HYDROLOGICAL AND SEDIMENT YIELD MODELLING IN LAKE TANA BASIN, BLUE NILE ETHIOPIA

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DEDICATION

This thesis is dedicated to my father-in-law, the late Amare Tabor
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Shimelis Gebriye
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**ABSTRACT**

Land and water resources degradation are the major problems on the Ethiopian highlands. Poor land use practices and improper management systems have played a significant role in causing high soil erosion rates, sediment transport and loss of agricultural nutrients. So far limited measures have been taken to combat the problems. In this study a physically based watershed model, SWAT2005 was applied to the Northern Highlands of Ethiopia for modelling of the hydrology and sediment yield. The main objective of this study was to test the performance and feasibility of SWAT2005 model to examine the influence of topography, land use, soil and climatic condition on streamflows, soil erosion and sediment yield. The model was calibrated and validated on four tributaries of Lake Tana as well as Anjeni watershed using SUFI-2, GLUE and ParaSol algorithms. SWAT and GIS based decision support system (MCE analysis) were also used to identify the most erosion prone areas in the Lake Tana Basin. Streamflows are more sensitive to the hydrological response units definition thresholds than subbasin discretization. Prediction of sediment yield is highly sensitive to subbasin size and slope discretization. Baseflow is an important component of the total discharge within the study area that contributes more than the surface runoff. There is a good agreement between the measured and simulated flows and sediment yields with higher values of coefficients of determination and Nash Sutcliffe efficiency. The annual average measured sediment yield in Anjeni watershed was 24.6 tonnes/ha. The annual average simulated sediment yield was 27.8 and 29.5 tonnes/ha for calibration and validation periods, respectively. The SWAT model indicated that 18.5 % of the Lake Tana Basin is erosion potential areas. Whereas the MCE result indicated that 25.5 % of the basin are erosion potential areas. The calibrated model can be used for further analysis of the effect of climate and land use change as well as other different management scenarios on streamflows and soil erosion. The result of the study could help different stakeholders to plan and implement appropriate soil and water conservation strategies.

**Key words:** SWAT, Lake Tana, Blue Nile, hydrological modelling, watershed modelling, MCE, SUFI-2, GLUE, ParaSol, streamflows, sediment yield, erosion, water balance, model calibration

**INTRODUCTION**

**Background**

The major problem facing Ethiopia today is the acute shortage of food to feed the rapidly growing population. The population has grown dramatically over the last three decades to about 78 million. Ethiopia’s agriculture is increasingly unable to provide adequate food for the population that grows at 2.3 % per annum (CSA, 2005). This has resulted in further shrinkage of farm sizes. Yigremew (1999) reported that 62 % of the total farming households own one or less hectare of land.

Ethiopia experiences pervasive land, water and environmental degradation due to localized and global climatic anomalies. These leave the country to recurrent crop failures and sever food shortages. Low soil fertility coupled with temporal imbalance in the distribution of rainfall and the substantial non-availability of the required water at the required period are the principal contributing factors to the low and declining agricultural productivity. Hence, proper utilization of the available soil and water resources and development of irrigation is essential to Ethiopia's agricultural development and achievement of food security.

The poor land use practices, improper management systems and lack of appropriate soil conservation measures have played a major role for causing land degradation problems in the country. Because of the rugged terrain, the rates of soil erosion and land degradation in Ethiopia are high. The soil depth of more than 34 % of the land area is already less than 35 cm (Zemenfes, 1995; SCRP, 1996). Hurni (1989) indicated that Ethiopia loses about 1.3 billion metric tons
of fertile soil every year and the degradation of land through soil erosion is increasing at a high rate. According to Kruger et al., (1996) 4% of the highlands are now so seriously eroded that they will not be economically productive again in a foreseeable future. The Soil Conservation Research Project (SCRP, 1996) has estimated an annual soil loss of about 1.5 billion tons from the highland. According to the Ethiopian Highlands Reclamation Study (EHRS, 1984) soil erosion is estimated to cost the country 1.9 billion US$ between 1985 and 2010. These call for immediate measures to save the physical quality of soil and water resources of the country.

The Lake Tana Bain is one of the most affected area by soil erosion, sediment transport and land degradation. The land and water resources of the basin and the Lake Tana ecosystem are in danger due to the rapid growth of population, deforestation and overgrazing, soil erosion, sediment deposition, storage capacity reduction, drainage and water logging, flooding, pollutant transport, population pressure, over-exploitation of specific fish species. The available land and water resources are not utilized effectively to improve the livelihood and socioeconomic conditions of the inhabitants. Sediments, organic and inorganic fertilizers from the agricultural fields that enter the Lake by runoff may result in eutrophication. So far no effective measures have been taken to combat flooding, soil erosion and sedimentation problems. The lack of decision support tools and limitation of data concerning weather, hydrological, topographical, soil and land use; are factors that significantly hinder research and development in the area. There is a need for hydrological and sediment transport research of the Lake Tana Basin that can improve catchment management programs. Appropriate decision support tools are needed for better assessment of the hydrology and soil erosion processes for planning and implementations of soil and water conservation measures. The tools concern various hydrological and soil erosion models as well as geographical information system (GIS). The modelling tools will finally help to save the physical quality of the land.

Overview of Hydrological and Soil Erosion Modelling

Simulation programs implementing watershed hydrology and river water quality models are important tools for watershed management for both applied and operational research purposes. For this purpose several available empirical, physically based or conceptual models could be used. Empirical models are based on defining important factors through field observation, measurement, experiments and statistical methods (Petter, 1992). They are useful in predicting the hydrology or soil erosion, but are site specific and require long-term data (Elirehema, 2001). Physically based models are based on knowledge of the fundamental processes and incorporate the laws of conservation of mass and energy (Petter, 1992). These physical processes vary both temporally and spatially. They consider the spatial and temporal changes of different factors (Jaroslav et al., 1996). Physically based distributed watershed models play a major role in analyzing the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds.

Many hydrological and soil erosion models are developed to describe the hydrology, erosion and sedimentation processes. These models are generally meant to describe the physical processes controlling the transformation of precipitation to runoff and detachment and transport of sediments. Hydrological models are tools that describe the physical processes controlling the transformation of precipitation to streamflows. There are different hydrological models designed and applied to simulate the rainfall runoff relationship under different temporal and spatial dimensions. The focus of these models is to establish a relationship between various hydrological components such as precipitation, evapotranspiration, surface runoff, ground water flow and soil water movement (infiltration). Many of these hy-
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Hydrological models describe the canopy interception, evaporation, transpiration, snowmelt, interflow, overland flow, channel flow, unsaturated subsurface flow and saturated subsurface flow. These models range from simple unit hydrograph based models to more complex models that are based on the dynamic flow equations.

Erosion modelling is based on understanding the physical laws of landscape processes that occur in the natural environment. Erosion models can provide a better understanding of natural phenomena such as transport and deposition of sediment by overland flow and allow for reasonable prediction and forecasting. Many different models have been proposed to describe and predict soil erosion by water and associated sediment yield. They vary considerably in their objectives, time and spatial scales involved.

In recent years, distributed watershed models are increasingly used to implement alternative management strategies in the areas of water resources allocation, flood control, impact of land use change and climate change, and finally environmental pollution control. Many of these models share a common base in their attempt to incorporate the heterogeneity of the watershed and spatial distribution of topography, vegetation, land use, soil characteristics, rainfall and evaporation. Some of the watershed models developed in the last two decades are CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), EPIC - Erosion Productivity Impact Calculator (Williams, 1995), AGNPS (Agricultural None Point Source model) (Young et al., 1989), SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998) and HSPF (Hydrologic Simulation Program – Fortran) (Bicknell et al., 2001), ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation) (Beasley and Huggins, 1982), EROSION-3D (SCHMIDT, 1995), EUROSEM (European Soil Erosion Model) (Morgan et. al., 1997), WEPP (Water Erosion Prediction Project) (Foster and Lane, 1987) etc. Many of these watershed models are applied for runoff and soil loss prediction (e.g. Morgan 2001, Srinivasan et al., 1998, Gronsten and Lundekvam, 2006), water quality modelling (e.g. Debele et al., 2006, Santhi et al., 2006, Abbaspour et al., 2007), land use change effect assessment (e.g. Sheng et al., 2003, Claessens et al., 2006; Wu et al., 2007) and climate change impact assessment (e.g. Andersson et al., 2006, Huang et al., 2005; Zhang et al., 2007). Among the foregoing models, the physically based distributed model SWAT is a well established model for analyzing the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds. It is one of the watershed models for long-term impact analysis. It is widely applied in many parts of United States and many other countries (e.g. Bingner, 1996, Peterson and Hamlett, 1998; Srinivasan et al., 1998; Arnold et al., 1998; Benaman et al., 2005, Heuvelmans et al., 2004; Bouraoui, 2005). A comprehensive review of SWAT model applications is given by (Gassman et al., 2007). There are few applications of SWAT model to Ethiopian conditions in relatively small watershed areas (Alamirew, 2006, Kassa, 2007, Setegn et al., 2007). The present study considers large scale application of the model on a catchment area where most of the topographic features have slopes greater than 5 %. For estimation of curve number to slopes above 5% an equation developed by Williams (1995) can be used.

