

**MODELING RAINFALL-RUNOFF AND SEDIMENT YIELD IN THE
MILLE RIVER WATERSHED, LOWER AWASH SUB-BASIN,
ETHIOPIA**

MSc. THESIS

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**Modeling Rainfall-Runoff and Sediment Yield in the Mille River
Watershed, Lower Awash Sub-basin, Ethiopia**

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DEDICATION

I dedicate this Thesis manuscript to the whole of my family members for nursing me with affection and love and for their dedicated partnership in the success of my life.

STATEMENT OF AUTHOR

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ACRONYMS AND ABBREVIATIONS

AMC	Antecedent Moisture Condition
CN	Curve Number
CRWR	Center for Research in Water Resources
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
HEC-DSS	Hydrologic Engineering Center – Data Storage System
HEC-HMS	Hydrologic Engineering Center - Hydrologic Modelling System
HEC-GeoHMS	Hydrologic Engineering Center-Geospatial Hydrologic Modelling System
IHACRES	Identification of Unit Hydrograph and Components of Rainfall, Evaporation and Stream flow data
IHDM	Institute of Hydrology Distributed Model
ITCZ	Inter-Tropical Convergence Zone
LULC	Land Use/ Land Cover
MoWE	Ministry of Water and Energy
MUSLE	Modified Universal Soil Loss Equation
NMI	National Meteorological Institute
NRCS	Natural Resource Conservation Service
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent of BIAS
R ²	Coefficient of Determination
RMSE	Root Mean Squared Error
SCS	Soil Conservation Service
SRM	Snowmelt Runoff Model
SWAT	Soil and Water Assessment Tool
SWRRB	Simulator for Water Resource in Rural Basin
TOPMODEL	Topography Based Hydrological Model
USDA-ARS	United States Department of Agriculture – Agricultural Resource Service
USLE	Universal Soil Loss Equation
UTM	Universal Transverse Mercator
WATBAL	Water Balance Model
WATFLOOD	Waterloo Flood Forecasting Model

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ABSTRACT

Rainfall-runoff and sediment yield modeling of watersheds is very essential to solve water-associated problems and alleviating reservoir sedimentation problems caused by the soil erosion of the watershed. The general objective of this study was to model the Rainfall-runoff and sediment yield and to evaluate the performance of the HEC-HMS model of the Mille River watershed. Hydro-meteorological data collected from the National Meteorological Institute and Ministry of Water and Energy were used for model calibration and validation, whereas spatial data collected from different sources. The main materials and software like ArcGIS, HEC-GeoHMS, Arc Hydro, HEC-HMS, Rainbow, Mendeley, MS-Excel, MS-word and XLSAT were used. The methodology of this work was the following: data collection, data preparation, and quality assurance, data analysis and model setup, running model, model performance evaluation, and model result interpretation. In this study the simple canopy, simple surface, soil moisture accounting (SMA), Clark Unit Hydrograph, recession, Muskingum-Cunge, Modified USLE and volume ratio methods were adopted for canopy, surface, precipitation loss modeling, transform modeling, base flow, flood routing, modeling, erosion modeling and sediment modeling respectively. The Gage weight meteorological method was selected to assign the areal rainfall computed by Thiessen polygon method to each sub-basin and the monthly average meteorological method was used for evapotranspiration modeling. The model was calibrated from 1993-2008 and validation was done using observed data from 2009-2016. Storage coefficient and time of concentration are the most sensitive parameters for simulation of runoff. The model performance was checked and the results of stream flow calibration and validation $R^2 = 0.74$, $NSE = 0.65$, $RSR = 0.60$, $PBIAS = -7.10$ and $R^2 = 0.84$, $NSE = 0.69$, $RSR = 0.60$, $PBIAS = +14.18$ respectively and for sediment yield calibration and validation $R^2 = 0.72$, $NSE = 0.56$, $RSR = 0.67$, $Pbias = -15.50$ and $R^2 = 0.80$, $NSE = 0.54$, and $RSR = 0.68$ respectively. Based on these model performance results, the computed value of both the stream flow and sediment yield shows good agreement with the observed values appropriately. In this study, the HEC-HMS model simulates the average annual stream flow and average annual sediment yield of 11.42 m³/s and 8.34 Mt/year or 18.36 ton/ha/year respectively, for the period of 1993 to 2016 at the outlet of the Mille River watershed. The results of this study will be used by water resource managers and decision makers to conserve soil and water and taking appropriate flood and sediment control measures in the watershed.

Keywords: Calibration, HEC-HMS, Hydrologic modelling, Rainfall-Runoff, Sediment Yield, Mille River watershed and Validation.

1. INTRODUCTION

1.1. Background of the Study

Water resource management and soil conservation are critical components of sustainable development, particularly in regions facing challenges such as water scarcity, soil erosion, and sedimentation. Sustainable management of limited fresh water sources is a major challenge and is extremely important for the people living in the world. Failure to manage the water sources in an effective manner will adversely affect the society and the economy of the country. Management of water resources in a basin essentially requires understanding of dynamics of basin water and assessment of water availability for development use (Cosgrove and Loucks, 2015).

On a global basis, soil loss due to erosion (caused by water) is among the top ten complex environmental issues (Eswaran *et al.*, 2001; Ameh Peter Adegede, 2019). Soil erosion caused by water has two effects, 1) on site effects, and 2) off site effects (Vente, 2009). On-site effects are described by various factors such as the depletion of soil nutrients, decline of infiltration capacity, and surface sealing (Erkossa *et al.*, 2015). Whereas, off-site effects, include the passage of sediments and agronomic contaminants into waterways. This can cause sediment deposition in dams and watercourse, and downstream flooding due to increased flow and destruction to property (Vente, 2009).

Ethiopia is dominated by mountainous topography, the rainfall-runoff processes on the mountainous hilly slopes are the source of the surface water for much watershed of Ethiopian low land (Derib, 2005). Rainfall influences hydrological responses of a watershed, and this in turn influences soil erosion (Grunwald and Norton, 2000).

In Ethiopia, the Awash River basin is one of the major drainage basins, supporting various economic activities and ecosystems (Tufa, 2021). Within the Awash River basin, the Lower Awash sub-basin stands out due to its significance for agriculture, livestock, and human settlements (Getachew *et al.*, 2021). However, rapid population growth, land use changes, and climate variability have intensified pressure on water resources and land degradation in this region (Mengistu *et al.*, 2023). The Lower Awash sub-basin encompasses diverse landscapes, ranging from highlands to lowlands, and is characterized by variable rainfall patterns and agricultural practices. It is home to several watersheds, including the Mille River watershed, which plays a crucial role in the hydrology of the region (Getachew *et al.*, 2021).

The Mille River watershed is particular interest due to its unique geomorphological characteristics, land use patterns, and contributions to streamflow and sediment transport within the Lower Awash sub-basin (Mengistu *et al.*, 2023). The watershed faces specific challenges related to the soil erosion, sedimentation, and water quality degradation. Uncontrolled land use practices, deforestation, and inadequate soil conservation measures have led to increased sediment yield and reduced water availability for various purposes.

Hydrological modeling is a commonly used tool to estimate the basin's hydrological response due to precipitation. It allows to predict the hydrologic response to various watershed management practices and to have a better understanding of the impacts of these practices (Shaikh *et al.*, 2018). It is evident from the extensive review of the literature that the studies on comparative assessment of watershed models for hydrologic simulations are very much limited in developing countries (Putty and Prasad, 200; Kumar *et al.*, 2011). In estimating the amount of stream flow and sediment yield numerous hydrological models are available. These hydrological models are SWAT (Soil and Water Assessment Tool), HBV (Hydrologiska Byråns Vattenbalansavdelning), HEC-HMS (Hydrologic Engineering Center's Hydrologic Modelling System), LISFLOOD, SWMM (Storm Water Management Model), MIKE-SHE (Michael, Systeme Hydrologique European), and other hydrological models.

HEC-HMS developed by the United State Army Corps of Engineers, is designed to simulate the rainfall-runoff processes of dendritic watershed systems (Pak *et al.*, 2008). It is a deterministic model where the parameters values are remain constant for every simulation.

Therefore, from all the above hydrological models the HEC-HMS model has been applied in this study to model rainfall-runoff and sediment yield in the Mille River watershed. Most of the input data sets used for the model are secondary data those collected from the different sources. HEC-HMS stands out for its versatility in both event based and continuous simulations, making it a preferred model for flood forecasting, climate change assessment and water resources management. This study specifically focuses on modeling rainfall-runoff and sediment yield in the Mille watershed within the Lower Awash sub-basin in Ethiopia. The objective is to develop an integrated hydrological model that considers factors such as land use dynamics, soil properties, and topography to simulate rainfall-runoff processes and estimate sediment yield accurately. By gaining insights into the hydrological behavior of the Mille River watershed, the aims of this research is to contribute to sustainable water resource management, soil conservation, and resilience building in the watershed.

1.2. Statement of the Problem

Before planning any project on water resources in a certain river basin, first of all it is essential to estimate and evaluate the total available water resources and the sediment yield of that river watershed. Full utilization of the available water resources potential is not possible due to the topographical, and hydrological, the need for allowing a certain amount of water to flow in the river to maintain the river regime and other constraints.

The Mille River watershed is one of the sub-watersheds in the Lower Awash River sub-basin in Ethiopia which are characterized by severe desertification and land degradation, but high flood also occurs during high rainy seasons, mostly in the upper part of the watershed (Tadesse, 2022). The manifestations of desertification in the Lower Awash sub-basin include accelerated soil erosion by wind and water, increasing salinity of soils and near-surface groundwater supplies, a reduction in soil moisture retention, an increase in surface runoff and stream flow variability, plant biomass, a reduction in species diversity, and overall productivity (Tadesse, 2022). Soil erosion and sediment transport in the watershed due to deforestation, overgrazing, and poor land use practices which cause critical environmental issues and land degradation problems. This leads to the serious sedimentation problem on the reservoir of the Tendaho Dam which is located at the downstream of the watershed.

Unsustainable land use practices, including deforestation, overgrazing, and improper agricultural practices, have accelerated the rate of soil erosion in the Mille River watershed. As a result, sediment yield has increased significantly, leading to sedimentation in rivers, Tendaho dam reservoirs, and irrigation canals. The magnitude of sediment transported and the surface runoff in Mille River watershed had become a serious concern for planning, designing and implementing of the projects in the area. The deposition of sediments not only reduces water storage capacity but also degrades water quality, affects aquatic habitats, and exacerbates flooding risks during heavy rainfall extreme events. In addition, water storage is decreasing and accelerating the rate of soil erosion due to inadequate or poor land management practices.

In order to manage soil erosion or sedimentation problems, it is necessary to estimate and understand the surface runoff and sediment yield in the watershed. The goal of this study is to quantify the surface runoff and sediment yield in the Mille River watershed. Therefore, to fill this gap this research is used to estimate the amount of surface runoff and sediment yield for the Mille River watershed using the HEC-HMS model and it is contribute in identifying strategies of sediment alleviating programs of the watershed.

1.3. Objective of the Study

1.3.1. General objective

The general objective of this research is to model the rainfall-runoff and sediment yield using the HEC-HMS model in the Mille River watershed.

1.3.2. Specific objectives

- To evaluate the performance of the HEC-HMS model of the Mille River watershed.
- To model rainfall-runoff of the Mille River watershed.
- To estimate the amount of sediment yield in the Mille River watershed.

1.4. Research Questions

The research is focused on the analysis of rainfall-runoff and sediment yield modeling on Mille River watershed and attempts to answer the following questions:-

- How the performance of the HEC-HMS model is to estimate stream flow and sediment yield in the Mille River watershed?
- How much runoff produced at the outlet from the Mille River watershed?
- How much sediment yield produced at the outlet from the Mille River watershed?

1.5. Scope of the Study

The extent of this research is restricted to the modeling rainfall-runoff and sediment yield using the HEC-HMS model in Mille River watershed. It does not consider the assessment of the watershed stream flow and sediment yield by using another model and in addition, it does not consider the impact of land use land cover change on the stream flow and sediment yield. In general, the objective of this study is to estimate the amount of runoff and sediment yield of the Mille River catchment using the HEC-HMS model.

1.6. Significance of the Study

The significance of modeling of Rainfall-Runoff and sediment yield is getting a great issue for the future planning and management activities which help the government policymakers, Non-governmental Organizations (NGOs) and development organizations to formulate the appropriate watershed management policies, design effective evaluation and development programs in the watershed. So, it is important to use hydrological model to assess and predict the water availability of watershed. It can be also used as decision support system for development of different water resource projects, and provide information for the government, planners, decision makers and concerned persons while designing and developing the new water schemes in the sub-basin.

2. LITERATURE REVIEW

2.1. Rainfall-Runoff Process

The hydrological process is a natural driving process, when precipitated water may be intercepted by vegetation, and the rainwater continues some part of precipitation overland flow over the ground surface, infiltrates into the ground, and flows through the soil as sub-surface flow, and discharges into streams as surface runoff is a fundamental problem for the hydrologist. There are usually many rainfall records available for most countries, but the more complex and costly stream flow measurements that an engineer needs to evaluate water resources or potentially dangerous flood peaks are frequently scarce or nonexistent for the particular river that is the subject of the investigation (Demiss, 2019). For many years, assessing river discharges from rainfall has stimulated engineers' interest and creativity (Assefa, 2011). Accurately assessing the runoff discharges and flood extent is crucial to mitigate flood damages in the watershed (Belina *et al.*, 2025). However, direct measurement of peak flood values in watershed outlets is challenging, expensive, and time-consuming, making rainfall-runoff modeling a key tool (Belina *et al.*, 2025).

It is customary to express values of rainfall and river discharge in comparable terms to make comparisons easier. The amount of rainfall falling on a catchment area is normally expressed in millimeters (mm) depth but may be converted into a total volume of water, cubic meters (m^3). Alternatively, the river discharge is measured in cubic meters per second (m^3/s) for a comparable time and may be converted into total volume (m^3) and expressed as an equivalent depth of water (mm) over the catchment area. The discharge, often termed runoff or the defined period, is then easily compared with rainfall depths over the same period (Berhane, 2013). The surface subsystem of the hydrologic cycle is where the rainfall and runoff interaction takes place (Yilma and Kebede, 2023). The input to this system is the rainfall and the output is taken as the runoff at the outlet of the system (Assefa, 2011).

The rainfall-runoff relationship in the catchment is a complex and complicated phenomenon governed by a large number of known and unknown physiographic factors that vary both in space and time (Zhao *et al.*, 2022). Rain that falls on the watershed is transformed and abstracted in many different kinds of ways by a variety of component processes, including base flow, subsurface flow, evapotranspiration, overland flow, infiltration, interflow, percolation, and interception. Eventually, the rainwater emerges as runoff at the catchment outlet (Yousuf *et al.*, 2022).

2.1.1. Rainfall

Rainfall, which is generated when water vapor in the atmosphere condenses into droplets that can no longer be suspended in the air, is the most significant hydrologic parameter that is utilized as an input for various water resource management activities and hydrological modeling time (Berhane, 2013). Rainfall being the predominant forms of precipitation causing stream flow, especially the flood flow in the majority of rivers, unless otherwise stated the term rainfall synonymously with precipitation (Chow *et al.*, 1988). The occurrence of rainfall is dependent upon several factors such as prevailing wind directions, ground elevation, location within a continental mass, and location with respect to mountain ranges all have a major impact on the possibility of precipitation (Chow *et al.*, 1988). Rainfall is considered the most critical element of the hydrological cycle, as it affects the environment both directly and indirectly (Bharti and Singh, 2015).

