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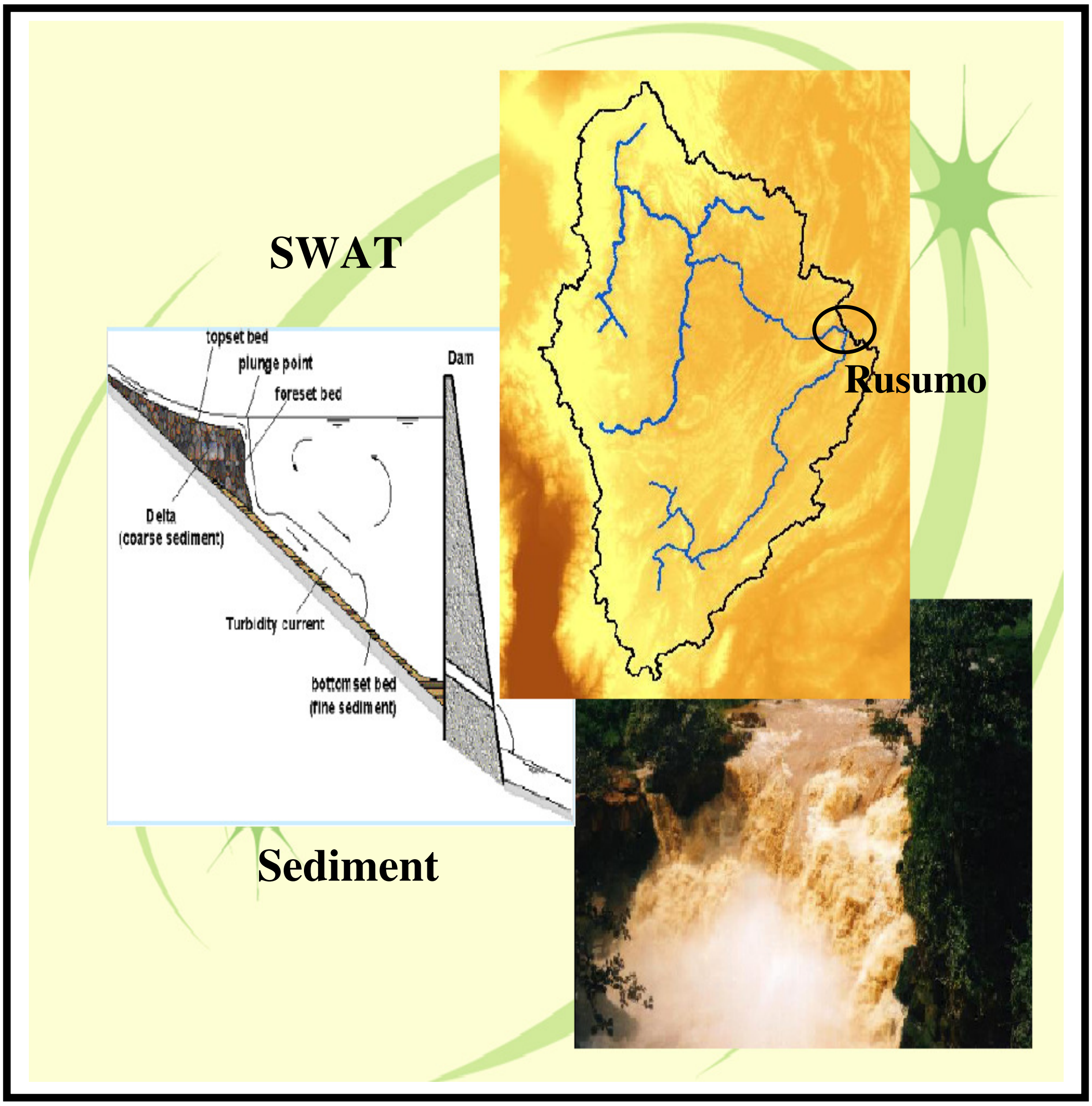

Modelling of Sediment Yield and Deposition in the Planned Rusumo Hydropower Reservoir Using SWAT Model

Arsène Aimé Habyarimana Mukubwa

MSc Thesis WSE-HI.08-13
April 2008

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Master of Science Thesis
by
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This research is done for the partial fulfilment of requirements for the Master of Science degree at the UNESCO-IHE Institute for Water Education, Delft, the Netherlands

Delft
April 2008

« L'idéal est comme une étoile. Vous ne réussissez pas à la tenir entre vos doigts. Mais comme le matin sur l'océan sans fin, choisissez-la comme guide, et, en la suivant, vous atteindrez votre but ».

Carl Schurz

Abstract

Erosion and sediment transport are among the major problems of water and soil degradation in the Nile basin. Sedimentation impacts many aspects of the environment among which water quality, water supply, flood control, river regulation, reservoir lifespan, irrigation, navigation, fishing, tourism, etc. Consequently, sediment transport problems have attracted increasing attention from the public and engineers.

With the current water scarcity issue, also observed in the Nile basin, the common tendency in different water management policies is to harvest, conserve, and use water efficiently. In the same line, reservoirs or dams are being constructed for different purposes and benefits.

Recently, the Rusumo Falls hydroelectric project, a cooperative effort by Burundi, Rwanda, and Tanzania has been approved. The Rusumo falls are located on the Kagera River about 2km downstream of the Kagera-Ruvubu Rivers' confluence. Both tributaries to Kagera River, i.e. Nyabarongo and Ruvubu, are known for their high sediment load content. The high concentration in sediment may lead to the sedimentation of the reservoir and consequently to a loss of storage capacity and this would affect the reservoir benefits among which the power generation.

Therefore, an anticipated quantification of sediment yield and deposition in the reservoir are required for proper management of both the watershed and the reservoir.

To achieve that goal, a Soil and Water Assessment Tool (SWAT) model was built for estimating the sediment yield in the Kagera catchment upstream of the Rusumo falls. The output information was then fed into the empirical methods i.e. Ort (1930) and the method of rate of storage capacity loss, in order to estimate the sedimentation of the planned Rusumo hydropower reservoir.

The results showed that part of the sediment will be deposited in the wetland area far upstream of the dam, and the remaining part in the pool just behind the dam. Moreover, a loss between 2.5 and 10% of the storage capacity of the reservoir within a period of ten years after the implementation of the dam project was predicted.

Finally, the (SWAT) model has proved to be a useful tool in modeling sediment yield within Kagera catchment with very limited data. In addition, the present study found that the resolution of the digital elevation model, and the number of hydrologic response units used in the model set up have an influence on results.

Keywords: Reservoir sedimentation; SWAT; Empirical methods.

Acknowledgement

I would like to express my deepest gratitude to my supervisors Dr Ann van Griensven and Dr Biswa Bhattacharya for their valuable advice and guidance in this study. Special thanks and gratitude are due to Dr Ann van Griensven for her genuine day to day support, valuable advice and sincere comments which allowed me to complete the present work.

I also want to express my gratitude to Mr Robert Muganga, the coordinator of Projet de Gestion Nationale des Resources en Eau, PGNRE-Rwanda. The PGNRE provided access to the database of hydrological and meteorological data which helped in building and without which the calibration would not have been possible.

In a special way, I am grateful to the Decision Support System component of the Water Resources Planning and Management of the Nile Basin Initiative which provided the scholarship and financed this study. My sincere thanks are due to Dr Abdulkalim H. Seid and Dr Hesham A. Ghany for their valuable advices, comments, and time despite their tight schedules.

I am deeply indebted to Mr. Augustin Mugenzi for his enthusiasm and valuable advices as an expert in field of water in Rwanda. He allowed me to consult his home library several times in the data collection period.

I also want to express my gratitude to Mr. Jean Pierre for his commitment and support in collecting data. He connected me with different people who provided with me sediment transport data.

Finally, I wholeheartedly want to express my gratitude to my fiancée Ghislaine Umwali for helping and assisting me in the field work. Her constant and continuous encouragement proves her love and support during the entire course of this work.

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List of acronyms

ADB	African Development Bank
ARS	Agriculture Research Service
AvSwatDB	ArcView SWAT Database
AVSWATX	ArcView SWAT
CREAMS	Chemical, Runoff and Erosion from Agricultural Management Systems
CRU	Climatic Research Unit
DEM	Digital Elevation Model
DWGA	Daily Weather Generator Algorithm
DWSM	Dynamic Watershed Simulation Model
FAO	Food and Agriculture Organization
GIS	Geographic Information system
GLEAMS	Groundwater Loading Effects on Agricultural Management Systems
GRASS	Geographical Resource Analysis Support System
HSPF	Hydrological Simulation Program – Fortran
IDW	Inverse Distance Weighting
LH	Latin Hypercube
MUSLE	Modified Universal Soil Loss Equation
NBI	Nile Basin Initiative
NELSAP	Nile Equatorial Lakes Subsidiary Action Program
OAT	One factor At a Time
ROTO	Routing Outputs to Outlets
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resources in Rural Basins
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WXGEN	Weather generator tool

1 Introduction

1.1 Background

As elsewhere around the world, erosion and sediment transport are one of the major problems of water and soil degradation in the Nile basin. Sedimentation alone affects many aspects of the environment such as soil erosion, water quality, water supply, flood control, river regulation, reservoir lifespan, groundwater table, irrigation, navigation, fishing, tourism, etc. It has therefore attracted attention from the public, engineers, as well as researchers in all the above mentioned fields.

With the current water scarcity issue, also observed in the Nile basin, the common tendency concerns in different water management policies are to harvest, conserve, and use water efficiently. In the same line, reservoirs or dams are being constructed for different purposes and benefits. For instance, in Western Sudan, shortage of water for domestic uses and livestock supply, caused water sources to be centres for tribal conflicts. To address that issue, small dams were constructed on seasonal wadis as most appropriate and promising water harvesting techniques (Gismalla 2007).

However, the construction of reservoirs, especially large reservoirs, greatly changes the natural river conditions and causes a number of environmental and ecological problems related to sedimentation. Due to the reduction of flow velocity within the reservoir, the sediment carried by flow largely deposits in the reservoir. In the absence of the sediment flushing measures, this deposition induces the loss of storage capacity of the reservoir. The consequent sedimentation and loss of storage capacity, hence affect reservoir benefits, such as flood control, water supply, irrigation, power generation, fishing and recreation.

Hydropower reservoirs are losing their capacity due to sedimentation processes, and are therefore seriously threatened in their performance. The pool behind the dam generates favourable conditions for particle settling, such that important storage capacity is lost. Furthermore, significant changes can occur in the stream basin due to the redistribution of sediments and discharges, notably downstream. Without any mitigating measures the viability of many reservoirs is questionable, as the impacts and losses are not balanced by the profits.

It is apparent that for mastering the reservoir-sedimentation issues the use of strategies for controlling reservoir sedimentation becomes increasingly important. Obviously a good prediction of the processes and the endeavour to better understanding of the reservoir behaviour is essential. In the same line, the present research is justified by an urgent need to address opportunities in seeking a solution to present challenges in the river basin management regarding erosion and sediment transport using modelling tools and modern techniques. The erosion as a spatial and temporal phenomenon needs a continuous monitoring. The development of a dynamic model to quantify sediment yield and deposition in the reservoir is then a necessity for watershed management, and for maximizing the benefit of the reservoir on long-term basis.

Moreover, given the fact that models are not yet able to describe all macro-and micro-elements and corresponding processes of reality, it is deemed dangerous to believe in the predicted output variables of importance especially in cases of ungauged basins

(Griensven and Meixner 2007). Increasing attention is being paid to accurately predict the model reliability beyond the range of condition for which the model has been successfully calibrated and verified (Pao-Shan Yu et al. 2000). This is mainly done by carrying out uncertainty analysis.

1.2 Problem description

Recently, one of the first infrastructure projects planned under the Nile Basin Initiative, the Rusumo Falls hydroelectric project, a cooperative effort by Burundi, Rwanda, and Tanzania has been approved. The Rusumo falls are located on the Kagera River about 2km downstream of the Kagera-Ruvubu Rivers' confluence, where the river forms the border between Rwanda and Tanzania. Kagera originates from Nyabarongo River on Rwandan side whereas Ruvubu River originates from Burundi.

On one hand, soil erosion is a serious problem in Burundi due to the high erosion due to rainfall. According El-Hassanin (2002), the soil erodibility factor for Burundi Oxisol soils was estimated as 0.01 t h^{-1} M J^{-1} mm^{-1}. The erodibility factor values ranged from 0.003 for storms producing soil losses less than 0.5 t ha^{-1} to 0.024 for storms producing soil losses greater than 5 t ha^{-1}.

The most important river in the project area, from Burundi side, is Ruvubu, which is the main river that feeds into the River Nile. Its catchment area is 10, 200 km^2 and stretches 286 km. It flows from the peaks in Ngongo at a height of 2300m, through the centre of the country, where its major tributaries concentrate, and heads towards the Northeast to join the Nyabarongo River and Kagera River. The average contribution of Burundi to the Kagera, the main tributary of Lake Victoria, is estimated to be 3.1 million cubic meters per annum.

On the other hand, Rwanda, as a land of thousand hills, is subject to considerable steep gradients. The precipitation is large and estimated between 900 and 1200 mm/year. During rainy seasons, the daily mean precipitation varies from 14 to 56 mm/day. From those geological, topographical and hydrological conditions a lot of sediments are produced and moved. According to the Ministry of Agriculture and Livestock 14Mtones per year of lands are estimated to be lost due to erosion. The tributaries of the Kagera River on Rwanda's side, like Nyabarongo River, are known for there high sediment load content.

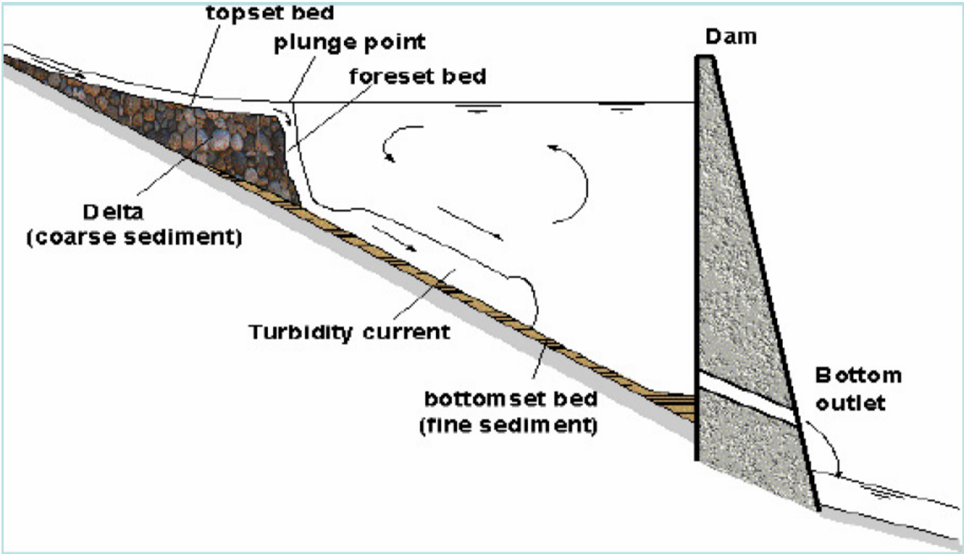


Figure 1.1 Reservoir sedimentation

The Rusumo Falls Project was found to be associated with socio-economic and environmental potential risks among which population resettlement, public health (increase of malaria and bilharzias), impacts on natural habitats such as flooding of 250 km^2 of wetlands, impacts of changes in the hydrological and sediments regime on the Akagera National Park and water hyacinth accumulation in the reservoir. The accumulation of the sediments in the reservoir would obviously lead to a progressive loss of storage in the reservoir (Figure 1.1). If not controlled, this may hinder the optimal operation of the reservoir; hence affect the power production expected.

Beside the lack of observed data in the quasi ungauged Kagera River basin, the process of sediment yield and transport is very complex and there is still a little and reliable information in the great lakes region that would lead to basic decision support tools.

Therefore, the anticipated quantification of sediment yield and deposition in the reservoir are required for proper management of both the watershed and the reservoir based on data acquired from other sources than site observed data.

1.3 Objectives

The main objectives of this research was to build a SWAT model for estimating the sediment yield in the Kagera catchment upstream of the Rusumo falls, and to estimate the sedimentation of the planned Rusumo hydropower reservoir.
The specific objectives will include:

i. An estimation of sediment yield per month;
ii. An estimation of long-term sediment deposition;
iii. A sensitivity analysis leading to identification of parameters that influence erosion processes in the Kagera catchment;
iv. An identification of other factors influencing the sediment modelling in the Rusumo catchment.

1.4 Methodology

To address the objective of this study, the methodology used includes:

i. A literature review on the studies done on soil erosion and sediment transport in the tributaries of Kagera River and elsewhere in the world;

ii. Acquisition and analysis of available and required data from remote sensing as well as from direct measurements. Among the data collected were climate data that include rainfall as well as stream flow data.

iii. Building the sediment routing model using the Soil and Water Assessment Tool (SWAT) with the aim of routing the sediment till the entrance of the river into the planned reservoir. In the model set up, simulations where carried out into two batches; first considering the Nyabarongo catchment alone, and then the whole catchment under study after.

iv. Predicting long-term deposition of the sediments in the planned Rusumo reservoir using empirical methods. In this process, SWAT model flow and sediments results were used as input data for the empirical expressions.

v. Carrying out a sensitivity analysis through different scenarios with the aim of identifying parameters that influence sediment transport in the concerned section of Kagera catchment.

1.5 Thesis report overview

The present thesis report comprises six chapters. The first chapter introduces the study through a background and a description of the problem. It also summarizes the main objectives of this study and the methodology used to meet the objectives.

The second chapter discusses erosion and sediment in the study area and the reservoir sedimentation in general. It then review the literature on numerical modeling of reservoir sedimentation, and particularly discusses the Soil and Water Assessment Tool, then closes on the methods used in estimating the sediment deposition in the reservoirs.

The third chapter gives a brief insight of the study area and the Rusumo Falls Hydropower Project. In the forth chapter, prior to their use, the collected and measured data are presented and analyzed.

The fifth chapter discusses the model set up and the results obtained. It also includes the scenarios run and the corresponding findings. The sixth and last chapter, present conclusions and recommendations made.

2 Literature review

2.1 Erosion and sediments

Soil erosion and sedimentation are among the world's modern environmental concerns. In many parts of the world, soil erosion has not only caused land deterioration and hampered the development of agriculture and industry, but also increased sediment yield from the watershed.

Water erosion is the most important type of erosion because runoff is essential to transport the eroded sediment. In the entire process of erosion and transport, soil erosion, soil loss and sediment yield in a basin are three different but closely related concepts. Xiaoqing (2003) defined sediment yield as the total sediment outflow from a watershed or drainage basin, measurable at a cross-section of reference in a specified period of time.

In the comprehensive planning of a medium or small watershed, if the gross erosion and sediment delivery ratio are known, the sediment yield can be predicted. Here the redelivery ratio stands for a ratio between the sediment yield and the amount of sediment removed from the entire watershed surface during the same period of time.

2.2 Erosion in Rusumo catchment

The land degradation by erosion is particularly a critical problem in Burundi and Rwanda. The various conditions supporting this phenomenon include rainfall often with high intensity, important slopes of the grounds, agricultural overexploitation with loose soils. The effects of erosion are numerous and observed in agricultural sector, with the loss of good arable lands, as well as on the existing infrastructures (silting of reservoirs, difficulties in water treatment, etc).

All stakeholders are aware of this problem. However, even if various trials on erosion have been performed in Rwanda, nobody can truly quantify the phenomenon at the scale of the country as a whole.

Different studies have shown that important erosion in Rwanda is not very much related to the intrinsic brittleness of the grounds, rather to the strong declivity or the cultivation methods, and of course to the intensive rainfalls. Rwanda is strongly exposed to the three principal types of erosion: sheet, drain and gully erosion.

Sheet and drain erosions are often related to the weak cover of the grounds, and mainly to the of inappropriate cultivation methods. They generally carry the topmost layer of the grounds made of fine sediments, rich in organic matter. These sediments come to charge the rivers downstream and can be carried to long distances. On the other hand, the gullies can be generated by the accumulation of human activities other than agriculture (tracks or footpaths, dwellings), and they are at the origin of the transport of coarse materials such as stones and gravels which in turn charge the beds of the rivers and affect at the same time their banks.

