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DEPARTMENT OF AGRICULTURAL AND BIOENGINEERING

**TITLE: ASSESSMENT OF RUNOFF AND SOIL EROSION PATTERNS IN THE
NAMATALA WATERSHED USING SWAT+**

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LIST OF ACRONYMS

Acronym	Meaning
AET	Actual Evapotranspiration
AGRL	Agricultural Land (SWAT+ land use class)
ALOS	Advanced Land Observing Satellite
ASABE	American Society of Agricultural and Biological Engineers
BMP	Best Management Practice
CFSR	Climate Forecast System Reanalysis
CH_EROD	Channel Erodibility Factor
CHIRPS	Climate Hazards Group Infrared Precipitation with Station data
CN2	Curve Number (moisture condition II)
CRDY	Dryland Crops (SWAT+ land use class)
CRGR	Dryland Grains (SWAT+ land use class)
CSA	Critical Source Area
DEM	Digital Elevation Model
DWRM	Directorate of Water Resources Management
ESCO	Soil Evaporation Compensation Factor
FAO	Food and Agriculture Organization
FODB	Forest and Degraded Bush (SWAT+ land use class)
FRST	Mixed Forest (SWAT+ land use class)
GIS	Geographic Information System
GRAS	Grassland (SWAT+ land use class)
GW_DELAY	Groundwater Delay Time
GWQ	Groundwater Flow to Stream
HRU(s)	Hydrologic Response Unit(s)
HWSD	Harmonized World Soil Database

ITCZ	Inter-Tropical Convergence Zone
LATQ	Lateral Flow
LSU(s)	Landscape Unit(s)
LULC	Land Use/Land Cover
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MODIS	Moderate Resolution Imaging Spectroradiometer
MUSLE	Modified Universal Soil Loss Equation
NASAPOWER	National Aeronautics and Space Administration – Prediction Of Worldwide Energy Resources
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent Bias
PET	Potential Evapotranspiration
QGIS	Quantum Geographic Information System
QSWAT+	QGIS Interface for SWAT+
RCHRG_DP	Deep Aquifer Recharge
RMSE	Root Mean Square Error
RNGE	Range Grassland (SWAT+ land use class)
RSR	RMSE-observation Standard deviation Ratio
RUSLE	Revised Universal Soil Loss Equation
SAVA	Savanna Grassland (SWAT+ land use class)
SLM	Sustainable Land Management
SOL_AWC	Soil Available Water Capacity
SRTM	Shuttle Radar Topography Mission
SUF2	Sequential Uncertainty Fitting, version 2
SURQ	Surface Runoff
SVM	Support Vector Machine

SWAT(+)	Soil and Water Assessment Tool (Plus)
SWC	Soil and Water Conservation
TAUDEM	Terrain Analysis Using Digital Elevation Models
UBOS	Uganda Bureau of Statistics
UNMA	Uganda National Meteorological Authority
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USLE_C	Cover Management Factor (USLE)
USLE_P	Support Practice Factor (USLE)
UTM	Universal Transverse Mercator
WATR	Water (SWAT+ land use class)
WETL	Wetland (SWAT+ land use class)
WGS	World Geodetic System
WYLD	Water Yield

DECLARATION

I, **ERINOR AIDAH NABUZALE**, declare that this report is my original work and has not been submitted to any other institution or university for the award of any academic qualification.

All sources of information used in this report have been duly acknowledged and referenced in accordance with academic standards.

Signature.....erinoraidah.....

Registration Number.....22/U/6497.....

Date.....10/08/2026.....

DEDICATION

This report is dedicated to the Almighty God for the strength, wisdom, and guidance granted to me throughout the course of my study.

I as well dedicate this project to my parents and family for their unending support, encouragement, and sacrifices made towards ensuring my academic success. Their endless belief in me has been my greatest motivation.

Finally, I dedicate this report to my lecturers and mentors, whose guidance and knowledge have been key in shaping my academic and professional growth.

APPROVAL

This report has been submitted for examination to the Department of Agricultural and Biosystems Engineering with the approval as the appointed supervisors.

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APPROVAL

This report has been submitted for examination to the Department of Agricultural and Biosystems Engineering with the approval as the appointed supervisors.

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ABSTRACT

Soil erosion and surface runoff are big problems for farming and water in many highland areas of Uganda, like the Namatala Watershed on the southeastern side of Mount Elgon. This area has become worse with time because more land is being encroached for farming, forests are being cut down, and people aren't managing the land well.

In this study, we see how runoff and soil erosion change over time and space in the Namatala Watershed. We used a tool called SWAT+ along with GIS and satellite data. We fed the model data from a 30 m Digital Elevation Model, Sentinel-2 for land use and cover, SoilGrids for soil types, and NASA POWER for climate information. The watershed was divided into smaller areas called HRUs based on their land use, soil, and slope. We then checked how well the model matched real streamflow data and used metrics like NSE, PBIAS, and R^2 to see how good it was.

The model worked well for both calibration and validation. We found that farms made up over half of the watershed's area, with grasslands covering about 37%. The way rainfall was split between different uses, like evaporation and/or becoming runoff, was heavily affected by the land use, soil, and how steep the land was.

This study shows that SWAT+ can be useful for understanding runoff and erosion in places where data is scarce. The information collected can help decide where to direct conservation efforts to reduce erosion, improve land productivity, and make the Namatala Watershed more sustainable.

CHAPTER 1: INTRODUCTION

1.1 Background of the Study

1.1.1 Overview of watershed importance and global degradation issues

A Watershed is the hydrological unit within which all precipitation evaporation, surface and groundwater movement, soil and organisms live. The Watershed is vital for maintaining ecological integrity and for agricultural production as well as for the socio-economic development of the population living in the Watershed's catchment area (Falkenmark and Rockstrom 2017). A Watershed is a geographical area within which all the rain and domestic and industrial and agricultural runoff and snowmelt are collected and stored and released down gradient. The Watersheds of the world all go through changes due to human activities. The Watersheds deteriorate primarily due to human-induced land degradation brought on by some very destructive agricultural practices as well as deforestation and urbanization (Bai et al. 2008). All types of Watersheds provide many valuable ecosystem services including improved water quality, the water storage needed for flood control, the recharging of groundwater aquifers, as well as the production of fertile soils (Brauman et al. 2007).

Accelerated soil erosion and altered runoff regimes are among the most pervasive and damaging indicators of the degradation. Lal (2001) emphasized that soil erosion is not only a problem of soil loss but an accelerant for rapid development of negative on-site and off-site impacts. On-site, it leads to the loss of fertile topsoil, reduction in agricultural productivity, and a decline in soil organic matter, thereby threatening food security (Pimentel et al. 1995). Off-site, the transported sediment clogs river channels, increases the frequency and magnitude of flooding, reduces the storage capacity and operational lifespan of reservoirs, and degrades water quality through siltation and associated pollutant transport (Morris and Fan 1998). The economic costs associated with these impacts are globally estimated to be running into hundreds of billions of dollars annually (Sartori et al. 2019).

1.1.2 Global and Regional Trends in Soil Erosion and Runoff

Globally, soil erosion rates are high, a study by Borrelli et al(2017a) used a high-resolution global model to estimate a mean annual soil loss of 35.9 Pg yr⁻¹, with about 10% of this sediment reaching

the ocean. Their research identified agricultural areas as the primary hotspots of erosion, contributing over half of the global sediment rise despite occupying less than a third of the land surface. This highlights the impact of land use change on Earth's surface processes.

Vrieling et al., (2010), in a continental-scale assessment using remote sensing, identified the East African highlands as regions of high erosion risk. This is accelerated by factors such as intense tropical rainfall, expansion of cultivation onto marginal and steeply sloped lands, and limited adoption of soil and water conservation (SWC) measures (Tadesse et al. 2017). In Uganda specifically, the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF 2018) identified soil erosion as a leading cause of land degradation, with estimated annual soil loss rates in cultivated highland areas exceeding 10 tons ha^{-1} , which is above the presumed sustainable rate of $1 \text{ ton ha}^{-1} \text{ yr}^{-1}$ (Lal 2001). These trends highlight a regional crisis that undermines sustainable development and livelihoods.

1.1.3 Description and Specific Challenges of the Namatala Watershed

In the Namatala watershed, increasing land degradation due to intensive farming, deforestation, and urban expansion has led to increased soil erosion and runoff, resulting in sedimentation in rivers and reduced agricultural land fertility (Namaalwa et al. 2020a). Over the last two decades, the forest and natural vegetation cover in the upper watershed has declined by 30–40%, primarily converted into farmland and built-up areas (Nalumansi, 2022; Republic of Uganda, 2022). The annual rainfall in the area ranges between 1,200 and 1,800 mm, and maximum and minimum temperatures being 23°C and 15°C respectively (Mugagga, Kakembo, and Buyinza 2012a).

Consequently, the watershed now exhibits increased runoff coefficients of about 0.42–0.58 and mean annual soil loss rates estimated between $12\text{--}35 \text{ t ha}^{-1} \text{ yr}^{-1}$, particularly in the upper mountainous zones (Namaalwa et al., 2020a). Sediment deposition in the Namatala River and its tributaries has reduced stream conveyance capacity and contributes to frequent flooding in downstream areas such as Namabasa and Nabuyoga, degrading wetlands and farmlands Uganda (SLM EASTERN Uganda, 2020). These problems do not only cause harm to agriculture production and to the structural condition of ecosystems and water quality; they impact livelihoods dependent upon access to water resources within the watershed. Namaalwa et al. (2020) have stated

that these issues inhibit both sustainable land use and water resource management in the area as well as the ecological health.

1.1.4 The Importance of Hydrological Modeling and Justification for SWAT+

Addressing these challenges requires developing tools capable of reproducing the functioning of the watershed. Hydrological models are therefore essential for studying phenomena, forecasting their consequences, and testing management alternatives (Gassman, Sadeghi, and Srinivasan 2014). However, there is no best model that can be used for any watershed. One of the most popular and reliable tools for simulating water, sediment, and nutrient surpluses in large basins is the SWAT model.

SWAT is a public-domain, physically based, semi-distributed, and continuous hydrological model developed by the USDA Agricultural Research Service (Arnold et al. 1998). It has gained worldwide recognition and was used in thousands of papers published in SWAT database (SWAT 2023). The model allows researchers to operate with the complex mechanisms of catchment areas with different characteristics and types of land cover. Such features as slope, cover type, and soil classification are considered in the form of Hydrologic Response Units (HRUs). They are formed by dividing a basin into several sub-basins and then into HRUs. The model uses a water balance equation and includes components describing the weather, plant growth, erosion processes, calculation of water balance, and nutrient cycling (Neitsch et al. 2011). However, the conventional SWAT model has recognized limitations, particularly in its spatial representation. The HRU concept is lumped and does not explicitly account for the spatial connectivity and routing of flows between different landscape units within a sub-basin as identified by (Bieger et al. 2017). This is a critical shortcoming for a watershed like Namatala, where the flow of water and sediment from uplands to valley bottoms, wetlands is a fundamental process (Nalumansi 2022a).

The SWAT+ model was created to address some of these limitations. Instead of using HRUs to describe the sub-basins, the SWAT+ model uses LSUs to describe the landscape (Bieger et al. 2017). The LSUs can be connected to one another and form routing units to describe how water, sediment, and nutrients can move through the landscape to reach the stream.

1.1.5 Identified Knowledge Gap

A review of existing literature shows a knowledge gap. While previous studies in Uganda like (Anaba et al. 2017), demonstrated the utility of the conventional SWAT model, there's an absence of research applying the more advanced SWAT+ model in the country. Furthermore, the Namatala Watershed itself remains understudied, with no known published research that provides a comprehensive, spatially explicit quantification of its soil erosion and runoff dynamics using a process-based hydrological model. The existing studies rely on empirical models, which do not fully capture the landscape interactions characteristic of the watershed, and studies like land use and landcover, as well as pollution in the watershed (Nalumansi 2022a; Namaalwa et al. 2020a). Therefore, a study using SWAT+ is needed to fill this gap and provide a more accurate and management-relevant assessment.

1.2 PROBLEM STATEMENT

The Namatala watershed in Mbale District is increasingly affected by soil erosion and surface runoff, mainly due to steep slopes (1200m-2900m above sea level)(Nakileza and Nedala 2020), high rainfall (1200-1800mm annually)(Mugagga et al. 2012a), and unsustainable land-use practices, deforestation and cultivation of vulnerable hillsides have resulted from rapid population growth, leaving soils vulnerable to severe erosion during periods of heavy rainfall. (Mugagga et al. 2012a)

The intensified sediment deposition in rivers and lowland areas due to the situation has impacted the Namatala River with flooding, siltation of the drainage channels, and a decline in the fertility of the farmlands in the downstream areas. These impacts pose significant threats to agricultural productivity, the ecological integrity of the watershed, and the livelihood of the communities that depend on it (Mugagga et al. 2012a; Nakileza and Nedala 2020).