The rainfall pattern and intensity greatly influences the runoff. If the rainfall intensity is lower than the equilibrium capacity, then all the water reaching the land surface will infiltrate to the soil, whereas rainfall intensity is greater than the equilibrium infiltration capacity, but less than the initial infiltration capacity, at the beginning all the water will infiltrate. If the infiltration capacity drops below the rainfall intensity, some of the water will persist on the ground surface. Finally, if the rainfall intensity is greater than the initial infiltration capacity, some water will immediately remain on the land surface (Berhane, 2013).

The magnitude of rainfall varies highly in space and time dimensions, its irregular patterns pose myriad challenges for its precise measurements (Bharti and Singh, 2015). The variation is brought about by differences in the type and scale of development of precipitation-producing processes and is strongly influenced by local and regional factors, such as topography and wind direction at the time of rainfall. It is, however, assumed that each individual rain gauge is representative of a very considerable area around it (Chow *et al.*, 1988). The systematic averaging methods Thiessen polygon, isohyets, and reciprocal distance can be developed to account for variations in space to obtain a representation of areal precipitation values from point observation (Garg, 2005).

2.1.2. Runoff

Runoff means the draining or flowing off of precipitation from a catchment area through a surface channel. It thereby depicts the catchment's output for a particular time period (Sarma *et al.*, 2016). Once the rain or snowmelt water has reached the ground surface of the earth it will start infiltrate the soil surface, except on impermeable areas of bare rock, on areas of completely frozen soil, on some artificial surfaces where surface runoff will start almost immediately (Bevin, 2001). Before the runoff starts for a given precipitation or rainfall, the requirements for evapotranspiration, initial loss, infiltration, and detention storage must be met (Sarma *et al.*, 2016). When these conditions are met, excess rainfall "overland flows," or stores up storage over the surface and drains off of it, to smaller channels over the land surfaces. Till the flow reaches the catchment outflow, flows from various small channels join larger channels, and flows from these in turn combine to form a larger stream. Surface runoff is the flow that occurs in this mode, where it constantly moves across the surface as overland flow, through the channels as open channel flow, and out of the catchment outlet (Sarma *et al.*, 2016).

A portion of the groundwater that seeps through the soil's upper crusts travels laterally and emerges at a site distance from the point of entrance. Runoff interflow, through flow, storm seepage, underground storm flow, and quick return flow are used to refer to various components of runoff. Sometimes the interflow is divided into two categories: delayed interflow and prompt interflow, or the interflow with the smallest time lag between the infiltration and the outflow. Another way that the water can seep in is by going through a deep percolation process and getting to the soil's groundwater store. The groundwater travels a convoluted and protracted route before reaching the surface. The time lag, or the interval of time between a flow into the soil and an outflow from it, is quite important and typically occurs over months or years. Groundwater flow, often known as groundwater runoff, is this portion of runoff. In perennial streams, groundwater flow provides the flow during dry seasons (Sarma *et al.*, 2016).

There are different factors that affect the amount of runoff generated are meteorological and physical factors. The climatic elements such as type of precipitation (snow, rain, sleet, hail, drizzle etc.), rainfall intensity, rainfall duration, rainfall amount, distribution of rainfall over the watersheds, direction of storm movement, antecedent precipitation and consequent soil moisture etc. (Berhane, 2013).

The physical characteristics (like land use, vegetation cover, elevation, soil type, drainage area, slope, basin shape, topography, direction of orientation, drainage network patterns lakes, ponds, sink and reservoirs) in the basin, which prevent runoff from continuing downstream (Beven, 2012).

2.2. Soil Erosion Processes

Soil erosion involves detachment, transport, and deposition of soil particles by water or wind. The process may be natural or accelerated by human interference in the environment. As the study by (Van Rijn, 1993) the two major types of erosion are geologic erosion and accelerated erosion. Geologic erosion, usually referred to as natural erosion acting over long geological periods, occurs when the soil is in its natural environment. Usually under natural geologic erosion rates, soil properties and soil profiles develop to approach an equilibrium condition. Accelerated erosion was soil loss over geologic erosion. The forces involved in accelerated erosion are attacking forces, which remove and transport the soil particles, and resisting forces, which retard erosion (Chekol, 2006).

Detachment of individual soil particles may occur when water strikes the surface by overcoming the interconnecting forces holding the soil particles together. This was commonly referred to as a raindrop splash or a single drop of rain. As the inducing events of rainfall continue, water infiltrates into the soil at a rate controlled by the intensity of water hitting the surface and the infiltration capacity of the vertical soil profile. Water that was not infiltrated begins to pond on the surface. When sufficient depth is achieved at the surface, water flow would begin in the direction of the steepest slope that is unimpeded. This begins the hydrologic process referred to as overland flow or runoff (Chekol, 2006).

According to a study by (William *et al.*, 1999) the removal of a uniform thin layer of soil by raindrop splash or water runoff is called sheet erosion. Watersheds are commonly divided into upland areas and channels. In the upland areas, overland flow is conceptually divided between rill flow mechanisms and inter-rill flow mechanisms, which occur on hill slopes. As overland flow converges from various portions of the upland area and becomes more concentrated, it becomes sufficiently erosive to form shallow channels, referred to as rills (Omuto *et al.*, 2009). In the inter-rill areas, runoff occurs as a very thin, broad sheet, sometimes referred to as sheet flow. Both detachment and transport and detachment may occur in the inter-rill and rill areas. As erosive power increases, the small rills may converge to form larger surface channels, called gulley (Chekol, 2006).

2.3. Sediment Yield

Sediment is the fragmented substance, mainly created by chemical, physical and organic weathering of rocks from the earth's outer layer with extent from huge boulders to colloidal size fragments and differ in profile from smoothed to sharp. Sediment transport by the flowing water which is the focus of this study is strongly linked to the surface soil erosion due to the rainfall. The water seeping into the ground can contribute landslides or surface erosion which may become the main source of sediment from the rivers. Sediment yield refers to the amount of sediment eroded discharged by a stream flow at any given point over some time, which will enter a reservoir located at the downstream limit of its tributary watershed (Sidelil, 2019). Sediment yield is also the end product of erosion or wearing away of the land surface by the action of wind, water, ice, and gravity (Reservoir Sedimentation, n.d.). The correlation of sediment yield to erosion is complicated by the problem of determining the sediment delivery ratio, which makes it difficult to estimate the sediment load entering a reservoir based on the erosion rate within the watershed (Morris and Fan, 2009). Sediment yield from a watershed (in units of mass/time or mass/area/time) is an overall or integrated expression of all soil erosion and sedimentation processes occurring in the watershed areas contributing sediment at its outlet (Lane *et al.*, 2001). The total amount of onsite sheet, rill, and gully erosion in a watershed is known as gross erosion. However, not all of this soil material eroded enters the stream system. Some of the material is deposited as alluvial fans, along river channels, and across flood plains. The portion of the eroded material that is transported through the stream network to some point of interest is referred to as the sediment yield (Arabi *et al.*, 2008).

Therefore, the amount of sediment transport depends on different factors such as rainfall intensity, rainfall amount, soil type, slope, climate, runoff, geologic formation, ground cover, land use land cover, topography, sediment characteristics-grain size, mineralogy, channel hydraulic characteristics, upland erosion rate, drainage density, shape, size, and alignment of channels, erosion and sedimentation (Abraha, 2009). The most common unit of sediment yield is tones per year or tones per km² per year. The sediment transport by the flowing water which is the focus of this study is strongly linked to the surface soil erosion due to the rainfall. The water seeping in to the ground can contribute landslides or surface erosion which may become the main source of sediment from the rivers. Generally, the soil erosion brings sediment transport and then sedimentation which can be described as the continuous cycle of sediment.

2.4. Impact of Soil Erosion and Sediment Load

According to (Pimentel *et al.*, 1995), one of the biggest agricultural and environmental issues on the planet is soil erosion. Soil erosion by water threatens the environment and the livelihood in Ethiopia not only through its long-term effect on soil productivity and sustainable agriculture but also as a primary source of sediment that fills reservoirs and pollutes streams (Abraha, 2009). Ethiopia is subject to water erosion, and the loss of topsoil is accelerating. According to (Gashaw, 2015), the average annual rate of soil loss in Ethiopia is estimated to be 12 tons/ha/year, and it can drastically exceed this on steep slopes with a soil loss rate greater than 300 tons/ha/year, where vegetation is denuded. The problem is very serious in Ethiopian highland areas.

The vegetation cover is widely accepted as an important parameter in the erosion and sediment yield of drainage basins. Hence, understanding how land use and land cover changes influence the hydrology of the watershed enables planners to formulate policies to minimize the undesirable effects of future land use and land cover changes (Sulamo *et al.*, 2021). It has a greater impact on erosion than any other single factor.

2.5. Relationship of Soil Erosion and Sediment Yield

The relationship between the amount of soil eroded at the upstream point and waterborne sediment delivered to a downstream location is important for designing hydrological facilities, planning integrated water resource development and determining water pollution loadings (Lane *et al.*, 2000). Soil erosion and sediment yield strongly depend on the local climatic (rainfall or snow), land (surface slope), soil and vegetation conditions (Van Rijn, 1993). The potential for soil erosion varies from watershed to watershed depending on the configuration of the watershed (like topography and shape), the soil characteristics, the local climatic conditions, and the land use and management practices implemented on the watershed (Yilmaz *et al.*, 2011). The MUSLE uses the amount of runoff to model soil erosion and sediment yield. The main strength of MUSLE is the prediction accuracy and the possibility of estimating the sediment yields of single event storms. The soil susceptibility to erosion is expressed by a soil erodibility factor (Neitsch and Arnold, 2005). In general, the soil erosion varies according to land use land cover and agro-climatic zone (Abraha, 2009). The sediment yield from a watershed is an integrated result of all water erosion and transport processes occurring in the entire contributing area (Lane *et al.*, 2000).

2.6. Hydrological Models

Hydrological models are the significant tools for water resource management and its impact on the environment (Hussainzada and Lee, 2021). They are simplified, conceptual representation of the components of the hydrologic cycle. The real world system is characterized by hydrological models. Hydrological models can be used to estimate the design flood hydrograph in addition to the magnitude of the design flood peak (Kalita, 2008). Hydrological models are employed to simulate runoff, erosion, and sediment yield processes spatiotemporally (Ahmadianfar *et al.*, 2016). Watershed scale modeling has emerged as an important scientific research and management tool, particularly in efforts to understand and control water pollution (Daniel, 2011).

2.6.1. Types of hydrological model

According to (Chow *et al.*, 1988), stochastic and deterministic models are often considered to be at the top level of the classification tree, because of the way they treat the randomness of hydrologic phenomena. The stochastic models use local hydrometric data to predict flows. These models allow for some randomness that results in different outputs and are based on analysis of past events, commonly rainfall and river discharge (Ahmad *et al.*, 2002). The deterministic models generally produce a single output of runoff for a given rainfall under identical physical environments. According to (Cunderlik, 2003) the deterministic hydrologic models can be classified into three main categories based on the spatial representation of data. They are lumped, semi-distributed, and distributed models.

i) Lumped models: In this model, the whole catchment is considered as one which assesses the watershed response simply at the outlet without obviously counting for an individual sub-basin response, and the average value of each parameter is used for the entire catchment and the results are not that accurate for the large catchments. In this type of hydrological model the input parameters do not represent the physical features of hydrological processes and the model parameters are area-weighted averages (Singh, 2018). These models do not apply to event-based processes and predict discharge only at the outlet (Singh, 2018). If the interest is primary in the discharge prediction only, then these models can provide just as good simulations as complex physically based models (Dawei Han, 2011). Examples of these models are the Water Balance Model (WATBAL), Snowmelt Runoff Model (SRM), Identification of unit Hydrograph and Components from Rainfall, Evaporation and Stream flow data (IHACRES).

ii) Semi-distributed models: these model is partly permitted to change in space with a division of the watershed into a number of sub-basins. The structures of these models are more physically based than the structure of lumped models and less demanding input data than fully distributed models. The parameters of these models are partially allowed to vary inspace by dividing the basin into a number of smaller sub-basins. The SWAT, HEC-HMS, HBV model, and TOPMODEL are examples of semi-distributed models.

iii) Distributed models: this type of models takes into account the spatial variability of watershed characteristics. It divides the watershed into units that are assumed homogeneous. The distributed modeling approach attempts to incorporate data concerning the spatial variation of parameters together with computational algorithms to evaluate the influence of this distribution on simulated rainfall-runoff behavior. Its parameters are fully allowed to vary in space at a resolution usually chosen by the user. They require large amounts of input data (Singh, 2018). However, the governing physical processes are modeled in detail, and if properly applied, they can provide the highest degree of accuracy (Karna, 2020). Examples of these types of distributed models are HYDROTEL, MIKE11/SHE, IHDM, LISTFLOOD and WATFLOOD.

2.6.2. Hydrological model selection

The choice of the best model depends to a large extent on the prevailing problem and should incorporate the accuracy of prediction, simplicity of the model, consistency of parameter estimates, and sensitivity of results to changes in parameter values (Ibrahim and Dan'azumi, 2020). Several hydrological models are simulating the hydrological process at different temporal and spatial scales. Various criteria can be used for choosing the proper hydrological model for a specific problem. Further, some criteria are also user-dependent and subjective, such as the personal preference for graphical user interface, computer operation system, input-output management, and structure and clarity for users. The selection of a hydrological model takes into consideration the following four fundamental selection criteria (Cunderlik and Simonovic, 2007):

- Is the model capable of simulating continuous or single-event hydrological processes? (The adequacy of the hydrological processes that need to be modeled to estimate the outputs).
- The price (Does the investment appear to be worthwhile for the objectives of the project?).

- Does the model predict the variables required by the projects? (The required model output is important to the project and therefore to be estimated by the model).
- The availability of the input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?),

For this study, the HEC-HMS model was selected since it fulfills all the above criteria. Besides, the model was selected because, the HEC-HMS model is free of charge, publicly available, accessible, and widely used all over the world for simulating hydrologic systems.

2.7. General Model Descriptions

2.7.1. The ArcGIS

The ArcGIS is one of several Geographic Information Systems (GIS), which is a powerful integrated suite of GIS applications capable of performing advanced mapping, data management, and geo-processing of spatial data (Weizhe, 2007). It is a computer-based system for storing, retrieving, analyzing, and displaying geographical data. For data formatting, processing, and coordinate transformation, ArcGIS is used. DEM, land use land cover, geographical names, digital graph line data, registered satellite, and land ownership are all possible components of a geographic information system (Saleh *et al.*, 2011). ArcGIS can perform the same task much more quickly by using elevation data and geometric algorithms. To aid in the creation of basin models for such projects, a GIS companion product was created. The extension is called Geospatial Hydrologic Modeling (HEC-GeoHMS). It can be used to produce basin and meteorological models that can be used in conjunction with the program (Saleh *et al.*, 2011).

2.7.2. The Arc Hydro

Arc Hydro is a geospatial and temporal data model for water resources that operates within ArcGIS software (Maidment, 2002). It is accompanied by a suite of tools that were co-developed by ESRI (Environmental Systems Research Institute) and CRWR (Center for Research in Water Resources) that facilitate hydrologic analysis, link features across several data layers, and populate feature attributes in the data framework (Maidment, 2002). Arc Hydro is a data structure that supports hydrologic simulation models, but it is not itself a simulation model. Hydrologic simulation is accomplished by exchanging data between Arc Hydro and independent hydrologic model, by constructing a simulation model attached to Arc Hydro using a dynamic linked library (Maidment, 2002). The Arc Hydro framework consists of a geodatabase with a feature dataset, feature classes, geometric network, and relationship classes.

