ASSESSMENT OF IMPACTS OF LAND USE CHANGES ON WATER RESOURCES OF RIVER MPANGA CATCHMENT

BY

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APPROVAL

The undersigned approve that they have read and hereby recommend for submission to Kyambogo University a research thesis entitled: ASSESSMENT OF IMPACTS OF LAND USE CHANGE ON WATER RESOURCES OF RIVER MPANGA CATCHMENT, in partial fulfilment of the requirements for the award of MASTER OF SCIENCE IN WATER AND SANITATION ENGINEERING degree of Kyambogo University.

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DECLARATION

I, TURYAHABWE CATHERINE, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person or material which has been accepted for the award of any other degree of the university or other institute of higher learning, except where due acknowledgement has been made in the text and reference list.

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ABSTRACT

Mpanga Catchment has in recent decades been exposed to changes in land use/cover (LULC). This could have been due to intensive agricultural activities to sustain the needs of the increasing population. Transition in land use/cover tends to impact on the hydrology of a given catchment. This study assessed the impacts of land use changes on water resources of Mpanga catchment. The study was three-fold. Firstly, land use changes were identified and analysed. In the second step, the question of whether land use changes impacted on water resources was answered through hydrological modelling using Soil and Water Assessment Tool (SWAT). SWAT was automatically calibrated and validated using daily data from 2003 to 2013. Thirdly, the model was applied to conduct scenario analysis. Major land use/covers included cropland, forest, pasture, wetland, water body and settlement. Cultivated area increased by 31.79% while grassland and forests decreased by 31.79% and 11.38%, respectively. Hydrological model performance evaluation yielded Nash-Sutcliffe model efficiency (NSE) 0.86 and 0.77 during calibration and validation periods, respectively. Changes in the land uses between 2000 and 2014 increased stream flow ratios from 0.49 to 0.54, surface runoff from 0.26 to 0.33 and evapotranspiration ratios reduced from 0.49 to 0.44. Scenario analysis showed that the catchment was more influenced by the land use changes with respect to dry than wet conditions. Thus, control measures like agroforestry, deep tillage and banding should be adopted to minimize run off and facilitate infiltration and ground water recharge.

Key words: Catchment, land use/cover, water resources, scenarios, hydrological modelling

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DEDICATION

This report is dedicated to my Parents (Mugume Peter and Kyarimpa Jovanis), my brothers (Easton, Hilary and Mugisha), my princess Ahabwe Mary Claire and Musinguzi Mark and my fallen brother Mugume David (RIP).

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LIST OF ACRONYMS

AIO	Area of Interest
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
FAO-UNESCO	Food and Agriculture Organisation-United Nations Educational, Scientific and Cultural Organization.
GDEM	Global Digital Elevation Model
GIS	Geographical Information System
HRU	Hydrologic Response Unit
IWRM	Integrated Water Resources Management
LULC	Land Use Land cover
LULCC	Land use Land Cover Change
MoWE	Ministry of Water and Environment
NEMA	National Environment Management Authority
NFA	National Forestry Authority
NSE	Nash-Sutcliffe efficiency
RS	Remote Sensing
SCS-CN	Soil Conservation Service - Curve Numbers
SRTM	Shuttle Reconnaissance Topography Mission

SWAT	Soil and Water Assessment Tool
SWAT-CUP	Soil and Water Assessment Tool Calibration Uncertainty Program
UBOS	Uganda Bureau of Statistics
UNMA	Uganda National Metrological Authority
USGS	United States Geological Survey
UTM	Universal Transverse Mercator Coordinate System
UNEP	United Nations Environment Program

CHAPTER ONE: INTRODUCTION

1.1 Background of Study

Sustainable management of the earth’s surface including water resources and land remains a critical environmental challenge that society must address (Guzha et al., 2018). Besides ecosystem vulnerability, land use change is the major determinant of global environmental changes with potential severe impacts on climatological, hydrological and biodiversity response (Kundzewicz and Germany, 2012). This is majorly due to increase in population which is at 7.6 billion globally with a growth rate of 1.14 percent per year and Africa with 1.1 billion and is projected to increase to about 2.1 billion by 2050 (United Nations, 2019). Of these, 34.9 million are from Uganda with an average annual growth rate of 3.02 percent (Uganda Bureau of Statistics [UBOS], 2014).

With the continuous population growth, rapid urbanization, industrialization, expansion of agriculture and tourism, dramatic changes have taken place on a global scale in land use patterns on river catchments putting water resources and land under increasing stress (Global Water Partnership [GWP] and Integrated Network of Basin Organization [INBO], 2009). Studies have been carried out on land use impacts on stream flows in various parts of the world; for instance, Fohrer et al. (2001) and Tang et al. (2011) in China, Nie et al. (2011) in USA, Vaighan et al. (2018) in Iran, Levy et al. (2018) in Brazil, Mango et al. (2011), and Olang and Furst (2011) for the equatorial region; Legesse et al. (2003, 2004), Bewket and Sterk (2005), Rientjes et al. (2011), and Gebrehiwot et al. (2013) for Ethiopia among others. Though all these studies are in the Nile basin, other factors such as the change in meteorological conditions, regional differences and catchment characteristics need to be addressed in each region to fully understand how each catchment responds to the different models.

Of the depleted water resources, the once mighty River Mpanga in Western Uganda has not been spared. As the river flows through Kamwenge District towards Lake George, the area has been heavily deforested and the river banks cleared for cultivation and settlement (National Environment Management Authority [NEMA], 2016). This has affected the river’s retention capacity to precipitation and subsequent release into stream base flow leading to increase in flood peaks (BRL Ingenierie [BRLi], (2015).

The impacts of land cover/land use changes on hydrology have been assessed over the past several decades using field-based data-driven statistical methods (Brown et al., 2005) and hydrological modelling (Chu et al., 2010). In this study, Soil Water Assessment Tool (SWAT) model was used for rainfall- runoff modelling in the catchment. This model was adopted because the input variables can be easily obtained, has high computational efficiency, provides long-term watershed simulation and is open sourced (Neitsch et al., 2005; Arnold et al., 1998). Also, it has been successfully used by Mango et al. (2011) and Odira et al. (2010) to assess the effect of land use/cover changes on stream flow variations in the Nile basin. The results of this study will be used as a basis for future Integrated Water Resources Management (IWRM) processes within Mpanga catchment area to ensure sustainable management of this water resource.

1.2 Statement of the Problem

Land use has a finite impact on water catchment and storage which on large scale influences the water balance within a catchment. Most river basins have undergone massive change over the past years due to various land use activities. Of the affected rivers, River Mpanga which is the main fresh water resource for the communities that live along its banks has not been spared. The catchment is faced with tremendous changes triggered by the need to provide food and settlement for the increasing population that is growing at a rate of about 3.02% per annum as estimated by the National Population Census of 2014.

For effective planning and protection of such a vulnerable water resource under changing conditions, hydrological modelling should be done to compliment the available land use and cover data from satellite images since archives of aerial photos or satellite images of land cover with high spatial and temporal resolutions for long-term periods are difficult to obtain for the study area (Onyutha and Willems, 2018).

Studies have been done in Mpanga Catchment like the climate change impact investigations (BRLi, 2015) and ecological water quality assessments (Butsel et al., 2017). However, none or little emphasis has been put on the cause of the variations in streamflow resulting from land use changes. Hydrological modelling using SWAT can be used to investigate the variations in the stream flow given the changing land uses. Information from such models e.g. in the form of scenarios can help in planning of predictive adaptation measures to ensure sustainability of the resource.

1.3 Objectives of the Study

1.3.1 Main Objective

To assess the impacts of land use change on water resources of River Mpanga catchment.

1.3.2 Specific Objectives

1. To determine the different land use changes in the River Mpanga Catchment.
2. To investigate the influence of land use changes on the stream flow variations of River Mpanga.
3. To conduct scenario analysis on the extent to which the river flow can be affected under changing land uses.

1.4 Research Questions

1. What are the different land use changes in Mpanga Catchment?
2. How does the land use change affect the stream flow of River Mpanga?
3. To what extent can the river flow be affected under different land use changes?

1.5 Research Justification

- Understanding the types and impacts of land use/cover change is an essential indicator for resource base analysis and development of effective and appropriate response strategies for sustainable management of natural resources in the country in general and at the study area in particular.

- Some projects are being implemented on the rehabilitation of the Mpanga catchment in order to ensure sustainable management of the water resource and reduce the flooding risk of the downstream towns. Therefore, this work will provide an understanding of how land use change has impacted on the stream flow.

1.6 Significance

By detailing how land use changes influence hydrological responses, decision makers are in a better position to formulate policies that can mitigate the undesirable effects of future land use changes on the stream flow from an informed perspective.

1.7 Scope of the Study

1.7.1 Geographical scope

The research was limited to Mpanga catchment which covers the upstream, middle, and the Lower Mpanga Catchment which pours into Lake George.

1.7.2 Content Scope

The research was limited to analysis of different land use changes in the catchment, SWAT model set up, calibration, validation of the model, evaluation and recommendations on what to be done to restore the catchment to its original state.

1.7.3 Time scope

The research was carried out for a period of eleven months from October 2018 up to November 2019. The flow and weather data used was for a period of fourteen (14) years i.e. 2000-2013.

1.7.4 Conceptual framework

The land use and human factors in the catchment such as farming, human settlement, cultivation, industrialization, over grazing and sand mining were the driving forces in the system (Independent Variables). These were simulated to establish the impact on the stream flow of River Mpanga (Dependent Variable). The status of the land use change in turn influenced the introduction of decision variables for both land use and catchment hydrology. The intervening variables which were in form of policies, by-laws, afforestation and re afforestation were used to impose control measures and regulate land usage. The decisions made from the various constraints affected both the state of land use and the hydrology in the catchment. The land use and hydrological data variables were then modelled to simulate various scenarios to determine the impact on the River Mpanga flows.

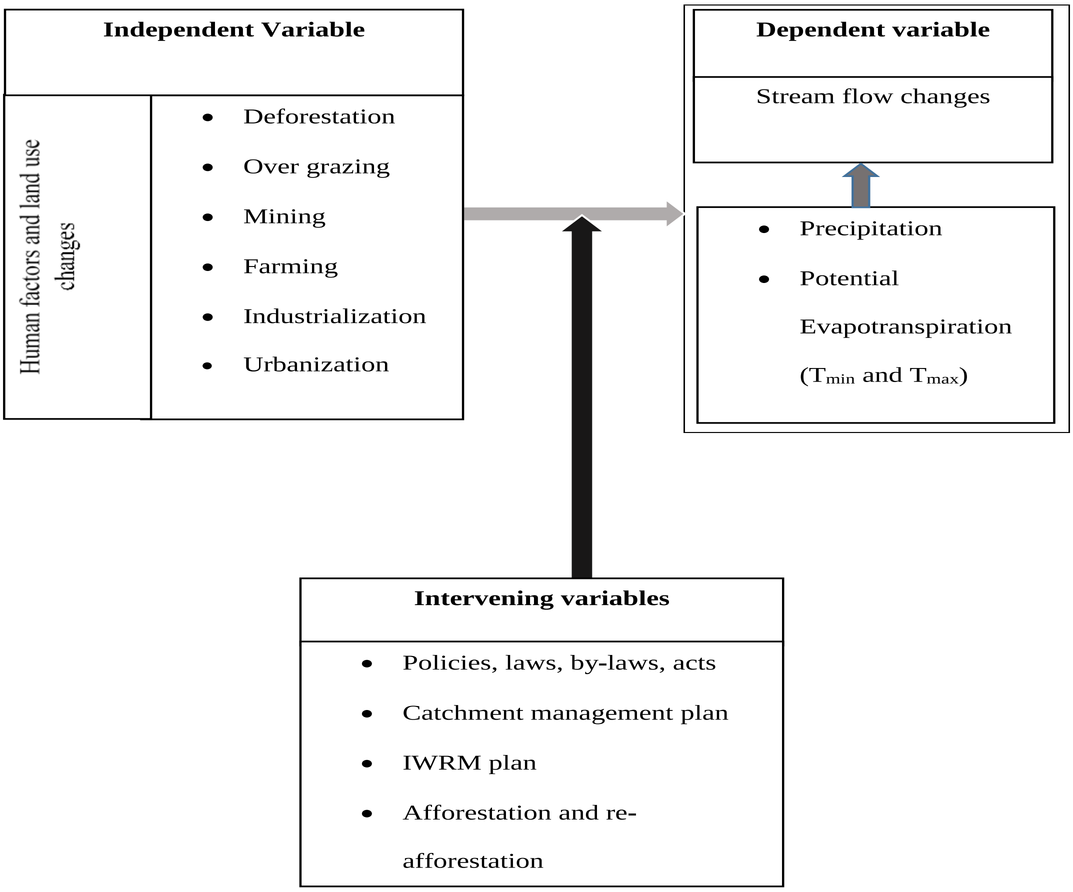


Figure 1-1: Conceptual Framework

1.7.5 Chapter Summary

The above chapter clearly looked at the introduction of the research, pointed out the gap that needed to be addressed, the objectives of the research and its contribution to the society, the scope of work that was done and the general framework on how the research was performed.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Under this section, literature on relevant topics were cited such as; definition and concepts of land use/cover changes and studies, hydrological models mainly (SWAT) model and its application.

2.2 Land use and land cover change definition

Land use is a more complicated term. Natural scientists define land use in terms of syndromes of human activities that alter land surface processes such as agriculture, forestry and building construction including biogeochemistry, hydrology and biodiversity (Ellis and Ramankutty, 2008).

Land use is the intended employment of and management strategy placed on the land cover by human agents, or land managers to exploit the land cover and reflects human activities such as industrial zones, residential zones, agricultural fields, grazing, logging, and mining among many others (Khawaldah, 2016).

Land use can be considered to reflect the degree of human activities directly related to land and making use of its resources or having an impact (Briassoulis, 2009). Two key aspects of land use are the products and benefits from use of the land and the operations applied to the land in order to produce these products and benefits.

The land use and land cover change assessment is an important step in planning sustainable land management that can help to minimize agro-biodiversity losses and land degradation, especially in developing countries (Hadgu, 2008).

2.3 Current state of River Mpanga catchment

River Mpanga runs through several areas of high ecological value that need appropriate protection if they are to be preserved for the future. From the report by BRLi (2015), it indicated that the lower slopes and foothills of the mountains have been modified to serve as agricultural land. Deforestation on the steep slopes, sand, gravel and stone extraction from river beds are enhancing soil and bank erosion. An increasing risk of landslides and lower river bank stability do not only pose a threat to people living in the area, but also increase turbidity of the water and sediment transportation downstream (BRLi, 2015).

2.4 Land use/ cover change and their impact on stream flow studies

According to Lambin et al. (2001), increasing demands of food production and agricultural lands are expanding at the expense of natural vegetation and grasslands. These land cover changes have been influenced by both the increase and decrease of a given population. These changes in land use/cover systems have important environmental consequences through their impacts on soil and water, biodiversity, and microclimate.

Kiggundu et al. (2018) indicated that the Murchison bay catchment of Lake Victoria has undergone huge land use and land cover transformations over the last three decades attributable to rapid population growth and urbanization. The prevailing changes in footprint between 1984 and 2015 were expansions of built–up land (20.58% to 49.59%) and open water bodies (not detected in 1984 to 1.74%), and decreases in the following sectors; agricultural lands (43.88% to 26.10%), forestland (23.78% to 17.49%), and wetlands (11.76% to 5.08%).

Chakilu and Moges (2017) compared land use maps of 1973 and 2013 in Gumara watershed in Upper Blue Nile. They concluded that most of the previous land use/cover types like forest and bush land have been changed into agriculture lands due to the expansion of population and competition for the natural resources.

According to Rientjes et al. (2011), forest cover decreased from 50 to 16% in the Gilgel Abay catchment in the Lake Tana basin over the period 1973–2001. This decreased the annual flow of the catchment by 12.1 %.

Bewket and Sterk (2005) in their research in Chemoga watershed in Ethiopia, reported that total annual stream flow decreased at a rate of 1.7 mm per year, whereas the annual rainfall decreased only at a rate of 0.29 mm per year. They attributed these changes to land cover/use and/ or degradation of the watershed that involved destruction of natural vegetative covers, expansion of croplands, overgrazing and increased area under eucalypt plantations.

Legesse et al. (2003) found that flow would reduce to about 8% if the dominantly cultivated/ grazing land of South Central Ethiopia was to be converted to woodland.

Brook et al. (2011) found out that modified land use/land cover affect hydrology. In their study, water yield increased during wet seasons (May - September) by 42.61% and 40.18% in respectively while declined during the dry season (October – April) by 20.61 % and 24.18 % for Anger Gutin and Tulu Gana watersheds, respectively.

Nie et al. (2011) indicates in his paper “Assessing impacts of Land use and Land cover changes on hydrology for the upper San Pedro watershed” that urbanization which increased by 0.44 to 2.24% from (1973-1997) was the major contributor to the increased surface runoff and water yield for the studied watershed. At the same time, the replacement of desert scrub or grassland by mesquite from 1973 to 1997 was identified as the second major predictor for the declines of base flow, percolation and for the increase of ET in the upper San Pedro watershed.

Mango et al. (2011) concluded that any further conversion of forests to agriculture and grassland in the Upper Mara River Basin headwaters would reduce dry season flows and increase peak flows, leading to greater water scarcity at critical times of the year and exacerbating erosion on hillslopes.

Mati et al. (2008) found that land use change between 1973 and 2000 had increased the peak flow of Mara River by 7%. Mwangi et al. (2016) estimated that land use change in the last 50 years contributed to 97% of the observed increase in mean streamflow of Nyangores River (a headwater tributary of the Mara River). The increase in mean streamflow observed by Mwangi et al. (2016) was attributed to reduced water use by vegetation (transpiration) following deforestation. Trees are generally known to consume (transpire) more water than most vegetation and therefore deforestation reduces water removal by trees from soil and groundwater. Deforestation and intensification of agriculture are likely to cause increase in surface runoff due to degradation of the watershed which reduces its capacity to absorb rainwater (reduced infiltration) (Recha et al., 2012). This may manifest as increased peak flows as observed by Mati et al. (2008) in the Mara River Basin.

According to Fohrer et al. (2001), the impact of land use change on the annual water balance was relatively small due to compensating effects in a complex catchment. The decrease of forest due to a grassland bonus amplifies the peak flow rate and thus increases the risk of flooding.

Tang et al. (2011) in their study of “Detecting the effect of land-use change on streamflow, sediment and nutrient losses by distributed hydrological simulation” in Miyun Reservoir in Northern China, they discovered that decrease in precipitation and increase in air temperature were the dominant factors in runoff decrease. Afforestation, a water–soil conservation practice, positively affected the reduction of non-point source pollution; however, it also caused a reduction of streamflow.

Levy et al. (2018) in the study “Land Use Change Increases Streamflow Across the Arc of Deforestation in Brazil” found out that Deforestation increased dry season low flow by between 4 and 10 percentage points corresponding to a regional- and time-averaged rate of increase in specific streamflow of 1.29 mm/year^2, equivalent to a 4.08 km^3/year^2 increase.

Vainghan et al. (2018) in their study “Modelling impacts of climate and land use change on streamflow, nitrate, and ammonium in the Kor River, Southwest of Iran”

Land use changes were found to have a little impact on stream flows but a significant impact on water quality, particularly under an urban development scenario.

However, most of the empirical evidences indicated that land use and land cover changes and socioeconomic dynamics have a strong relationship; as population increases the need for cultivated land, grazing land, fuel wood, settlement areas also increase to meet the growing demand for food and energy, and livestock population. Thus, population pressure, lack of awareness and weak of management are considered as the major causes for the deforestation and degradation of natural resources.

2.5 Hydrological modelling

The measurement of each and every variable in space and time is not possible to understand and predict the behaviour of hydrological systems (Khorchani et al., 2018). Therefore, hydrological modelling is considered as the heart of hydrological studies to solve and manage various hydrological problems (Jain and Singh, 2017).

Hydrological models require meteorological data and spatial-temporal watershed characteristics for accurate evaluation, modelling and prediction of the dynamic water balance of a watershed (Kumar et al., 2018).

Mango et al. (2011) in their paper applied Soil Water Assessment Tool (SWAT) to investigate the response of the headwater hydrology of the Mara River to scenarios of continued land use change and projected climate change. The results of the analysis indicated that any further conversion of forests to agriculture and grassland in the basin headwaters would reduce dry season flows and increase peak flows, leading to greater water scarcity at critical times of the year and exacerbating erosion on hillslopes.

Im et al. (2009) used the model MIKE SHE to describe the impact of forest-to-urban land use conversion on watershed hydrology. The results from the changes in land use was a runoff increase in the whole watershed and overland flow due to the expansion in urban area that encroached on forest land. Urbanization increases runoff flow by decreasing the infiltration rate and evapotranspiration.

2.5.1 Brief history of hydrological models

A model represents the physical, biological and/or chemical catchment characteristics and simulates the natural hydrological processes. It aids in making decisions, particularly where data or information are scarce or there are large numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability when correctly chosen and adjusted to extract the maximum amount of information from the available data. Hydrological models can be classified as deterministic or random models, lumped, semi distributed and fully distributed.

2.5.1.1 Lumped models

Parameters do not vary spatially within the basin and response is evaluated only at the outlet, without explicitly accounting for the response of individual sub basins. It describes the process mathematically in a lumped conceptual way. The advantages of the lumped conceptual models are the simplicity and limited requirements of input data. Some examples are SCS-CN based models and Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation and Stream (IHACRES) (Jakeman at al., 1900).

2.5.1.2 Semi-distributed models

The parameters of the semi distributed models are partially allowed to vary in space by dividing the basin into a number of smaller sub basins. In other words, semi-distributed models are a set of algorithms that generates input required for hydrologic/hydraulic modelling by considering subunits of the water shed under study (American Society of Civil Engineers [ASCE], 1998). One advantage is that the structure is more physically based than the lumped models and they require less data input than distributed models. Examples of semi-distributed models include; Storm Water Management Model (SWMM) (Girona´s et al., 2010), Hydrologic Engineering Centre – Hydrologic Modelling System (HEC-HMS) (Ebrahim et al., 2013), Soil Water Assessment Tool (SWAT) (Betrie et al., 2011) and Hydrologiska Byr˚ans Vattenavdelning (HBV) (Bergstr¨om, 1976).