Concerning the quantity of soil losses due to erosion, the literature considers specific point, but does not give reliable figures on the country's scale. Some studies estimated a soil loss varying between 4 and 90t/ha/an. However, these figures are to be handled carefully since they are dated before the 1994 genocide event, which affected very clearly the implemented anti-erosive measures and the forests in general.

2.3 Reservoir sedimentation

Sedimentation poses an ongoing threat to the vitality of the world's reservoirs. Globally, the overall annual loss rate of reservoir storage capacity is estimated at 1 to 2 per cent of the total storage capacity (Xiaoqing, 2003).

In China in 1989, 232 large and medium-sized reservoirs had a total loss of 11.5 billion m3, accounting for 14.3 per cent of the total capacity of 80.4 billion m3.

In Italy, an analysis of 268 reservoirs distributed over the country with a mean age of 50 years showed the following loss of reservoir storage capacity: 1.5 per cent of the reservoirs were completely filled by sediment, 4.5 per cent had lost 50 per cent of their storage capacity, and 17.5 per cent had lost 20 per cent of their storage.

The Ichari Reservoir in India silted up to crest level of the spillway in two years. The Austin Reservoir lost 41.5 per cent of its total storage volume from 1893 to 1897, and the dam gave way in 1900.

The new Lake Austin of the Colorado River in Texas lost 95.6 per cent of its capacity in 13 years, the Habra Reservoir in Algeria 58 per cent in 22 years, and the Wuchieh Reservoir in Taiwan 98.7 per cent in 35 years.

All these examples show how severe the reservoir sedimentation problem is, and not only in the developing countries but also in most advanced countries.

2.4 Numerical modeling of reservoir sedimentation

Nowadays, the prediction of reservoir sedimentation is mainly based on numerical modelling, though empirical methods are still in use. Different numerical models of reservoir sedimentation have been established based on laws governing water flow and sediment transport.

Sediment transport and its induced channel deformation are the results of water flow motion. Simultaneously, the modified channel has in turn its effects on the flow. As a consequence to that, sediment related numerical models include both the flow motion and sediment transport sub models. The two sub models are solved simultaneously and their solutions are known as coupled solutions.

The major drawback of sedimentation models remains the uncertainty related to sediment transport computations, and to the estimation of river channel resistance.

2.5 SWAT

2.5.1 SWAT description

SWAT - the Soil and Water Assessment Tool - was developed by the ARS/USDA as an integrator of the simulators CREAMS, GLEAMS, SWRRB and ROTO (Arnold et al., 1996). It includes modules for river basin modelling, hydrologic river routing, sediment, nutrient and pesticide transport. The calculation time step is daily.

SWAT has been developed and used for analysing agricultural management practices, water supply management and climate change effects on water, sediment and agricultural chemical yield in large complex watersheds with varying soils, land use and management conditions over long periods of time. To satisfy this objective, the model is partly physically based and partly distributed; uses readily available inputs; is computationally efficient to operate on large basins in a reasonable time; and runs in continuous time (daily updating of the water balance, plant growth, nutrient and pesticide concentrations, etc.) and capable of simulating long periods for computing the effects of management changes.

The water quantity processes simulated by SWAT include precipitation, evapotranspiration, surface run-off and lateral, ground water and river flow. The water quality section includes the calculation of the wash off of sediment, nutrients and pesticides and the percolation of the latter two. Nutrient transformations as well as crop growth and agricultural management practices are also incorporated.

The simulator is integrated in a GIS by an ArcView or GRASS pre-processor. Subbasin delineation is automated by means of a Digital Elevation Model (DEM). Within the subbasins, Hydrological Response Units (HRU) can be defined by combining land use and soil maps.

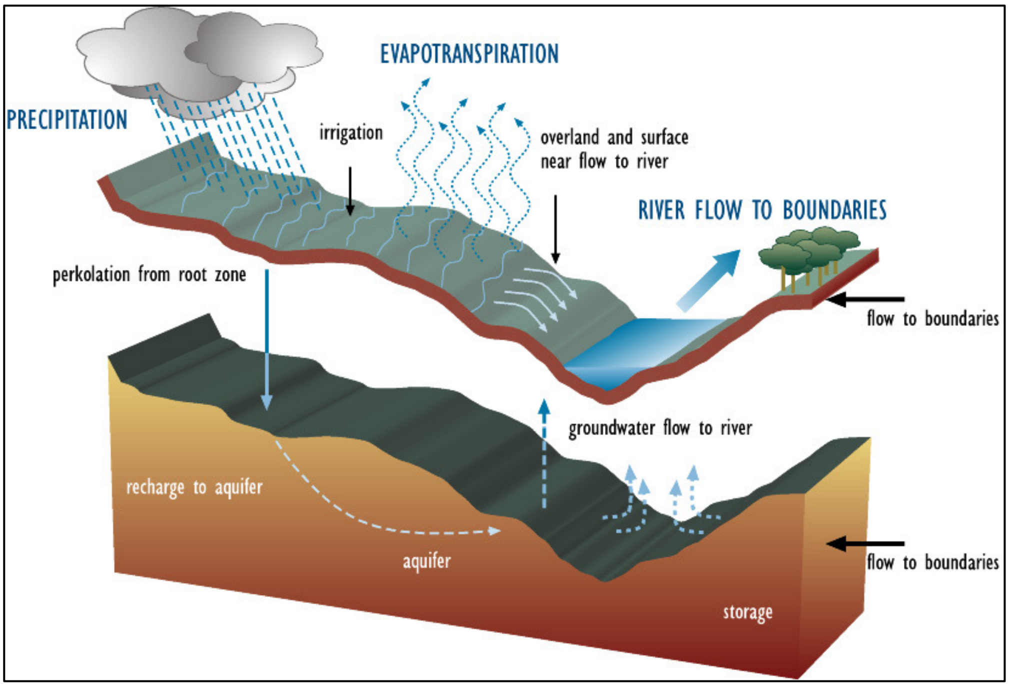


Figure 2.1 Scheme of the hydrologic cycle in SWAT

2.5.2 The structure of SWAT

The SWAT operates at several levels: basin, sub-basin and HRU. An HRU (Hydrological Response Unit) represents a sub-division in the sub-basin that is characterised by a unique combination of land use and soil type. The HRU has no location in the sub-basin model, but is only defined as a fraction of the sub basin that can be represented by a unique combination of soil and land use.

The program calculations follow these levels. In a first step, the program calculates the fluxes of each HRU (per surface unity e.g. m²). These outputs will be aggregated to sub-basin output, in accordance to the fractions of the HRU. The sub basin outputs will then be routed through river reaches according to the river network.

The input is structured in a similar way, were certain files represent the whole basin, others the sub-basins and finally the HRU's, as described in Tab. IV-2.

Table 2.1 File structure in SWAT

BASIN		SUBBASIN	
*.tmp	temperature (optional)	*.gw	groundwater parameters
*.pcp	precipitation (optional)	*.rte	river routing parameters
*.fig	model structure	*.swq	river water quality parameters
*.cod	model operation parameters	*.wgn	weather generator parameters
file.cio	all names of input files	*.sub	geometry and areal percentage of each subbasin
*.bsn	General parameters for the basin	HRU	
crop.dat	crop database	*.hru	geometry and areal percentage of each HRU.
till.dat	tillage database	*.sol	soil characteristics
pest.dat	pesticide database	*.mgt	management practices
fert.dat	fertilizer database	*.chm	Initial chemical concentrations

2.5.3 How does SWAT model the sediment yield?

Erosion caused by rainfall and runoff is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). MUSLE is a modified version equation of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith in 1965 and 1978 respectively (Neitsch et al. 2002a).

For each subbasin, sediment yield is computed with the MUSLE as follows:

$$Y = 11.8(V\,q_p)^{0.56}(K)(C)(PE)(LS)(RF) \qquad \text{Eq. 2.1}$$

where Y is the sediment yield from the subbasin in t time, V is the surface runoff column for the subbasin in m^3, q_p is the peak flow rate for the subbasin in $m^3 s^{-1}$, K is the soil erodibility factor, C is the crop management factor, PE is the erosion control practice factor, and LS is the slope length and steepness factor. RF is the rock factor (fraction that is not rock).

The LS factor is computed with the equation (Wischmeier and Smith, 1978)

$$LS = \left(\frac{\lambda}{22.1}\right)^{\xi}(65.41 * \sin(S)^2 + 4.564 * \sin(S) + 0.065) \qquad \text{Eq. 2.2}$$

The exponent ξ varies with slope and is computed in SWRRB with the equation

$$\xi = 0.6\ [1 - \exp(-35.835\,S)] \qquad \text{Eq. 2.3}$$

The crop management factor, C, is evaluated for all days when runoff occurs using the equation,

$$C = \exp[(\ -0.2231 - CVM)\exp(-0.00115\,CV) + CVM] \qquad \text{Eq. 2.4}$$

Where CM is the soil cover (above ground biomass+residue) in $kg \cdot ha^{-1}$ and CVM is the minimum value of C

2.5.4 Modelling sediment in the reservoirs

SWAT incorporates a simple mass balance model to simulate the transport of sediment into different water bodies including the reservoirs (Neitsch et al. 2002a). When calculating sediment movement through a water body, SWAT assumes that the system is completely mixed. Simply this implies that as sediment enters the water body it is instantaneously distributed throughout the volume.

2.5.4.1 Mass balance

The mass balance equation for sediment in a water body is:

$$sed_{wb} = sed_{wb,i} + sed_{flowin} - sed_{stl} - sed_{flowout} \qquad \text{Eq. 2.5}$$

Where

sed_{wb}: amount of sediment in the water body at the end of the day (metric tons)

$sed_{wb,i}$: amount of sediment in the water body at the beginning of the day (metric tons)

sed_{flowin}: amount of sediment added to the water body with inflow (metric tons)
$sed_{flowout}$: amount of sediment transported out of the water body with outflow (metric tons)
sed_{stl}: amount of sediment removed from the water by settling (metric tons)

2.5.4.2 Settling

The amount of suspended solid settling that occurs in the water body on a given day is calculated as a function of concentration. The initial suspended solid concentration is:

$$conc_{sed,i} = \frac{\left(sed_{wb,i} + sed_{flowin}\right)}{\left(V_{stored} + V_{flowin}\right)} \qquad \text{Eq. 2.6}$$

Where
$conc_{sed,\,i}$: initial concentration of suspended solids in the water (Mg/m^3)
$sed_{wb,\,i}$: amount of sediment in the water body at the beginning of the day (metric tons)
sed_{flowin}: amount of sediment added to the water body with inflow (metric tons)
V_{stored}: volume of water stored in the water body or channel at the beginning of the day (m^3H_2O)
V_{flowin}: volume of water entering the water body on a given day (m^3H_2O)

Settling only occurs when the sediment concentration in the water body exceeds the equilibrium sediment concentration specified by the user, $conc_{sed,\,eq}$.

The concentration of sediment in the water body at the end of the day is then calculated:

$$conc_{sed,f} = \left(conc_{sed,i} - conc_{sed,eq}\right).\exp\left[-k_s.t.d_{50}\right] + conc_{sed,eq}$$

$$\text{if } conc_{sed,i} > conc_{sed,eq} \qquad \text{Eq. 2.7}$$

$$conc_{sed,f} = conc_{sed,i} \text{ if } conc_{sed,i} \le conc_{sed,eq} \qquad \text{Eq. 2.8}$$

Where
$conc_{sed,\,i}$: initial concentration of suspended solids in the water body (Mg/m^3)
$conc_{sed,\,f}$: final sediment concentration in the water body (Mg/m^3)
$conc_{sed,\,eq}$: equilibrium concentration of suspended solids in the water body (Mg/m^3)
k_s: decay constant (1/day)
d_{50}: the median particle size of the inflow sediment (µm)
t: length of time step (1 day).

For ponds, reservoirs, and potholes, the median particle size of the inflow sediment is calculated:

$$d_{50} = \exp\left[0.41 \cdot \frac{m_c}{100} + 2.71 \cdot \frac{m_{silt}}{100} + 5.7 \cdot \frac{m_s}{100}\right] \qquad \text{Eq. 2.9}$$

Where
d_{50}: the median particle size of the inflow sediment (µm)

m_c: percent of clay in the surface soil layer in the subbasin;
m_{silt}: percent of silt in the surface soil layer in the subbasin;
m_s: percent of sand in the surface soil layer in the subbasin.
The amount of sediment settling out of solution on a given day is then calculated as:

$$sed_{stl} = \left(conc_{sed,i} - conc_{sed,f}\right) \cdot V \qquad \text{Eq. 2.10}$$

Where
sed_{stl}: amount of sediment removed from the water by settling (metric tons);
$conc_{sed,\,i}$: initial concentration of suspended solids in the water body (Mg/m^3);
$conc_{sed,\,f}$: final sediment concentration in the water body (Mg/m^3)
V: volume of water in the impoundment (m^3 H_2O)

2.5.5 SWAT application

SWAT predictions of sediment loss were tested in seven watersheds in Texas (Arnold et al. 1995, Srinivasan et al. , 1998, and Santhi et al., 2001), a watershed in Indiana (Arnold and Srinivasan, 1998; and Engel et. al., 1993), New York (Bennaman and Shoemaker, 2005), Maryland (Chu et al., 2004), and India (Tripathi et al., 2004). Studies varied in watershed sizes, interval and duration of measured sediment loss, validation criteria and many more. All studies concluded that SWAT sediment predictions showed general agreement with measured values

The worldwide application of SWAT reveals that it is a versatile tool that can be used to integrate multiple environmental processes, which support more effective watershed management and the development of better-informed policy decisions.

2.5.6 Comparisons of SWAT with Other Models

According to Gassman (2007), Borah and Bera (2003; 2004) provide extensive comparisons of SWAT with several watershed scale hydrologic and non-point-source pollution models. In the 2003 paper, they report that DWSM, HSPF, SWAT, and other models have hydrology, sediment, and chemical components applicable to watershed scale catchments, and concluded that SWAT is a promising model for continuous simulations in predominantly agricultural watersheds.

In the 2004 paper, they compiled 17 SWAT, 12 HSPF, and 18 DWSM applications. They concluded that SWAT and HSPF were suitable for predicting yearly flow volumes, sediment and nutrient loads, generally good for monthly predictions except for months having extreme storm events and hydrologic conditions, and poor in simulating daily extreme flow events. In contrast, DWSM reasonably predicted distributed flow hydrographs and concentration or discharge graphs of sediment, nutrient, and pesticides at small time intervals.

Three peer-reviewed papers evaluated the performance of SWAT using observed data from the same watershed. Van Liew et al. (2003) compared the stream flow predictions of SWAT and HSPF on eight nested agricultural watershed within the Washita River Basin in south-western Oklahoma. They found that differences in model performance were mainly attributed to the runoff production mechanisms of the two models. Furthermore, they concluded that SWAT gave more consistent results than HSPF in estimating stream flow for agricultural watersheds under various climatic conditions and may therefore be better suited for investigating the long term impacts of climate variability on surface-water resources.

Saleh and Du (2004) calibrated SWAT and HSPF with daily flow, sediment, and nutrients measured at five stream sites of the Upper North Bosque River watershed located in Central Texas. They concluded that the average daily flow, sediment and nutrient loading simulated by SWAT were closer to measured values than HSPF during both the calibration and verification periods.

El-Nasr et al. (2005) found that both SWAT and MIKE-SHE simulated the hydrology of Belgium's Jeker river basin in an acceptable way. However, MIKE SHE predicted slightly better the overall variation of its river flow.

2.5.7 Calibration Technique Studies

SWAT input parameters are physically based and are allowed to vary within a realistic uncertainty range for calibration. Calibration techniques are generally referred to as either manual or automated. With manual calibration, the user compares measured and simulated values and better judgment is used to determine which variables to adjust, how much to adjust them, and when the results are reasonable.

Santhi et al. (2001) calibrated and validated SWAT for stream flow, sediment, nitrogen and phosphorus loss simulations for the Bosque River in Texas (Gassman et al. 2007). These authors present a general procedure for manual calibration suggesting sensitive input parameters, realistic uncertainty ranges and reasonable regression results (i.e., satisfactory R^2 and Nash-Sutcliffe Coefficient of Efficiency values).

Automated methods link SWAT with an optimization scheme to automate the calibration procedure. Van Griensven and Bauwens (2003) used the shuffled complex evolution optimization scheme, PARASOL, to automate SWAT calibration. The user inputs calibration parameters and ranges along with measured daily flow and pollutant data. The automated calibration scheme controls up to several thousand model runs to find the optimum input data set.

2.6 Processes of deposition in reservoirs

2.6.1 Movement of sediment in reservoirs

Sediment movement mainly depends on water flow. In a reservoir, there are two main patterns of flow motion, namely backwater flow and quasi-uniform flow. Under the conditions of backwater flow, the water depth increases longitudinally, and the flow velocity decreases accordingly. Sediment transport may have two patterns.

The first pattern is sediment transport under open channel flow, where sediment particles diffuse to the whole section. As the flow velocity decreases longitudinally, deposition takes place; this is called backwater deposition.

The second pattern is sediment transport by density current, which is formed by a heavy sediment load with fine particles, which dives into the bottom of the reservoir and moves along the channel bed towards the dam. The sediment transport under quasi-uniform flow is similar to that of natural rivers. When the incoming sediment load is different from the sediment transport capacity of the flow, longitudinal deposition or erosion will occur.

In summary, the sediment transport patterns in reservoirs may be classified as follows:

(1) Sediment transport under quasi-uniform open channel flow;
(2) Sediment transport under backwater flow:
    (i) Sediment transport under open channel flow;
    (ii) Sediment transport by density current.

2.6.2 Empirical estimation of long-term deposition in reservoirs

2.6.2.1 Method of trap efficiency

The trap efficiency of the reservoir is defined as the ratio of the sediment deposited in a reservoir to the total incoming sediment. Trap efficiency, β, is related to various parameters, such as the ratio of reservoir storage capacity, *V*, to the average annual runoff, *W*; the ratio of retention period to the average flow velocity in the reservoir; and the specific storage of the reservoir, i.e. the ratio of the reservoir storage to the river basin area above the reservoir. The most commonly used method was developed by Brune (Xiaoqing 2003). Based on large reservoirs in the United States, Brune determined the relationship between β and *V/W*.

The average value of β may be determined by the following expression:

$$\beta = \frac{V/W}{0.012 + 0.0102\, V/W} \qquad \text{Eq. 2.11}$$

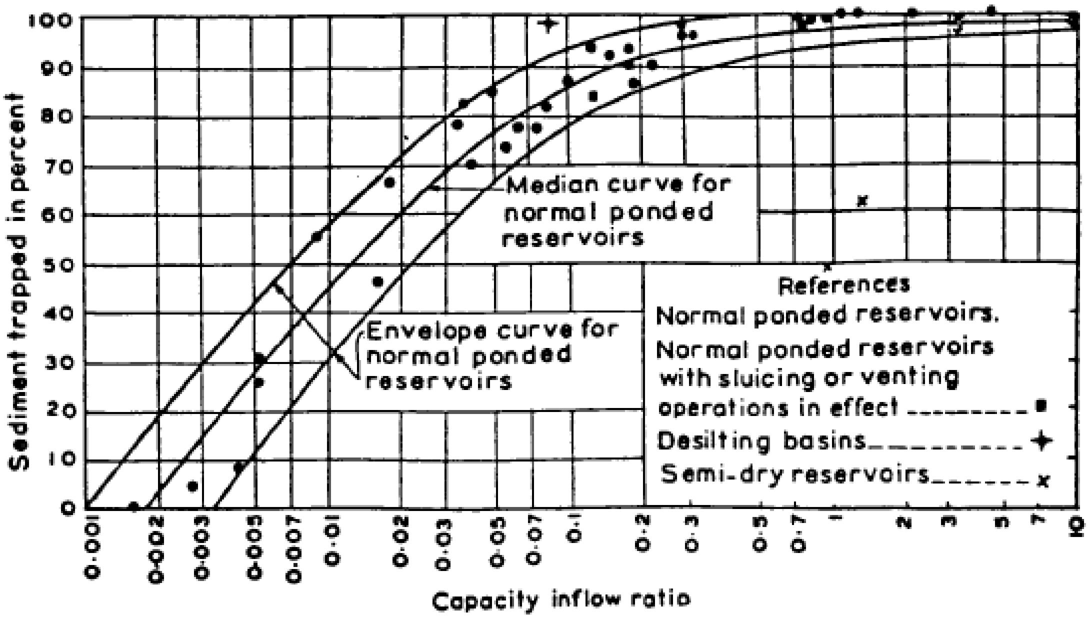


Figure 2.2 Trap Efficiency Curve by Brune

2.6.2.2 The method of rate of storage capacity loss

Where flow and sediment data are insufficient at the planning stage of some small and medium-sized reservoirs, an empirical expression for determining the value of α is obtained based on 25 reservoirs mainly in North and Northwest China(Xiaoqing 2003).

