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Sediment Yield Modelling Using SWAT Model in Tropical Regions

Cases of Rugezi, Koka reservoir, Simiyu and Pangani Catchments in Rwanda, Ethiopia, Tanzania, respectively

Nile Basin Capacity Building Network

NBCBN-RE

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Sediment Yield Modelling Using SWAT Model

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"Cases of Rugezi, Koka Reservoir, Simiyu and Pangani Catchments in Rwanda, Ethiopia, Tanzania"

By

Joel Nobert
Subira Munishi- Kongo
Deusdedith Magoma
Baligira Robert
Jean Claude Musabyimana
Mohamed Elshamy
Ahmed Moustafa Elbelasy
Neveen Yousif
Ibrahim Ahmed Ali Babikir
Didier Haguma
Semu Ayalew Moges
Endale Bewketu Ambaye

Coordinated by

Dr. Preksedis Marco NDOMBA
Dar Es-Salam University

Scientific Advisor

Prof. Dr. Roland Price
UNESCO-IHE

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NBCBN-SEC Office
Hydraulics Research Institute
13621, Delta Barrages, Cairo, Egypt
Email: nbcbn-sec@nbcbn.com
Website: www.nbcbn.com

Project Title
Knowledge Networks for the Nile Basin
Using the innovative potential of Knowledge Networks and CoP's in strengthening human and institutional research capacity in the Nile region.
Implementing Leading Institute
UNESCO-IHE Institute for Water Education, Delft, The Netherlands (UNESCO-IHE)
Partner Institutes
Ten selected Universities and Ministries of Water Resources from Nile Basin Countries.
Project Secretariat Office
Hydraulics Research Institute – Cairo - Egypt
Beneficiaries
Water Sector Professionals and Institutions in the Nile Basin Countries

Short Description

The idea of establishing a Knowledge Network in the Nile region emerged after encouraging experiences with the first Regional Training Centre on River Engineering in Cairo since 1996. In January 2002 more than 50 representatives from all ten Nile basin countries signed the Cairo Declaration at the end of a kick-off workshop was held in Cairo. This declaration in which the main principles of the network were laid down marked the official start of the Nile Basin Capacity Building Network in River Engineering (NBCBN-RE) as an open network of national and regional capacity building institutions and professional sector organizations.

NBCBN is represented in the Nile basin countries through its nine nodes existing in Egypt, Sudan, Ethiopia, Tanzania, Uganda, Kenya, Rwanda, Burundi and D. R. Congo. The network includes six research clusters working on different research themes namely: Hydropower, Environmental Aspects, GIS and Modelling, River Morphology, flood Management, and River structures.

The remarkable contribution and impact of the network on both local and regional levels in the basin countries created the opportunity for the network to continue its mission for a second phase. The second phase was launched in Cairo in 2007 under the initiative of; Knowledge Networks for the Nile Basin. New capacity building activities including knowledge sharing and dissemination tools specialised training courses and new collaborative research activities were initiated. The different new research modalities adopted by the network in its second phase include; (i) regional cluster research, (ii) integrated research, (iii) local action research and (iv) Multidisciplinary research.

By involving professionals, knowledge institutes and sector organisations from all Nile Basin countries, the network succeeded to create a solid passage from potential conflict to co-operation potential and confidence building between riparian states. More than 500 water professionals representing different disciplines of the water sector and coming from various governmental and private sector institutions selected to join NBCBN to enhance and build their capacities in order to be linked to the available career opportunities. In the last ten years the network succeeded to have both regional and international recognition, and to be the most successful and sustainable capacity building provider in the Nile Basin.

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FOREWORD

This report is one of the final outputs of the research activities under the second phase of the Nile Basin Capacity Building Network (NBCBN). The network was established with a main objective to build and strengthen the capacities of the Nile basin water professionals in the field of River Engineering. The first phase was officially launched in 2002. After this launch the network has become one of the most active groupings in generating and disseminating water related knowledge within the Nile region. At the moment it involves more than 500 water professionals who have teamed up in nine national networks (In-country network nodes) under the theme of "Knowledge Networks for the Nile Basin". The main platform for capacity building adopted by NBCBN is "Collaborative Research" on both regional and local levels. The main aim of collaborative research is to strengthen the individual research capabilities of water professionals through collaboration at cluster/group level on a well-defined specialized research theme within the field of River and Hydraulic Engineering.

This research project was developed under the "Cluster Research Modality". This research modality is activated through implementation of research proposals and topics under the NBCBN research clusters: Hydropower Development, Environmental Aspects of River Engineering, GIS and Modelling Applications in River Engineering, River Morphology, flood Management, and River structures.

This report is considered a joint achievement through collaboration and sincere commitment of all the research teams involved with participation of water professionals from all the Nile Basin countries, the Research Coordinators and the Scientific Advisors. Consequently the NBCBN Network Secretariat and Management Team would like to thank all members who contributed to the implementation of these research projects and the development of these valuable outputs.

Special thanks are due to UNESCO-IHE Project Team and NBCBN-Secretariat office staff for their contribution and effort done in the follow up and development of the different research projects activities.

Ir. Jan Luijendijk

Project Director
UNESCO-IHE
j .luijendijk@unesco-ihe.org

Eng. Amel M. Azab

Network Manager
NBCBN-SEC. Office
a_azab@nbcbn.com

1

INTRODUCTION

1.1 Background

The results of Sediment yield modeling using SWAT model in Simiyu River catchment (SRC) suggests that the model can be applied in tropical regions and ungauged catchments (i.e. poor data regions) (Ndomba and Neveen, 2004; Ndomba, *et al*., 2005). However, the latter findings could not be generalized for entire tropical regions unless a few catchments in the tropics are studied. Further model improvement in SRB had been hindered by the lack of data and funds for sediment-sampling fieldwork.

This research project is developed within the NBCBN-RE activities, and sometimes presented to the ATP seeking funding opportunity for applied research, under Research Theme: Catchment Management. The study intended to apply the same methodology as applied in SRB to Four (4) of the subcatchments in the Nile River Basin (NRB), which are severely affected by erosion problems and sediment flow data is readily available or could be cheaply collected. These are Rugezi River catchment (RRC) in Rwanda, Koka Reservoir Catchment (KRC) in Awash River Basin, Ethiopia and Simiyu River catchment (SRC) and Pangani River catchment (PRC) in Tanzania. The data required include hydro-meteorological, geology, soil types, land-use, Topography (i.e. Digital Elevation Models, DEM), suspended sediment concentrations, reservoir bathymetry information, catchment maps, soil conservation programs reports, stream channel geometry and mechanics conditions (e.g. roughness).

1.2 Description of the Case Studies

1.2.1 Rugezi River Catchment

Rugezi River catchment (RRC) is located in the Northern part of Rwanda and covers an area of about 196 Km2 (Figures 1.1 and 1.2). Rugezi catchment in Rwanda is a typical example, where the hydropower reservoir downstream has been silted and rills and gullies in the upland catchment, are evident (3rd GIS and Modeling research cluster workshop, 2005). Some sources associated the electrical power rationings in Rwanda, during the recent period from 2005, with the sedimentation problem of the hydropower reservoirs in Rugezi catchment. According to the Ministry of Agriculture and livestock, 14 million tones per year of lands are lost due to erosion.

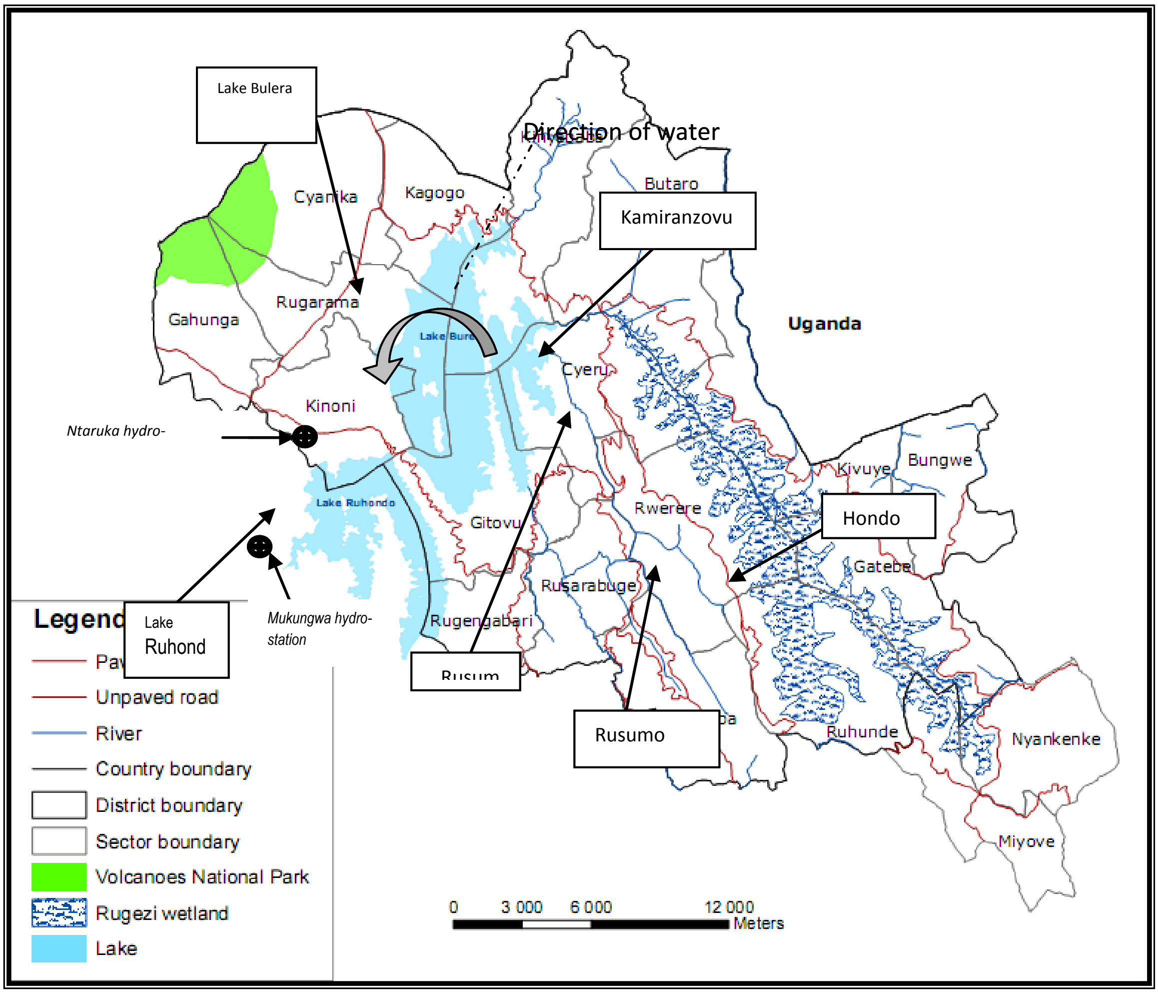

Figure 1.1: A location map of Rugezi River catchment (Source: Willetts, 2008)

It extends between latitudes 1o21'30" South and 1o36'11" South and between longitudes 29o49'59" East and 29o59'50" East. Basing on the National Population Census carried out in 2002 (GoR 2003) and an annual growth rate of 2.8 %, the population around Rugezi catchment is estimated to be about 120,000 people. Of these 90% are involved in agriculture and depend heavily on natural resources for livelihoods (REMA, 2005). Population pressure combined with land degradation is considered the major reasons that prompted people to invade Rugezi wetland for agricultural purposes (REMA, 2005).