2.5.1.3 Distributed models

This type is more complex and takes into account the spatial variability of both physical characteristics and meteorological conditions. These types of models for instance HYDROTEL (Fortin et al. 2001), MIKE SHE (Danish Hydraulic Institute [DHI], 1999) and MIKE 11 (DHI, 1999) require a large amount of data and their parameters are fully allowed to vary in space at a resolution chosen by the user.

Distributed models are said to provide highest accuracy in the rainfall runoff modelling but if accurate data is available.

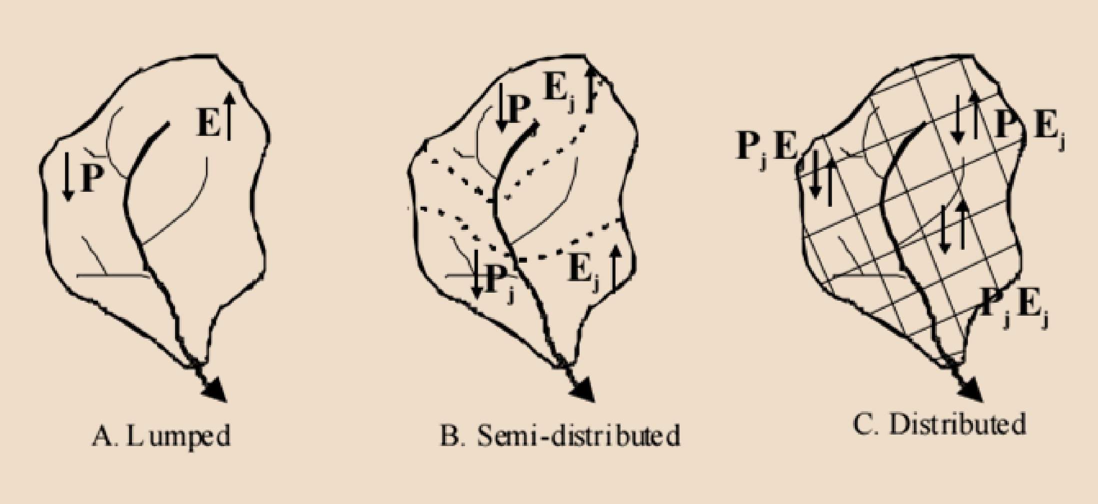


Figure 2-1: Types of models (Source: Neitsch et al., 2009)

2.5.2 Description of some models

2.5.2.1 MIKE SHE

MIKE SHE covers the major processes in the hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow and channel flow and their interactions (DHI, 1999). MIKE SHE uses MIKE 11 to simulate channel flow. MIKE 11 includes comprehensive facilities for modelling complex channel networks, lakes and reservoirs, and river structures, such as gates, sluices, and weirs (Graham and Butts, 2005). There are, however, important limitations to the applicability of such physics based models. For instance, it is widely recognized that such models require a significant amount of data and the cost of data acquisition may be high; the relative complexity of the physics-based solution requires substantial execution time.

2.5.2.2 TOPMODEL

TOPMODEL is a rainfall-runoff model that takes advantage of topographic information (specific catchment area and wetness index) related to runoff generation, although Beven et al. (1991) prefer to consider TOPMODEL as not a hydrological modelling package, but rather a set of conceptual tools that can be used to reproduce the hydrological behaviour (in particular the dynamics of surface or subsurface contributing areas) of catchments in a distributed or semi-distributed way (Beven and Kirkby, 1979).

2.5.2.3 HEC-HMS

Model HEC-HMS (Hydrologic Engineering Centre – Hydrologic Modelling System) is a continuator of model HEC-1 developing since 60s by the US Army. It is mainly lumped model. Its great advantage is that fact, that it is a freeware, also in Internet available. The model package HMS is designed to simulate the precipitation-runoff processes of dendritic watershed systems. For HEC-HMS model an extension of ArcView 3.x called HEC-GeoHMS was also created. This extension is able to derive some basic hydrological characteristics of the basin-watersheds, water flow directions, flow accumulations, slopes, etc. With HMS both manual and automatic calibration of parameters is possible. Regarding the type of a model (suitable for catchments up to 500 km2) the calibration takes place on short flood events.

2.5.2.4 SWAT model

The SWAT model is a physically-based continuous time, spatially distributed model designed to simulate water, sediment, nutrient and pesticide transport at a catchment scale on a daily time step. The model was developed by the U.S. Department of Agricultural Research Service (ARS) and scientists at Universities and research agencies around the world. Arc SWAT extension of Arc GIS is a graphical user interface for the SWAT model. The SWAT model is developed and refined by the water balance equation below which is the base of the hydrologic cycle simulation in SWAT.

$$Sw_t = Sw_0 + \sum_{i=1}^{t} R_{day} + Q_{surf} - E_a - W_{seap} - Q_{gw} \qquad 2.1$$

in which SW_t is the final soil water content (mm), SW_O is initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), $Wseep$ is the amount of water entering the vadose zone from the soil profile on day i (mm), and Qgw is the amount of return flow on day i (mm). SWAT is a deterministic model such that each successive model run that uses the same inputs will produce the same outputs.

SWAT model first divides a watershed into sub basins which is connected through a stream channel and then these sub basins are further divided into smaller homogenous units with a unique combination of soil, land use and vegetation types in a watershed known as Hydrologic Response Units (HRU). SWAT uses the CN method to partition precipitation into either infiltration, which can then reach a stream by several flow paths, or to overland runoff, which flows directly to a stream (Neitsch et al., 2005).

2.5.3 Sensitivity analysis

According to Neitsch et al. (2005), the sensitivity analysis identifies the effect of changing the calibration parameters on stream flow. Identification of the key parameters and the parameter precision required for calibration is mandatory (Arnold et al., 2012). Sensitivity analysis can most likely complete the calibration step by varying successively or simultaneously the parameters around optimal values (measured or calibrated), clarifies the "domain of indifference" of each parameter within the quality of the simulation which is not significantly impaired. This allows to detect the parameters to which the model is insensitive and simplify the calibration step.

2.5.4 Calibration

The process of estimating the values of model parameters which cannot be accessed directly from the field data is called Calibration. Calibration can be accomplished manually or using auto calibration tools in SWAT that is Soil Water Assessment Tool-Calibration and Uncertainty Program (SWAT CUP). This study adopted auto calibration tool SWAT CUP since it links SUFI 2 algorithm to SWAT according to Narsimlu et. al., (2015).

2.5.5 Model validation

This is the most critical step, starting by checking if the calibrated model simulates correctly the series of data (spatial and temporal) which is not used during calibration. The validation can be done either in a purely intuitive way as the visual comparison of results made using graphs or tables, or analytically as the statistical comparison of results made with appropriate testing or using experimental criteria such as the criterion of Nash-Sutcliffe (1970).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

This chapter deals with the description of acquisition of various land use maps, hydrological and remote sensing data. Methodology for generation of input parameters for SWAT model using basic thematic layers is also described. Procedures for calibration, validation and performance evaluation of the model are also described in this chapter.

3.2 Study Area

3.2.1 Location

Mpanga catchment is located in the south-western Uganda. It is along the border with Democratic Republic of the Congo and is part of the Lake George and Lake Albert sub-basins situated within the Nile basin. It covers a surface of approximately 2171 km^2, with its waters flowing over a distance of approximately 200 km through the districts of Kabarole, Kyenjojo and Kamwenge before discharging into Lake George as shown in Figure 3-1.

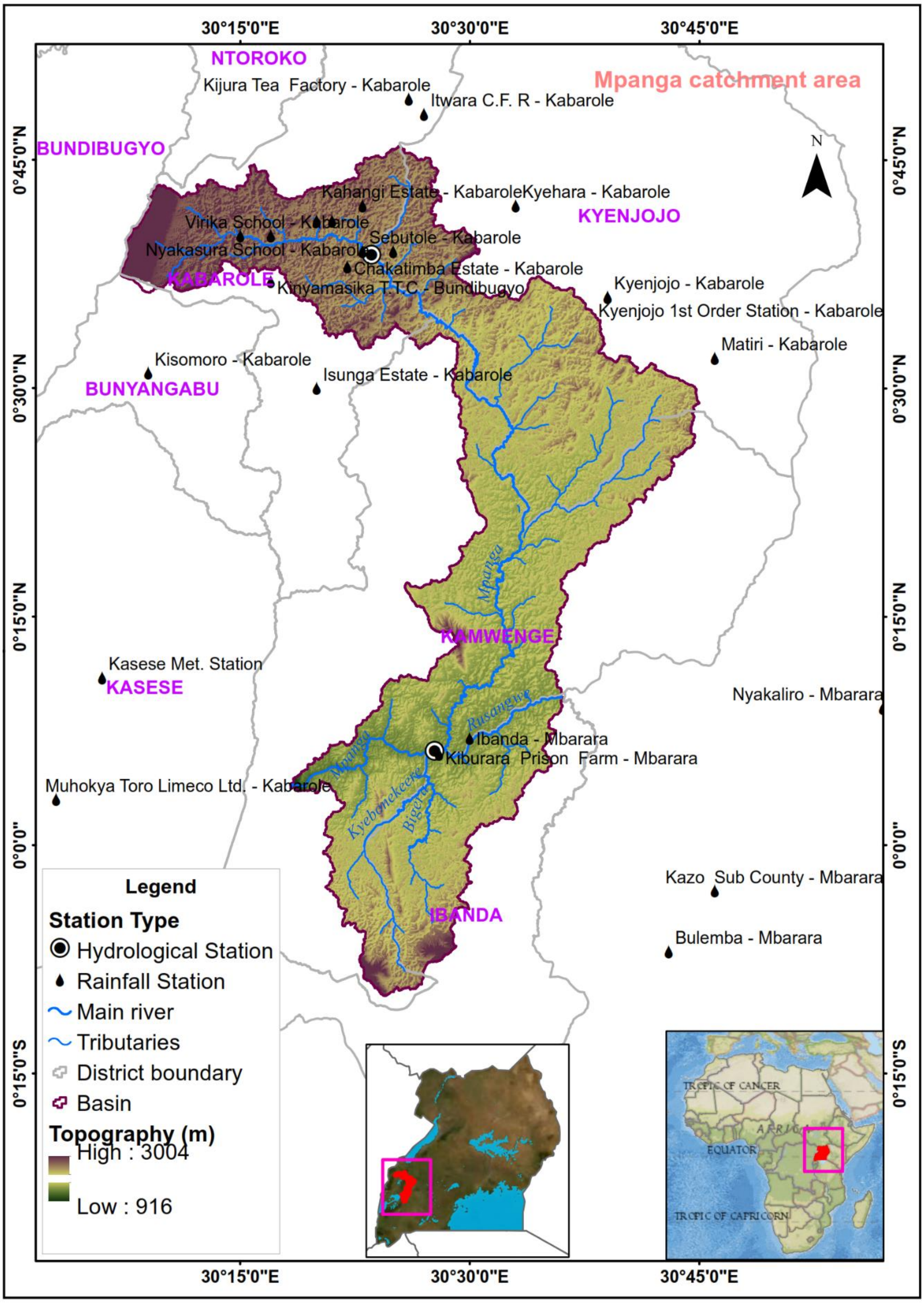


Figure 3-1: River Mpanga catchment

3.2.2 Topographic and geophysical features

Altitudes range from 3,004 m in the source areas down to 915 m at the outlet. The northern part of the Mpanga catchment is hilly but the southern region consists of gentle sloping land with few undulations.

3.2.3 Relief and Climate

The catchment comprises of a variety of climatologically and ecologically different regions. They range from a year-round wet climate in the source area of the steep Rwenzori mountains (2000-3000 mm annual rainfall), over a wet climate with two short dry seasons per year (1400 mm annual rainfall) in the mid-range regions of the system, to the drier downstream region (1000 mm annual rainfall) with pronounced dry and wet seasons. Depending on altitude and season, mean temperatures from source to mouth areas vary from below 10 °C to over 22 °C.

3.2.4 Land use and vegetation cover

The area is covered by cropland (subsistence and commercial), forests (dense, moderate and sparse), settlements (urban and rural setups), wetlands/swamps, woodland (dense, moderate and sparse) and waterbodies.

3.3 Data collection and processing

The spatially distributed rainfall-runoff hydrological modelling data needed for the Arc SWAT interface include Digital Elevation Model (DEM), Land Use/Land Cover (LULC) map, Soil map, Weather data (precipitation, temperature, solar radiation, wind velocity, relative humidity) and Stream flow (discharge) data. This data was collected from various sources as presented below in Table 3-1. It was pre-processed before using it as the input to the hydrological model.

Table 3-1: Type and Sources of Data Collection

Data Type	**Scale/ Period (s)**	**Source (s)**	**Description**
Digital Elevation Model (DEM)-Terrain	30 m × 30 m	United States Geological Surveys (USGS) -Earth Explorer (EE) website	Shuttle Radar Topography Mission (SRTM) (.tiff)
Land Use and Land Cover (LULC) map	2000, 2008 and 2014	National Forestry Authority (NFA) offices in Kampala	Reclassified LULC map of 2000,2008 and 2014 (.img)
Soil map	1:5,000,000	Food Agricultural Organisation (FAO) http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases-FAO UNESCO-soil-map of the world/en/	Clipped Soil map for Mpanga catchment showing Soil types, classification and physical properties

Data Type	**Scale/ Period (s)**	**Source (s)**	**Description**
Daily observed stream discharge RGS. 84215	2000 - 2013	Ministry of Water & Environment (MoWE) offices in Luzira	Stream discharge values (m^3/s)
Daily observed rainfall data	2000 - 2013	Global Weather Data for SWAT https://globaleather.tamu.edu/	Precipitation (mm)
Daily observed temperature (min and max)			Temperature (°C)
Solar radiation			Solar (MJ/m^2)
Relative humidity			Relative Humidity (fraction)
Average wind speed			Wind (m/s)
Administrative boundary maps of the project area	2018	Uganda Bureau of Statistics (UBOS), 2018	(.shp file)

3.3.1 Digital Elevation Module (DEM)

An SRTM DEM of 30 m resolution for Uganda was downloaded from United States Geological Survey (USGS) website https://lta.cr.usgs.gov [Accessed 4th June 2019]. It was processed in ArcGIS environment by defining its projection to Northern Hemisphere using WGS 1984/UTM zone 36N coordinates system where Uganda lies. The Area of Interest (AOI) was then clipped out using the obtained administrative boundary map from UBOS to get the exact study area. This topographical/terrain data was used to delineate the watershed and sub-basins as the stream network, longest reaches, and drainage surfaces.

3.3.2 Land Use and Land Cover (LULC) Data

The classified 2000, 2008 and 2014 National Land Cover maps at scale of 1:250 000 with a 30 m resolution were obtained from National Forestry Authority (NFA) in Kampala. This was after the LULC raster maps for Uganda downloaded from Global Land Cover were found to have a very low resolution. The maps were projected at WGS 1984/UTM zone 36N coordinate system and the AOI was extracted with the help of Mpanga Catchment basin watershed boundary polygon using the ArcGIS Spatial Analyst tools. The land use/cover maps were reclassified to provide the spatial information regarding the land uses/covers for agriculture/cropland, human settlements (built-up areas), forested areas, water bodies, wetlands and other lands.

3.3.3 Soil map

The soil map developed by Food Agricultural Organisation of the United Nations (FAO-UNESCO) at a scale of 1:5,000,000 was downloaded from http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases-FAO UNESCO-soil-map of the world/en/ [Accessed 5th June, 2019] and used for SWAT model. It was geo-processed to the dataset format compatible with Arc SWAT, appended to a user soil dataset, built a watershed specific soil lookup table, clipped the AOI and created a soil GIS layer for Mpanga catchment. The soil map provides the information about the Soil type, soil classification and physical properties like texture, soil depth and soil drainage attributes needed for the SWAT model. Using the Arc SWAT soil database of US and soil properties such as clay content, sand content, loam content and hydrological group; a comparative study was made to identify SWAT user soils having the same characteristics as soils of the study area. Three best soils namely; BENSON = Black loamy over red clay loams, SWANTON = Dark red clays sometimes underlain by laterite and WEIDER = Grey-humus clays, Grey sands and Red sandy-clay-loamy soils were identified.

3.3.4 Weather/Meteorological Data

To simulate regional weather, inputs of minimum and maximum daily temperatures, daily precipitation, daily relative humidity, daily solar radiation and daily average wind speed data were required. The observed daily data of the weather stations in the catchment were downloaded from Global Weather Data for SWAT https://globalweather.tamu.edu/ [Accessed 29th June, 2019] for the years 2000 -

2013. This is because the weather data obtained from Ministry of water and Environment had a lot of missing values that could not allow successful model simulation. More so the data was a representative of the period in which a lot of concerns have been raised as regards the changes in the Mpanga catchment area.

3.3.5 Stream Flow (Hydro – Meteorological) data

The daily river discharge/flow data was obtained from Ministry of Water and Environment for the River Gauging Station (RGS) No. 84215. The observed daily stream flow data was converted to average monthly stream flow using pivot tables in excel. It was then arranged in SWAT CUP format as required by calibration inputs.

This data was used to perform calibration and validation of the SWAT model. The stream flow data for first three (3) years (2000 to 2002) was used for the warm up period. Warm period is the time allowance given to the software during simulation to first get used to data before simulation of the final results. The data for 2003 to 2008 was used for model calibration and the remaining five (5) years of data (2009 -2013) for model validation.

3.3.6 Software and equipment used in data processing

The equipment, Geographical Information Systems (GIS) and Remote Sensing (RS) software used in this research include;

i) ArcGIS 10.2 which provides most spatial modelling tools in the Arc Tool Box.

ii) Arc SWAT 2012.10.2.19 Plug-in – used to simulate stream discharge from the hydrological model of the catchment. This was obtained from http://www.brc.tamus.edu/swat/ArcSWAT.html [Accessed 30th June, 2019].

iii) SWAT-CUP 2012 - used to detect sensitive parameters, automatically calibrate and validate results https://swat.tamu.edu/software/swat-cup [Accessed 15th July, 2019].

iv) Google Earth pro - used verify streams and land use/cover based on the year of data acquisition.

v) Microsoft package (MS Word, Excel, Power point).

3.4 Estimation of stream flow

To estimate the stream discharge along its length, hydrological model (rainfall-runoff modelling) was built using SWAT tool. Arc-SWAT is an ArcGIS extension which is a graphical user interface for the Soil Water Analysis Tool (SWAT) installed as a plug-in to be used in analysis (Arnold et al. 2012).

3.4.1 SWAT Model Input and Set-Up

Figure 3-2 shows the processes that were undertaken to set up a SWAT model. Among the steps include automatic watershed delineation, HRU analysis, creation of input tables and SWAT simulation.

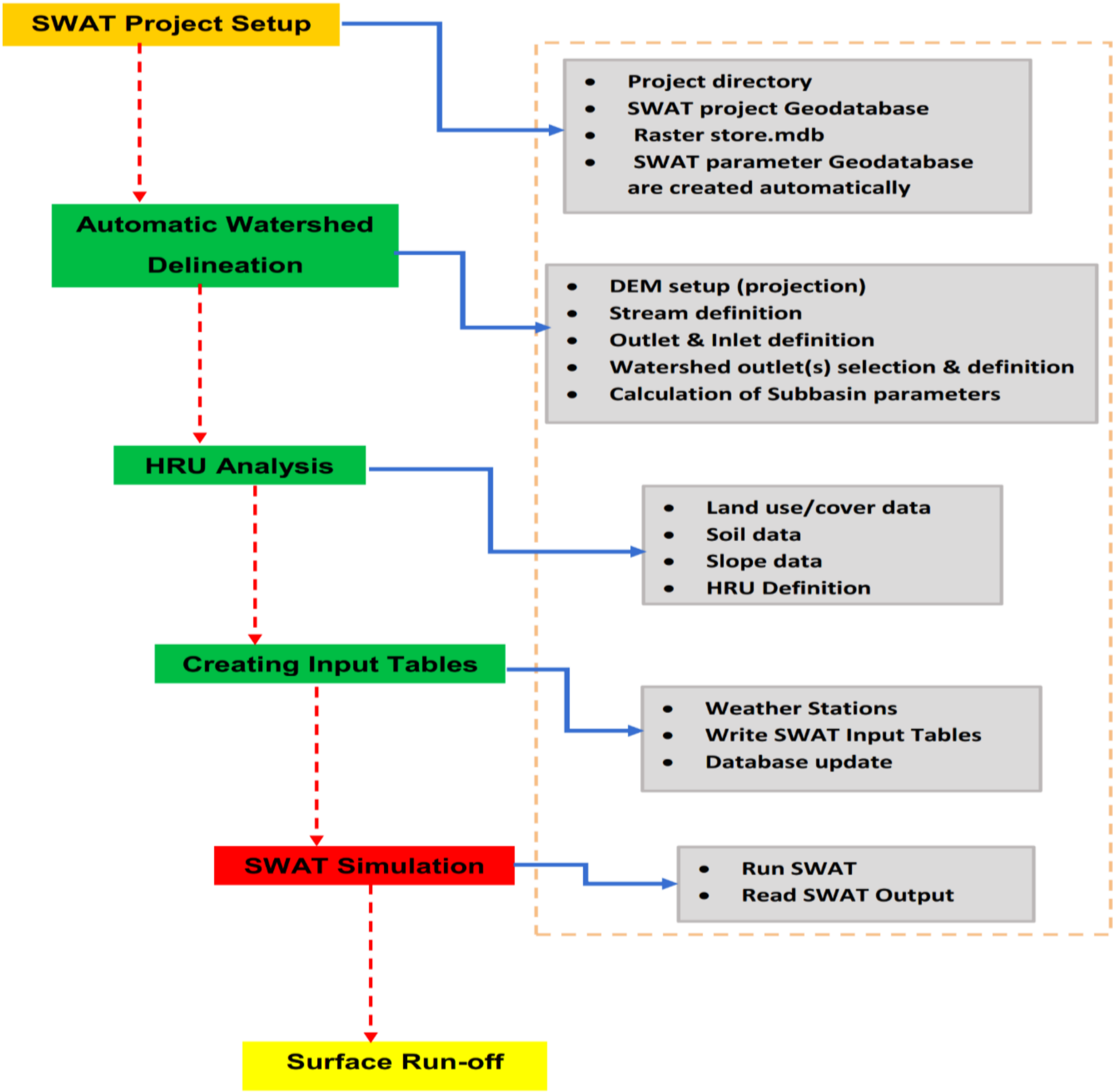


Figure 3-2: Steps involved in setting up ArcSWAT hydrological model (Source: Arnold et al., 2012)

3.1.1.1 Terrain (DEM) processing for Watershed Delineation

The watershed delineation process in hydrological modelling includes five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub basin parameters. Arc SWAT automated watershed delineation interface was used to delineate the watershed. Under DEM setup, a defined and projected clipped 30 m resolution DEM was used. Stream definition on DEM-based conditions was performed to get flow direction and accumulation. Many outlets were created automatically by the software based on the given threshold but only one at the outlet was selected as the gauging point for the catchment calibration.