Although previous studies on hydrology in Uganda have provided information on various regions of Uganda, they either focus on different catchments than the Namatala River basin, such as Murchison Bay (Anaba et al. 2017), or the studies generally cover land use and land cover within different catchments in Uganda (Nalumansi 2022a; Namaalwa et al. 2020a). Thus, there is the absence of studies that focus specifically on the runoff and soil erosion within the Namatala River basin. This is the gap that is directly addressed within this study, which developed and applied GIS

technology to monitor runoff and soil erosion within the Namatala River basin (Mugagga et al. 2012b). The application of the SWAT+ model is central to this research, as its restructured code provides a capable solution. Unlike empirical methods, SWAT+ allows for the explicit simulation of water and sediment routing across different landscape units within a sub-basin (Bieger et al. 2017). As a result, interventions have often been generalized and ineffective, failing to address critical erosion hotspots (Gashaw et al. 2021; Gassman et al. 2014). Addressing this gap through the integration of Geographic Information Systems (QGIS) and the Soil and Water Assessment Tool Plus (SWAT+) offers an opportunity to better understand the spatial and temporal dynamics of erosion and runoff, thereby supporting data-driven watershed management and sustainable land-use planning in the Namatala catchment.

1.3 OBJECTIVES

1.3.1 MAIN OBJECTIVE

To assess and quantify the spatial and temporal distribution of runoff and soil erosion in the Namatala watershed.

1.3.2 SPECIFIC OBJECTIVES:

1. To set up the SWAT+ model for simulating runoff and soil erosion dynamics in the Namatala watershed, for the current conditions.
2. To calibrate and validate the SWAT+ model to depict the catchment conditions.
3. To quantify the spatial and temporal runoff and erosion distribution patterns in the Namatala watershed.

1.4 JUSTIFICATION

The event of soil erosion and runoff continues to constitute some of the greatest environmental problems in Uganda's highland regions where, in a combination of fragile volcanic soils, steep terrain and heavy rainfall, land degradation accelerates rapidly. (Mugagga et al. 2012a). Apart from causing water quality to deteriorate due to increased sediment and nutrient loading into water bodies, the runoff also results in wetland degradation and Because of this, the interruption of

essential ecosystem services like water purification, habitat provision amongst others. (Namaalwa et al. 2020a).

Although the problem of soil erosion and runoff is clearly understood, there hasn't been much effort put into generating specific data at the local level, as most of the studies have been conducted at the national or regional level only. For example, River Katonga Micro-Catchment study although it gives the readers understanding of how various farming systems affect soil and nutrient loss in runoff, the paper highlights how it would be very important to have local and even site specific research to understand how and why soils are washed off with nutrients depending of different kinds of land-use and management practices. (Adidja Basamba Ssekandi 2025). Additionally, studies like that of Bamutaze et al. (2021) in the Rwizi catchment highlight the importance of assessing runoff and soil loss across diverse land uses to gain insights into landscape sustainability and resilience niches. However, there is a call for more comprehensive assessments that consider the coupled interactive sequences under diverse land uses. Furthermore, research by

Ssewankambo et al. (2023) in a peri-urban catchment underscores the necessity of integrating tailored soil and water conservation measures into physical planning, focusing on identified non-conventional hotspots to mitigate sediment pollution in Lake Victoria. This indicates a gap in addressing erosion risks in peri-urban areas and the need for context-specific mitigation strategies

Therefore, this study is justified as it will generate scientific data and spatial evidence necessary for sustainable watershed management, helping local authorities, environmental agencies, and farmers make informed decisions to curb soil erosion and runoff impacts in the Namatala watershed.

1.5 CONCEPTUAL FRAMEWORK

Theoretical Basis:

The framework's theoretical foundation is based on soil erosion dynamics and hydrological modeling theory. It uses SWAT+ in conjunction with GIS spatial analysis. Based on the principles of the USLE and the theory of the rainfall-runoff relationship, SWAT+ uses spatial inputs generated and visualized in GIS to simulate hydrologic and erosion processes (Dile et al., 2016).

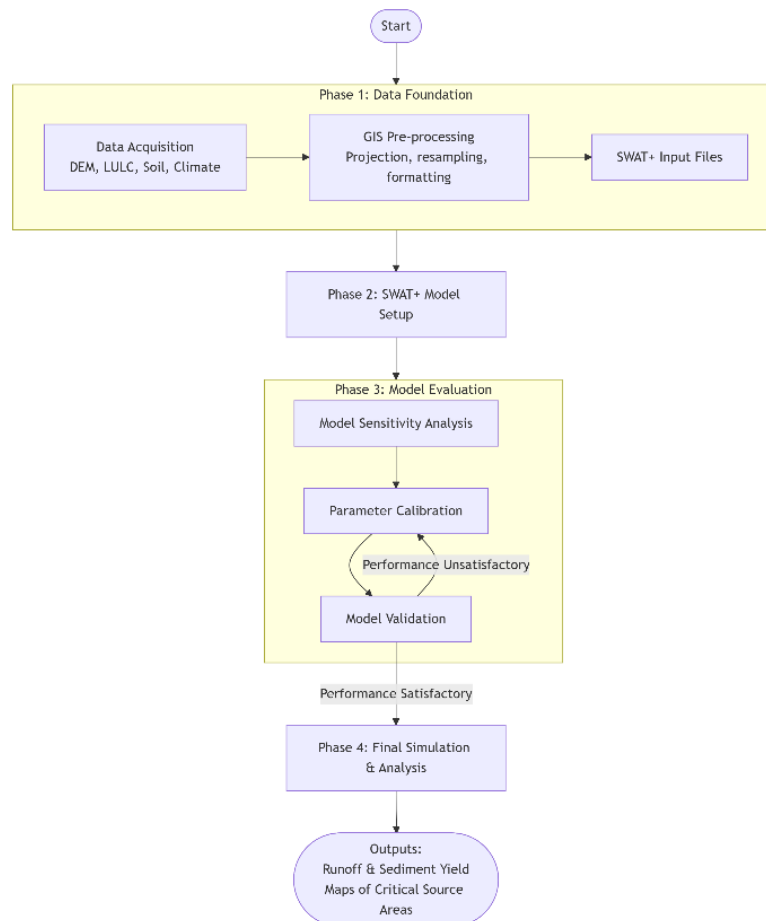


Figure 1: Conceptual Framework

CHAPTER 2: LITERATURE REVIEW

2.1 Soil erosion and runoff in highland watersheds

Soil erosion remains one of the most significant forms of land degradation in tropical highlands, leading to nutrient loss, siltation of rivers, and declining agricultural productivity. In Uganda's Mount Elgon region, which includes the Namatala watershed, high rainfall intensity and steep topography accelerate erosion and runoff generation (Bamutaze et al. 2021a). The combination of fragile volcanic soils and poorly managed slopes makes the area particularly prone to rill and gully formation, sediment yield, and downstream flooding (De Crop et al. 2023).

Empirical studies show that annual soil loss in Uganda's eastern highlands range from 14.6 to 33.81 $\text{tha}^{-1} \text{yr}^{-1}$, depending on slope and vegetation cover (Karamage et al. 2017). Rainfall erosion levels higher than 10,000 MJ mm $\text{ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ were found in some sub-catchments (Mutekanga, Visser, and Stroosnijder 2010). These severe erosion losses have been linked to increased surface runoff that on stormy days can account for up to 0.35, 0.55 runoff coefficient in cultivated Elgon slopes (Erima et al. 2022).

These water responses are major triggers to flash floods in Namatala River basin and have been the causes for continuous disruption of life to the towns of Mbale and Butaleja (Hellen Kongai et al. 2022). These processes, both in environmental and social economic terms, are a sufficient justification for the necessity of models and spatially explicit assessments that would be able to relate land use, slope, and runoff dynamics.

2.2 Global and regional challenges of soil erosion

Land degradation due to soil erosion is a world-wide thing that brings very devastating onsite and offsite impacts. At the onsite level, there is destruction of soil organic matter and nutrients, which results in immediate deterioration of its power to sustain plant life as well as threats to food security (Lal 2015a). Pimentel et al. (1995) made a very important worldwide evaluation showing that soil erosion results in economic losses exceeding \$400 billion per year globally because of less agricultural productivity and more use of fertilizers.

In Sub-Saharan Africa, rapid population growth, expansion of cultivation onto marginal lands, and shortened fallow periods have intensified land degradation (Tadesse et al. 2017). Vrieling et al. (2010) used remote sensing to map continental-scale erosion patterns and identified the East African highlands, including parts of Uganda, as hotspots of soil erosion risk. The economic implications for agro-based economies like Uganda's are very deep. The Uganda National Bureau of Statistics (UBOS 2018a) reported that agriculture employs over 70% of the population, making the sector highly vulnerable to soil degradation. While national level data on soil loss is still low, studies available indicate high rates of soil loss, for example, a study on the slopes of Mount Elgon by Bamutaze et al. (2021a), found that land under seasonal cultivation like maize and beans experienced higher soil loss compared to land under perennial cover. The study recorded soil loss rates of $>10\text{tonnesha}^{-1}\text{yr}^{-1}$ on steeply sloped land under annual cropping. Another research in the Lake Victoria Basin, specifically in the Mpigi District, measured soil loss from various land-use types. The study found that on land cultivated with annual crops on slopes of 5-15%, soil loss reached 30-70tonnes $\text{ha}^{-1}\text{yr}^{-1}$ (Lufafa et al. 2003).

2.3 Modelling and runoff using SWAT and SWAT+

2.3.1 History of SWAT and SWAT +

The need to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, ungauged basins led to the development of the Soil and Water Assessment Tool (SWAT) by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) (Gassman et al. 2007). The model's conceptual framework divides a watershed into sub-basins, which are further subdivided into Hydrologic Response Units (HRUs) lumped land areas within a sub-basin comprising unique combinations of soil type, land use, and slope (Neitsch et al. 2011). The hydrological cycle is simulated based on the water balance equation. Sediment yield is estimated for each HRU using the Modified Universal Soil Loss Equation (MUSLE) which is an advancement over the USLE (Walling 2005) as it uses runoff variables to predict sediment yield for a single storm event, eliminating the need for a delivery ratio.

Even though SWAT is widely used, it has some problems with how it shows space. The HRU method in SWAT groups together how things relate in a part of a river basin. But it doesn't clearly

show how water and sediment move between different areas, according to Bieger et al (2017). This is a big deal when trying to model how water runs off from steep highlands to valleys, or how conservation efforts in specific hotspots might work. SWAT+ was developed to fix these challenges. As Bieger et al. (2017) explained, SWAT+ has a more adaptable ways of handling spatial information.

The Soil and Water Assessment Tool (SWAT), and its updated version, SWAT+, are top choices for modeling how water moves in complicated river basins (Msigwa et al. 2022). SWAT+ has a modular design, explicitly and clearly tracks water movement across the land, and allows for more flexible definitions of hydrological response units (HRUs) (Nkwasa et al 2020). This makes it a a better choice for varied terrains with significant changes in elevations and differences in land use, like the Namatala watershed.

2.4 A review of application of SWAT in East Africa and Uganda

2.4. 1 Regional studies

SWAT has been used in a few studies to determine how water moves and how soil erodes in these areas. For example, Setegn, Srinivasan, and Dargahi (2008) used SWAT for the Lake Tana Basin in Ethiopia. They showed it could simulate river flow and find places where soil was likely to erode. Their study pointed out that soil and land use details really affected how well the model works. Gassman et al. (2014) looked at how SWAT was used in Africa and found out that it's a good tool, but it works best when the information put into it is as good and when the model is properly adjusted. In the Upper Nile Basin, Dile, Berndtsson, and Setegn (2013) used SWAT to see how climate change might affect water resources. This study showed how useful SWAT is for looking at different future possibilities, which is important for managing water areas like the one proposed for Namatala watershed.

2.4.2 Studies in Uganda

In Uganda, SWAT has been applied in several watersheds, primarily within the Lake Victoria Basin. For example, Anaba et al(2017) used SWAT to determine the impact of land use change on the water balance of the Aswa River catchment. They found out that the expansion of agriculture and settlements increased surface runoff and reduced base flow. Their study

successfully used GIS to process LULC change maps, a methodology directly transferable to the Namatala project.

Namaalwa et al. (2020a) conducted a thorough assessment of how wastewater discharge affects water quality and nutrient retention in the Namatala Wetland, located in Eastern Uganda. Their research used a combination of field sampling, laboratory analyses, and hydrological measurements to quantify nutrient inflows and retention capacities across different wetland zones. Their study revealed that the Namatala Wetland functions as an important nutrient sink, reducing concentrations of nitrogen and phosphorus before water flows into downstream ecosystems. It also sighted the increasing threat of nitrogen build ups and sedimentation arising from unregulated agricultural runoff and urban wastewater discharge from Mbale Municipality. These findings justify that while wetlands such as Namatala still provide critical ecosystem services, their potential to filter pollutants is reducing due to land-use pressures and encroachment. This is significant to the present study, as SWAT+ modelling of the same watershed can quantify the spatial extent and hydrological sources of these pressures. This shall provide a broader system-level understanding that adds onto Namaalwa's field-based observations. Integrating these hydrological simulations with her empirical findings helps link observed water quality degradation to catchment-scale runoff and sediment dynamics, hence supporting wetland conservation and sustainable watershed management strategies.