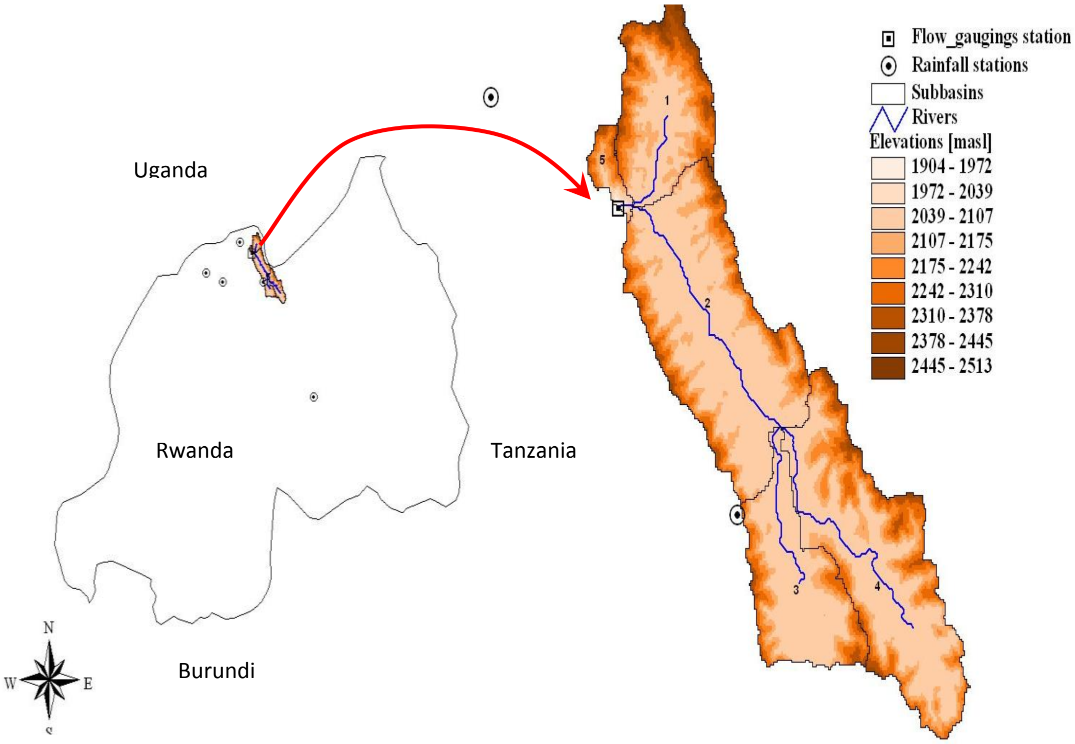

Figure 1.2: A location map of regular hydro-meteorological monitoring stations in Rugezi River catchment (3rd NBCBN GIS and Modelling research cluster workshop, 2005)

The Mean Annual Rainfall (MAR) on the hillsides is 1200 mm/yr at ‘Rwerere- Colline’ rainfall station whereas at the marsh surface it is 1050mm/yr at Rwerere-Marais rainfall station. The Rugezi catchment is made up of two sub catchments: The Rugezi main catchment (164 Km²) and Kamiranzovu catchment (32 Km²). The Rugezi main catchment located in high altitude is situated immediately east of Lakes Bulera and Luhondo below the high peaks of the Virunga volcanoes. It drains via the Hondo River, from its northwestern end, over two waterfalls, into Lake Bulera.

This swamp is embedded between mountains which dominate it by 400 m. The hillsides are very steep because many of them have a slope up to 35 %. Formerly, this swamp, originated from the trapping of runoff in a synclinal depression behind a quartzitic ridge that led formation of a vast waterlogged valley (Hategekimana, 2005). The outlet is located at “Rusumo” flow gauging station at latitude 1º25´03" South, longitude 29º49´59" East.

1.2.2 Koka Reservoir Catchment

Koka Reservoir Catchment (KRC): Ethiopia is situated in the North Eastern part of Africa, which lies between 3°30’and 14°50’ North latitudes and 32°42’ and 48°12’ East longitudes (Figure 7). It is one of the largest countries in Africa and has rugged topography with an altitude range of 100 meters below sea level to 4500 m above sea level. The county is bordered by Sudan in the West, Eritrea in the North, Djibouti and Somalia in the East and Kenya in the South. The Awash River rises in the Central Ethiopian Highlands at an altitude of 3000 m to the west of Addis Ababa after flowing through Koka Reservoir, it flows north-east wards along the rift valley until eventually discharges into Lake Abe. Sedimentation of Koka Reservoir has been an on going problem since the beginning of its impoundment. As such, over the 40 years of the reservoir history, at least four bathymetric surveys have been undertaken to estimate the extent of sedimentation in the reservoir. Based on the 1999 bathymetric survey, the storage capacity of the reservoir has been reduced from 1650 Mm3 in 1960 to 1186 Mm3 in 1999. Growing population and rising demand of cultivated land hand in hand with mostly traditional and inaccurate land use and the dangerously increasing deforestation has brought up soil erosion as one of the main impacts on nature and the loss of agricultural potential. Additionally the excessive overexploitation makes the soil even more susceptible for fluvial and upland erosion, which again is responsible for the increased sediment transport and deposition in the reservoir (DH MoWR, 1999).

The Awash basin has a total area of 110,000 km^2. The basin is divided into; Western Catchment of 64,000 km^2 and the Eastern Catchment 46,000 km^2 with only western catchment contributing to the main river flows. The eastern Catchment drains into desert area. The Koka catchment lies within the western catchment and has an area of approximately 11,000 km^2 (Figure 1.3) Koka Reservoir is situated about 90 km South East of Addis Ababa in the Awash Basin and at the longitude of 39˚ 10' E and latitude of 8˚ 25' N. The erosion rates in the Awash basin as a whole and in the Koka reservoir catchment in particular is high with values generally exceeding 6,000 t/km^2/y and occasionally as high as 15,000 to 20,000 t/km^2/y.

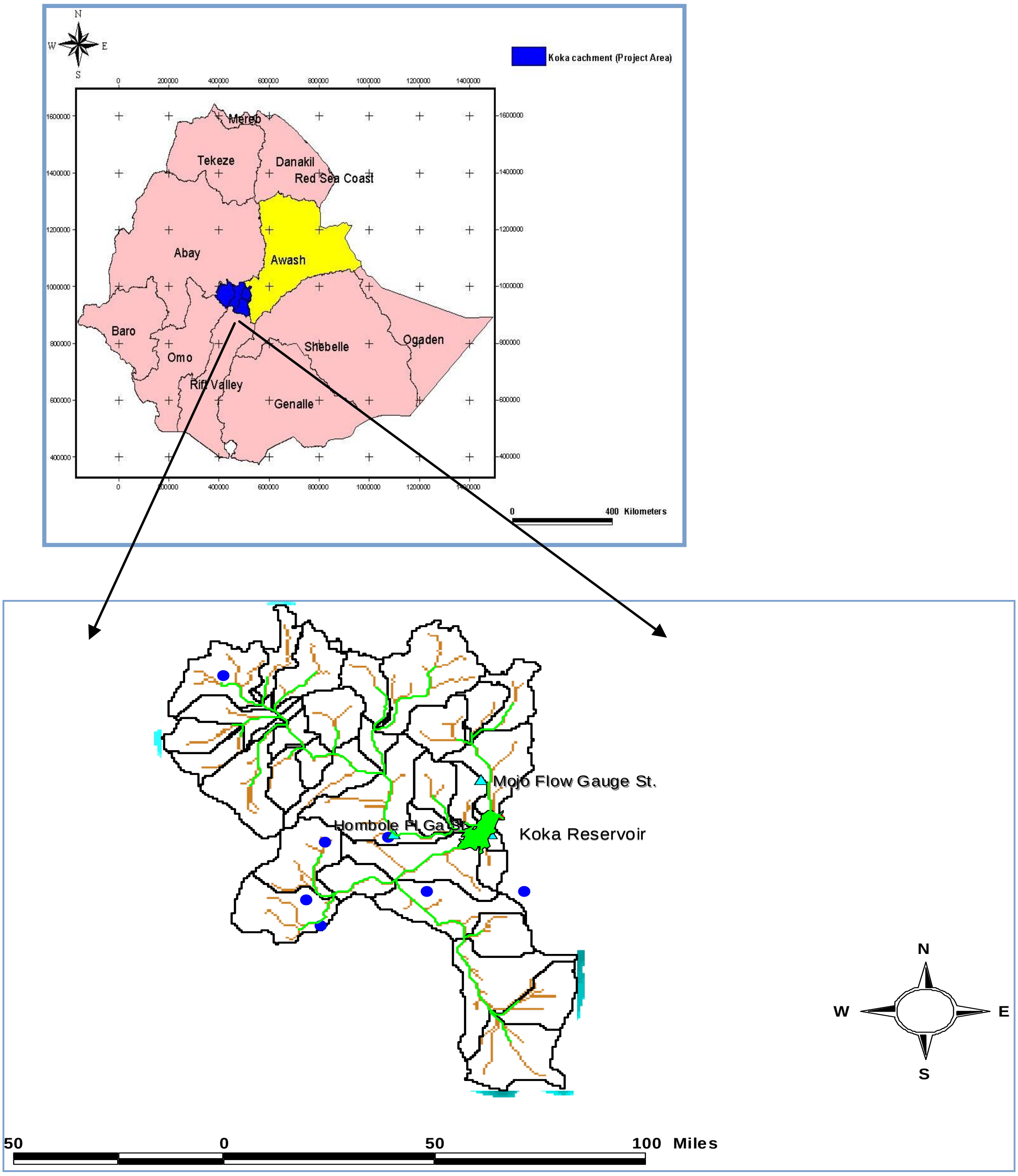

Figure 1.3: Location map of Koka Reservoir Catchment

The high rate of erosion in the catchment area is mainly due to negative impacts of human activities and gully erosion. The Climate of the Awash Basin is characterized by the Inter-Tropical Convergence Zone (ITCZ) and the seasonal rainfall distribution within the basin results from the annual migration of the ITCZ. In the March the ITCZ advances across the basin from the South, bringing the small rains. In June and July it reaches it's most Northerly location beyond basin which then experiences the heavy rains. The ITCZ returns South wards during August to October, restoring the drier Easterly air stream which prevails until the cycle repeats in March (DH WoWR, 1985). The mean annual temperature at Koka reservoir is 22.8°C with a maximum of 27.8°C in June. The mean annual wind speed at Koka is 1.2 m/s, with the windiest month being June and July with the mean monthly values of 1.9 and 1.6 m/s respectively. The weather systems that cause rainfalls over the study area are Sub Tropical Jet (STJ), Inter Tropical Convergence Zone (ITCZ), Red Sea Convergence Zone (RSCZ), Tropical Easterly Jet (TEJ) and the Somalia Jet (SJ). The area is dominated by bimodal rainfall type. According to the National Meteorological Services Agency, the study area is characterized by quasi-double maxima rainfall pattern, with a small peak in April and maximum peak in August. The rainfall in the highlands shows a strong correlation with altitude (Lemma, 1996).

The Southern section of the basin, including the catchment of Koka reservoir, has a more prolonged exposure to the moist air streams. Due to the orographic effect, the rainfall increases from East to West and the Mean Annual Rainfall (MaR) the catchment area is 1012 mm. The mean monthly rainfall data recorded at the meteorological stations (available in the catchment area) are plotted in Figure 1.4 below.

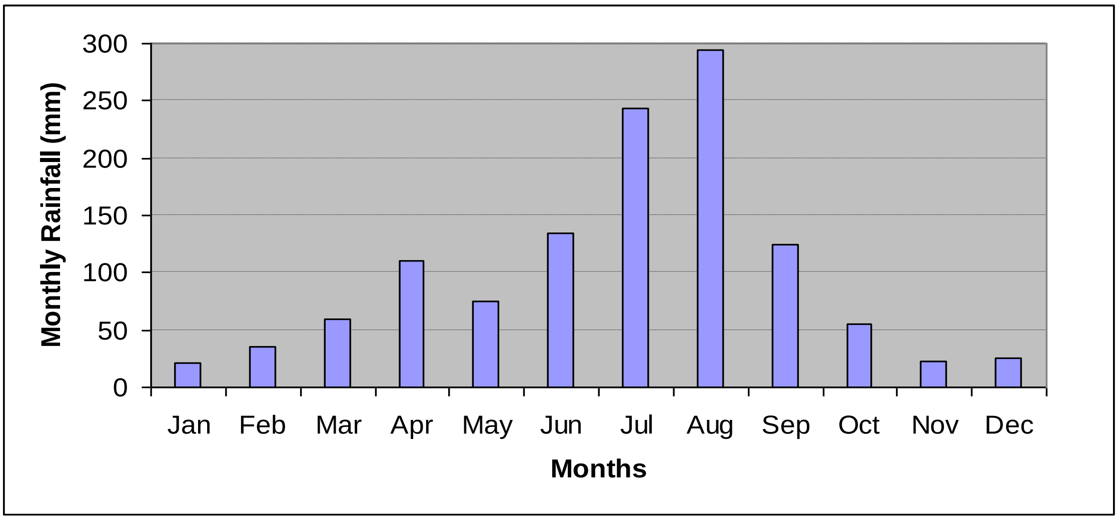

Figure 1.4: Mean Monthly Rainfall of the Catchment Area (Source: Department of Hydrology, MoWR, 1996, Ethiopia)

Two major geological formations can be found in the area of the Awash Basin: the highlands of the Ethiopian Plateau and the lowlands of the Rift Valley. The uplifting of the plateau during the Cretaceous period at the end of the Mesozoic Era (about 70 million years ago) was followed by a series of parallel normal faults as a result of the diverging tectonic platforms of Somalia and Afar in the Tertiary period of the Cainozoic Era (about 30 to 25 million years ago), Ethiopian Geological Survey Enterprise (1981). The bedrocks and soils in the area are important for the amount and composition of transported sediments in the river. The geology of the basin is predominated by sedimentary rocks such as limestone and sandstone. Site investigation in the reservoir area carried out before the dam construction indicates that the area intended for water storage (reservoir area) was alluvial plain, through which the river runs in meanders. The deposits consist of clay, sand and tuff. Boring test was performed on this alluvial deposit revealed an upper part consisting of clay, some zones of sand and tuff (Nor Consults, 1997).