Watershed models prediction uncertainties

An important issue to consider in the prediction of hydrology, sediment yield and water quality is uncertainties in the predictions. The main sources of uncertainties are:

(i) simplifications in the conceptual model. For example, the simplifications in a hydrologic model, or the assumptions in the equations for estimating surface erosion and sediment yield, or the assumptions in calculating flow velocity in a river,
(ii) processes occurring in the watershed but not included in the model. For example, wind erosion, soil losses caused by landslides,

(iii) processes that are included in the model, but their occurrences in the watershed are unknown to the modeler or unaccountable; for example, reservoirs, water diversions, irrigation, or farm management affecting water quality,

(iv) processes that are not known to the modeler and not included in the model. These include dumping of waste material and chemicals in the rivers, or processes that may last for a number of years and drastically changes the hydrology or water quality such as constructions of roads, bridges, tunnels and dams, and

(v) errors in the input variables such as rainfall and temperature.

Calibration and uncertainty Analysis

The ability of a watershed model to accurately predict stream flow and sediment yield is evaluated through sensitivity analysis, model calibration, and model validation. The sensitive parameters are further used to find the most reasonable parameter values for better estimations of the streamflows and sediment yield. Many distributed watershed models use different factors and parameters for the simulation of the hydrological processes. Hence, it is essential for these models to pass careful calibration tests and uncertainty analysis. The use of several calibration and uncertainty analysis techniques are common among researchers (e.g. Abbaspour 2004, 2005; Eckhardt and Arnold, 2001; Yang et al., 2007). In this thesis application of SUFI-2, ParaSol and GLUE calibrations and uncertainty algorithms are discussed.

Objectives of the study

Lake Tana Basin is of significant importance to Ethiopia and the downstream countries concerning the water resources aspects and the ecological balance of the area. Many years of miss management, constraints imposed by population growth, and draughts are causing its rapid detrition. To safeguard this ecologically sensitive basin, economical, social and technical measures must be taken with no further delay. The great ecological tragedy of the Aral Sea is an important reminder to us of one-sided human intervention. The present research is an attempt to obtain a scientific understanding of the basin as well as defining adequate tools for long term predictions of the basin characteristics. The focus is on the various hydrological aspects and surface erosion of the basin. The thesis concerns the application of the physically based watershed model, SWAT2005 in the area. The main objective was to test the performance and feasibility of SWAT2005 model to examine the influence of topographic, land use, soil and climatic condition on streamflows, soil erosion and sediment yield. The specific focus are i) identify and organize the existing weather, measured streamflows and sediment yield, land use and soil database of the Lake Tana basin for testing of a watershed model and development of different management scenarios ii) to identify the most sensitive flow and sediment parameters in the area and to validate the SWAT model for prediction of stream flow and sediment yield using different calibration and uncertainty analysis algorithms. iii) to assess the model sensitivity to sub-basin delineation, slope discretization and rainfall variability on streamflows and sediment yield in the study area iv) to assess the hydrological water balance of the lake Tana basin as well as the lake’s water balance. v) to identify erosion sensitive areas in the Lake Tana basin.
DESCRIPTION OF THE STUDY AREA

Location, topography, climate and Drainage basins of Ethiopia

Ethiopia is situated in East Africa which lies between 3°30’ and 14°50’ North latitudes and 32°42’ and 48°12’ East longitudes. It has a surface area of about 1.127 million km². The country consists of three climatic zones depending on topography and geographic location: the cool zone above 2,400 meters where temperatures range from near freezing to 16 °C; the temperate zone at elevations of 1,500 to 2,400 meters with temperatures from 16 to 30 °C and the hot zone below 1,500 meters with both tropical and arid conditions and daytime temperatures ranging from 27 to 50 °C. Annual rainfall varies from less than 100 mm in the low lands along the border with Somalia and Djibouti to 2400 mm in the southwest highlands, with a national average of 744 mm/year. The topography of Ethiopia ranges from very high mountain ranges (the Semien Mountains, Ras Dejen 4,620 m, and the Bale Mountains), to one of the lowest elevation in Africa (the Danakil depression 125 m). The main rainy season is from June to September (longer in the southern highlands) preceded by intermittent showers.
from February to March; the rest of the year is mainly dry weather. Ethiopia is known for its enormous water resources potential. It is still known as the water tower of Africa, the source of the Nile River and many transboundary rivers. The total annual runoff is estimated about 110 billion m$^3$, and only less than 5% is used in the country, the remaining leaves the country as transboundary rivers such as Blue Nile, Baro-Akobo, Wabi Shebele, Tekeze, Genale-Dawa etc. Ethiopia has three principal drainage systems (Ethiopia, 2008). The first and largest is the western system, that includes the watersheds of the Blue Nile (known as the Abbay in Ethiopia), the Tekeze, and the Baro rivers. All three rivers flow west to the White Nile in Sudan. The second system is the Rift Valley internal drainage system, composed of the Awash River, the Lakes Region, and the Omo River. The Awash flows northeast to the Denakil Plain before it dissipates into a series of swamps and Lake Abe at the border with Djibouti. The Lakes Region is a
self-contained drainage basin, and the Omo flows south into Lake Rudolf, on the border with Kenya. The third system is the Shebele and Genale rivers. Both of these rivers originate in the Eastern Highlands and flow southeast toward Somalia and the Indian Ocean. Only the Genale (known as the Jubba in Somalia) makes it to the sea; the Shebele disappears in sand just inside the coastline. Figure 1 shows the different major river basins of Ethiopia.

General Characteristics of Area under Investigation

Blue Nile River Basin

The Blue Nile River (Abbay/አብይ in local language) originates from the Lake Tana in Ethiopia. It flows south from Lake Tana and then west across Ethiopia and northwest into Sudan. The Blue Nile eventually joins the White Nile at Khartoum, Sudan and the Nile continuous through Egypt to the Mediterranean Sea at Alexandria. The river has a drainage area of 199812 km² and supplies nearly 84 % of the water of the Nile River during high-flow season. It accounts for about 17.5 % of the land area and 50 % of its annual average surface water resources of Ethiopian. It is the main source of water for Ethiopia, Sudan and Egypt (Peggy et al., 1994). Flow volumes along the Blue Nile range from approximately 4 billion m³ annually at the outlet of the Lake Tana to 50 billion m³ at the Ethio-Sudan border. From Lake Tana, the Blue Nile travels 35 km to the Tissisat falls, where the river drops 50 m; it then flows through a gorge, which in some places is as deep as 1,200 m. The major tributaries joining the Blue Nile between Lake Tana and Sudan border are: Beshilo, Didaessa, Finchaa, Guder, Muger, Wenchi, Jemma, Birr, Temcha and Beles. The flow of the Blue Nile reaches its maximum discharge in the main rainy season (from June to September), when it supplies more than two thirds of the water of the Nile river. The basin has an average annual runoff of about 50 billion m³.

Lake Tana Basin

Lake Tana basin is one of the major basins that significantly contribute to the livelihoods of tens of millions of people in the lower Nile river basin. Lake Tana basin comprises a total area of 15,096 km² including the lake area. The mean annual rainfall of the catchment area is about 1280 mm. The annual mean actual evapotranspiration and water yield of the catchment area is estimated to be 773 mm and 392 mm, respectively (Setegn et al., 2008). It is rich in biodiversity with many endemic plant species and cattle breeds; it contains large areas of wetlands; it is home to many endemic birds and cultural and archaeological sites. This basin is of critical national significance as it has great potentials for irrigation; hydroelectric power; high value crops and livestock production; ecotourism and others. Lake Tana is located in the country's northwest highlands (Lat 12° 0' North, Lon 37° 15' East) (Figure 2). The lake is a natural type which covers 3000 – 3600 km² area at an elevation of 1800 m and with a maximum depth of 15 m. It is approximately 84 km long, 66 km wide. It is the largest lake in Ethiopia and the third largest in the Nile Basin. Gilgel Abay, Ribb, Gumera and Megech are the main rivers feeding the lake which contributes more than 93 % of the inflow. It is the main source of the Blue Nile River that is the only surface outflow for the Lake. The climate of the region is 'tropical highland monsoon' with main rainy season between June and September. The air temperature shows large diurnal but small seasonal changes with an annual average of 20°C.

Anjeni Gauged watershed

Anjeni gauged watershed is situated in 37°31'E / 10°40'N, in the Northern part of Ethiopia. Its altitude ranges from 2407 to 2507 m above sea level. Hydrological catchment area is 113.4 ha. Mean annual rainfall and temperature is 1690 mm and 16°C, respectively. The watershed was established by the Soil Conservation Research Programme (SCRP) in 1981 with the support of the Swiss Agency for Development and Cooperation (SDC). The land use map
of Anjeni area indicated that 36% of the land is cultivated for field crops, legumes and vegetables, 36% of the watershed is pasture land and 29% of the watershed is forest land (Figure 3a). The majority of the soil type of the watershed is similar to Lake Tana basin except Vertic Luvisols, Humic Nitisols, Haplic Lixisols, Haplic Lixisols, Haplic Lixisols, Haplic Lixisols, Haplic Lixisols, Haplic Acrisols, Humic Alisols and Dystric Cambisols (Figure 3b).