3.1.1.2 Creating and determining Hydrologic Response Units (HRUs)

After watershed delineation, the creation of Hydrologic Response Units (HRUs) process was executed. Under the land use/ soils/ slope definition subsection, the geo-referenced classified land-use land-cover (secondary) raster map was imported into Arc SWAT in HRU Analysis section. The land use/cover, soil and slope data and their look up attribute tables were also imported and defined as required by SWAT. The LULC and Soils were reclassified, overlapped and connected with the SWAT catalogues and ready for HRU definition. The LULC was reclassified into five classes in “SWAT Land Use Classification Table” namely; FRST – Forests, AGRL – Agricultural land, WATR – Water bodies, URBN – Settlements/Built-up, WETL – Wetlands and PAST – Pasture and Grasslands.

The soils were reclassified into three groups/types corresponding to SWAT database for FAO soils in “SWAT Soil Classification Table”. These included BENSON = Black loamy over red clay loams, SWANTON = Dark red clays sometimes underlain by laterite and WEIDER = Grey-humose clays, Grey sands and Red sandy-clay-loamy soils.

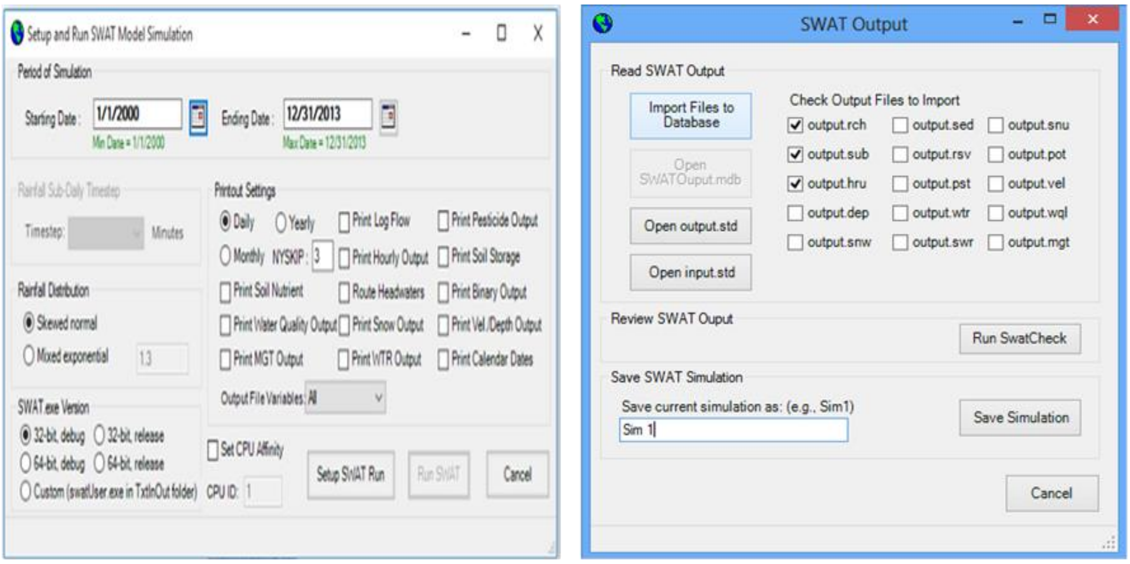
Also, in SWAT Slope Classification Table, five slope classes in number were set each having the lower and upper class limit in percentage (%) namely; class 1 (0 – 5%), class 2 (5 – 20%), class 3 (20 – 30%), class 4 (30 – 55%) and class 5 (55 – 9999%). When the overlay option was executed, the HRU feature class and Overlay reports were created.

Still under HRU Analysis, during the HRU definition, the threshold levels set for land use, soil and slope were used to define the number of HRUs within the sub-basin as well as the watershed. The minimum threshold areas of 6% for land use, 4% for soil class and 2% for slope were set. During this process, SWAT divides the basins into smaller pieces which have the particular soil, land use/cover and slope range combination known as HRU. The option to create multiple HRUs per sub-basin was enabled and generalized based on dominant land use, soil, and slope characteristics.

3.1.1.3 Weather data definition, SWAT setup and Run

The weather data files were imported into SWAT. These files contained data of the same starting and ending dates for the ease of SWAT simulation. The WGEN_user option of generating weather data was used. Only the files containing the coordinate locations of the validated weather data (precipitation (pcp), temperature (tmp), relative humidity (rh), wind speed (wind) and solar radiation (solar) were imported into SWAT. All swat input tables were selected and written automatically. The SWAT model was finally setup for simulation by selecting and defining the simulation period of 2000 to 2013, rainfall-runoff/routing method, rainfall distribution and potential evapotranspiration method in the "SWAT Setup and Run" screen.

According to the acquired data Table 3-1, the model was simulated from 2000 to 2013 (14 years), and the first 3 years were used as a warm-up period to allow the processes simulated to reach a dynamic equilibrium and decrease the uncertainty of the initial conditions of the model. The simulation includes both dry and wet years and leap years occurring in the historical period as in Figure 3-3. The final simulation was saved as Sim 1.


Setup and Run SWAT Model Simulation

Period of Simulation

Starting Date : 1/1/2000

Min Date = 1/1/2000

Ending Date : 12/31/2013

Max Date = 12/31/2013

Rainfall Distribution: ● Skewed normal ○ Mixed exponential 1.3

SWAT.exe Version: ● 32-bit, debug ○ 32-bit, release ○ 64-bit, debug ○ 64-bit, release ○ Custom (swatUser.exe in TxtInOut folder)

Printout Settings: ● Daily ○ Yearly ○ Monthly NYSKIP: 3

☐ Print Log Flow ☐ Print Pesticide Output ☐ Print Hourly Output ☐ Print Soil Storage ☐ Print Soil Nutrient ☐ Route Headwaters ☐ Print Binary Output ☐ Print Water Quality Output ☐ Print Snow Output ☐ Print Vel./Depth Output ☐ Print MGT Output ☐ Print WTR Output ☐ Print Calendar Dates

Output File Variables: All

☐ Set CPU Affinity CPU ID: 1

SWAT Output

Read SWAT Output

Check Output Files to Import

☑ output.rch ☐ output.sed ☐ output.snu
☑ output.sub ☐ output.rsv ☐ output.pot
☑ output.hru ☐ output.pst ☐ output.vel
☐ output.dep ☐ output.wtr ☐ output.wql
☐ output.snw ☐ output.swr ☐ output.mgt

Review SWAT Ouput

Save SWAT Simulation

Save current simulation as: (e.g., Sim1) Sim 1

Figure 3-3: SWAT model setup, running SWAT check and saving simulations

3.4.2 *Sensitivity Analysis*

Sensitivity analysis is used to estimate the rate of change in model outputs in relation to change in the model inputs. It helps to determine which parameters are important for accurate results (Abbaspour, 2015). SWAT-CUP used the multiple regression analysis to determine the sensitive parameters. Then, the *t*-distribution which is a statistical distribution was used to get the statistic value (*p*-value) of each parameter while keeping all the others constant. The smaller the *p*-value, the more sensitive and significant is the parameter. Generally, a *p*-value < 0.05 is the accepted point at which to reject the null hypothesis (Abbaspour, 2015).

Global sensitivity analysis was conducted using a built in SWAT CUP to establish the most sensitive parameters and varies all parameters simultaneously. Only 15 parameters were chosen for sensitivity analysis as shown in Table 3-2. SWAT simulations were done for the entire period (2000 – 2013), where the period 2000 – 2002 served as a warm-up period.

Table 3-2: SWAT input parameters used to carry out sensitivity analysis

No.	Parameter name	Description	Range		Method
			Min	Max	
1	Cn2.mgt	Moisture condition II curve number	-0.2	0.2	Replace
2	Esco.hur	Soil evaporation compensation factor	0	1	Replace
3	Sol Awc.sol	Available water capacity of the soil layer	0	1	Relative
4	Sol Z.sol	Depth from soil surface to bottom of	-0.2	0.2	Relative
5	Gwqmn.gw	Threshold water level in shallow aquifer	0	2	Replace
6	Sol K.sol	Saturated hydraulic conductivity of first	0	200	Replace
7	Alpha Bf.gw	Base flow alpha factor	0	1	Replace
8	Epco.hur	Plant uptake compensation factor	0	1	Replace
9	Ch N2.rte	Manning’s value for the main channel	0	0.3	Replace
10	Ch K2.rte	Effective hydraulic conductivity of main	0	500	Replace
11	Surlag.bsn	Surface runoff lag coefficient	0	24	Replace
12	GW	Groundwater evapotranspiration	0.0	0.2	Replace
13	GW Delay.gw	Ground delay (days)	30	450	Replace
15	OV_N.hru	Manning's "*n*" value for overland flow	0.0	1	Replace

Note: (1): Multiplying initial parameter by value in percentage; (2): replacing initial parameter by value

3.4.3 SWAT Model Calibration

Model calibration is the process of tuning the model parameters within recommended ranges to match the simulated output with the observed data. Therefore, it involves the modification of parameter values and comparison of predicted output of interest to measured/recorded data at selected outlet until a defined objective function is achieved (Abbaspour, 2015).

In this study, after the most sensitive model parameters were identified, they were used for the calibration of the SWAT models by using SWAT-CUP combined with SUFI-2 method. This is an automatic calibration procedure used SWAT CUP based on the recommendations given in SWAT CUP user manual by Abbaspour, (2015). The parameters were automatically adjusted in order to simulate the streamflow to meet the observed value. The model calibration process was performed for the same period (2003–2008).

Steps followed in calibration of stream flow using SWAT CUP

Figure 3-4 shows the steps followed in calibration of the stream flow using SWAT CUP. These include SWAT CUP project setup, calibration inputs, executable files and calibration outputs as detailed below.

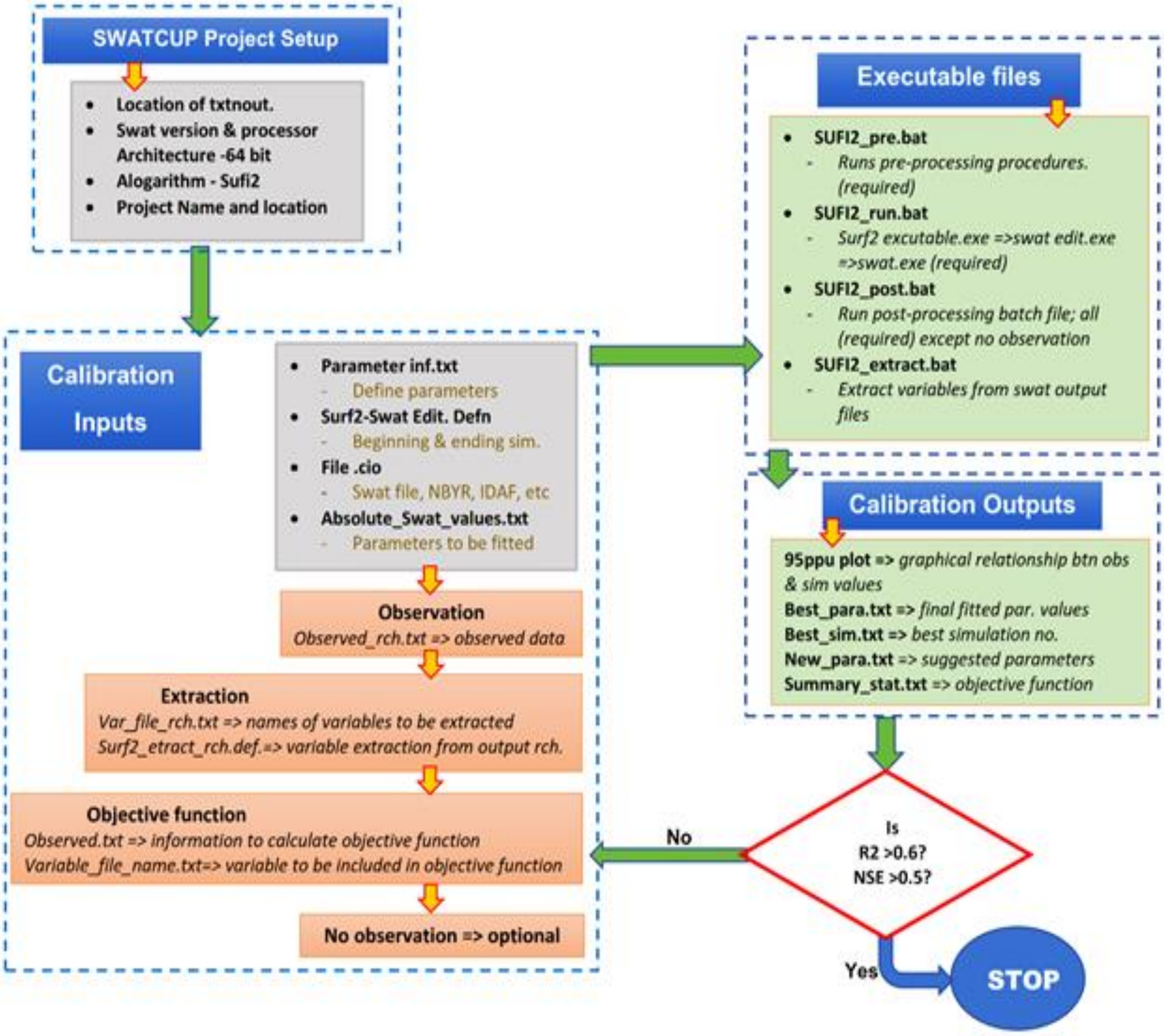


Figure 3-4: Calibration process using SWATCUP (Source: Abbaspour, 2015)

❖ **SWAT CUP project setup**

- TxtInOut folder of SWAT was copied to a new directory where all the CUP simulations were to be developed.
- SWAT CUP was opened and by clicking on the top left start icon, a TxtInOut folder for SWAT simulation to be used for calibration was selected.
- Under SWAT version selection, version 2012 and 64-bit processor architecture were selected.

- Then SUFI2 was chosen as the calibration method for the project.
- Finally, on project set-up, the project name was defined and project location was also defined as new directory created in the first step.

❖ **Calibration inputs**

- Once the project was created, the next steps focused on defining the "Calibration inputs" located on the Project Explorer area of the interface.
- Par_inf.txt file. In this file, 15 parameters to be optimized were defined and configured using both form view and text view. Number of simulations was also defined as 50. The "relative" option was used only for spatial parameters.
- SUFI2_swatEdit.def file. Here the starting and ending simulation numbers were defined as 1 and 50 respectively.
- "File.cio" file. Here NBYR (number of years simulated) = 14yrs, IYR (beginning year of simulation, not including warm up period) = 2003, and NYSKIP (number of years to skip-warm up years) = 3 were defined.
- "Absolute_SWAT_Values.txt" file. This table contains predefined values that are assumed to be the max valid ranges for some of the parameters. No modifications were done in this file as instructed by the user manual.
- Observations / Observed_rch.txt file. Observed stream flow data was input here, number of observed variables was defined as 1 since we only had one gauging station, observed variable =>FLOW_OUT_21 and number of data points => 4018.
- Extraction / Var_file_rch.txt. Here, file name of the observations defined in "Observed_rch.txt" was defined as FLOW_OUT_21.

- SUFI2_extract_rch.def file. Here, definition of how variables should be extracted from the Output.rch file was made as; number of variables to get => 1, variable column number(s) in the swat output file => 7, total number of sub-basins => 23, number of sub-basins to get for the first variable => 1, beginning year of simulation not including the warm up period => 2003, end year of simulation => 2013, time step => (1) daily.
- Objective function / Observed.txt. This file contains all the information of the “Observed_rch.txt” plus some additional information for the calculation of the objective function. Number of observed variables was kept as 1, Objective function was chosen as R^2 (3), min value of objective function => 0.5, name of the variable => FLOW_OUT_1, Number of data points => 4018. Observed stream flow data was also input in this section. Consistency with Observed_rch.txt inputs was ensured.
- Objective Function / Var_file_name.txt. Here, the variable to be included in the objective function was defined as FLOW_OUT_21.
- No observation sections. Used for the extraction and visualization of uncertainties in the variables for which we have no observations but would like to see how they are simulated. This section was left out since it is optional.
- When all the Calibration inputs were all configured according to the above steps, on the “Home” tab was clicked followed by “save all” then “close all” and then “Calibrate” wheel and then select “Execute all”.
- A DOS windows asked for confirmation of start of process, “Y” was written followed by hitting enter to start execution process. After that the window was

closed by clicking OK, the execution of SUFI 2. Run. Bat followed by also clicking OK and the simulations started.

- Once the simulations were finished, by clicking OK the window was closed and went back to the main SWAT CUP interface. Once there, clicked OK to “Start the execution of SUFI2_post.bat” some messages appeared. After going back to the main interface, iteration was saved. The results appeared in the Iteration History section.
- The saved Iteration had record of all the calibration inputs used, and provided “Calibration Outputs” and “Sensitivity Analysis” results.

❖ Calibration outputs

SWAT CUP has very many calibration outputs but the most important ones include:

- 95 percent prediction uncertainty (95ppu plot) which illustrate graphically the relationship between the observed and simulated data.
- Best parameters (Best_Pae.txt) information text file that contains the minimum and maximum parameter values and their final fitted values.
- New parameters (New_Par.txt) information text file that contains the suggested parameter ranges for the next iteration.
- Summary statistic (Summary_Stat.txt) information text file that shows the value of the objective function that is NSE and R^2.
- All these steps are summarised in the model flowchart as in Figure 3-4.

The degree to which all uncertainties are accounted for is quantified by a measure referred to as the *P*-factor, which is the percentage of measured data bracketed by the

95% prediction uncertainty (95PPU). The best parameter values were selected based on whether the width of the uncertainty band (*R*-factor) was close to zero and the *P*-factor was close to one. The goodness-of-fit measures used to evaluate the models predictions included both the Nash-Sutcliffe (NSE) value and the Coefficient of Determination (R^2) value. The R^2 value is an indicator of the strength of the relationship between the observed and simulated values and ranges from 0 to 1. The NSE simulation indicates how well these values fit the 1:1 line. If R^2 and NSE values are close to zero, the model is considered "unacceptable or poor" however if the values are 1.0 then the model is considered "perfect" as in Table 3-3. NSE value of 0.5 or higher was considered acceptable level of accuracy for this simulation.

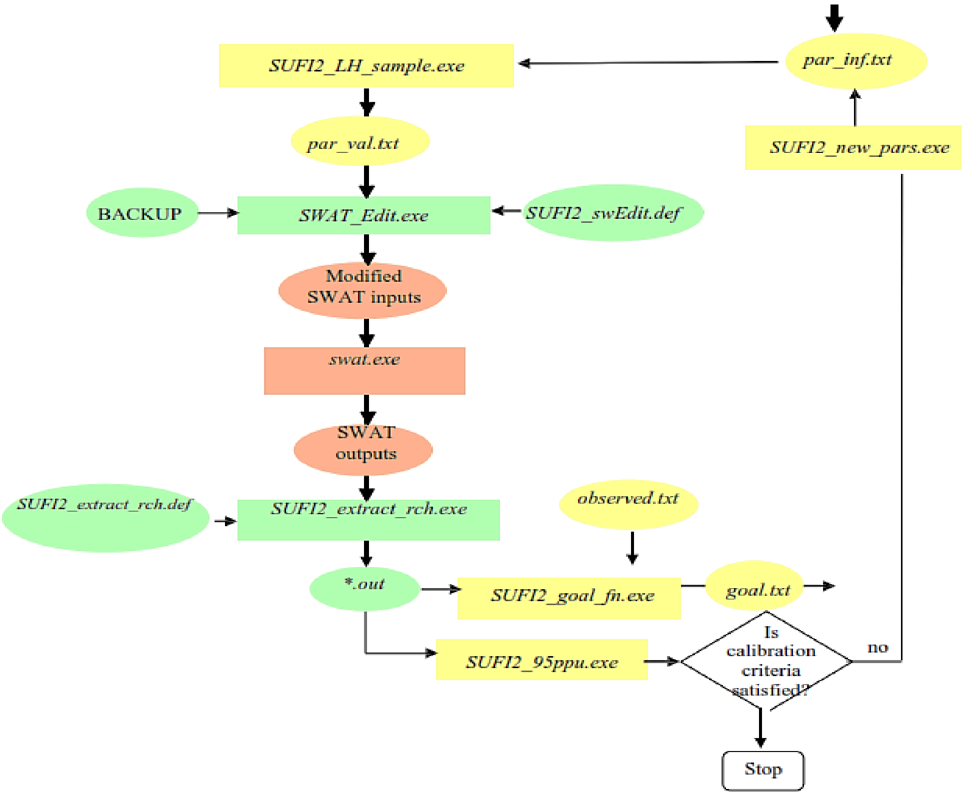


Figure 3-5: Summary of SUFI2 algorithm operation in SWAT CUP (Source: Abbaspour, 2015)

3.4.4 Model validation

Model validation is the process of determining the degree to which a model or simulation is a correct representation of the observed behaviour from the perspective of the intended uses. This validation process is also conducted by using Arc SWAT program though in this study SWAT-CUP was used. The data for a period of 5 years from 2009 to 2013 was used for the model validation process.