The upper Awash Basin (upstream of Koka Reservoir) is extensively cultivated by the farmers. The upper most part, rich of rainfall, is mainly used for crop production like barley and 'Teff '(Ethiopian common food grain). Acacia and eucalyptus trees are prevailing ones, but due to the growing demand of fuel wood they are cleared from time to time by the local users. The effect of land use on sediment yield can be clearly seen by comparing the runoff and sediment yield in the rivers. Land use in the area is mainly dominated by moderately to intensively cultivated subsistence based cropland, grazing land, settlement and some parts of the highland areas are covered by eucalyptus trees, shrubs and grass. A serious problem occurs because of the very rigorous way of using soil as a natural resource (Halcrow, 1989).

1.2.3 Pangani River Catchment

The Pangani River Catchment (PRC) is located between coordinates 36°20' E, 02°55' S and 39°02' E, 05°40' S in the North Eastern part of Tanzania and covers an area of about 42,200 km2, with approximately 5% in Kenya (Figure 1.5). The Pangani River has two main tributaries, the Kikuletwa (1DD1) and the Ruvu (1DC1) (Figure 1.5), which join at NYM, a reservoir of some 140 km^2.

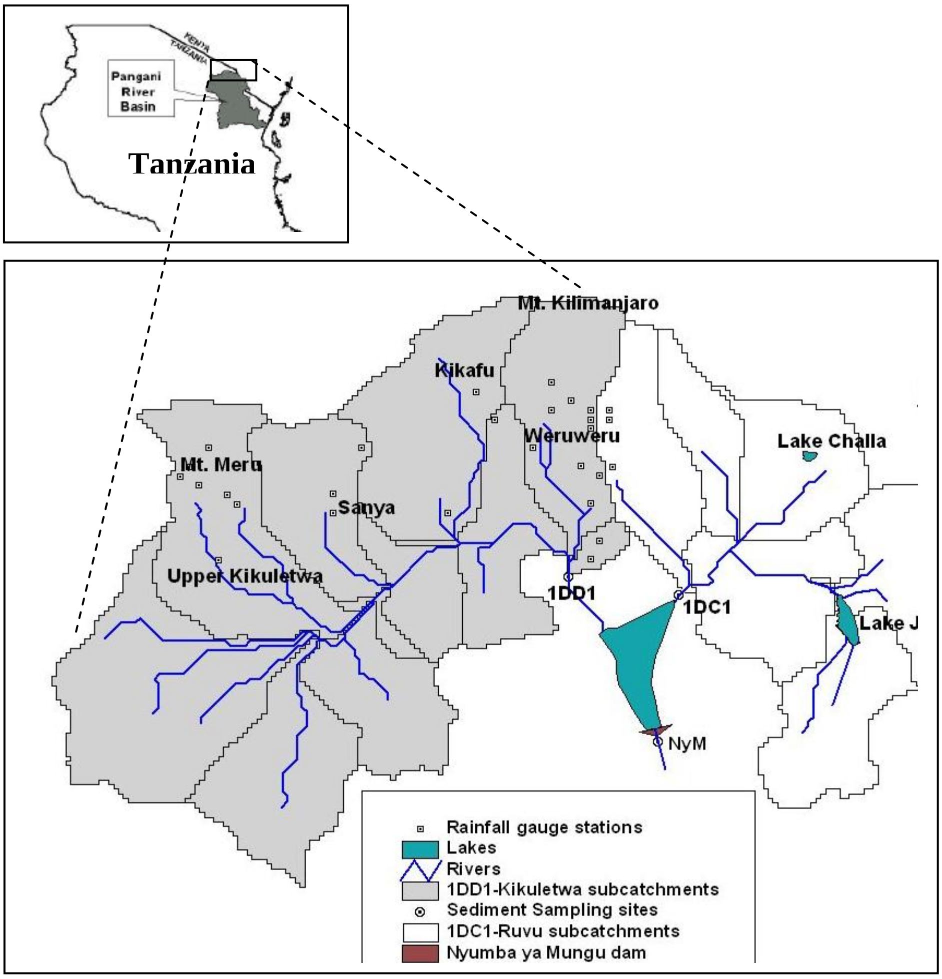

Figure 1.5: A location map of Pangani River Catchment (PRC), upstream of Nyumba Ya Mungu (NYM) dam

The study area is the NYM Reservoir catchment located in the upstream of PRB (Fig. 1.1). The main subcatchments in the study area are Weruweru, Kikafu, Sanya, Upper Kikuletwa and Mount Meru. The catchment of NYM occupies a total land and water area of about 12,000 km^2 (Ndomba, 2007). It is located between coordinates 36°20'00" E, 3°00'00" S and 38°00'00" E, 4o3'50" S. This area has a Mean Annual Rainfall (MAR) of about 1000 mm. The rainfall pattern is bimodal with two distinct rainy seasons, long rains from March to June and short rains from November to December (Rohr, 2003). Recent findings by Rohr and Killingtveit (2003) indicate that the maximum precipitation on the southern hillside of Mount Kilimanjaro takes place at about 2,200 m.a.s.l., which is 400 – 500 m higher than assumed previously. The altitude in the study area ranges between 700 and 5,825 m.a.s.l. with Mount Killimanjaro peak as the highest ground. Based on the Soil Atlas of Tanzania, the main soil type in the upper PRB is clay with good drainage (Hathout, 1983). Actively induced vegetation, forest, bushland and thickets with some alpine desert chiefly characterize the catchment land cover. The majority of the population in the basin depends on irrigated agriculture directly or indirectly. Agriculture is concentrated in the highlands, while the lowlands are better suited for pastoralism. The basin is also important for hydropower generation, which is connected to the national grid. Hydropower plants, which are downstream of NYM Reservoir are NYM (8MW), Hale (21MW), and New Pangani falls (66MW).

1.3 Statement of the Problem

Although, a number of workers have conducted erosion studies in tropics, the lack of compelling tool or method has hindered adoption and implementation of their findings (Yanda, 1995; Ndomba et al. 2005; Ndomba, 2007). Both mathematical and parametric methods require a lot of information, which is a major constraint in many parts of the developing world (Yanda, 1995). These countries have no appropriate and accurate soil erosion prediction models, although the Soil Loss Estimation Model for Southern Africa (SLEMSA) and the Universal Soil Loss Equation (USLE) are used in different tropical countries (Mulengera 1999). The SLEMSA, which was developed initially for Zimbabwe, still needs some modifications. It has so far not been widely used or tested outside Zimbabwe and in some instances have shown to give unrealistic soil loss values (Mulengera 1999). Assessment of SWAT model as a tool for predicting sediment yield in tropics is imperative for this research. Therefore, Rugezi catchment in Rwanda, Koka Reservoir Catchment in Ethiopia, Simiyu River catchment and Pangani River Catchment in Tanzania are chosen as study cases.

1.4 Purpose

The overall objective of this study is to assess the suitability of SWAT model as sediment yield modelling tool in the Nile River Basin (NRB), with particular interest in the tropical regions. Specifically the SWAT model was tested by the authors in four (4) selected Nilotic catchments: Rugezi, Koka, Simiyu and Pangani in Rwanda, Ethiopia and Tanzania, respectively.

1.5 Significance and Relevance of the Study

The study of sedimentation problems and possible mitigation measures is essential in planning the optimal and efficient management of the water potential resources. Efficient utilization of water resources is only possible through good planning and design of water resources projects such as flood control structures, hydropower generation, irrigation, water supply schemes and other hydraulic structures like bridges etc. One way of achieving this is by applying and customizing comprehensive watershed models such as SWAT. The expected outputs of this study include: i) A list of major hydrological factors that influence erosion processes in the selected case studies; ii) A summary of soil erosion conservative measures suitable for reduction of sediment yield loads in the study cases; and iii) Based on the model performance a generalized statement on the suitability of SWAT model in the tropics is drawn.

In terms of relevance this research project complies with the Cairo NBCBN Declaration of June 2004 which stipulated the need for clusters integration and possible crosscutting activities. Therefore, the output of this study will directly pave the way for cluster integrations.

1.6 Research Questions and/or Hypotheses

The general research question of the study "Is SWAT model developed in temperate region and developed world suitable for tropics and Nilotic catchments at large?" The specific questions include: i) Does Soil and Water Assessment Tool (SWAT) captures seasonal dynamics of sediment delivery to the outlet of the catchment/downstream reservoirs? ii) What are the prevailing sediment delivery drivers in the study cases? iii) Which catchment sediment management techniques can reduce sedimentation problems in the catchments?

2

LITERATURE REVIEW

2.1 General

Reservoir sedimentation is a complex process that varies with catchment sediment production, rate of transportation and mode of deposition. Reservoir sedimentation depends on the river regime, flood frequencies, reservoir geometry and operation, flocculation potential, sediment consolidation, density currents and possibly land use changes over the life expectancy of the reservoir (Julien, 1995). Sedimentation problems generally occur at locations where the sediment transporting capacity of the hydraulic system is reduced due to the decrease of the steady (currents) and oscillatory (waves) flow velocities and related turbulent motions. Examples are: the expansion of the flow depth and width due to natural variations or artificial measures (dredging), the presence of vortex or eddy zones, flow separation zones and dead water zones. However, sedimentation (as well as erosion) also is a basic phenomenon of nature dealing with loose sediments within the transporting cycle from source to sink locations. Human interference in these natural sedimentation areas will always lead to relatively large maintenance cost and should therefore be avoided as much as possible. Sedimentation often shortens considerably the effective lifetime of reservoirs or lakes (Julien, 1995).

A broad definition of sedimentation has been given by (Vanoni, 1975). Sedimentation embodies the processes of erosion, entrainment, transportation, deposition, and the compaction of sediment (Vanoni, 1975). These are natural processes that have been active throughout geological times and have shaped the present landscape of our world (Vanoni, 1975). The principal external dynamic agents of sedimentation are water, wind, gravity, and ice (Vanoni, 1975). Although each may be important locally, only the hydrospheric forces of rainfall, runoff, and streamflow forces are considered in this study.

Sediment yield is the amount of eroded sediment discharged by a stream at any given point (Morris and Fan, 1998). It represents the total amount of fluvial sediment exported by the catchment tributary to a measurement point, and is the parameter of primary concern in reservoir studies. Because, much eroded sediment is redeposited before it leaves a catchment, the sediment yield is always less than and often much less than, the erosion rate within that same catchment (Morris and Fan, 1998). Besides, Sediment yield is a measure of the response of the fluvial system to processes taking place in the drainage basin (De Boer *et al*., 2005).

Sediment delivery ratio is a measure of the diminution/attenuation of eroded sediments, by deposition, as they move from the point of erosion to any designated downstream location. This also may be expressed as a percentage of the onsite eroded material that reaches a given measuring point (Vanoni, 1975).

Sediment yield models vary greatly in complexity from simple regression relationships linking annual sediment yield to climatic and physiographic variables, semi distributed physics based models such as a SWAT, to complex distributed simulation models (Garde and Ranga Raju, 2000). Formal erosion modeling or some other systems can be used to quantify erosion and sediment yield (Morris and Fan, 1998). The fraction of the eroded sediment delivered to the point of interest is determined by applying delivery ratios. Properly applied, this method can provide information on both the type of erosion and its spatial distribution across the catchment. Determining the sediment delivery ratio is a critical step in converting estimates of soil erosion within a basin into a quantitative value of sediment yield (Morris and Fan, 1998). Sediments and associated pollutants mobilized by sheet and rill erosion may be re-deposited by a variety of mechanisms prior to reaching stream channels, where transport processes are generally more efficient.

2.2 SWAT Model Overview

SWAT is a basin-scale, continuous-time model that operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds (Arnold, et al., 1995). The model is physically based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the subwatershed area and are not identified spatially within a SWAT simulation. Alternatively, a watershed can be subdivided into only subwatersheds that are characterized by dominant land use, soil type, and management.

