gauging station covering about 90 % of the total watershed. Percent difference between simulated and observed data (D), Correlation coefficient (R^2) and Nash and Sutcliffe simulation efficiency (E_{ns}) (Nash and Suttcliffe 1970) were used to evaluate the model's performance during calibration and validation processes.

Result and discussion

Sensitivity Analysis

We carried out Sensitivity analysis to identify sensitive parameter that significantly affected surface runoff, base flow and sediment yield. Curve number (CNII), available water capacity (SOL_AWC), average slope steepness (SLOPE), saturated hydraulic conductivity (SOL_K), maximum canopy storage (canmx) and soil depth (SOL_Z) and soil evaporation compensation factor (ESCO) were relatively high sensitive parameters that significantly affect surface runoff.

Threshold water depth in shallow aquifer for flow (GWQMN), base flow Alpha factor (ALPHA_BF), and deep aquifer percolation fraction (rchrg.dp) were other parameters that mainly influence base flow.

We also identified average slope Steepness, USLE cover or management factor, USLE support Practice factor , average slope length, Linear factor for channel sediment routing and exponential factor for channel sediment routing as the most sensitive parameters that significantly affect sediment yield.

Calibration and validation

Once we have identified the most sensitive parameters, values of selected model parameters were varied iteratively within a reasonable range during various calibration runs until a satisfactory agreement between observed and simulated streamflow and sediment data were obtained. Five years daily flow and measured sediment data were used for flow and sediment calibration respectively.

Flow Calibration resulted in Nash–Sutt cliffe simulation efficiency (ENS) of 0.76, correlation coefficient (R2) of 0.87, and mean deviation of 3.29 % showing a good agreement between measured and simulated monthly flows.

The model with calibrated parameters was validated by using an independent set of measured flow and sediment data which were not used during model calibration. We used three years measured flow and sediment data for validation processes. Accordingly, good match between monthly measured and simulated flows in the validation period were demonstrated by the correlation coefficient (R^2) of 0.83 ,Nash-Sutcliffe simulation efficiency (ENS) of 0.68 and a mean deviation of measured and simulated flows for the monthly flow was found to be -5.4

Table 1 Calibration and validation statistic for monthly measured and simulated Streamflow

Parameter	Calibrated(1998-2002)	Validated (2003-2005)
R^2	0.87	0.83
E_{ns}(Nash-Sutcliffe model efficiencies)	0.76	0.68
D%(deviation of mean discharge)	3.29	-5.4

Table 2 Comparison of monthly measured and simulated flows

Period	Average flow (m3/s)	
	Measured	Simulated
Calibration (1998-2002)	31.63	32.69
Validation (2003-2005)	33.98	32.15