3.4.5 Model performance evaluation and analysis

Moriasi et al. (2007) recommended two quantitative statistics be used in model performance evaluation in watershed runoff simulations: The Nash-Sutcliffe Efficiency (NSE) and regression coefficient or coefficient of determination (R^2). Moreover, Moriasi et al. (2007) suggested a general performance rating for the recommend statistics for SWAT model simulation as presented in Table 3-3 and these were based on in this study.

Table 3-3: Performance ratings of recommended statistics for streamflow simulation

Performance rating	NSE	R^2
Unsatisfactory	$NSE \leq 0.5$	$R^2 < 0.6$
Satisfactory	$0.5 < NSE \leq 0.65$	$0.50 < R^2 \leq 0.65$
Good	$0.65 < NSE \leq 0.75$	$0.65 < R^2 \leq 0.75$
Very good	$0.75 < NSE \leq 1$	$0.75 < R^2 \leq 1$

Nash–Sutcliffe Efficiency (NSE)

The Nash–Sutcliffe Efficiency (NSE) simulation is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance. It indicates how well the plot of observed versus simulated value fits the 1:1 line. If the measured value is the same as all predictions, NSE is 1. If the NSE is between 0 and 1, it indicates deviations between measured and predicted values. If NSE is negative, predictions are very poor, and the average value of output is a better estimate than the model prediction (Nash and Sutcliffe, 1970). NSE is defined as:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_{mean}^{obs}\right)^2} \right] \qquad (3.1)$$

Where Q_i^{obs} is the i^{th} observed streamflow, Q_i^{sim} is the i^{th} simulated streamflow, and Q_{mean}^{obs} is the mean of observed data.

Regression coefficient or coefficient of determination (R^2)

The regression coefficient or coefficient of determination (R^2) is the proportion of the total variance in the observed data that can be explained by the model. R^2 is the portion of the total variation explained by fitting a regression line and is regarded as a measure of the strength of a liner relationship between observed and simulated data. The closer the value of R^2 to 1 i.e. R^2>0.6, the higher is the agreement between the simulated and the measured flow.

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_{mean}^{obs}\right)\left(Q_i^{sim} - Q_{mean}^{sim}\right)}{\sqrt{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_{mean}^{obs}\right)^2} \sqrt{\sum_{i=1}^{n} \left(Q_i^{sim} - Q_{mean}^{sim}\right)^2}} \right] \qquad 3.2$$

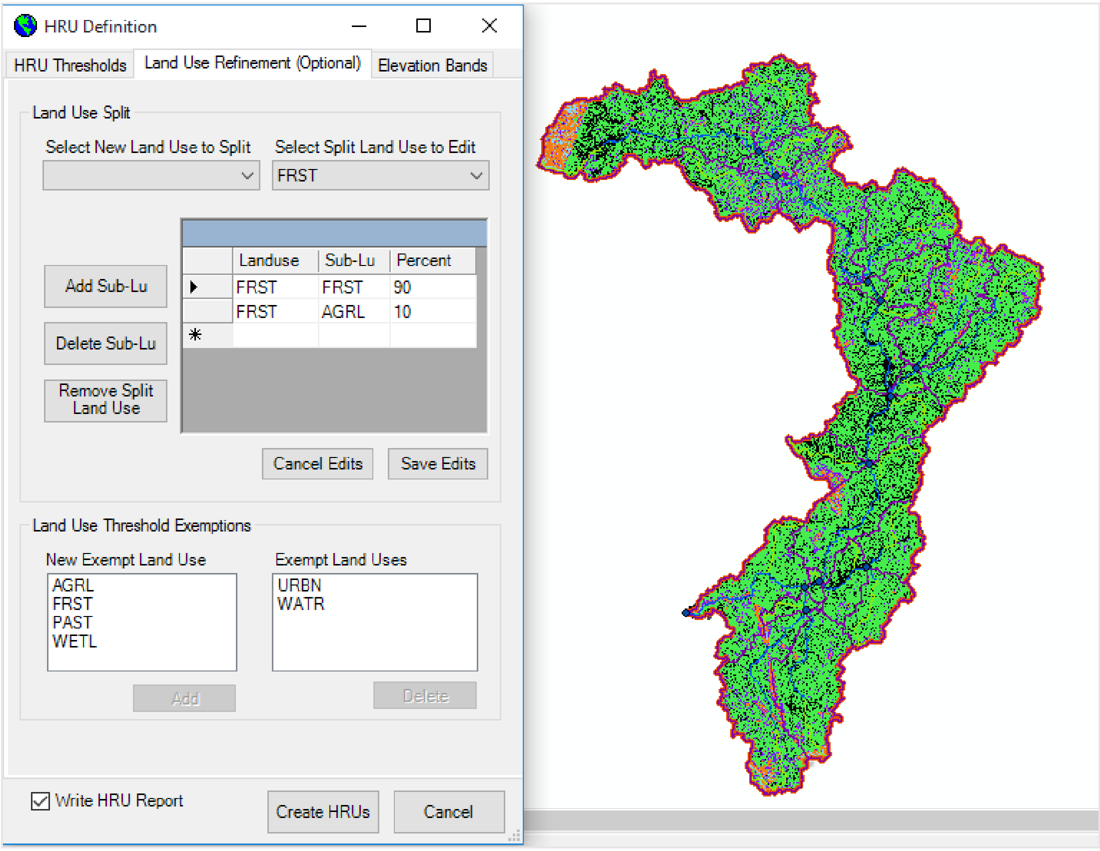
Where Q_i^{obs} is the i^{th} observed streamflow, Q_i^{sim} is the i^{th} simulated streamflow, and Q_{mean}^{obs} is the mean of observed data.

The whole process of model set-up, sensitivity analysis, calibration, validation and evaluations led to a final and properly analysis of the model. This helped to verify that the SWAT model was the most appropriate for this research.

3.4.6 Evaluation of Stream flow due to land use / land cover change (LULCC) scenario analysis

To explore the sensitivity of model outputs to land use/land cover changes mainly on the discharge of River Mpanga, land use scenarios were developed and explored. Attempts were made to ensure these were realistic scenarios in accordance to the ongoing trends of land use changes within the catchment. The land use scenarios included; conversion of forest land to crop land, cultivated area to forest land, pasture to crop land, wetlands to agricultural land and finally wetland to bare land.

This was carried out by adjusting the land use classes in the HRU analysis under HRU definition in the land use refinement option in Arc SWAT. These were adjusted by splitting the original land use with a 10%, 25%, 50% and 75% as shown in Figure 3-6. The process was repeated for all the land use classes and the SWAT model simulated to obtain the output results for each scenario. Finally, the TxtInOut folder was imported in the SWAT CUP and simulated with the fixed model parameters to obtain the simulated flows of each scenario.



Land Use Split

Select New Land Use to Split:

Select Split Land Use to Edit: FRST

Landuse	Sub-Lu	Percent
FRST	FRST	90
FRST	AGRL	10

Land Use Threshold Exemptions

New Exempt Land Use:
AGRL
FRST
PAST
WETL

Exempt Land Uses:
URBN
WATR

☑ Write HRU Report

Figure 3-6: Land use scenario analysis for conversion of forest land to Agriculture

CHAPTER FOUR: RESULTS, ANALYSIS AND DISCUSSION

4.1 Introduction

This chapter explains how land use has changed from 2000 to 2014 and watershed modelling due to these changes in River Mpanga catchment. It also details the sensitivity analysis, calibration, validation and evaluation of the model. It finally concludes with results of the flows obtained after simulation of different land uses in Mpanga Catchment and possible measures as per the scenario analysis results.

4.2 Land use/land cover changes

Figure 4-1 shows the logarithmic plot of land use/cover for the land use maps of 2000, 2008 and 2014. Agriculture/crop land was the most dominant land use in all the three land use maps with 71435 ha in 2000, 149778 ha in 2008 and 156312 ha in 2014. This was followed by Grassland which covered 91381 ha in 2000, 27068 ha in 2008 and 22536 ha in 2014. Forest was the next major land use covering 47710 ha in 2000, 25474 ha in 2008 and 23181 ha in 2014. Open water had the least coverage in these land uses with 125 ha in 2000,118 ha in 2008 and 110 ha in 2014.

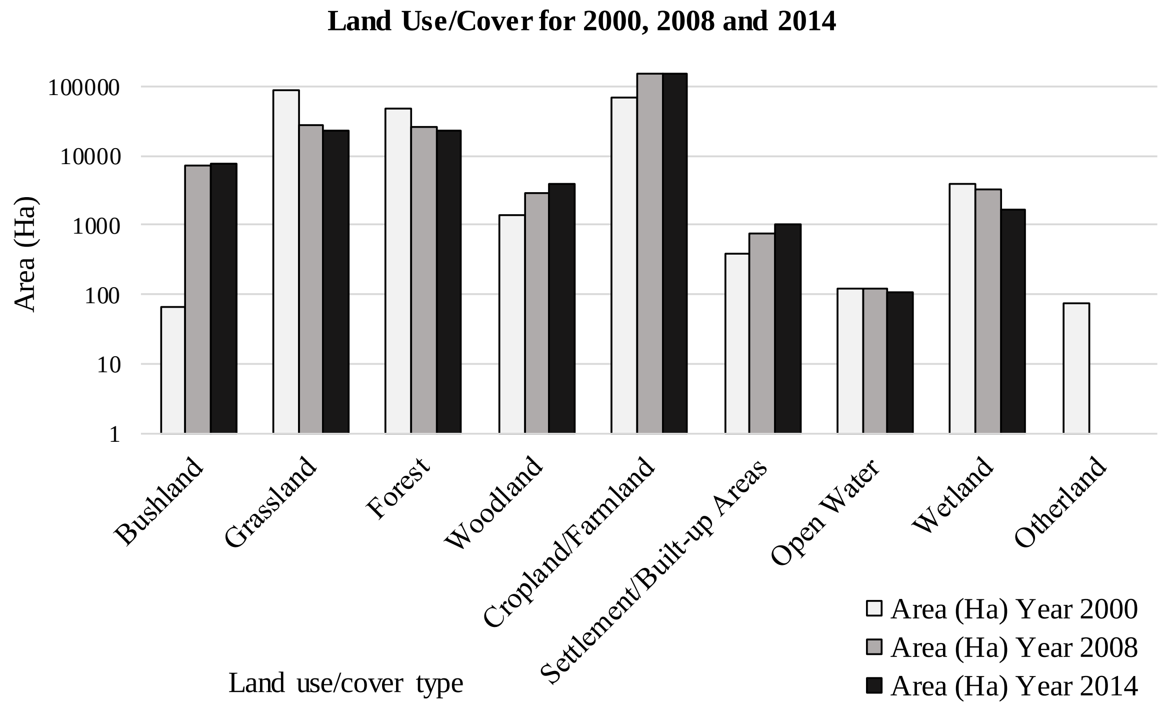


Figure 4-1: Land use/cover of River Mpanga Catchment

Table 4-1 shows that, in 2000 most of the area was occupied by grassland (42.19%), cropland/farmland (32.98%) and forest (22.03%) distantly followed by wetland (1.85%), settlement (0.18%), woodland (0.65%), open water (0.06%), bushland (0.03%) and other land (0. 03%). In 2008 the area was occupied by cropland /farmland (69.15%), grassland (12.50%), forest (11.76%), bushland (3.27%) and distantly followed by woodland, settlement, open water and wetland. In 2014, cropland was still dominant with (72.17%), followed by forest (10.70%), grassland (10.40%), bushland (3.62%), woodland (1.82%), settlement (0.48%), open water (0.05%) and wetland (0.76%).

Table 4-1: Land use /cover classes and their area coverage in Mpanga catchment

	Area (ha)			**Area (%)**		
Reclassified LULC	2000	2008	2014	2000	2008	2014
Bushland	67	7087	7843	0.03	3.27	3.62
Grassland	91381	27068	22536	42.19	12.50	10.40
Forest	47710	25474	23181	22.03	11.76	10.70
Woodland	1404	3000	3946	0.655	1.39	1.82
Cropland/Farmland	71435	149778	156312	32.98	69.15	72.17
Settlement/Built-up Areas	395	750	1036	0.18	0.35	0.48
Open Water	125	118	110	0.06	0.05	0.05
Wetland	4012	3328	1639	1.85	1.54	0.76
Other land	74	0	0	0.03	0.00	0.00
TOTAL	216603	216603	216603	100	100	100

4.2.1 Land use/cover changes in Mpanga catchment

Figure 4-2 shows how land use/cover has changed between 2000 and 2008. Between 2000 and 2008, the area under farmland, settlements and bushland had increased. The largest increment was in the area under farmland which increased by 36.17%, followed by bushland at 3.24% and settlement with 0.17%. Grassland, forest areas, open water and wetlands decreased. The decline was greatest for the grassland areas which reduced by 29.69 %. This was followed by forests which reduced by 10.27%, wetland by 0.316% and finally open water at 0.003%.

In related studies, according to Egeru and Majaliwa (2009) they found out that small scale farming had a significant influence on land use/cover changes; they observed that in Soroti District, the recovery efforts and cultivation for self-reliance led to drastic increases in small-scale farming between 1986 and 2001 at the expense of woodlands and bushlands as more hectares were converted to cropland. Rientjes et al. (2011) in their study in Gilgel Abbay showed that in the time period 1986–2001 forest land decreased from 32.9% to 16.7% while agricultural land increased from 40.2% to 62.7 %. Bewket (2003) identified agricultural conversion of 79 % of the Riverine forests of the Chemoga watershed within the Blue Nile basin in about 40 years (1957 – 1998).

Also, Kizza et al. (2017) in the study carried out in Lake Bunyonyi catchment between 1999 and 2005 indicated that small-scale farmland gained variably from all the land use/covers. It gained 26.02 km^2 from woodlots (71.7%), 5.75 km^2 (15.9%) from wetlands, 3.25 km^2 (9%) from open water, 1.23 km^2 (3.4%) from tropical high forest and 0.0245 km^2 (0.1%) from grasslands. Gwate et al. (2015) found out that between 1993 to 2004, water and grassland cover decreased by about 6.7% and 4.3% respectively. Wooded land slightly decreased by 1.6% owing to human encroachment. The area occupied by irrigated fields increased by 20.2% and the built up area increased by 100%. With the increasing population growth of 55,000 between 2000 and 2014 with a growth rate of 3.02 in Mpanga catchment as estimated by the National Population census report of 2014, more land had been cleared to carry out agriculture and settlement. Most people in the area have encroached on the river banks of River Mpanga and other water resources leading to a decrease in the area covered by the open water bodies. Therefore, this explains the magnitude of change experienced in these land cover units between 2000 and 2008 in Mpanga catchment.

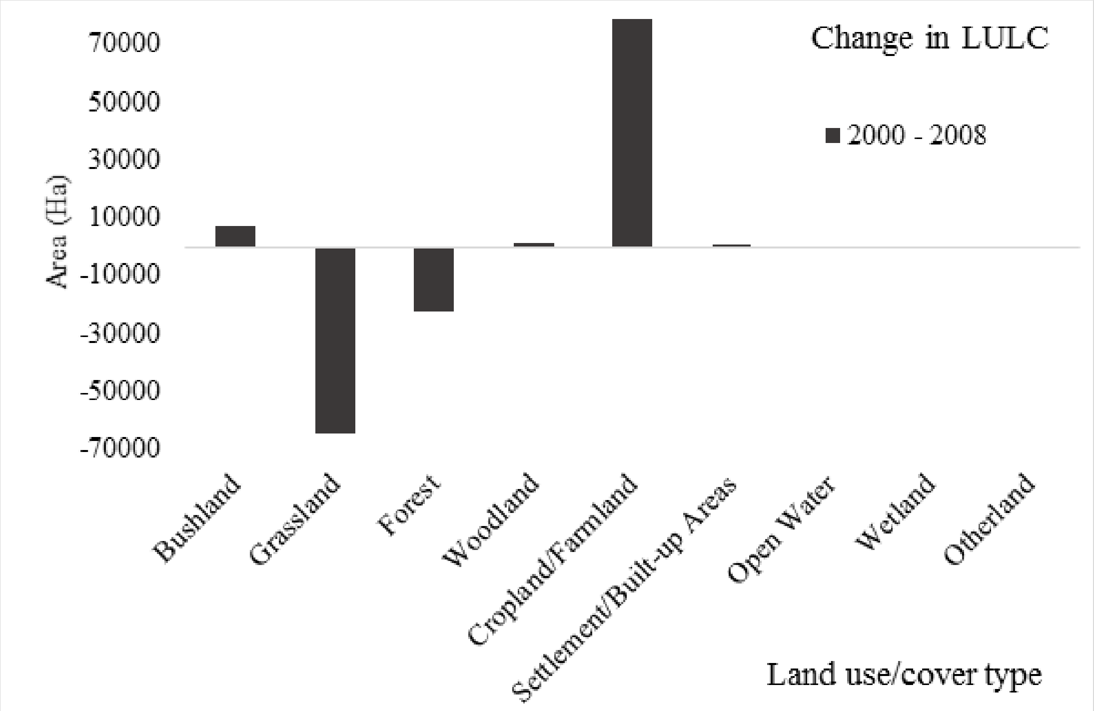


Figure 4-2: Land use/cover changes between 2000 – 2008

Figure 4-3 shows the land use/cover changes between 2008 and 2014. It indicates that between 2008 and 2014, the area under cropland/ farmland increased greatly with a percentage of 3.02%, followed by woodland 0.43%, bushland with 0.35% and then settlement by 0.13%. Also grassland reduced by 2.1%, forest by 1.06% and wetland by 0.78%. Gwate et al. (2015) in South Africa on Modder River concluded that cultivation increased at the expense of forested land and grassland in the catchment. This is in agreement with Barasa et al. (2018) who concluded that the highest gains in the land amongst the land use systems were experienced in subsistence agricultural land and grasslands protected, while the highest losses were seen in grasslands unprotected and woodland/forest in Uganda.

According to the report by the BRLi (2015) in Mpanga Catchment, it attributed the changes in the catchment to anthropogenic pressures on the wetlands and the construction of valley dams on the streams feeding the wetland areas. The decrease in grassland cover suggests that other land use options such as cultivation were encroaching into grasslands. Cutting down of trees for various uses such as firewood and timber has led to the decline on the forest cover. The decrease in the water body could be linked to invasion of river banks by small scale farmers due to continued failure of enough rainfall to sustain the rain fed agricultural practices especially in the middle and the lower parts of the catchment. The increment in cropland/farmland is attributed to increased population growth in the region mainly in Fort Portal town whose population increased from 41,000 in 2002 to 54,275 in 2014 which has been designated as “tourist city of Uganda” attracting a lot of people in the region.

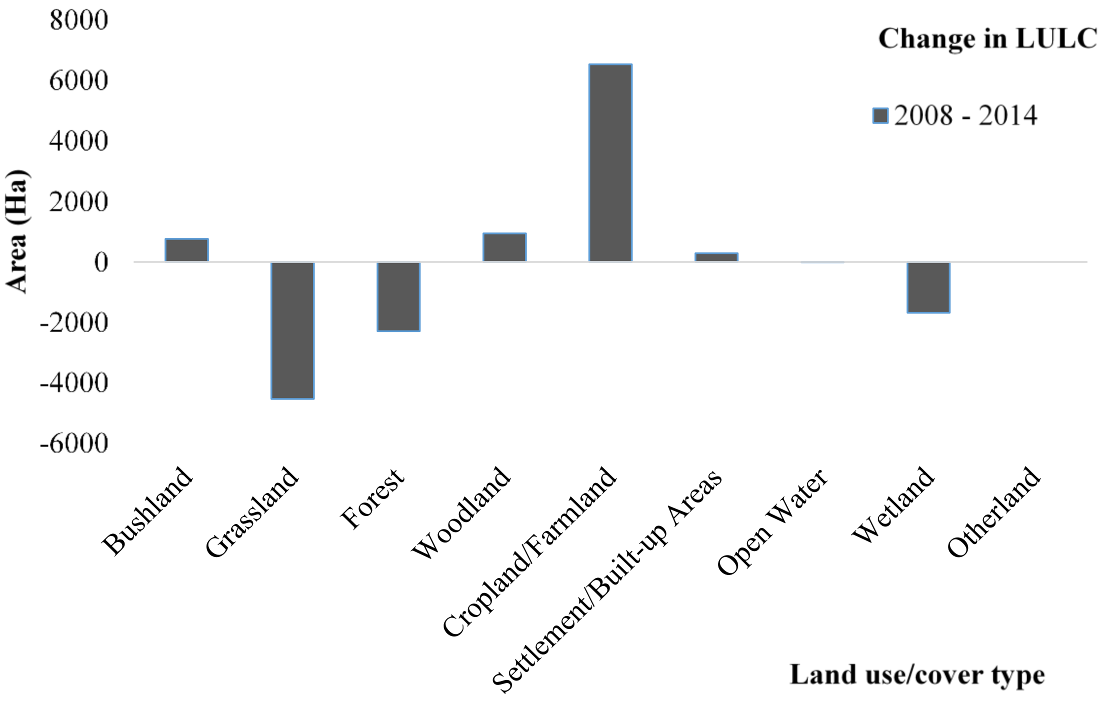


Figure 4-3: Land use /cover change between 2008 - 2014 for Mpanga catchment

Summary

2000–2014. Over the past fourteen years, the major change in land use/cover was the increase of the cultivated area at 39.19% at the expense of grassland 31.79% and forests at 11.38%. Woodland increased remarkably in all the years. Mpanga catchment having a lot of land occupied by the national park, measures have been put in place to relocate people from the parks and game reserves to stop the encroachment leaving the woodlands to recover. The settlement /built-up area also changed significantly due to rapid population growth in the catchment mainly in Fort portal town which has been designated a “tourist city of Uganda” attracting a lot of people in the region.