METHODS

The present study concerns the application of a physically based watershed model SWAT2005 in the Lake Tana Basin and Anjeni gauged watershed. The application of the model involved calibration, sensitivity and uncertainty analysis. For this purpose SUFI-2, ParaSol and GLUE calibration and uncertainty analysis algorithms were used.

Description of Soil and Water Assessment tool - SWAT Model

SWAT2005 is a public domain model actively supported by the USDA (United States Department of Agriculture) – ARS (Agricultural Research Service) at the Grassland, Soil and Water Research Laboratory in Temple, Texas, USA. SWAT is a river basin scale, a continuous time, a spatially distributed model 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). SWAT can analyze both small and large watersheds by subdividing the area into homogenous parts. As a physically-based model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in terms of land cover, soil type and slope within a watershed. The SWAT system embedded within geographic information system (GIS) that can integrate various spatial environmental data including soil, land cover, climate and topographic features. Currently SWAT is imbedded in an ArcGIS interface called ArcSWAT. It is computationally efficient, uses readily available inputs and enables users to study long-term impacts.

Hydrological Component of SWAT

The simulation of the hydrology of a watershed is done in two separate division. One is the land phase of the hydrological cycle that controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin. Hydrological components simulated in land phase of the Hydrological cycle are canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds, tributary channels and return flow. The second division is routing phase of the hydrologic cycle that can be defined as the movement of water, sediments, nutrients and organic chemicals through the channel network of the watershed to the outlet. In the land phase of hydrological cycle, SWAT simulates the hydrological cycle based on the water balance equation.

\[
SW_t = SW_0 + \sum_{i=1}^{t} \left( R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right)
\]

In which \( SW_t \) is the final soil water content (mm), \( SW_0 \) is the initial soil water content on day \( i \) (mm), \( t \) is the time (days), \( R_{day} \) is the amount of precipitation on day \( i \) (mm), \( Q_{surf} \) is the amount of surface runoff on day \( i \) (mm), \( E_a \) is the amount of evapotranspiration on day \( i \) (mm), \( W_{seep} \) is the amount of water entering the vadose zone from the soil profile on day \( i \) (mm), and \( Q_{gw} \) is the amount of return flow on day \( i \) (mm).

Brief description of some of the key model components are provided in this thesis. More detailed descriptions of the different model components are listed in (Arnold et al., 1998, Neitsch et al., 2005).

Surface runoff occurs whenever the rate of precipitation exceeds the rate of infiltration. SWAT offers two methods for estimating surface runoff: the SCS curve number procedure (USDA-SCS, 1972) and the Green & Ampt infiltration method (Green and Ampt, 1911). Using daily or sub daily rainfall, SWAT simulates surface runoff volumes.
and peak runoff rates for each HRU. In this study, the SCS curve number method was used to estimate surface runoff because of the unavailability of sub daily data for Green & Ampt method.

The SCS curve number equation is (USDA-SCS, 1972):

\[ Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \]  

(2)

In which, \( Q_{surf} \) is the accumulated runoff or rainfall excess (mm), \( R_{day} \) is the rainfall depth for the day (mm), \( S \) is the retention parameter (mm). The retention parameter is defined by equation 3.

\[ S = 25.4 \left( \frac{100}{CN} - 10 \right) \]  

(3)

SWAT2005 version includes two methods for calculating the retention parameter; the first one is retention parameter varies with soil profile water content and the second method is the retention parameter varies with accumulated plant evapotranspiration. The soil moisture method (equation 4) overestimates runoff in shallow soils. But calculating daily CN as a function of plant evapotranspiration, the value is less dependant on soil storage and more dependant on antecedent climate.

\[ S = S_{max} \left( 1 - \left[ \frac{SW}{SW + \exp(w_1 - w_2 \cdot SW)} \right] \right) \]  

(4)

In which \( S \) is the retention parameter for a given day (mm), \( S_{max} \) is the maximum value that the retention parameter can have on any given day (mm), \( SW \) is the soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm), and \( w_1 \) and \( w_2 \) are shape coefficients. The maximum retention parameter value, \( S_{max} \), is calculated by solving equation 3. using \( CN_1 \).

\[ S_{max} = 25.4 \left( \frac{100}{CN_1} - 10 \right) \]  

(5)

When the retention parameter varies with plant evapotranspiration, the following equation is used to update the retention parameter at the end of every day:

\[ S = S_{prev} + E_o \cdot \exp \left( \frac{-cncoef \cdot S_{prev}}{S_{max}} \right) - R_{day} - Q_{surf} \]  

(6)

In which \( S_{prev} \) is the retention parameter for the previous day (mm), \( E_o \) is the potential evapotranspiration for the day (mm/day), \( cncoef \) is the weighting coefficient used to calculate the retention coefficient for daily curve number calculations dependent on plant evapotranspiration, \( S_{max} \) is the maximum value the retention parameter can achieve on any given day (mm), \( R_{day} \) is the rainfall depth for the day (mm), and \( Q_{surf} \) is the surface runoff (mm). The initial value of the retention parameter is defined as \( S=0.9 \cdot S_{max} \).

The SCS curve number is a function of the soil’s permeability, land use and antecedent soil water conditions. SCS defines three antecedent moisture conditions: I – dry (wilting point), II – average moisture, and III – wet (field capacity). The moisture condition I curve number is the lowest value the daily curve number can assume in dry conditions. The curve numbers for moisture conditions I and III are calculated with equations 7 and 8.

\[ CN_i = CN_2 \cdot \frac{20 \cdot (100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636 \cdot (100 - CN_2)])} \]  

(7)

\[ CN_3 = CN_2 \cdot \exp[0.00673 \cdot (100 - CN_2)] \]  

(8)

Typical curve numbers for moisture condition II are listed in various tables (Neitsch et al., 2005). The values are appropriate for a 5 % slope. Williams (1995) developed an equation to adjust the curve number to a different slope:
\[ CN_{s2} = \frac{(CN_1 - CN_2)}{3} \left[ 1 - 2 \cdot \exp(-1386 \cdot sp) \right] + CN_2 \]  
(9)

In which \( CN_1 \) is the moisture condition I curve number, \( CN_2 \) is the moisture condition II curve number for the default 5% slope, \( CN_3 \) is the moisture condition III curve number for the default 5% slope, \( CN_{s2} \) is the moisture condition II curve number adjusted for slope and slp is the average percent slope of the sub basin.

SWAT calculates the peak runoff rate with a modified rational method. There are many methods that are developed to estimate potential evapotranspiration (PET). Three methods are incorporated into SWAT: the Penman-Monteith method (Monteith, 1965), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves et al., 1985). For this study we have used Hargreaves method due to limitation of weather data such as wind speed, humidity and sunshine hours.

The simulation of groundwater is partitioned into two aquifer systems i.e an unconfined aquifer (shallow) and a deep-confined aquifer in each sub basin. The unconfined aquifer contributes to flow in the main channel or reach of the sub basin. Water that enters the deep aquifer is assumed to contribute to stream flow outside the watershed (Arnold et al., 1993). In SWAT2005 the water balance for a shallow aquifer is calculated with equation 10.

\[ aq_{sh,i} = aq_{sh,i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{deep} - w_{pump,sh} \]  
(10)

In which \( aq_{sh,i} \) is the amount of water stored in the shallow aquifer on day i (mm), \( aq_{sh,i-1} \) is the amount of water stored in the shallow aquifer on day i-1 (mm), \( w_{rchrg} \) is the amount of recharge entering the aquifer on day i (mm), \( Q_{gw} \) is the groundwater flow, or base flow, into the main channel on day i (mm), \( w_{revap} \) is the amount of water moving into the soil zone in response to water deficiencies on day i (mm), \( w_{deep} \) is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm), and \( w_{pump,sh} \) is the amount of water removed from the shallow aquifer by pumping on day i (mm). The steady-state response of groundwater flow to recharge is estimated by equation 11 (Hooghoudt, 1940).

\[ Q_{gw} = \frac{800 \cdot K_{sat} \cdot h_{wtabl}}{L_{gw}} \]  
(11)

In which \( K_{sat} \) is the hydraulic conductivity of the aquifer (mm/day), \( L_{gw} \) is the distance from the ridge or subbasin divide for the groundwater system to the main channel (m), and \( h_{wtabl} \) is the water table height (m). Water table fluctuations due to non-steady-state response of groundwater flow to periodic recharge is calculated by equation 12 (Smedema and Rycroft, 1983).

\[ \frac{dh_{wtabl}}{dt} = \frac{w_{rchrg,sh} - Q_{gw}}{800 \cdot \mu} \]  
(12)

In which \( \frac{dh_{wtabl}}{dt} \) is the change in water table height with time (mm/day), \( w_{rchrg,sh} \) is the amount of recharge entering the aquifer on day \( i \) (mm) and \( \mu \) is the specific yield of the shallow aquifer (m/m). Assuming that variation in groundwater flow is linearly related to the rate of change in water table height, equations 11 and 12 can be combined to obtain:

\[ \frac{dQ_{gw}}{dt} = 10 \cdot \frac{K_{sat}}{\mu \cdot L_{gw}^2} \left( w_{rchrg,sh} - Q_{gw} \right) = \alpha_{gw} \cdot \left( w_{rchrg,sh} - Q_{gw} \right) \]  
(13)

In which \( \alpha_{gw} \) is the baseflow recession constant or constant of proportionality. The baseflow recession constant, \( \alpha_{gw} \), is a direct index of groundwater flow response to changes in recharge (Smedema and Rycroft, 1983). \( \alpha_{gw} \) varies from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with a rapid response. Although the baseflow recession constant may be calculated, the best estimates are obtained by...
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Analyzing measured streamflows during periods of no recharge in the watershed.