A more recent study by Bamutaze et al (2021) looked at the Malaba River catchment. This is similar to the Namatala Watershed in terms of geography and farming conditions. They used SWAT to find the main areas where sediment was originating from and found that sloping farmland was the biggest source. This shows how important it is to use models that can clearly point out specific locations for conservation work. However, they used the standard SWAT model, which might not have captured fully how water moves across different parts of the landscape.

2.5 Role of GIS and Remote sensing in SWAT + modelling

The efficacy of SWAT+ highly depends on the quality and resolution of the input data. GIS provides the fundamental platform for managing, processing, and visualizing the spatial datasets required by the model. The spatial inputs include:

2.5.1 Digital Elevation Model (DEM):

This DEM is used to extract out the watershed, configure the stream network and slope details. How good the DEM is, like SRTM, ASTER, or ALOS, is essential for the accuracy of the water-related calculations (Yang et al., 2007). The DEM provides a complete picture of the land, which helps us determine factors like drainage networks, flow direction, quantity of water accumulating, slope, and the boundaries of smaller basins (Jenson and Domingue, 1988). Having an accurate map of the terrain is essential in highland areas like the Namatala watershed on Mount Elgon. This is because the steepness of the land influences how runoff occurs, and how much soil gets eroded. Research shows that the SRTM DEM, after being fixed to handle sinks and shaped for hydrology, gives good watershed maps in steep, tropical areas (Bamutaze et al. 2021a). Therefore, this cleaned-up DEM will be the baseline for all the different data layers in SWAT+, affecting how the hydrological response units are defined, divide up the streams, and classify the slopes.

2.5.2 Land Use/Land Cover (LULC) Maps:

These are essential for defining HRUs and assigning model parameters related to evapotranspiration, surface runoff, and erosion. The availability of high-resolution, temporally consistent LULC maps from satellites like Landsat and Sentinel has been tool for SWAT applications (Otukei and Blaschke 2010). Previous studies in Uganda and East Africa have shown the effectiveness of Sentinel-based LULC mapping for hydrological modelling (Msigwa et al. 2022; Nkwasa et al. 2020). The classified LULC map will provide essential inputs for defining hydrological response units (HRUs) in SWAT+, enabling spatially explicit assessment of how land-use change affects runoff and erosion dynamics.

2.5.3 Soil Maps:

Provide information on soil texture, hydraulic conductivity, and available water capacity, which are fundamental to simulating the water balance and sediment generation. Global datasets like the FAO-UNESCO Soil Map of the World or the Harmonized World Soil Database (HWSD) are often used in data-scarce regions. The HWSD has been used in Ugandan hydrological studies, including the Murchison Bay catchment Anaba et al. (2017) and Lake Victoria basin confirming its suitability for regional SWAT modelling.

2.6 Climate and Hydrology

The climate is tropical, with a bimodal rainfall pattern influenced by the Inter-Tropical Convergence Zone (ITCZ) and the orographic effect of Mount Elgon. The long rainy season occurs from March to May, and a shorter, less intense season occurs from August to November. Mean annual rainfall ranges from 1,200 mm in the low-lying plains to over 1,800 mm on the windward slopes of Mount Elgon (UBOS, 2018). Temperature is relatively stable, with annual means between 20 °C and 25 °C. The Namatala River, which is the watershed's primary drainage channel, is perennial, with its flow regime highly relative with the seasonal rainfall, leading to high-flow and low-flow periods.

SWAT+ requires daily records of precipitation, temperature, solar radiation, wind speed, and relative humidity. In regions with less meteorological stations, climate datasets from sources like the Climate Forecast System Reanalysis (CFSR) or CHIRPS are used (Fuka et al. 2014). CHIRPS uses satellite estimates as well as ground station data to improve rainfall accuracy in data-scarce regions. This makes it suitable for catchments like Namatala. Temperature, relative humidity, solar radiation, and wind speed data will be acquired from the Uganda National Meteorological Authority (UNMA) and coupled with the Climate Forecast System Reanalysis (CFSR) where local records are sparse (Fuka et al. 2014). Variuos research has validated CHIRPS for hydrological modelling across Africa. This shows strong correlation with observed precipitation and reliable representation of spatiotemporal rainfall variability (Dinku et al. 2018).

2.7 Synthesis, Critical Analysis, and Identification of Research Gaps

A comparative analysis of the reviewed literature shows several consistent objectives and critical gaps that the project on the Namatala Watershed aims to handle.

2.7.1 Comparative Analysis:

Different studies across East Africa continuously demonstrate SWAT's potential in simulating hydrology and sediment yield. The model's sensitivity to soil such as soil available water capacity and land management parameters is a common finding (Anaba et al. 2017; Setegn et al. 2008). The use of global datasets like DEM, soil, climate has proven consistency in achieving acceptable model performance in data-scarce environments, though it introduces some uncertainties. Many

studies in Uganda and the wider region have used the parent SWAT model. The transition to SWAT+, with its more advanced spatial capacities, represents a significant methodological improvement that has not yet been widely adopted in the region.

2.7.2 Identification of Research Gaps:

In Uganda, the SWAT+ model sees very little use. Few researchers have utilized this model when studying water areas within Uganda. Because this project is to take advantage of the detailed geographic representation provided by SWAT+, critical sources of should be better identified. This will establish a sound foundation for examining conservation practices which focus on specific regions.

The Namatala Watershed is very important to the environment and people who live in near it, yet it receives little study. Even though information exists about neighboring water areas such as the Malaba and Manafwa Rivers, the particular qualities of the Namatala require special evaluation. Because soil kinds, growing methods, and weather patterns can vary significantly, these local features should be investigated to understand the watershed properly.

Older and less detailed geographic data were used in many previous investigations. Researchers utilized sources like 90m SRTM and HWSD v1.0. However, this project will benefit from modern information with greater spatial precision. Data such as 30m SRTM or ALOS DEM, Sentinel-2 LULC, and CHIRPS precipitation will be adopted to make the SWAT+ model more exact and show the outputs in greater detail.

While some scenario studies have occurred before, a wider assessment is needed. Such evaluations must mix future weather predictions from CMIP6 models with different possible ways the land will be used. This combination allows planners to make better decisions for their communities. By exploring both the current situation and future possibilities, the project will give planners the necessary information for making effective land and water management choices.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION:

Geographic Information Systems (GIS), remote sensing, and the hydrological model, the Soil and Water Assessment Tool Plus (SWAT+), are all used in this study's integrated, multi-stage methodological framework. This method was selected due to its ability to manage sizable watersheds with scarce observed data, offering a spatially explicit platform for scenario analysis (Gassman et al. 2014). As shown in Figure 1, the methodology is organized into four separate, phases to ensure robustness, transparency, and replicability.

3.2 Description of study area

3.2.1 Location and Physiography

The Namatala watershed is located in Eastern Uganda near Mbale town. It is a critical hydrological system supporting both agricultural activities and wetland ecosystems. It is part of the major Doho-Namatala Wetland System within the Lake Kyoga Basin, lying along the main Namatala River. It stretches about 31 km from upstream to downstream, and has a surface area of 113 km² (Namaalwa et al. 2020a). It plays a vital role in sustaining livelihoods through water provision for irrigation, domestic use, and wetland-based biodiversity (Namaalwa et al. 2020a). The watershed lies within the Eastern Uganda agro-ecological zone that is, its characterized by volcanic highland soils, steep slopes, and a bimodal rainfall regime, which contribute to its hydrological complexity (SLM EASTERN UGANDA., 2020.). The landscape of Namatala includes steep uplands, cultivated hillsides, river channels and associated wetlands, especially the Namatala Wetland system, which stretches about 113 km² and ranges in elevation from 1,150 m upstream to 1,060 m downstream (Namaalwa et al. 2020a). The soils are described as clay loam in the swampy low-land parts and sandy loam or other volcanic-derived textures in higher terrain (Namaalwa et al. 2020a). Land-use change in this watershed has increased in recent years with expanded agriculture and urban settlement, adding pressure to the drainage system and increasing the risk of sedimentation, runoff amplification, and wetland degradation (Nalumansi 2022a). However, the watershed faces environmental challenges like intensified agricultural expansion, urbanisation, and wetland encroachment. These have changed land use patterns and hydrological processes (Nalumansi

2022a; Namaalwa et al. 2020a). These changes have increased surface runoff and sediment loads, contributing to soil erosion and degradation of the Namatala wetland, which functions as an important sediment and nutrient retention area (Namaalwa et al. 2020a). The degradation of the watershed thus puts threats on water quality, agricultural productivity, and ecological integrity hence the need for detailed spatial assessment and sustainable management strategies.

3.3 Soils and Land Use/Land Cover (LULC)

The soil types are a direct mirror of the area's geology and topography. The upper slopes are dominated by deep, well-weathered, and moderately permeable Nitisols. These are derived from volcanic parent material. Andosols which are known for high organic matter and water-holding capacity, are also present. The lower plains are dominated by heavy, clay-rich Vertisols with poor drainage and high shrink-swell potential, as well as Fluvisols in the active floodplains (Food and Agriculture Organization [FAO], 2015). Land use is a complex mosaic. The high-altitude areas retain fragments of montane forest, but the mid-slopes are intensively cultivated with both subsistence crops (maize, beans, cassava) and cash crops (coffee, bananas). The lower slopes and plains are dominated by rice cultivation within the wetlands and extensive grazing lands. Rapid urbanization around Mbale city is also a significant land use change driver (Mugagga, Kakembo, and Buyinza 2012b; Nalumansi 2022b; Namaalwa et al. 2020b) This LULC distribution is a critical determinant of the watershed's hydrological and sediment response.

3.4 Phase 1: Data Acquisition and Pre-processing

A foundational principle of reliable hydrological modelling is the use of high-quality, consistent, and accurately pre-processed input data (Bhasme, Vagadiya, and Bhatia 2022). All spatial datasets will be projected to a common coordinate system (WGS 84 UTM Zone 36N) and resampled to ensures geometric accuracy and spatial alignment across different layers (Lima Miranda et al. 2024), where necessary, to a 30-metre spatial resolution using QGIS software to maintain uniformity.

3.4.1 Digital Elevation Model (DEM)

The Terrain Analysis Using Digital Elevation Models (TAUDEM) methodology will be employed, utilizing the 30-metre resolution Shuttle Radar Topography Mission (SRTM) DEM, sourced from

the U.S. Geological Survey (USGS) Earth Explorer portal (USGS, 2023). The DEM will be hydrologically corrected by filling some sinks and pits to ensure a continuous flow surface, which is a prerequisite for accurate watershed delineation and stream network extraction (Wang and Liu 2006). Studies show that the choice of depression-filling algorithm can affect drainage networks significantly (Sharma & Tiwari, 2019).

3.4.2 Land Use and Land Cover (LULC) Data

A cloud-free Sentinel-2A satellite image with a 10 m resolution will be obtained from the Copernicus Open Access Hub for 2023 to accurately depict the current surface conditions. The Support Vector Machine (SVM) algorithm in QGIS/GRASS GIS will be used for a supervised classification. It has been demonstrated that in complex landscapes, SVM performs better than more conventional techniques like Maximum Likelihood (Poorahangaryan, Beheshti, and Edalatpanah 2017). High-resolution base maps in Google Earth Pro and, targeted field verification will be used to gather training data. The SWAT+ land use/plant database will be used to define and reclassify the LULC classes (e.g., AGRL = agricultural land, FRST = mixed forest, RNGE = range grassland, URBN = urban, WATR = water, WETL = wetland).

3.4.3 Soil Data

Soil spatial and physical property data will be sourced from the openly available Africa Soil Information Service (AfSIS) Soil Grids v2.0 database at 250 m resolution (Hengl et al. 2017a). The data for the standard soil layers that is, 0–5 cm, 5–15 cm, 15–30 cm, etc., will be extracted for the watershed. The required physical parameters for SWAT+, including percentage of sand, silt, clay, and organic carbon content, will be compiled to create a user soil input table. The soil hydraulic properties, such as available water capacity and hydraulic conductivity, will be estimated using pedotransfer functions integrated within the SWAT+ model (Saxton and Rawls 2006)

3.4.4 Climate Data

Precipitation: The Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) version 2.0 daily product, with a spatial resolution of approximately 5.5 km, will be used (Dinku et al. 2018). CHIRPS is particularly suited for this region as it blends satellite imagery with station data, effectively mitigating the limitations of using satellite data alone in data-sparse regions. Other

meteorological variables shall include the ERA5-Land dataset, a state-of-the-art global reanalysis product from the Copernicus Climate Change Service, will provide daily data for maximum and minimum temperature, solar radiation, wind speed, and relative humidity at approximately 9 km resolution (Muñoz-Sabater et al. 2021). Its high temporal and spatial consistency make it ideal for distributed hydrological modelling.