The USDA-SCS runoff curve number is used to estimate surface runoff from daily precipitation. The curve number is adjusted according to moisture conditions in the catchment (Arnold *et al*., 1995). SWAT model uses Modified USLE (MUSLE) to estimate sediment yield (Arnold, *et al*., 1995). SWAT can also be run on a sub-daily time step basis using the Green-Ampt infiltration.

2.2.1 SWAT Developmental History

The development of SWAT is a continuation of USDA Agricultural Research Service (ARS) modeling experience that spans a period of roughly 30 years. Early origins of SWAT can be traced to previously developed USDA-ARS models (**Figure 2**) including the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980), the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), and the Environmental Impact Policy Climate (EPIC) model (Izaurralde et al., 2006), which was originally called the Erosion Productivity Impact Calculator (Williams, 1990).

The current SWAT model is a direct descendant of the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold and Williams, 1987), which was designed to simulate management impacts on water and sediment movement for ungauged rural basins across the U.S. Development of SWRRB began in the early 1980s with modification of the daily rainfall hydrology model from CREAMS. A major enhancement was the expansion of surface runoff and other computations for up to ten subbasins, as opposed to a single field, to predict basin water yield. Other enhancements included an improved peak runoff rate method, calculation of transmission losses, and the addition of several new components: groundwater return flow (Arnold and Allen, 1993), reservoir storage, the EPIC crop growth submodel, a weather generator, and sediment transport. Further modifications of SWRRB in the late 1980s included the incorporation of the GLEAMS pesticide fate component, optional USDA-SCS technology for estimating peak runoff rates, and newly developed sediment yield equations. These modifications extended the model's capability to deal with a wide variety of watershed water quality management problems. Arnold et al. (1995b) developed the Routing Outputs to Outlet (ROTO) model in the early 1990s in order to support an assessment of the downstream impact of water management within Indian reservation lands in Arizona and New Mexico that covered several thousand square kilometers, as requested by the U.S. Bureau of Indian Affairs.

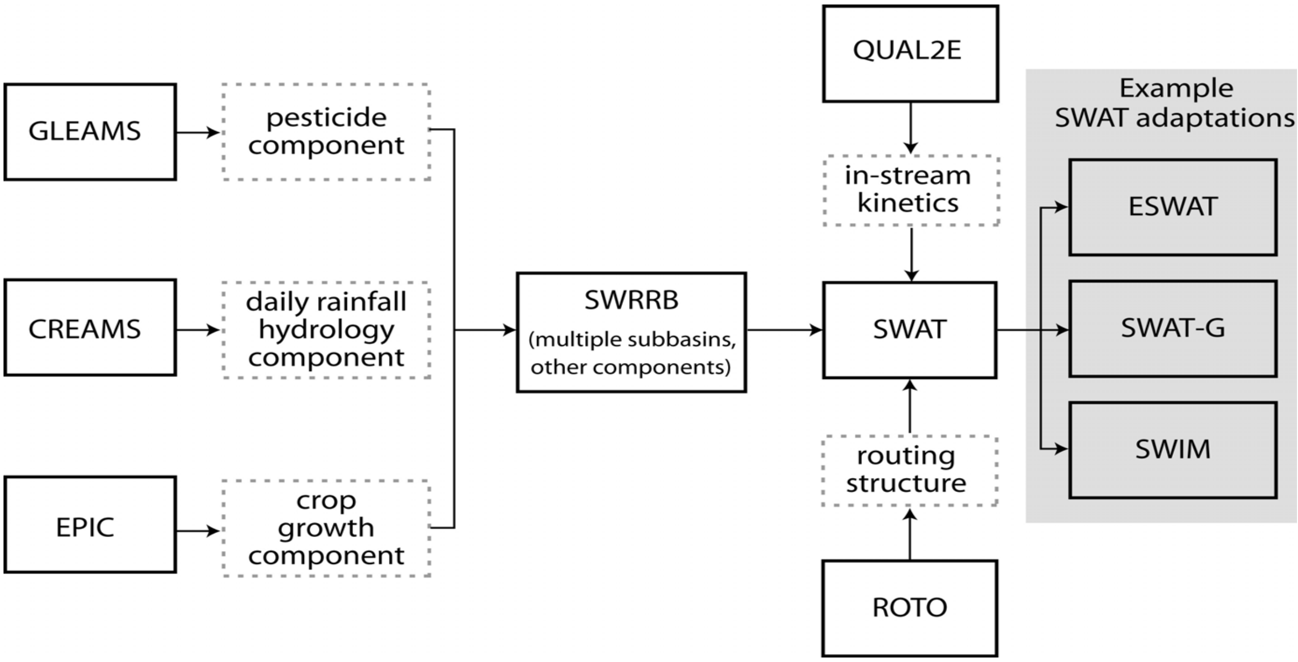

Figure 2: Schematic of SWAT developmental history, including selected SWAT adaptations, Gassman, et al. (2007).

The analysis was performed by linking output from multiple SWRRB runs and then routing the flows through channels and reservoirs in ROTO via a reach routing approach. This methodology overcame the SWRRB limitation of allowing only ten subbasins; however, the input and output of multiple SWRRB files was cumbersome and required considerable computer storage. To overcome the awkwardness of this arrangement, SWRRB and ROTO were merged into the single SWAT model (fig. 1). SWAT retained all the features that made SWRRB such a valuable simulation model, while allowing simulations of very extensive areas. SWAT has undergone continued review and expansion of capabilities since it was created in the early 1990s. Key enhancements for previous versions of the model (SWAT94.2, 96.2, 98.1, 99.2, and 2000) are described by Arnold and Fohrer (2005) and Neitsch et al. (2005a), including the incorporation of in-stream kinetic routines from the QUAL2E model (Brown and Barnwell, 1987), as shown in figure 1.

2.2.2 Climatic Inputs and HRU Hydrologic Balance

Climatic inputs used in SWAT include daily precipitation, maximum and minimum temperature, solar radiation data, relative humidity, and wind speed data, which can be input from measured records and/or generated. Relative humidity is required if the Penman-Monteith (Monteith, 1965) or Priestly-Taylor (Priestly and Taylor, 1972) evapotranspiration (ET) routines are used; wind speed is only necessary if the Penman-Monteith method is used. Measured or generated sub-daily precipitation inputs are required if the Green-Ampt infiltration method (Green and Ampt, 1911) is selected. The average air temperature is used to determine if precipitation should be simulated as snowfall. The maximum and minimum temperature inputs are used in the calculation of daily soil and water temperatures. Generated weather inputs are calculated from tables consisting of 13 monthly climatic variables, which are derived from long-term measured weather records. Customized climatic input data options include: (1) simulation of up to ten elevation bands to account for orographic precipitation and/or for snowmelt calculations, (2) adjustments to climate inputs to simulate climate change, and (3) forecasting of future weather patterns, which is a new feature in SWAT2005.

The overall hydrologic balance is simulated for each HRU, including canopy interception of precipitation, partitioning of precipitation, snowmelt water, and irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers. Estimation of areal snow coverage, snowpack temperature, and snowmelt water is based on the approach described by Fontaine et al. (2002). Three options exist in SWAT for estimating surface runoff from HRUs, which are combinations of daily or sub-hourly rainfall and the USDA Natural Resources Conservation Service (NRCS) curve number (CN) method (USDA-NRCS, 2004) or the Green-Ampt method. Canopy interception is implicit in the CN method, while explicit canopy interception is simulated for the Green-Ampt method.

A storage routing technique is used to calculate redistribution of water between layers in the soil profile. Bypass flow can be simulated, as described by Arnold et al. (2005), for soils characterized by cracking, such as Vertisols. SWAT2005 also provides a new option to simulate perched water tables in HRUs that have seasonal high water tables. Three methods for estimating potential ET are provided: Penman-Monteith, Priestly-Taylor, and Hargreaves (Hargreaves et al., 1985). ET values estimated external to SWAT can also be input for a simulation run. The Penman-Monteith option must be used for climate change scenarios that account for changing atmospheric CO2 levels. Recharge below the soil profile is partitioned between shallow and deep aquifers. Return flow to the stream system and evapotranspiration from deep-rooted plants (termed "revap") can occur from the shallow aquifer. Water that recharges the deep aquifer is assumed lost from the system.

2.2.3 Flow and Pollutant Loss Routing, and Auto-Calibration

Flows are summed from all HRUs to the subwatershed level, and then routed through the stream system using either the variable-rate storage method (Williams, 1969) or the Muskingum method (Neitsch et al., 2005a), which are both variations of the kinematic wave approach. Sediment, nutrient, pesticide, and bacteria loadings or concentrations from each HRU are also summed at the subwatershed level, and the resulting losses are routed through channels, ponds, wetlands depressional areas, and/or reservoirs to the watershed outlet. Contributions from point sources and urban areas are also accounted for in the total flows and pollutant losses exported from each subwatershed. Sediment transport is simulated as a function of peak channel velocity in SWAT2005, which is a simplified approach relative to the stream power methodology used in previous SWAT versions. Simulation of channel erosion is accounted for with channel erodibility factor. A final feature in SWAT2005 is a new automated sensitivity, calibration, and uncertainty analysis component that is based on approaches described by van Griensven and Meixner (2006) and van Griensven et al. (2006b).

2.3 SWAT Adaptations in the Global Context

A key trend that is interwoven with the ongoing development of SWAT is the emergence of modified SWAT models that have been adapted to provide improved simulation of specific processes, which in some cases have been focused on specific regions. Notable examples (fig. 1) include SWAT-G, Extended SWAT (ESWAT), and the Soil and Water Integrated Model (SWIM). The initial SWAT-G model was developed by modifying the SWAT99.2 percolation, hydraulic conductivity, and interflow functions to provide improved flow predictions for typical conditions in low mountain ranges in Germany (Lenhart et al., 2002). Further SWAT-G enhancements include an improved method of estimating erosion loss (Lenhart et al., 2005) and a more detailed accounting of CO2 effects on leaf area index and stomatal conductance (Eckhardt and Ulbrich, 2003). The ESWAT model (van Griensven and Bauwens, 2003, 2005) features several modifications relative to the original SWAT model including: (1) sub-hourly precipitation inputs and infiltration, runoff, and erosion loss estimates based on a user-defined fraction of an hour; (2) a river routing module that is updated on an hourly time step and is interfaced with a water quality component that features in-stream kinetics based partially on functions used in QUAL2E as well as additional enhancements; and (3) multiobjective (multi-site and/or multi-variable) calibration and autocalibration modules (similar components are now incorporated in SWAT2005). The SWIM model is based primarily on hydrologic components from SWAT and nutrient cycling components from the MATSALU model (Krysanova et al., 1998, 2005) and is designed to simulate "mesoscale" (100 to 100,000 km^2) watersheds. Recent improvements to SWIM include incorporation of a groundwater dynamics submodel (Hatterman et al., 2004), enhanced capability to simulate forest systems (Wattenbach et al., 2005), and development of routines to more realistically simulate wetlands and riparian zones (Hatterman et al., 2006).

2.4 SWAT Applications in Global Context

Several studies showed the robustness of SWAT in predicting sediment loads at different watershed scales. Saleh et al. (2000) conducted a comprehensive SWAT evaluation for the 932.5 km^2 upper North Bosque River watershed in north central Texas, and found that predicted monthly sediment losses matched measured data well but that SWAT daily output was poor. Srinivasan et al (1998) concluded that SWAT sediment accumulation predictions were satisfactory for the 279 km^2 Mill Creek watershed, again located in north central Texas. Santhi et al. (2001a) found that SWAT-simulated sediment loads matched measured sediment loads well for two Bosque River (4,277 km^2) subwatersheds, except in March. Arnold et al. (1999b) used SWAT to simulate average annual sediment loads for five major Texas river basins (20,593 to 569,000 km^2) and concluded that the SWAT predicted sediment yields compared reasonably well with estimated sediment yields obtained from rating curves. Besides Texas, the SWAT sediment yield component has also been tested in several Midwest and northeast U.S. states. Chu et al. (2004) evaluated SWAT sediment prediction for the Warner Creek watershed located in the Piedmont physiographic region of Maryland. Evaluation results indicated strong agreement between yearly measured and SWAT simulated sediment load, but simulation of monthly sediment loading was poor. Tolston and Shoemaker (2007) modified the SWAT2000 sediment yield equation to accountfor both the effects of snow cover and snow runoff depth (the latter is not accounted for in the standard SWAT model) to overcome snowmelt-induced prediction problems identified by Benaman et al. (2005) for the Cannonsville Reservoir watershed in New York. They also reported improved sediment loss predictions. Jha et al. (2007) found that the sediment loads predicted by SWAT were consistent with sediment loads measured for the Raccoon River watershed in Iowa. Arabi et al. (2006b) report satisfactory SWAT sediment simulation results for two small watersheds in Indiana. White and Chaubey (2005) report that SWAT sediment predictions for the Beaver Reservoir watershed in northeast Arkansas were satisfactory. Sediment results are also reported by Cotter et al. (2003) for another Arkansas watershed. Hanratty and Stefan (1998) calibrated SWAT using water quality and quantity data measured in the Cottonwood River in Minnesota. In Wisconsin, Kirsch et al. (2002) calibrated SWAT annual predictions for two subwatersheds located in the Rock River basin, which lies within the glaciated portion of south central and eastern Wisconsin. Muleta and Nicklow (2005a) calibrated daily SWAT sediment yield with observed sediment yield data from the Big Creek watershed in southern Illinois and concluded that sediment fit seems reasonable. However, validation was not conducted due to lack of data.