The rate of storage capacity loss may be expressed as:

$$\alpha = 0.0002G^{0.95}\left(\frac{V}{F}\right)^{-0.8} \qquad \text{Eq. 2.12}$$

Where G is the annual rate of erosion in the basin above a reservoir in t km^{-2},
F is the drainage area above the reservoir in m2,
V is the reservoir storage capacity in m3, and
α is the rate of storage capacity loss in %.

Moreover, the life span of the reservoir can be estimated based on Orlt (1930) expression:

$$V_t = V_0\left(1-\frac{W_s}{V_0}\right)^t \qquad \text{Eq. 2.13}$$

Where *Vt* is the storage capacity at t years of the reservoir's operation in m3,
Vo is the initial storage capacity in m3, and
Ws is the annual sediment load in m3.

2.6.3 Numerical modelling of reservoir sedimentation

Based on the laws governing water flow and sediment transport, numerical models of reservoir sedimentation can be established and used to predict the future situation of reservoir sedimentation. The processes for establishing the numerical model include three steps of approximate schematization and four steps of feedback. The first step of approximate schematization is to describe the engineering problem by physical processes; the second step is to describe the physical processes by mathematical equations, and the third one is to obtain the numerical solution of the mathematical equations. Each feedback step is the process of verifying each step of approximate schematization.

Sediment transport and its induced channel deformation are the result of water flow motion. Simultaneously, the deformed channel morphology has its effect on flow motion. Therefore, a sediment numerical model includes two sub models of flow motion and sediment transport. These two sub models should be solved simultaneously, and their solutions are called coupled solutions. When channel deformation is not so intensive, to simplify the computation process, the two sub models can be solved step by step, the first being that of flow motion and the second being that of sediment transport. Such a solution is called an uncoupled solution and is common practice nowadays.

The development of numerical models is seeing a move from one-dimensional to three-dimensional models. The natural situation is always a three-dimensional one. At present, three-dimensional numerical sediment models are still only on the horizon, as the commonly used numerical models are either one or two-dimensional. The selection of a suitable numerical model depends on the characteristics of the problem. If a one-dimensional model can simulate the problem, it is unnecessary to use a two-dimensional model, since the computer time of the latter is much longer than the former. In some special cases, a combined model may be used. In some river reaches a one-dimensional model is used, and in the remaining river reaches a two-dimensional model is used to meet engineering requirements.

At present, no analytical solution can be obtained for any sediment numerical model. Numerical approaches must be used to find the solution. There are a number of numerical approaches, including the finite difference approach, which is the most common.

The numerical models must be calibrated and verified by separate sets of field data. The accuracy of the result of verification must meet engineering requirements.

3 Study area

3.1 Location

The planned Rusumo Falls hydroelectric power project is located on the Kagera River in south-east of Rwanda in the eastern province at about 144 km from the City of Kigali, the capital city of Rwanda (Figure 3.1). The dam will be implemented at about 2km downstream of the Kagera-Ruvubu confluence in a gorgeous landscape of Kagera River along with waterfalls at about 1,300 m a.s.l.

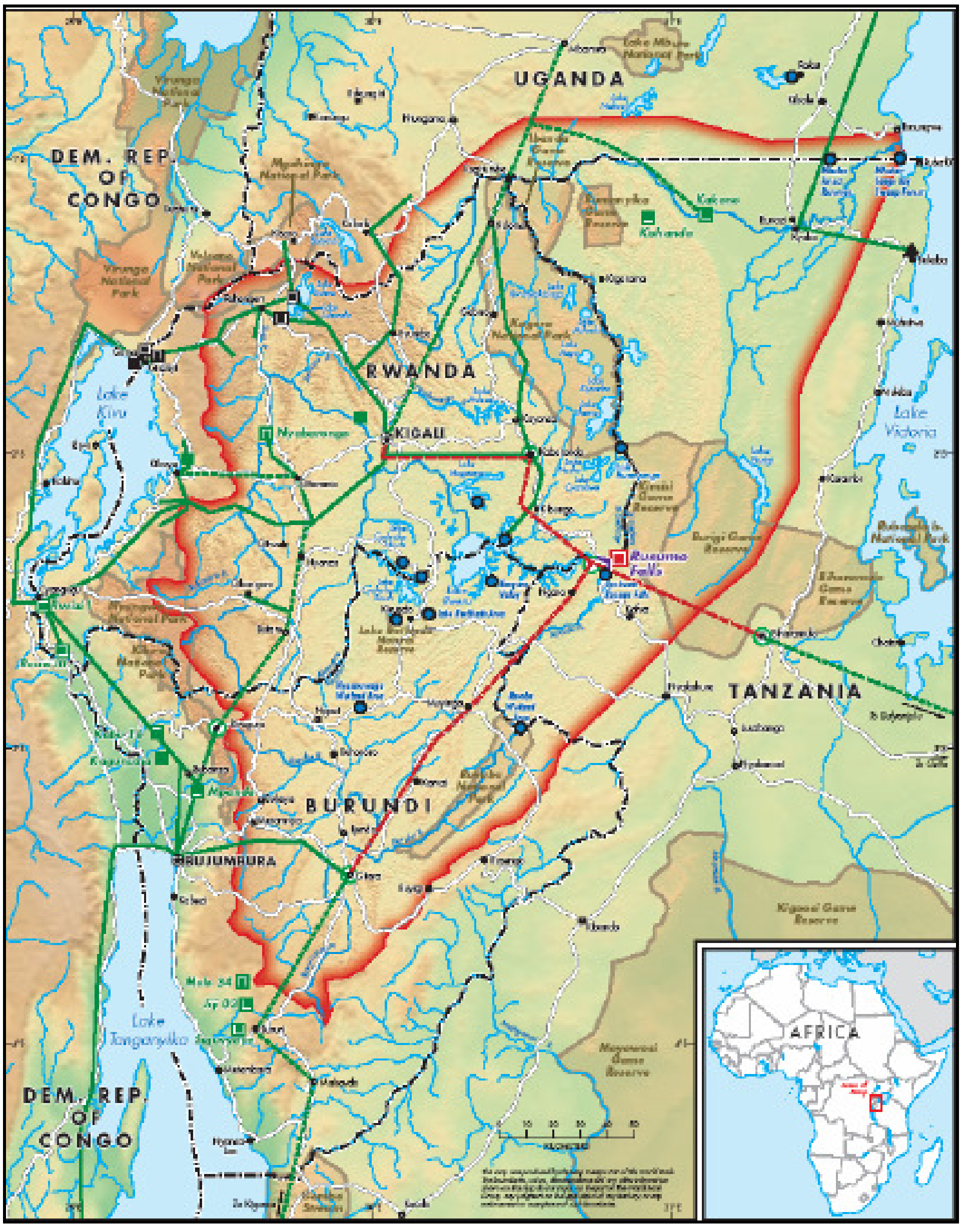


Figure 3.1 Rusumo Falls hydroelectric power project area, source (ADB 2006)

The Kagera River has its main sources in the north-eastern side of Congo Nile divide in Burundi (Ruvubu) and in the south-western highlands of Rwanda (Nyabarongo). It drains its water in the Lake Victoria from which the White Nile starts. The main

tributaries of the Kagera River up to Rusumo are Ruvubu River gathering the waters from Burundi and Nyabarongo River flowing from Rwanda. At the dam location, Kagera River has a watershed area of about 30,780km^2.
The relief is made up of plateaus with shaped valleys and rounded hills that are covered by scattered savannah woodlands and grassland, recalling the vegetation of the semi-arid East African plateaus. The dominant hills rise up to 1,350m a.s.l. and the medium altitude in Rusumo district is 1,500m with a dominant top hill at 1,750m (Gatwe Mountain).

3.2 The Ruvubu River

The Ruvubu River rises in the southern part of the Congo-Nile divide in the tropical rain forest of Burundi in the province of Kayanza. Its head lies in the Kibira National Park at about 2,000m a.s.l. and traverses about 350 km to its confluence with the Kagera River on the border between Rwanda and Tanzania (Nzeyimana 2003). It is estimated that the Ruvubu River drains an area of 12,300km^2 in central and northern Burundi. It flows on slopes of about 0.15% upstream and less than 0.02% downstream at its confluence with the Kagera.
The main tributary of Ruvubu River is the Ruvyironza which runs from south Burundi at Rutovu in Bururi province, meanders through the central plateaus and collects other waters mainly from the Mushwabure, Waga, Mubarazi Rivers to name but few.

3.3 The Nyabarongo River

The Nyabarongo River flows over 300 km from its source in south-western Rwanda to its outlet into Lake Rweru in south-eastern Rwanda. It takes its source from Mwogo and Mbirurume, and runs northwards. After collecting waters of Mukungwa River from the elevated volcanic zone, it switches to southwards direction where it collects water from Nyabugogo River before it meets Akanyaru. Akanyaru River is the main tributary of Nyabarongo that flows from the highlands of Nyungwe National Park on the Congo-Nile divide to then form the border between Rwanda and Burundi until the junction with Nyabarongo at about 50 km south of Kigali. From that confluence, the Nyabarongo River flows eastwards through swampy valleys and small lakes in the lowlands of Bugesera in south-eastern Rwanda. From the Lake Rweru outlet, the Nyabarongo River changes the name to Akagera and meanders through a swampy terrain for about 60 km before it meets the Ruvubu River flowing through the Tanzanian plateaus.

3.4 Climate and hydrological data

The local climatic data observed at Rusumo station reflects the general climatic trend of East-Africa specifically the region of north-western Tanzania, south-eastern Rwanda and north-eastern Burundi characterized by low precipitation volumes per annum and rain deficits (WFP, 2001).
The mean daily temperature is close to 24^{o}C. Most of the country has minimum night temperatures of around 10^{o}C and maximum daytime temperatures of around 34^{o}C. Regarding the precipitations, the average monthly rainfall on the central plateau is 85mm(Nzeyimana 2003). Four seasons are recorded throughout a year: (1) a short dry season in December-January, (2) a major rainy season from February through May, (3)

a major dry period from June to September and (4) a short rain season from late October to early December (Atlas of Rwanda, 1981).
According to the climatic data for the region, the maximum precipitations are recorded in April-may. So, as the Kagera waters inflow comes mainly from the Ruvubu and the Nyabarongo sub-catchments whose heads lie in the Nile-Congo Divide that receives an annual average rainfall of 1,800 mm because of high altitude and vegetation covered with tropical forests.

3.5 The Rusumo Falls hydroelectric power project

The Rusumo falls hydroelectric power project comprises a conventional gravity dam in the main river channel with a full supply level of 1325 m, approximately 5m above normal river levels. The dam would be 12m high, and include spillway gates(NELSAP 2005). Power facilities would include intake above the dam, a 460m power tunnel and a three unit powerhouse with an installed capacity of 61.5 MW under a head of 35 m.

The reservoir upstream the dam will be extended on the Ruvubu and Nyabarongo rivers, and would marginally affect levels on Lake Rweru situated 70km far away upstream the dam. Upstream flooding from the dam is estimated as in the order of 400 km^2, which include 125km^2 of existing lake and 250km^2 of existing wetlands and 15 km^2 of valley slopes. According to NBI-NELSAP synopsis report(NELSAP 2005), sediment loads are not supposed to be an issue.

4 Data collection and analysis

4.1 SWAT data

The modelling using SWAT imposes two types of data: data for the SWAT database and data for the hydrological model.
The database includes land use, soil types, and weather data. However, since the SWAT only possesses the USA data, the later had to be updated to cover the study area. This was achieved by replacing the following files located in the AVSWATX/AvSwatDB directory:

- Crop.at
- Crop.dbf
- Usersoil.dbf
- Userwgn.dbf

The hydrological data used in the present study include rainfall, temperature, flow rates, and sediment concentration data.

The rainfall data used were recorded form ten gauging stations. They were recorded on the daily basis and cover the period of 1971 – 1985. With regard to missing data at certain stations, they have been estimated with inverse distance weighting (IDW) and nearest neighbours' method (Haguma 2007), and stations with many missing data were ignored. However, there was a risk in acting this way of attributing the false precipitation values to the true observed flow rates.

With regard to temperature data, SWAT uses minimum and maximum. However, the ground data recorded are only averages of the two values. Consequently, remote sensing data from CRU/DWGA covering the entire Nile basin were used.

On the other hand, stream flow records from three stations were used in the sensitivity and calibration processes. Those are Nyabarongo-Kigali, Nyabarongo-Kanzenze, and Kagera-Rusumo. Unfortunately, data for the Akanyaru and Ruvubu rivers were not available. In most cases, the stream flows were recorded on daily basis covering the period of 1971 – 1990.

The flow data at Kanzenze were plotted together with precipitation data from the three stations located in the corresponding catchment (Figure 4.1, 4.2, and 4.3). The aim of this operation was to check whether the observed rainfall were really able to produce the recorded stream flow rates.

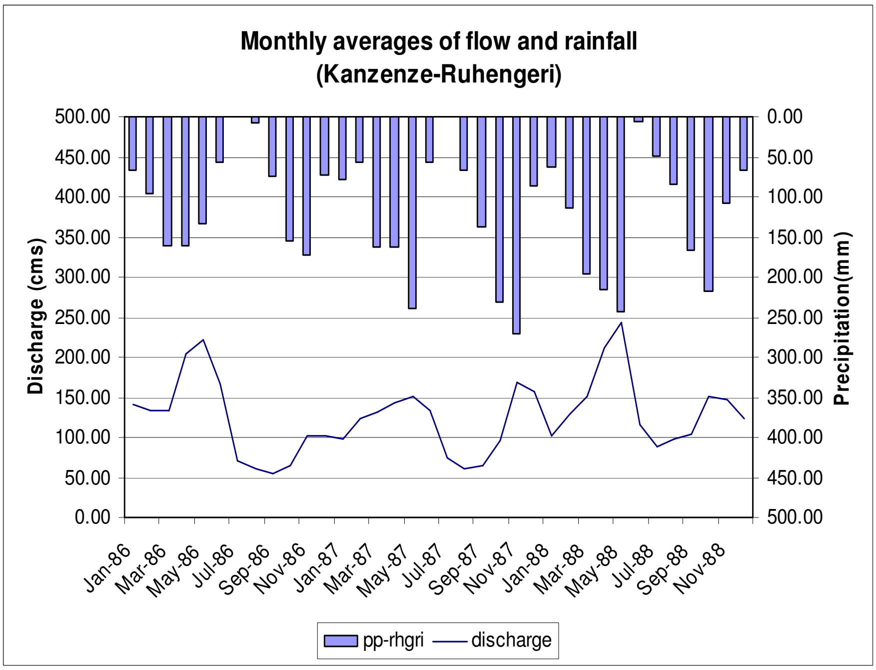


Figure 4.1 Precipitation of Ruhengeri station and discharge at Kanzenze station

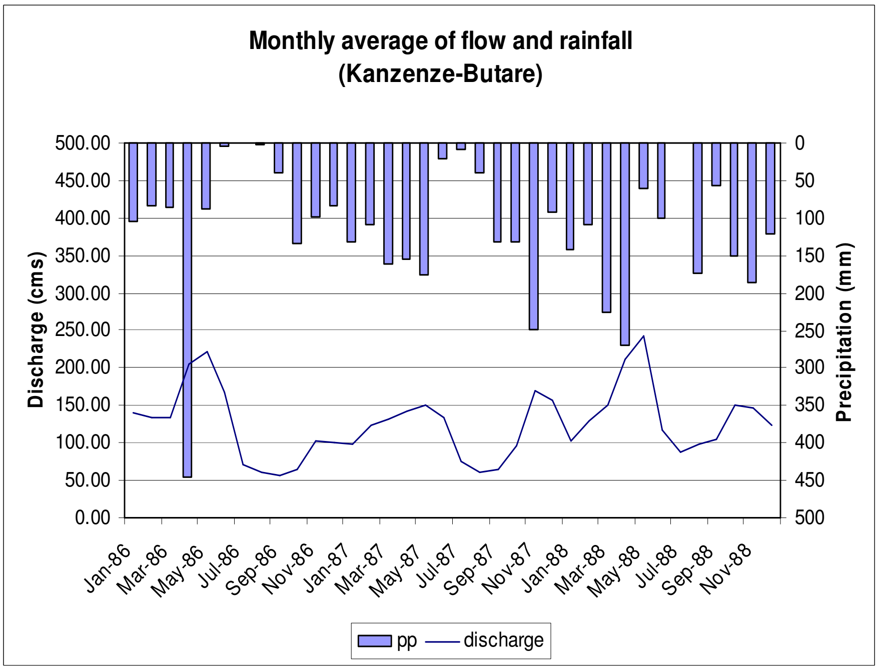


Figure 4.2 Precipitation of Butare station and discharge at Kanzenze station

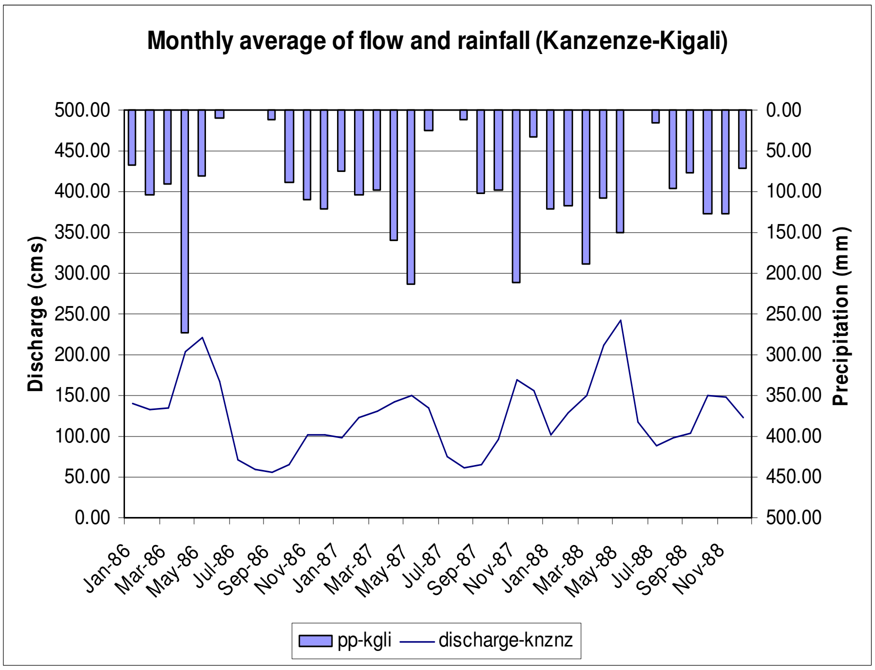


Figure 4.3 Precipitation of Kigali station and discharge at Kanzenze station

In all the three cases, the flow picks correspond to high intensity rainfall.

The same checking procedure was applied to the flow rates but this time with the sediment concentrations though the data were not enough to draw any conclusions (Figure 4.4, 4.5, and 4.6). Each time, the correlation coefficient was computed between the two variables as shown in Table 4.1, 4.2, and 4.3. The correlation coefficient was determined in order to indicate the strength and direction of a linear relationship between two variables.