This has been summarised in the Table 4-2 below. In related studies, similar conclusions were made by Egeru and Majaliwa (2009), Kizza et al. (2017), Bewket and Sterk (2005), Kiggundu et al. (2018) and Barasa et al. (2010). Egeru and Majaliwa (2009) who carried out a study in Soroti District in western Uganda concluded that small-scale farming was the major land use type in the region and it kept increasing at the expense of other land uses. Kiggundu et al. (2018) in their study in the Murchison Bay catchment in the northern shoreline of Lake Victoria basin noted decreases in the agricultural lands (from 43.88% to 26.10%), forestland (from 23.78% to 17.49%), and wetlands (from 11.76% to 5.08%) at the expense of built-up land. Barasa et al. (2010) found out that for the last 35 years small scale (non-uniform) farming enormously increased from 60% in 1975 to 75% in both 1987 and 1999 while areas covered by tropical high forest and woodlands in Kirima sub-county decreased from 32%, 7% in 1975 to 16%, 4% in 1987.

Table 4-2: Land use/cover change summary for River Mpanga catchment

	Change in LULC		% Change in LULC	
Cover type	2000 - 2008	2008 - 2014	2000-2008	2008-2014
Bushland	7020	756	3.241	0.349
Grassland	-64313	-4532	-29.692	-2.092
Forest	-22236	-2293	-10.266	-1.059
Woodland	1596	946	0.737	0.437
Cropland/Farmland	78343	6534	36.169	3.017
Settlement	355	286	0.164	0.132
Open Water	-7	-8	-0.003	-0.004
Wetland	-684	-1689	-0.316	-0.780
Other land	-74	0	-0.034	0.000

Figure 4-4 shows the land use maps for Mpanga catchment for the years of 2000, 2008 and 2014. The land use/cover map for 2000 i.e. Fig 4-4 (a) shows that the biggest part was covered with the green vegetation mainly grassland (42.19%), forests (22.03%), cropland (32.9%), wetland (1.85%), bushland (0.03%), woodland (0.65%), settlement (0.18%) and open water (0. 06%). As observed in Fig 4-4 (b) most of the grassland and forest cover had been cleared to pave way for the cropland which increased by 36.98% with grassland reducing by 29.69% and forest by 10.27%. In Fig 4-4 c the cropland increased slightly by 3.02% as grassland reduced further by 2.1% and forest by 1.06%. Settlement increased from 0.18% in 2000 to 0.48% in 2014. This is one of the reasons for the decrease in the forest and grassland cover to pave way for settlement and agriculture land to provide food for the increasing population.

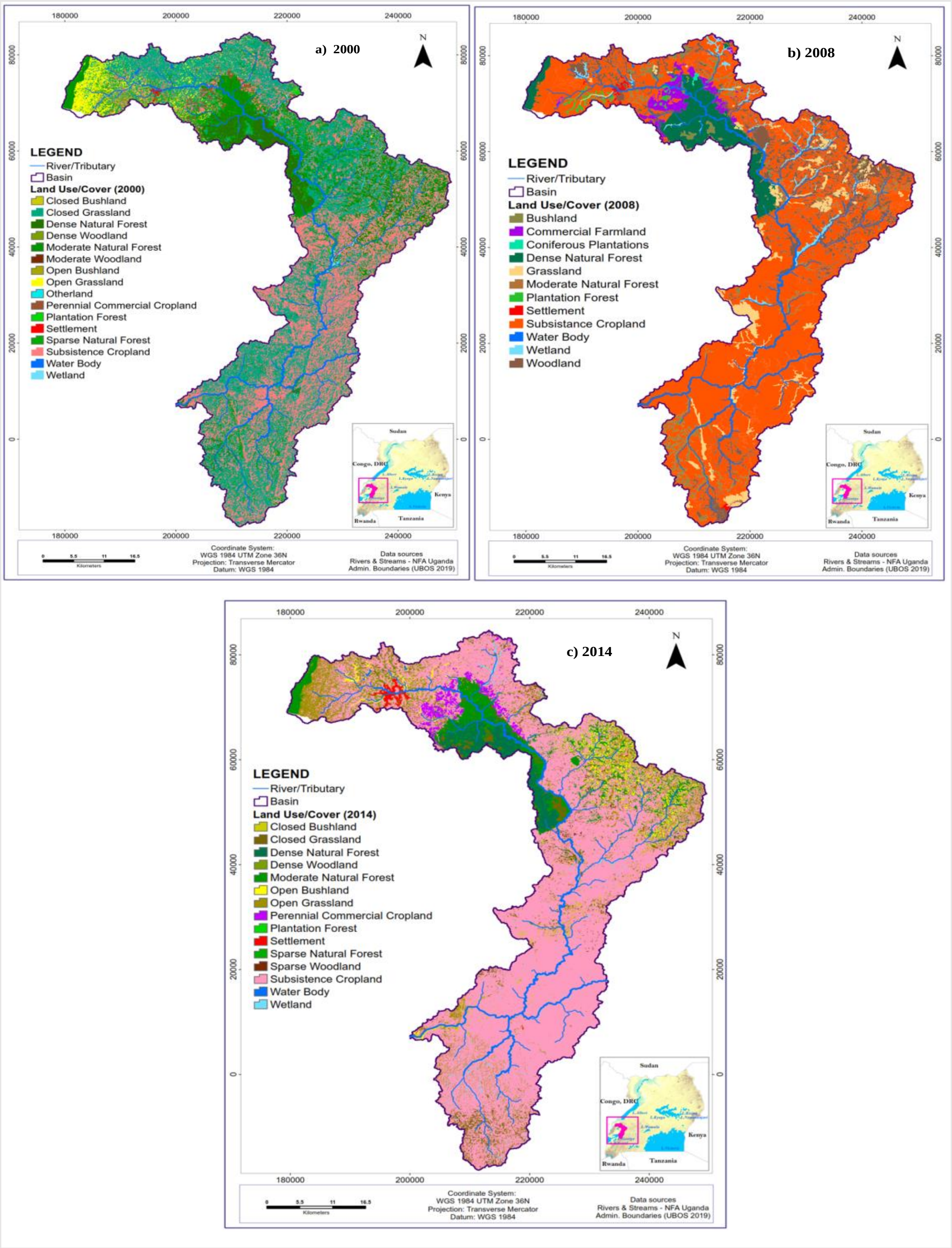
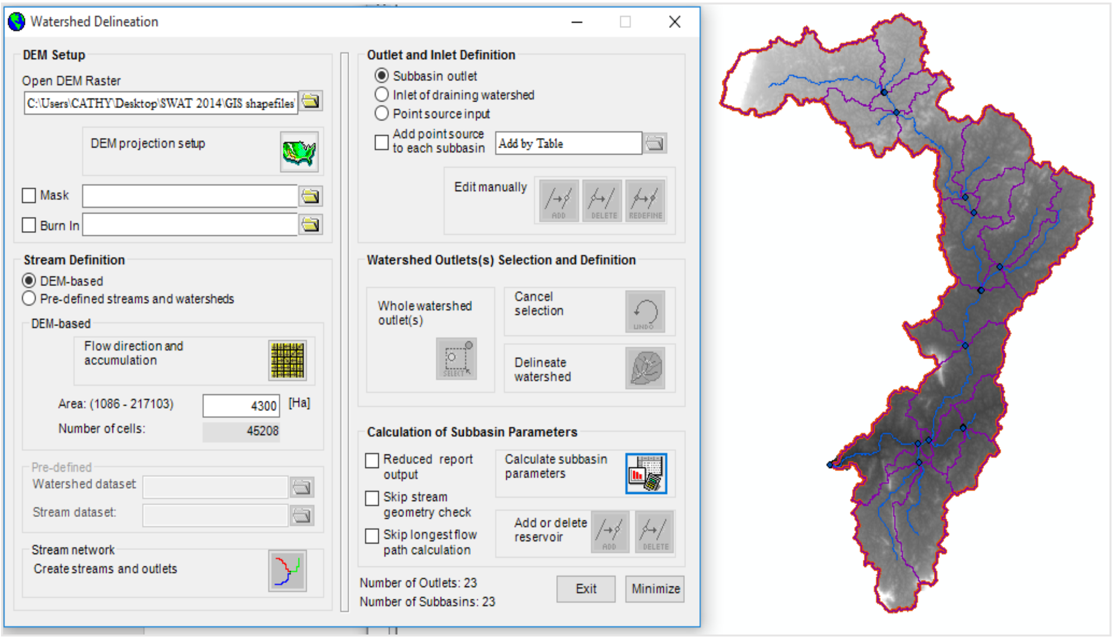


Figure 4-4: Land-use/ cover maps of River Mpanga catchment for (a) 2000, (b) 2008 and (c) 2014

4.3 Hydrological modelling of the stream flow changes in response to the land use changes in the catchment

4.3.1 Terrain (DEM) of Watershed

The Arc SWAT hydrological modelling of watershed was successfully carried out to get the basic watershed properties such as watershed area, slope, flow length, stream network density, and outlet point. This was through delineation of watershed with the help of a catchment DEM under terrain pre-processing in ArcGIS environment as shown in Figure 4-5.


Watershed Delineation

DEM Setup

Open DEM Raster: C:\Users\CATHY\Desktop\SWAT 2014\GIS shapefiles

☐ Mask

☐ Burn In

Stream Definition

● DEM-based

○ Pre-defined streams and watersheds

DEM-based

Area: (1086 - 217103) 4300 [Ha]

Number of cells: 45208

Outlet and Inlet Definition

● Subbasin outlet

○ Inlet of draining watershed

○ Point source input

☐ Add point source to each subbasin

Watershed Outlets(s) Selection and Definition

Calculation of Subbasin Parameters

☐ Reduced report output

☐ Skip stream geometry check

☐ Skip longest flow path calculation

Number of Outlets: 23

Number of Subbasins: 23

Figure 4-5: Delineated Mpanga catchment,its subasins and outlet

Inland sub-basin outlets were automatically gauge stations, main river channels, and other topographical features in the watershed added by Arc SWAT. The general elevation report for the total watershed shows that the highest elevation is 3004 m, lowest as 916 m and average is 1369 m above sea level as shown in Figure 4-6.

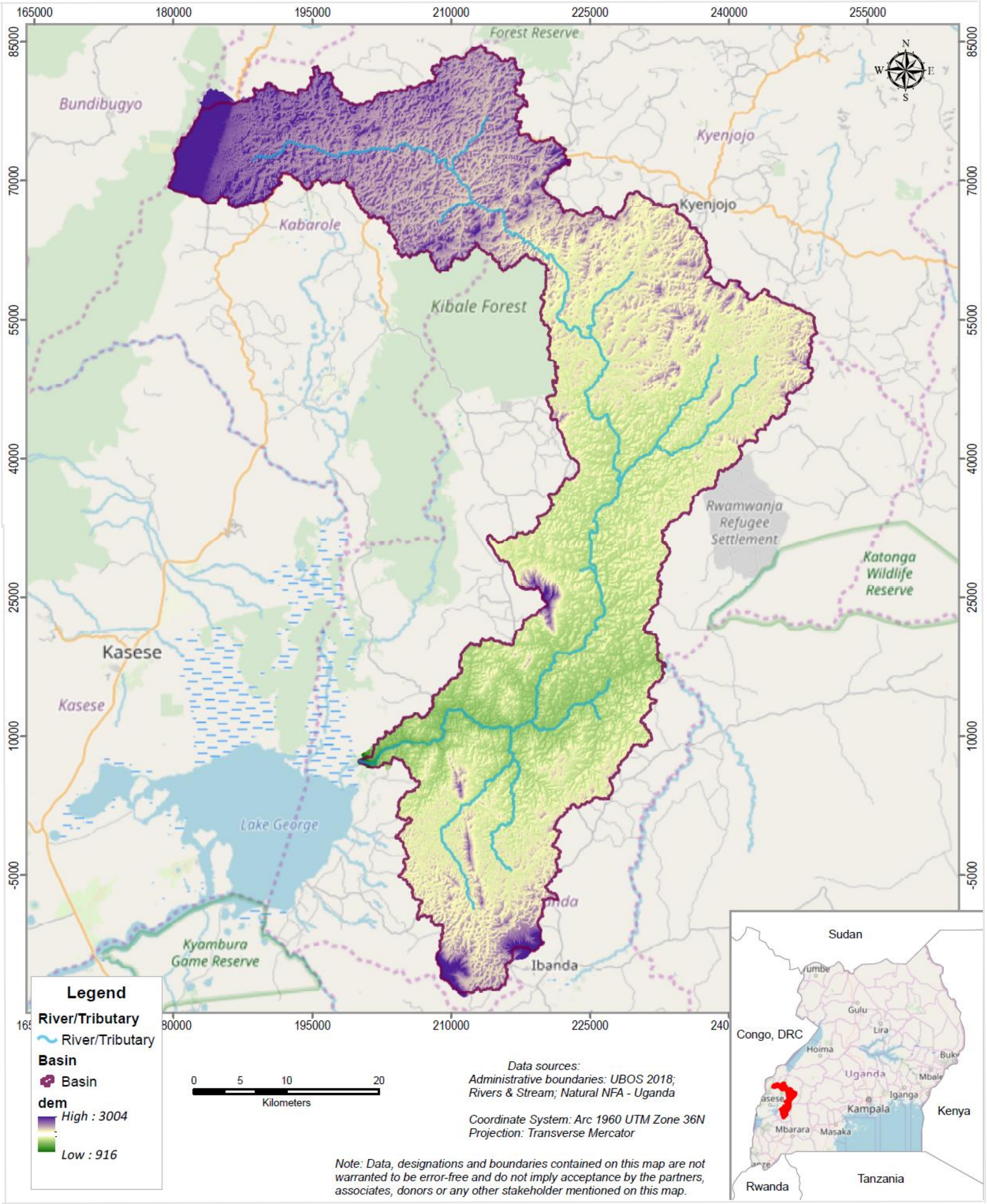


Figure 4-6: Delineated DEM showing topography and slopes of Mpanaga catchment

Finally, a total number of 23 sub-basins, reaches (streams) and monitoring points were obtained. Every sub-basin was assigned a Grid Code, Sub-basin ID, ElevMax, ElevMin, AverElev, Shape area, HydroID and Outlet ID, Slopes and XY coordinates. The smallest and biggest sub basins obtained in the watershed were 0.014377 km^2

and 69.714km^2 in area. For reaches, each was assigned an ArcID, Grid Code, From Node, To Node, Sub-basin from Sub-Basin to Reach Length, Slope, Reach Width, MinElev, MaxElev, OutletID and HydroID respectively. The shortest and longest reaches obtained in the watershed were 46.32 km and 2171 km in length respectively. The shortest and longest flow paths were 8.7175 km and 286.94 km long. After the general dendritic delineation of the catchment area, the total size of basin was 2171.032 km^2 with its main watershed monitoring/gauging or outlet point at 0612 N, 302742 E Gauge 84215 in Figure 4-7.

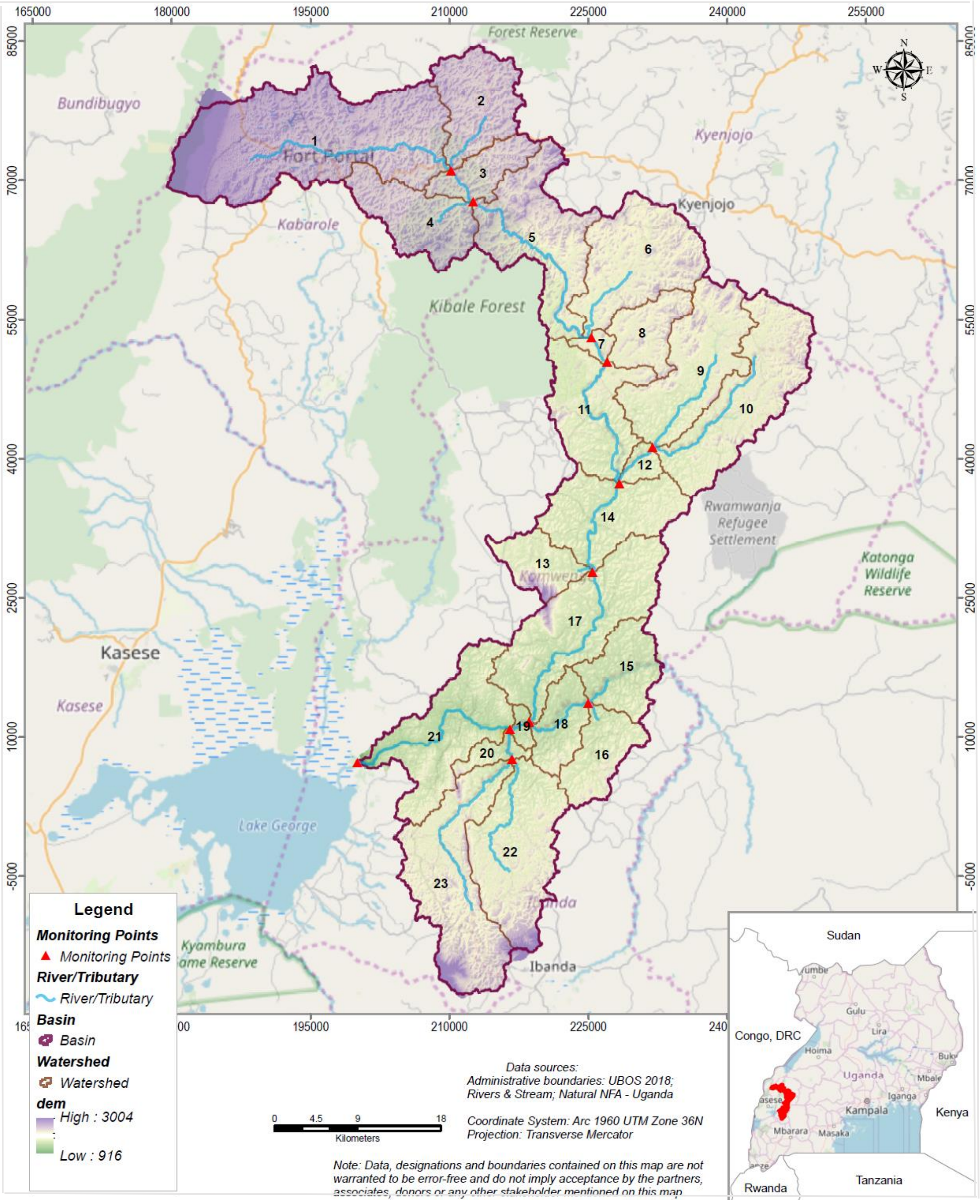


Figure 4-7: Delineated watershed boundary, stream work and outlet of the Mpanga basin

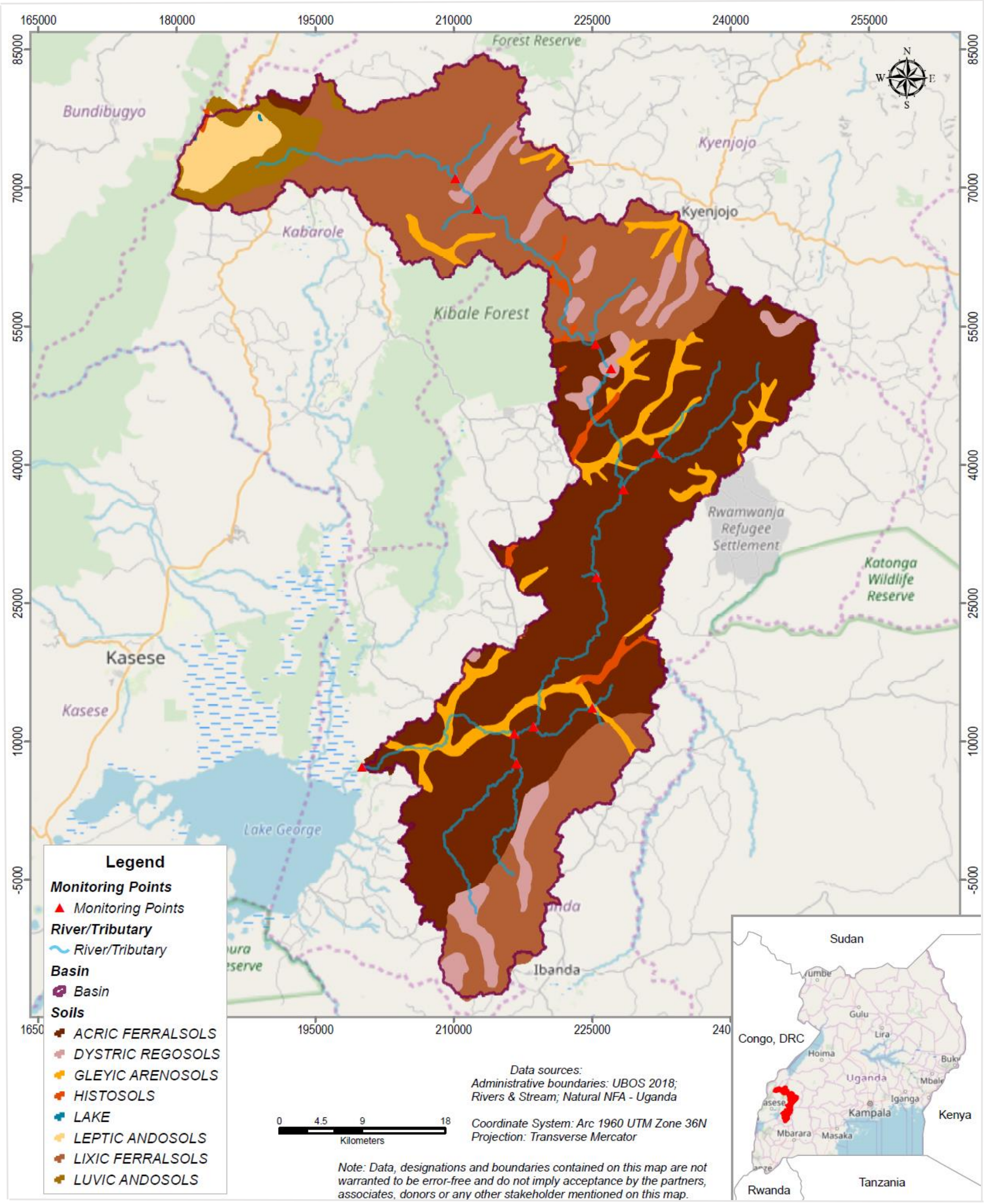
4.3.2 Hydrologic Response Units (HRUs) for Mpanga catchment

The definition of HRUs in Arc SWAT through overlaying the obtained classified land use/cover map, soil map and slope. The nine (9) classes of the classified LULC map as in Figure 4-8 was further grouped and reclassified to suit SWAT database. Seven (7) new classes and their areas of coverage were obtained as shown in Table 4-3. These classes were agricultural land (AGRL) which included perennial, commercial cropland, subsistence cropland, forest covers (FRST) i.e. dense, moderate and sparse natural forest. The settlement /built-up areas (URBN), waterbodies (WATR), wetlands (WETL), pasture (PAST) and other land covers (BARR) as shown in Figure 4-1.