**Sediment Component**

SWAT calculates the soil erosion and sediment yield with the Modified Universal Soil Loss Equation (MUSLE) 14 , (Williams and Berndt, 1977).

\[
\text{sed} = 11.8 \times \left( Q_{\text{surf}} \times q_{\text{peak}} \times \text{area}_{\text{hr}} \right)^{0.56} \\
\times K_{\text{USLE}} \times C_{\text{USLE}} \times P_{\text{USLE}} \times L_{\text{USLE}} \times \text{CFRG}
\]

(14)

In which sed is the sediment yield on a given day (metric tons), \( Q_{\text{surf}} \) is the surface runoff volume (mm/ha), \( q_{\text{peak}} \) is the peak runoff rate (m\(^3\)/s), area\(_{\text{hr}}\) is the area of the HRU (ha), \( K_{\text{USLE}} \) is the soil erodibility factor (0.013 metric ton m\(^3\) hr/(m\(^3\)-metric ton cm)), CUSLE is the cover and management factor, \( P_{\text{USLE}} \) is the support practice factor, \( L_{\text{USLE}} \) is the topographic factor and CFRG is the coarse fragment factor. The details of the USLE factors and the descriptions of the different model components can be found in (Neitsch et al., 2005).

**Routing face of the hydrological cycle**

In SWAT2005 water is routed through the channels network using either the variable storage routing or Muskingum river routing methods. The details of the water routing methods are discussed in Neitsch et al., (2005). The sediment routing model Arnold et al., (1995) that simulates the sediment transport in the channel network, consists of two components operating simultaneously: deposition and degradation. To determine the deposition and degradation processes the maximum concentration of sediment calculated by equation 15 in the reach is compared to the concentration of sediment in the reach at the beginning of the time step. A brief description of sediment routing components of SWAT2005 is given below (Neitsch et al., 2005).

The maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity and is calculated by equation 15.

\[
\text{conc}_{\text{sed, ch, mx}} = C_{\text{sp}} \cdot v_{\text{ch, pk}}^{\text{sp, exp}}
\]

(15)

In which \( \text{conc}_{\text{sed, ch, mx}} \) is the maximum concentration of sediment that can be transported by the water (ton/m\(^3\) or kg/l), \( C_{\text{sp}} \) is a coefficient defined by the user, \( v_{\text{ch, pk}} \) is the peak channel velocity (m/s), and spexp is exponent parameter for calculating sediment reentrained in channel sediment routing that is defined by the user. It normally varies between 1.0 and 2.0.

The maximum concentration of sediment calculated by equation 15 in the reach is compared to the concentration of sediment in the reach at the beginning of the time step, \( \text{conc}_{\text{sed, ch, i}} \). If \( \text{conc}_{\text{sed, ch, i}} \geq \text{conc}_{\text{sed, ch, mx}} \), deposition is the dominant process in the reach segment and the net amount of sediment deposited is calculated by equation 16. If \( \text{conc}_{\text{sed, ch, i}} < \text{conc}_{\text{sed, ch, mx}} \), degradation is the dominant process in the reach segment and the net amount of sediment reentrained is calculated by equation 17.

\[
\text{sed}_{\text{dep}} = \left( \text{conc}_{\text{sed, ch, i}} - \text{conc}_{\text{sed, ch, mx}} \right) \cdot V_{\text{ch}}
\]

(16)

\[
\text{sed}_{\text{deg}} = \left( \text{conc}_{\text{sed, ch, mx}} - \text{conc}_{\text{sed, ch, i}} \right) \cdot V_{\text{ch}} \cdot K_{\text{CH}} \cdot C_{\text{CH}}
\]

(17)

In which \( \text{sed}_{\text{dep}} \) is the amount of sediment deposited in the reach segment (metric tons), \( \text{sed}_{\text{deg}} \) is the amount of sediment reentrained in the reach segment (metric tones), \( V_{\text{ch}} \) is the volume of water in the reach segment (m\(^3\)), \( K_{\text{CH}} \) is the channel erodibility factor (cm/hr/Pa), and \( C_{\text{CH}} \) is the channel cover factor.

The final amount of sediment in the reach is determined from equation 18.

\[
\text{sed}_{\text{ch}} = \text{sed}_{\text{ch, i}} - \text{sed}_{\text{dep}} + \text{sed}_{\text{deg}}
\]

(18)

In which \( \text{sed}_{\text{ch}} \) is the amount of suspended sediment in the reach (metric tons), \( \text{sed}_{\text{ch, i}} \) is the amount of suspended sediment in the reach at the beginning of the time period (metric tons).
The amount of sediment transported out of the reach is calculated by equation 19.

\[ \text{sed}_{\text{out}} = \text{sed}_{\text{ch}} \cdot \frac{V_{\text{out}}}{V_{\text{ch}}} \]  

(19)

In which \( \text{sed}_{\text{out}} \) is the amount of sediment transported out of the reach (metric tons), \( V_{\text{out}} \) is the volume of outflow during the time step (m³).

**Model Input**

The spatially distributed data (GIS input) needed for the ArcSWAT interface include the Digital Elevation Model (DEM), soil data, land use and stream network layers. Data on weather and river discharge were also used for prediction of streamflow and calibration purposes.

**Digital Elevation Model**

Topography is defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. A 90 m by 90 m resolution DEM (Figure 4) was downloaded from SRTM (Shuttle Radar Topography Mission) website on 20 September 2007 (Jarvis et al., 2006). A high resolution DEM (2 m by 2 m) was also obtained from Soil Conservation Research Programme (SCRP), University of Bern, Switzerland. The DEM was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. Subbasin parameters such as slope gradient, slope length of the terrain, and the stream network characteristics such as channel slope, length, and width were derived from the DEM.

**Soil Data**

SWAT model requires different soil textural and physico-chemical properties such as soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. These data were obtained mainly from the following sources: Soil and Terrain Database for north-eastern Africa CD-ROM (Food and Agriculture Organization of the United Nations FAO, 1998), Major Soils of the world CD-ROM FAO, 2002, Digital Soil Map of the World and Derived Soil Properties CD-ROM FAO, (1995), Properties and Management of Soils of the Tropics CD-ROM Van Wambeke (2003), Abay River basin Integrated Development Master Plan Project - Semi detailed Soil Survey and the Soils of Anjeni Area, Ethiopia (SCRP 2000). Major soil types in the basin are Chromic Luvisols, Eutric Cambisols, Eutric Fluvisols, Eutric Leptosols, Eutric Regosols, Eutric Vertisols, Haplic Alisols, Haplic Luvisols, Haplic Nitisols and Lithic Leptosols (Figure 5a).

**Land Use**

Land use is one of the most important factors that affect runoff, evapotranspiration and surface erosion in a watershed. The land use map of the study area was obtained from ministry of water resources Ethiopia and Soil Conservation Research Programme (SCRP), University of Bern, Switzerland. We have reclassified the land use map of the area based on the available topographic map (1:50,000), aerial photographs and satellite images. The reclassification of the land use map was done to represent the land use according to the specific land cover types such as type of crop, pasture and forest. Figure 5b shows that more than 50 % of the Lake Tana watershed is used for agriculture.

**Weather Data**

SWAT requires daily meteorological data that could either be read from a measured data set or be generated by a weather generator model. In this study, the weather variables used for driving the hydrological balance are daily precipitation, minimum and maximum air temperature for the period 1978 – 2004. These data were obtained from Ethiopian National Meteorological Agency (NMA) for stations located within and around the watershed (Figure 6). Weather data were also obtained from Soil Conservation Research Programme (SCRP) project office Addis Ababa, Ethiopia. In addition, we have used a weather generator developed by (Schuel and Abbaspour, 2007) to fill the gaps due to missing data.
River Discharge and Sediment yield

Daily river discharge values for Ribb, Gumera, GilgelAbay, Megech rivers and the outflow river Blue Nile (Abbay) were obtained from the Hydrology Department of the Ministry of Water Resources of Ethiopia. These daily river discharges at four tributaries of Lake Tana: Gumera, GilgelAbay, Megech and Ribb rivers gauging stations (Figure 6) were used for model calibration (1981 – 1992) and validation (1993-2004). Figure 7 shows that the peak flows for all inflow rivers are in August. But the outflow river gets its peak flow at the month of September. There is a one month delay of peak flow for outflow river. This is due to the influence of the lake that retards the flow before it reaches the outlet. The data record of the outflow river (Abbay) at BahirDar gauge station was not used for model calibration and validation. This is due to the fact that a significant difference between the default simulated and measured stream flow data were observed. Water is withdrawn from the lake for irrigation and other purposes. But the amount of these abstraction losses are not estimated and documented well. The outflow river measured data were used to study the water balance of the lake and to get an estimate of the amount of unknown losses of water from the lake. River discharge and sediment measurements on Minchet River were used for the simulation of the stream flow and sediment yield in Anjeni gauged watershed.