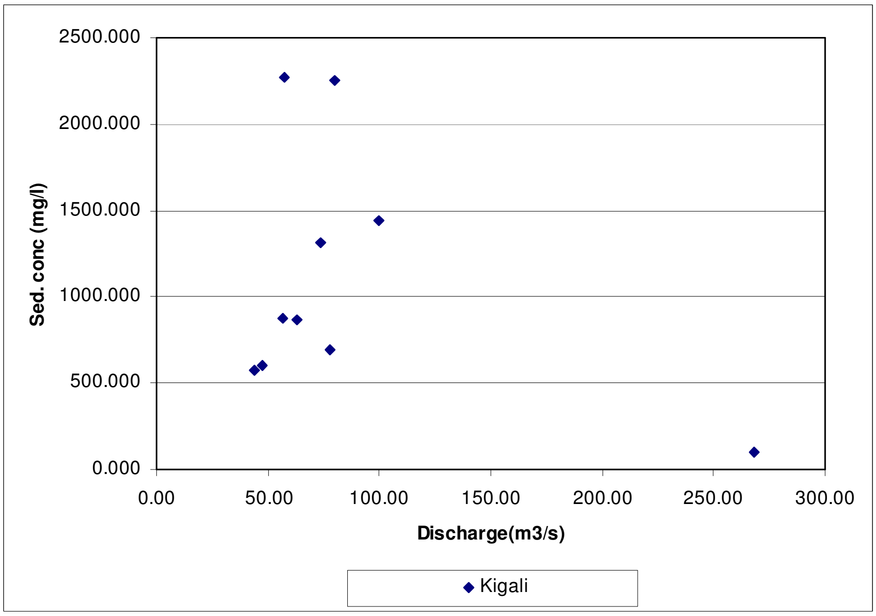


Figure 4.4 scatter plot of discharge and sediment concentration at Kigali station

Table 4.1 Correlation between discharge and sediment concentration at Kigali station

	Discharge m3/s	Sed.Conc (mg/l)
Discharge m3/s	1	
Sed.Conc (mg/l)	-0.385144794	1

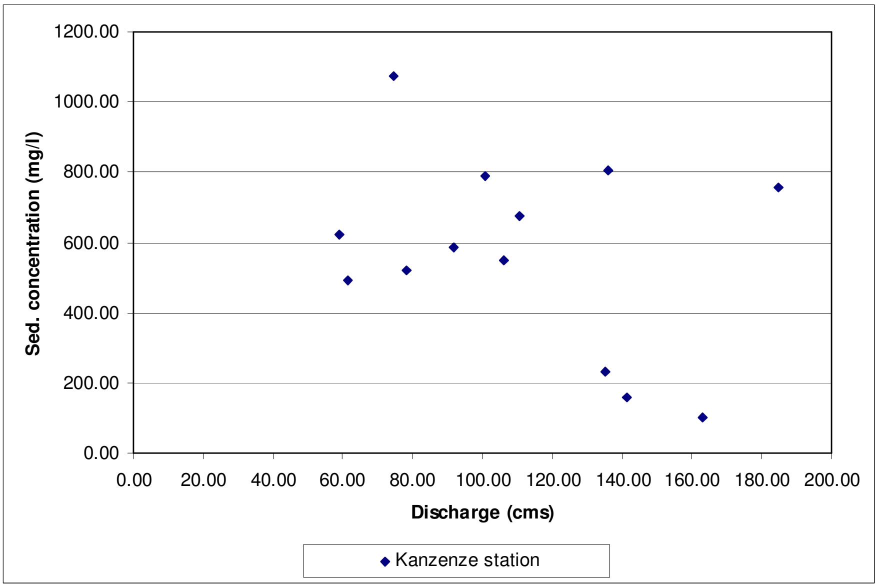


Figure 4.5 Scatter plot of discharge and sediment concentration at Kanzenze station

Table 4.2 Correlation between discharge and sediment concentration at Kanzenze station

	Discharge (m3/s)	Sed. Conc (mg/l)
Discharge (m3/s)	1	
Sed. Conc (mg/l)	-0.337833753	1

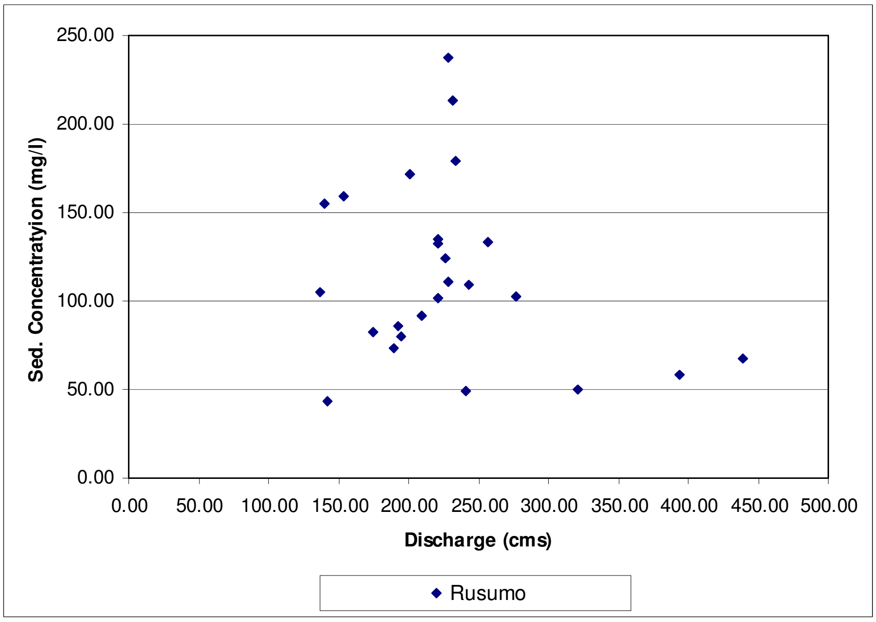


Figure 4.6 Scatter plot of discharge and sediment concentration at Rusumo station

Table 4.3 Correlation between discharge and sediment concentration at Kanzenze station

	Discharge m3/s	Sed.Conc (mg/l)
Discharge m3/s	1	
Sed.Conc (mg/l)	-0.245270311	1

In all the three cases the correlation between the two variables was small according to Cohen interpretation (Cohen 1988). As consequence to that, it was not possible to establish neither a linear relationship nor a rating curve between the two variables.

4.2 Sediment concentration data

These are the scarce data in the basin. On Rwandan side, few observations were made between 1975 and 1978 at three stations: Nyabarongo-Kigali, Nyabarongo-Kanzenze, and Kagera-Rusumo. They were collected on daily basis, but few points are remaining. The Kigali station has 10 observations, Kanzenze 13 observations, and Rusumo 25 observations. In each year, two to nine daily observations were recorded.

The sediment concentrations were recorded in term of sediment transport rate. Later on, they were converted into the sediment concentration by dividing them with the corresponding flow rates.

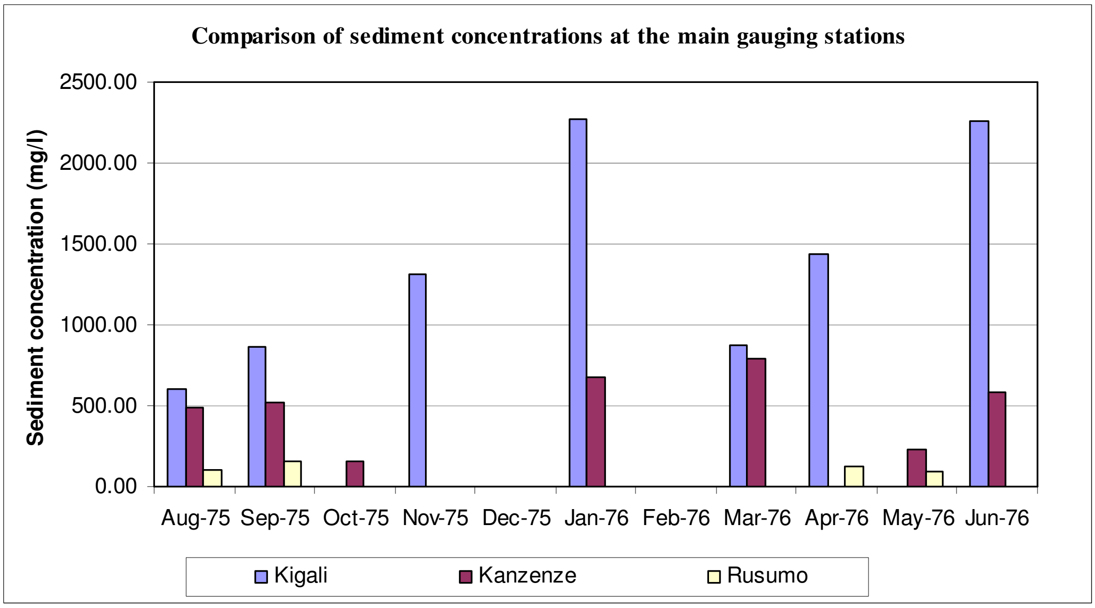


Figure 4.7 Comparison of sediment concentrations at the main gauging stations

Table 4.4 Summary of statistics of sediment concentration data (mg/l)

Kigali		*Kanzenze*		*Rusumo*	
Mean	1100.24	Mean	566.32	Mean	114.12
Standard Error	227.68	Standard Error	76.88	Standard Error	10.17
Median	871.46	Median	585.63	Median	104.78
Standard Deviation	719.98	Standard Deviation	277.18	Standard Deviation	50.86
Kurtosis	-0.39	Kurtosis	-0.15	Kurtosis	0.19
Skewness	0.69	Skewness	-0.20	Skewness	0.75
Range	2172.08	Range	973.61	Range	194.86
Minimum	100.48	Minimum	100.97	Minimum	43.05
Maximum	2272.56	Maximum	1074.58	Maximum	237.91
Count	10	Count	13	Count	25

Though the station at Kanzenze is located after the confluence of two important rivers, Nyabarongo and Akanyaru, it shows lower values in terms of concentration. In the absence of both discharge and sediment data on Akanyaru, it may not be easy to support any reason that could be given. However, two reasons might be advanced. One is the fact that the Kanzenze station is located in the wetlands area. The flow might arrive at the station when some particles have already settled and scattered with the flow in the wetlands. However this can only be proved if a decrease in the flow rate and slope after the confluence of Nyabarongo and Akanyaru could have been observed. The second one might be the dilution of the Nyabarongo flow by the Akanyaru flow, assuming that the later has a considerable low concentration in sediment. Again this reason could not be supported due to the lack of both sediment and flow data of Akanyaru river. Beside all these, a permanent error also in the rating curve at any of these stations may be the source of the trend.

4.3 Sediment sampling

During the data collection stage of this study, four samples were taken from Nyabarongo River at Kigali station with the aim of supporting the existing ones and hence producing the rating curve between flow and sediment concentration.

4.3.1 Sampling techniques

The sediment-sampling method and frequency of collection are dictated by the hydrologic and sediment characteristics of the stream, the required accuracy of the data, and the proposed use of those data collected. To acquire a representative sample, one must first obtain a sample that adequately defines the concentration of particles over the full depth of the sampled vertical. Secondly, a sufficient number of verticals must be sampled to adequately define the horizontal variation in the cross section. The type of sampler used to collect the sample, the method of depth integration, the site at which the samples are collected, and the number of verticals needed to define the stream's concentration depend on the flow conditions at the time of sample collection, characteristics of the sediment being transported, the accuracy required of the data, and the objectives of the program for which the samples are being collected.

As far as site selection is concerned, a stream-data site is best defined as a cross section displaying relatively stable hydrologic characteristics and uniform depths over a wide range of stream discharges, from which representative water quality and sediment data can be obtained and related to a stage-discharger rating for the site.

With regard to the methods used, ideally the best procedure for sampling any stream to determine the sediment discharge would be to collect the entire flow of the stream over a given time period, remove the water, and weigh the sediment. Obviously, this method is a physically impossible. Instead, the sediment concentration of the flow is determined by (1) collecting depth-integrated suspended-sediment samples that define the mean discharge-weighted concentration in the sample vertical and (2) collecting sufficient verticals to define the mean discharge weighted concentration in the cross section.

In the context of the present study, the four samples collected were not taken in the above described way due to the lack of appropriate sediment sampling equipment. In all cases all the samples were collected on a single vertical and only one sample was taken from that vertical.

4.3.2 Results obtained

Table 4.5 Particle size distribution

Particle size(mm)	% Retained (Sple 1)	% Retained (Sple 2)	% Retained (Sple 3)	% Retained (Sple 4)
0.063	0	0	0	0
0.042	19.9	52	51.9	67.5
0.028	15.4	0	0	0
0.022	16.6	0	0	0
0.015	0	0	0	0
0.0098	0	16	0	0
0.0078	0	0	0	0
0.0056	0	0	0	0
0.0028	0	0	0	0
0.0022	16	0	0	0
0.0018	0	0	0	0
0.0012	0	0	0	0
0.00098	0	0	0	0
0.00076	0	0	0	16.2
0.0001	32.1	32	48.1	16.3

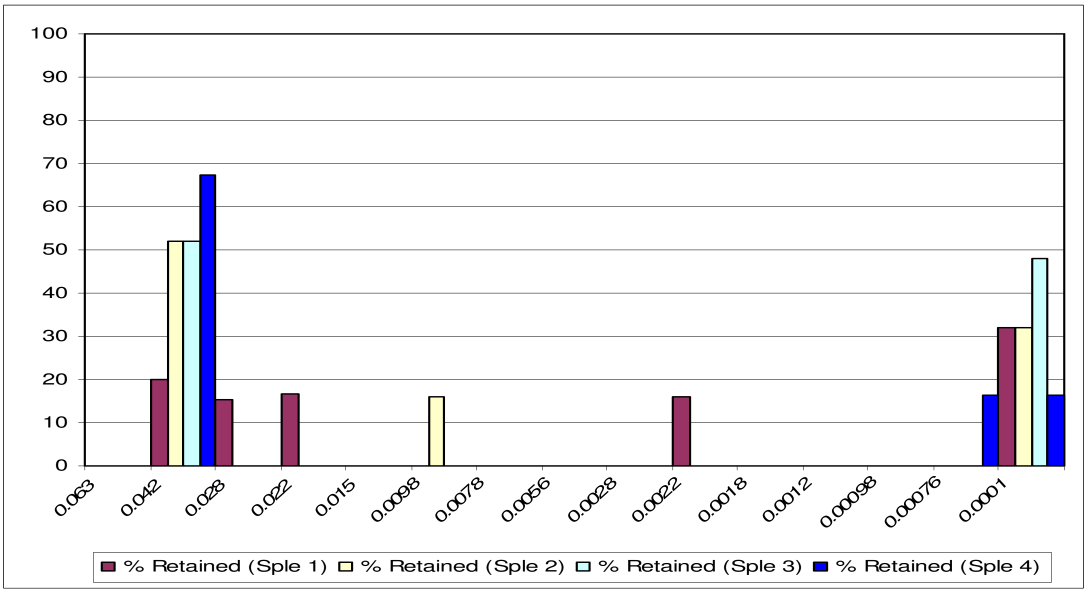


Figure 4.8 Particle size distribution

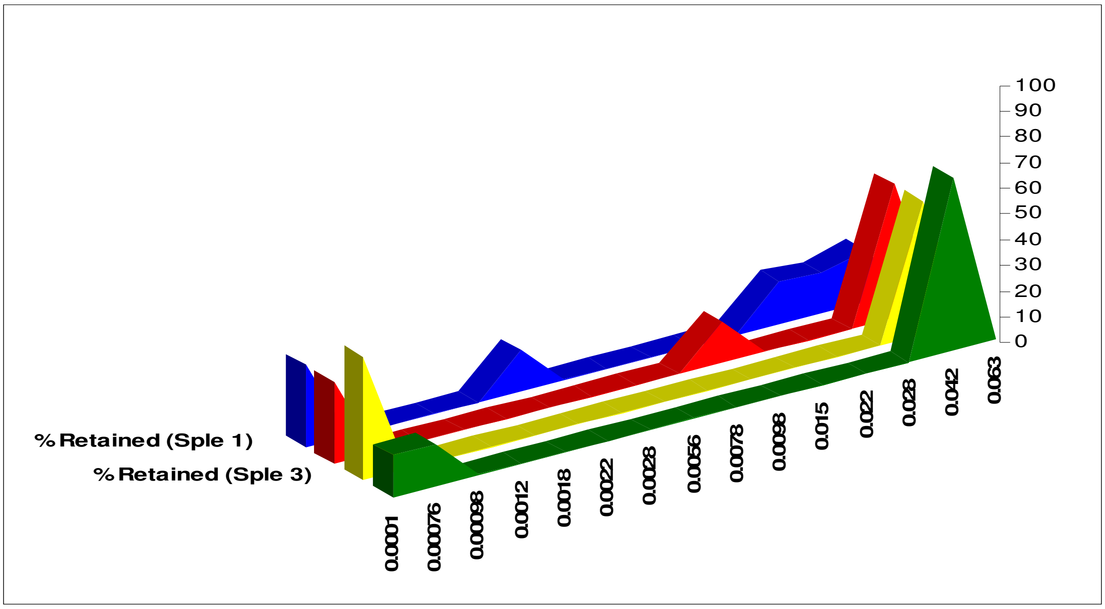


Figure 4.9 Particle size distribution

4.3.3 Observation and discussion

Vertical distributions of suspended-sediment particle sizes vary among streams and among cross sections within a stream(Edwards and Glysson 1970). However, as a general rule, the finer particles are uniformly distributed throughout the vertical, and the coarser particles are concentrated near the stream bed.

Generally, the particles in the samples taken were concentrated in two most dominant classes of silt and clay (table 4.6). The first class is made of particles passing 0.063 and retained on the sieve 0.042mm. The second class includes very fine particles passing sieve 0.00076 and retained on 0.0001mm.

Table 4.6: Distribution of sediment fractions in the samples

Sample Name	Fractions in %		
	Sand	Silt	Clay
1	0	51.9	48.1
2	0	68	32
3	0	51.9	48.1
4	0	67.5	32.25
Rusumo	0	25.4	74.6

Sample 3 and 4 were taken when the flow has started falling as the rainy season was ending. In this case the big particles were expected to be settling leaving small particles in suspension.

The samples taken do not cover all classes of the sediment. This may be attributed to the fact that they might have been taken from a point where the mixture was poor. The instruments used also were not appropriate and this had influenced a lot the sampling process. Finally, the method used could not allow taking different point on different verticals.

Though all the samples do not present accurate results, but they provided concentration values close to the observed ones.

5 Rusumo hydrological model

5.1 Introduction

This section of the report discusses the work done and the main results obtained. The Rusumo hydrological model was built using the Soil and Water Assessment Tool (SWAT). First and foremost a hydrological model was built for the Nyabarongo river basin up to Kanzenze station situated far upstream the dam location (Figure 5.1). After that, the model was extended to cover the entire catchment. In all these cases, the procedure outline included the model set up, calibration, and validation of flow using Kanzenze and Rusumo time series of discharge and sediment.

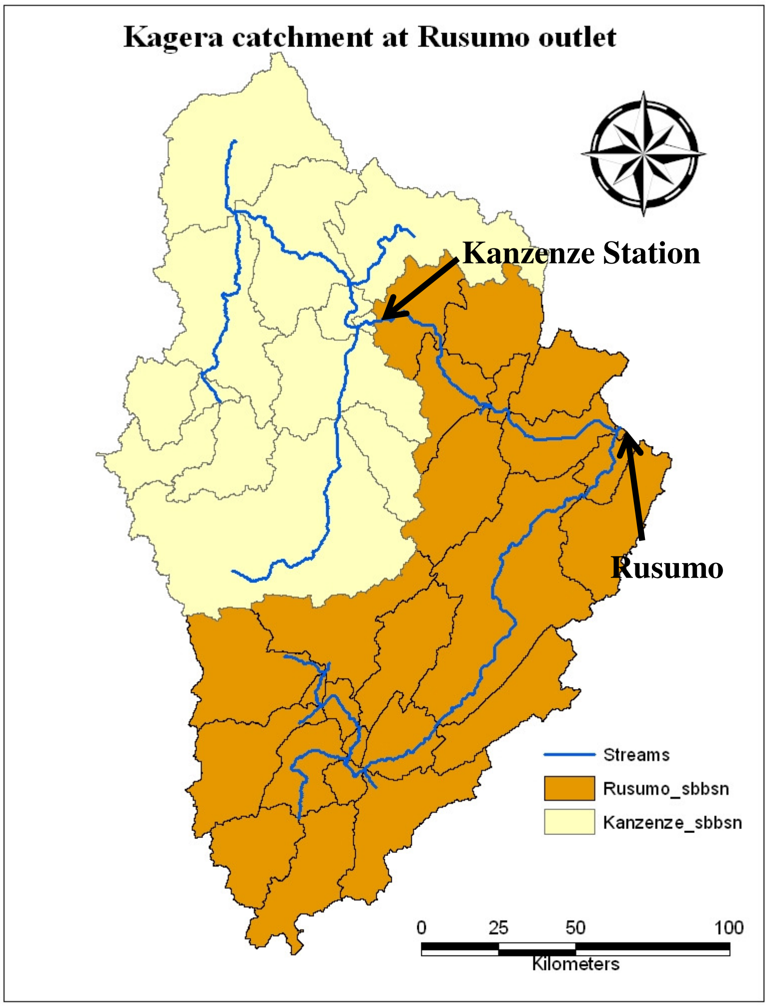


Figure 5.1Location of Kanzenze and Rusumo gauging stations

The results obtained from SWAT model were then fed into empirical methods in order to estimate the long-term sediment deposition in the reservoir. The main results obtained were summarised in the form of maps, charts, and/or tables.