Table 4-3: The original, grouped and reclassified LULC classes of Mpanga Catchment

Land Use/Cover	**Group**	**Class name (SWAT)**	**Area (ha)**		
			2000	**2008**	**2014**
Dense Natural Forest Moderate Natural Forest Sparse Natural Forest	Forest	FRST	47710	25474	23181
Grassland/Pasture	Pasture	PAST	91381	27068	22536
Perennial Commercial Cropland Subsistence Cropland	Cropland	AGRL	71435	149778	156312
Wetland	Wetland	WETL	4012	3328	1639
Water Body	Water	WATR	125	118	110
Settlement	Settlement	URBN	395	750	1036
Other land	Other land	BARR	74	0	0

The geo-referenced and clipped catchment soil map produced three (3) original soil groups of Black loamy over red clay loams (Gleyic Aerosols), Grey-humose clays, Grey sands and Red sandy-clay-loamy soils (Lixic Ferrasols) and Dark red clays sometimes underlain by laterite (Nitisols). These were finally reclassified into three (3) soil classes based on Arc SWAT database. They included BENSON = Black loamy over red clay loams, SWANTON = Dark red clays sometimes underlain by laterite and WEIDER = Grey-humose clays, Grey sands and Red sandy-clay-loamy soils. These can be seen in the Figure 4-9 and Table 4-4.



Data sources:
Administrative boundaries: UBOS 2018;
Rivers & Stream; Natural NFA - Uganda

Coordinate System: Arc 1960 UTM Zone 36N
Projection: Transverse Mercator

Note: Data, designations and boundaries contained on this map are not warranted to be error-free and do not imply acceptance by the partners, associates, donors or any other stakeholder mentioned on this map.

Figure 4-8: Soil map of Mpanga watershed area

Table 4-4: Reclassified SWAT soils

No.	Soil name	FAO Soil Name	SWAT Database name	Area [ha]	% cover
1	Black loamy over red clay loams	Gleyic Aerosols	Benson	16474	7.59
2	Dark red clays sometimes underlain by laterite	Nitisols	Swanton	75145	34.61
3	Grey-humose clays	Lixic Ferrasols	Weider	125483	57.80
4	Grey sands				
5	Red sandy-clay-loamy soils				

Mpanga catchment has many sub-basins with varying slopes, therefore multiple slopes were defined during HRU definition. A total of five (5) slope classes and their ranges as shown in Table 4-5 were provided due to the flat, gentle, moderate and steep gradients of the basin.

Table 4-5: Slope bands used in this model

Slope class	Lower – Upper limits	Area [ha]	Watershed Area (%)
1	0-5	39619.56	18.25
2	5- 20	148990	68.6
3	20-30	20192.59	9.3
4	30-55	7000.482	3.22
5	55-9999	1300.56	0.599

Lastly, for reasonable estimation of stream flow given by the multiple scenarios the 6% land use/cover, 4% soil and 2% slope threshold combination were taken into account. This value means that for any sub-basin in the watershed, the LULC, soils or slope covering less than the specified values of 4 % will be neglected to reduce the amount of data generated by SWAT. Finally, a total of 335 HRUs and 23 of sub-basins were created for the Mpanga Catchment. The total catchment area of Mpanga Catchment basin was 217103 (ha) as per the SWAT report.

Table 4-6 shows water balance ratios for each land use that contributed to stream flow in 2000, 2008 and 2014. The stream flow ratios increased from 0.49 in 2000 to 0.54 in 2014 an indication of reduced infiltration as the base flow ratios reduced from 0.74 to 0.6. Also surface runoff ratios increased from 0.26 to 0.33. This shows that a lot of vegetation has been cleared to pave way for settlement and agricultural land as reported by NEMA (2016). Increased crop lands and reduced forest cover results in increased stream flow due to crop soil moisture demand. Crops need less soil moisture than forests; therefore, the rainfall satisfies the shortage of soil moisture in agricultural lands more quickly than in forests there by generating more runoff (Mwanji et al., 2016). Likewise, Baker et al. (2013) reported that land use changes resulted in increased surface runoff and decreased groundwater recharge for the Njoro watershed located in Kenya’s Rift Valley.

The evapotranspiration ratios reduced from 0.49 in 2000 to 0.44 in 2014. This indicates that a lot of vegetation has been cleared and land left bare with less cover to transpire back to the atmosphere. In a related study, Getahun et al. (2015) evaluated the impacts of historical land use change on hydrology of the Melka Untie watershed located in Ethiopia using semi distributed hydrological model (i.e., HBV). The study showed that deforestation and associated increase in agricultural activities reduced evapotranspiration and increased streamflow during the main rainy season. Brook et al. (2011) quantified the impacts of human induced land use change for Angar watershed located in Ethiopia and concluded that mean annual evapotranspiration, percolation and base-flow declined whereas surface runoff and sediment yield increased.

In similar studies, Nobert and Jeremiah (2012) examined the impacts of land use change on Wami River located in Tanzania using SWAT model. The study reported decreased average streamflow, increased runoff, and decreased base flow in response to land use changes driven by deforestation and increased agriculture and urbanization from 1987 to 2000. The CN_2 increased from 73.8 to 77.56 for 2000 - 2014. This curve number being a function of the soil permeability, land use/cover and the antecedent soil moisture, it therefore affects the rate of surface runoff generation.

Table 4-6: Water balance ratios for each land use that contributed to stream flow in 2000, 2008 and 2014

	YEAR		
	2000	**2008**	**2014**
Stream flow/Precipitation	0.49	0.51	0.54
Base flow/Total flow	0.74	0.69	0.67
Surface Runoff/Total flow	0.26	0.31	0.33
Percolation/Precipitation	0.28	0.28	0.28
Deep Recharge/Precipitation	0.01	0.01	0.01
ET/Precipitation	0.49	0.47	0.44
CN_2.mgt	73.8	74.14	77.56

4.3.3 Sensitivity Analysis

Figure 4-10 and Table 4-7 show the overall results of global sensitivity and their rankings after 100 simulations. The simulation found that out 15 flow parameters which were sensitive to the model, 7 parameters were more sensitive and were ranked according to their levels of sensitivity. The first three (3) parameters were the most sensitive with the p-value less than the alpha value ($p < 0.05$). The SCS runoff curve number (CN_2) was the most sensitive parameter. The curve number estimates runoff based on the relationship between precipitation, hydrologic soil group and land uses. Other researchers like Getachew and Melesse (2012), Mutenyo et al. (2013) and Anaba et al. (2017) also found out that the SCS curve number was the most sensitive streamflow parameter in modelling hydrology in their studies. This was followed by Surface runoff lag time (Surlag) and Groundwater evapotranspiration coefficient (GW Revap.gw). Other parameters were also sensitive though p >0.05. These were the Manning's "*n*" value for overland flow (OV_N.hru), Groundwater delay (GW_DELAY), base flow recession factor (Alpha_Bf) and the available water capacity of soil layer (Sol_Awc).

In related studies mainly in the Nile basin for example Mango et al. (2011) found out that ESCO, CN2, ALPHA-BF, GWQMN, SOL-Z, REVAPMN among others were the most sensitive parameters in the Upper Mara River Basin, Kenya. This was in close agreement with Odiira et al. (2010) who found out that SOL_AWC, ESCO, GWQMN, REVAPMN, CN2 and GWREVAP were the most sensitive parameters in the River Nzoia catchment in Kenya.

Although, the rest of the parameters were found not to be sensitive to flow in the catchment as their *p*-values were much greater than 5%, other studies like, Betrie et al. (2011), Asres and Awulachew (2011) and Costa et al. (2015) found some of them to be sensitive in their studies. This is expected as conditions such as land use/ covers, soil characteristics and climatic factors vary from one catchment to the other.

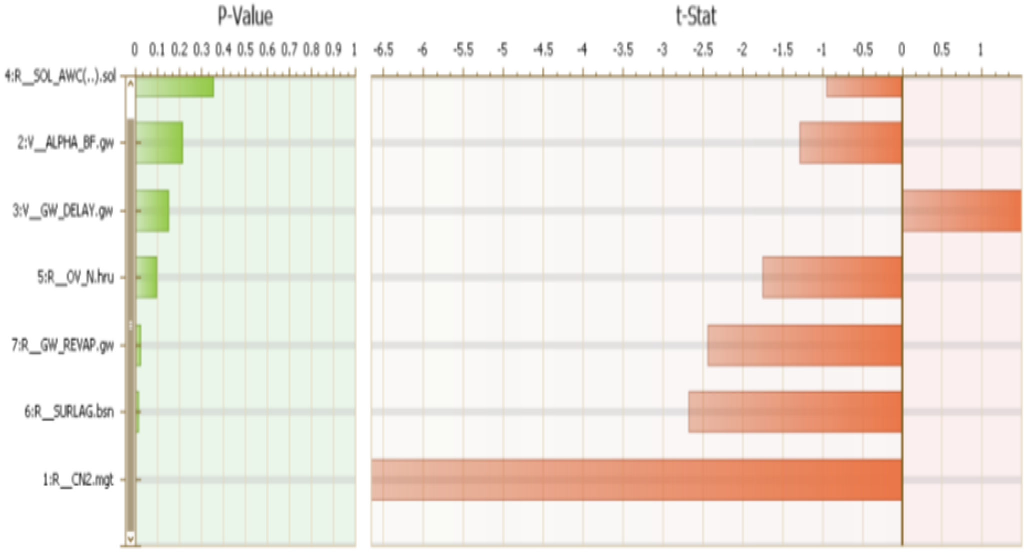
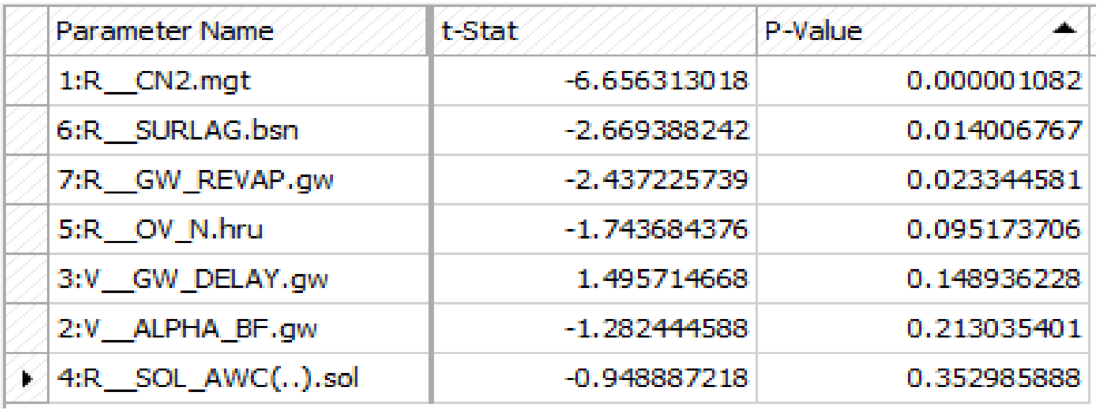


Figure 4-9: Global sensitivity analysis graph after iteration in SWAT-CUP

Table 4-7: Provides the calibrated sensistive values and considered parameters



Parameter Name	t-Stat	P-Value
1:R__CN2.mgt	-6.656313018	0.000001082
6:R__SURLAG.bsn	-2.669388242	0.014006767
7:R__GW_REVAP.gw	-2.437225739	0.023344581
5:R__OV_N.hru	-1.743684376	0.095173706
3:V__GW_DELAY.gw	1.495714668	0.148936228
2:V__ALPHA_BF.gw	-1.282444588	0.213035401
4:R__SOL_AWC(..).sol	-0.948887218	0.352985888

Figure 4-11 shows the scatter dotty after SWAT-CUP calibration. These plots are a representative of parameter values or relative changes versus objective function. The main purpose of these graphs are to show the distribution of the sampling points as well as to give an idea of parameter sensitivity (Abbaspour, 2015). The sampling points were all above 0.8 hence the objective function was sensitive to the parameters. CN_2.mgt revealed the highest level of sensitivity to the objective function by indicating a trend with a sharp and clear peak while SOL_AWC. (sol) revealed the lowest diffused peak indicating that the parameter was less sensitive.

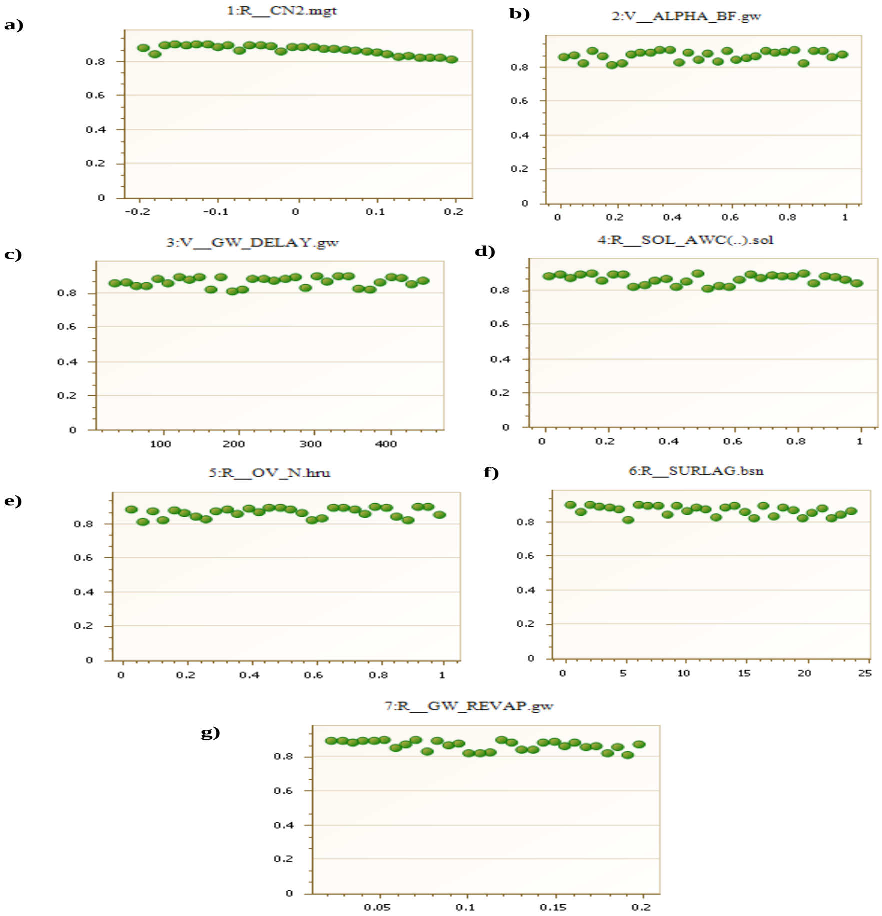


Figure 4-10: Calibration output showing objective function versus parameter values

4.3.4 SWAT model calibration and validation

Figure 4-13 shows 95PPU plots for daily flow data from 2003 to 2008 of the gauged station for both observed and simulated flow after calibration for land uses of 2000, 2008 and 2014.

The results indicate that, most of the observations with different parameters are bracketed by the 95PPU (for NSE value of 0.88, 0.84 and 0.87), signifying that

SUF12 is capable of capturing the model behaviour. The SWAT simulation results look satisfactory for the prediction of discharge and the final parameter ranges for Mpanga catchment. This is in agreement with Narsimlu et al. (2015) in the article about calibration and uncertainty analysis for stream flow in India concluded that most of the observed values during the calibration and validation were within the boundaries of 95PPU. The percentage of observed data being bracketed by 95PPU during calibration was 82 % and during validation 76 %, which indicates a good performance of the model.

By analysis, the observed and simulated values were close with discrepancies in the regions of peak flow which the SWAT calibrated model for the basin had more difficulty in simulating. There is still some tendency of overestimating the model in the recession phase immediately after the highest flow peaks especially in the beginning periods of each year. This could be attributed to uncertainties that exist in the catchment.

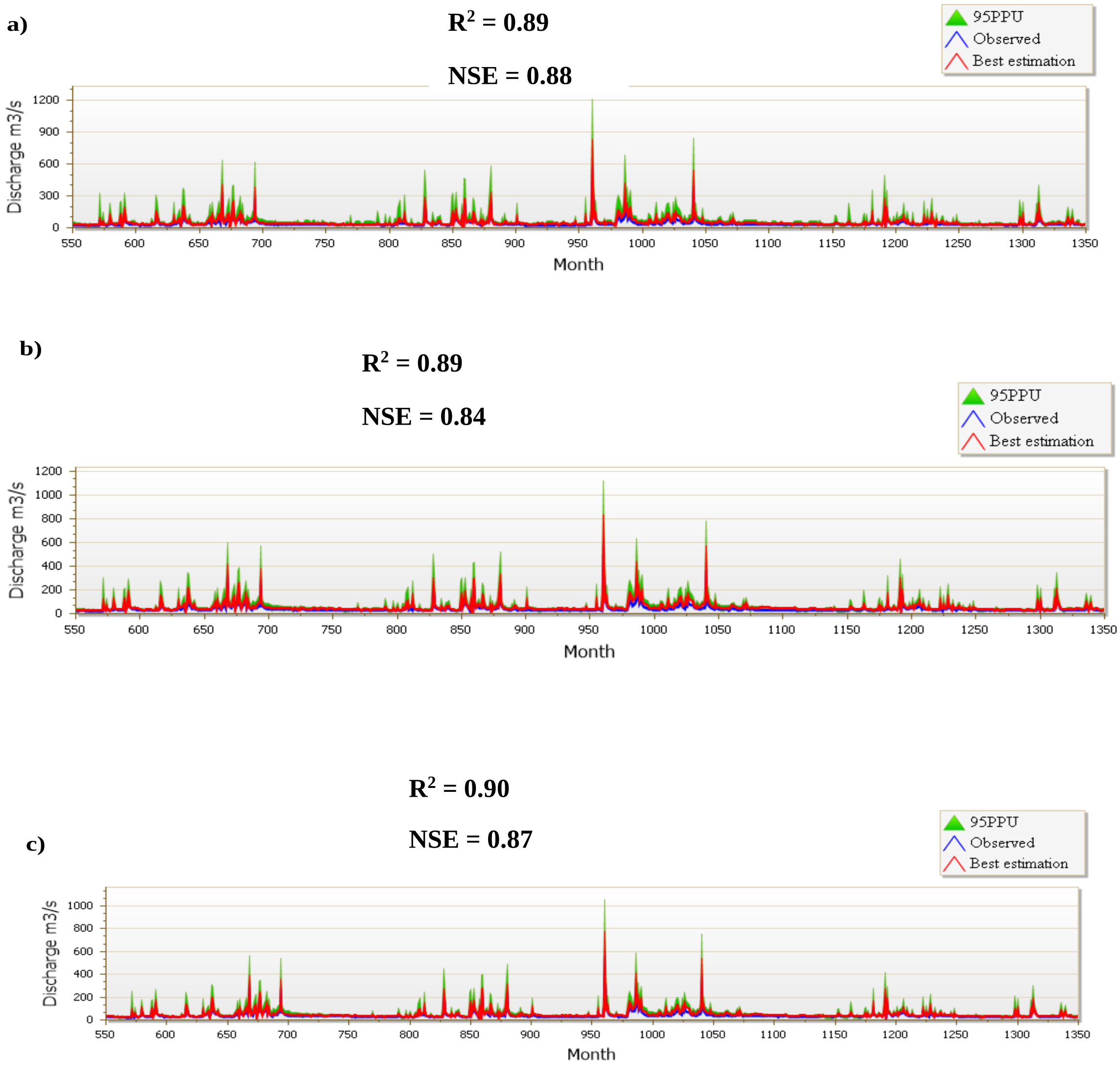


Figure 4-11: Observed and simulated stream flow of River Mpanga after calibration

Table 4-8 indicates that the physical processes involved in the generation of stream flows in the watershed were adequately captured by the model. The simulated daily flow matched the observed values for the calibration period from 2003 to 2008 with the coefficient of determination R^2 and NSE values as shown in Table 4-8. Values of $R^2 > 0.6$ and NSE > 0.5 for the calibration of the daily simulated stream flow are usually considered as adequate for an acceptable calibration as stated in Table 3-3.

The *p*-factor and *r*-factor were also very good with values of 0.72 and 0.81 for 2014, 0.75 for 2008 and 0.76 and 0.66 for 2000 respectively. The range of the *p*-factor varies from 0 to 1, with values close to 1 indicating a very high model performance and efficiency, while the *r*-factor is the average of the 95PPU band divided by the standard deviation of the measured variables and varies in the range 0-1 (Abbaspour et al., 2007; Yang et al., 2008).

It shows that the model performed well in the validation and calibration periods implying the set of optimized parameters during calibration process for Mpanga catchment can be taken as the representative set of parameters for the watershed. Hence, the model simulations can be used for various water resource management and development aspects.

Table 4-8: Calibration results for land use/cover maps of 2000, 2008 and 2014

Period	**Calibration**		
	2000	**2008**	**2014**
Coefficient of determination (R^2)	0.89	0.89	0.90
Nash and Sutcliffe Coefficient (NSE)	0.88	0.84	0.87
p-factor	0.76	0.75	0.72
r-factor	0.66	0.75	0.81

4.3.5 Model validation and evaluation

Validation period from 2009-2013, the simulated daily flows matched the observed flows with coefficient of determination $R^2 = 0.93$ and NSE = 0.73 on average for the years of 2000, 2008 and 2014. Also, values of $R^2 > 0.6$ and NSE > 0.5 for the validation of the daily or monthly simulated stream flow are usually considered as adequate for an acceptable calibration. The p-factor of 0.80 and r-factor of 0.84 were obtained. Statistical model efficiency criteria fulfilled the requirement of $R^2 > 0.6$ and NSE > 0.5 which is recommended by SWAT developer. This showed the model parameters represent the processes occurring in the watershed to the best of their ability given available data and may be used to predict and manage watershed response for various outputs. The daily flow model validation results indicated generally a good fit between measured and simulated output.