Fig. 4. DEM of the Lake Tana Basin (meter above sea level)

Fig. 5. a) Left - Soil types b) right - Land cover maps of Lake Tana Basin.
Model Calibration and Evaluation

The calibration and uncertainty analysis were done using three different algorithms, i.e., Sequential Uncertainty Fitting (SUFI-2) (Abbaspour et al., 2004, 2007), Parameter Solution (ParaSol) Van Griensven et al., (2006), and Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992). These methods were chosen for their applicability to both simple and complex hydrological models. SUFI-2 and GLUE algorithms account for several sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. But ParaSol assesses only model parameter uncertainty. The degree to which uncertainties are accounted for, is quantified by a P-factor which is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU). The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin Hypercube Sampling method (Abbaspour et al., 2007). Another measure quantifying the strength of a cali-
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Calibration or uncertainty analysis is the r-factor which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. The goodness of calibration and prediction uncertainty is judged on the basis of the closeness of the p-factor to 100% (i.e., all observations bracketed by the prediction uncertainty) and the r-factor to 1. The two indices, i.e., the p-factor and the r-factor, are calculated by Equations 20 and 21.

\[ p\text{-factor} = \frac{1}{n} \sum_{i=1}^{n} (y_{i,97.5\%}^M - y_{i,2.5\%}^M) \] (20)

\[ r\text{-factor} = \frac{p\text{-factor}}{\sigma_{obs}} \] (21)

In which \( y_{i,97.5\%}^M \) and \( y_{i,2.5\%}^M \) represent the upper and lower boundaries of the 95PPU, and \( \sigma_{obs} \) is the standard deviation of the measured data.

The other factor is the goodness of fit that can be quantified by the coefficient of determination (R²) and Nash-Sutcliffe efficiency (NSE) between the observations and the final best simulations. Coefficient of determination (R²) and Nash-Sutcliffe coefficient (NSE) are calculated by equations 22 and 23. RMSE-observations standard deviation ratio (RSR) and Percent bias (PBIAS) were also used for evaluation of sediment yield prediction efficiency.

\[ R^2 = \frac{\left[ \sum_{i=1}^{n} (Q_{m,j} - \overline{Q}_m)(Q_{s,j} - \overline{Q}_s)^2 \right]}{\sum_{i=1}^{n} (Q_{m,j} - \overline{Q}_m)^2 \sum_{i=1}^{n} (Q_{s,j} - \overline{Q}_s)^2} \] (22)

\[ NSE = 1 - \frac{\sum_{i=1}^{n} (Q_m - Q_s)^2}{\sum_{i=1}^{n} (Q_{m,j} - \overline{Q}_m)^2} \] (23)

\[ RSR = \frac{\text{RMSE}}{\text{STDEV}_{obs}} = \sqrt{\frac{\sum_{i=1}^{n} (Q_{i,obs} - Q_{i,sim})^2}{\sum_{i=1}^{n} (Q_{i,obs} - \overline{Q}_{i,mean})^2}} \] (24)

Percent bias (PBIAS): PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). PBIAS is calculated with equation 25.

\[ PBIAS = \frac{\sum_{i=1}^{n} (Q_{i,obs} - Q_{i,sim})^2 \times 100}{\sum_{i=1}^{n} (Q_{i,obs})} \] (25)

In which PBIAS is the deviation of data being evaluated, expressed as a percentage.

MCE-GIS tool for Decision support system
Multi-Criteria Evaluation (MCE) model (under IDRISI GIS environment) is a method for decision support where a number of different criteria are combined to meet one or several objectives (Voogd, 1983; Carver, 1991). Many GIS software systems provide the basic tools for evaluating such a model. For this study we have used GIS software called IDRISI which has an MCE module (Paper IV). A detailed description of the method is found in IDRISI32 Guide to GIS and Image Processing (Eastman, 2001).

**MODEL SETUP**

The model setup involved five steps: (1) data preparation, (2) subbasin discretization, (3)
HRU definition, (4) parameter sensitivity analysis, (5) calibration and uncertainty analysis.

The required spatial data sets were projected to the same projection called Adindan UTM Zone 37 N, which is the transverse mercator projection parameters for Ethiopia, using ArcGIS 9.1. The DEM was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. We have used DEM mask that was superimposed on the DEM since the model uses only the masked area for stream delineation. A predefined digital stream network layer was imported and superimposed onto the DEM to accurately delineate the location of the streams. The Land use/Land cover spatial data were reclassified into SWAT land cover/plant types. A user look up table was created that identifies the SWAT code for the different categories of land cover/land use on the map as per the required format. The soil map was linked with the soil database which is a soil database designed to hold data for soils not included in the U.S. The watershed and subwatershed delineation was done using DEM data. The watershed delineation process include five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of subbasin parameters. For the stream definition the threshold based stream definition option was used to define the minimum size of the subbasin. The ArcSWAT interface allows the user to fix the number of subbasins by deciding the initial threshold area. The threshold area defines the minimum drainage area required to form the origin of a stream. Different scenarios were tested to study the effect of subbasin discretization on SWAT model performance on streamflow. To explore the sensitivity of SWAT outputs to threshold area values for subbasin delineation, six different scenarios were tested in the Lake Tana Basin using the same DEM (Paper I). The first scenario was the value suggested by the interface, 49954 hectares. Other 5 scenarios were cases below and above the suggested threshold value (14500, 24977, 37465, 62442, 74931 and 87419 hectares). Other six scenarios were also tested for sediment yield predictions. Subdividing the sub watershed into areas having unique land use, soil and slope combinations makes it possible to study the differences in evapotranspiration and other hydrologic conditions for different land covers, soils and slopes. The land use, soil and slope datasets were imported overlaid and linked with the SWAT databases. To define the distributions of HRUs both single and multiple HRU definition options were tested. For multiple HRU definition five scenarios were tested for their efficiency in predicting streamflow in the Lake Tana Basin (Paper I). These were 20 % - 10 % - 20 %, 10 % - 20 % - 10 %, 10 % - 10 % - 20 %, 20 % - 20 % - 10 %, and 25 % - 30 % - 20 %. Each scenario was arranged in order of land use percentage over subbasin area, soil class percentage over land use area and slope class percentage over soil area. Land uses that cover a percentage of the subbasin area less than the threshold level were eliminated. After the elimination processes the area of the land use is reallocated.

<table>
<thead>
<tr>
<th>Classes</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
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<tr>
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<td>Lower Limit</td>
<td>Upper limit</td>
<td>Lower Limit</td>
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<tr>
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<td>&gt;5</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1. Multiple slope discretization scenarios (Scenario 1 is assigned to single slope discretization option)
so that 100 % of the land area in the sub-
basin is included in the simulation.
In ArcSWAT there are two major categories
of slope discretization i.e., single slope and
multiple slope options. In the analysis of
slope discretization effect on suspended
sediment yield, both single and multiple
slope discretization options were tested (Pa-
per II). The different scenarios are listed in
Table 1.
The simulation of sediment yield was also
done for different conditions of rainfall vari-
ability (±5 %, ±10 %, ±20 %). Here, the
aim was to evaluate the correlation between
annual rainfall, discharge and sediment yield.
This analysis helped to study the response of
soil erosion and sediment transport to rain-
fall variability (Paper II).
The parameter sensitivity analysis was done
using the ArcSWAT interface Van Griens-
ven et al., (2006) for the whole catchment.
Twenty six hydrological parameters were
tested for sensitivity analysis for the simula-
tion of the stream flow in the study area.
Here, the default lower and upper bound
parameter values were used. The details of
all hydrological parameters are found in the
ArcSWAT interface for SWAT user’s man-
ual (Winchell et al., 2007).
After setting up of the model, the default
simulations of stream flow, using the default
parameter values, were done in the Lake
Tana Basin for the calibration period (1978-
1992). The default simulation outputs were
compared with the observed streamflow
data on four tributaries of Lake Tana. In this
study the automatic calibration was done
after the model was manually calibrated and
reached to stage that the differences be-
tween observed and simulated flows were
minimized and shown improved objective
function values. The data for period 1981 to
1992 were used for calibration in the Lake
Tana Basin. Independent precipitation, tem-
perature and streamflow datasets (1993 to
2004) were used for validation of the model
in the four tributaries of Lake Tana basin.
Periods 1978 to 1980 and 1990 to 1992 were
used as “warm-up” periods for calibration
and validation purposes, respectively. The
warm-up period allows the model to get the
hydrologic cycle fully operational. Ten years
of precipitation, air temperature, river dis-
charge and sediment measurements on Minchet River were also used for the simula-
tion of the stream flow and sediment yield in
Anjeni Gauged watershed (Papers II and
III). The period from 1984 to 1988 was used
for calibration and the period from 1989 to
1993 for validation.