Finally, three scenarios were run to identify certain factors influencing sediment modelling in the Kagera sub-catchment under study.

5.2 Subdivision of the catchment

Based on the particulars of the planned dam such as the height of the dam, the Digital Elevation Model (DEM) was used to identify the area that would be flooded. This was achieved by using the Spatial Analyst tool extension incorporated within the ArcView tool. With the above mentioned tool, the area below the elevation of 1330m a.s.l. was identified (Figure 5.2) as well as the area below 1325m a.s.l. (Figure 5.3). From both tasks, it was observed that the reservoir area would extent upstream in two directions corresponding to the two important rivers: Nyabarongo and Ruvubu. On Ruvubu side, the reservoir would reach about 35km, and some 87km on Nyabarongo side. The most important aspect noticed was that Lake Rweru situated some 62km upstream the dam site was part of the reservoir and hence its level would be affected. However, when the water level was raised only at 1325m, the lake was not that much affected (Figure 5.4).

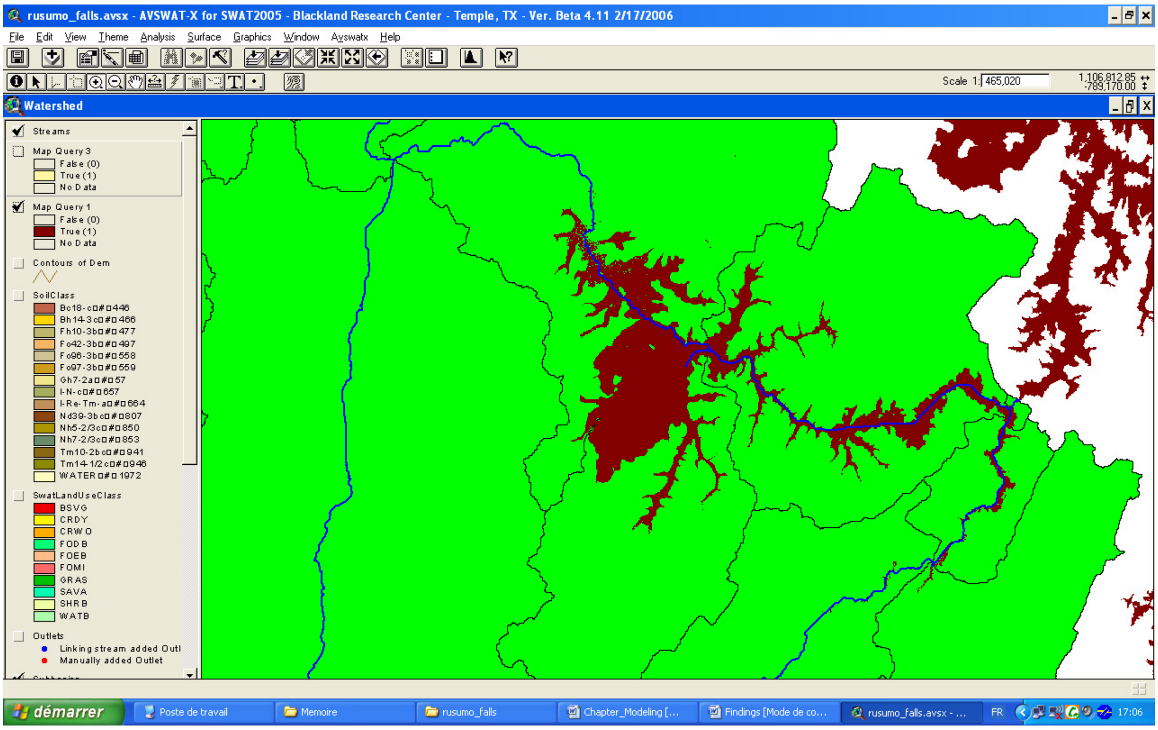


Figure 5.2 Flooded area below 1330m a.s.l

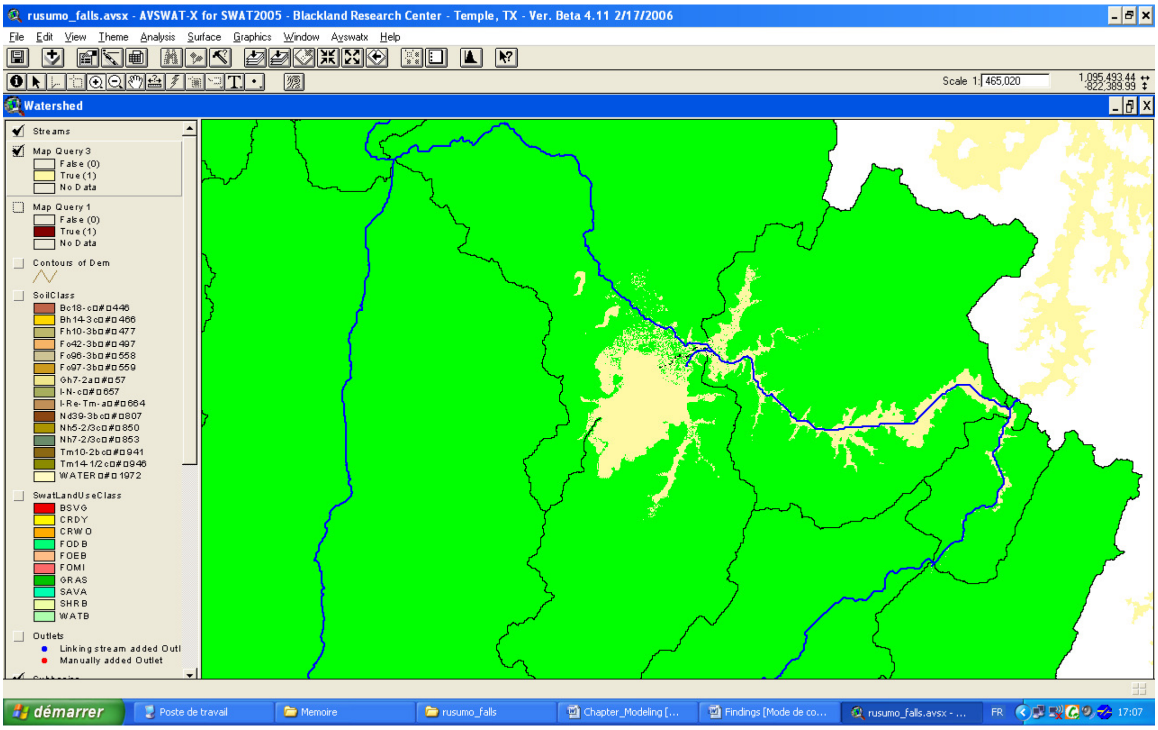


Figure 5.3 Flooded area below 1325m a.s.l

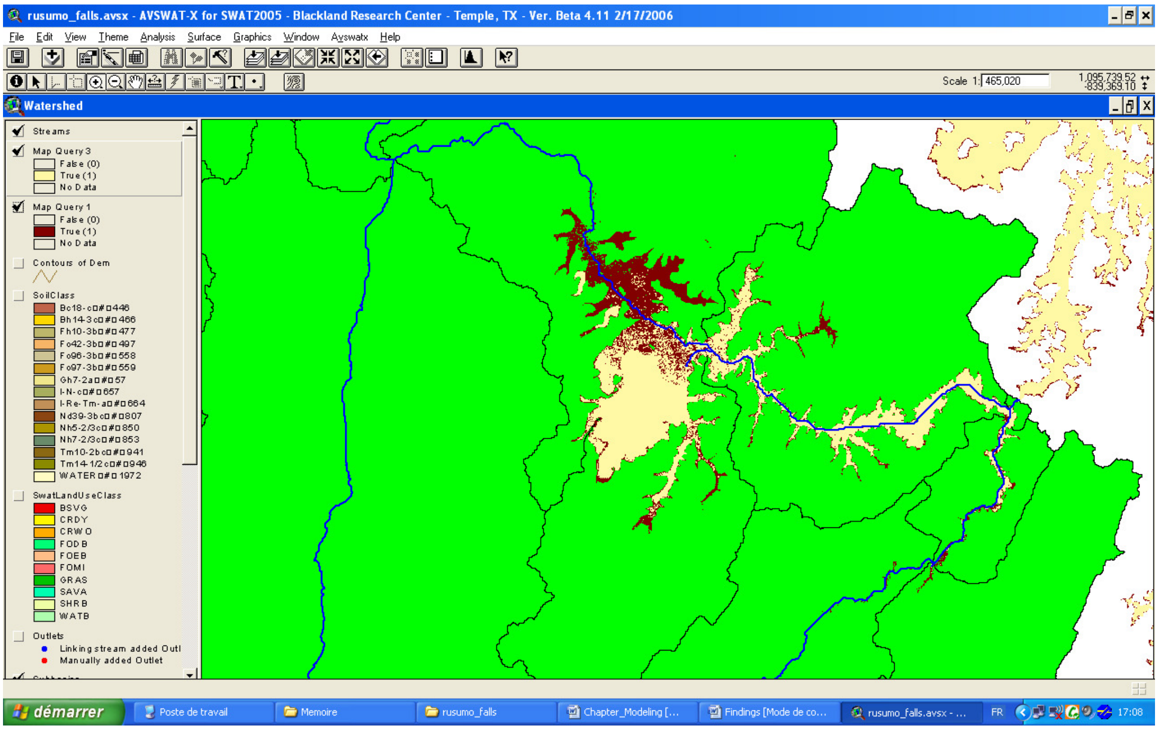


Figure 5.4 Comparison of the two flooded areas: below 1325m and 1330m

Back to the concern of this work, the presence of Lake Rweru as another reservoir complicated a bit the modelling of sediment deposition in a sense that the sediments from Nyabarongo and Ruvubu would not settle at the same location as expected from the beginning. The reservoir upstream, Lake Rweru, was hence expected to trap the sediments from Nyabarongo River, while those from Ruvubu would be held by the dam itself (Figure 5.5).

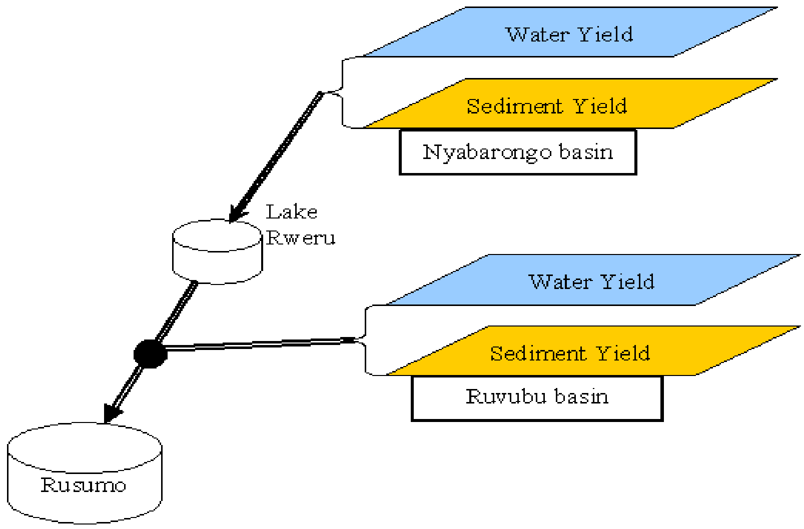


Figure 5.5 Sediment yield conceptual model for Kagera river basin

From the beginning of the study, the objective was to build the sediment transport model and calibrate it using Rusumo gauging station data. The obtained results would indeed include sediments yielded by Nyabarongo as well as Ruvubu, which would be used to estimate the deposition in the reservoir. The new anticipated situation imposed then the division of the deposition estimation task into two: estimating the sediment deposition in Lake Rweru and nearby wetlands on one side, and estimation of sediment in the dam reservoir mainly from Ruvubu River.

5.3 Kanzenze section

In order to build the model at this location the following data were needed: the flow rate data and sediment data prior to the lake location. With regard to flow rate records, time series from Kanzenze station, situated at some 45km upstream lake Rweru, were obtained and used. At the same station few sediment concentration data were also available and used to make a scattered plot while comparing observed records and simulated concentration.

5.3.1 Watershed delineation

In the watershed delineation process, watersheds are segmented into several hydrological connected sub-watersheds for later use in watershed modelling with SWAT. The key procedures included loading the DEM, defining the focused area, specifying the minimum sub-watershed area, reviewing the stream network points and running the calculation of the sub-basin parameters.

At the end of this process, the Kanzenze watershed was subdivided into 13 sub-basins with a threshold area of 55000ha.

5.3.1.1 DEM setup

The DEM data used were produced by Shuttle Radar Topographic Mission (SRTM). The SRTM 90m digital elevation model has a resolution of 3 arc-second at the equator, and are provided in a 5x5 deg mosaic tiles. It is accessible for free at http://www.ambiotek.com/srtm in the ASCII file format which was converted into raster format and pre-processed using ArcGIS functions.

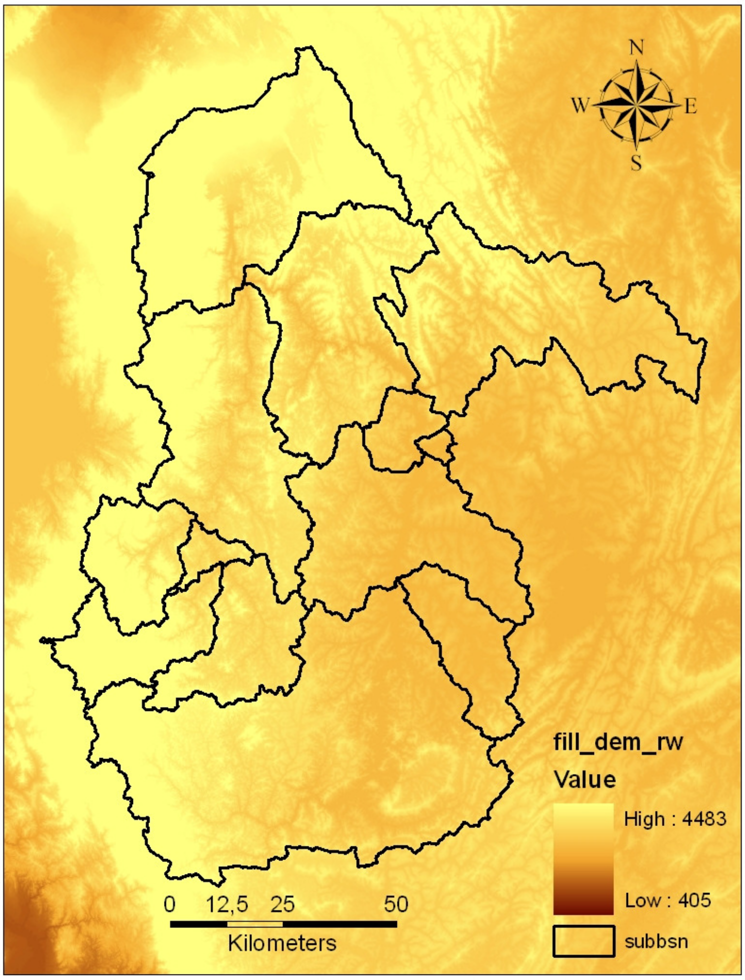


Figure 5.6 DEM covering Nyabarongo basin till Kanzenze

5.3.1.2 Stream definition

In this section of the watershed delineation, initial stream network and sub basin outlets were defined. The AVSWAT allow the user to set the minimum size of the sub basins or threshold area. The threshold area defines the minimum drainage area required to form the origin of a stream.

In this particular study, values of threshold area were varied with the aim of obtaining a catchment covering the main rivers in the Rusumo basin, i.e. Nyabarongo and Ruvubu Rivers.

On the generated river network, an outlet was defined at the anticipated location of the future Rusumo reservoir, just after the confluence of Kagera and Ruvubu rivers.

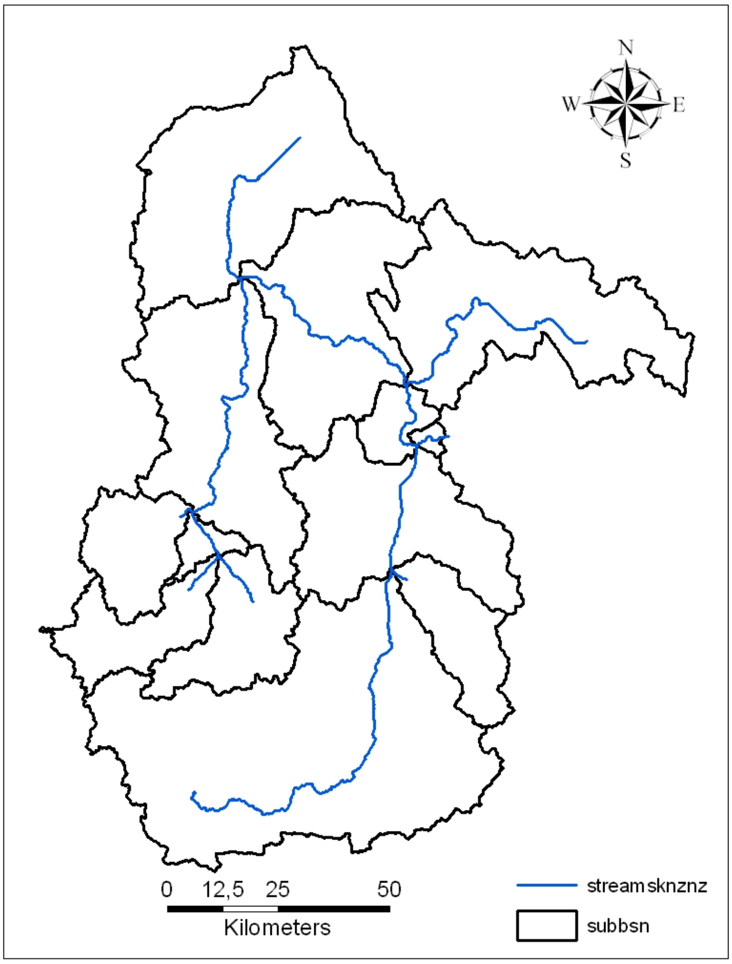


Figure 5.7 Streams and sub basins of Nyabarongo basin till Kanzenze

5.3.2 Land use and soil characterization

Land Use and Soil Characterization for a watershed are performed using AVSWATX tool. With this tool, the land use and soil themes were loaded into the project. The themes can be either grid or shape. In the present study, the soil map used was obtained from FAO world soil classification.

From both figures 5.6 and 5.7, the sub catchment land use is dominated by cropland/woodland, shrub land, and savannah with 41.51%, 24.85%, and 14.94% of total area respectively.

Regarding the soil type distribution, the dominant soil has the clay-loam texture and occupies 36% of the entire sub catchment (Figure 5.8 and 5.9).