SWAT sediment simulations have also been evaluated in Asia, Europe, and North Africa. Behera and Panda (2006) concluded that SWAT simulated sediment yield satisfactorily throughout the entire rainy season based on comparisons with daily observed data for an agricultural watershed located in eastern India. Kaur et al. (2004) concluded that SWAT predicted annual sediment yields reasonably well for a test watershed in Damodar-Barakar, India, the second most seriously eroded area in the world. Tripathi et al. (2003) found that SWAT sediment predictions agreed closely with observed daily sediment yield for the same watershed. Mishra et al. found that SWAT accurately replicated the effects of three checkdams on sediment transport within the Banha watershed in northeast India. Hao et al. (2004) state that SWAT was the first physically based watershed model validated in China's Yellow River basin. They found that the predicted sediment loading accurately matched loads measured for the 4,623 km2 Lushi subwatershed. Cheng et al. (2006) successfully tested SWAT using sediment data collected from the 7,241 km2 Heihe River, another tributary of the Yellow River. In Finland, Bärlund et al. (2007) report poor results for uncalibrated simulations performed within the Lake Pyhäjärvi watershed. Gikas et al. (2005) conducted an extensive evaluation of SWAT for the Vistonis Lagoon watershed, a mountainous agricultural watershed in northern Greece, and concluded that agreement between observed and SWAT predicted sediment loads were acceptable. Bouraoui et al. (2005) evaluated SWAT for the Medjerda River basin in northern Tunisia and reported that the predicted concentrations of suspended sediments were within an order of magnitude of corresponding measured values.

2.5 Sensitivity, Calibration, and Uncertainty Analyses

Sensitivity, calibration, and uncertainty analyses are vital and interwoven aspects of applying SWAT and other models. Numerous sensitivity analyses have been reported in the SWAT literature, which provide valuable insights regarding which input parameters have the greatest impact on SWAT output. As previously discussed, the vast majority of SWAT applications report some type of calibration effort. SWAT input parameters are physically based and are allowed to vary within a realistic uncertainty range during calibration. Sensitivity analysis and calibration techniques are generally referred to as either manual or automated, and can be evaluated with a wide range of graphical and/or statistical procedures. Uncertainty is defined by Shirmohammadi et al. (2006) as "the estimated amount by which an observed or calculated value may depart from the true value." They discuss sources of uncertainty in depth and list model algorithms, model calibration and validation data, input variability, and scale as key sources of uncertainty. Several automated uncertainty analyses approaches have been developed, which incorporate various sensitivity and/or calibration techniques, which are briefly reviewed here along with specific sensitivity analysis and calibration studies.

2.5.1 Sensitivity Analyses

The sensitivity analysis method implemented in SWAT is called the Latin Hypercube One- Factor- At- a-Time (LH-OAT) design as proposed by Morris (1991). The LH sensitivity analysis combines the strength of Global and local sensitivity analysis methods (Van Griensven & Srinivasan, 2005). The LH-OAT performs LH sampling followed by OAT sampling. LH sampling (McKay et al., 1979) uses a stratified sampling approach that better covers a sampling hypercube with fewer samples. This method identifies parameters that do not have significant influence on model simulations or real world observations for specific catchments (Van Griensven et al. 2006).

2.5.2 Calibration Approaches

Besides manual calibration, SWAT model also includes an automated calibration procedure (Van Griensven and Srinivasan, 2005). The calibration procedure is based on Shuffled Complex Evaluation- University of Arizona Algorithm (SCE-UA) as proposed by Duan et al. 1992. Auto calibration option provides a powerful, labour saving tool that can be used to substantially reduce frustrations and uncertainty that often characterizes manual calibration (Van Liew et al., 2005)

2.5.3 Uncertainty Analyses

Van Greinsven and Meixner (2006) describe several uncertainty analysis tools that have been incorporated into SWAT2005, including a modified SCE algorithm called "parameter solutions" (ParaSol), the Sources of Uncertainty Global Assessment using Split Samples (SUNGLASSES), and the Confidence Analysis of Physical Inputs (CANOPI), which evaluates uncertainty associated with climatic data and other inputs.

2.6 Comparisons of SWAT with Other Models

Borah and Bera (2003, 2004) compared SWAT with several other watershed-scale models. In the 2003 study, they report that the Dynamic Watershed Simulation Model (DWSM) (Borah et al., 2004), Hydrologic Simulation Program - Fortran (HSPF) model (Bicknell et al., 1997), SWAT, and other models have hydrology, sediment, and chemical routines applicable to watershed-scale catchments and concluded that SWAT is a promising model for continuous simulations in predominantly agricultural watersheds. In the 2004 study, they found that SWAT and HSPF could predict yearly flow volumes and pollutant losses, were adequate for monthly predictions except for months having extreme storm events and hydrologic conditions, and were poor in simulating daily extreme flow events. In contrast, DWSM reasonably predicted distributed flow hydrographs and concentration or discharge graphs of sediment and chemicals at small time intervals.

Saleh and Du (2004) found that the average daily flow, sediment loads, and nutrient loads simulated by SWAT were closer than HSPF to measured values collected at five sites during both the calibration and verification periods for the upper North Bosque River watershed in Texas. Singh et al. (2005) found that SWAT flow predictions were slightly better than corresponding HSPF estimates for the 5,568 km2 Iroquois River watershed in eastern Illinois and western Indiana, primarily due to better simulation of low flows by SWAT. El-Nasr et al. (2005) found that both SWAT and the MIKE-SHE model (Refsgaard and Storm, 1995) simulated the hydrology of Belgium's Jeker River basin in an acceptable way. However, MIKE-SHE predicted the overall variation of river flow slightly better. Srinivasan et al. (2005) found that SWAT estimated flow more accurately than the Soil Moisture Distribution and Routing (SMDR) model (Cornell, 2003) for 39.5 ha FD-36 experimental watershed in east central Pennsylvania, and that SWAT was also more accurate on a seasonal basis.

It should be noted that some comprehensive sediment yield models such as SWAT (Arnold *et al*., 1995) in Table 2.1 below do not require sediment delivery ratio. The sediment load is routed from upstream to downstream. However, for reliability, the results of both erosion models and sediment yield models should be calibrated against sediment yield measurements at one or more points in the study catchment.

Table 2.1: Comparison of five recently developed physically-based erosion and sediment yield models as modified from Bathurst (2002) and as reported in Ndomba (2007)

Model Feature		**Models**				
		SHETRAN (Bathurst, 2002)	**WEPP** (Lane *et al.*, 1992)	**EUROSEM** (Morgan *et al.*, 1998)	**LISEM** (De Roo *et al.*, 1996)	**SWAT** (Arnold *et al.*, 1995)
Simulation type:	Continuous	Y	Y	N	N	Y
	Single event	Y	Y	Y	Y	N
Basin size		<2000 km^2	<2.6 km^2	Small basin	Small basin	Larger basin
Spatial distribution		Grid	Grid	Uniform slope planes	GIS raster	HRU
Overland flow:	Rainfall excess	Y	Y	Y	Y	Y
	Upward saturation	Y	N	N	Y	Y
Erosion process:	Raindrop impact/overland flow	Y	Y	Y	Y	Y
	Rilling	N	Y	Y	Y	Y
	Crusting	N	N	Y	Y	N
	Channel banks	Y	N	Y	N	Y
	Gullying	Y	N	N	N	N
	Landsliding	Y	N	N	N	N
Output	Time-varying sedigraph	Y	N	Y	Y	Y
	Time-integrated yield	Y	Y	Y	Y	Y
	Erosion map	Y	Y	N	Y	Y
Land use		Most vegetation covers	Wide range of land use	Mainly agricultural	Mainly agricultural	Wide range of land use

Note: Y=Yes; N=No; Simulation type: can the model simulate continuous periods or is it limited to single rainfall events? Basin size: what is the maximum basin size which can be simulated? Spatial distribution: how is spatial variability represented? Overland flow: is overland flow (important for routing sediment) generated by rainfall excess over infiltration and by upward saturation of the soil column? Erosion process: what processes are included in the model? Output: does the model provide time-varying sediment discharge (sedigraph), time-integrated (bulk) yield and a spatially distributed erosion map? Land use: what sort of land covers can be simulated?

In the critical review of SWAT model applications, Gassman et al., (2005) reported the results of various researchers that compared the performance of SWAT model with other hydrologic models like Dynamic Watershed Simulation Model (DWSM), Hydrologic Simulation Fortran-Program (HSPF), MIKE-System Hydrologic European (MIKE-SHE). Gassman et al., (2005) cited the work of Borah and Bera (2004) who reported SWAT and HSPF were suitable for predicting yearly flow volumes, sediment loads, and nutrient losses for monthly predictions except for months having extreme storm events and hydrologic conditions and poor in simulating daily extreme flow events. Similar work show that DWSM reasonably predicted distributed flow hydrographs and concentrations or discharge graphs of sediment, nutrient, and pesticides at small time intervals. In addition, Gassman et al., (2005) reported the finding of El-Nasir et al. (2005) who reported SWAT and MIKE-SHE simulated the hydrology of Belgium’s Jeker River Basin in an acceptable way. However, MIKE-SHE predicted the overall variation of river flow slightly better.

2.7 SWAT Applications in the Regional Context

A summary of SWAT model applications in selected catchments in Nilotic countries is presented in Table 2.2 with information of the country, case studies, catchment hydrological characteristics, purpose of model applications and the authors being indicated as reported in Ndomba and Birhanu (2009). The locations of the study cases are as per **Figure 2.1**.

Table 2.2: SWAT model applications in the region as reported in Ndomba and Birhanu (2008)

Name of the Basin	Simiyu	Simiyu Ndagalu	1DD1	WeruWeru	Nyando	Sondu	Upper Tana	Lake Ziway	Hare River	Upper Part of Awash	Kagera River
Catchment Area (Km^2)	11,000 (5320 modeled)	10,659	7,280	101	3587	3050	10,000	7300	167	7240	57,364
Elevation/ Elevation Range (amsl)	1143 - 1927	1135-2021	900 - 5000	2001-4177	1100-3000	Not Given	730 - 4700	1636	1180-3480	Highlands (1800 to 3554) Lowlands (1550 to 1800)	1100-4500
Mean Annual Precipitation (MAP) (mm)	825	1000	Arid/Semi Arid (500-600). Humid (1000 - 2000)	1500-3000	1000-1600	Not Given	Up to 1800	650	890 at lowlands and 1430 at highlands	850 - 1000 on plain area and 1200 mountains	Upto 1800
Spatial Features	Arid	Arid	Semi-arid to Humid	Humid	Flood Prone	Mountainous	High Physiographic Variation	Semi Arid/Sub Humid	Steep Mountains and abrupt faults	Humid to Subhumid (highlands) and Semi arid to arid (lowlands	Diverse in Topography Climate and Landform
Purposes of Application	Land and Water Management	Sediment Yield Study	Hydrology, Soil erosion and sediment yield	Water Resources Assessment	Landuse, Climate and Reservoir Storage Change	Landuse Change	Catchment Management	Climate change and Water Availability	Landuse/Land cover change	Hydrology and Soil Erosion	Water resources Management
Authors and year of publication	Mulungu and Munishi, (2007)	Ndomba et al.,(2005)	Ndomba et al.,(2007, 2008)	Birhanu et al.,(2007)	Sang (2005)	Jayakrishnan et al., (2005)	Jacobs and Srinivasan (2005)	Zeray et a., (2007)	Tadele and Forch (2007)	Chekole et al., (2007)	Didier (2007)

Figure 2.1: Location of SWAT model applications in Nilotic Countries (Ndomba and Birhanu, 2008)

2.7.1 Sensitivity, Calibration, Validation, Uncertainty and Model Performance

Table 2 provides the full range of the performances and suitable parameters developed in the course of SWAT modeling. Besides, Table 2 stipulates various simulation techniques used. Model calibration and validation periods vary based on data availability and purpose of application.