Application of MCE to Lake Tana
catchment
In this study a decision had to be made re-
garding the selection of potential areas for
soil erosion. The decision was made after
combination of four criteria (factor maps)
using MCE decision wizard. The first factor
considered was slope factor, the steeper the
slope and the longer the slope length, the
higher will be the erosion rate. The second
criterion was the land cover which controls
the detachability and transport of soil parti-
cles and infiltration of water into the soil.
The soil type also plays a significant role for
erosion depending upon its physical prop-
erties and sensitivity to erosion. A layer which
contains all rivers within the catchments was
also considered as a contributing factor in
the study. Here, it was assumed that flood
plains near to streams or rivers are more eas-
ily washed especially during high flow sea-
sons.

RESULTS AND DISCUSSION
The results and discussion part of this thesis
concerns the summary of the attached pa-
ers. The details are found in the papers ap-
pended to this thesis.

Paper I: Hydrological Modelling in the
Lake Tana Basin, Ethiopia using SWAT
model
The main objective of this study was to test
the performance and feasibility of the
SWAT2005 model for prediction of stream-
flows in the Lake Tana Basin. It includes
five components: (i) the analysis of
SWAT2005 model sensitivity to the level of
subbasin discretization, (ii) effect of land
use, soil and slope threshold in defining
HRU on SWAT2005 model performance, (iii) flow parameter sensitivity analysis (iv) SWAT2005 model calibration and validation for flow at Gilgel Abay, Gumera, Ribb and Megech rivers of Lake Tana Basin using manual and automatic calibration methods and (v) analysis of base flow and other hydrological components.

The SWAT2005 model efficiency was assessed using the default simulation result and the measured flow data. It was observed that the threshold area of 14500 hectares produced 34 subbasins that accounts for the main drainage lines within the watershed. This area resulted in a better representation of the hydrological processes and produced streamflow yields that had a better model efficiency in comparison to the measured streamflow. The overall results indicated that the simulation of streamflow is not significantly affected by changing threshold area from 1/3 to 7/3 of suggested threshold area. This is because the prediction of surface runoff is related to curve number that is not affected much by the size of the subbasin.

The analysis of HRU definition indicated that multiple scenarios that accounts for 10% land use, 20% soil and 10% slope threshold combination give a better estimation of streamflow in the Lake Tana Basin. It resulted in 214 HRUs for the whole basin. The comparison between the default model predictions and measured discharge produced the highest Nash-Sutcliffe efficiency (NSE).

The parameter sensitivity analysis was done using the ArcSWAT interface for the whole catchment area. Twenty six hydrological parameters were tested for sensitivity analysis for the simulation of the stream flow in the study area. The most sensitive parameters considered for calibration were soil evaporation compensation factor, initial SCS Curve Number II value, base flow alpha factor [days], threshold depth of water in the shallow aquifer for “revap” to occur [mm], [days], available water capacity [mm WATER/mm soil], groundwater "revap" coefficient, channel effective hydraulic conductivity [mm/hr] and threshold depth of water in the shallow aquifer for return flow to occur [mm].

The comparison between the observed and simulated flow discharge values for twelve years of simulations indicated that there is a good agreement between the observed and simulated flows using SUFI-2, GLUE and ParaSol algorithms with higher values of coefficient of determination (R²) and Nash Sutcliffe efficiency (NSE) for Gilgel Abay, Gumera and Ribb rivers. Calibrated and validated model predictive performance for all rivers on daily flows is summarized in Table 3. The SUFI-2 results indicated that the p-factor which is the percentage of observations bracketed by the 95% prediction uncertainty (95PPU), brackets 83% of the observation and r-factor equals 0.81 for GilgelAbay river. The 95PPU brackets only 53% of the observations and r-factor equals to 0.39 for Megech river during calibration period. Further more 79% of the observed data bracketed by 95PPU for GilgelAbay river, 73% for Gumera, 65% for Ribb and 57% for Megech rivers during the validation period. It shows that the SUFI-2 did not capture the observations well during calibration period for Megech river. This problem coupled with the lower values of NSE and R² for Megech river indicate that there is uncertainty in simulated flow due to errors in input data such as rainfall and temperature and/or other sources of uncertainties such as upstream dam constructions for town water supply, diversion of streams for irrigation, and other unknown activities in the subbasins. We have used the Hargreaves method to calculate evapotranspiration that depends on minimum and maximum temperatures.

The lack of meteorological data did not allow to consider additional factors. We have assumed that the model deficiency in Megech watershed could be due to the input uncertainties as well as construction of infrastructures in the upstream of the watershed. However, we cannot rule out the possibility of an error in the type of soil and the corresponding soil properties in the area. This can cause some uncertainty in the simulated results. Another issue is the soil erosion that
affects the structure, infiltration capacity and other properties of the soil. Since the model does not consider the effect of soil erosion on runoff, the predictions can be uncertain. Hargreaves method does not include the effect of wind on evapotranspiration. In cases where the wind is a predominating factor the method can introduce some errors.

The validation result was good for GilgelAbay, Gumera and Ribb rivers with high values of $R^2$ and NSE (Table 2). Time series of measured and simulated daily flows with respect to the depth of rainfall in Gilgel Abay river basin indicated that both the observed and simulated flow discharge follow the rainfall pattern of the area. The higher discharge occurs during the months of June to September. This high flow corresponds to the longer rainy season. Above 75% of annual flow occurs in this period. Figure 8 shows the time series of measured and simulated daily flow at GilgelAbay river gauge station during validation period.

The annual average rainfall and other hydrological components were compared for each year of the calibration and validation periods for GilgelAbay river (Table 3). The water fluxes indicated that in a wet year surface runoff dominates water yield which is the

<table>
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<th>ET (mm)</th>
<th>SW (mm)</th>
<th>PERC (mm)</th>
<th>SURQ (mm)</th>
<th>GW_Q (mm)</th>
<th>LAT_Q (mm)</th>
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<td>235</td>
<td>55</td>
<td>100</td>
<td>69</td>
</tr>
<tr>
<td>2003</td>
<td>Wet</td>
<td>1658</td>
<td>700</td>
<td>137</td>
<td>562</td>
<td>278</td>
<td>390</td>
<td>110</td>
</tr>
</tbody>
</table>

ET=Actual Evapotranspiration from HRU, SW=Soil water content, PERC=water that percolates past the root zone during the time step, SURQ=Surface runoff contribution to streamflow during time step, TLOSS=Transmission losses, water lost from tributary channels in the HRU via, transmission through the bed, GW_Q=Ground water contribution to streamflow, LAT_Q=Lateral flow contribution to streamflow, WYLD=water yield (water yield=SURQ+LATQ+GWQ-TLOSS-pond abstractions)
total amount of water leaving the HRU and entering main channel during the time step. However, in a dry year, lateral flow contribution makes up a larger part of the water yield. The model can better predict the surface runoff than the groundwater contribution to stream flow during wet season. One reason could be due to the soil data quality and estimation of the curve number at dry moisture condition. Since the SCS curve number is a function of the soil’s permeability, land use and antecedent soil water conditions the estimation of curve number at dry moisture condition (wilting point) might not be efficient in that watershed.

The calibration process using SUFI-2 algorithm gave the final fitted parameters for each river basin (Table 4). The final values for CN2, Soil_AWC include the amount adjusted during the manual calibration. These parameters were incorporated into the SWAT2005 model for validation and further applications.

The baseflows were evaluated on an annual basis for Gilgelabay, Gumera, Megech, and Ribb river basins. The baseflow filter program by (Arnold and Allen, 1999) generates a range of predicted baseflow volumes. On an annual basis, the measured flow at Gilge-
Hydrological and sediment yield modelling in Lake Tana basin, Blue Nile Ethiopia

The analysis of Lake Tana water balance indicated that 65% of the annual precipitation is lost by evapotranspiration in the basin during calibration as compared to 56% during validation period. Surface runoff contributes 31% and 25% to the water yield during calibration and validation periods, respectively. Whereas the ground water contribute 45% and 54% to the water yield during calibration and validation periods respectively.

The simulated annual water balance components for the Lake Tana Basin indicated that 65% of the annual precipitation is

<table>
<thead>
<tr>
<th>No.</th>
<th>Sensitive parameters</th>
<th>Lower and Upper bound</th>
<th>Final fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>GilgelAbay River</td>
</tr>
<tr>
<td>1</td>
<td>ESCO</td>
<td>0 - 1</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>CN2</td>
<td>±25%</td>
<td>-10</td>
</tr>
<tr>
<td>3</td>
<td>ALPHA_BF</td>
<td>0 - 1</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>REVAPMN</td>
<td>0 - 500</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>SOL_AWC</td>
<td>±25%</td>
<td>0.2</td>
</tr>
<tr>
<td>6</td>
<td>GW_REVAP</td>
<td>±0.036</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>CH_K2</td>
<td>0 - 5</td>
<td>4.6</td>
</tr>
<tr>
<td>8</td>
<td>GWQMN</td>
<td>0 - 5000</td>
<td>108</td>
</tr>
</tbody>
</table>

Table 4. SWAT flow sensitive parameters and fitted values after calibration using SUFI-2
dicated that the estimated annual precipitation falling on the lake is 1375 mm and the evaporation loss from the Lake is about 1248 mm. Inflow from the main rivers and small streams to the lake was estimated to be 3.7 billion m³. Whereas the outflow from the lake through Blue Nile river is estimated about 4 billion m³. There is an annual surplus of 0.5 billion cubic meter of water. Part of this excess water is used for irrigation practices by the surrounding local farmers, groundwater loss and other unidentified abstractions.