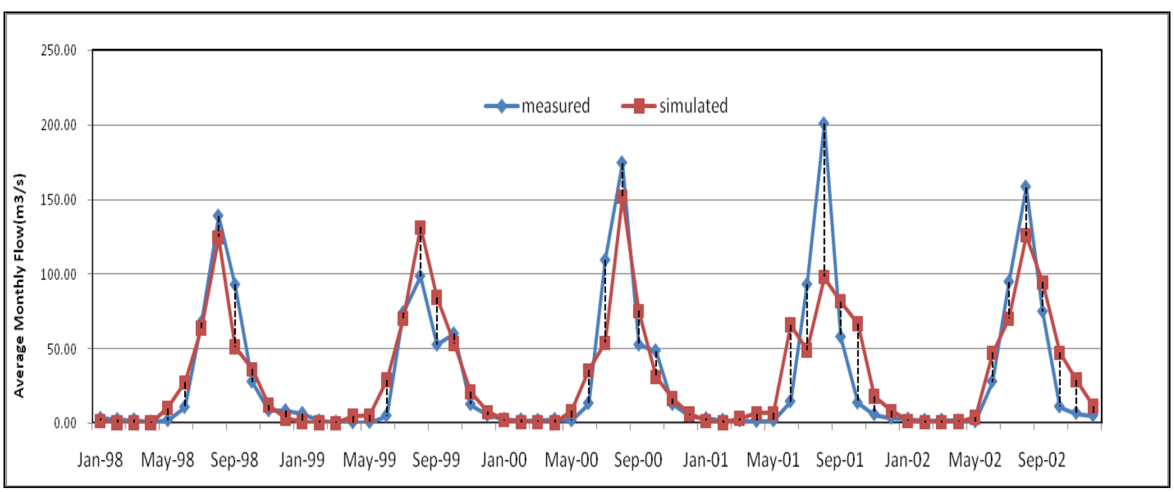

Figure 2: Calibration results of average monthly measured and simulated flow

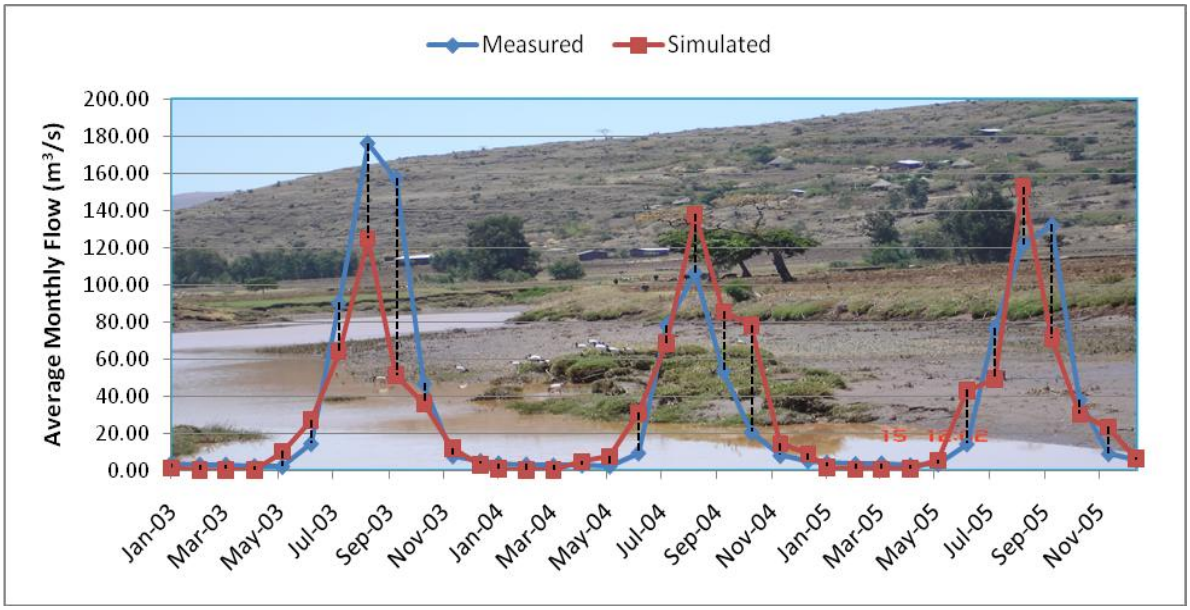

Figure 3: Validation results of average monthly measured and simulated flow

In calibrating sediment a good agreement between simulated monthly sediment yields with measured sediment yield was verified by correlation coefficient (R^2) of 0.85, Nash-Sutcliffe model efficiency (E_{NS}) 0.74 and mean deviation (D) of -14.2% . In validating sediment, a match between simulated and measured sediment was demonstrated by correlation coefficient (R^2) of 0.79, Nash-Sutcliffe model efficiency (E_{NS}) 0.62 and mean deviation (D) of -16.9%.

Table 3 Calibration and Validation results of monthly measured and simulated sediment yield

Parameter	**Calibrated (1998-2002)**	**Validated (2003-2005)**
Correlation coefficient (R^2)	0.85	0.79
Nash-Sutcliffe model efficiencies(E_{ns})	0.74	0.62
Deviation of mean discharge (D %)	-14.2	- 16.9

Table 4 Average Monthly and Annually Measured and Simulated Sediment Yield for calibration and validation periods

Simulation periods	Average Measured Sediment Yield		Average Simulated Sediment Yield	
	(t/ha/m)	(t/ha/yr)	(t/ha/m)	(t/ha/yr)
1998-2002 (calibration)	1.80	21.6	1.55	18.6
2003-2005 (Validation)	1.91	22.92	1.60	19.2