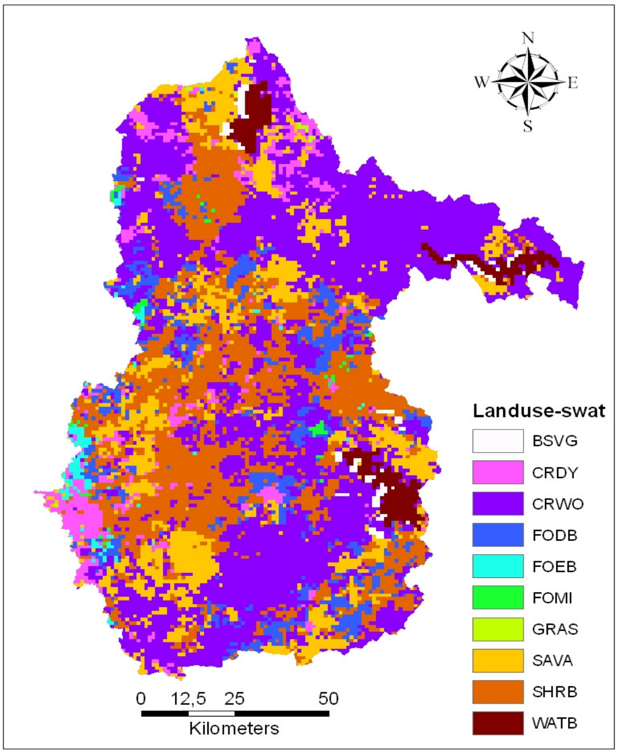


Figure 5.8 Land use map of Nyabarongo basin at Kanzenze

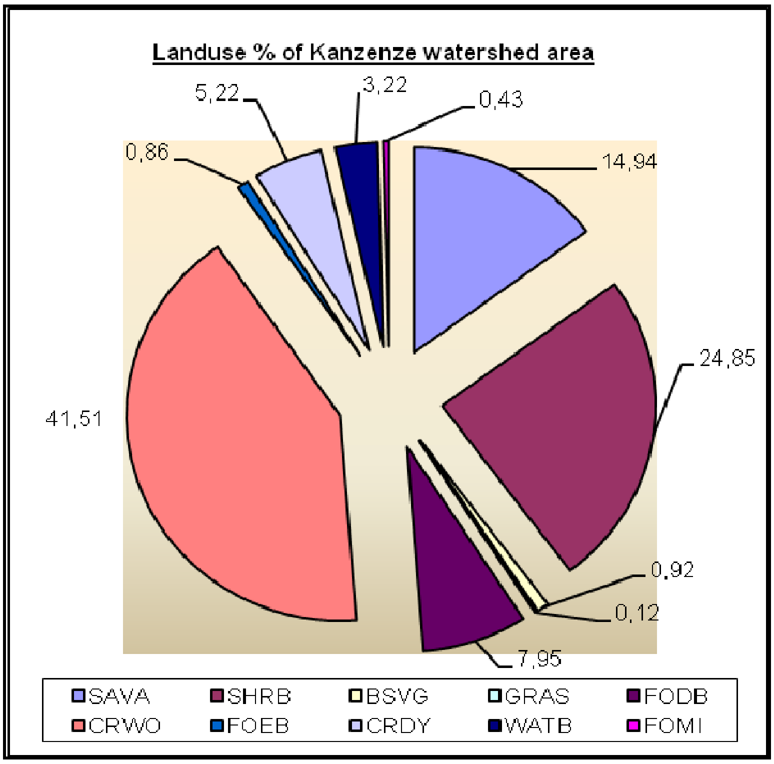


Figure 5.9 Land use distribution over the sub-catchment

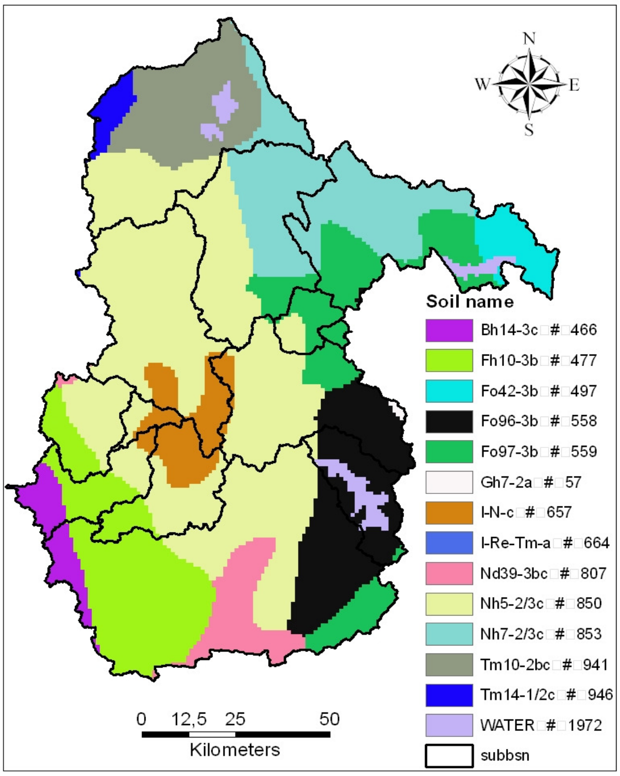


Figure 5.10 Soil map of Nyabarongo basin at Kanzenze

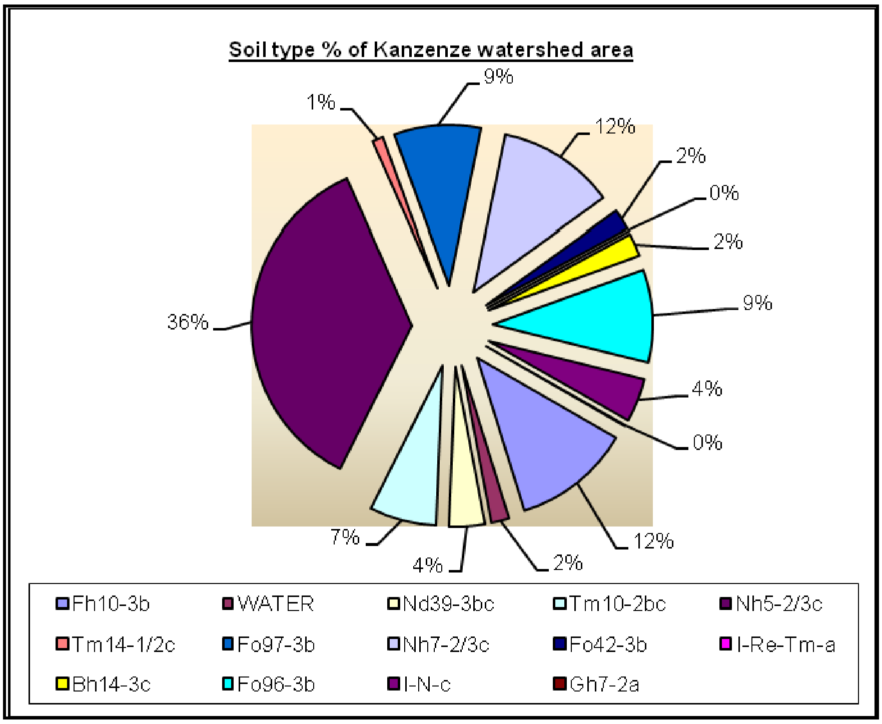


Figure 5.11 Soil type distribution over the sub-catchment

5.3.3 HRU distribution

Once the land use and soil data layers have been imported, the distribution of Hydrologic Response Units (HRUs) within the watershed must be determined. The

HRUs Distribution command in the AVSWATX (ArcView SWAT) menu allows the user to specify criteria used in determining the HRU distribution. One or more unique land use/soil combinations (HRU) can be created for each sub basin. For this particular section of the study, the 70 HRUs were created using 15% and 10% of land use and soil type respectively.

5.3.4 Importing weather data

Weather data to be used in a watershed simulation are loaded once the HRU distribution has been completed. The AVSWATX (ArcView SWAT) tool menu allows the users to load weather station locations into the current project and assign weather data to the sub-watersheds. For each type of weather data loaded, each sub-watershed is linked to one and nearest gauge. The weather data include rainfall, temperature, solar radiation, wind speed, and relative humidity. As far as this study is concerned, only rainfall and temperature data were uploaded while the remaining ones were left to be generated by the weather generator tool (WXGEN) incorporated within SWAT.

5.3.5 Sensitivity analysis and calibration

Sensitivity analysis is a process of determining the rate of change in the model output with respect to changes in the model input parameters. It is a necessary process to identify key parameters and precision parameters required for calibration. Table 5.1 shows the parameters and their codes as used in the sensitivity analysis and calibration.

Model calibration refers to a process of estimating model parameters by comparing model predictions for a given set of assumed conditions with observed data for the same condition. Model validation involves running a model using input parameters determined during the calibration process. Refsgaard (1997) considered validation as a process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations, although sufficiently accurate can vary based on project goals (Moriasi, 2007).

In the present study, the sensitivity analysis was carried out using Latin Hypercube – One factor At a Time (LH-OAT) method. The LH-OAT sensitivity analysis method is a strong tool that combines the robustness of the Latin Hypercube sampling technique that ensures that the full range of all parameters has been sampled with the precision of an OAT designs assuring that the changes in the output in each model run can be unambiguously attributed to the input changed in such a simulation leading to a robust and efficient sensitivity analysis method (Griensven 2008). The results revealed that out of the 27 parameters tested; only 16 were sensitive to flow output. The second sensitive analysis test was done on both flow and sediments combined. The results showed that the same parameters as in the first run were sensitive but the ranking was different.

With regard to the calibration process, it was done based on the results obtained from the sensitivity analysis keeping in mind findings from different studies. According to Neitsch (2002b), three parameters are more sensitive to surface runoff than others. Those are CN2 (curve number), Sol-AWC (soil available water capacity), and ESCO (soil evaporation compensation factor. On the other hand, calibration of subsurface flow also involves three parameters: the groundwater "revap" coefficient (GW_REVAP), the threshold depth of water in the shallow aquifer for "revap" to occur (REVAPMN), and the threshold depth of water in the shallow aquifer required for base flow to occur (GWQMN).

Other parameters that play important role include the channel hydraulic conductivity (CH_K), and the baseflow alpha factor (ALPHA_BF).

Table 5.1 Parameter codes for sensitivity analysis, automatic model calibration

Par	Name	Type	Description	Location
1	ALPHA_BF	Sub	Baseflow alpha factor [days]	*.gw
2	GW_DELAY	Sub	Groundwater delay [days]	*.gw
3	GW_REVAP	Sub	Groundwater "revap" coefficient	*.gw
4	RCHRG_DP	Sub	Deep aquifer percolation fraction	*.gw
5	REVAPMN	Sub	Threshold water depth in the shallow aquifer for "revap" [mm]	*.gw
6	QWQMN	Sub	Threshold water depth in the shallow aquifer for flow [mm]	*.gw
7	CANMX	Sub	Maximum canopy storage [mm]	*.hru
8	GWNO3	Sub	Concentration of nitrate in groundwater contribution [mg N/l]	*.gw
10	CN2	Sub	Initial SCS CN II value	*.mgt
15	SOL_K	Sub	Saturated hydraulic conductivity [mm/hr]	*.sol
16	SOL_Z	Sub	Soil depth [mm]	*.sol
17	SOL_AWC	Sub	Available water capacity [mm H20/mm soil]	*.sol
18	SOL_LABP	Sub	Initial labile P concentration [mg/kg]	*.chm
19	SOL_ORGN	Sub	Initial organic N concentration [mg/kg]	*.chm
20	SOL_ORGP	Sub	Initial organic P concentration [mg/kg]	*.chm
21	SOL_NO3	Sub	Initial $N0_3$ concentration [mg/kg]	*.chm
22	SOL_ALB	Sub	Moist soil albedo	*.sol
23	SLOPE	Sub	Average slope steepness [m/m]	*.hru
24	SLSUBBSN	Sub	Average slope length [m]	*.hru
25	BIOMIX	Sub	Biological mixing efficiency	*.mgt
26	USLE_P	Sub	USLE support practice factor	*.mgt
27	ESCO	Sub	Soil evaporation compensation factor	*.hru
28	EPCO	Sub	Plant uptake compensation factor	*.hru
30	SPCON	Bas	Lin. re-entrainment parameter for channel sediment routing	*.bsn
31	SPEXP	Bas	Exp. re-entrainment parameter for channel sediment routing	*.bsn
33	SURLAG	Bas	Surface runoff lag time [days]	*.bsn
34	SMFMX	Bas	Melt factor for snow on June 21 [mm H2O/ºC-day]	*.bsn
35	SMFMN	Bas	Melt factor for snow on December 21 [mm H2O/ºC-day]	*.bsn
36	SFTMP	Bas	Snowfall temperature [ºC]	*.bsn
37	SMTMP	Bas	Snow melt base temperature [ºC]	*.bsn
38	TIMP	Bas	Snow pack temperature lag factor	*.bsn
41	NPERCO	Bas	Nitrogen percolation coefficient	*.bsn
42	PPERCO	Bas	Phosphorus percolation coefficient	*.bsn
43	PHOSKD	Bas	Phosphorus soil partitioning coefficient	*.bsn
50	CH_EROD	Sub	Channel erodibility factor	*.rte
51	CH_N	Sub	Manning's nvalue for main channel	*.rte
52	TLAPS	Sub	Temperature lapse rate [°C/km]	*.sub
53	CH_COV	Sub	Channel cover factor	*.rte
54	CH_K2	Sub	Channel effective hydraulic conductivity [mm/hr]	*.rte
60	USLE_C	Sub	Minimum USLE cover factor	crop.dat
61	BLAI	Sub	Maximum potential leaf area index	crop.dat

5.3.6 Results and discussion

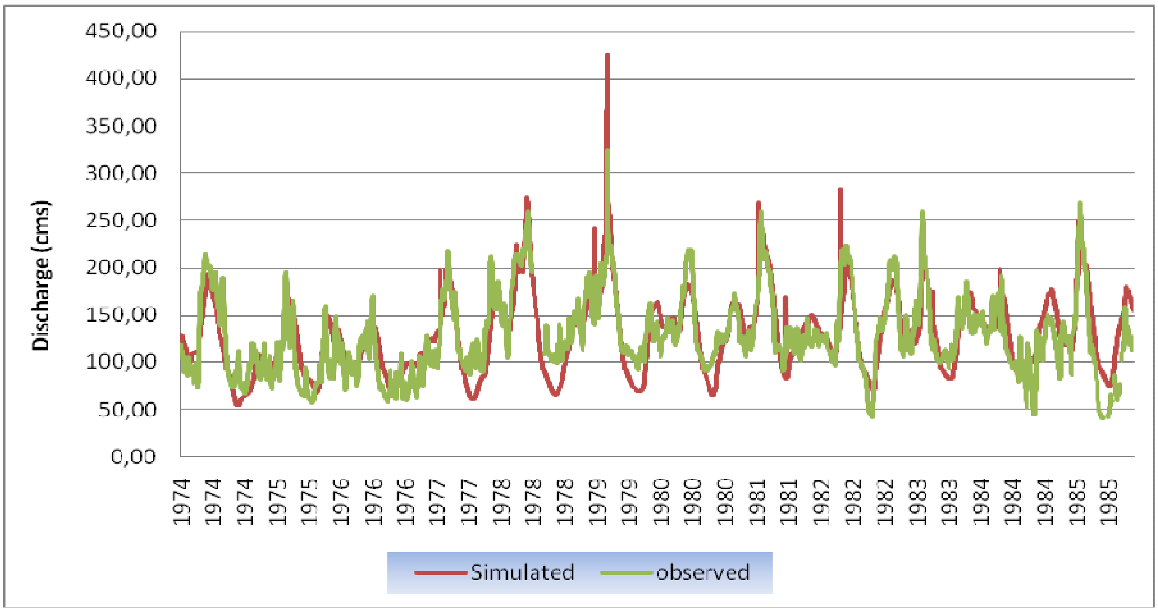


Figure 5.12 Calibration at Kanzenze

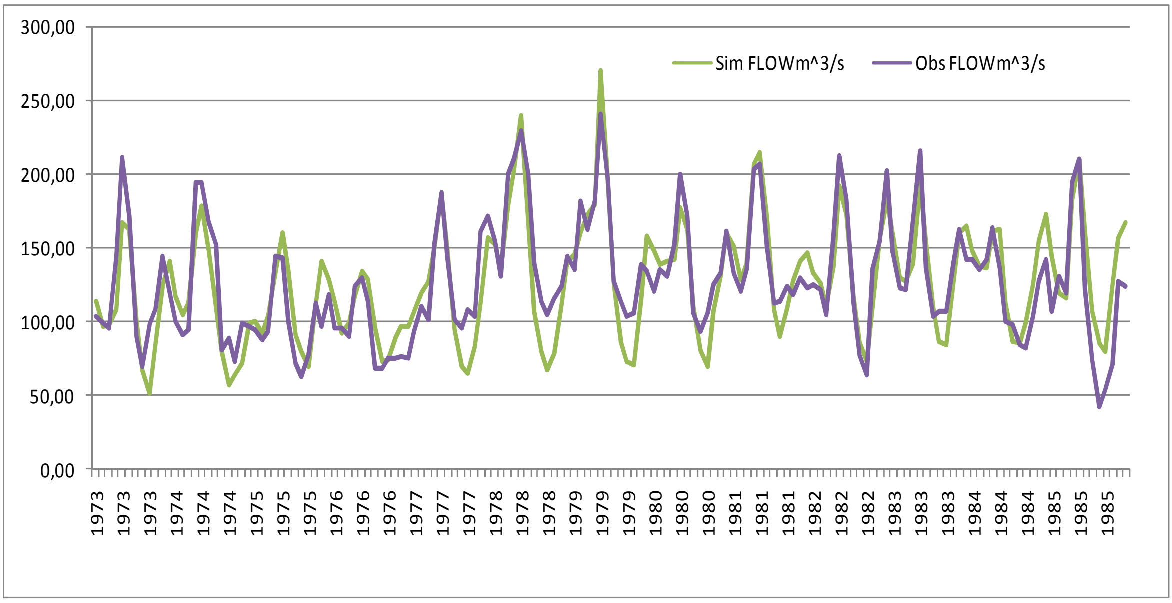


Figure 5.13: Calibration at Kanzenze

From Figure 5.10 and 5.11, a general agreement between daily observed and simulated flows was noticed with an acceptable Ns coefficient of 0.66, though the model underestimated low flows since 1977 until 1980.

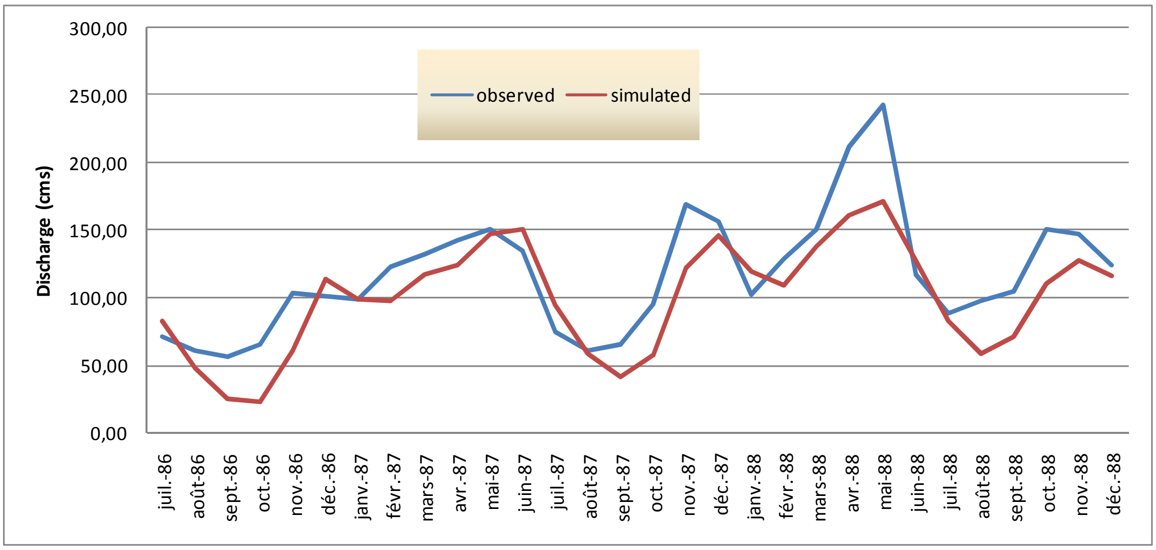


Figure 5.14 Validation at Kanzenze

As a general observation, the observed and validation flow rate values are comparable with average values of 124.73 m^3/s and 104.59m^3/s respectively.

Table 5.2 Summary of model performance at Kanzenze station

Kanzenze station		
Indicator	Calibration	Validation
Ns	0.66	0.55

From Table5.1 it was deduced that the values of Ns coefficient are acceptable (<0.5) though the validation was not successful as compared to the calibration.

In the absence of calibration and validation sediment concentration data, the few available observed concentration values were plotted together with simulated ones against the corresponding discharges. From Figure 5.14, it was deduced that the simulated values fell in the crowd of observed ones but with a general overestimation. The means of observation and simulated were 566mg/l and 1026mg/l (Table 4.4 and 5.2).