Table 5. Sensitivity of SWAT subbasin delineation to threshold area

<table>
<thead>
<tr>
<th>Minimum area (ha)</th>
<th>Number of subbasins</th>
<th>Simulated annual average sediment yield (t/ha)</th>
<th>Measured annual average sediment yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>37</td>
<td>34.7</td>
<td>24.6</td>
</tr>
<tr>
<td>1.7</td>
<td>23</td>
<td>36.3</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>13</td>
<td>36.9</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>9</td>
<td>36.9</td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>7</td>
<td>37.0</td>
<td></td>
</tr>
</tbody>
</table>

In this paper the physically based SWAT2005 model was applied to Anjeni gauged watershed for prediction of soil erosion and sediment yield. There are limited sediment data in Ethiopia to do large scale calibration and validation of watershed models for sediment yield. The first goal of the present study was to test the efficiency of SWAT2005 model in predicting sediment yield by acquiring the most sensitive sediment parameters in Anjeni gauged watershed. The second goal was to develop calibrated sediment parameters so that the model can be used in ungauged watersheds with similar topography and agro climatic characteristics for prediction of sediment yield. The article discusses four issues (i) impact of subbasin discretization on simulation of sediment yield, (ii) slope discretization effect on sediment yield, (iii) calibration, validation and model evaluation and (iv) effect of rainfall variability on prediction of sediment yield.
concentration which is a variable depending on the channel length from the most remote point to the subbasin outlet. The second case is the sediment routing through channels that is a function of the peak channel velocity. This factor is a function of channel length and its cross sections which are affected by the subbasin size. Hence the prediction of sediment yield is related to subbasin size.

Subdividing the subbasins into areas having unique land use, soil and slope combinations makes it possible to study the differences in evapotranspiration and other hydrologic conditions for different land cover, soil and slope types. We have studied the specific impact of slope discretization on sediment yield modelling. In multiple slope scenarios the slope discretization that consists of fine slope classes such as 0-1, 1-3, 3-5 and >5 gave optimum average monthly sediment yield. Whereas scenario 4 that consists of broad range of slope class 0-5, 5-10, 10-15 and >15 gave higher sediment yield. This shows that scenario 4 did not consider the deposition of sediment during transport process and the majority of the soil particles eroded by surface runoff are transported into the streams. The second scenario (0-1, 1-3, 3-5, >5) that accounts for lower slope ranges considers higher deposition of soil materials during the transport processes so that there is less suspended sediment yield at the outlet of the watershed as compared to other scenarios. The results show that slope gradient and slope length (topographic factor) parameters used in the MUSLE equation are sensitive factors that can affect the SWAT2005 sediment yield predictions. This is particularly important if subbasins are known to have a wide range of slopes.

The most sensitive parameters for predictions of sediment yield in Anjeni watershed are linear parameter for calculating the maximum amount of sediment that can be entrained during channel sediment routing, channel cover factor, channel erodibility factor, USLE equation support practise factor, exponent parameter for calculating sediment reentrained in channel sediment routing, and minimum value of USLE C factor for land cover/plant.

### Table 6. Sensitive parameters for sediment yield prediction and calibrated values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower bound</th>
<th>Upper bound</th>
<th>Rank</th>
<th>Relative Sensitivity</th>
<th>Calibrated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing (Spcon)</td>
<td>0.0001</td>
<td>0.01</td>
<td>1</td>
<td>5.09</td>
<td>0.005</td>
</tr>
<tr>
<td>Channel cover factor (Ch_Cov)</td>
<td>0</td>
<td>1.00</td>
<td>2</td>
<td>4.08</td>
<td>0.35</td>
</tr>
<tr>
<td>Channel erodibility factor (Ch_Erod)</td>
<td>0</td>
<td>1.00</td>
<td>3</td>
<td>3.12</td>
<td>0.50</td>
</tr>
<tr>
<td>USLE equation support practise factor (USLE_P)</td>
<td>0</td>
<td>1.00</td>
<td>4</td>
<td>0.44</td>
<td>0.8</td>
</tr>
<tr>
<td>Exponent parameter for calculating sediment reentrained in channel sediment routing (Spexp)</td>
<td>1</td>
<td>2.00</td>
<td>5</td>
<td>0.06</td>
<td>1.39</td>
</tr>
<tr>
<td>Minimum value of USLE C factor for land cover/plant (USLE_C)</td>
<td>-25</td>
<td>25.00</td>
<td>6</td>
<td>0.00</td>
<td>0.27</td>
</tr>
</tbody>
</table>
channel cover factor, USLE equation support practice factor, exponent parameter for calculating sediment re-entrained in channel sediment routing, and minimum value of USLE C factor for land cover/plant. These parameters are listed in Table 6 with their calibrated values.

The sensitive parameters were adjusted to the level where they could represent the characteristics of the existing land use and topographic condition of the watershed. The final fitted values are listed in Table 6. Figures 9 compares the monthly simulated with measured sediment yields. The figures indicate adequate calibration and validation results over the whole range of sediment yield.

The statistical comparison between the measured monthly sediment yield and best simulation result from SUFI-2 algorithms showed a good agreement. The result was verified by NSE=0.81, PBIAS=28 %, RSR=0.23 and R²=0.85 for calibration and NSE=0.79, PBIAS=30 %, RSR=0.29 and R²=0.80 for validation periods. The NSE, RSR and PBIAS results were good for both calibration and validation periods. The high values of R² statistics indicate good correlation between measured and simulated sediment yields.

The estimated sediment yield is a function of the surface runoff and peak rate of runoff. The sediment yield has direct relation with the rainfall and streamflow. Figure 10 shows mean monthly rainfall, catchment discharge and suspended sediment yield. It shows that the higher rainfall the higher will be the surface runoff and the suspended sediment yield. Rainfall and runoff are responsible factors for the detachment, transport and deposition of sediment particles. At the beginning of the rainy season sediment concentration increases rapidly, reaching a peak in June in most years, i.e. in the first month with intensive rainfall. Sediment yield and river discharge increases about one month later, reaching a peak in July/August. The average peak rainfall in the area is in July and the average peak discharge is in August. The higher value of sediment yield is observed during July and August both for calibration and validation periods. During July and August there is higher intensity of rainfall that contributes to the higher surface runoff.

The evaluation of sediment yield sensitivity to the rainfall fluctuations indicated that a 10 % increase in annual rainfall increases the streamflow with 20 % and the sediment yield by 24 %. But 10 % reduction of rainfall resulted in 19 % reduction of streamflow and 28 % reduction in sediment yield. Figure 11 shows the correlations between streamflow and sediment yield as a function of rainfall variability. The sediment yield responses to rainfall scenarios show that surface erosion is quite sensitive in Anjeni watershed to fluctuations in precipitation levels. This sediment yield sensitivity to rainfall fluctuations is analyzed with the existing landuse scenario. The current landuse scenario indicated that more than 80 % of the land area is intensively used for agriculture mainly for field crops.
Paper III: Streamflow Calibration and Validation of SWAT2005/ArcSWAT in Anjeni Gauged Watershed, Northern Highlands of Ethiopia

The application of the model involved data processing, model setup, sensitivity analysis, calibration and validation of the model. We conducted the simulations of streamflow on a monthly basis to compare the modelling output with the observed flow data for the period 1984 to 1993. The simulation from 1981 to 1983 was considered as a “warm-up” period for the model to allow hydrologic processes to reach a certain level of equilibrium. The watershed was divided into 19 subbasins and these subbasins were further divided into 83 hydrological response units (HRU’s).

Twenty six hydrological parameters were tested for sensitivity analysis of streamflow simulations. The most eight sensitive were considered for calibration processes. The details of all hydrological parameters are found in the ArcSWAT interface for SWAT user’s manual (Winchell, 2007).

A combination of manual and automatic calibration method was used for the calibration of SWAT2005 model using the measured stream flow data. For this analysis a seven years record from June 1984 to December 1989 with meteorological and hy-
Hidrometric flow data were used, including two years of ‘worm-up’ period. After many trials a good agreement was found between observed and simulated flows at Anjeni station as shown in Figure 12a and indicated by the coefficient of determinations ($R^2$), 0.90 and the Nash-Sutcliffe simulation efficiency (NSE), 0.89 Figure 13a.

Model validation was done using the calibrated parameters. Model validation involved re-running the model using input data independent of data used in calibration. Five years observed flow data from January 01, 1990 to December 31, 1993 from Anjeni hydrometric measurements were used to validate the model. The validation process gave $R^2$ and NSE as 0.91 and 0.89, respectively (Figure 12b). This showed that there is a good agreement between monthly measured and simulated flows (Figure 13b).