Validation results illustrated by Table 4-9 and Figure 4-14 show that SWAT is able to simulate the hydrological characteristics of the River Mpanga catchment. Just as with the graphical and table results, the model simulated streamflow discharge better during the calibration period than the validation period. The relatively low statistical measures during the validation can be attributed to the quality of the observed data used as there were many missing days.

Table 4-9: Validation results for land use/cover maps of 2000, 2008 and 2014

Period	**Validation**		
	2000	2008	2014
Coefficient of determination (R^2)	0.93	0.93	0.93
Nash and Sutcliffe Coefficient (NSE)	0.75	0.69	0.77
p-factor	0.71	0.76	0.80
r-factor	0.69	0.77	0.84

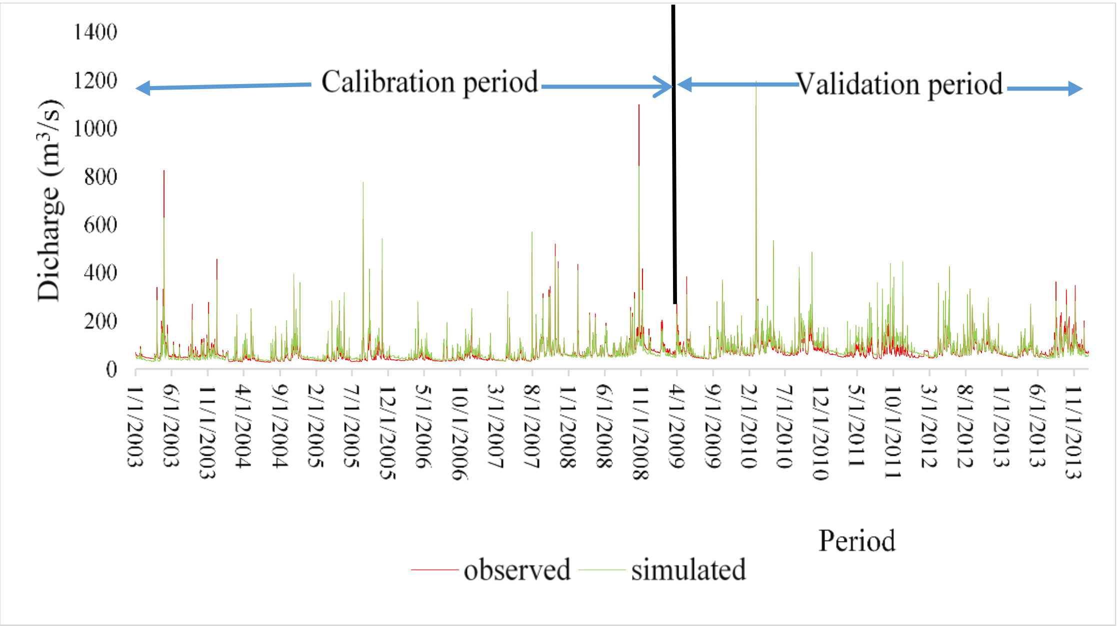


Figure 4-12: Time series plots of observed and simulated flows during calibration and validation period

Figure 4-14 shows the daily observed and simulated runoff hydrograph during calibration period for 2000, 2008 and 2014. In Fig.4-14 a, the hydrographs have a correlation coefficient of 0.8949. The slope is 0.9698. In Fig.4-14 b, the correlation coefficient is 0.8944 with a slope of 1.0423 and in Fig.4-14 c, the correlation coefficient of 0.9056 and the slope of 1.0088. Between 2000 and 2014 a lot of vegetation had been cleared increasing the slope. With the increased slope, the lag time is reduced and once it rains most of the water finds its way to the stream in the shortest period.

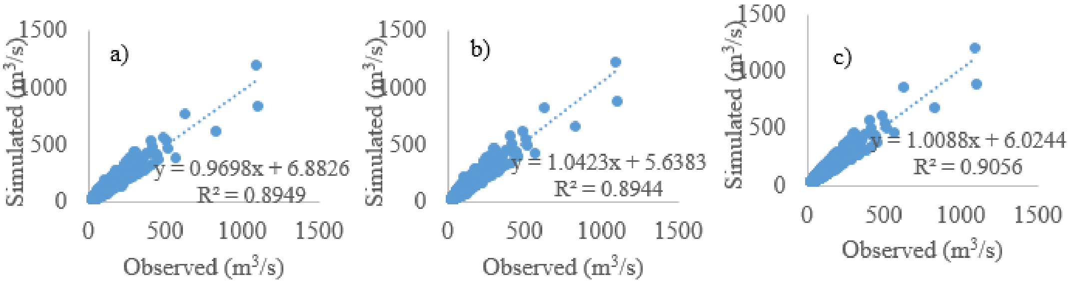


Figure 4-13: Comparison of daily observed and simulated runoff hydrograph during calibration period for 2000, 2008 and 2014

Figure 4-15 shows the peak observed and simulated runoff hydrograph during calibration period for 2000, 2008 and 2014. There is an increasing trend in the coefficient of determination as observed in Figure 4-15 a, b and c. Also the slope is increasing steadily. This implies that less is being done to curb down the opening up of land which has persistently increased the slope.

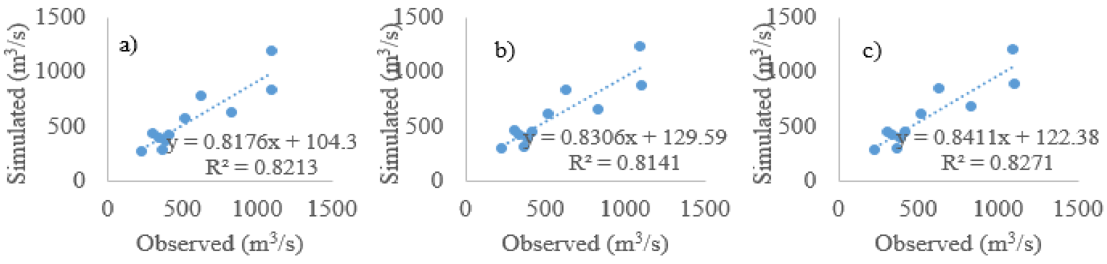


Figure 4-14: Comparison of peak observed and simulated flows in each year during calibration 2000, 2008 and 2014

Figure 4-16 shows the minimum observed and simulated runoff hydrograph during calibration period for 2000, 2008 and 2014. There is a slight increase in the coefficient of determination between 2000 and 2008 and then a decrease between 2008 and 2014 as observed in Figure 4-16 a, b and c. Also the slope is decreasing steadily. Uncertainties were relatively high during low flow seasons which can be seen on the graph.

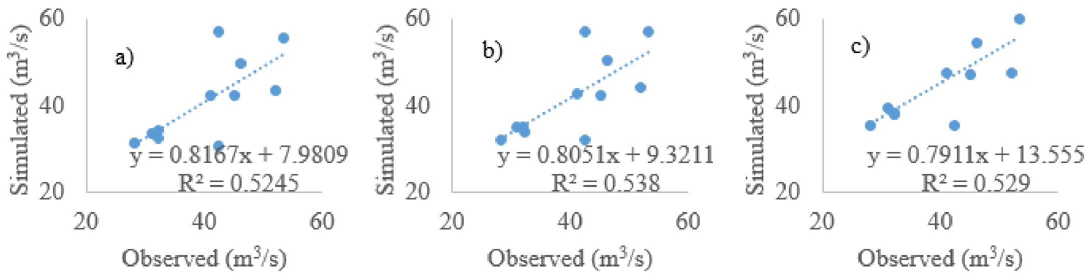


Figure 4-15: Comparison of minimum observed and simulated flows in each year during calibration period 2000, 2008 and 2014

Figure 4-17 shows the average yearly observed and simulated runoff hydrograph during calibration period for 2000, 2008 and 2014. There is a slight increase in the coefficient of determination between 2000 and 2008 and then a decrease between 2008 and 2014 as observed in Figure 4-16 a, b and c. Also the slope is decreasing steadily with a slight increase in Figure 4-16 c. Uncertainties were relatively high during average yearly flow with the plot tending more to observed flow than the simulated flow hence, under estimating the model which can be seen on the graph.

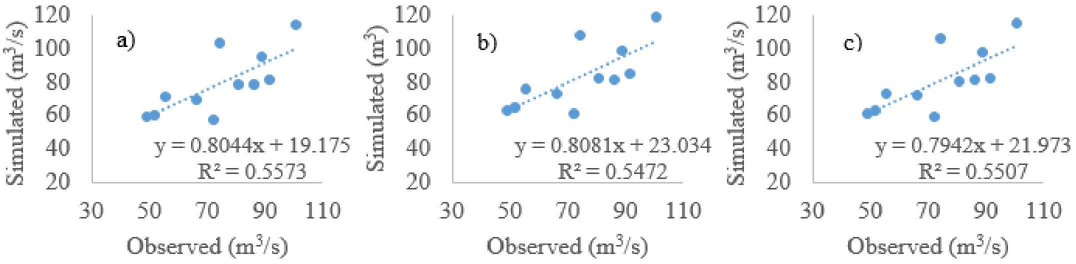


Figure 4-16: Comparison of average yearly simulated and observed runoff in each year during calibration for 2000, 2008 and 2014

4.4 Evaluation of stream flow due to land use change/cover scenario analysis

Figure 4-18 shows the maximum, minimum and mean annual flows in each year under the scenario of changing 10% forest land to agriculture land. From Figure 4-18 (a), changing 10% of forest cover into agricultural land led to an increase in the maximum event in each year by 17.88% on average. Under the same scenario, minimum and mean annual flows were 42.88% and 47.51% respectively (Figure 4-18 b and c). Simulations under all land use change scenarios as summarised in Table 4-10 indicated reduced base flow and average flow over the period of simulation. The overall difference of these three curves show the increasing trend of low flow due to land use/cover change of the catchment. This implies that the catchment is influenced by the land use changes more with respect to dry than wet conditions as seen in Figure 4-19.

Such information is vital for predictive planning of eco-hydrological conditions of the catchment. However, for wet conditions, a small amount of change in land use results into a huge flood event that can be so catastrophic though in a short run unlike the impacts of dry conditions which tend to be felt over a long period of time on livelihood. This relates with Mango et al. (2011) who concluded that any further conversion of forests to agriculture and grassland in the basin headwaters of Mara River basin would reduce dry season flows and increase peak flows leading to greater water scarcity at critical times of the year.

However, the differences in stream flow changes among the scenarios of various land use/cover by 25%, 50% and 75% were minimal. This is in agreement with Onyutha and Willems (2017) who concluded that change in catchment behaviour due to anthropogenic influence in the Nile basin where the study area is located over the selected time period was minimal.

Therefore, improving existing agricultural land management practices, regulating water allocation to maintain an environmental flow regime in the river, and afforestation measures should be emphasised if the catchment is to be protected from further destruction. More so, measures should be put in place to prevent occurrence of extreme flows since their occurrence leads to a lot of destruction.

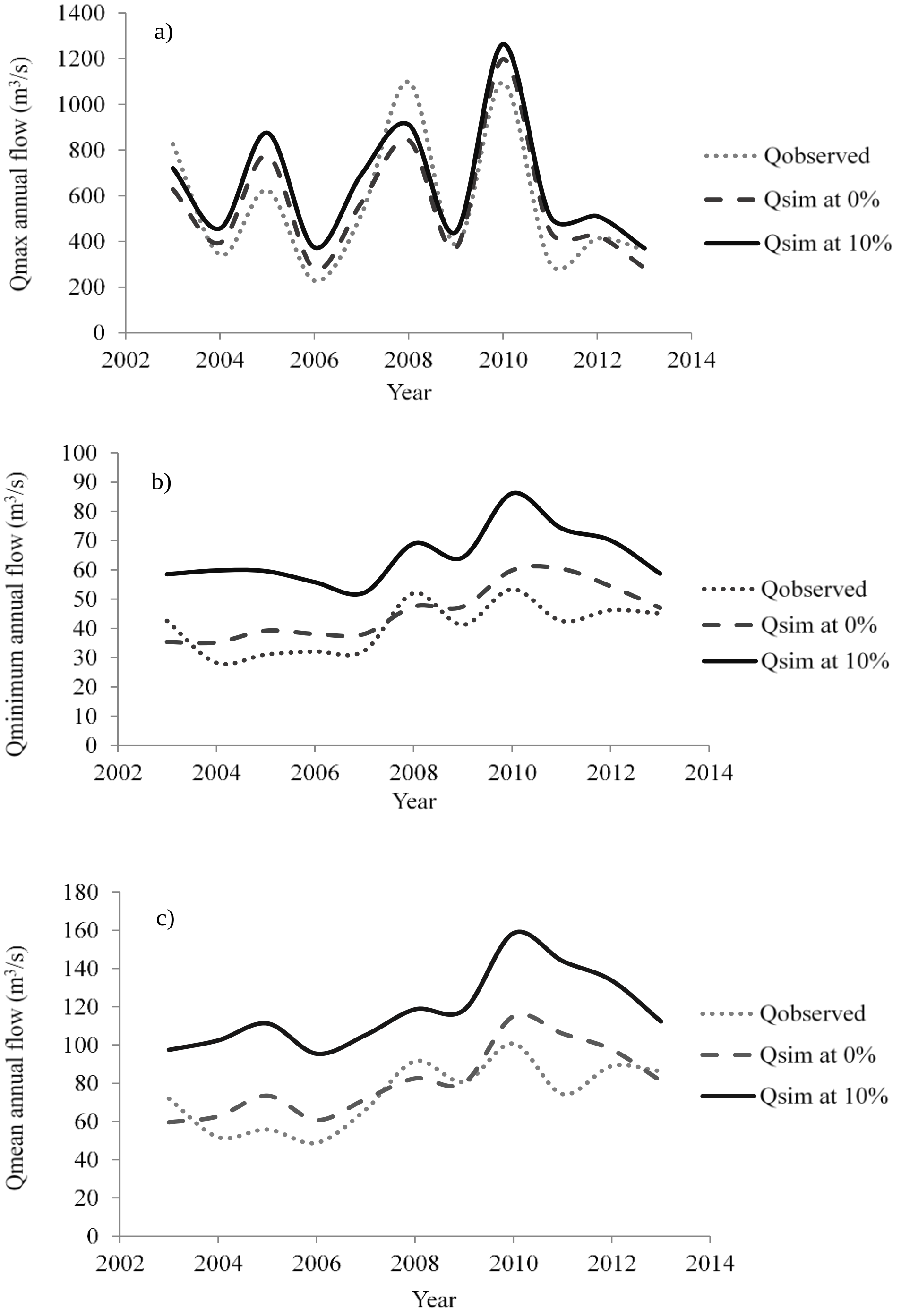


Figure 4-17: Maximum (a), minimum (b) and mean (c) annual peak flows for scenario analysis of 10% increment of forest cover to agricultural land – In the legend,e.g. “Qsim at 10%” indicates simulated flow after changing 10% of forest to agricultural land

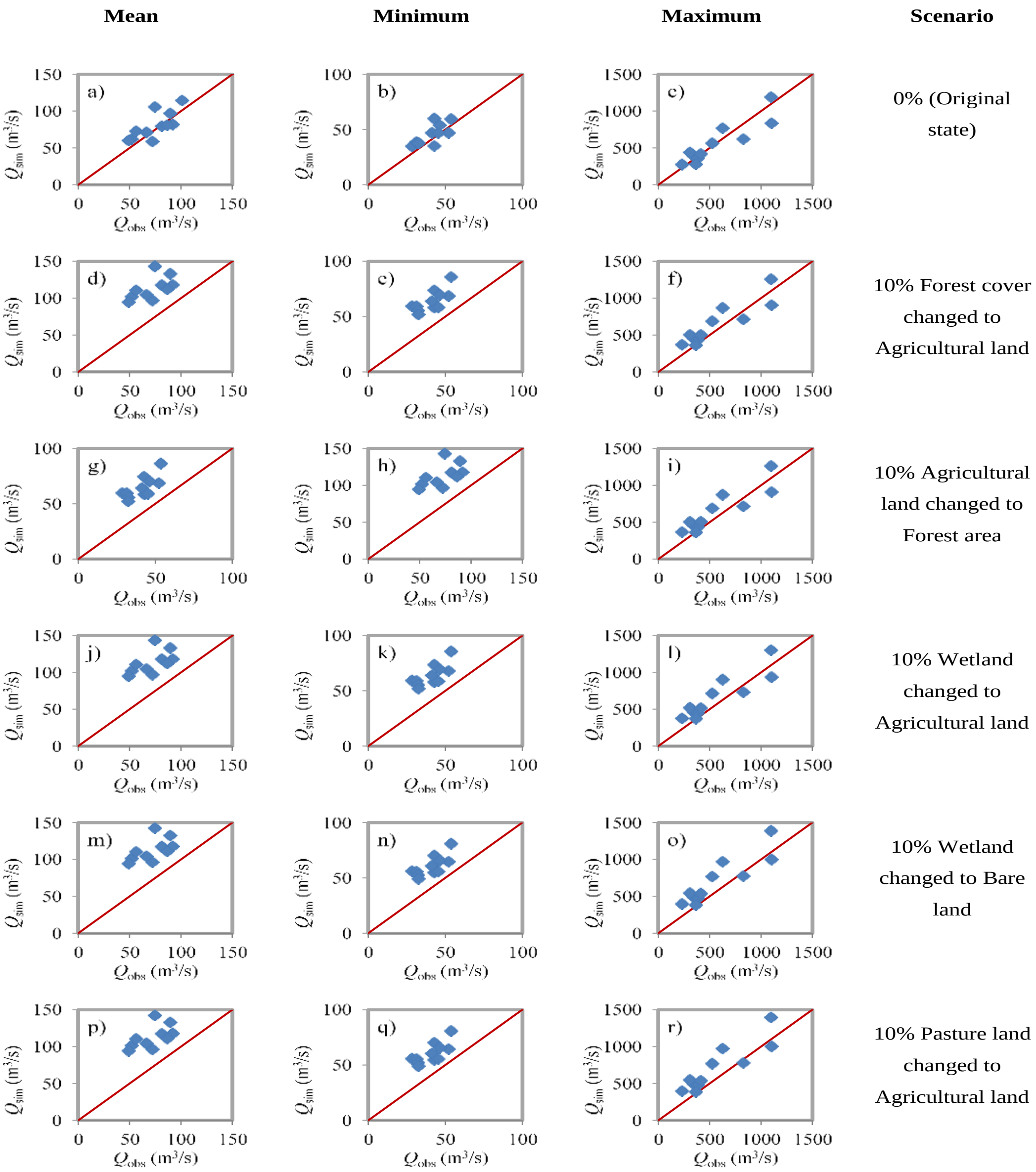


Figure 4-18: Mean, minimum and maximum flows based on scenario analysis

Charts (a, b, c) denote the original case without modifying the land use, (d, e, f) show reduction of 10% forest land to agricultural area, (g, h, i) 10% conversion of agriculture land to forest (j, k, l), 10% wetland to agriculture, (m, n, o) conversion of 10% wetland to bare land and (p, q, r) denote the change in 10% pasture to agriculture land

Table 4-10: Average mean, minimum and maximum annual flows under various scenario analysis

Scenario (10% change)	**Annual mean flows (m^3/s)**	**Annual minimum events (m^3/s)**	**Annual maximum events (m^3/s)**
Forest cover to agricultural land	47.51	42.88	17.88
Agricultural land to forest cover	47.23	43.74	17.95
Wetland to agricultural land	47.61	42.58	21.17
Wetland to bare land	46.74	35.27	27.98
Pasture to agricultural land	46.81	34.62	28.46

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

This research assessed the impact of different land use/cover changes on the River Mpanga flow. In order to investigate whether the flow variation could be attributable to changes in the land use, different land use maps i.e. 2000, 2008 and 2014 were assessed at catchment scale using SWAT to simulate daily runoff using data (falling within the period 2000-2013) for River Mpanga.

5.1.1 Land use/cover change

The prevailing changes in footprint between 2000 and 2008 were expansion of cropland (17.78%), bushland (3.24 %), settlement (0.17 %) at the expense of forest land (10.27%), grassland (29.69%), wetlands (0.316%) and open water (0.003%). Between 2008 and 2014, the area under cropland/ farmland increased with a 3.02%, followed by woodland 0.43%, bushland 0.35% and settlement 0.13%. On the other hand, grassland reduced by 2.1%, forest by 1.06% and wetland by 0.78%.

5.1.2 Application of the hydrological model to analyse the stream flow changes

SWAT model was successfully evaluated through sensitivity analysis, model calibration, validation and evaluation. It was found to produce a reliable estimate of monthly runoff for the watershed which was confirmed by various model efficiency measures like R^2 and NSE during evaluation. The model gave a realistic “goodness of fit” measures between observed and simulated flow with R^2 and NSE values above 0.8 and 0.75 respectively. Thus, SWAT model has shown that it is able to give realistic output for assessment of land use changes impact on the river flow in Mpanga catchment and can be applied anywhere else for a similar purpose. Also the model is not only limited to analysis of land use change but its capable for investigating climate change impacts, sediment and water quality monitoring among others which renders it a suitable tool for water resources management.

5.1.3 Scenario analysis

Conversion of land uses form their original state had an impact of the stream flow in following manner:

- Forest land to cropland led to an increase in maximum, minimum and mean annual flow of 17.88 m^3/s, 42.88 m^3/s and 47.51 m^3/s respectively.
- Agricultural land to forest cover increased the flow by 17.9 m^3/s for maximum flows, 43.7 m^3/s for minimum annual events and 47.23 m^3/s for mean annual flows.
- Conversion of wetland to cropland resulted into 21.17 m^3/s for maximum annual events, 42,58 m^3/s for minimum annual flow and 47.61 m^3/s for mean annual flows.
- Wetland to bare land yielded 27.98 m^3/s for the maximum stream flows, 35.27 m^3/s for minimum flows and 46.74 m^3/s for mean annual flows.
- Pasture land to cropland resulted into 28.46 m^3/s for maximum flows, 34.62 m^3/s for minimum annual events and 46.81 m^3/s for mean annual flows.