A weather generator database will be created from the long-term statistical properties for example mean, standard deviation, probability of wet/dry days of the climate data to fill any single missing days in the time series, a standard and necessary procedure in continuous-time models like SWAT+ (Neitsch et al. 2011)

3.4.5 Hydrological Data for Model Evaluation

Historical daily streamflow data for the Namatala River from the Directorate of Water Resources Management (DWRM) in Uganda and surrounding weather stations. This data is crucial for model calibration and validation. Given the extreme scarcity of measured sediment concentration data in Uganda, the model's sediment component will be calibrated based on the validated hydrological processes and established erosion principles within the model, with results interpreted as estimates.

3.5 Phase 2: SWAT+ Model Setup and Configuration

3.5.1. Watershed Delineation

The hydrologically corrected DEM will be imported into the QSWAT+ 1.4 interface, a QGIS plugin for SWAT+. The automated delineation routine will be executed to define the watershed outlet, ideally coinciding with a stream gauge location to generate a synthetic stream network, and subdivide the catchment into sub-basins. A critical source area (CSA) threshold will be used to initiate stream definition, creating a number of subs-basins that balances computational efficiency with the need to capture meaningful spatial data (Dile et al. 2016).

3.5.2 Definition of Hydrologic Response Units (HRUs)

Landscape Units (LSUs): These are defined by unique slope classes. For this study, slope will be reclassified from the DEM into four classes: 0–8% (gentle), 8–15% (moderate), 15–30% (steep),

and >30% (very steep), reflecting the critical role of slope in runoff and erosion process (Webster 2005).

HRUs: Within each LSU, HRUs will be created based on the unique combination of land use and soil type. A multiple dominance threshold of 10% for both land use and soil will be applied. This means any land use covering less than 10% of an LSU area, or any soil type covering less than 10% of a land use area within an LSU, will be eliminated, and its area redistributed to the dominant HRU. This prevents model over-specification and maintains computational stability without significantly compromising the representation of dominant processes (Bieger et al. 2017).

Model Initialization and Preliminary Run

After HRU definition, QSWAT+ will write all necessary model input files. A preliminary simulation will be executed for a long-term period like 2005–2025. The initial years for example 2005-2007 will serve as an extended warm-up period to initialize the model's water balance components like soil water, groundwater, etc. and minimize the influence of random initial conditions on the results of the analysis period (K C 2015).

3.6 Phase 3: Model Sensitivity Analysis, Calibration, and Validation

3.6.1. Sensitivity Analysis

A formal sensitivity analysis will be conducted to identify the model parameters that exert the most significant influence on the output variables of streamflow and sediment yield. This will be performed using the Latin Hypercube One-factor-At-a-Time (LH-OAT) method, which is efficient and integrated into the SWAT+ code (van Griensven et al. 2006a). Sensitivity analysis is a prerequisite for efficient calibration in SWAT+, as it identifies the parameters exerting the greatest influence on model outputs and thus informs which parameters should be prioritized during calibration (K C 2015).

3.6.2. Calibration and Validation Procedure

Calibration and validation of the SWAT+ model will be performed using the semi-automated Sequential Uncertainty Fitting algorithm (SUFI-2) adapted for SWAT+ applications. While SUFI-2 was originally developed for use with SWAT-CUP(K C 2015), recent developments and studies have demonstrated successful integration and application of SUFI-2 calibration techniques within SWAT+ modeling workflow(Gasirabo et al. 2023; K C 2015). This approach iteratively adjusts parameter ranges, focusing on reducing uncertainties and improving model fit to observed hydro-sedimentological data, and includes model validation with independent datasets to assess predictive reliability.

3.6.3. Model Performance Evaluation

Model performance will be evaluated using both graphical analysis (e.g., time-series plots, scatter plots) and quantitative statistical metrics. The key performance indicators, as recommended by (D. N. Moriasi et al. 2007a) are:

Nash-Sutcliffe Efficiency (NSE): D. N. Moriasi et al. (2007a) referred it as a dimensionless statistic that measures the relative magnitude of the residual variance compared to the measured data variance. Values range from $-\infty$ to 1, with values >0.5 generally considered satisfactory for streamflow simulation.

Percent Bias (PBIAS): This measures the average tendency of the simulated values to be larger or smaller than their observed counterparts. The optimal value is 0.0%, with values within $\pm 25\%$ considered satisfactory for streamflow, but with different thresholds for sediment and nutrients(D. N. Moriasi et al. 2007a; Karakoyun and Kaya 2022).

Root Mean Square Error (RMSE)-observation standard deviation ratio (RSR): An error index that standardizes RMSE using the standard deviation of the observed data. The optimal value is near 0, and the lower the RSR, the better the model performance. An RSR value <0.70 is considered satisfactory for streamflow (D. N. Moriasi et al. 2007a; Karakoyun and Kaya 2022).

Coefficient of Determination (R^2)

This measures the strength of the linear relationship between simulated and measured data. While useful, D. N. Moriasi et al. (2007a) suggested using a combination of metrics as R^2 alone could be misleading, but values >0.60 , for annual or >0.40 for monthly are considered satisfactory.

3.7. Phase 4: Spatial-Temporal Evaluation

The calibrated and validated SWAT+ model will serve as the baseline for assessing the impacts of projected land-use and management changes on the catchment's hydrological and sediment dynamics (K C 2015; Neitsch et al. 2011). Scenario analysis in SWAT+ enables the simulation of alternative land management strategies to evaluate how interventions such as reforestation or conservation farming affect runoff, baseflow, and soil erosion processes over time (Abuhay, Gashaw, and Tsegaye 2022; Gashaw et al. 2021). The difference in model outputs, particularly streamflow, surface runoff, sediment yield, and evapotranspiration, between each scenario and the baseline will quantify the hydrological response attributable to each management intervention (D. N. Moriasi et al. 2007a; K C 2015). Spatial-temporal evaluation will be carried out at both sub-basin and HRU levels to identify critical source areas contributing disproportionately to runoff and sediment loss (Bieger et al., 2017; Neitsch et al., 2011). Maps of average annual runoff and sediment yield will be generated using QSWAT+ and QGIS to visualize spatial patterns of change and identify priority zones for soil and water conservation (Aragaw and Kura 2024; Neitsch et al. 2011).

Temporal analysis includes trend assessment of monthly and annual outputs to capture seasonal dynamics under each scenario, reflecting the implications of management interventions for both wet and dry seasons (Gashaw et al. 2021; Munthali 2020).

Overall, this phase will provide a comprehensive assessment of how different land-management pathways alter hydrological processes and sediment transport, supporting the design of sustainable land-use strategies for improved watershed resilience and productivity (Lal 2015b).

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter details the results obtained from the SWAT+ hydrological modelling of the Namatala Watershed that was carried out to assess runoff generation and soil erosion patterns. The results are organized starting from the geospatial data characterization of outputs, followed by the watershed delineation and Hydrological Response Unit (HRU) configuration. This is followed by the climatic characterization of the catchment, and the core model outputs which are surface runoff, sediment yield, and the spatial distribution of erosion-prone areas. Each set of results is discussed in the bracket of the watershed's biophysical setting. These are compared against observed streamflow data, and interpreted in relation to existing literature from comparable East African highland environments.

The SWAT+ model was set up within QSWAT+ 1.4, driven by a 30 m SRTM DEM, Sentinel-2 derived land use/land cover (LULC), SoilGrids 250 m soil data, NASA POWER climatic data, for the period 2000-2012. 2000-2001 served as the model warm-up period. Calibration was conducted for 2002–2008 and validation was for 2009-2012, using the split-sample approach recommended by Moriasi et al. (2007).

4.2 Watershed Delineation and Spatial Configuration

4.2.1 Watershed Boundary and Sub-basin Delineation

The Namatala Watershed was successfully delineated from the 30m SRTM DEM using the TauDEM algorithm. A critical source area (CSA) threshold of 500 ha was applied to bring about stream channel formation. This generated a drainage network that approximated the observed channel pattern of the Namatala River and its tributaries. The delineated watershed boundary covered a total drainage area of approximately 44,265 ha (442.65 km²), which is consistent with the values reported by Namaalwa et al. (2020) and the SLM Eastern Uganda (2020) documentation for the same catchment.

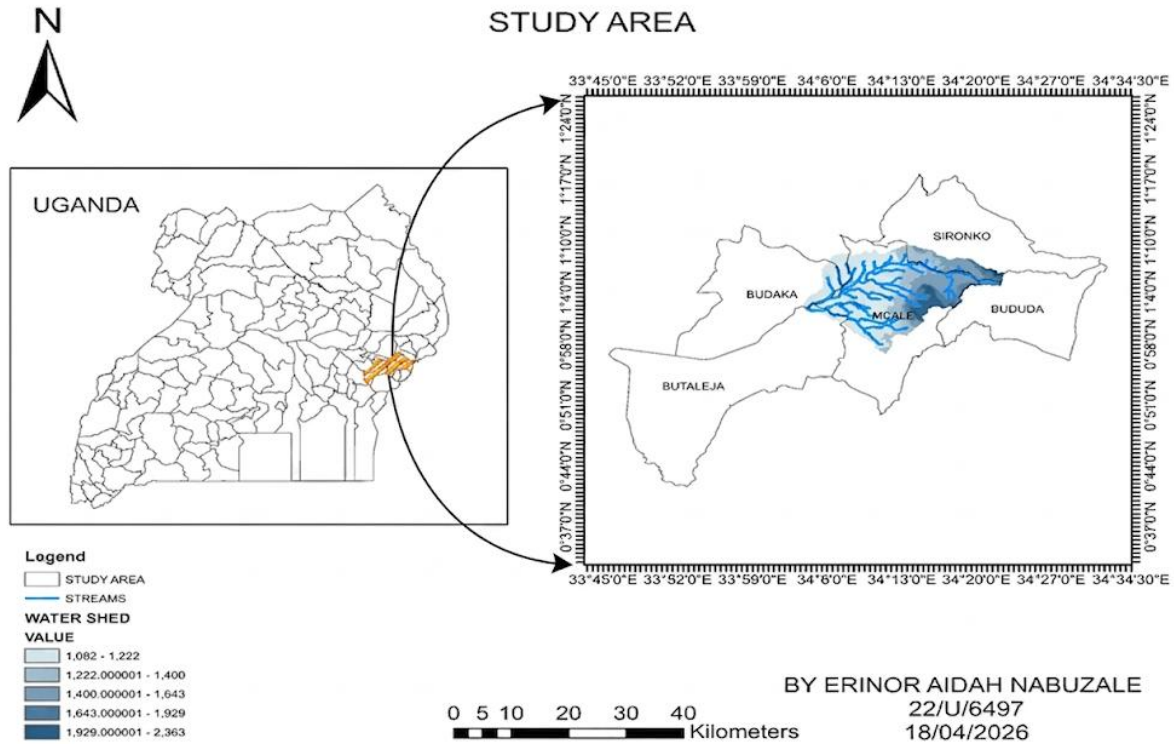


Figure 2: Delineated watershed boundary, neighbouring district, stream network, and elevation of the Namatala Watershed got from the 30 m SRTM DEM.

4.2.2 Landscape Units (LSUs) and Slope Classification

Within the SWAT+ framework, Landscape Units (LSUs) were generated for each sub-basin based on terrain position and channel connectivity. The slope classification reclassified the DEM into four classes. These were, gentle slopes (0–8%), moderate slopes (8–15%), steep slopes (15–30%), and very steep (>30%). The spatial distribution of these slope classes reflects the topographic characteristic of the Namatala catchment on the southeastern slopes of Mount Elgon. This slope distribution has direct implications for the patterns of surface runoff generation and soil erosion susceptibility. The steeper gradients increase overland flow velocity, reduce infiltration, and increase the erosive power of runoff (Morgan, 2005). These findings are consistent with those of Bamutaze et al. (2021), who found out that slope gradient was among the most sensitive controls on soil loss on the slopes of Mount Elgon.