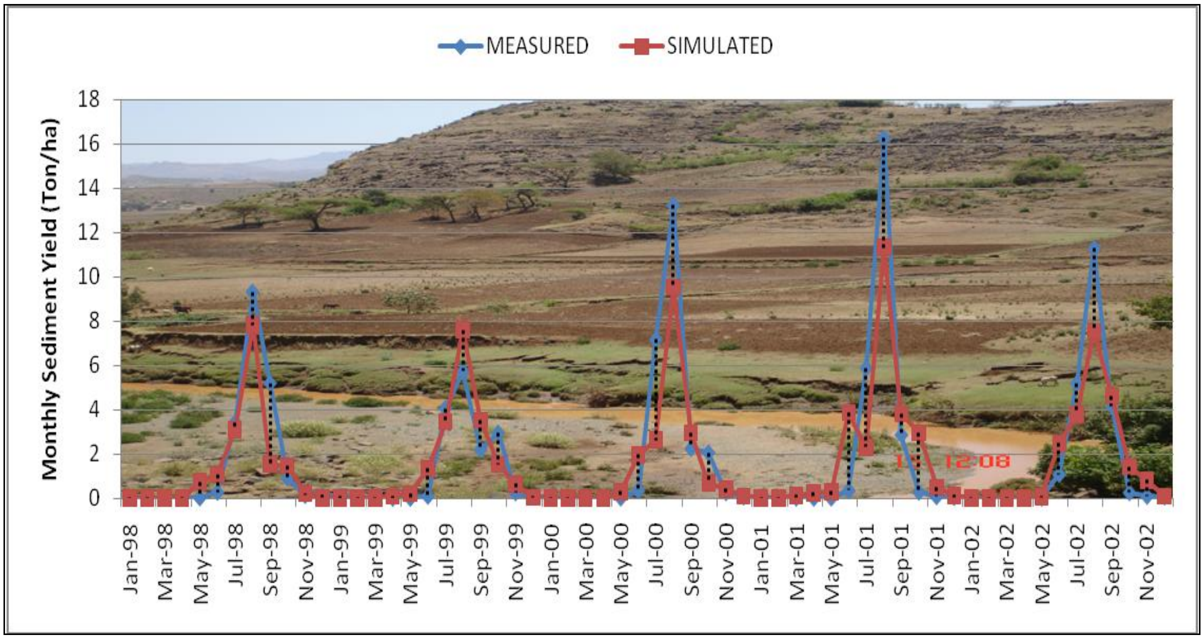

Figure 4: Calibration results of monthly measured and simulated sediment yield

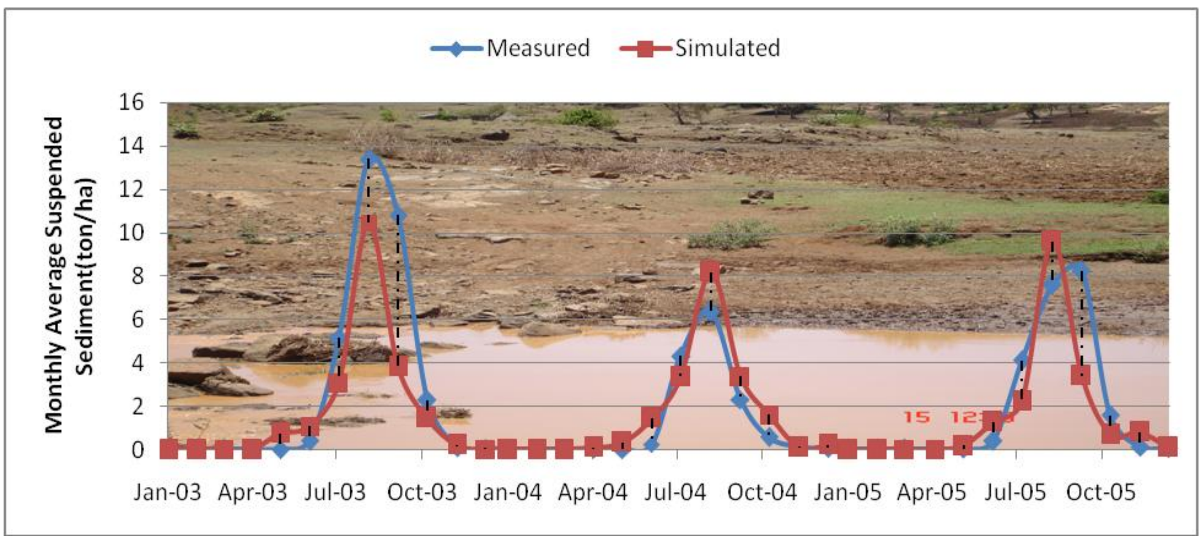

Figure 5: Validation results of monthly measured and simulated sediment yield

Spatial pattern of Sediment source areas

After Calibration and validation, the model was run for a period 10 years .From the model simulation output, sediment source areas were identified in the Watershed.10 years annual average measured suspended sediment generated from the sediment rating curve was 20.7 ton/ha/yr and the simulated annual average suspended sediment yield by SWAT model was 16.2 t/ha/yr. The spatial distribution of sediment generation for the Gumara watershed is presented in Figure 6. The spatial distribution of sediment indicated that, out of the total 30