2.7.3. The HEC-GeoHMS

The HEC-GeoHMS is an interfacing tool between ArcGIS and HEC-HMS Model software. It is a geospatial hydrology toolkit in ArcGIS to create hydrologic inputs that can be directly used with the HEC-HMS model. It helps to allow visualizing the spatial information, export and files catchment physical characteristics (like curve number, basin lag & time of concentration) from the Digital Elevation Model of the catchment and ArcGIS data, delineate sub-basins, perform spatial analysis and streams to create hydrologic parameters and in addition, it constructs inputs to hydrologic models and support with information preparation (Gumbrecht, 2022). The HEC-GeoHMS creates the background map files, basin model files, meteorological model files, and a grid cell parameter (Guduru *et al.*, 2023) which can be used by the HEC-HMS to develop a hydrological model. HEC-GeoHMS creates the drainage network by analyzing the digital terrain data and transforming the drainage paths and watershed boundaries into a hydrologic data structure to represent the drainage network (Mohd *et al.*, 2016). The relationship between ArcGIS, HEC-GeoHMS, and HEC-HMS is illustrated in the following Figure 1, with the vertical dashed line separating the role of GIS and watershed hydrology (Gumbrecht, 2022).

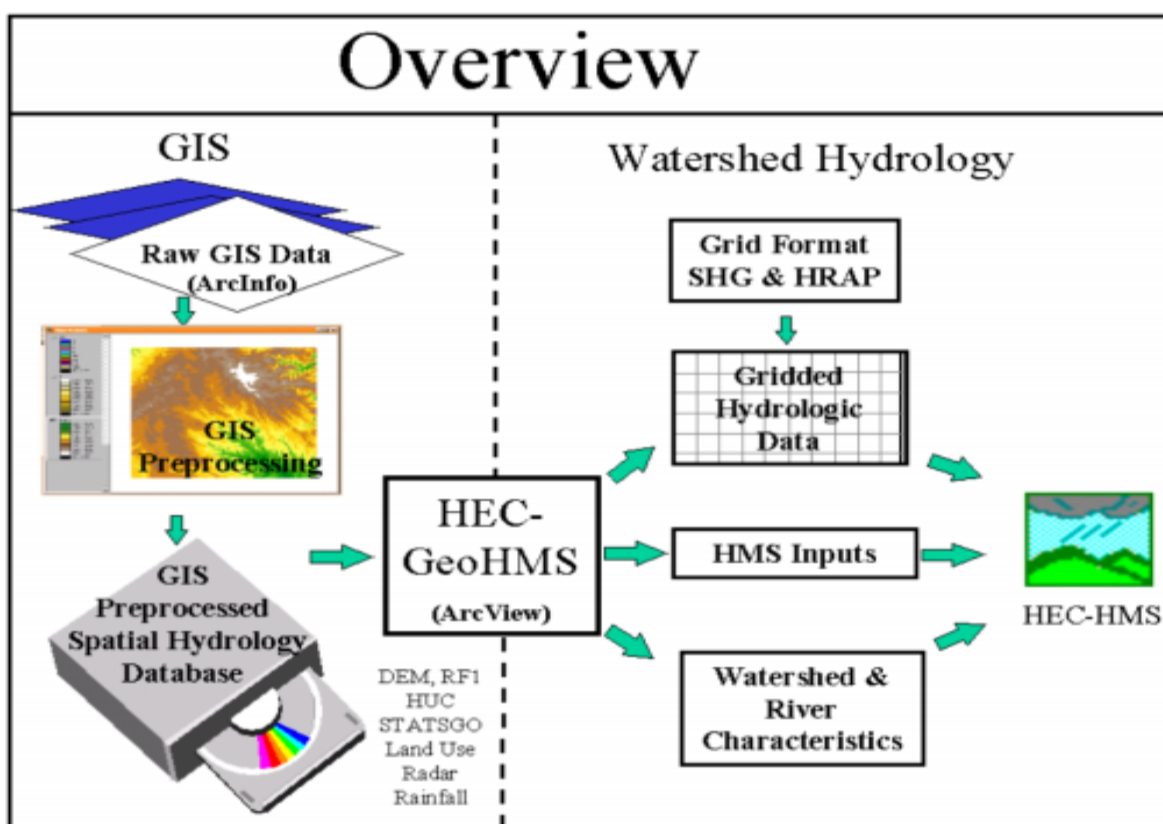


Figure 1. Overview of GIS, HEC-GeoHMS, HEC-HMS and hydrology programs (Gumbrecht, 2022).

2.7.4. HEC-HMS model

HEC-HMS model is an open-source computer software developed by the United States Army Corps of Engineering's Hydrologic Engineering Center that helps simulate the hydrologic cycle (rainfall, evapotranspiration, infiltration, base flow, and surface runoff) of a catchment by describing its physical and meteorological properties of a watershed and aids in recreating its hydrologic cycle. The program is a generalized modeling system capable of representing many different watersheds. It is a computer program designed to simulate the Precipitation-runoff of dendritic watersheds (USACE, 2009). Previously, the HEC-HMS model paid attention to modeling rainfall-runoff processes but currently starting from the release of the HEC-HMS model in 2013 the combination of ArcGIS integrated with HEC-GeoHMS for watershed development and HEC-HMS for watershed sediment yield analysis proved to be an effective method for approximating the sediment yield of any given watershed (Cheng, 2015).

HEC-HMS model is the semi-distributed deterministic model which means that the parameters of the model are to some extent acceptable to fluctuate in space by separating the sub-basin into minor sub-basins, the physically based model which means the scope of the physical modeling occurrence, movement, distribution, and storage of water and their variability are within space and time. HEC-HMS requires the availability of data but is less demanding on input data than the distributed models and uses conservation of mass (continuity equation) and conservation of momentum (momentum equation) governing channel flow equations of fundamental physics laws. HEC HMS divides a watershed into sub-basins. Each sub-basin is connected through a junction in a channel. It easily operates huge tasks in relation to hydrological studies, including losses, runoff transform, open channel routing, analysis of meteorological data, rainfall-runoff simulation, and parameter estimation (USACE, 2000).

The HEC-HMS omits any detailed accounting of movement of water within the soil. It includes models of infiltration from the land surface. But it does not model storage and movement of water vertically within the soil layer (Verma *et al.*, 2010). All models included in HEC-HMS are deterministic. Moreover, the HEC-HMS uses separate models that compute runoff volume, models of direct runoff, and models of base flow. It has nine different loss methods, some of which are designed primarily for simulating events, while others are intended for continuous simulation. The HEC-HMS uses a separate model to represent each component of the runoff process that is illustrated in the Figure 2.

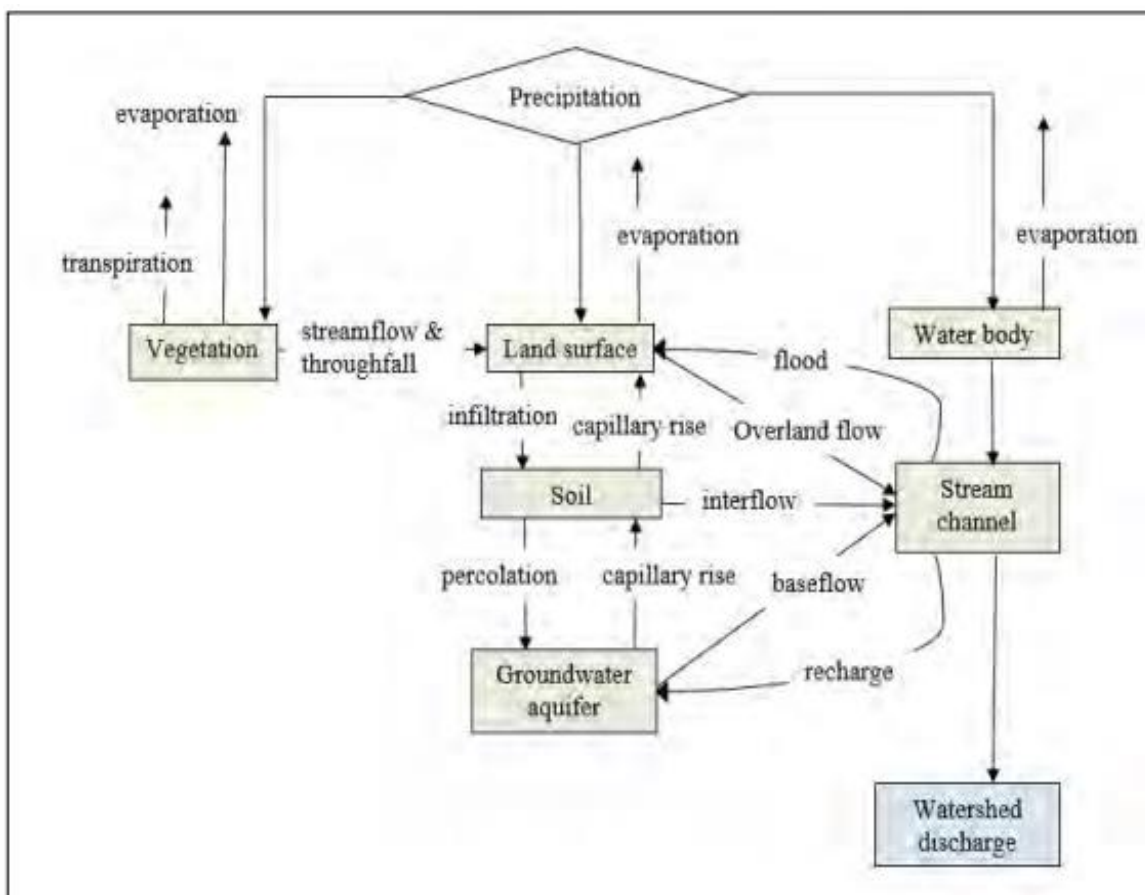


Figure 2. Typical HEC-HMS representation of watershed runoff (Scharffenberg et al., 2006).

2.8. Related Previous Works Using the HEC-HMS Model

Several studies have been conducted in different regions under different soil and climatic conditions by using the HEC-HMS Model.

The study conducted by (Amare, 2021) deals with the Estimation of stream flow and sediment yield using the HEC-HSM model in the Rift Valley Basin of the Gidabo River watershed, Ethiopia. In this study, the HEC-HMS model simulates annual stream flow and sediment yield for various watershed outlet periods, ranging from 1997-2017, with averages of 12.64 m³/s and 114,317.17 tons/year.

Application of HEC-HMS Model for Evaluating impact of land use land cover change in Fetam Catchment, Ethiopia by (Gebreslassie, 2020) was concluded that HEC-HMS model for Fetam Catchment both the calibration and validation results showed good match between measured and simulated stream flow data with the coefficient of determination (R^2) of 0.74 and Nash-Sutcliffe efficiency (NSE) of 0.67 for calibration, and NSE of 0.51 and R^2 of 0.65 for validation.

Husen (2020) has carried out the Application of the HEC-HMS Model for Rainfall-Runoff Simulation of the Weyb River Watershed, Genale Dawa River Basin, Ethiopia. The study predicts storm flows using the HEC-HMS model and compares it with other models to minimize flooding and drought risks. Peak discharges for different return periods are obtained by the HEC-HMS model for the 2, 5, 10, 25, 50, and 100 years, storms are 196.20 m³/s, 300.7 m³/s, 375.1 m³/s, 515.2 m³/s, 692.4 m³/s and 850.0 m³/s respectively.

Abebe (2020) has carried out Rainfall-Runoff modeling using the HEC-HMS model in the case of the Bilate watershed, Ethiopia. The hydrologic model was used to determine the peak flow discharge for return periods of 2, 10, 25, 50, and 100 years. The following results were obtained using the HEC-HMS model 241.8 m³/s, 314.8 m³/s, 651.2 m³/s, 738.01 m³/s, and 1,152.1 m³/s.

(Guduru *et al.*, 2023) modeled rainfall-runoff modeling using the HEC-HMS model for the Meki River watershed, Rift Valley Basin, Ethiopia. The model was calibrated and validated using 18-year stream flow data and 6-year data from 2005-2010, achieving high-efficiency ratings. Flood prediction was conducted using 24-hour rainfall depth of 2, 10, 25, 50 and 100 years return period and found to be 133.21 m³/s, 178.1 m³/s, 239.7 m³/s, 313.2 m³/s and 346.19 m³/s respectively.

Kedir (2020) conducted study on Rainfall-Runoff simulation and Modeling using HEC-HMS model in Dechatu Watershed. In this study the results showed a total volume of runoff 150.20 M m³ during the 50 years of the simulation. The peak discharge was found to be 2,528.7 m³/s and the model evaluation has showed, indicating that the results of the simulation are satisfactory.

Yibeltal (2016) studied that the Rainfall-Runoff Modelling for Sustainable Water Resources Management in the case of Gumara Watershed, Ethiopia. The predicted peak discharge was close to the observed value, but the simulated peak discharge was far apart. The actual observed discharge is 256.9 m³/s, whereas the simulated peak discharge is 578.9 m³/s. This represents a 322 m³/s difference.

Namara *et al.* (2014) conducted the study on the Rainfall-Runoff modeling using HEC-HMS: the case of Awash Bello Sub-catchment, Upper Awash Basin, Ethiopia. The model performance had shown with NSE = 0.855, R² = 0.867, PBIAS = 4.59% for calibration and NSE = 0.739, R² = 0.863, PBIAS = 5.67% for validation, respectively.

By the successful accomplishing of calibration and validation, the peak flood from the model (573.7 m³/s) was compared with direct observed flow (546.4 m³/s) and model provided nearly the same result with the direct observed flow.

Hanfare (2019) conducted the study on Analysis of the Effect of Climate Change on the Flood Hazard using the HEC-HMS model for Logia Sub-watershed, Lower Awash Sub-basin, Ethiopia. The result of calibration and validation of stream flow R² and NSE were 0.74, 0.72, and 0.77 and 0.74 respectively. For 50-year return period, the flood hazard map of base period indicates that 336 ha, 482.2 ha, 16.48 ha, and 10.88 ha which correspond to very high, high, moderate and low flood hazard, respectively. The flood hazard map at future showed that approximately 1,204.3 ha up to 1,361.9 ha area is expected to be flooded under future climate change scenarios of which significant areas are under agricultural and residential areas. Therefore, the study showed that due to the combined effect of projected variation in rainfall and temperature there will be increment of flood hazard in the Logia sub-watershed.

Tassew *et al.* (2019) has carried out the Application of HEC-HMS model for Flow Simulation in the Lake Tana Basin, in the case of Gilgel Abay catchment, Upper Blue Nile Basin, Ethiopia. The comparison of the observed and simulated hydrographs and the model performance (NSE = 0.884) and their correlation (R² = 0.925) showed that the model is appropriate for hydrological simulations in the Gilgel Abay catchment.

Shammi Haque (2018) studied that the Effect of Climate and Land Use Changes on Sediment Load for Brahmaputra River Basin Using HEC-HMS model. The simulated annual average sediment load at Bahadurabad transit from calibrated and validated HEC-HMS model is about 370.20 Mt/year. For future climate changes, synthetic approach for changing precipitation about -25% to 40% have been performed. For -25% to 40% changes of baseline precipitation in future, average annual sediment load varies from -31.34% to 41.92% of climatic base period values. For 40% increase of precipitation in future, annual sediment load from Brahmaputra River Basin will increase up to 525.38 Mt/year.

Adhikari (2020) conducted the study on the Application of HEC-HMS to the investigation of soil erosion and sediment yield by surface runoff. The total sediment load from HEC-HMS for nine hours of rainfall was 11.8 ton and the total sediment concentration was 1.92 gm/l. The result of the total sediment yield in HEC-HMS model was divided into three sediment types such as sand, clay, and silt.

3. MATERIALS AND METHODOLOGY

3.1. Description of the Study Area

3.1.1. The study area location

Awash Basin is among the 12 major river basins of Ethiopia, which is located between $7^{\circ} 53' 42''$ to $12^{\circ} 07' 20''$ N and $37^{\circ} 56' 56''$ to $43^{\circ} 17' 04''$ E. The total length of the river is about 1,200 km and it covers an area of 116,000 km², with altitudes in the range of 240 m to 4187 m above mean sea level.