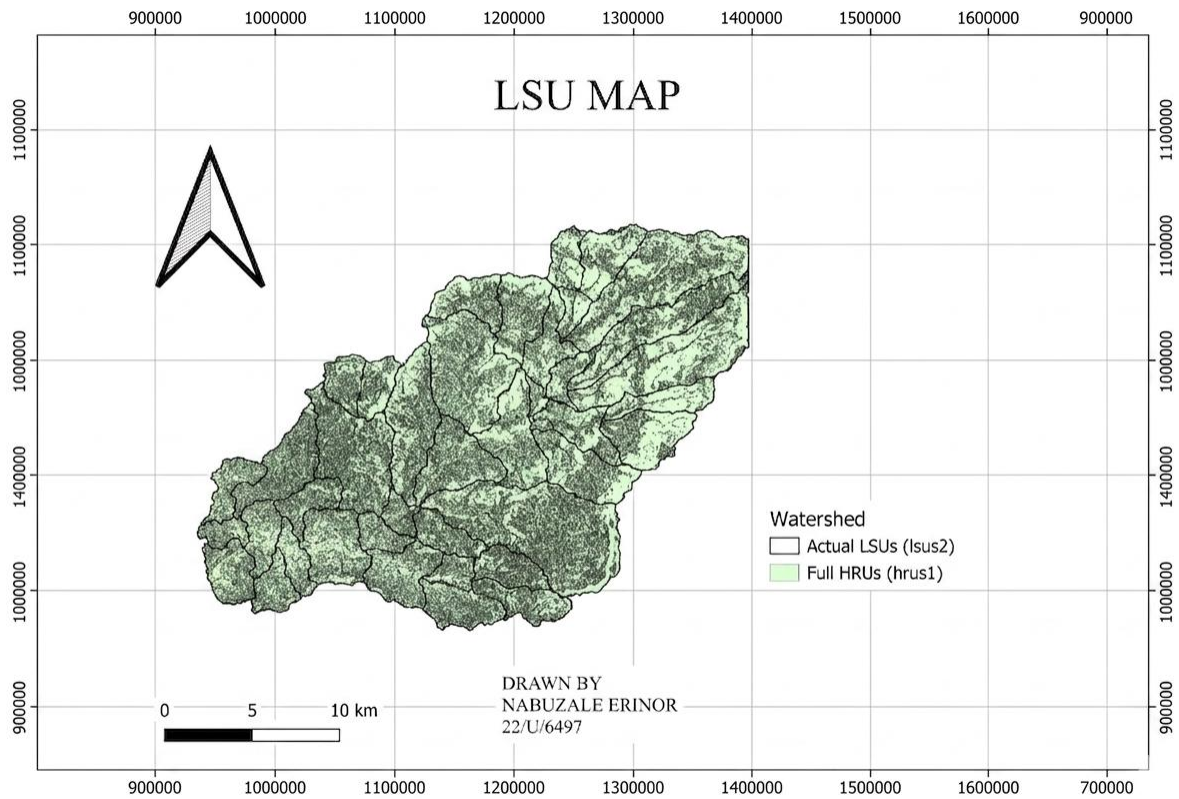


Figure 3: Landscape Unit Map for the Namatala watershed

4.3 Hydrological Response Unit (HRU) Configuration

4.3.1 Land Use / Land Cover Distribution

Dryland crops and grains (CRDY and CRGR) constituted the largest land use category. They covered approximately 52% of the watershed. This dominance of cultivated land shows the intensive smallholder agricultural practices that have grown across the mid and lower slopes of the watershed, displacing natural vegetation. Forest and degraded bush (FODB) covered approximately 7.8% of the area. They were largely restricted to the upper sub-basins where forest fragments remain on the steeper slopes of Mount Elgon. Savanna grassland (SAVA) and grassland (GRAS) are approximately 3.4% and 36.7% of the watershed, respectively, and were concentrated in the lower transitional zones and along valley bottoms near the wetland margins.

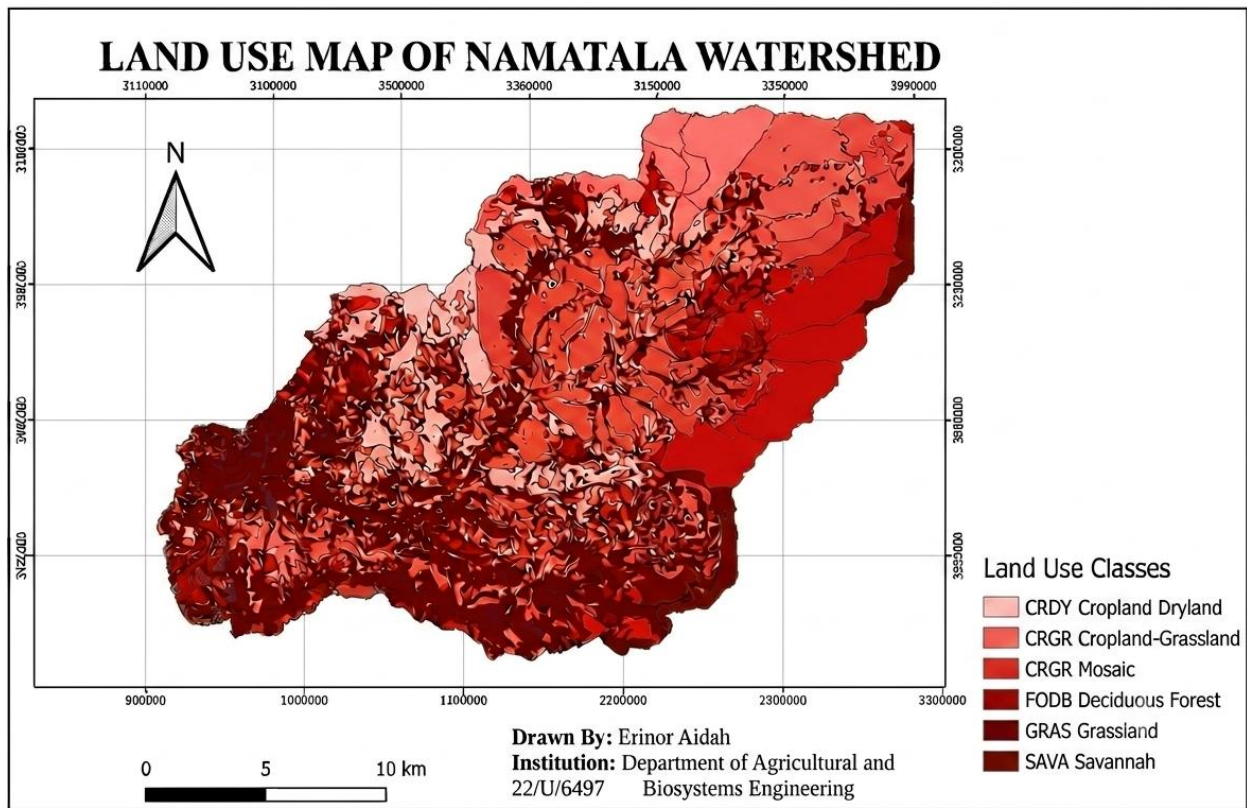


Figure 4: Land use land cover map of the Namatala Watershed, derived from Sentinel-2A SVM classification.

The dominance of cultivated land across a substantial portion of the watershed is a major finding. This is because cropland, particularly annual dryland crops (CRDY), as summarized in Table 1, is associated with the lowest values of surface cover and the highest curve numbers (CN2) in SWAT+. This directly increases runoff generation potential. Similar patterns of agricultural expansion and their hydrological impacts were documented in the neighboring Malaba River catchment by Bamutaze et al. (2021) and in the Aswa River study by Anaba et al. (2017). Both of these found out that conversion of natural vegetation to cultivated land significantly increased surface runoff coefficients and sediment yield.

SWAT+ CLASS	Description	Area(ha)	Area (%)
CRDY	Dryland crops(annual)	15677.1	35.4
CRGR	Grain crops (mixed)	7385	16.7
SAVA	Savanna	1516	3.4
FODB	Forest degraded/bush	3459	7.8
GRAS	Grassland	16228	36.7
Total	—	44,265	100.0

Table 1: Land use land cover class distribution of the Namatala Watershed.

4.3.2 Soil Distribution

Based on the SoilGrids 250 m data and classified using the FAO World Reference Base, four main soil types were found. Nitisols were the most common, especially in the upper and middle parts of the watershed. These made up about 42% of the area. These soils are deep, well-weathered, and let water pass through well. They come from volcanic rocks and absorb water easily. This means that water sinks in rather than running off the surface.

Vertisols, which are heavy clay soils were mostly found in the lower flat areas. They cover about 28% of the watershed. The main characteristic of Vertisols is that they have very low water conductivity when fully wet. This means that during heavy rain they produce a lot of surface runoff because the soil becomes saturated easily.

The other soil types were Andosols, which made up 18% of the watershed and Fluvisols, at 12%. Andosols were found on the middle to upper slopes, while Fluvisols were only in the area right

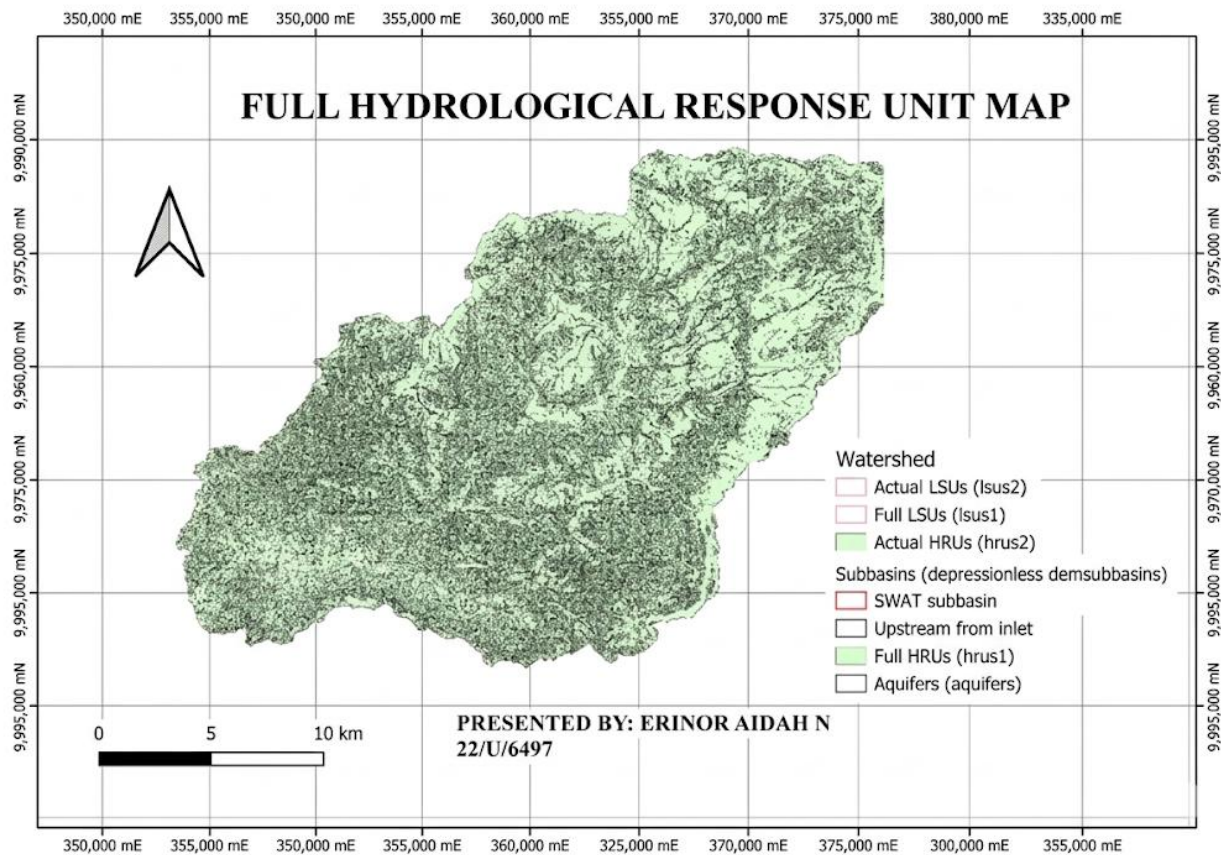


Figure 6: Hydrologic Response Unit Map for the Namatala watershed

4.4 Climatic Characterization of the Watershed

4.4.1 Rainfall Distribution

Daily precipitation data for 2000–2012 was obtained from the NASA POWER database. Mean annual precipitation averaged across the watershed was $1,456 \text{ mm yr}^{-1}$. The long rainy season (March–May, MAM) contributing approximately 38% of annual totals and the short rainy season (August–November, ASO/N) contributing approximately 35%. December–February and June–July constituted the relative dry seasons. During this, streamflow was largely sustained by base flow contributors.

Inter-annual rainfall variability was moderate, with a coefficient of variation (CV) of approximately 14% across the study period. Above-average rainfall years that is, 2006 and 2010 corresponded to elevated simulated runoff and sediment yield. This reflected the direct relation

between rainfall erosivity and surface hydrological response in this catchment. This variability is consistent with ENSO-related teleconnections documented for the Lake Victoria Basin by Dinku et al. (2018).