Table 2.3: SWAT model applications results in some selected Nilotic catchments as reported in Ndomba and Birhanu (2008)

Name of the Basin	Type of data used	Mode of Calibration	Period of Calibration/ Simulation	Period of Validation	Performance Efficiency Adopted	Model Performance	Sensitive Parameters
Simiyu (TZ)	High resolution	Daily	5 (1976 - 1980)	3 (1981- 1983)	IVF ,CE	Calibration IVF=143%,CE=13.73%, Verification IVF=106% & CE=40.54%.	CN2, ALPHA_BF, SURLAG, ESCO, SOL_AWC, CH_K2, SOL_Z
Simiyu Ndagalu (TZ)	Coarse Resolution	Annual, Seasonal	1 (Seasonal), 20 (Annual)	Not Provided	IVF,CE	IVF=98% and CE(Calibration=58%)	CN2, SOL_AWC,CH_K2, REVAPMN, GW_REVAP,GW_REVAP, ALPHA_BF,SOL_AWC
1DD1 (TZ)	High/Coarse Resolution	Daily, Monthly	1977 - 1982	3 (1970 to 1972)	IVF, CE	Daily Calib (IVF=100%, CE=54.6%). Monthly Calib.(IVF=100%,CE=68%) Daily Verif (CE=68%)	CN2, SURLAG, GWQMN, RCHRG_DP, SLOPE, SOL_Z
WeruWeru (TZ)	Coarse Resolution	Annual, Monthly	15 (Annual) 1(Seasonal)	Seasonal (March 1982 to Feb 1983)	IVF, CE	IVF=100%, Calibration 82%, Verification 59%	CN2,REVAPMN,GW_REVAP, SOL_AWC, ALPHA_BF, GW_DELAY
Nyando (KY)	Good Resolution	Annual, Daily	10 (Annual) 3 (Daily)	3years (1986 to 1988)	R^2, CE	Annual R^2 26% to 72%. Daily R2 45% to 72%. CE 48% to 75%. And in verification R^2 from 6% to 77%, CE from 61% to 69%	SOL_AWC, CN2, ESCO, GWQMN,GW_REVAP,REVAPMN
Sondu (KY)	Course Resolution	Monthly	10 (1979-1988)	9 (1989-1997)	CE	Calib (-69% to -72%, Verif.(8% to 10%)	SOL_AWC, ESCO
Upper Tana (KY)	Course Resolution	Monthly	18 (1978-1995)	Not used	Not Reported	Not Reported	Not Reported
Lake Ziway (ET)	Good Resolution	Monthly	15 (1981 to 1995	5 (1996 to 2000)	R^2	Calib and Valid. 20% to 70%	CN2, GWQMN, ESCO, SLOPE, RCHRG_DP,GW_REVAP, GW_DELAY
Hare River (ET)	Good Resolution	Annual, Monthly	6 (1980 to 1985)	6 (1986 to 1991)	R^2,CE, RMSE	R^2 (72% to 92%); Annual CE (41% to 92%); Monthly CE(43% to 82%)	CN2, SOL_AWC,SOL_Z, SOL_K, ESCO, SLOPE, GW_REVAP, REVAPMN, ALPHA_BF
Awash River (ET)	Good Resolution	Daily, Weekly Monthly	4 (1989 to 1992)	6 (1993 to 1998)	CE, $R^{2,}$ Percent Difference (D)	Calibration 78% to 87% (daily CE), -3.22% to -3.3% (weekly D),78% to 87%(monthly R^2). Verification	CN2, SOL_AWC, SLOPE, SOL_K, ESCO, SOL_Z, CANMX
Kagera River (R,B,U,T)	Coarse Resolution	Monthly	6 (1974 to 1979)	5	CE	Using local data (63% Calib and -136% Verif. Using global data, (41% to 43% calib) and -1.19% to -21,03% verif)	Not Reported

R, B, U, T ***refers to Rwanda, Burundi, Uganda, and Tanzania***

2.7.2 Sensitivity Analysis

SWAT model has been applied in various catchments of Nilotic countries with varied Physiographic and climatic conditions. The climatic characteristics of these catchments range from arid/semi arid to humid. The applications cover small to large basins covering basin areas from 101 km^2 to 57,364 km^2 and the SWAT model applications include climate change, landuse change, water availability, sediment yield and erosion modelling and water resources assessment/management.

Both manual or expert knowledge and automatic optimization tools have been used to calibrate the parameters. Data for calibration was split into two portions with nearly 70% for calibration and 30% for verification. Except in one of the applications, longer period was used for model calibration than validation. Seasonal calibration and validation were performed on daily or monthly basis after long-term annual water balance analysis. The calibration and validation periods range from 1 to 20 and 1 to 9 years, respectively. Long term simulations were conducted on annual basis. In these applications Curve Number (CN2), Soil Available Water Capacity (SOL_AWC), Ground water Slope (SLOPE), Soil hydraulic Conductivity (SOL_K), Soil Evaporation Compensation factor (ESCO), Soil depth (SOL_Z) were the most sensitive parameters.

2.7.3 Uncertainty Analysis

Lack of available climatic data was a challenge in SWAT modelling in the catchments of Nilotic countries (Mulungu and Munishi, 2007; Jacobs and Srinivasan, 2004; Sang, 2005; Birhanu *et al.*, 2007; Ndomba *et al*., 2005; Ndomba et al., 2008). It implies that the scarcity of climatic data was a setback for better hydrologic predictions even if high resolution spatial data was used. Besides, limited availability of spatial data resulted to unsatisfactory performance of SWAT model in some catchments such as Sondu River basin (Jayakrishnan *et al.*, 2005). Besides Harmel et al. (2000) and Moon et al. (2004) indicated SWAT hydrologic responses are sensitive to choice of climatic inputs. Besides, several hydrological model specialists demonstrated that the quantity and quality of the input data is often the limiting factor in successful model simulations (Ndomba *et al*., 2008; Hughes and Beater, 1989; Sorooshian, 1991). In fact most of the applications in the Nilotic countries focused on evaluating the input data uncertainty as discussed above and in various authorities (Ndomba et al., 2008; Ndomba and Birhanu, 2008)

2.7.4 Model Performance – Calibration and Validation

The Sondu River basin, calibration results indicated that the Nash and Sutcliffe Coefficient of Efficiency (CE) both in calibration and validation periods were poor. CE obtained were -69%, -72%, -69% (during calibration) and -8%, 10%, and -8% (during verification) for Traditional, Current adoption and Future adoption respectively. The authors, Jayakrishnan, *et al.*, (2005), attributed the poor performance of the model to inadequate rainfall and other model input data. In particular, limited digital data on landuse, soil and elevation were a challenge in the course of modeling. Simulations of traditional technology and future adoption scenarios involved differences of up to 19% in the mean monthly streamflow compared to the observed data, resulting in poor simulation efficiencies (Jayakrishnan, *et al.*, 2005). Although, the CE of model calibration and validation were poor (Table 2), the hydrologic study in Sondu River basin showed that comparable water balance simulation was obtained. Better elevation data and subbasin delineation and more detailed soil and weather data combined with detailed parameter calibration efforts were recommended to improve the results. In conclusion, Jayakrishnan *et al.*,(2005) indicated that SWAT model developed and widely applied in United States can possibly be applied in the African catchments with a higher effort in input data collection for the model setup (Jayakrishnan. *et al.*, 2005).

The study in Hare River basin concluded that the SWAT model had predicted monthly and annual flows satisfactorily and the model is useful to analyze the impacts of landuse/land cover changes on streamflow even in basins with limited data (Tadele and Forch, 2007).The results of Upper part of Awash River basin case study concluded that the SWAT model accurately tracked the measured flows and simulated well the monthly sediment yield.

The case study of Upper Tana River basin demonstrated a successful application of SWAT with limited readily available data (Jacobs and Srinivasan, 2004). In the Nyando basin the performance of ten years (1971-1980) calibration of mean annual flow resulted to a coefficient of determination (R^2) between 26% and 72%. And three years (1976-1978) daily flow calibration model performance (R^2) was from 45% to 72%, and the CE was from 48% to 75%. Lower R^2 results were attributed to lack of representative rainfall recording stations (Sang, 2005). Three (3) years (1986 to 1988) model validation resulted to an R^2 between 6% to 77% and CE between 61% to 69% at four gauging stations (1GB05, 1GB03, 1GD07, and 1GD03).

In Kagera River basin, at Rusumo gauging station, using rain gauge data the CE is 63%(calibration) and -136%(validation) and CE varies from 41% to 43% (calibration) and -1.19% to -21.03% (validation) using the globally available data. The low performance during validation was attributed to a possible change of flow regime. And the calibration and validation of SWAT at Kigali flow gauging station is poor and attributed to variability in topography, climate and geomorphology of the area (Didier, 2007). Modelling performance were poor and Didier (2007) attributed the poor performance of SWAT model to the coarse nature of the free accessible global data sets, model resolution, variability in topography and climate and landform of the study area. In most cases climatic global data sets have coarse resolution and have difficulties to represent climatic variability within catchments of small or medium size. Furthermore they cannot represent areas with specific physical processes such as Orographic precipitations (Didier, 2007). However, the observed and simulated hydrographs have same trend except that simulated streamflow peaks are higher. The results at the sub watershed indicate that observed and simulated streamflow have good agreements both in calibration and validation periods. The model predicted the base flow correctly and gave reasonable result for surface runoff. Didier (2007) recommended modeling the catchment at sub watershed level with high resolution data sets. In another study global data sets that are available online (topographical data, SRTM; soil data, FAO soil maps; land use, global land use maps; climatic data, precipitation, temperature, solar radiation etc.) didn't produce promising results and Didier (2007) recommended the use of high resolution data sets.

The long term water balance for WeruWeru catchment for 15 years (1972 to 1986) and temporal calibration and validation resulted promising results and it was reported that SWAT can be a useful tool to assess the water resources availability in small mountainous watersheds (Birhanu et al.,2007).

In the study of Simiyu River Sub-catchment Mulungu and Munishi (2007) reported that though the estimated long-term average water balance (1976-1983) shows a close agreement between the observed (74.56mm) and estimated (78.66) the Simiyu River catchment modelling result shows that peak discharges were underestimated and some peak flows were not captured at all. Besides, the model performance efficiencies are not satisfactory. In the study five years (1976-1980) calibration and three years (1981-1983) validation were performed at Ndagalu station and the CE and the Index of Volumetric Fit (IVF) results are 13.73%, and 143% respectively during calibration period, and 40.54% and 106% respectively during validation period. The poor performance of the model were attributed to uneven rainfall stations distribution and poor representation of local rainfall storms by the rainfall data used in hydrological simulations (Mulungu and Munishi, 2007). In the study though high resolution data was used the simulation results were not satisfactory and was concluded that the SWAT model fit results were not improved by increasing the spatial detail (Mulungu and Munishi, 2007).

The study on sediment yield modeling in Simiyu Ndagalu river basin indicated that the observed and simulated annual volumes are comparable and better simulation of ground water component than surface runoff. However, some of runoff peaks were not captured properly (Ndomba *et al.,* 2005). The study showed that parameters of the water balance estimated at one sub-catchment with good data was used in developing a sediment yield model for the entire basin and reasonable estimates of sediment load was obtained for the ungauged catchment despite the course resolution of spatial data (soil). The results indicate the suitability of the freely available geo-spatial data for the development of complex models like SWAT to use in estimation of hydrological variables in the ungauged catchments. From the results of their finding Ndomba *et al.* (2005) recommended the application of the model in ungauged catchments (poor data regions).

Long-term sediment modelling in the 1DD1-Kikuletwa catchment indicates that estimated and observed annual total sediment loads are comparable. However, according to Total Mass balance controller (TMC) as objective function the simulated loads overestimates the observed by 28.7%. In addition it was also reported that the SWAT model captured 56% of the variance of the observed daily sediment loads during calibration (Ndomba, 2007). The SWAT model application in longer period (i.e. 37 years) has predicted well the reservoir sediment accumulation with a relative error of estimate of 2.6 percent and it was shown that such estimation accuracy can be attributed to both sound sediment sampling programme design and well calibrated components of SWAT model (Ndomba et al., 2007). The study in 1DD1-Kikuletwa River basin indicated that the predicted and measured long-term sediment yields are comparable and for catchments where sheet erosion is dominant SWAT model is a better substitute of the sediment-rating curve and long-term prediction of sedimentation rate can be done with reasonable accuracy (Ndomba, 2007; Ndomba et al., 2007).