Table 5.3 Summary of flow and sediments results at Kanzenze

Simulated at Kanzenze station			
Sed. Concentration	mg/L	Flow	m3/s
Average	1026	Average	126.88
Minimum	259	Minimum	51.70
Maximum	2860	Maximum	270.00

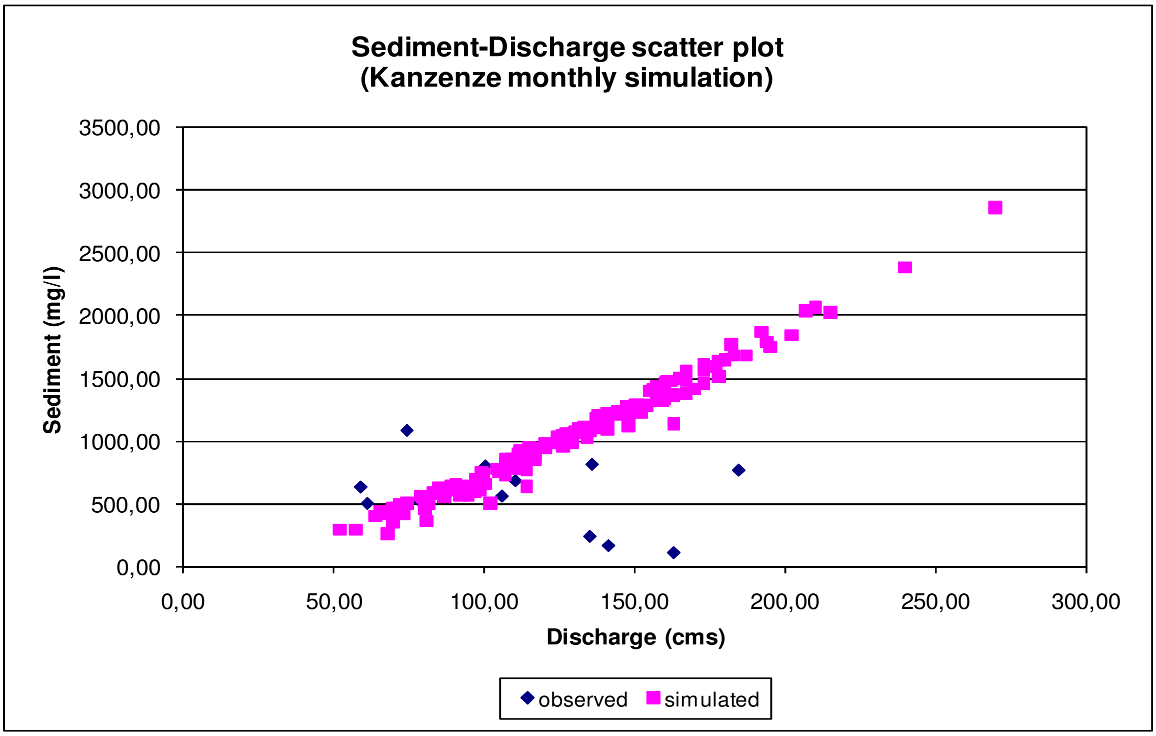


Figure 5.15 Sediment – discharge scatter plot for both observed and simulated cases

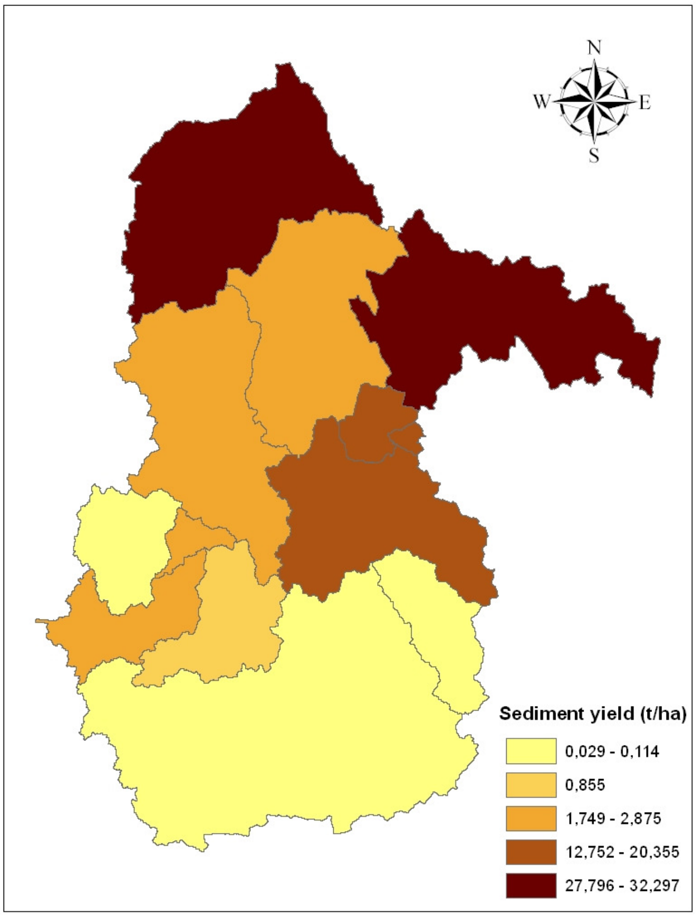


Figure 5.16 Annual average sediment yield (t/ha) on the Nyabarongo catchment

Figure 5.15 above shows the sub catchments that contribute most to sediment yield. Catchment with high annual sediment yield lie in the region the region with steep slopes of the Congo-Nile ridge, and with high rainfall intensity.

5.4 Rusumo falls section

5.4.1 Watershed delineation

In the second model set up exercise, the catchment of Kagera River up to Rusumo was entirely considered. The same procedure followed in the case of Kanzenze was also adopted for the entire catchment.

The catchment delineation was done on the same digital elevation model (DEM), and the threshold area for stream definition was set at 85000ha. This resulted in subdivision of the catchment into 21 subbasins (Figure 5.16).

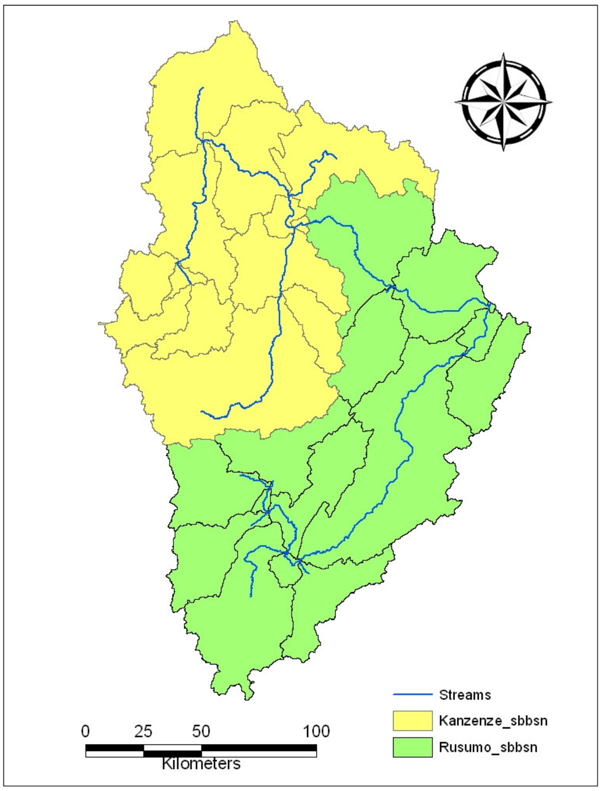


Figure 5.17: Kagera basin up to Rusumo and its main sub catchments

5.4.2 Land use and soil characterization

As in the previous case, Land Use and Soil Characterization for the catchment were performed using AVSWATX tool.

From both figures 5.16 and 5.7, the catchment land use is dominated by cropland/woodland, shrub land, and savannah with 51.90%, 13.76%, and 13.43% of total area respectively.

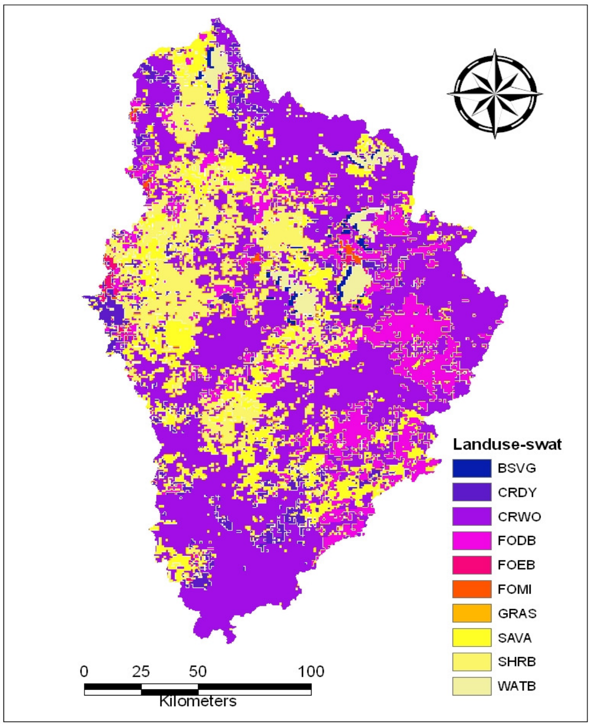


Figure 5.18 Land use map of Kagera basin up to Rusumo

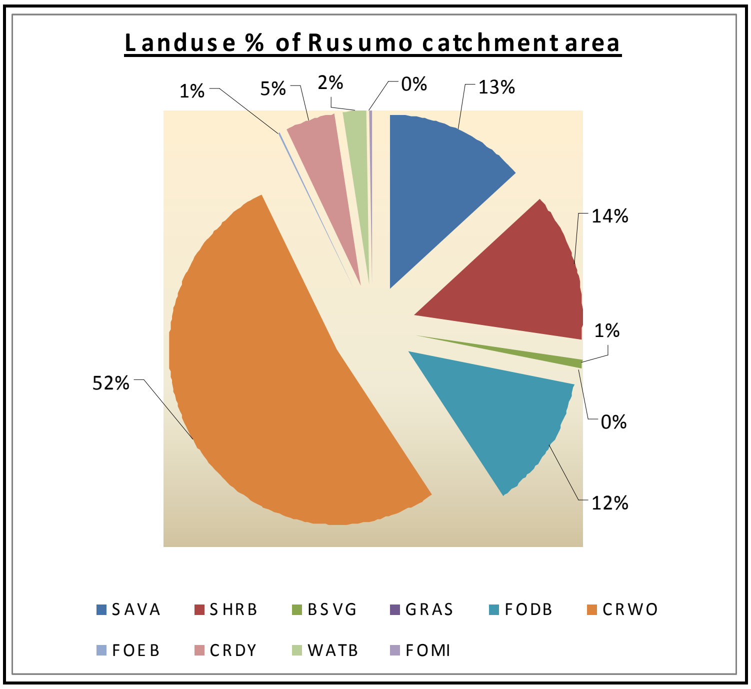


Figure 5.19 Land use distribution over the sub-catchment

Regarding the soil type distribution, the dominant soil type (Fo97-3b) has the clay-loam texture and occupies 34.83% of the entire catchment (Figure 5.18 and 5.19).

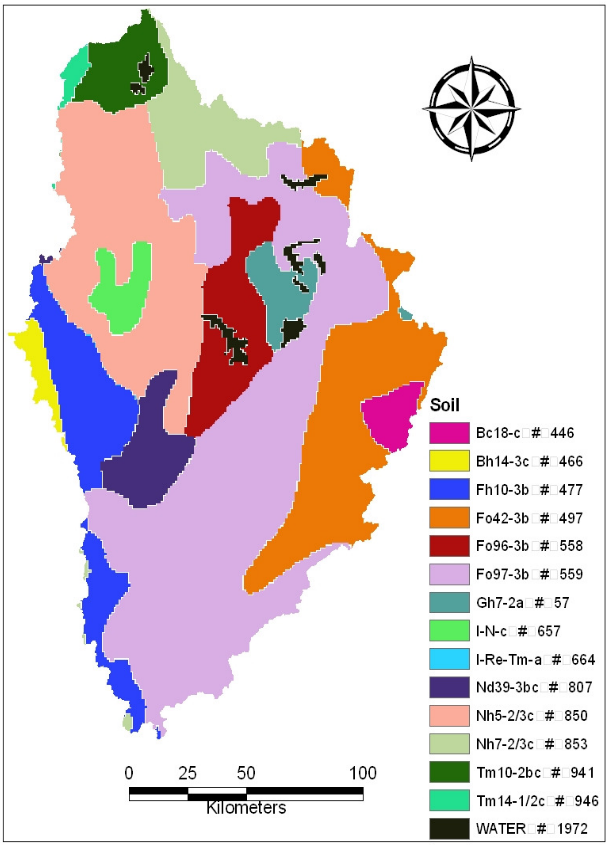


Figure 5.20 Soil map of Kagera basin up to Rusumo

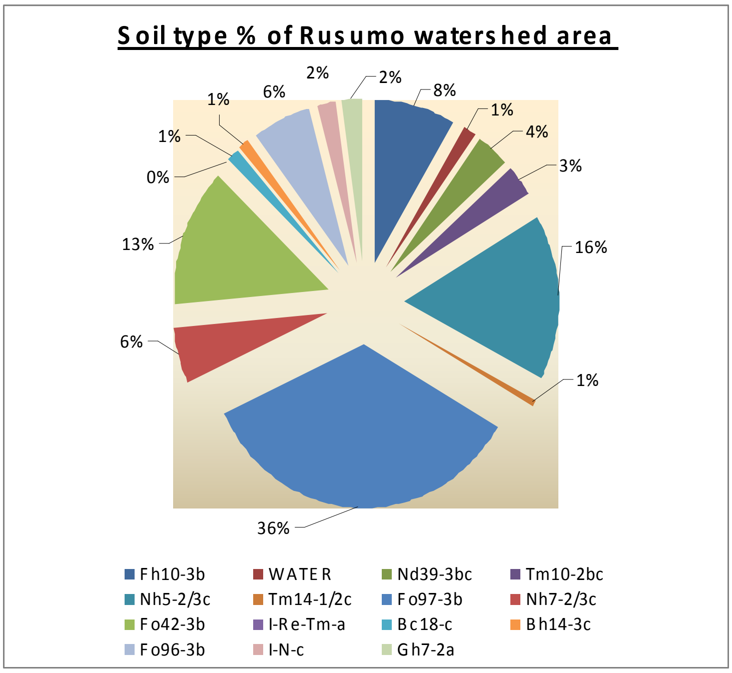


Figure 5.21 Soil type distribution over the sub-catchment

5.4.3 Results and discussion

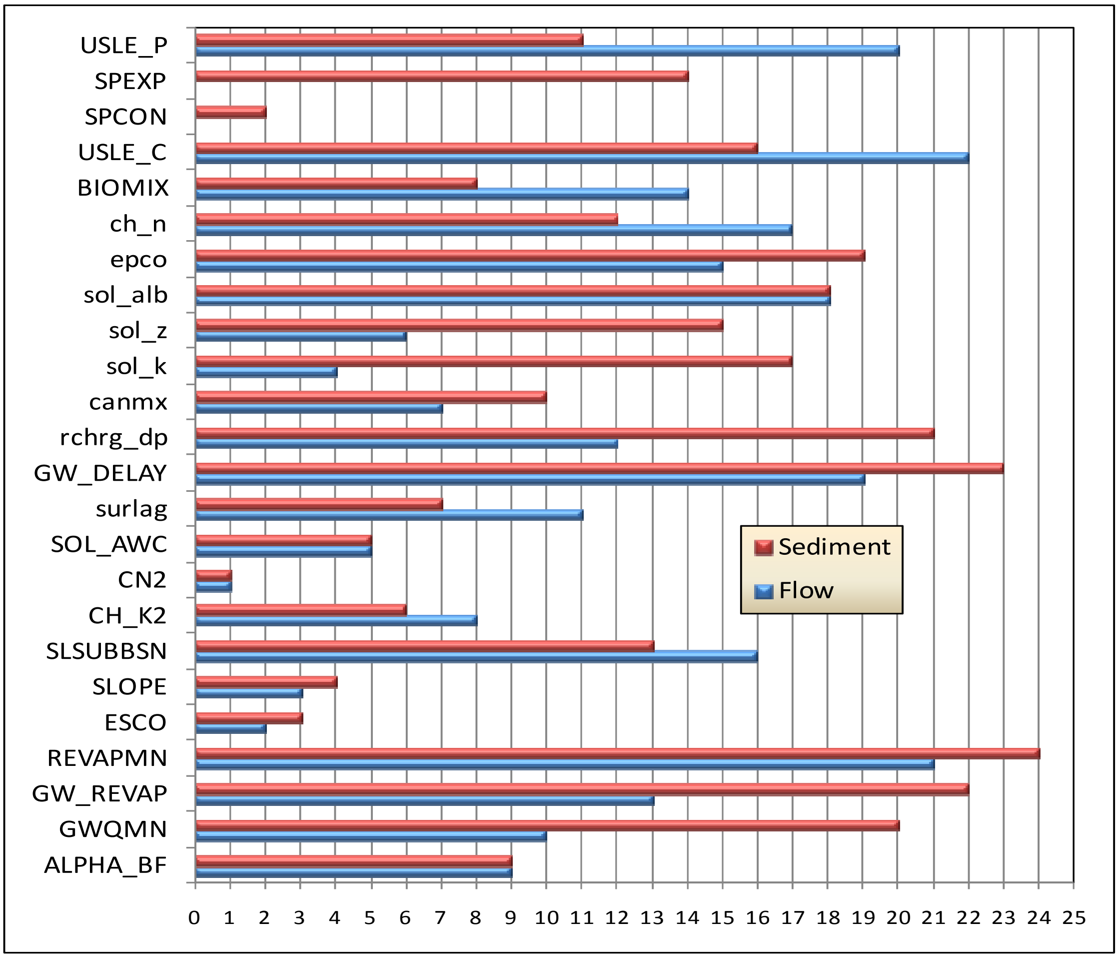


Figure 5.22 Model parameter sensitivity analysis results

Figure 5.22 present the 24 most sensitive parameters out of the 34 over which the sensitivity analysis was carried on. Moreover, out the 24 only 2 were only sensitive to flow while the remaining 22 were sensitive to both flow and sediment.

However, the most sensitive parameters for both sediment and flow were the same but with a slight difference in ranking. The most sensitive parameters include ALPHA_BF, CH_K2, CN2, ESCO, GWQMN, SLOPE, SOL_AWC, SOL_K, SURLAG, CANMAX, and SPCON for sediment.

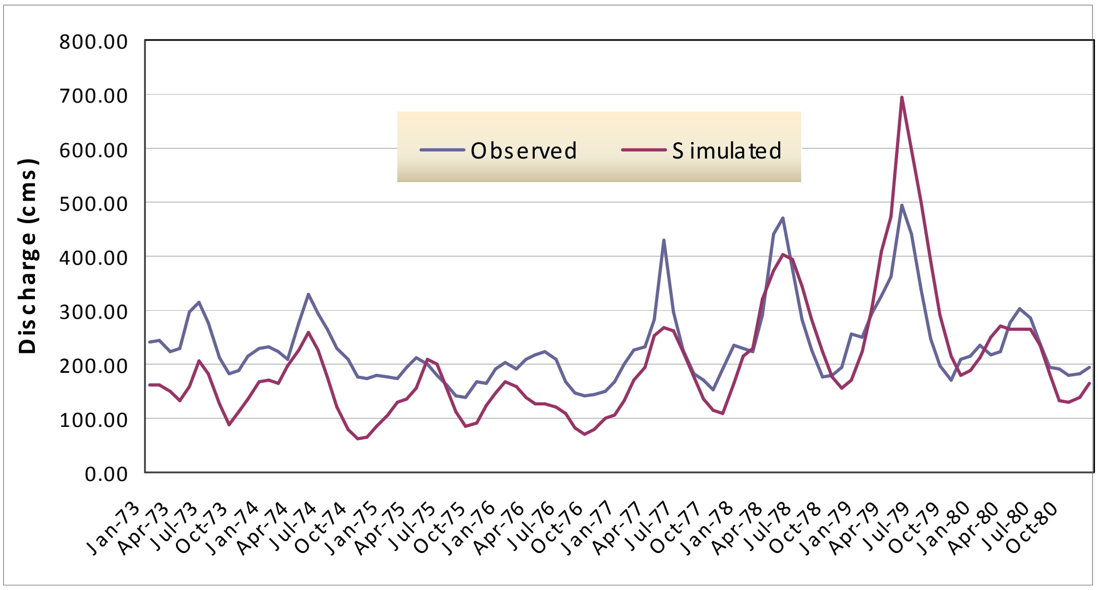


Figure 5.23 Monthly calibration results at Kanzenze

As depicted in Figure 5.23 above, the calibration at Rusumo was not successful. The agreement between the observed and simulated was weak and the Ns coefficient of -0.41, less than 0.50, was not acceptable. The model predicted low flows except in May 1979, where it overestimated the peak.