The Mille River is one the tributary of the Awash River at the lower section of the lower Awash River Sub-basin and joined main Awash River upstream of Tendaho Reservoir. Mille River originates and drain from the high lands of north wollo to the low land of the Afar region. It is located between $11^{\circ} 32' 31.73''$ N and $39^{\circ} 35' 07.24''$ E at the north high land of wollo and $11^{\circ} 24' 50.9''$ N and $40^{\circ} 45' 33.5''$ E at the outlet of the watershed (Figure 3). The total area coverage of the watershed is around 4,543.60 square kilometers.

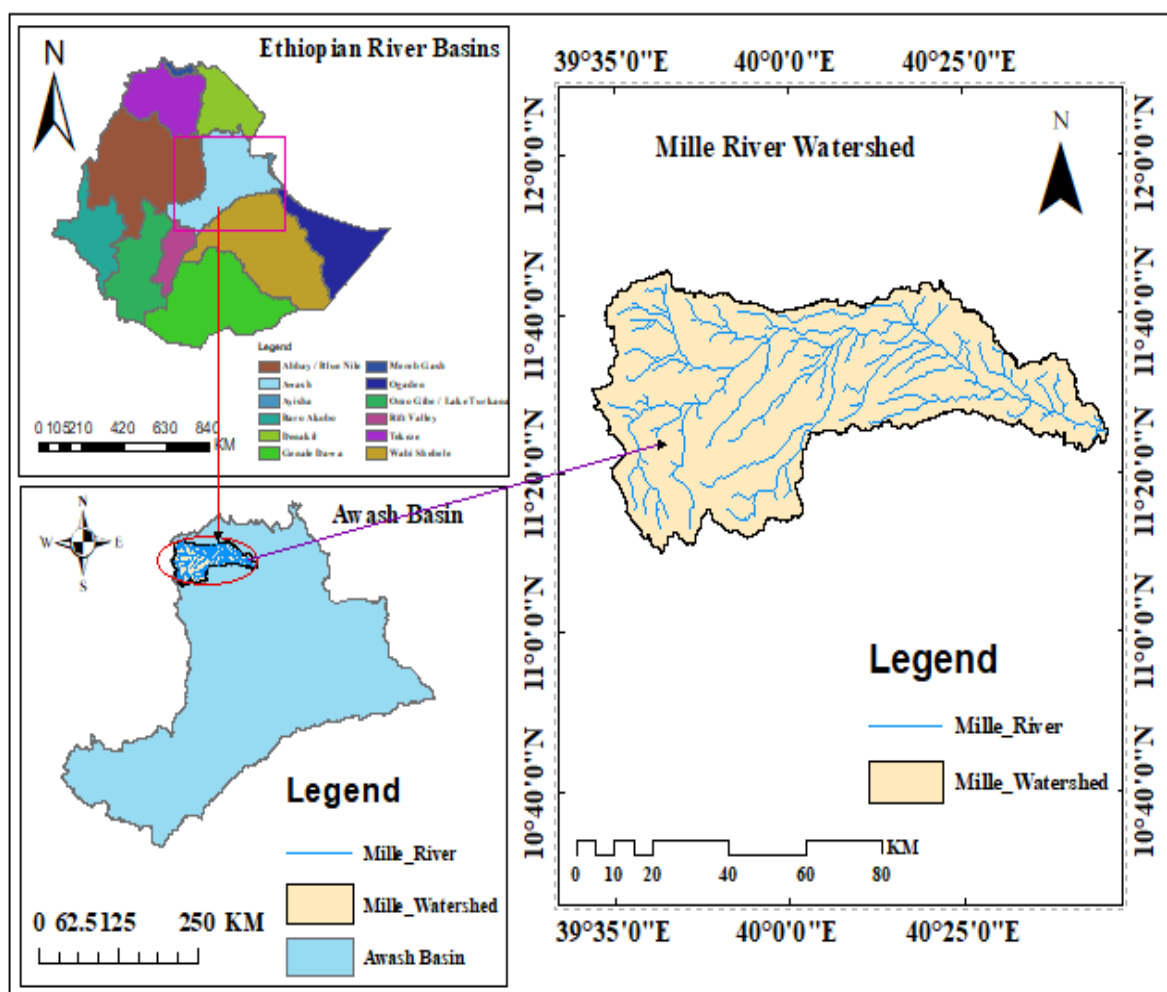


Figure 3. The location map of the study area.

3.1.2. Geology and topography

Lower Awash River Sub-basin is characterized by extensive floodplain (including terrace) stretching from Logia town in the northwest to Asayita town and as far as Buri plain in the southeast, few kilometer northwest of Asmara hill/volcano (Tadesse, 2022). Awash creates broad meander belt as wide as 12 to 15 km around Dubti area and Det-Bahari-Galifage areas. The floodplain is mainly underlain by silty clay, across which the Awash River laterally wanders forming meandering channel pattern (Tadesse, 2022). Generally, the floodplain and terraces are covered by thick riparian vegetation (riverine forest) mainly of prosopis, spiny trees and shrubs, except areas covered by old cotton plantations and new sugarcane plantations. Extensive areas on both sides of the present-day courses of Awash River are covered by natural riparian vegetation, which commonly occur in the Ethiopian Rift valley, back swamps, naturally recharged floodplain by floodwater, support riparian vegetation. The topography of the Mille River watershed is characterized by steep slopes of ridges and mountains in the upper part to a gentle slope in the lower part (Bati, 2022). The study area, which is a one of the watershed of Lower Awash Sub-basin consists of variety of landscape with various topographical features with elevation variation from 3,651 m to 473 m above m.s.l in the Figure 4. The slope of the watershed described as shown in the Figure 5.

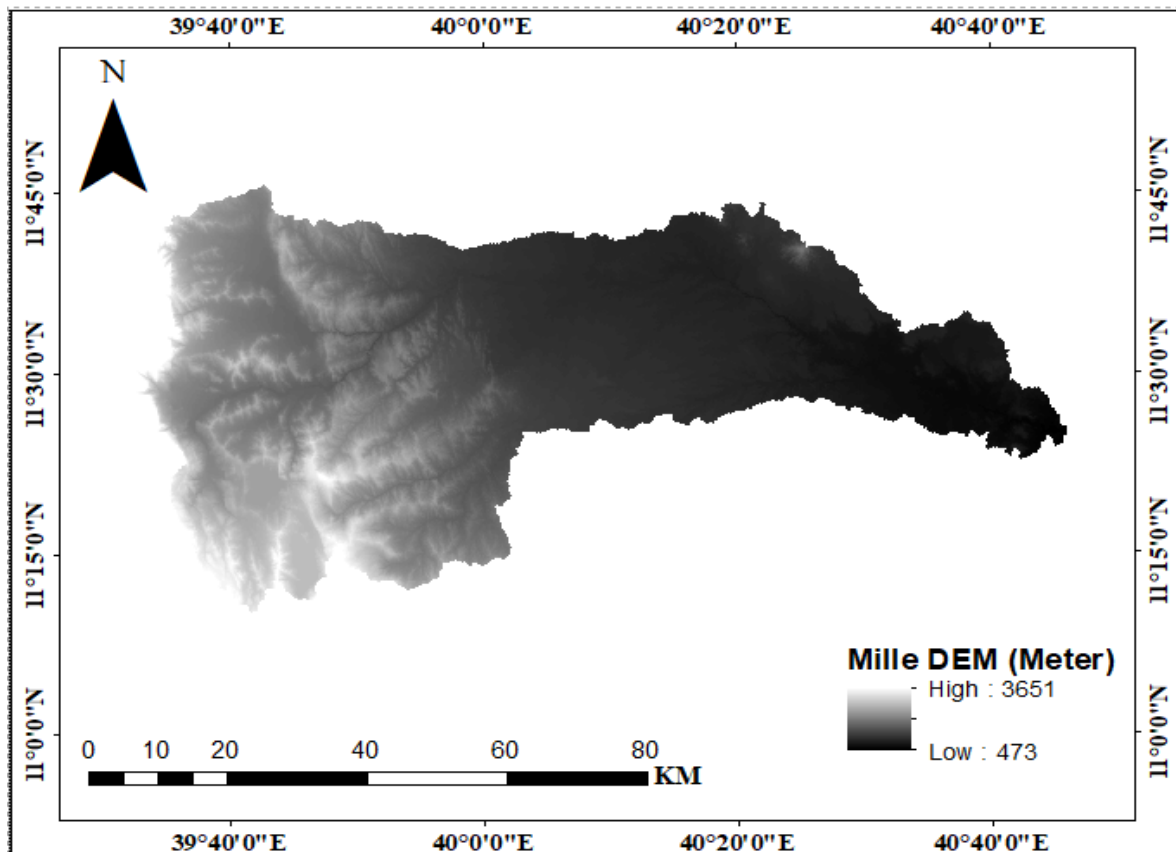


Figure 4. The Digital Elevation Model of the study Area.

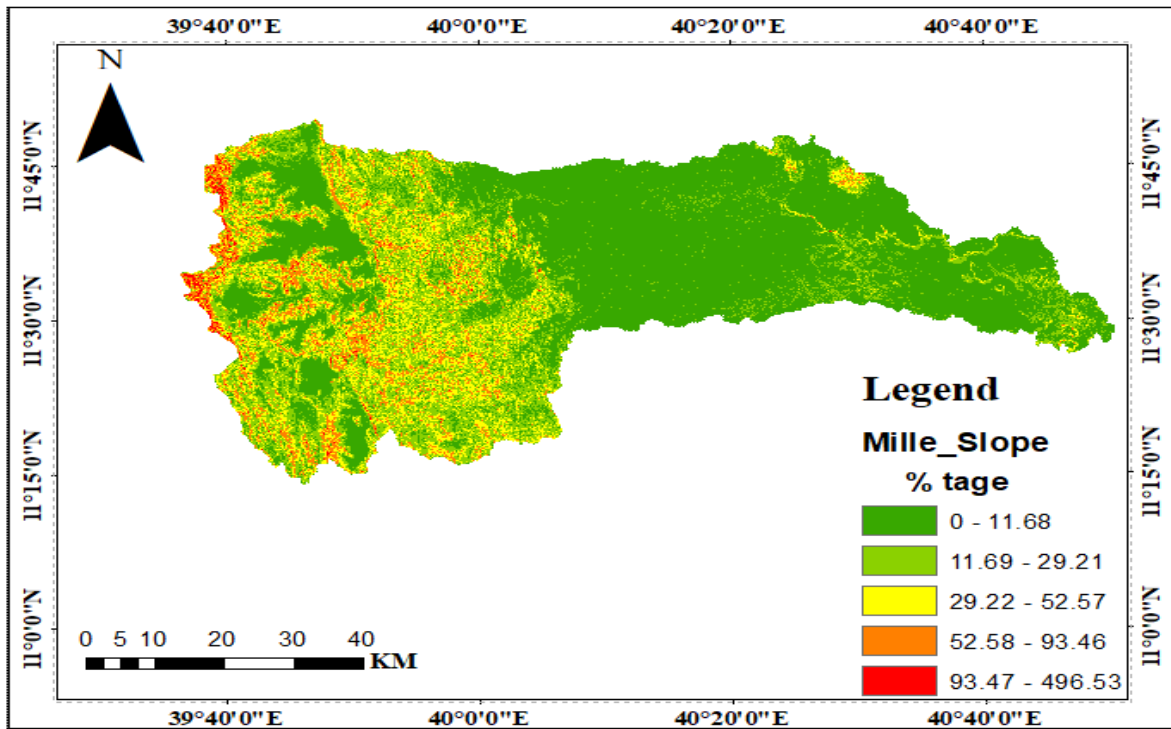


Figure 5. Slope classification of the Mille River watershed.

3.1.3. Climate

The climate of Awash River Basin is influenced by Inter-Tropical Convergence Zone (ITCZ) (Koriche, 2012). There are three seasons in the Awash River Basin based on the movement of the Intertropical Convergence Zone (ITCZ) and the amount of precipitation timing (Jilo *et al.*, 2019). The three seasons are named: Kiremt, which is from June to September (rainy season), Bega, which is from October to January (dry season), and Belg, which is from February to May (small rainy season). Therefore, the rainfall was categorized under the bi-modal patterns of rainfall. The climate of the Mille River watershed is varies from semi-humid sub-tropical at the western part to semi-arid at the some east part of the watershed. The mean annual rainfall of the watershed varies from 1,182.77 mm to 717.52 mm. Similarly, the average yearly temperature varies from 14.98 °C in the upper basin to 29.68 °C in the lower basin of the watershed. Based on classification of the climate of the country, the watershed has hot arid type of climate. The distributions of rainfall and temperature over the watershed are strongly related to the altitude.

3.2. Data Collection and Analysis

3.2.1. Spatial data

The spatial data like Digital Elevation Model (DEM), Soil data and Land use land cover (LULC) data are used in this research were collected from different sources.

3.2.1.1. Digital Elevation Model (DEM) data

Topography is defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution (Setegn, 2010). In other words, the DEM is any digital representation of a topographic surface and specifically to a raster or regular grid of spot heights. The DEM data was used as an input for the HEC-HMS Model along with soil and land use land cover data to characterize; the surface of the watershed, slope, altitude, delineate drainage system, catchment, sub-catchments, stream network, quantify catchment variables, soil moisture and flow time in the catchment. In this study, the high resolution DEM (30x30m) data was obtained from the elevation databases of shutter radar topographic mission (SRTM) <http://earthexplorer.usgs.gov/>.

3.2.1.2. Land use land cover data

The land use land cover map gives the spatial extent and classification of the various land use land cover classes of the study area. It is one of the main input data of the HEC-HMS model. The LULC information is on ArcGIS format and should be processed to get ready and merge with the soil type data. The LULC 2016 data of study area was obtained from Ministry of Water and Energy (MoWE).

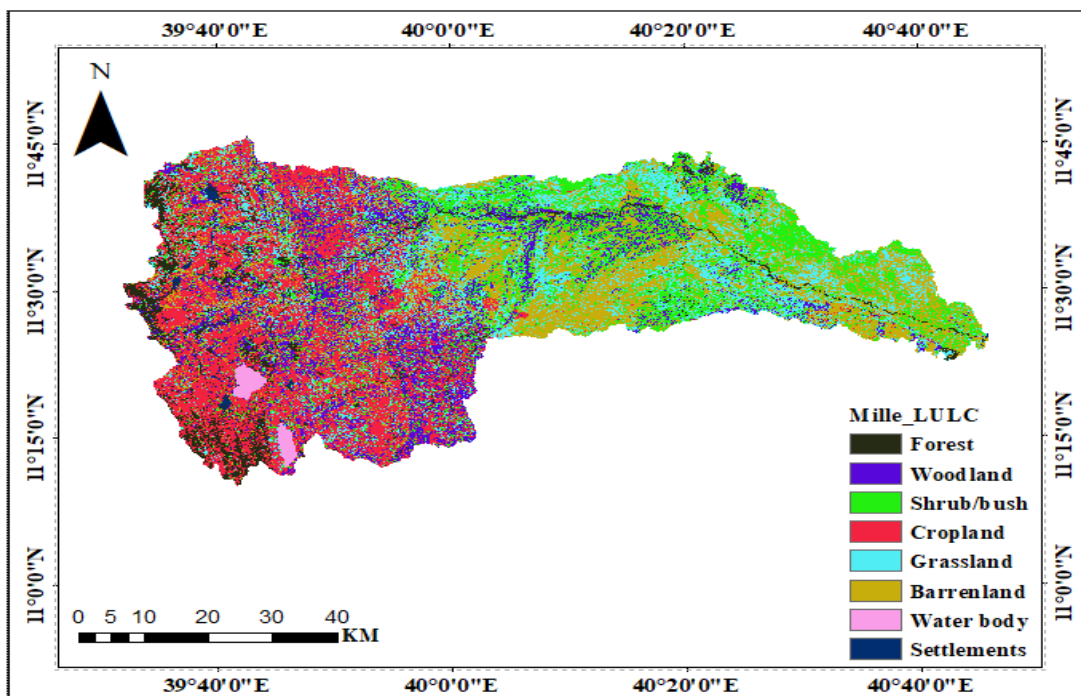


Figure 6. Land use land cover classification of the Mille River watershed.