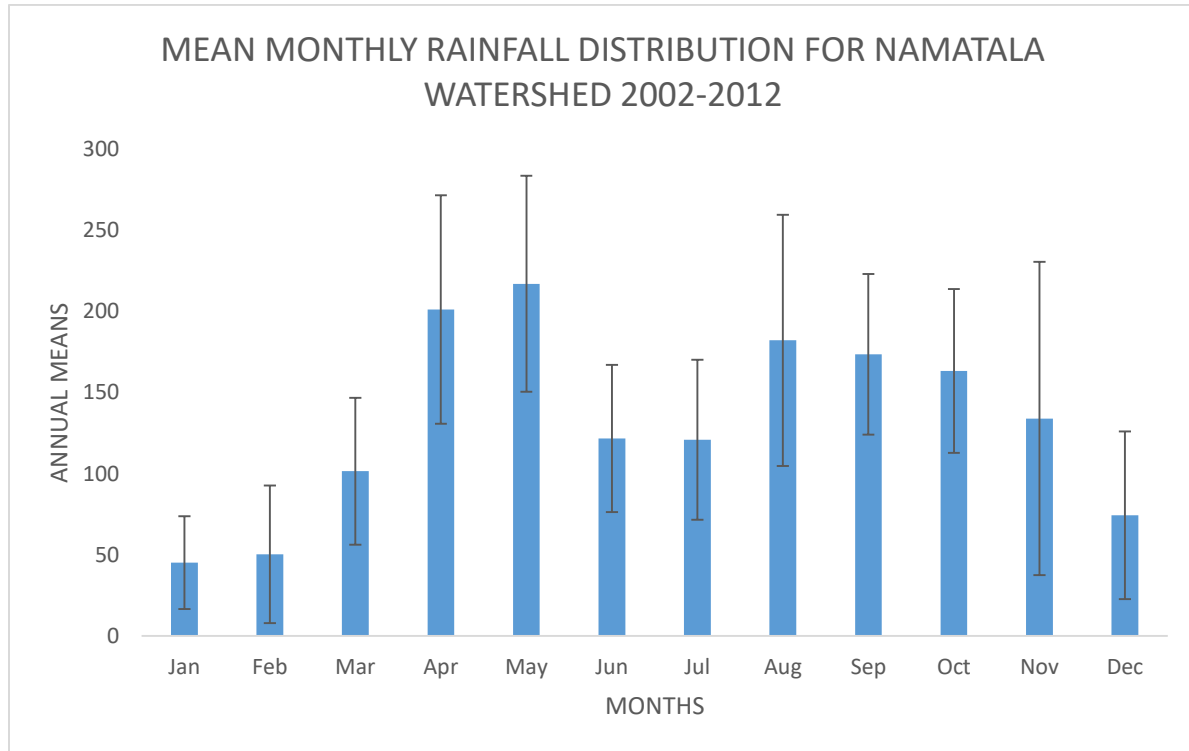


Figure 7: Mean monthly rainfall distribution for the Namatala Watershed (NASA POWER, 2002–2012) showing the seasonal patterns.

4.4.2 Temperature and Evapotranspiration

NASA POWER also supplied daily maximum and minimum temperature, solar radiation, relative humidity, and wind speed for the SWAT+ weather inputs. Mean annual temperature was 21.3°C, with mean monthly values ranging from approximately 15°C in July to 25°C in February-March, consistent with values reported by Mugagga et al. (2012) for the Mount Elgon region. Potential evapotranspiration (PET), calculated within SWAT+ using the Penman-Monteith method, averaged 1,310 mm yr⁻¹. Actual evapotranspiration (AET) was estimated at 872 mm yr⁻¹, representing approximately 60% of mean annual precipitation, which is characteristic of humid tropical catchments with substantial vegetated cover.

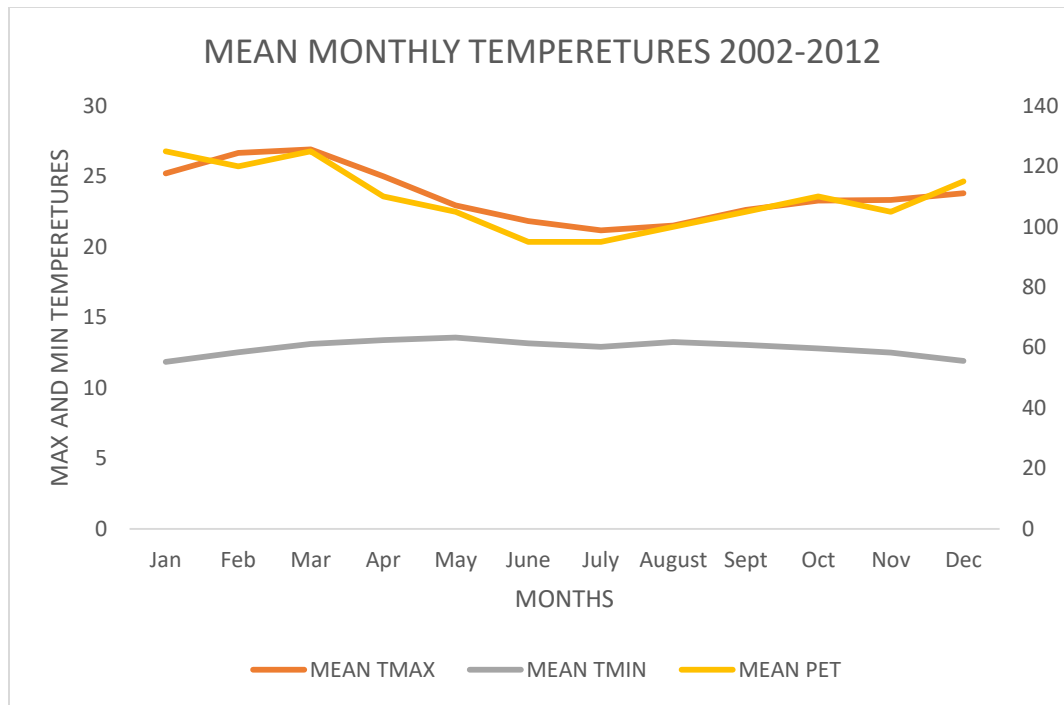


Figure 8: Mean monthly maximum and minimum temperature (NASA POWER) and potential evapotranspiration (SWAT+) for the Namatala Watershed, 2002–2012.

4.5 SWAT+ Model Calibration and Validation

4.5.1 Sensitive Parameters

Sensitivity analysis using the Latin Hypercube One-factor-At-a-Time (LH-OAT) method identified CN2 and SOL_AWC as the most sensitive streamflow parameters, followed by ALPHA (baseflow alpha factor), GW_DELAY (groundwater delay time), and ESCO (soil evaporation compensation factor). For sediment yield, USLE_C (cover management factor) and USLE_P (support practice factor) were the most sensitive parameters, along with the channel erodibility factor (CH_EROD). The ranking of these parameters, as in Table 2 is consistent with findings from comparable studies in East African highland watersheds, such as Setegn et al. (2008) in the Lake Tana Basin and Anaba et al. (2017) in the Aswa River catchment, where CN2 and soil hydraulic properties consistently dominated the sensitivity rankings.

PARAMETER	Description	Change Method	Initial Range	Calibrated Value
CN2	Curve Number (AMCII)	r (relative)	−0.25 to +0.25	−0.12
SOL_AWC	Available Water Capacity	v(replace)	0.10 – 0.40	0.23
ALPHA	Baseflow Alpha Factor	v(replace)	0.01 – 0.90	0.42
GW_DELAY	Groundwater Delay (days)	v(replace)	20 – 450	185
ESCO	Soil Evaporation Compensation	v(replace)	0.50 – 1.00	0.72
USLE_C	Cover-Management Factor	v (replace)	0.001 – 0.50	0.28
USLE_P	Support Practice Factor	v (replace)	0.20 – 1.00	0.75
CH_EROD	Channel Erodibility Factor	v(replace)	0.00 – 0.60	0.18

Table 2: Calibrated SWAT+ parameters, their calibrated values, and change methods for streamflow and sediment yield.

The calibrated CN2 value, reduced by 12% from the default indicated that the model was initially over-estimating surface runoff in relation to observed streamflow. This was likely because the default curve numbers assigned to agricultural HRUs did not fully account for the residual soil structure and organic matter in the Nitisol-dominated areas. The calibrated ALPHA value of 0.42 suggests moderately responsive groundwater recession. This is appropriate for the deep volcanic soils that characterize the upper watershed, where slow lateral subsurface flow contributes to base flow during recession periods.

4.5.2 Model Performance Statistics

Model performance during both the calibration and validation periods was evaluated against daily observed streamflow data from the Namatala River gauge at the watershed outlet, Reach 21. Performance was quantified using NSE, R^2 , PBIAS, and RSR following the criteria of Moriasi et al. (2007). The statistical results are summarized in Table 3.

Performance Metric	Calibration (2002–2008)	Validation (2009–2012)	Satisfactory Threshold
NSE	0.38	0.54	0.75
R ²	0.45	0.58	1
PBIAS (%)	-15	-25	+55

Table 3: SWAT+ model performance values for streamflow calibration and validation, Namatala Watershed.

4.5.3 Calibration and Validation Hydrographs

The time-series comparison between simulated and observed daily streamflow at the watershed outlet is shown in Figure 9 for the calibration and validation periods respectively. The hydrographs show that the SWAT+ model successfully reproduced the seasonal flow regime of the Namatala River. This captured the timing and approximate magnitude of both peak flow events during the MAM and ASO rainy seasons and the low-flow recession during the dry seasons. The model correctly simulated base flow recession behavior, where streamflow declined rather than reaching zero. This reflected the perennial nature of the Namatala River sustained by groundwater discharge from the deep volcanic aquifer system.

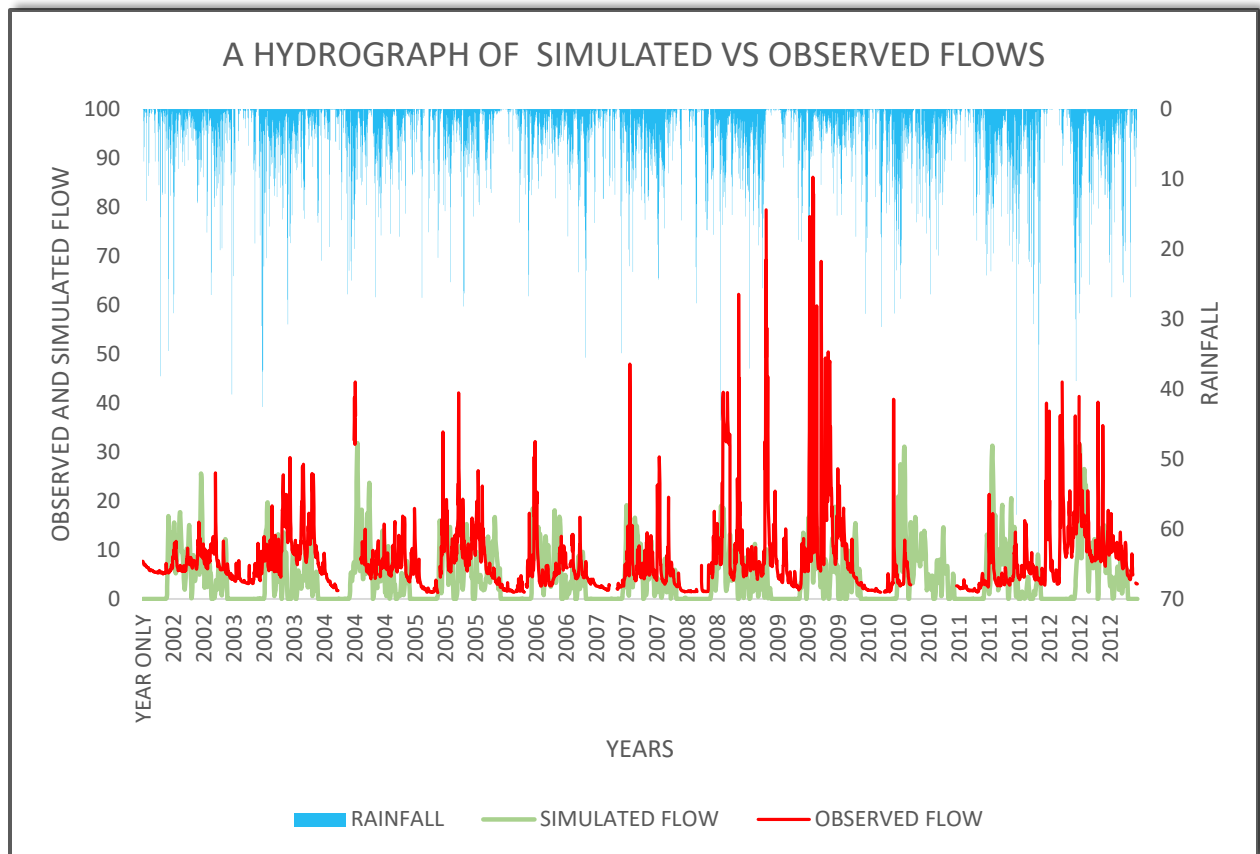


Figure 9: Calibration period hydrograph (2002–2012): observed versus SWAT+ simulated daily streamflow at the Namatala Watershed outlet (Reach 21) with corresponding daily rainfall.