This implies that the catchment is influenced by the land use changes more with respect to dry than wet conditions. Conversion of wetland to agricultural land and forest to agricultural area resulted into the highest mean annual flows.

5.2 Recommendation

5.2.1 Catchment management measures

- The changes in land use/cover have caused an impact on hydrology by increasing the incidences and intensities of flooding and drought occurrences in Mpanga catchment. Therefore, control mechanisms such as reducing the rate of deforestation which was evidently the high contributing factor and proper land use management practices especially in the cultivated areas through agroforestry, deep tillage and banding to minimize run off and facilitate infiltration and ground water recharge should be implemented.
- SWAT model used in this research was very helpful since it is able to use limited data inputs. However, within other regions it may not be sufficient enough to judge the results by using only one model. Therefore, there is a need to look at other hydrological models in order to have more accuracy of the outputs and give better results of the effects of land use changes on the hydrology of the catchment.
- Supplementary economic activities for small farmers in the sub-catchment may boost their earnings and as such reduce their demand on forests and woodlands for energy sources to protect the catchment in order to maintain enough flow in the river.

- Establishment of riparian buffer vegetation using appropriate plant species will increase infiltration and water storage in the sub-catchment and reduce sediment loading and surface runoff in the watershed.
- Finally, for a more accurate modelling of hydrology, more effort will be required to improve the quality of available input data mainly the flows of the river.

5.2.2 Future studies on Mpanga catchment

- Sediment dynamics in response to land use change and hence its impact on the reservoir management and operation.

- Land use changes reflect human factors thus, separation of human factors from climate variability is required. Also, the extent to which each human factor is contributing to each hydrological change should be analysed.
- The application of advanced GIS and Remote Sensing in watershed modelling, monitoring and management for future benefits of all stakeholders.
- Comparison of models at local scale as simulating efficiency of the models varies depending on uncertainty introduced by calibration strategy, model input and structure and parameterization, among other factors.

5.3 Limitations

- The available flow data from the Ministry had a lot of missing data making it hard to successfully simulate the model for a quite long time

- The availability of hydro-meteorological data also affected the accuracies of the results since it had a lot of missing values limiting the number of years used in the model simulation.

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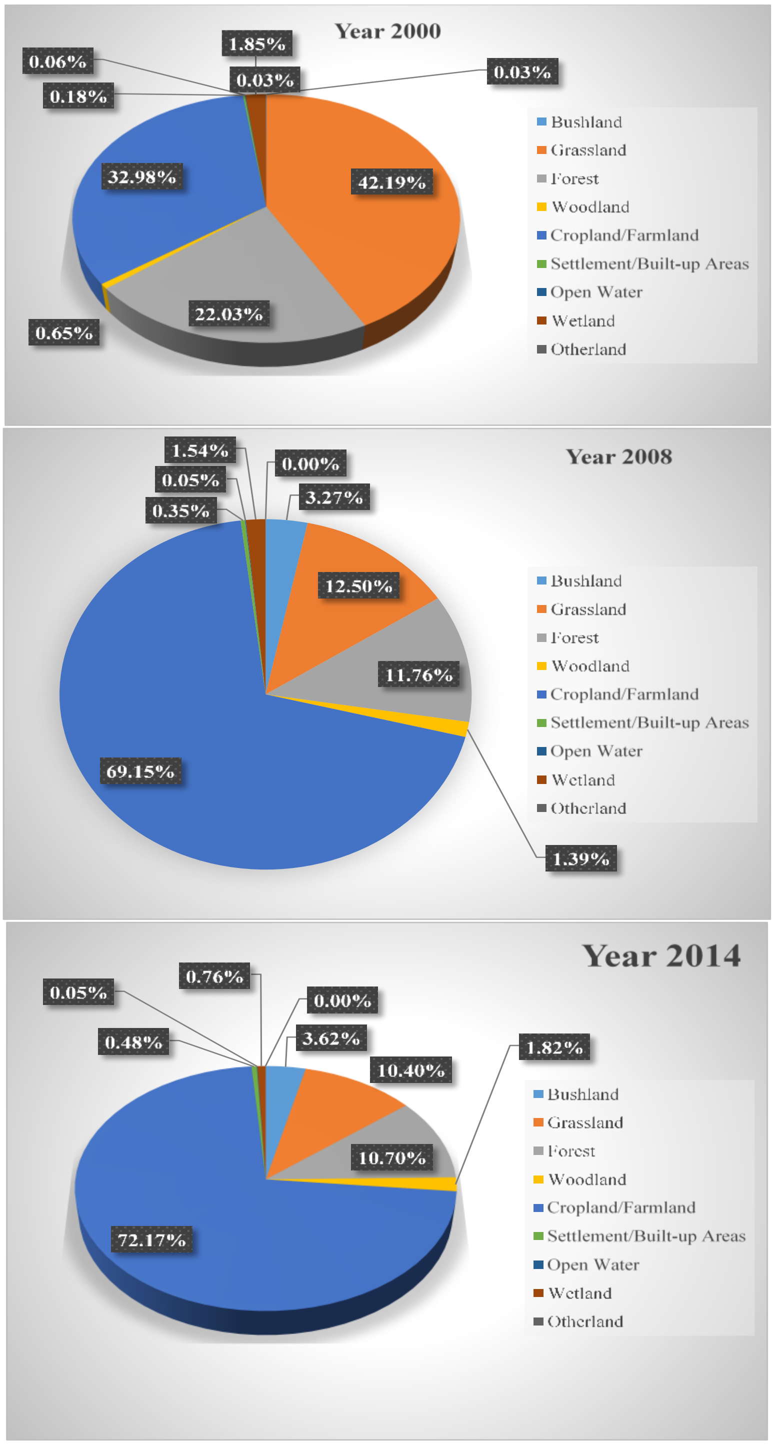
APPENDIX

Appendix 1: Land use for 2000, 2008 and 2014



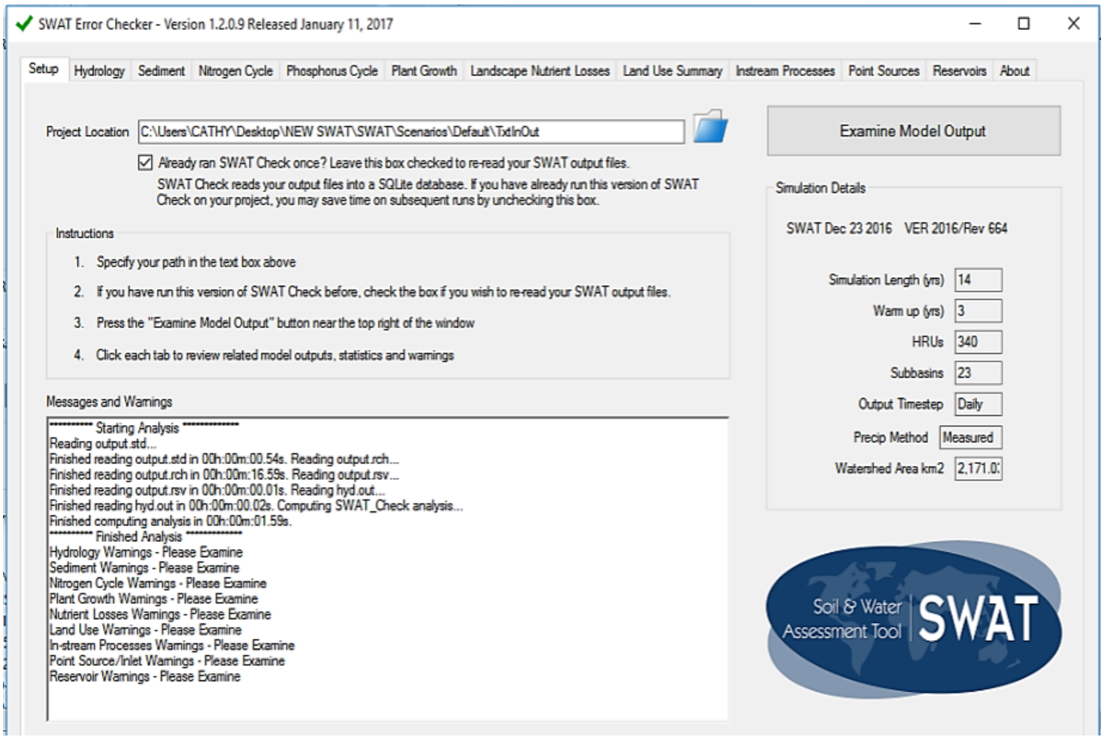
Appendix 2: Calibration and Validation

List of parameters used in SWAT tool for surface and groundwater modeling

Cn2	Moisture Condition Ii Curve Number
Precipitation	Daily Precipitation (Mm H_2O)
CNCOEF	Weighting coefficient used to calculate the retention coefficient for daily curve; number calculations dependent on plant evapotranspiration
CLAY	% clay content
SAND	% sand content
SOL_BD	Moist bulk density (Mg/m^3)
SOL_K	Saturated hydraulic conductivity of first layer (mm/hr)
OV_N	Manning's *n* value for overland flow
SLSUBBSN	Average slope length (m)
CH_L (1)	Longest tributary channel length in sub-basin in (km)
CH_S (1)	Average slope of tributary channels (m/m)
CH_N (1)	Manning's *n* value for tributary channels
SURLAG	Surface runoff lag coefficient
SUB_KM	Area of the sub-basin (km^2)
CH_K (1)	Effective hydraulic conductivity (mm/hr)
CH_W (1)	Average width of tributary channel (m)
CH_L (1)	Longest tributary channel length in sub-basin (km)
ESCO	Soil evaporation compensation coefficient

CANMX	Maximum canopy storage
GW_DELAY	Delay time for aquifer recharge (days)
GWQMN	Threshold water level in shallow aquifer for base flow (mm H_2O)
APLHA_BF	Base flow recession constant
REVAPMN	Threshold water level in shallow aquifer for revap (mm H_2O)
GW_REVAP	Revap coefficient
RCHRG_DP	Aquifer percolation coefficient
GW_SPYLD	Specific yield of the shallow aquifer (m/m)

Appendix 3: Automatic watershed delineation, SWAT model running process, reading output and Error checker.



Project Location: C:\Users\CATHY\Desktop\NEW SWAT\SWAT\Scenarios\Default\TxtInOut

☑ Already ran SWAT Check once? Leave this box checked to re-read your SWAT output files.
SWAT Check reads your output files into a SQLite database. If you have already run this version of SWAT Check on your project, you may save time on subsequent runs by unchecking this box.

Instructions

1. Specify your path in the text box above
2. If you have run this version of SWAT Check before, check the box if you wish to re-read your SWAT output files.
3. Press the "Examine Model Output" button near the top right of the window
4. Click each tab to review related model outputs, statistics and warnings

Simulation Details

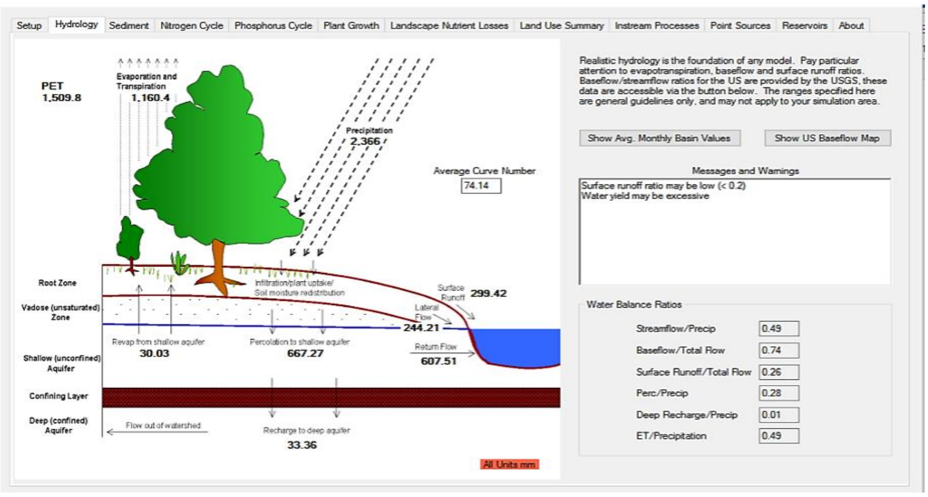
SWAT Dec 23 2016 VER 2016/Rev 664

Simulation Length (yrs): 14
Warm up (yrs): 3
HRUs: 340
Subbasins: 23
Output Timestep: Daily
Precip Method: Measured
Watershed Area km2: 2,171.0:

Messages and Warnings

```
********** Starting Analysis *************
Reading output.std...
Finished reading output.std in 00h:00m:00.54s. Reading output.rch...
Finished reading output.rch in 00h:00m:16.59s. Reading output.rsv...
Finished reading output.rsv in 00h:00m:00.01s. Reading hyd.out...
Finished reading hyd.out in 00h:00m:00.02s. Computing SWAT_Check analysis...
Finished computing analysis in 00h:00m:01.59s.
********** Finished Analysis *************
Hydrology Warnings - Please Examine
Sediment Warnings - Please Examine
Nitrogen Cycle Warnings - Please Examine
Plant Growth Warnings - Please Examine
Nutrient Losses Warnings - Please Examine
Land Use Warnings - Please Examine
In-stream Processes Warnings - Please Examine
Point Source/Inlet Warnings - Please Examine
Reservoir Warnings - Please Examine
```

Appendix 4: Hydrology of Mpanga catchment for the years 2000, 2008 and 2014



Realistic hydrology is the foundation of any model. Pay particular attention to evapotranspiration, baseflow and surface runoff ratios. Baseflow/streamflow ratios for the US are provided by the USGS, these data are accessible via the button below. The ranges specified here are general guidelines only, and may not apply to your simulation area.

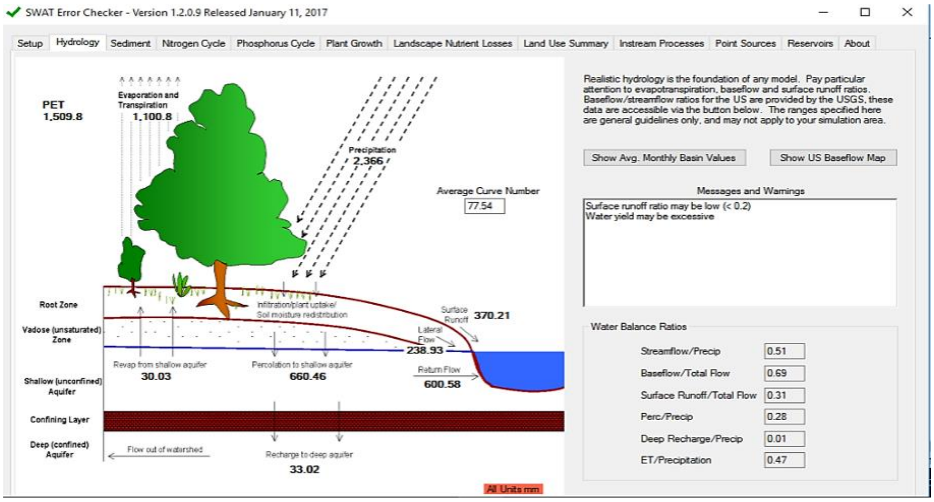
Average Curve Number: 74.14

Messages and Warnings

Surface runoff ratio may be low (< 0.2)
Water yield may be excessive

Water Balance Ratios

Streamflow/Precip: 0.49
Baseflow/Total Flow: 0.74
Surface Runoff/Total Flow: 0.26
Perc/Precip: 0.28
Deep Recharge/Precip: 0.01
ET/Precipitation: 0.49



Realistic hydrology is the foundation of any model. Pay particular attention to evapotranspiration, baseflow and surface runoff ratios. Baseflow/streamflow ratios for the US are provided by the USGS, these data are accessible via the button below. The ranges specified here are general guidelines only, and may not apply to your simulation area.

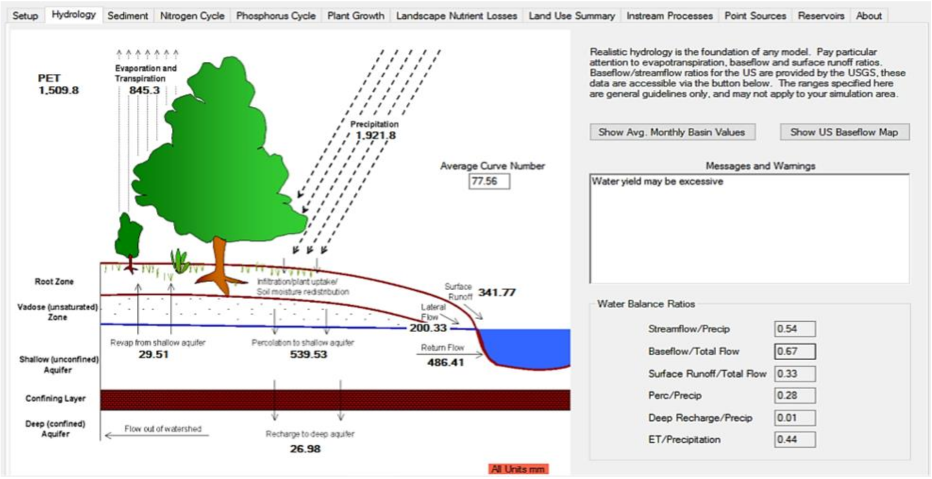
Average Curve Number: 77.54

Messages and Warnings

Surface runoff ratio may be low (< 0.2)
Water yield may be excessive

Water Balance Ratios

Streamflow/Precip: 0.51
Baseflow/Total Flow: 0.69
Surface Runoff/Total Flow: 0.31
Perc/Precip: 0.28
Deep Recharge/Precip: 0.01
ET/Precipitation: 0.47



Realistic hydrology is the foundation of any model. Pay particular attention to evapotranspiration, baseflow and surface runoff ratios. Baseflow/streamflow ratios for the US are provided by the USGS, these data are accessible via the button below. The ranges specified here are general guidelines only, and may not apply to your simulation area.

Average Curve Number: 77.56

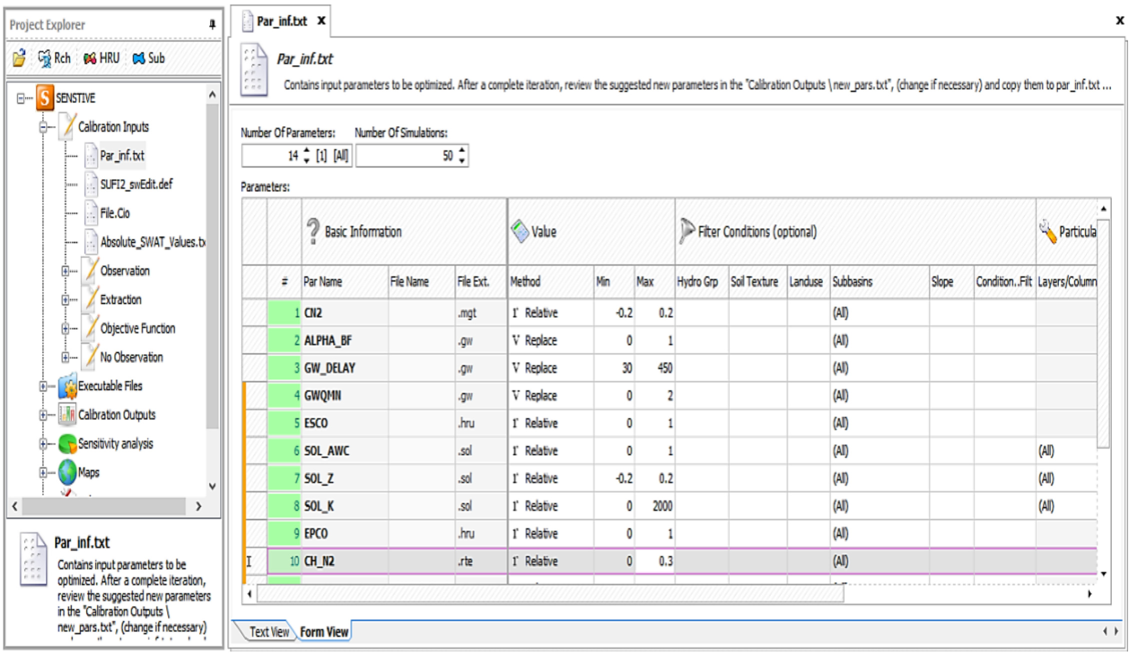
Messages and Warnings

Water yield may be excessive

Water Balance Ratios

Streamflow/Precip: 0.54
Baseflow/Total Flow: 0.67
Surface Runoff/Total Flow: 0.33
Perc/Precip: 0.28
Deep Recharge/Precip: 0.01
ET/Precipitation: 0.44

Appendix 5: Sensitivity analysis using swatcup tool



Par_inf.txt

Contains input parameters to be optimized. After a complete iteration, review the suggested new parameters in the "Calibration Outputs \ new_pars.txt", (change if necessary)

Par_inf.txt

Contains input parameters to be optimized. After a complete iteration, review the suggested new parameters in the "Calibration Outputs \ new_pars.txt", (change if necessary) and copy them to par_inf.txt ...

Number Of Parameters: 14 [1] [All]

Number Of Simulations: 50

Parameters:

	Basic Information			Value			Filter Conditions (optional)						Particula
#	Par Name	File Name	File Ext.	Method	Min	Max	Hydro Grp	Soil Texture	Landuse	Subbasins	Slope	Condition..Filt	Layers/Column
1	CN2		.mgt	r Relative	-0.2	0.2				(All)			
2	ALPHA_BF		.gw	v Replace	0	1				(All)			
3	GW_DELAY		.gw	v Replace	30	450				(All)			
4	GWQMN		.gw	v Replace	0	2				(All)			
5	ESCO		.hru	r Relative	0	1				(All)			
6	SOL_AWC		.sol	r Relative	0	1				(All)			(All)
7	SOL_Z		.sol	r Relative	-0.2	0.2				(All)			(All)
8	SOL_K		.sol	r Relative	0	2000				(All)			(All)
9	EPCO		.hru	r Relative	0	1				(All)			
10	CH_N2		.rte	r Relative	0	0.3				(All)			