The dominant LULC of the study area are categorized as forests, barren land, woodland, grassland, cropland, shrub/bush land, settlements and water body. Among these, the cropland (24.68%) is the most dominant one in the study area as shown in Figure 6.

Table 1. Land use land cover types of the Mille River watershed.

No.	Name of LULC	Perimeter (km)	Area (km ²)	Coverage (%)
1	Barrenland	37,506.077	912.4317	20.08
2	Cropland	35,093.558	1,121.2911	24.68
3	Forests	8,969.013	274.3542	6.04
4	Grassland	38,329.426	716.0409	15.76
5	Settlements	473.158	14.6754	0.32
6	Shrub/bush	43,230.177	858.1914	18.89
7	Woodland	34,000.061	607.9158	13.38
8	Water body	47.281	38.6982	0.85

3.2.1.3. Soil data

Soil data is another major input data for the HEC-HMS model used for computation of Curve Number (CN) that was used in the SCS method of runoff estimation. Like the Digital Elevation Model (DEM), soil data resolution has also a significant impact on the modeling of runoff and sediment yield. The soil data of the watershed is classified in to different hydrologic soil groups by using lookup Tables. Hydrologic soil groups are groups of soils with similar tendency for runoff under similar storm and cover conditions. After pre-processing of soil maps using ArcGIS based on the rules of hydrologic soil group classifications developed by the United State Natural Resource Conservation Service (NRCS), the hydrologic soil map watershed was generated and grouped: as A, B, C and D. The soil map of the study area was obtained from Ministry of Water and Energy (MoWE). The major soil types of the study area are Eutric Cambisols, Calcaric Fluvisols, Leptosols, Eutric Regosols, Vitric Andosols, Haplic Solonchaks and Eutric Vertisols. Among these, the dominant soil types are Eutric Cambisols, Calcaric Fluvisols and Leptosols, which have an area coverage of 46.81, 27.47% and 11.08% respectively.

Table 2. The soil types of the Mille River watershed.

No.	Name of the soil	Perimeter (km)	Area (km ²)	Percentage (%)
1	Vitric Andosols	596.6578	348.1524	7.66
2	Eutric Cambisols	993.1131	2,126.9171	46.81
3	Calcaric Fluvisols	790.6966	1,248.0124	27.47
4	Leptosols	802.4972	503.5957	11.08
5	Eutric Regosols	299.0123	137.6056	3.03
6	Haplic Solonchaks	211.7667	63.1754	1.39
7	Eutric Vertisols	291.0304	79.2212	1.74
8	Other	47.2810	36.9190	0.81

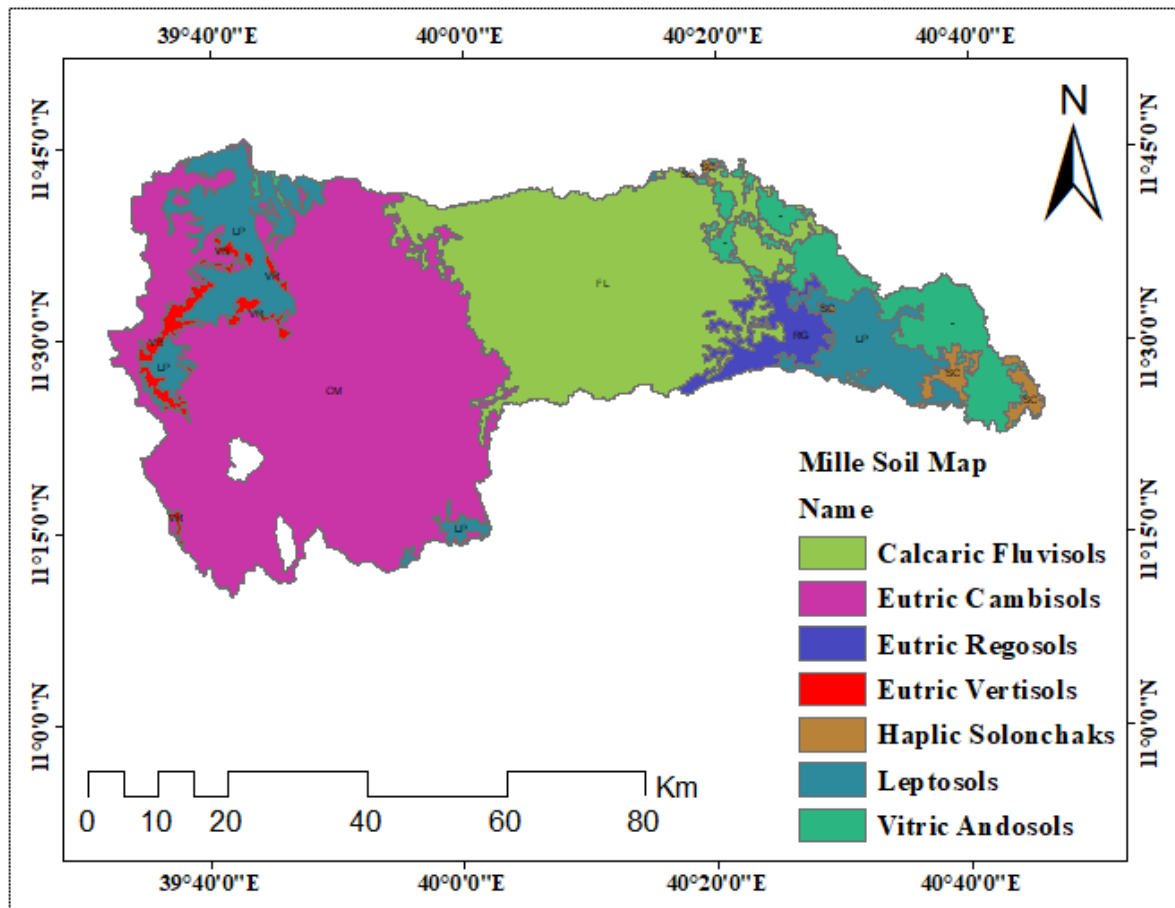


Figure 7. The soil classification of the Mille River watershed.

3.2.2. Meteorological data

The HEC-HMS model needs daily records of meteorological data. The data collected are based on their homogeneity of the pattern, which can be the representative to the watershed. The continuous the HEC-HMS model requires the daily values of the precipitation and evapotranspiration for the simulation of the runoff. The daily evapotranspiration data used in this study is estimated from the collected maximum temperature, minimum temperature, and extra-terrestrial radiation. The meteorological data were collected from the Ethiopian National Meteorological Institute (NMI).

3.2.2.1. Rainfall data analysis

Rainfall data is one of the basic input requirements for the HEC-HMS model. The rainfall data of 30 years (1993 to 2022) for the selected representative rainfall stations in the study area were shown in the Table 3. These rainfall stations were Bati, Haik, Mersa, Mille and Sirinka stations.

Table 3. The locations and yearly average rainfall for each stations.

No	Name of Station	Latitude	Longitude	Altitude	Data Series	Mean Annual Rainfall (mm)
1	Bati	11.19639	40.01539	1,637m	1993-2022	939.55
4	Haik	11.30532	39.68021	1,985m	1993-2022	1,211.73
3	Mersa	11.66381	39.66605	1,578m	1993-2022	1,072.11
4	Mille	11.42558	40.76694	487m	1993-2022	317.83
5	Sirinka	11.751	39.61428	1,861m	1993-2022	1,070.85

The meteorological data gathering of this study ranges from 1993 to 2022 years. The mean monthly rainfall of the Mille River watershed ranges between 3.24 mm to 313.20 mm. The bimodal patterns of rainfall with the highest rainfall during the month of April, July and August is the characterization of Mille River catchment precipitation stations as shown in Figure 8.

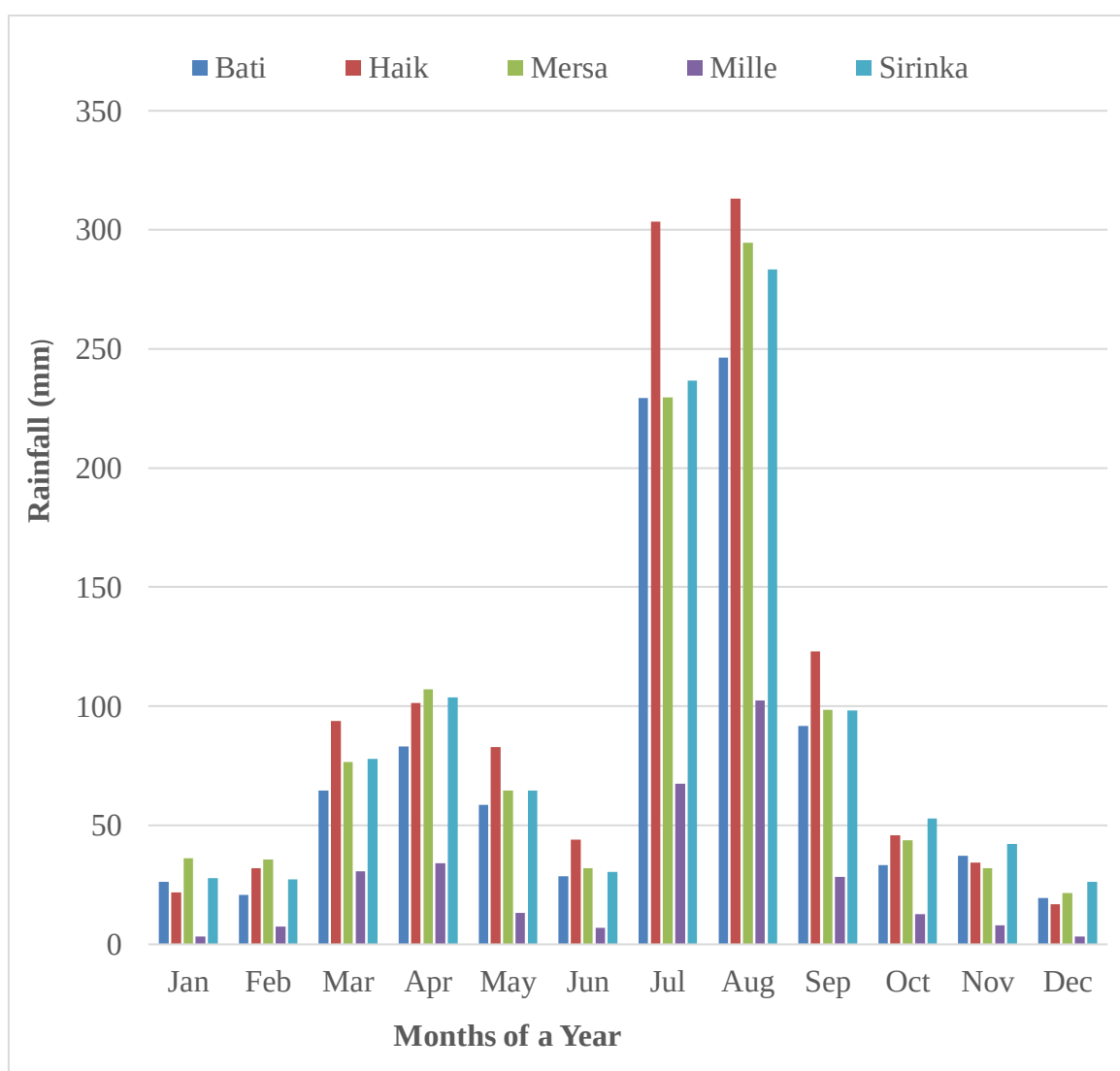


Figure 8. The mean monthly Rainfall of the selected stations (1993 – 2022).

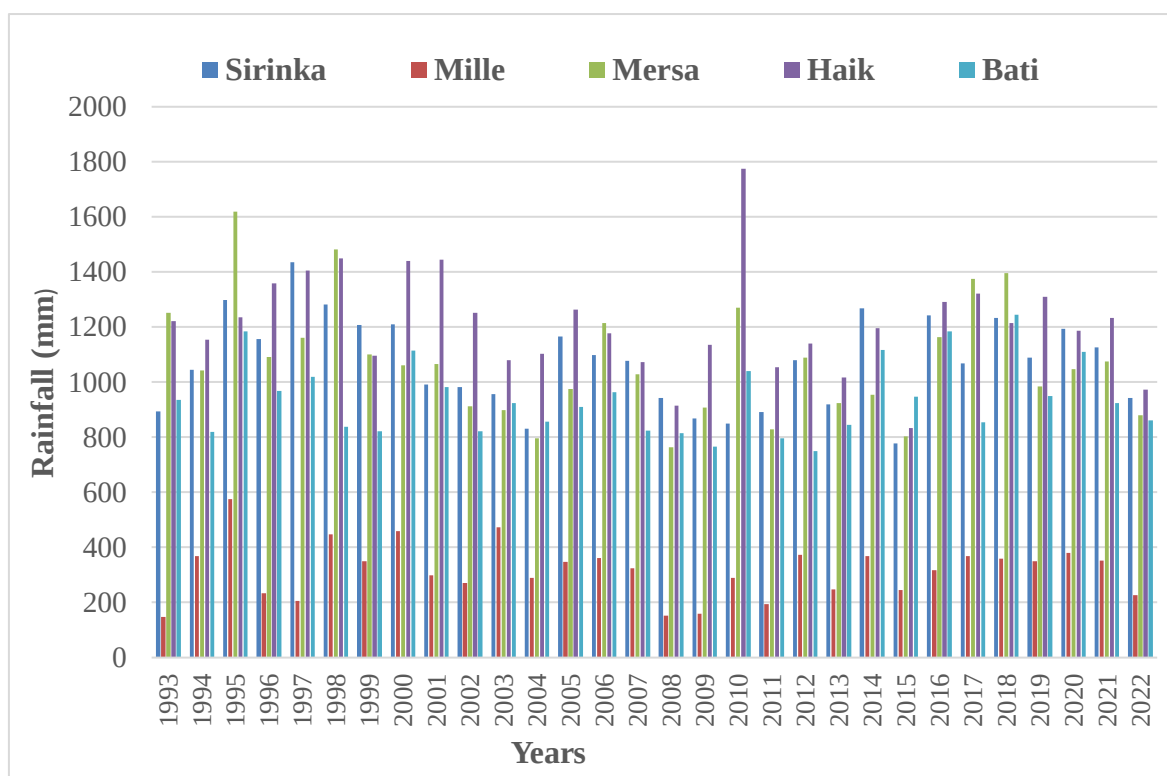


Figure 9. The mean annual rainfall the Mille Rive catchment (1993 -2022).

3.2.2.2. Temperature data analysis

The average minimum temperature varies from 11.67 °C in December to 17.71 °C in June and the maximum temperature ranges from 26.64 °C in January to 33.83 °C in June. Air temperature regulates the growth and development of many plants by regulating the rate of biochemical processes. The growth of many crops ceases below a critical temperature of 5 °C or above 35 °C adversely affecting the yield (FAO, 1978).

Table 4. The mean monthly maximum and minimum temperature of the Mille Watershed.