SWAT sub basins, 18 sub-basins produce average annual sediment yields ranging from 11-22 ton/ha/yr, while most of the low land and wetland areas are in the range of 0-10 ton/ha/yr.

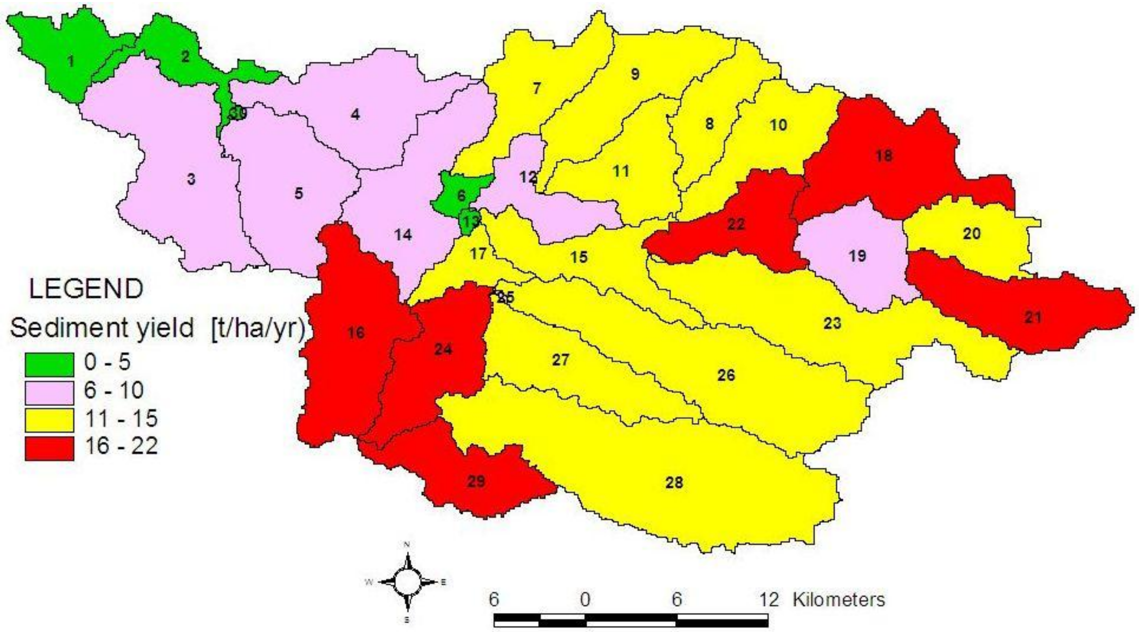

Figure 6: Spatial Distribution SWAT simulated annual sediment yield classes by sub basin (t/ha/yr), Number (1-30) are sub basin numbers

Scenario Analysis

Once the model has been validated and the results are considered acceptable, the model is ready to be parameterized to the conditions of interest (e.g., to evaluate impact of land use change, management and conservation practices). After detail analysis of the problems and benefits of the existing physical conservation practices in the watershed, we tested the model with alternative scenario analysis of vegetation filter strip (buffer) with varying width to reduce sediment production from critical sub watersheds. In evaluating Impact filter strips, three management scenarios were considered and simulated:

I. Base Case (no filter Strip)
II. Filter strip 5 m wide on all HRUs (hydrologic response units) in selected sub watersheds; and
III. Filter strips 10 m wide on all HRUs in selected sub watersheds

With implementation of vegetation strips ,an average annual sediment yields can be reduced by 58 % to 62 % with 5m buffer strip and 74.2 to 74.4 % with 10m filter strips(table 5 ,figure 7 and 8)

Table 5 Average annual change in sediment yield due to implementation of vegetation (filter strips) of varying widths in selected critical Sub Watersheds.