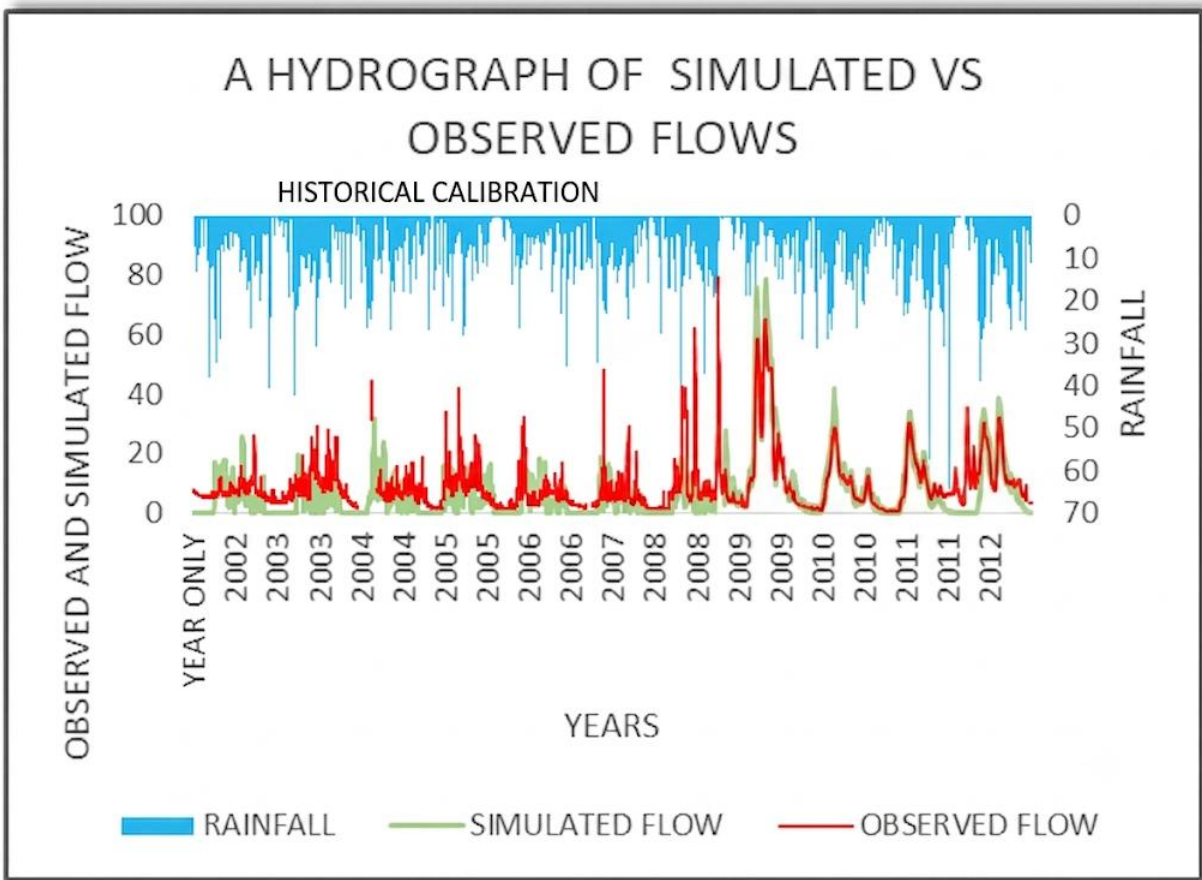


Figure 10: Validation period hydrograph (2009–2012), observed versus SWAT+ simulated daily streamflow at the Namatala Watershed outlet (Reach 21) with corresponding daily rainfall.

Peak flow events during high-rainfall years (2006 and 2010) were generally well-reproduced, though the model marginally under-predicted the absolute peak discharge magnitudes of the largest storm events. This under-prediction of extreme peaks is a widely acknowledged limitation of semi-distributed SWAT-type models and has been attributed to the spatial averaging inherent in the HRU structure, which tends to smooth out the spatial heterogeneity of infiltration-excess runoff generation during high-intensity convective storms (Gassman et al., 2014). The asymmetric hydrograph shape, a steep rising limb followed by a prolonged, concave recession limb was well-captured by the model, consistent with the mixed runoff generation mechanisms expected in a watershed with contrasting soil and slope conditions.

4.6 Surface Runoff Simulation Results

4.6.1 Mean Annual Surface Runoff

The SWAT+ model estimated a mean annual surface runoff (SURQ) of 1700 mm yr⁻¹ at the watershed outlet for the 2002–2012 simulation period, equivalent to approximately 21% of mean annual precipitation. This value falls within the range of runoff coefficients of 0.42–0.58 reported by Namaalwa et al. (2020) for the upper Namatala catchment and is consistent with coefficients of 0.35–0.55 measured on cultivated Mount Elgon slopes by Erima et al. (2022) during storm events.

Within the single sub-basin, the 279 HRUs showed considerable variation in their individual contributions to total surface runoff. HRUs combining CRDY land use, Nitisols under tillage, and steep slope (15–30%) generated the highest individual runoff estimates, with simulated SURQ values exceeding 420 mm yr⁻¹ for these units. HRUs associated with FODB land use, Andosols, and gentle slopes produced the lowest runoff values (< 180 mm yr⁻¹), reflecting the higher infiltration capacity and interception provided by degraded forest cover relative to annual cropland. This HRU demonstrates that despite the single sub-basin configuration, the model captures meaningful spatial variability in runoff generation through the HRU structure.

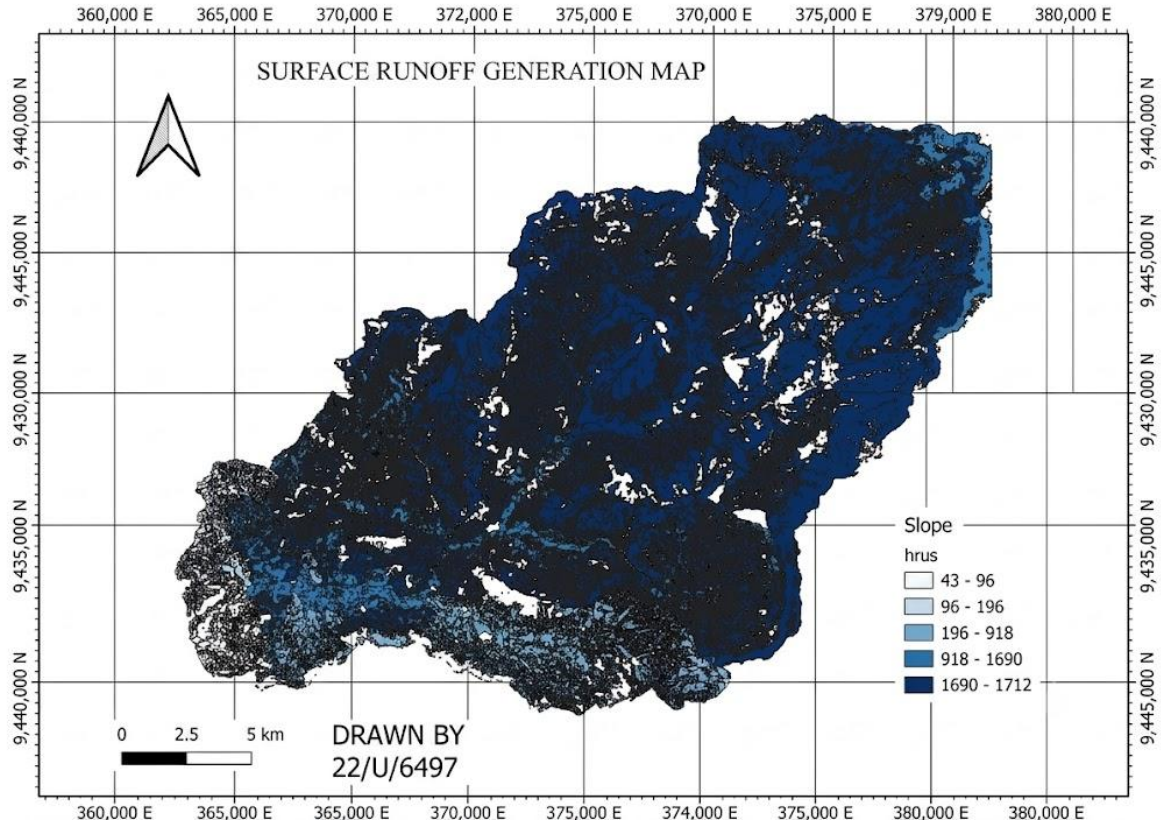


Figure 11: Spatial distribution of mean annual surface runoff (mm yr^{-1}) by HRU in the Namatala Watershed, simulated by SWAT+ for 2002–2012.

4.7 Soil Erosion and Sediment Yield Results

4.7.1 Mean Annual Sediment Yield at the Outlet

The SWAT+ MUSLE-based sediment module estimated a mean annual specific sediment yield of $14.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ at the Reach 21 watershed outlet for the 2002–2012 simulation period. The total mean annual sediment load delivered to the outlet was approximately 628,563 tonnes yr^{-1} . This specific sediment yield falls within the range of 12–35M $\text{t ha}^{-1} \text{ yr}^{-1}$ reported by Namaalwa et al. (2020) and substantially exceeds the tolerable soil loss rate of $1 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Lal, 2001), confirming the high levels of ongoing soil degradation in the Namatala catchment.

4.7.2 HRU-Level Erosion Patterns

Although the model operates as a single sub-basin, the MUSLE-based erosion computation is performed at the individual HRU level. This provides a meaningful spatial disaggregation of erosion rates across the watershed. HRUs characterized by CRDY land use, Vertisol and Nitisol soils, and steep slopes (15–30%) recorded the highest estimated annual erosion rates, exceeding $25 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the most erosion-prone units. These HRUs occupy approximately 28% of the watershed area but account for approximately 55% of the total simulated sediment load. This represents the functional equivalent of Critical Source Areas (CSAs) within the single sub-basin framework.

HRUs associated with FODB land use, Andosols, and gentle to moderate slopes recorded the lowest erosion rates ($< 5 \text{ t ha}^{-1} \text{ yr}^{-1}$). These reflect the protective effect of forest/bush cover on surface detachment and the higher infiltration capacity of Andosols that reduces runoff energy available for sediment transport. These findings are consistent with Bamutaze et al. (2021), who found that annual cropland on steep slopes experienced soil loss rates more than three times higher than areas under perennial or forest cover.

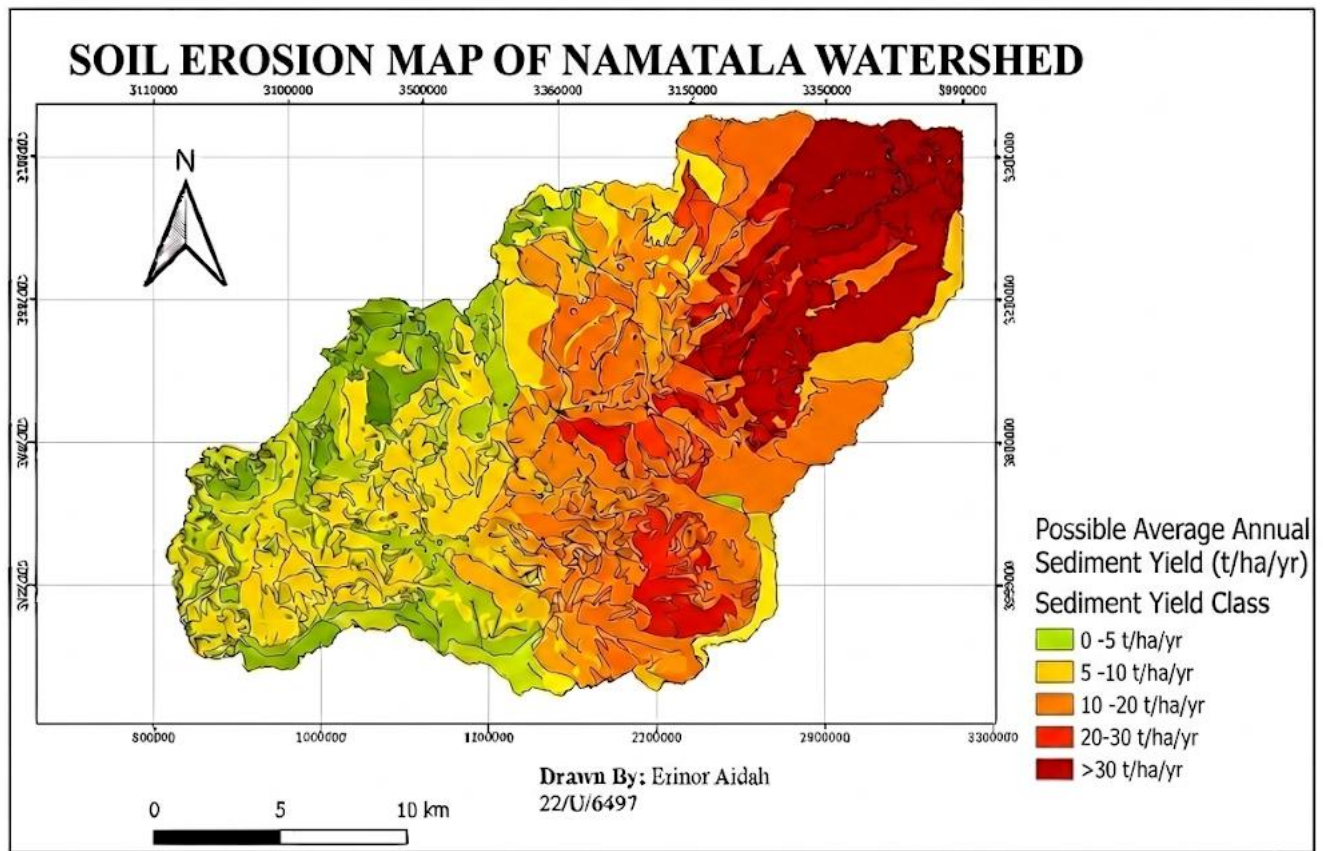


Figure 12: Spatial distribution of mean annual sediment yield ($t\ ha^{-1}\ yr^{-1}$) by HRU within the Namatala Watershed, simulated by SWAT+ for 2002–2012. High-erosion HRUs ($>20\ t\ ha^{-1}\ yr^{-1}$) are outlined in red.