The mean/average monthly maximum and minimum temperature of the watershed.												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Tmax	26.64	27.62	29.23	30.50	32.12	33.83	31.64	30.05	30.36	29.37	27.99	26.83
Tmin	12.48	13.44	14.69	16.30	16.79	17.71	17.36	16.61	16.66	13.76	12.29	11.67

Where; Tmax and Tmin are the average monthly maximum and minimum temperatures respectively. The monthly mean temperature for maximum and minimum of the Mille River catchment of five meteorological stations is shown in the Figure 11.

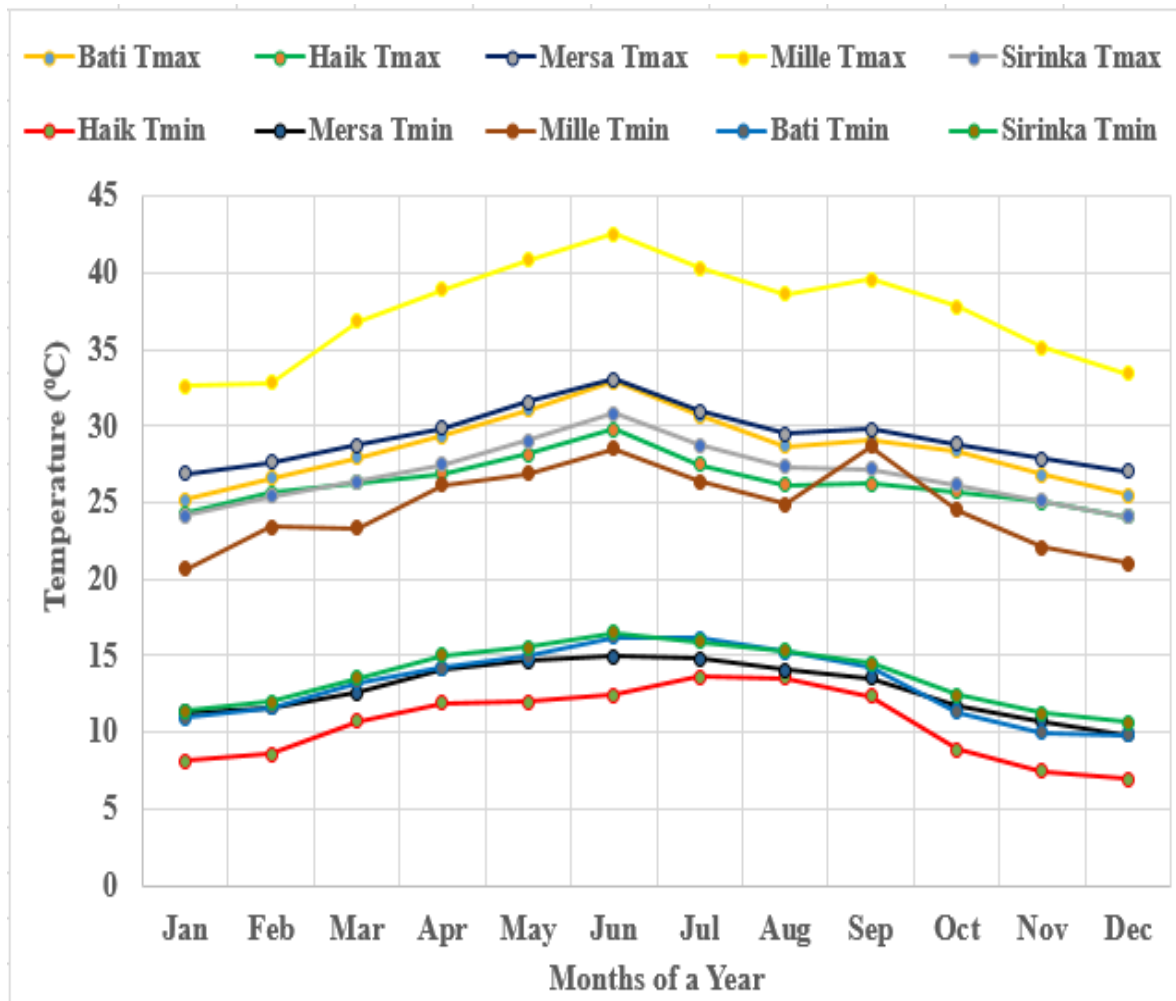


Figure 10. The mean monthly minimum and maximum temperature of the stations (1993-2022).

3.2.2.3. Evapotranspiration (ET) data analysis

Evapotranspiration (ET) is the combination of two separate processes of water losses by direct evaporation from soil and plant surfaces, and transpiration, in which water moves from the soil through plants to leaves where it is vaporized and diffuses through the stomata to the ambient air. Evapotranspiration is one of the most important components in the hydrologic cycle (Kurbah, 2017). Accurate estimation of the potential evapotranspiration (ETO) is essential for the estimation of the runoff in the watershed and for planning, design and operation of irrigation systems. There are many empirical methods for estimating ETO that require many weather data which are not readily available, but some of the methods require only air temperature for ETO estimation.

The most widely used methods for ETO estimation from daily meteorological data is the Penman Monteith method, and it has been proposed as the standard model for validating other formulations and estimating ETO because it can be determined unambiguously, providing consistent values in all regions and climates. The main drawback of the Penman-Monteith method and other evaporation estimating methods such as Priestley-Taylor method is that it requires weather or climate data (such as solar radiation or sunshine hour, temperature, relative humidity, and wind speed) that are often unavailable (Moratiel *et al.*, 2020). But these data are commonly lacking or of questionable quality in developing countries like Ethiopia and particularly in this research thesis area.

In such situations, temperature based evapotranspiration (TET) methods such as Hargreaves method and Thornthwaite methods are particularly useful. Air temperature is one of the most widely recorded meteorological parameters. Therefore, TET methods temperature databases are critically important for evapotranspiration estimation in the study area of Mille River watershed based on the available data and in this study the Hargreaves method is used for the estimation of evapotranspiration. The Hargreaves method of PET determination is based on the following equation:

$$PET = 0.0023 * Ra * (T_m + 7.8) * (T_{max} - T_{min})^{0.5} \dots\dots\dots (1)$$

Where; T_m is daily mean air temperature ($^{\circ}C$), T_{max} is daily maximum air temperature ($^{\circ}C$), T_{min} is daily minimum air temperature ($^{\circ}C$), Ra is extra-terrestrial radiation ($MJm^{-2} day^{-1}$) and PET is potential evapotranspiration (mm/day).

Table 5. The mean daily and monthly Evapotranspiration of the Mille River catchment.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Daily PET	4.05	4.42	5.11	5.44	5.78	6.02	5.52	5.23	5.14	4.93	4.38	4.01
Monthly PET	125.48	124.67	158.52	163.24	179.09	180.56	171.26	162.27	154.14	152.29	131.46	124.38

3.2.3. Hydrological data

3.2.3.1. Stream flow data

The hydrological data are required for the calibration, uncertainty analysis and validation purpose for the HEC-HMS model. Based on the extent of calibration and validation, the stream flow data was arranged as per the requirement of the HEC-HMS model. The stream flow data from 1993 to 2008 year were obtained from Ministry of Water & Energy (MoWE).

3.2.3.2. Sediment data

Estimation of sediment yield is very significant in water resource studies for the design of reservoirs, designing water treatment plant and evaluating the potential sedimentation of reservoirs lakes and ponds (Amare, 2021). The sediment data were collected from Ministry of Water & Energy (MoWE). If adequate and reliable records of flow and sediment data are available, various methods could be employed for the estimation of sediment loads in the river watershed (Amare, 2021). There are few sediment data that have measured suspended sediment data which was not data of all monthly days rather it is sample taken in different seasons within different years in the Mille River watershed, therefore rating curve was used for good estimation of the sediment loads in the study area watershed. The sediment rating curve is a relationship between the river discharge and sediment concentration or load (Morris and Fan, 1998).

Generally, a sediment rating curve may be plotted showing average sediment concentration or load as a function of discharge averaged over daily, monthly or other time periods. So using a rating curve, the records of discharges are transformed into records of sediment concentration or load. Commonly, the relation is the following form (Morris and Fan, 1998).

$$Q_s = aQ^b \dots\dots\dots (2)$$

Where, Q_s is the suspended sediment concentration (ton/day), Q is the stream flow discharge (m^3/s), and a , b are regression constants.

The most commonly used sediment rating curve is power function. The raw data collected is the sediment concentration (mg/l). Thus, the data of sediment which is in concentration form have to change into sediment load in ton per day to create the sediment rating curve. This value is converted into sediment load by the time-series sediment rating curve computing technique is the following form (Morris and Fan, 1998).

$$Q_s = 0.0864 * Q * C \dots\dots\dots (3)$$

Where, Q_s is the sediment load in (ton/day), Q is the stream flow discharge (m^3/s), C is the sediment concentration (mg/l) and 0.0864 is conversion factor. The data for sediment rating curve development is shown in the Appendix A, Table 9.

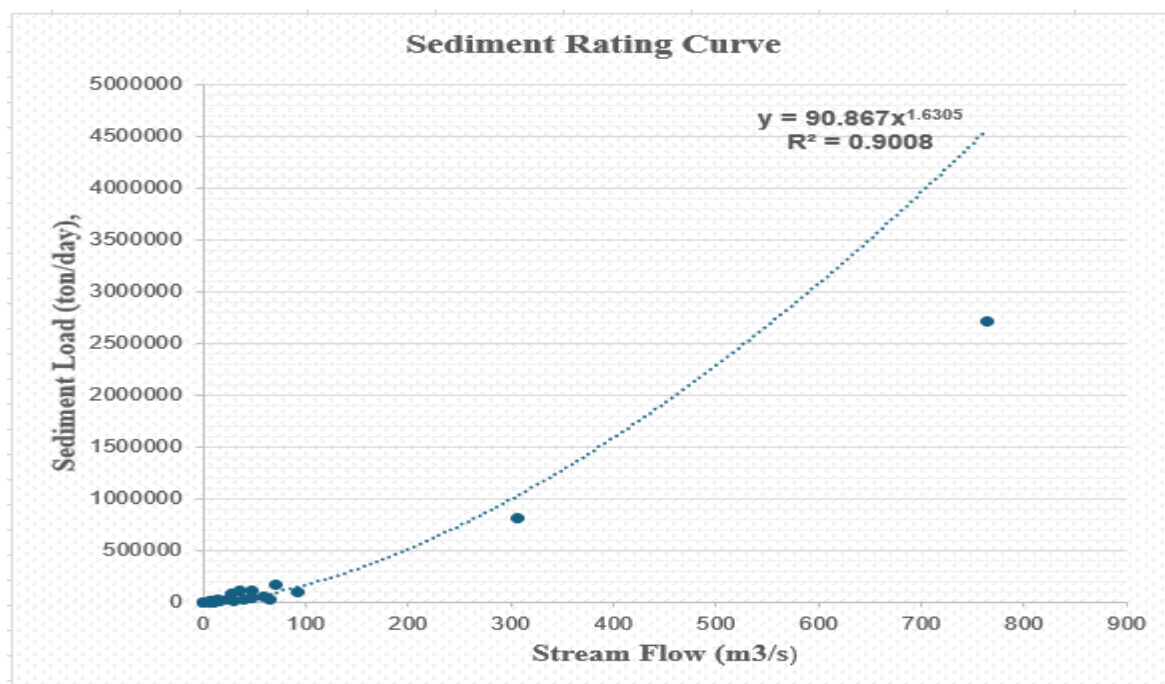


Figure 11. Sediment rating curve of Mille River gauging station.

The continuous daily time step sediment yield for the station was generated by using the sediment rating curve equation (Equation 4) which has obtained from the above sediment rating curve data plot and used to sediment yield model calibration and validation processes.

$$Q_S (\text{Mille River}) = 90.867 * Q^{1.6305} \dots\dots\dots (4)$$

3.3. Meteorological Data Quality Analysis

3.3.1. Filling missing hydro-meteorological data

The missing records of any rainfall gauge or the absence of an observer from a stations causes a short gap or break in the records of rainfall at the stations. These gap can be filled before using the rainfall data for the analysis. The surrounding station located within the watershed or basin helps to fill in the missing data on the assumption of hydro-meteorological similarity between the groups of the stations. For this study, the missing rainfall station was estimated or filled by using the Normal Ratio method because the difference of normal annual precipitation of station with missed data and the surrounding stations within study area were more than 10% for all years. Mathematically, the normal ratio methods are given as equation 5:

$$P_X = \frac{N_X}{M} \left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \dots + \frac{P_m}{N_m} \right] \dots\dots\dots (5)$$

Where, P_x is the missing data at station x , N_x is the missing data stations normal annual rainfall, $P_1, P_2, P_3, \dots, P_m$ are the rainfall at station 1, 2, 3, $\dots, m$, $N_1, N_2, N_3 \dots N_m$ are the normal annual rainfall at station 1, 2, 3, $\dots, m$ and m is number of nearby gauges.

Table 6. The percentage of missing data of the meteorological stations.

No	Name of station	Latitude	Longitude	Altitude	Data Series	Missed Data (%)	Remark
1	Bati	11.19639	40.01539	1,637m	1993-2022	3.05	Filled
2	Sirinka	11.751	39.61428	1,861m	1993-2022	3.88	Filled
3	Mille	11.42558	40.76694	487m	1993-2022	30.93	Filled
4	Haik	11.30532	39.68021	1,985m	1993-2022	8.74	Filled
5	Mersa	11.66381	39.66605	1,578m	1993-2022	17.25	Filled

3.3.2. Homogeneity test of the rainfall data

The main uses of homogeneity test is to identify a change in the statistical properties of the time series data which is caused by either natural or man-made factors. These include the relocation of the observation station and land use land cover change. Test of homogeneity is required for validation purposes and also there is a shared need for such tests with other climatic variables. Homogeneous rainfall records is required in hydrologic design. Because of the uncertainty about possible changes, graphical methods was used in climatology and hydrology to obtain some insight into the homogeneity of a rainfall records. In this study, the Rainfall-homogeneity test was carried out using Rainbow software. Rainbow is a software package developed by the Institute for Land and Water Management of the K.U.Leuven (Zilitinkevich, 1995). The programme is designed to test the homogeneity of hydrologic records and to execute a frequency analysis of rainfall and evaporation data (Zilitinkevich, 1995). The program especially suitable for predicting the probability of occurrence of either low or high rainfall amounts, both of which are important variables in the design and management of irrigation systems, drainage network, and reservoirs. Homogeneity test is based on the cumulative deviation from the mean as expressed using the mathematical equation proposed by (Dirk Raes *et al.*, 2006). This software rescaled time series data by dividing cumulative deviation of annual rainfall data to cumulative standard deviation value.

$$S_k = \sum_{i=1}^k (X_i - X_{bar}) \dots\dots\dots k = 1, \dots, n \dots\dots\dots (6)$$

Where; X_i are the records from the series $X_1, X_2, \dots, X_n$, X_{bar} is the mean, S_K is the residual mass curve.

For a homogeneous record, one may expect that the S_K fluctuate around zero in the residual mass curve since there is no systematic pattern in the deviation X_i 's from the average values X_{bar} .

To perform the homogeneity test, annual cumulative rainfall data of the stations were computed and analyzed using the Rainbow software and the result of the homogeneity test were presented in figure 13.