2.7.5 Recommended Further Research Work

Input data of various types/quality such as coarse/high- resolution, measured and global internet spatial and climate data sets were used. The results of one study indicated that model performance efficiency was higher with the use of high-resolution data sets. However the study at Simiyu River catchment indicated that higher resolution of spatial data in larger catchments does not necessarily improve the performance of SWAT model application.

It should be noted that the authors are aware that the performance of the SWAT model applications in the case studies can not be compared objectively because the performance is affected by modeling efforts/techniques, input data quality and catchment representation of important hydrological features. Regarding input data quality, an effort is required to gather the required representative data, particularly precipitation, as it is a moisture input to most hydrologic models including SWAT. Our modeling experience with SWAT model applications suggests that poor catchment representation of important hydrological features may lead to poor performance of the model. However based on the review, SWAT model seems to perform satisfactorily in catchments of Nilotic countries and thus there exists prospects for its wide applications in the region. Since the basins are characterized by scarce data we propose the use of high resolution data for small basins. In order to improve the input data for SWAT model application and as a follow research we propose that the global climatic data be validated using ground climatic station data sets.

We would like to note that little or none has been done in Nilotic countries catchments to compare application results between SWAT model and other hydrologic models such as DWSM, HSPF, and MIKE-SHE which have equal or better modelling efficiencies. These models have hydrology, sediment, and chemical routines applicable to watershed scale catchments. However, previous studies elsewhere by Borah and Bera (2003; 2004) indicated that the results of SWAT are promising for continuous simulations in predominantly agricultural watersheds than DWSM, HSPF.

2.8 SWAT Model Choice

The worldwide application of SWAT reveals that it is a versatile model that can be used to integrate multiple environmental processes, which support more effective catchment management and the development of better-informed policy decisions. The model will continue to evolve as users determine needed improvements that will enable more accurate simulation of currently supported processes, incorporate advancements in scientific knowledge and provide new functionality that will expand the SWAT simulation domain. This process is aided by the open-source status of the SWAT code and ongoing encouragement of collaborating scientists to pursue needed model development. The foundational strength of SWAT is the combination of upland and channel processes that are incorporated into one simulation package. However, every one of these processes is a simplification of reality and thus subject to the need for improvement.

In addition to the capability of the model as discussed above, several workers as reported in Ndomba and Birhanu (2008) have satisfactorily applied SWAT model for sediment yield modeling in poorly gauged catchments in Tanzania and the region at large. In order to apply the model operationally, Ndomba *et al*. (2005) recommended for SWAT model validation and/or customization in the tropical region.

3

METHODOLOGY

3.1 General

In this study the testing of the SWAT model was conducted in selected four case studies within the Nilotic countries catchments where sedimentation problems are have been reported. It is assumed Application of SWAT in Three (3) study cases spatially distributed in Nile River Basin with readily available sediment flow data and/or field based data would complement to the endeavors that are aiming at answering the stipulated research questions. The study used available streams flows, climatic, sediment flow and spatial data to setup, calibrate, validate the model. In one of the cases the study managed to use primary data on sediment flow. This was possible as it was supported by other initiative. In order to ascertain the suitability of SWAT model for the tropics, in this context, Nilotic countries' catchments, literature review on model applications in similar hydrological conditions worlds globally and the region was crucial and considered. The application of SWAT model in this study is similar to the one in the previous study conducted in Simiyu River Basin (Ndomba and Neveen, 2004; Ndomba et al. 2005).

3.2 SWAT Model Applications Procedures and Assumptions

The researchers of this study outlined a step by step procedure for the key tasks as presented below. This approach acknowledges that the model is complex and it is made up of multitude of parameters. If not properly applied it may result into parameter uncertainty problems. Therefore, elaboration is made below for each of the key task and its respective expected output.

Data analysis: data preparation and analysis (statistics, length of the records, wet years, spatial and temporal variability of rainfall, etc). The analysis was meant to guide and provide data for SWAT modeling. For instance, spatial variability justified the need of distributed modeling.

Setting up of the SWAT model. This was meant to schematize the problem matter. It is worthy noting that input spatial data used included base maps and global spatial thematic maps of various resolutions. Similarly, climatic data used include rainfall data from regular ground monitoring network and global data. Sensitivity analysis of Hydrology and sediment transport components parameters were conducted without and/or with observed data, and before and after calibration. In this case LH-OAT and PEST were used as sensitivity analysis tools. Various lengths of simulations (i.e. 2, 4, 6, 8 yrs) were tested in order to capture model input (parameter and data) uncertainty. Spatial representation of the model (lumped, semi and fully distributed) were tested. Such analysis was used to guide SWAT modeling framework design, and identification of sensitive parameters and uncertainty in model representation. Manual and automatic calibrations techniques were tested. Various auto-calibration routines, such as PEST, SCE-UA, and SUFI2 were tested. Sensitive model parameters were adjusted within their feasible ranges during calibration to minimize model prediction errors for daily flow and monthly sediment load. Various lengths of simulations (i.e. 2, 4, 6, 8 yrs) were tested in order to capture model input (parameter and data) uncertainty. The effects of spatial representation of the model (lumped, semi and fully distributed) were checked. The performance of the model between using filled and raw rainfall was checked.

The adoption of this approach assumes a number of counts. Application of SWAT model is in line of GIS and Modelling cluster vision. The model runs under ArcGIS environment and the successful application requires a deep knowledge in modeling. Although, the principal external dynamic agents of sedimentation are water, wind, gravity, and ice (Vanoni, 1975) where each may be important locally, only the hydrospheric forces of rainfall, runoff, and streamflow forces are considered in this study. Sheet erosion is idealized as key erosion processes in tropics and Nilotic catchments at large (Nile FRIEND, 2009). It should be recalled that SWAT is mainly meant for estimating sheet erosion/yield rates.

4
RESULTS AND DISCUSSIONS

4.1 General

The findings are presented in such as manner to illustrate on how the research questions have been addressed. It should be recalled that each study objective was linked to research question. Thus, the presentation below follows suit.

4.2 Sensitive Parameters Controlling Sediment Generation and Routing

Seven (7) out of nine (9) SWAT parameters that directly govern the sediment yield and transport in the catchments analyzed were found to be sensitive (Table 4.1) in the study cases, PRB, SRB, and KRB. It should be noted that rank 10 signifies that a parameter is not sensitive/important. These parameters can be categorized into two groups that are upland and channel factors. The former group includes parameters such as P_USLE, C_USLE, K_USLE, BIOMIX, and RSDIN; whereas Csp, CCH, KCH and spexp parameters belong to the latter group.

Table 4.1: Sensitivity analysis results of sediment component of SWAT for three case studies, PRC, SRC and KRC

SN	Parameter	Description of parameter	PRC Rank	SRC Rank	KRC Rank
1.	Csp	Linear re-entrainment parameter for channel sediment routing	1	2	1
2.	CCH	Channel cover factor	2	5	2
3.	**P_USLE**	**USLE support practice factor**	**3**	**3**	**3**
4.	KCH	Channel erodibility factor [cm/h/Pa]	4	6	4
5.	spexp	Exponential re-entrainment parameter for channel sediment routing	5	4	5
6.	**C_USLE**	**Minimum USLE cover factor**	**6**	**7**	**6**
7.	BIOMIX	Biological mixing efficiency.	7	1	7
8.	K_USLE	USLE soil erodibility factor [t.ha.h./(ha.MJ.mm]	10	10	10
9.	RSDIN	Initial residue cover [kg/ha]	10	10	10

However, it should be noted that only channel routing parameters with Serial number 1, 2, 4, and 5 in the Table were used for calibrating SWAT model in all cases. Based on catchment sediment management scenarios simulation results the study has found that all sorts of farming practices captured by P_USLE and C_USLE SWAT model parameters are the main determining management techniques in reducing soil loss/sediment yield in the upland catchments and subsequent sedimentation problems in the downstream reservoirs. Accordingly, proper soil and water conservation practices are among the most effective and inexpensive alternative measures to reduce sedimentation problems and preserving reservoir storage for a longer lifetime.

4.3 Model Performance

The discussion in this section is focusing on the study cases where there was relative adequate data (Table 4.2). For instance, in Koka reservoir catchment the results of the model performance measures according to Nash and Sutcliffe efficiency (CE) for flow calibration and validation are 68 and 63, respectively. For sediment calibration and validation, CE is 66 and 68, respectively. The calibration and validation results have shown that measured and simulated values were closely related with relative error of 7.5 %.

Table 4.2: SWAT model performance for the four case studies, RRC, KRC, PRC and SRC

Variables	**Performance indicators**	**Time step**	**Study cases**			
			RRC	**KRC**	**PRC**	SRC
Runoff	Calibration, CE (%)	Daily	49.15	68	54.6	38
		Monthly	-	-	65	82
	Validation, CE (%)	Daily	51.4	63	68	30
		Monthly	-	-	77.4	81
	IVF (%)		95.6	-	100	104.12
Sediment yield rate	Calibration, CE (%\)	Daily	-	66	56	24
		Monthly	-		-	83
	Validation, CE (%)	Daily	-	68	-	16
		Monthly	-	-	-	80
	Relative Error (%)		-	7.5	2.6	0.76

Note: "-" not evaluated as a result of missing data.

Sediment yield calibration results for SRC for the period from 1970 to 1975 in daily and monthly time steps are presented in Table 4.2 and Fig. 4.1. The result from SWAT model at daily time step is fair with model performance of CE= 24. Sediment loads in the peak flood events such as that in 1970, 1792 and 1974 are over-predicted. However, the performance of the model in simulating monthly sediment loads is good with CE= 83.

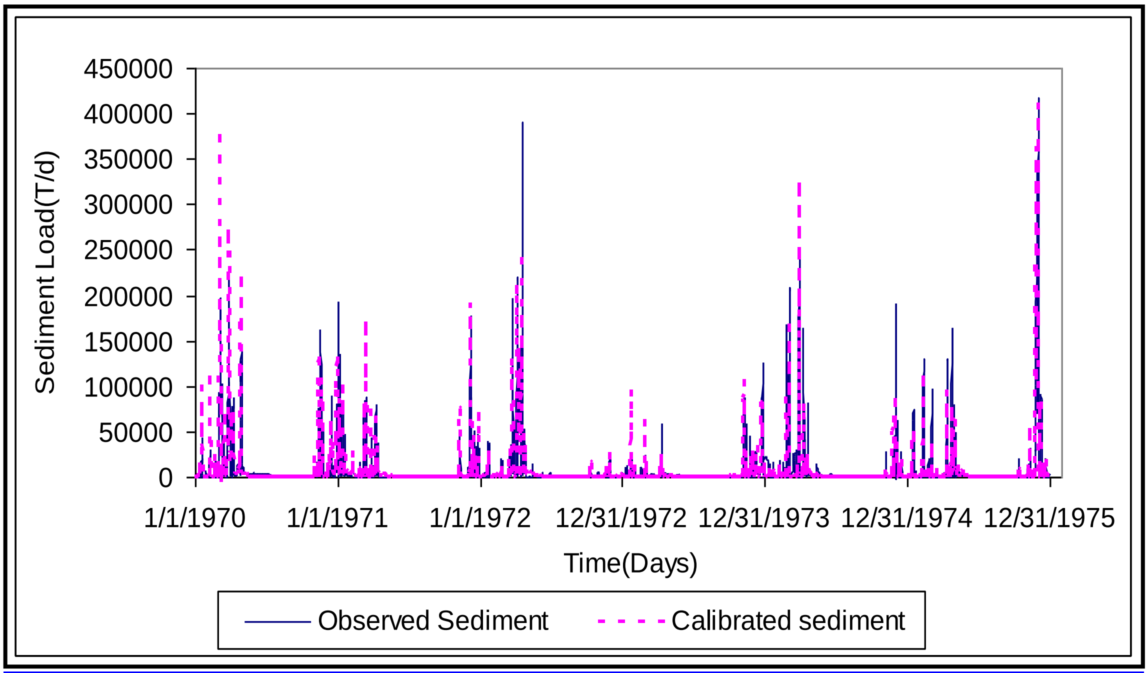

Figure 4.1: Comparison between observed and simulated Simiyu daily sediment for calibration period from 1970 and 1975 at main bridge outlet.

The sediment modeling was validated for the priod 1976 to 1978 (Fig. 4.2), Daily sediment load is fairly simulated with model performance of CE = 16. Sediment loads during the peak flood events are over-predicted such as months of April in 1976 and November in 1978. On the other hand in January 1977 and April 1978 are under-predicted. However, the performance of the model in simulating monthly sediment loads is good with CE = 80.