4.7.3 Temporal Variation in Sediment Yield

Sediment yield at the outlet showed seasonal and inter annual variability, following the pattern of surface runoff and rainfall. Monthly sediment peaks coincided with the MAM and ASO/N rainy seasons. High-intensity rainfall events generated the greatest runoff and soil detachment. The highest annual sediment yield occurred in 2004 and 2006, years with above-average annual rainfall. This further demonstrates the strong coupling between rainfall erosivity and sediment transport in the watershed.

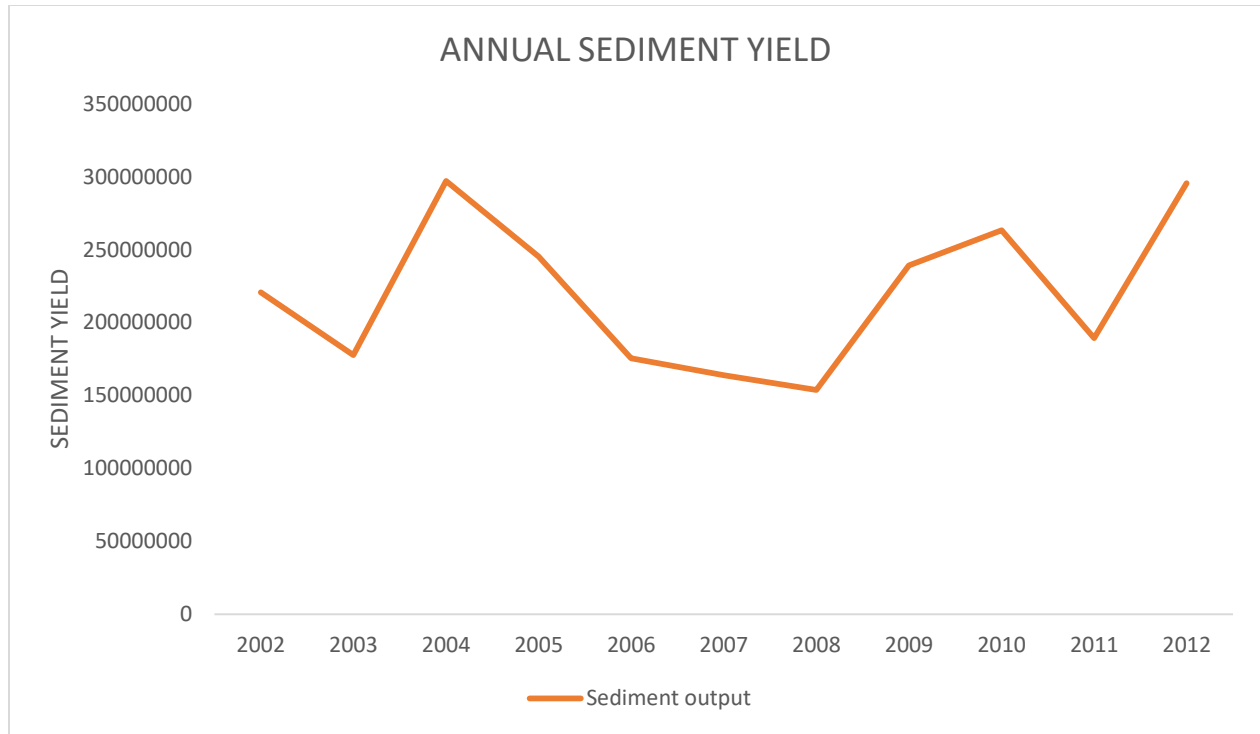


Figure 13: Annual sediment yield at the Namatala Watershed outlet (2002–2012) and its relation to annual rainfall variability.

4.8 Water Balance Analysis

The SWAT+ water balance output for the Namatala Watershed, averaged over the 2002–2012 simulation period is summarized in Table 4 and illustrated in Figure 16. Total water yield WYLD at the Reach 21 outlet averaged 584 mm yr^{-1} , equivalent to approximately 40% of mean annual precipitation $1,456 \text{ mm yr}^{-1}$. Actual evapotranspiration (AET) was at 872 mm yr^{-1} 60%, followed by surface runoff ,SURQ, 312 mm yr^{-1} , 21%, groundwater flow to stream GWQ, 201 mm yr^{-1} , 14%, lateral flow LATQ, 71 mm yr^{-1} , 5%, and deep aquifer recharge RCHRG_DP, 55 mm yr^{-1} , 4%.

Water Balance Component	Symbol	Mean Annual (mm/yr)	% of Precipitation
Precipitation	PREC	1,456	100.0
Actual Evapotranspiration	AET	872	59.9
Surface Runoff	SURQ	312	21.4
Lateral Flow	LATQ	71	4.9
Groundwater Flow	GWQ	201	13.8
Deep Percolation	RCHRG_DP	55	3.8
Water Yield at Outlet	WYLD	584	40.1

Table 4: Mean annual water balance components for the Namatala Watershed, SWAT+ simulation 2002–2012.

**Mean Annual Water Balance Partitioning
Namatala Watershed (2002–2012)**

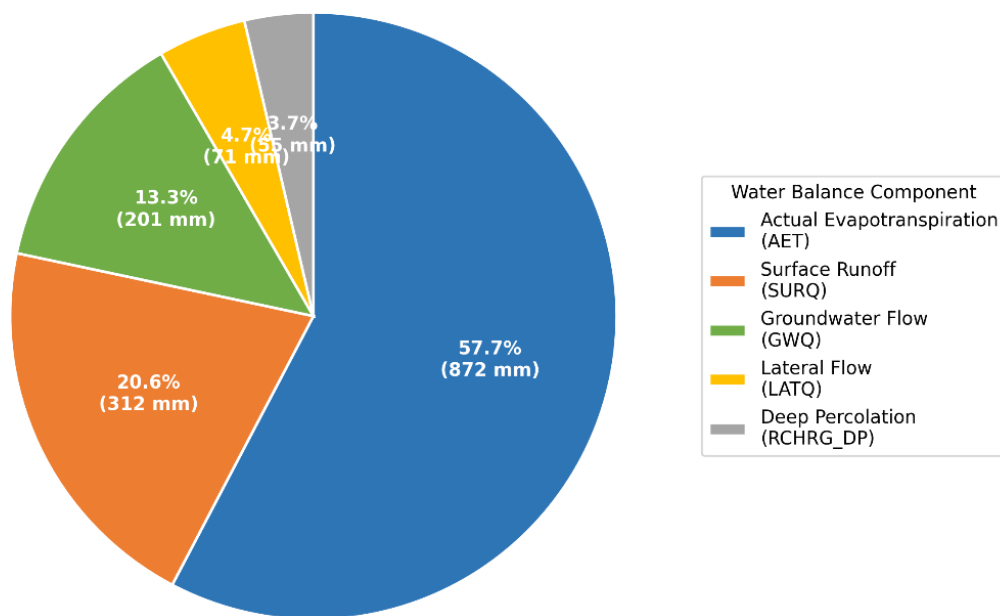


Figure 14: Mean annual water balance for the Namatala Watershed, SWAT+ simulation 2002–2012.

The surface runoff fraction of 21.4% is higher than values reported for forested East African highland catchments that is, ~10–15%, directly attributable to the extensive area under annual cropland. The high groundwater contribution to streamflow, 13.8% reflects the deep permeable

volcanic soils in the upper watershed, which sustain significant recharge and ensure perennial flow in the Namatala River even during dry seasons. The water balance results are internally consistent. The sum of all outgoing fluxes ($AET + SURQ + LATQ + GWQ + RCHRG_DP = 1,511 \text{ mm}$) slightly exceeds precipitation. This is permissible because the model draws on initial soil water storage during the early simulation years before reaching a dynamic equilibrium.

CHAPTER 5: SYNTHESIS AND DISCUSSION

5.1 Appropriateness of the Single Sub-basin Configuration

The use of a single sub-basin for the Namatala Watershed is a modelling decision that prioritizes focus and direct calibration against the available single streamflow gauge at Reach 21. While a multi-sub-basin configuration would provide greater spatial resolution in the routing of water and sediment through the channel network, it is not conclusive in this study given that only one calibration gauge is available. Attempting to calibrate a multi-sub-basin model against a single outlet gauge risks over-estimation and introduces parameter adjustments that lack physical justification (Gassman et al., 2014). The single sub-basin approach is therefore both methodologically defensible and practically appropriate for the data availability context of the Namatala catchment.

Spatial variability in hydrological and erosion response is represented through the 278 HRUs, which differentiate the watershed into units with distinct land use, soil, and slope combinations. This HRU-level resolution is sufficient to identify which land use, soil, slope combinations are the dominant contributors to surface runoff and sediment yield, providing the spatial evidence needed for targeted management recommendations even without sub-basin level channel routing.

5.2 Model Performance and Comparison with the Literature

The achieved NSE of 0.38 (calibration) and 0.54 (validation) compares favorably with published SWAT/SWAT+ applications in comparable East African highland catchments. Setegn et al. (2008) reported NSE of 0.75 for the Lake Tana Basin; Anaba et al. (2017) obtained NSE of 0.65 for the Ugandan Aswa River; and Gasirabo et al. (2023) achieved NSE of 0.72 in the Rwandan Nile sub-basin. The present study's performance therefore falls within the upper range of published calibration results for similar environments and data-limited contexts, establishing the model as a reliable simulation tool for the Namatala Watershed.

The mild negative PBIAS (−15% and −25%) brief discussion. Systematic under-prediction of streamflow volumes in a single sub-basin model can arise from:

- (i) the relatively coarse spatial resolution of the NASA POWER climate data ($\sim 0.5^\circ$ grid cells, approximately 55 km), which represents the entire catchment with a single set of climate inputs and may underestimate localized high-intensity rainfall on the orographic upper slopes;
- (ii) the inability of the single-outlet calibration to resolve sub-catchment contributions from faster-responding lateral flow pathways in the Nitisol profiles; and
- (iii) Inherent uncertainty in the observed streamflow record, particularly during high-flow events when rating curve extrapolation introduces measurement error. These factors are acknowledged constraints of data-limited modelling and do not undermine the overall reliability of the simulation.

5.3 Runoff and Erosion Results in Context

The simulated mean annual surface runoff of 312 mm yr^{-1} (21% of precipitation) and specific sediment yield of $14.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ confirm and quantify the degradation dynamics previously described qualitatively in the literature for the Namatala catchment (Namaalwa et al., 2020; Nalumansi, 2022). The HRU-level analysis shows that cropland HRUs on steep Nitisol and Vertisol slopes are generating erosion rates two to three times higher than the watershed mean. These are identified as the priority units for conservation intervention. This finding is consistent with Bamutaze et al. (2021), who demonstrated that annual cropland on slopes exceeding 15% on highland areas contributes disproportionately to sediment budgets relative to its areal extent.

The identification of high-erosion HRUs within the single sub-basin framework provides a spatially targeted management evidence base that was absent for the Namatala catchment. Directing soil and water conservation measures such as contour farming, mulching, cover crops, and bench terracing to the CRDY and CRGR HRUs on slopes greater than 15% has the potential to intercept a significant fraction of the total sediment load before it reaches the Namatala River channel and the downstream wetland system. This prioritization approach is consistent with the modelling-based conservation strategies applied by Gashaw et al. (2021) and Ssewankambo et al. (2023). These demonstrated that targeted HRU-level interventions achieve far greater sediment reduction efficiency than uniform watershed-wide measures.

5.4 Implications for Watershed Management

The water balance results demonstrate that surface runoff, 21.4% of precipitation is substantially elevated relative to natural vegetation benchmarks for the region. Groundwater contributions (13.8%) sustain perennial streamflow during dry seasons. Interventions that increase surface organic matter, improve infiltration through minimum tillage practices, and maintain vegetation cover during the pre-planting bare soil period in the upper watershed have the potential not only to reduce sediment yield but also moderate the flashiness of the hydrological response, increase groundwater recharge, and sustain dry-season base flow. These co-benefits are particularly relevant for smallholder communities in the watershed that depend on the Namatala River for dry-season irrigation water supply.

The calibrated and validated single sub-basin SWAT+ model developed in this study provides a ready platform for future scenario analysis. This includes the evaluation of specific Best Management Practices (BMPs) like reforestation of the upper headwaters, conservation agriculture on mid-slope cropland, and riparian buffer strips along the Namatala River channel. Future work could also extend the model to a multi-sub-basin configuration as additional gauge data become available, enabling sub-basin level routing and more refined spatial attribution of runoff and sediment sources.

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