Selected critical Sub Watersheds	Average Annual Sediment Yield t/ha/yr) (1996-2005)			Percent Reduction in Sediment Yield	
	Base Case (no filter strip)	Field Strip or Buffer (5m wide)	Field Strip or Buffer (10m wide	Field Strip or Buffer (5m wide)	Field Strip or Buffer (10m wide)
11	11.800	4.5	3.03	-0.62	-74.35
16	18.200	7.6	4.68	-0.58	-74.30
17	12.100	4.6	3.11	-0.62	-74.29
22	17.600	6.8	4.54	-0.61	-74.23
24	21.300	8.2	5.48	-0.62	-74.29
28	12.700	4.9	3.28	-0.61	-74.19
29	19.200	7.4	4.95	-0.61	-74.23

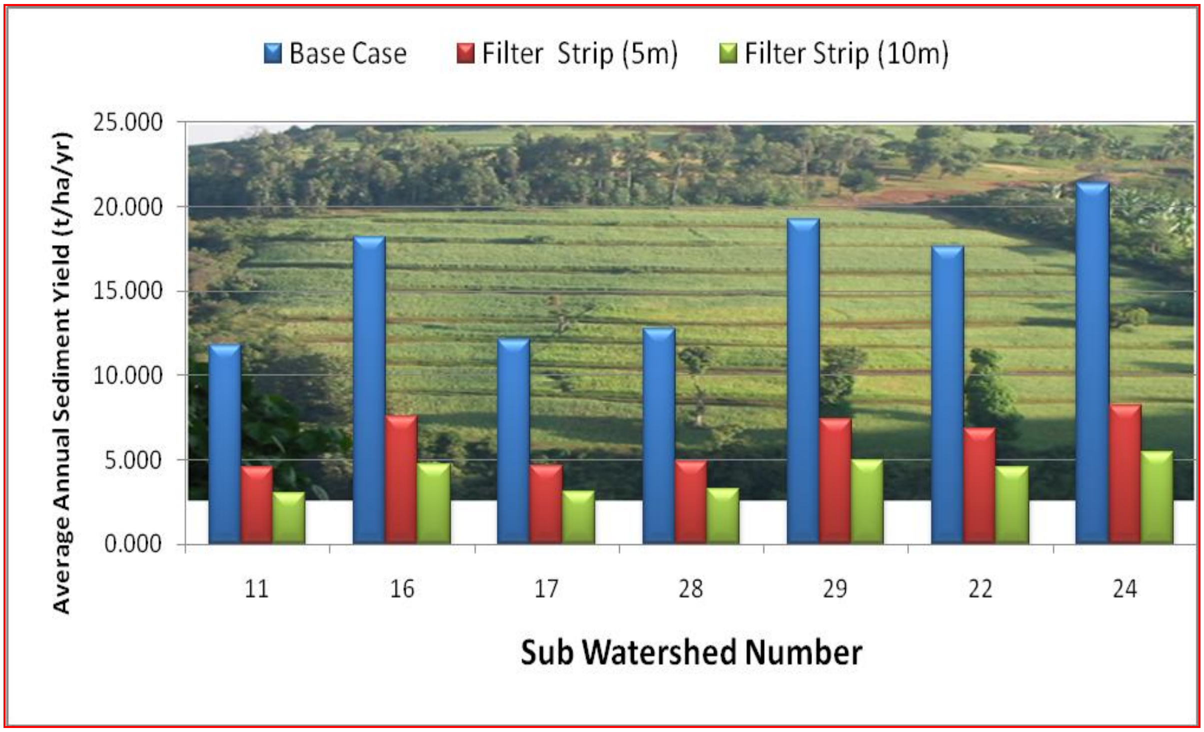

Figure 7: Reduction in sediment yield (t/ha/y) due to implementation of different width of filter strips as compared to the base case