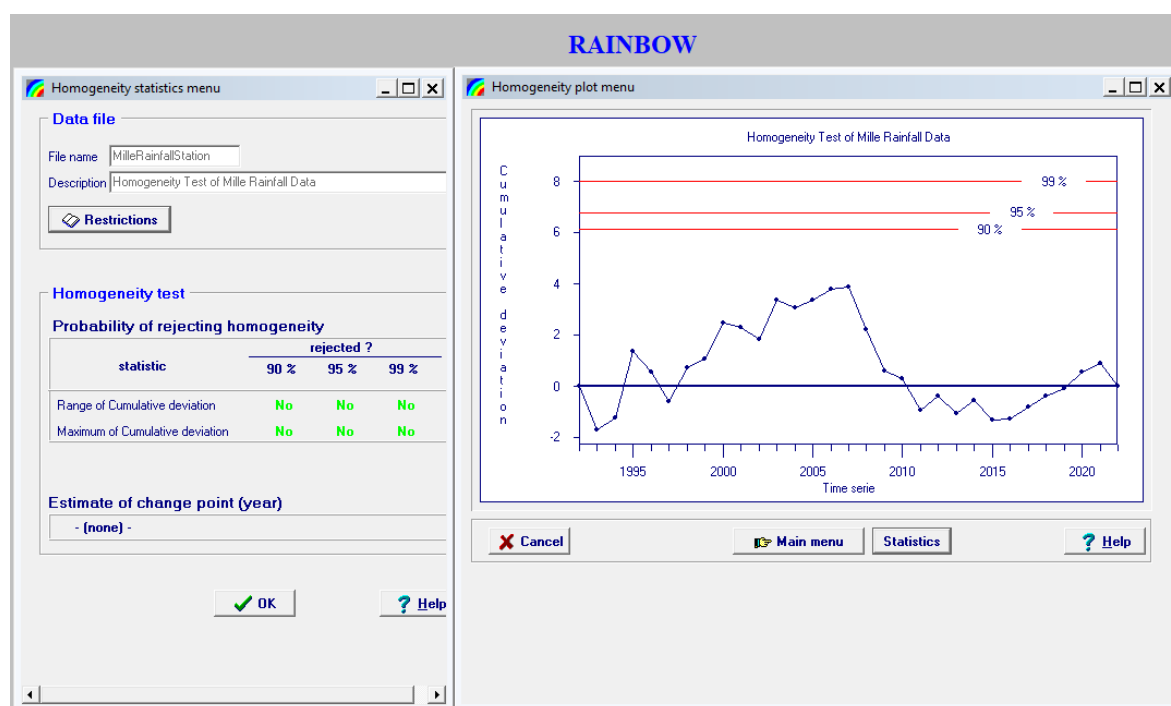


Figure 12. Homogeneity test of Mille rainfall station using Rainbow software.

3.3.3. Consistency of rainfall data

The consistency of rainfall data was checked by using the double mass curve analysis through plotting the graph of cumulative rainfall collected against the cumulative average collected at the selected station in the same period. The annual mean flow of the certain stations that are used for the model calibration and validation can be cross-checked with the reference station by using double mass curve analysis consistency. The double mass curve analysis equation as follows:

$$P_{cx} = P_x * \frac{M_c}{M} \dots\dots\dots (7)$$

Where, P_{cx} is the corrected precipitation/rainfall, P_x is the original recorded precipitation/rainfall data, M_c is the corrected slope of double mass curve, and M is the original slope of double mass curve.

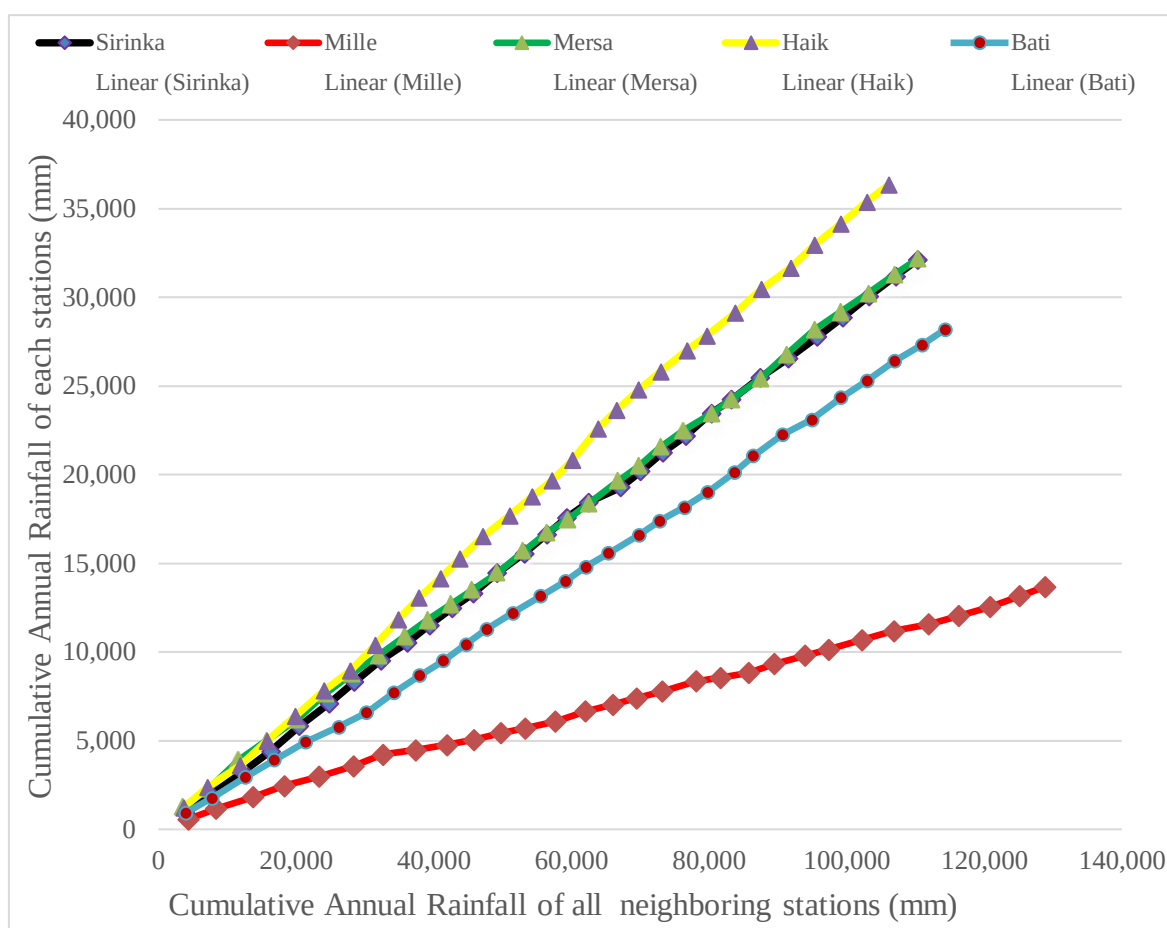


Figure 13. Double Mass Curve Analysis of selected rainfall data.

3.3.4. Outliers test

Outliers are data points that depart significantly from the trend of the remaining data (ERA, 2013). The retention or deletion of these outliers can significantly affect the magnitude of statistical parameters computed from the data, especially for small samples. Procedures for treating outliers require judgment involving both mathematical and hydrologic considerations. In this study, the American Water Resource Association Method was applied for outlier testing (Mirzaei *et al.*, 2014).

The following frequency equation can be used to detect the outliers from the gathered and filled data using the regression:

$$Y_H = Y_{mean} + K_n * S_y \dots \dots \dots (8)$$

$$Y_L = Y_{mean} - K_n * S_y \dots \dots \dots (9)$$

Where; Y_H is the higher outlier threshold in log unit and Y_L is the log of low outlier limit, K_n is the critical deviate taken from Table for sample n . S_y is the standard deviation of the logs of the sample flows, and Y_{mean} is the mean of the log of the sample flows.

3.4. Determination of Areal Rainfall

Areal Rainfall is the average rainfall over the watershed and is restricted to long-term averages values. It is expressed as a mean depth over the watershed area (Wilson, 1983). There are three major methods for determining the areal rainfall over the watershed. These are Arithmetic mean, Thiessen polygon and Isohyetal method (Wilson, 1983). For this study area, the Thiessen polygon method was used to compute areal rainfall of the study area. This technique assumes the rainfall is the same at any point over the watershed of the same area of the Thiessen polygon region. Mathematically, it is given as equation 10 below;

$$P_{av} = \sum_{i=1}^{n-1} \frac{A_i * P_i}{A_T} \dots\dots\dots (10)$$

Where, P_i is the observed rainfall at the centroid of the i^{th} polygon, A_T is total area of watershed, P_{av} is average rainfall and A_i is the area defined by the intersection of the Thiessen polygon and the basin boundary.

Table 7. Thiessen Gage weights for mille sub-basin.

No.	Station Name	Area Coverage (km ²)	Weights	Percentage (%)
1	Bati	1,279.833	0.282	28.168
2	Haik	1,253.328	0.276	27.584
3	Mersa	1,272.289	0.280	28.002
4	Mille	693.628	0.153	15.266
5	Sirinka	44.520	0.010	0.980

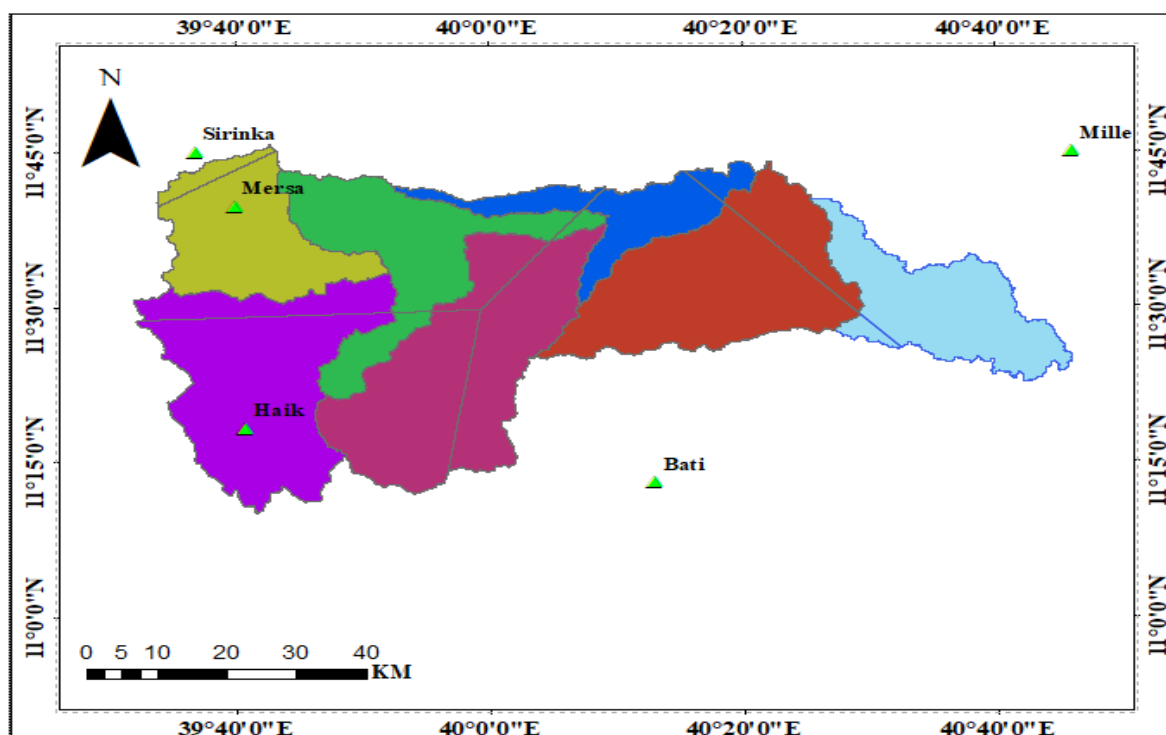


Figure 14. Thiessen polygon developed for Mille sub-basin.

Table 8. The estimated % weight factors for sub-basin and the meteorological stations.

No	Sub-basin	Sub-basin Area (km ²)	Station	Polygon Area (km ²)	Weights
1	W190	317.462	Bati	195.988	0.6173
			Mersa	84.567	0.2664
			Mille	36.907	0.1163
2	W220	948.446	Bati	390.909	0.4122
			Haik	452.668	0.4772
			Mersa	104.869	0.1106
3	W230	579.728	Bati	17.368	0.0300
			Haik	103.352	0.1783
			Mersa	459.008	0.7917
4	W270	502.923	Mersa	458.403	0.9115
			Sirinka	44.52	0.0885
5	W280	862.750	Haik	697.308	0.8082
			Mersa	165.442	0.1918
6	W290	502.657	Bati	22.771	0.0453
			Mille	479.886	0.9547
7	W300	829.632	Bati	652.797	0.7869
			Mille	176.835	0.2131

3.5. Estimating CN Values for Each Sub-basin

To convert the precipitation data to the runoff data, the curve number method was used. The curve number map was prepared by integrating the maps of vegetation, hydrologic soil groups and land use land cover map in ArcGIS software. The objective is to use soil and land use land cover data to create a curve number grid by using the HEC-GeoHMS model software. The land use land cover data of the basin, along with the soil information obtained was used while producing the polygon runoff curve number for the entire sub-basin (Abebe, 2020). After that the curve number values can be summarized to a single mean value for each sub-basin using the spatial analysis tools in ArcGIS software.

Table 9. The estimated CN for each sub-basin of the Mille River watershed.

No.	Name of Sub-watershed	Perimeter (km)	Area (km ²)	Basin Slope (%)	CN	Ia (mm)
1	W190	244.32	317.46	5.35	92.16	4.32
2	W220	242.94	948.45	7.55	90.22	5.51
3	W230	271.68	579.73	6.23	90.76	5.17
4	W270	164.34	502.92	2.42	86.35	8.03
5	W280	233.04	862.75	2.70	84.57	9.27
6	W290	223.26	502.66	2.64	91.25	4.87
7	W300	236.34	829.63	9.26	87.41	7.32

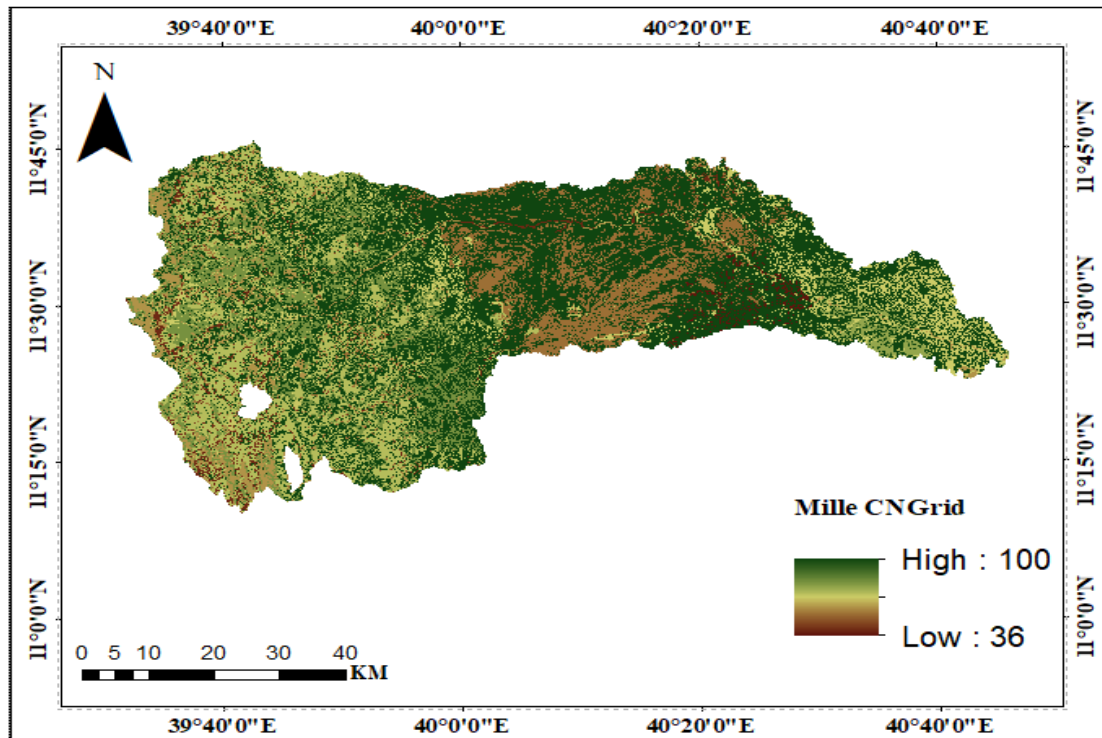


Figure 15. Curve Number Grid Map of Mille River watershed.