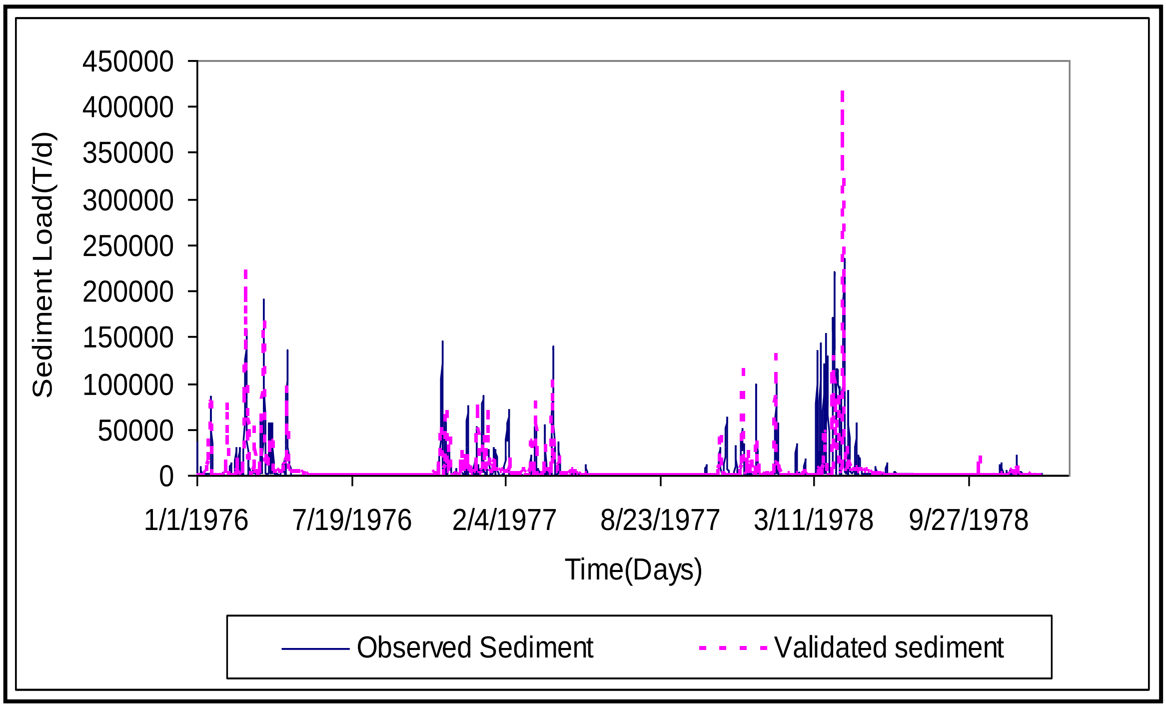

Figure 4.2: Comparison between observed and simulated Simiyu daily sediment for the validation period from 1976 and 1978 at main bridge outlet

For the case of PRC the SWAT model captured 56 percent of the variance (CE) and underestimated the observed daily sediment loads by 0.9 percent according to Total Mass Control (TMC) performance indices during a normal wet hydrological year, i.e., between November 1, 1977 and October 31, 1978, as the calibration period. SWAT model predicted satisfactorily the long-term sediment catchment yield with a relative error of 2.6 percent (Table 4.2 and Fig.4.3). Also, the model has identified erosion sources spatially and has replicated some erosion processes as determined in other studies and field observations in the PRC (Ndomba et al. 2008). This result suggests that for catchments where sheet erosion is dominant SWAT model may substitute the sediment-rating curve. However, the SWAT model could not capture the dynamics of sediment load delivery in some seasons to the catchment outlet (Ndomba et al. 2008). The particular study linked the latter problem to Model deficiency.

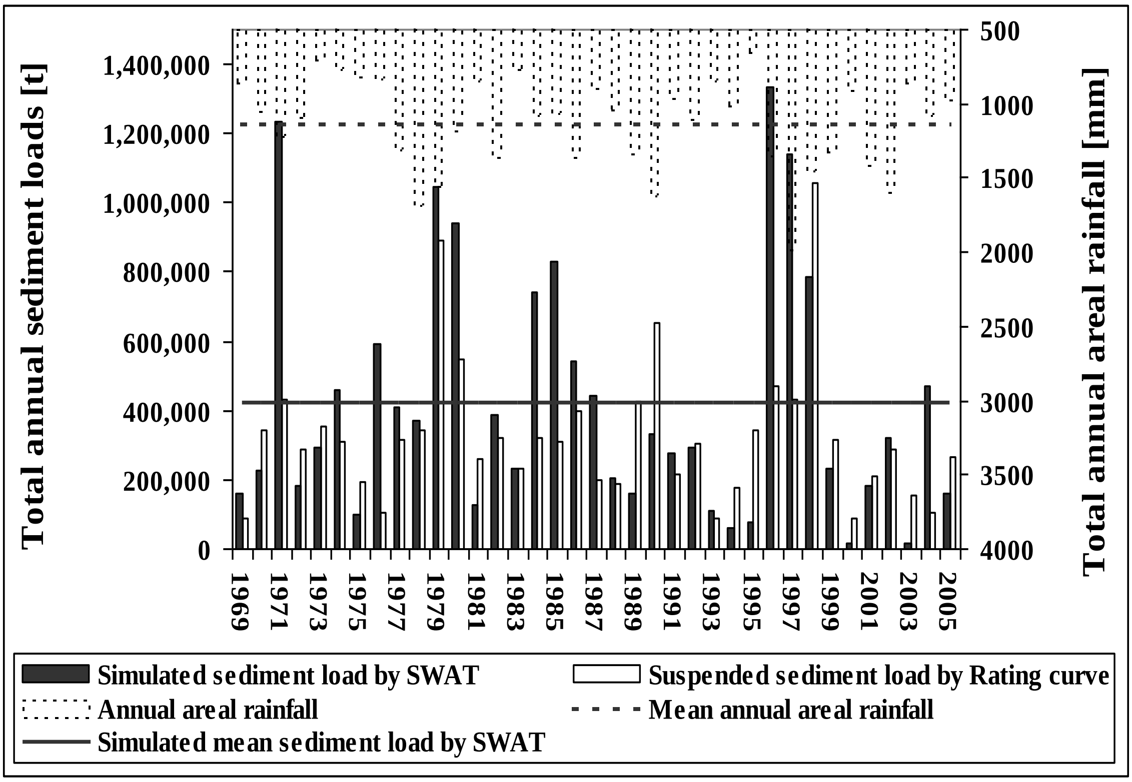

Figure 4.3: Pangani River Basin: SWAT simulations Vs Rating curve-sediment loads at 1DD1 (Annually), between January,1969 –December, 2005 (Ndomba et al.2008)

The performances of SWAT model in the case studies and others conducted in Nilotic catchments as reported in literatures basing on CE and IVF and Relative Errors (RE), suggest that the model can satisfactorily estimate sediment yield for even poorly gauged catchments (Ndomba and Neveen, 2004; Ndomba, *et al.*, 2005, Ndomba, 2007, Ndomba and Birhanu, 2008, Ndomba et al., 2008). Therefore, based on the latter and previous findings a preliminary statement could be lightly drawn on the applicability or suitability of SWAT model in sediment yield modeling for the tropics and Nilotic countries in particular.

5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study applied SWAT in four case studies in Nilotic countries using mostly available data. In few cases primary data was explored. These cases studies range from small to large catchments representing various climatic conditions in the region. Among others the study has found out that the method adopted is also reliable for poorly gauged catchments. Furthermore, based on review by previous workers and findings of this study the method seems to be robust and can be relied upon as a tool for catchment sediment management in tropics. However, the model could not capture dynamics of sediment load delivery in some seasons in one catchment. The particular study linked the latter problem to Model deficiency. Based on simulation results the study has found that all sorts of farming practices captured by P_USLE and C_USLE parameters are the main determining management techniques in reducing soil loss/sediment yield and subsequently sedimentation problems in the reservoir. Besides, performances of SWAT model in this case studies and others conducted in Nilotic catchments suggest that the model can satisfactorily estimate sediment yield for even poorly gauged catchments. It further suggests that the model can be used comfortably as research tool in reservoir sedimentation/sediment yield modeling studies. However, we appeal to those who want to apply SWAT in their case study should not apply it blindly. They need to consult experience from previous studies in Nilotic catchments.

5.2 Recommendations

The results of this study are not conclusive enough because some challenges have not been addressed. Although, the Input data of various types/quality such as coarse/high- resolution, measured and global internet spatial and climate data sets were used, still there is no agreement on the same. For instance, the results of one study indicated that model performance efficiency was higher with the use of high-resolution data sets. In another study, Simiyu River catchment, the results indicates that higher resolution of spatial data in larger catchments does not necessarily improve the performance of SWAT model application. It should be noted that the authors are aware that the performance of the SWAT model applications in the case studies can not be compared objectively because the performance is affected by modeling efforts/techniques, input data quality and catchment representation of important hydrological features. It is yet required to improve the input data quality and especially effort is required to gather the required representative data, particularly precipitation, as it is a moisture input to most hydrologic models including SWAT. In order to improve the input data for SWAT model application and as a follow research we propose that the global climatic data be validated using ground climatic station data sets.

The lesson learned from SWAT model applications is that poor catchment representation of important hydrological features, especially the wetlands/marsh or swamps, may lead to poor performance of the model. In most studies reviewed such features were not implemented. It is important to continue efforts in customizing SWAT is such environment. We would like to note that little or none has been done in Nilotic countries catchments to compare application results between SWAT model and other hydrologic models such as DWSM, HSPF, and MIKE-SHE which have equal or better modelling efficiencies. These models have hydrology, sediment, and chemical routines applicable to watershed scale catchments. However, previous studies elsewhere by Borah and Bera (2003; 2004) indicated that the results of SWAT are promising for continuous simulations in predominantly agricultural watersheds than DWSM, HSPF.

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List of Research Group Members

Name	Country	Organization	E-mail
Dr. Preksedis Marco Ndomba	Tanzania	University of Dar es Salaam	omndomba2002@yaoo.co.uk
Dr. Joel Nobert	Tanzania	University of Dar es Salaam	nobert@udsm.ac.tz
Dr. Subira Munishi- Kongo	Tanzania	University of Dar es Salaam	evasubira@yahoo.com
Mr. Deusdedith Magoma	Tanzania	Private Engineer	eng_dmagoma@yahoo.com
Dr. Baligira Robert	Rwanda	Kigali Institute of Science and Technology KIST	rbaligira@yahoo.fr
Eng. Jean Claude Musabyimana	Rwanda	Ministry of Agriculture and Animal Resources (MINAGRI)/	mussaclo1@yahoo.fr
Dr. Ahmed Moustafa Elbelasy	Egypt	Hydraulics Research Institute	a.El-Balasy@hri-egypt.org
Dr. Neveen Yousif	Egypt	Ain Shams University	neveen_yousif@hotmail.com
Mr. Didier Haguma	Rwanda	Private Engineer	
Dr. Semu Ayalew Moges	Ethiopia	Addis Ababa University	semu_moges_2000@yahoo.com
Mr. Endale Bewketu Ambaye	Ethiopia	Private Engineer	endale_bew@yahoo.com

Scientific Advisor:
Prof. Roland K. Price
Senior Advisor Hydroinformatics
UNESCO-IHE, the Netherlands

Full Profiles of Research Group Members are available on: The Nile Basin Knowledge Map
http://www.NileBasin-Knowledgemap.com

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Knowledge Networks for the Nile Basin

Sediment Yield Modelling Using SWAT Model in Tropical regions

This study applied SWAT in four case studies in Nilotic countries using mostly available data. In few cases primary data was explored. These cases studies range form small to large catchments representing various climatic conditions in the region. Among others the study has found out that the method adopted is also reliable for poorly gauged catchments. Furthermore, based on review by previous workers and findings of this study the method seems to be robust can be relied upon as tool for catchment sediment management in tropics. However, the model could not capture dynamics of sediment load delivery in some seasons in one catchment. The particular study linked the latter problem to Model deficiency.

Based on simulation results the study has found that all sorts of farming practices captured by P_USLE and C_USLE parameters are the main determining management techniques in reducing soil loss/sediment yield and subsequently sedimentation problems in the reservoir. Besides, performances of SWAT model in these case studies and others conducted in Nilotic catchments suggest that the model can satisfactorily estimate sediment yield for even poorly gauged catchments. It further suggests that the model can be used comfortably as research tool in reservoir sedimentation/sediment yield modeling studies.

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