**Paper IV: Identification of Erosion Potential Areas in Lake Tana Catchment, Ethiopia**

This paper explains the decision support systems with multi-criteria evaluations and physically based SWAT model in identifying erosion potential areas in the Lake Tana Catchments. The main objective of this study was to identify the most erosion sensitive areas. Two decision support models, SWAT and MCE, were used. SWAT calculates the soil erosion and sediment yield within each hydrological response units (HRU’s) within each subbasin. The GIS tool combines the slope, Landcover, soil and river layers as a major factor which contributes to soil erosion.

The output of the SWAT model has shown that 18.4% of the watershed area has high potential for soil erosion (Table 7) which produces an average annual sediment yield

<table>
<thead>
<tr>
<th>Class</th>
<th>Area (%)</th>
<th>Sediment yield (tones/ha)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44.3</td>
<td>0 – 9</td>
<td>Very low</td>
</tr>
<tr>
<td>2</td>
<td>18.8</td>
<td>9 – 17</td>
<td>low</td>
</tr>
<tr>
<td>3</td>
<td>18.5</td>
<td>17 – 30</td>
<td>moderate</td>
</tr>
<tr>
<td>4</td>
<td>18.4</td>
<td>30 - 65</td>
<td>Severe</td>
</tr>
</tbody>
</table>
of 30 to 65 tones per hectare. Based on the classes assigned to the annual sediment yield, the map was reclassified into four major categories of soil erosion hazards region i.e., very low, low, moderate and severe erosion conditions (Figure 14).

In the first scenarios the main consideration was given to the slope factor followed by the land cover and soil type, respectively. In all cases river factor was given the lowest priority in comparison with others. It was assumed that the position of rivers in the watershed plays less role for the rate of soil erosion than the other factors.

The pairwise comparison matrix indicates that the rating of land cover factor relative to slope gradient is 1:3. Soil is 1/5 times less important than slope, river factor is 1/9 less important than slope factor and so on (Table 8). The computed consistency ratio (CR) is 0.03 which is within the acceptable range (>0.10).

In the first scenario that gives high priority to slope gradient followed by land cover, soil and river factor, 25.5% of the land area is high erosion potential areas and 12% of the land areas are moderately erosion potential. But 22% of the land area has less erosion problem. In the third scenario that gives high priority to land cover followed by slope, soil and river factor only 28.5% of the watershed has a high potential for soil erosion. Scenario 4 that gives higher priority to soil data, 30.4% of the watershed has high potential for soil erosion (Table 9).

---

**Table 8. A pairwise comparison matrix for assessing the comparative importance of factors to identify erosion sensitive areas**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Slope</th>
<th>Landcover</th>
<th>Soil</th>
<th>Rivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landcover</td>
<td>1/3</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>1/5</td>
<td>1/3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Rivers</td>
<td>1/9</td>
<td>1/5</td>
<td>1/3</td>
<td>1</td>
</tr>
</tbody>
</table>

---

**Table 9. Erosion potential areas in the Lake Tana Basin under different scenarios**

<table>
<thead>
<tr>
<th>Class</th>
<th>Scenario 1 Area (%)</th>
<th>Scenario 2 Area (%)</th>
<th>Scenario 3 Area (%)</th>
<th>Scenario 4 Area (%)</th>
<th>Scenario 5 Area (%)</th>
<th>Scenario 6 Area (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.5</td>
<td>33.6</td>
<td>20.6</td>
<td>20.9</td>
<td>22.8</td>
<td>23.2</td>
<td>Nil</td>
</tr>
<tr>
<td>2</td>
<td>39.5</td>
<td>27.8</td>
<td>5.5</td>
<td>5.2</td>
<td>25.9</td>
<td>40.3</td>
<td>Slight</td>
</tr>
<tr>
<td>3</td>
<td>12.5</td>
<td>25.1</td>
<td>45.8</td>
<td>43.5</td>
<td>40.7</td>
<td>24.0</td>
<td>Moderate</td>
</tr>
<tr>
<td>4</td>
<td>25.5</td>
<td>13.5</td>
<td>28.1</td>
<td>30.4</td>
<td>10.6</td>
<td>12.5</td>
<td>High</td>
</tr>
</tbody>
</table>

---

*Fig. 14. Map showing sediment yield with in each subwatershed of Lake Tana Basin*
Finally the MCE erosion potential map was produced using the MCE model (Figure 15). The final map is a posterior probability map, showing erosion sensitive areas. The MCE maps were compared with the map developed based on the SWAT output. It can be observed that Scenario 1 and 3 produces a similar result with SWAT output. This indicates that land cover and slope factors contribute more to the rate of soil erosion than the other factors.

**SUMMARY AND CONCLUSION**

Land and water resources degradation are the major problems on the Ethiopian highlands. Poor land use practices and improper management systems have a significant role in causing high soil erosion rates, sediment transport and loss of agricultural nutrients. The present research is an attempt to obtain a scientific understanding of the Lake Tana basin as well as defining adequate tools for long term predictions of the basin characteristics. The focus is on the various hydrological aspects and surface erosion of the basin. SWAT2005 was tested and applied for the assessment of the hydrology and sediment yield in the Lake Tana Basin, Blue Nile Basin Ethiopia. The ability of SWAT to adequately predict streamflows and sediment yield was evaluated through sensitivity analysis, model calibration, and model validation. The model was successfully calibrated and validated for the four main tributaries of Lake Tana and Anjeni gauged watershed using different algorithms. The model evaluation statistics for streamflows and sediment yield prediction gave good results that was verified by NSE > 0.5 and R² > 0.50. The model was applied to the Lake Tana Basin for the modelling of the hydrological water balance. The sensitivity analysis of the model to subbasin delineation and HRU definition thresholds showed that the flow is more sensitive to the HRU definition thresholds than subbasin discretization. Prediction of sediment yield is highly sensitive to subbasin size due to the sensitivity of overland slope and slope length, channel slope, and drainage density. Variations in foregoing parameters may cause changes in sediment degradation and deposition and finally to the sediment yield. The slope discretization also affects the sediment yield prediction. SUFI-
2, GLUE and ParaSol algorithms gave good results in minimizing the differences between observed and simulated streamflows. The p-factor and r-factor computed using SUFI-2 and GLUE gave good result by bracketing more than 60% of the observed data. A SUFI-2 algorithm is an effective method but it requires additional iterations as well as the need for the adjustment of the parameter ranges. The hydrological water balance analysis showed that baseflow is an important component of the total discharge within the study area that contributes more than the surface runoff. More than 60% of losses in the watershed are through evapotranspiration. The annual average measured sediment yield was 24.6 tonnes/ha. The annual average simulated sediment yield was 27.8 and 30.5 tonnes/ha for calibration and validation period respectively. The correlation between the rainfall, discharge and sediment yield has shown that the amount and intensity of rainfall plays an important role for the sediment yield. SWAT and GIS-MCE were applied for the identification of erosion potential areas in the Lake Tana catchment. The SWAT model showed that 18.5% of the watershed is erosion potential areas. Whereas the MCE result indicated that from 25.5% of the basin are erosion potential areas. Despite different source of uncertainties, the SWAT model produced good simulation results for daily and monthly time steps. The study has shown that the SWAT model can produce reliable estimates of streamflows and sediment yield. The calibrated model can be used for further analysis of the effect of climate and land use change as well as to investigate the effect of different management scenarios on streamflows and sediment yields. The output of this study can help planners, decision makers and other different stakeholders to plan and implement appropriate soil and water conservation strategies.
REFERENCES


Arnold JG, Allen PM, and Bernhardt G. A comprehensive surface groundwater flow model. J. Hydrol. 1993; 142: 47-69


Bicknell BR, Imhoff JC, Kittle JL, Jobes TH, Donigian AS. Hydrologic Simulation Program-FORTRAN (HSPF), user's manual for version 12.0, 2001; USEPA,


Bouraoui F, Benabdallah S, Jrad A and Bidoglio G. Application of the SWAT


Debele B, Srinivasan R, Yves Parlange J. Coupling upland watershed and downstream water body hydrodynamic and water quality models (SWAT and CE-QUAL-2) for better water resources management in complex river basins. Environ Model Assess 2006.


Elirehema YS. Soil water erosion modelling in selected watersheds in Southern Spain. IFA 2001; ITC, Enschede.


FAO. (1998). The Soil and Terrain Database for northeastern Africa (CDROM) FAO, Rome


Green WH, Ampt GA. Studies on soil physics, 1. The flow of air and water through soils. Journal of Agricultural Sciences1911; 4: 11-24


Heuvelmans, G., B. Muys and J. Feyen. 2004). Analysis of the spatial variation in the parameters of the SWAT model with application in Flanders, Northern Belgium. Hydrology and earth systems Sciences, 8(5):931-939


Kassa T, Foerch G. Impacts of Land use/cover dynamics on streamflow: The case of Hare watershed, Ethiopia. In the proceedings of the 4th International SWAT2005 Conference 2007


REFERENCES


Sheng XB, Sun JZ, Liu YX. Effect of land-use and land-cover change on nutrients in soil in Bashang area, China. Journal of environmental sciences (China) 2003; 15 (4): 548-553