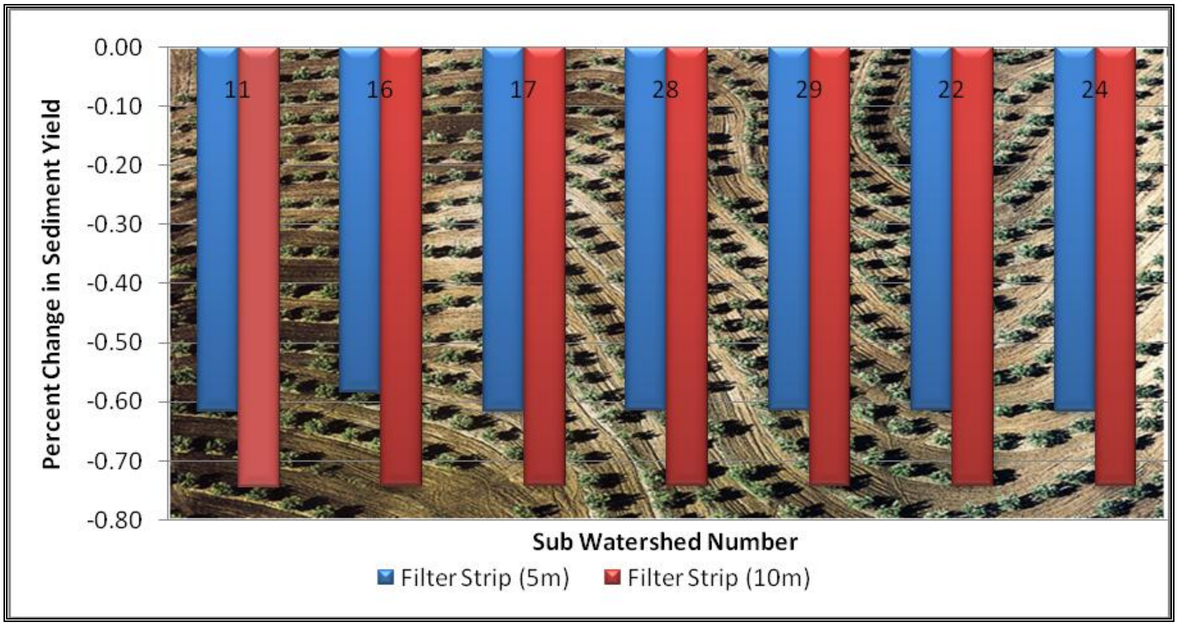

Figure 8: Percent Reduction in simulated average annual suspended sediment yield (t/ha/y) due to implementation of filter strips

Conclusion and recommendation

Even though the problem of soil erosion is recognized from gross erosion estimates and field observations, quantitative information and data are required at micro watershed level to develop alternative watershed management plans and for decision making. In this study, attempts were made to characterize the Gumera watershed in terms of sediment yield, identification of potential sediment source areas and evaluation of alternative management interventions to reduce the onsite and offsite impact of soil erosion in the watershed.

We evaluated the performance of SWAT model using Standard calibration and validation statistics. A good agreement between measured and simulated monthly streamflow was demonstrated by correlation coefficient (R^2 = 0.87), Nash-Sutcliffe model efficiency (ENS = 0.76) and mean deviation (D = 3.29) for calibration period and $R^{2 =}$ 0.83, ENS = 0.8 and D= -5.4 % for validation periods. The model over estimated simulated flow by 3.29 % and under estimated by 5.4 % for calibration (1998 -2002) and validation periods (2003-2005) respectively.

In simulating sediment yield, correlation coefficient (R^2 =0.85), Nash-Sutcliffe model efficiency (E_{NS}= 0.74.) and mean deviation (D=-14.2%) for calibration period and R^2=0.79, ENS =0.62 and D=-16.9% for validation periods were achieved. In both calibration and validation periods, simulated sediment yield were under estimated by 14.2% and 16.9 % respectively. Considering, the acceptable limits of statistical model evaluation criteria; these result indicate a good a match between measured and simulated sediment.

A good performance of the model in the Validation period indicates that the fitted parameters during calibration period can be taken as a representative set of parameters for Gumara watershed and further simulation and evaluation of alternative scenario analysis can be carried out for other periods using the SWAT model. The SWAT model prediction verified that about 72 % of the gumara watershed is erosion potential area contributing high sediment yield exceeding the tolerance limit (soil formation rate) in the study area.

Following calibration and validation of SWAT model, two scenario analyses were tested to reduce sediment loads from critical sub watersheds. The simulation results of the two scenario analysis (using vegetation filter strips of 5m and 10 m wide) indicated that implementing filter strips can reduce sediment yield by 58 % to 74 %. Overall, SWAT performed well in simulating runoff and sediment yield on monthly basis at the watershed scale and thus can be used as a planning tool for watershed management. The study can be further extended to similar watersheds in Abay River basin, other similar areas and can bridge the gap of adequate information between processes at the micro watershed and large watershed level.

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