Due to the presence of important wetland, the catchment was subdivided into two sub catchments: the first one far upstream dominated by Nyabarongo and Akanyaru rivers and the second covering the Rusumo falls and dominated mainly by Ruvubu River. The wetlands are located in the second sub catchment though the first one also accommodates reservoirs; Burera, Ruhondo and Muhazi lakes.

In the following step, the calibration of flow and sediment was done at Rusumo dam site. The multi-site calibration approach was used for the two different locations: Kanzenze and Rusumo, mainly due to the presence of the wetlands between the two stations that were judged to be trapping the sediments prior to the arrival in the reservoir. This was also checked in the following section of this report

5.5 Sedimentation of the reservoir

As discussed early in this section, the lake Rweru with its current reservoir behaviour will be part of the overall reservoir. As a consequence to that, computations on sedimentation of the reservoir were done into two folds. First the lake Rweru was considered as the receiving body of the sediments from Nyabarongo River. Next the computations were made for the entire reservoir taking into account the Ruvubu river contribution. However, due to the weakness of the empirical methods used and lack of sufficient data, it was not possible to integrate both cases as they are in the real world. Table summarizes the results of sedimentation computation.

The variables as used in the empirical expressions Eq.2.11, 2.12, and 2.13 are defined as:

β (beta): trap efficiency

V: reservoir storage capacity, also equivalent to initial storage capacity
W: average annual runoff
Vt: storage capacity at t years of the reservoir's operation
Ws: annual sediment load
G: annual rate of erosion in the basin above a reservoir
F: drainage area above the reservoir
α (alpha): rate of storage capacity loss

Table 5.4 Summary of sediment deposition computation results

Variable	Reservoir	Outlet	Values	Unit
G	Lake Rweru	Kanzenze	1851,000	t/km2
	Rusumo Falls	Rusumo	871,400	t/km2
F	Lake Rweru	Kanzenze	1,398E+10	m2
	Rusumo Falls	Rusumo	3,078E+10	m2
V	Lake Rweru	Kanzenze	2,511E+09	m3
	Rusumo Falls	Rusumo	4,000E+09	m3
W	Lake Rweru	Kanzenze	2,300E+09	m3
	Rusumo Falls	Rusumo	2,735E+09	m3
Ws	Lake Rweru	Kanzenze	9,763E+06	m3
	Rusumo Falls	Rusumo	1,012E+07	m3
Beta	Lake Rweru	Kanzenze	47,187	%
	Rusumo Falls	Rusumo	54,335	%
Alpha	Lake Rweru	Kanzenze	1,004	%
	Rusumo Falls	Rusumo	0,636	%
V after 10 years	Lake Rweru	Kanzenze	2,415E+09	m3
	Rusumo Falls	Rusumo	3,900E+09	m3
Reduction in volume in 10 years	Lake Rweru	Kanzenze	3,821	%
	Rusumo Falls	Rusumo	2,502	%

The results showed that the trap efficiency was higher at Rusumo than Rweru. This was due to the fact that the Rusumo reservoir had a bigger volume compared to Lake Rweru. However, Lake Rweru presented a higher percentage in storage volume loss due to a small volume compared to the dam reservoir, and the relatively higher annual rate of erosion.

To be noted is that in case the two reservoirs would be integrated, a remarkable change would be realised in Rusumo reservoir. The 47% trapped in Rweru correspond almost to the percentage of silt observed in the sediment samples taken at Kigali station. On the other hand, the sample taken at Rusumo showed that 75% of sediments were clayey. Therefore, there could be a chance that the Rusumo reservoir receives more of clay particles which settles hardly, and can be released if the retention period would not be that long.

5.6 Scenarios

In the present study different scenario were run in order to tap the influence of some parameters on modeling sediment transport in the Rusumo catchment. To mention some, the following factors were considered: the DEM resolution, the use of HRU, the consideration of wetlands and reservoirs present in the catchment.

5.6.1 DEM resolution

Two models were built on two different DEM of 1km and 90m resolutions respectively and the following were observed:

- The first observation made was the difference in the size of the catchment while considering the Kanzenze. With 1km resolution DEM, the catchment was reduced by 4%.

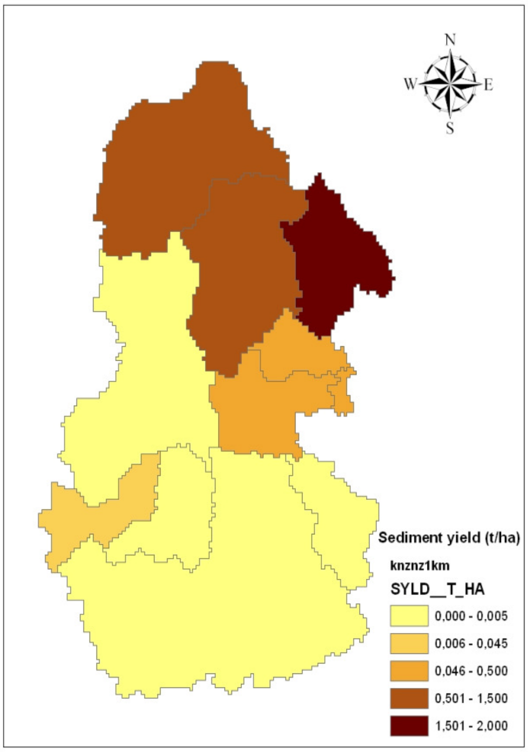
Table 5.5 Watershed area for 90m and 1km resolution DEM

DEM Resolution	Total catchment area (km^2)
90m	13977.826
1km	13387.000

- Another difference was observed in the generated flows and sediment. The model built on 1km resolution produced less sediment concentration in the flow after calibration using the same parameters as of the 90m. On one hand, this may be attributed to the fact that the slopes were underestimated in the 1km DEM, and the slope plays a significant role in routing the eroded soil into the reach. This can also be justified also by the surface runoff produced by the two options. The 1km DEM produced hardly the half of surface runoff produced by the 90m resolution. On the other hand, while comparing sub-basins yields, the sediment yield was influenced by underestimated area of the sub basins.

Table 5.6: Average annual basin values

DEM resolution	Water yield (mm)	Surface runoff (mm)	Sediment loading (t/ha)
90m	177.72	45.70	18.51
1km	25.37	22.28	0.03



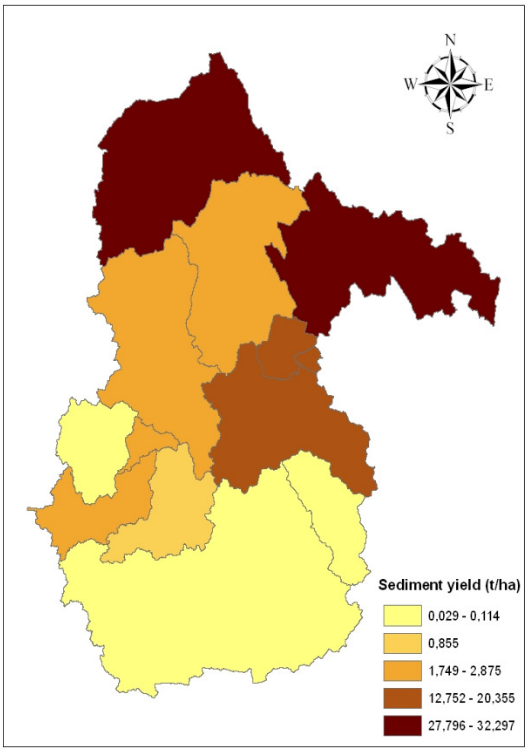


Figure 5.24: 1km resolution DEM

Figure 5.25: 90m resolution DEM

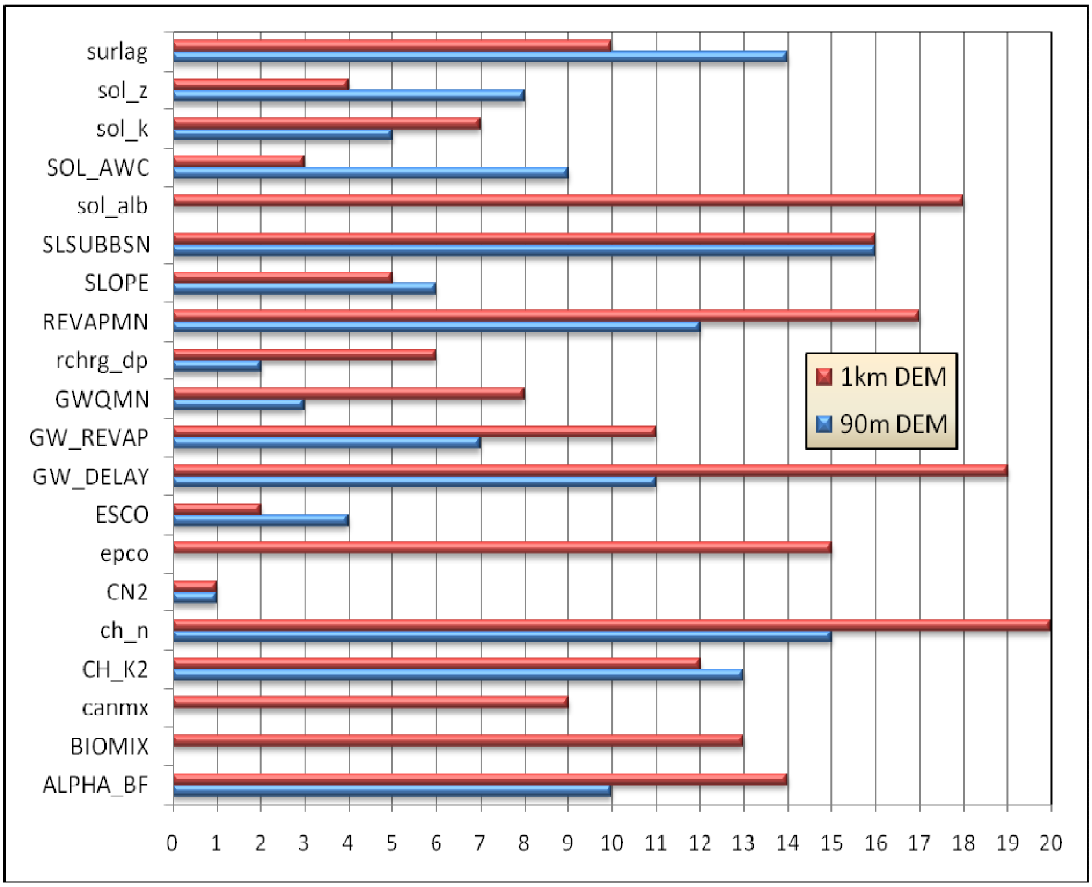


Figure 5.26 Model parameter sensitivity analysis results

Figure 5.26 present the results of a sensitivity analysis carried on the 27 model parameters used in the 1km and 90m resolution DEM with regard to flow. The results revealed that out of 27 only 16 were sensitive when considering the 90m resolution DEM, whereas the 1km resolution DEM included other 4 parameters in addition. Except for the Curve Number (CN2), other most sensitive parameters in this have different.

The most sensitive parameters include SOL_Z, SOL_K, SOL_AWC, SLOPE, RCHRG_DP, GWQMN, ESCO and CN2

5.6.2 HRU

An HRU (Hydrological Response Unit) represents a sub-division in the sub-basin that is characterised by a unique combination land use and soil type. By increasing the percentages of land use and soil type, the number of sub-divisions decreases and vice versa. In the present case the percentages were decreased to zero %, and the model predicted more sediment yield for the high erosive catchments.

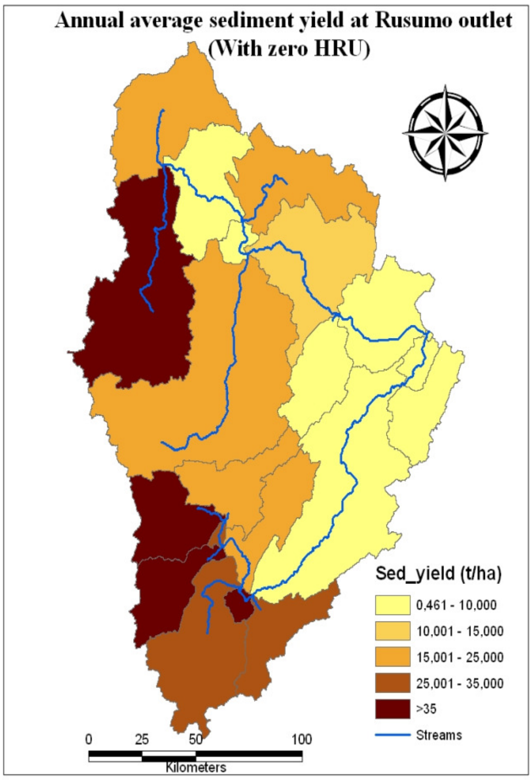


Figure 5.27: Sed. yield with zero %

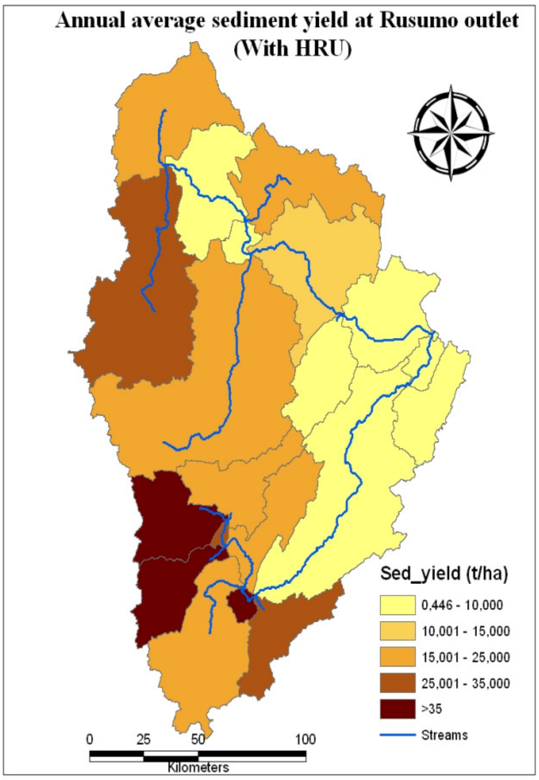


Figure 5.28: Sed. yield with 15 and 10%

5.6.3 Wetlands

There are wetlands in the Kagera catchment in up and downstream of the planned dam site. In this particular study, only upstream wetlands were included in the model to check its impact on sediment transport within the catchment. As depicted in figures 5.29 and 5.30, the sediment yield decreased only in the sub basins where the wetlands were included. They then proved their considerable ability to trap sediments.

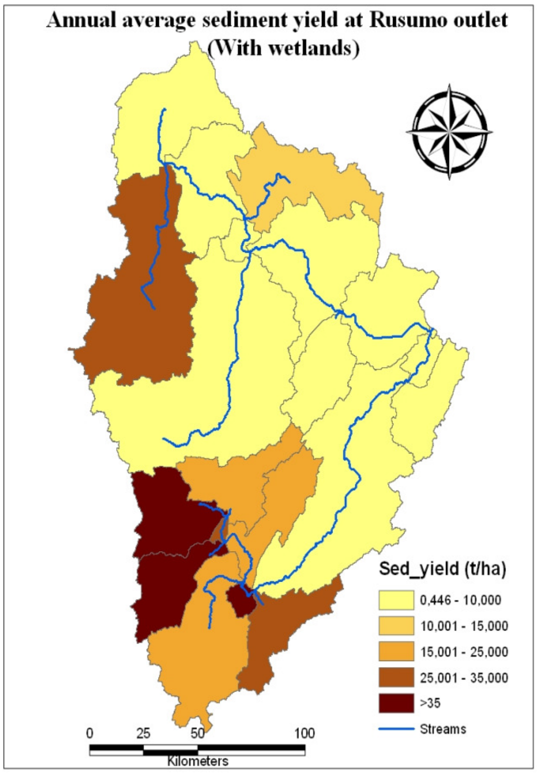


Figure 5.29: Sed. yield with wetlands

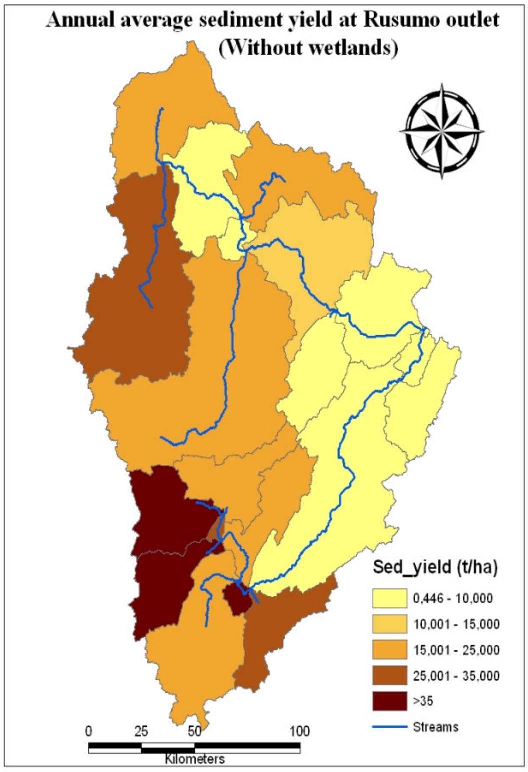


Figure 5.30: Sed. yield without wetlands

6 Conclusion and recommendations

6.1 Conclusions

The results showed that most of the sediment will be deposited in the wetland area far upstream of the dam, which accommodates the lake Rweru. Within a period of ten years, after the implementation of the dam project, the lake may lose its capacity by 3.8 to 10% using Ort (1930) and the method of rate of storage capacity loss methods respectively. On the other hand, the reservoir just behind the dam will be mainly influenced by the Ruvubu contribution with an approximate storage capacity loss of 2.5 to 6.4% using Ort (1930) and the method of rate of storage capacity loss methods respectively. However, this storage capacity loss remains high in case the influence of the lake Rweru would be incorporated efficiently.

The wetlands in the south-eastern part of the country have a considerable influence on sediment transport in Kagera River. Despite receiving also the contribution in sediment load from Ruvubu River, still the concentration in sediment was far less than the concentration in the river before the wetlands and the confluence.

The SWAT model has proved to be a useful tool in modeling sediment yield within a catchment with very limited data. Sediment transport estimates were reasonable on a monthly basis.

The definition of impoundments in the catchment also affects the sediment modeling. From the beginning of modeling, wetlands and reservoirs entities should be clearly distinguished. In the present study, the reservoirs trapped more sediment than the wetlands. This was due to the fact that they normally located on the stream network, hence always in contacts with sediments.

The factors influencing modeling of sediment transport in the catchment included the DEM resolution. With a varying topography in Kagera catchment, a model built on a finer resolution DEM lead to reasonable results in terms of catchment delineation and slope definition.

The finer the HRU percentages, the more sediment yielded. However, for very big catchment with less variability in land use and soil types, the computation may become time consuming.

6.2 Recommendations

For further improvement of the Kagera catchment modelling in terms of sediment transport, the following are the recommendations made:

- While estimating the deposition of sediment in the planned Rusumo reservoir, empirical methods were used. With those, it was not possible to integrate all the components of the reservoir including the reservoir far upstream the dam: Lake Rweru, and the pool just behind the dam. The use of other methods other than empirical. Moreover, the empirical methods used did not consider different influencing factors such as sediment particles size distribution among others. Therefore it is recommended to use preferably numerical methods that take into account processes involved in the sediment deposition.

- One of the major shortcomings of this work was the insufficient available sediment data. In order to overcome this problem, there is a need to identify strategic locations in the catchment in terms of sediment transport, and install data recording stations at those locations. However, establishing sustainable monitoring mechanisms of those stations is also an important issue since the existing ones also could have helped if operational

- Based on fact that deposition would start in the wetlands including the lake Rweru, there is need to conduct sound hydrologic studies in the region. The aim of those would include determination of long-term impact of sediment on the lake and the surrounding wetlands.

- The calibration of SWAT model also was found to be complex and time consuming, mainly due to a lot of parameters. Therefore, there is a need for studies aiming at improving that part of the tool.

- Finally, in the Nile basin, wherein this study was carried, a Nile Basin Decision Support System (DSS) component was established with a mandate to be operational and used by Nile riparian countries to exchange information, support riparian dialogue, and identify cooperative investment projects. However, information in some riparian countries is still scarce due to the absence of enough data on one hand, and the appropriate modeling tools on the other hand to generate and manage information. The approach used in this study, where numerical and empirical methods are integrated in sediment transport, may be recommended for other similar studies of the same constraints as this one.

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