3.6. Estimating the Impervious Area

The impervious surface is the percentage of land that is covered with impervious materials and any material covering the ground that prevents the infiltration of water in to the soil and the ground moisture cannot escape in to the atmosphere can be grouped as the impervious surface which results in increased surface flow. Impervious surface area for the catchment was defined by using the ArcGIS with the help of the Land use land cover map. The impervious surface have great impact on the watershed water quality and sediment yield, since the increase in the impervious surface results in the lowering of the ground water which leads water shortage. The impervious surface increase the runoff which in turn leads to the increase in flooding events and the rise in acquisition of sediment which imposes sever risks to the personal property and human life in the community living in the area.

The HEC-HMS model needs the percentage of impervious area for each sub-basin. Considering artificial surfaces area for each sub-basin of the Mille River watershed, percentage of the impervious area for each sub-basin has been estimated with the values ranging from 0 to 3% for each sub-basin. The HEC-HMS model needs the percentage of impervious area for each sub basin. Considering artificial surfaces area for each sub-basin of the Mille river watershed, percentage of the impervious area for each sub basin has been estimated with the values ranging from 0 to 3% for each sub-basin.

Table 10. Impervious percentages of different land use (Guthrie, 2001).

No.	Land Use Land Cover Type	Imperviousness Percentage (%)
1	Forest	1
2	Woodland	1
3	Shrub/Bush	3
4	Cropland/Agriculture	3
5	Grassland	3
6	Barrenland	3
7	Water Body	0
8	Settlements	8

The percentages of impervious surfaces of each Mille River catchment sub-basin are calculated by multiplying the values of the Table 10 for each land use land cover type and the percentage of area of each land use land cover of the sub-basin and adding the calculated results for the sub-basin. The percentages of impervious of each sub-basin are shown in the Table 11.

Table 11. The Percent of impervious and C factor of different LULC for sub-basins.

Sub-basin	Land Use Land Cover	Sub-basin Area (km ²)	LULC Area (km ²)	% of Impervious	Ratio	Average % Impervious
W190	Forest	317.4615	8.0550	1	0.025	2.76
	Woodland		29.4534	1	0.093	
	Shrub/Bush		119.5452	3	0.377	
	Cropland		2.4894	3	0.008	
	Grassland		85.8042	3	0.270	
	Barrenland		72.1143	3	0.227	
W220	Forest	948.4461	15.5934	1	0.016	2.54
	Woodland		203.6457	1	0.215	
	Shrub/Bush		155.6640	3	0.164	
	Cropland		306.2556	3	0.323	
	Grassland		127.3680	3	0.134	
	Barrenland		139.4136	3	0.147	
	Settlements		0.5058	8	0.001	
W230	Forest	579.7287	16.9911	1	0.029	2.48
	Woodland		132.3117	1	0.228	
	Shrub/Bush		87.2577	3	0.151	
	Cropland		191.8629	3	0.331	
	Grassland		81.9306	3	0.141	
	Barrenland		69.3738	3	0.120	
	Settlements		0.0009	8	0.000002	
W270	Forest	502.9236	70.7166	1	0.141	2.60
	Woodland		48.0123	1	0.095	
	Shrub/Bush		41.9922	3	0.083	
	Cropland		217.9863	3	0.433	
	Grassland		71.8983	3	0.143	
	Barrenland		45.2637	3	0.090	
	Settlement		7.0542	8	0.014	

W280	Forest		136.9746	1	0.159	2.32
	Woodland		116.8776	1	0.135	
	Shrub/Bush		52.5582	3	0.061	
	Cropland	862.7499	394.3764	3	0.457	
	Grassland		48.1113	3	0.056	
	Barrenland		68.3847	3	0.079	
	Water Body		38.6982	0	0.045	
	Settlement		6.7689	8	0.008	
W290	Forest		10.1277	1	0.020	2.91
	Woodland		13.9077	1	0.028	
	Shrub/Bush		157.9203	3	0.314	
	Cropland	502.6572	4.1976	3	0.008	
	Grassland		111.2850	3	0.221	
	Barrenland		204.8733	3	0.408	
	Settlement		0.3456	8	0.001	
W300	Forest		15.8958	1	0.019	2.81
	Woodland		63.7074	1	0.077	
	Shrub/Bush	829.6317	243.2538	3	0.293	
	Cropland		4.1229	3	0.005	
	Grassland		189.6435	3	0.229	
	Barrenland		313.0083	3	0.377	

3.7. Materials/Software

The models and software's were used for the study area are listed below:-

- ArcGIS software for visualizing, analyzing, compiling, and manipulating spatial information which was used as an input data for the HEC-GeoHMS.
- Arc Hydro and the HEC-GeoHMS for facilitating hydrologic modeling process and for preparing input data for the HEC-HMS model.
- HEC-HMS model for rainfall-runoff and sediment yield simulation.
- RAINBOW software for rainfall homogeneity test.
- XLSTAT for filling missing data.
- Mendeley Dektop software were used for citation.
- MS-Excel and MS-word for data preparation.

3.8. HEC-GeoHMS Model

HEC-GeoHMS has been developed by Hydrologic Engineering Center (HEC), California, USA, as geospatial hydrology toolkit for engineers and hydrologists with limited GIS software experience. It uses ArcGIS and the Spatial Analyst extension to visualize spatial information, document watershed characteristics, perform spatial analysis, and delineate sub- basins, streams and develop a number of hydrologic modelling inputs for the HEC-HMS (Husen, 2020).

Additionally, HEC-GeoHMS creates the background map files, basin model files, meteorological model files, and a grid cell parameter which is exported into HEC-HMS model (Guduru *et al.*, 2023). In this study, it is intended to derive parameters such as Curve Number (CN), initial abstraction (Ia), basin lag time, time of concentration, sub-basin slope and sub-basin area determination.

3.8.1. The terrain processing Using Arc Hydro and HEC-GeoHMS

The terrain pre-processing is the process of using the Digital Elevation Model (DEM) to define the study area watersheds (www.hec.usace.army.mil). In this study, Arc Hydro is an Arc-GIS compatible set of tools that was used to process a Digital Elevation Model (DEM) to identify watersheds, sub-watersheds, stream networks, and other features of watersheds that together characterize a basin's drainage behavior.

The main steps undertaken by terrain pre-processing are; the Digital Elevation Model (DEM) reconditioning, fill sinks, flow direction, flow accumulation, stream definition, stream segmentation, catchment grid delineation, catchment polygon processing, drainage line processing, drainage point processing, longest flow path for the catchment and slope determination.

3.8.2. Basin Model development Using HEC-GeoHMS

The HEC-GeoHMS tool is designed to have the output files from the Arc Hydro terrain preprocessing tools as inputs. The point of the extensive data preprocessing using Arc Hydro was to create input files for the HEC-GeoHMS tools. The HEC-GeoHMS used to create automatically sub-basins, longest paths and basin centroids. Additionally, the parameters such as length, average curve number and slope are assigned to the flow lines and the basins.

In general, HEC-GeoHMS uses spatial analyst tools to convert geographic information into parameters for each of the basins and flow lines. HEC-GeoHMS was also used to select HMS model, processing methods for calculating loss, transformation, base flow and channel route. By integrating ArcGIS tool, Digital Elevation Model (DEM), land use and land cover (LULC), soil type and the HEC-GeoHMS curve number was generated which is a parameter for determination of loss in Soil Conservation Service (SCS) method.

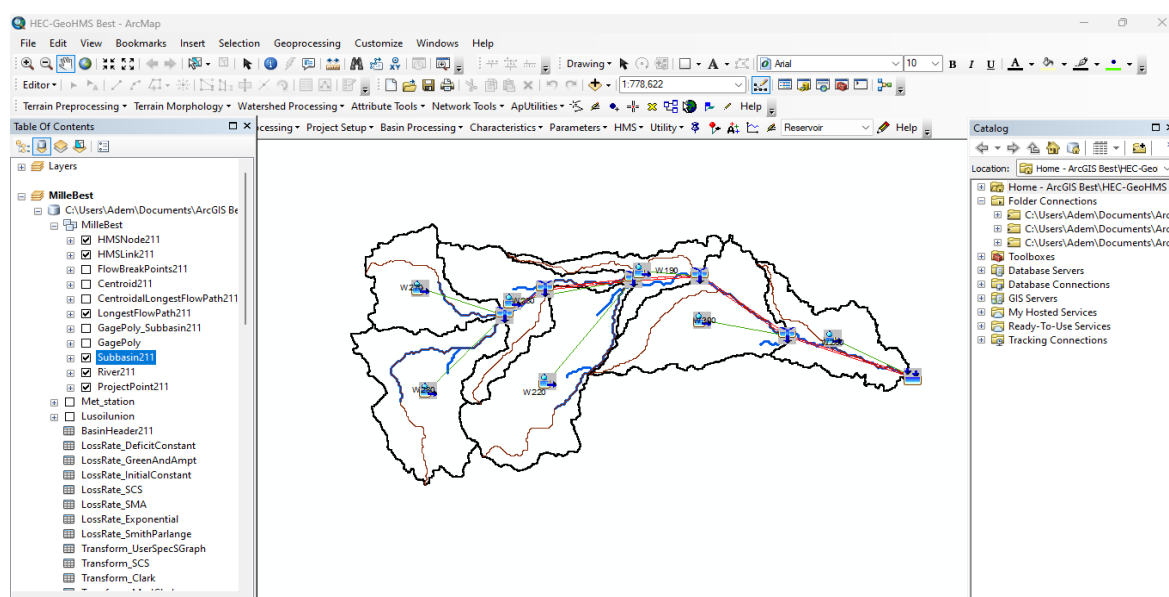


Figure 16. The final HEC-GeoHMS processed map ready for HEC-HMS model.

3.9. HEC-HMS Model

The HEC-HMS model is very popular and widely applied in several hydrological studies due to its ability to simulate short and long events runoff ease to operate (Guduru *et al.*, 2023). The HEC-HMS is a conceptual model that does not allow for the observation of the simulation process. It displays the resultant output from the supplied input (Yilma & Kebede, 2023). The surface runoff calculations is performed using soil moisture accounting (SMA) method which requires different parameters for implementation. The sub-basin element conceptually represents infiltration, surface runoff, and subsurface processes interacting together. Therefore, the HEC-HMS model is designed to simulate the rainfall-runoff processes of watershed systems.

3.9.1. HEC-HMS model setup

The first phase of hydrological modeling is HEC-HMS model set-up. HEC-HMS model setup has four main model components such as basin model, metrological model, control specification and input data (time series data). The Basin Model stores data regarding the characteristics and connectivity of the six objects (sub-basin, reach, junction, source, sink, and reservoir) in a graphic that can include any combination of these items (Belay *et al.*, 2022). The meteorological component is the first computational element by means of which precipitation input is spatially and temporally distributed over the river basin. Control specifications are one of the main components of a project, and principally used to control simulation runs and what time interval is used in the simulation.

The data input to the HEC-HMS model is possible through two ways. The first and simplest method is manual data input. Here the time series data is copied from Excel or any compatible format and pasted in the HEC-HMS model time series table for any time series data. The second and relatively complex is accompanied by saving the data in HEC-DSS and retrieving from it during analysis. For this study, from the above two method the manual data input method was used. Finally, the input data component stores parameters and boundary conditions for the basin and meteorological models within assigned gages and control specifications.

3.9.2. Basin model

The user can either develop the basin model in the HEC-HMS model itself or else by feeding the DEM into the HEC-GeoHMS, which is an extension tool of ArcGIS software. Basin model is the most important input to run the model and simulate rainfall-runoff over entire watershed (Majidi and Shahedi, 2012).

In the study, the basin model was developed using the HEC-GeoHMS 10.4 tool in the form of a background map file with all its hydrologic elements then imported into the HEC-HMS model. The hydrologic elements include seven sub-basins, five junctions, five reaches, one outlet and drainage networks.

3.9.2.1. Loss model

The runoff volume is often calculated by subtracting the volume of precipitation from the volume of water that is intercepted, penetrated, stored, evaporated, or transpired in the HEC-HMS loss models (Tassew *et al.*, 2019). There are eight methods for estimating losses in the HEC-HMS model: initial and constant, deficit and constant, Green and Ampt, exponential, SCS curve number, soil moisture accounting, Gridded SCS curve number and gridded soil moisture accounting. In this study, the soil moisture accounting (SMA) method was selected to estimate direct runoff from a specific or design rainfall. The SCS method is a simple, empirically supported method for estimating direct runoff amounts from storm rainfall events. It relies on the curve number, a function of soil type and land use, and is commonly used in various environments.

The surface runoff occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. The Soil Conservation Service (SCS) curve number equation is as follows (SCS, 1972):

$$Q_{surf} = \frac{(P - I_a)^2}{(P - I_a + S)} \dots\dots\dots (11)$$

Where, Q_{surf} is the accumulated runoff or rainfall excess (mm), P is the rainfall depth for the day (mm), I_a is the initial abstraction which includes surface storage, interception and infiltration prior to runoff (mm), and S = maximum potential retention (mm).

The initial abstraction (I_a) is a highly variable parameter that is normally correlated with soil and cover parameters and can be calculated using the equation:

$$I_a = 0.2 * S \dots\dots\dots (12)$$

The potential maximum retention (S) varies spatially due to changes in soil water content. The retention parameter is defined as:

$$S = \frac{25400}{CN} - 254 \dots\dots\dots (13)$$

Where, CN is the curve number for the day which is a function of land use land cover, soil type, hydrologic soil group, and antecedent moisture condition (AMC) is a key factor of the SCS-CN method, the constant 25.4 in equation used to convert the gives S in to mm.

The watershed Curve Number (CN) is affected by soil types, land use and land cover (LULC), topography and antecedent moisture condition (AMC). The CN values range from approximately 35 for permeable soils with high infiltration rates to 99 for water bodies (Arekhi, 2012). For watershed with different soil types, the weighted CN is necessary and computed by equation 8.

$$CN_w = \sum_{i=1}^n \frac{A_i * CN_i}{A_T} \dots\dots\dots (14)$$

Where, A_i is area of sub-basin, A_T is total area of watershed, CN_w is weighted curve number over sub-basin. The model calculates the peak runoff rate with a modified rational method as follows:

$$Q_{peak} = \frac{\alpha k * Q_{surf} * Area}{3.6 * t_{conc}} \dots\dots\dots (15)$$

Where, Q_{peak} is the peak runoff rate (m^3/s), αk is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm), $Area$ is the sub-basin area (km^2), t_{conc} is the time of concentration for the sub-basin (hr) and 3.6 is a unit conversion factor.

The soil moisture accounting (SMA) method simulates the movement and storage of water through the soil profile as well as multiple groundwater layers (Guide and Manual, 2008). Using the soil moisture accounting method allows for continuous simulation when combined with a canopy method that was extract water from the soil in response to potential evapotranspiration computed in the meteorological model. When both a canopy and surface method was used in combination with the soil moisture accounting loss method, the system can be conceptualized (Guide and Manual, 2008) as shown in the Appendix C figure 1.

3.9.2.2. Base flow model

The subsurface model is represented by a base flow model, which interacts with the infiltration and surface runoff processes. For this study, from the various base flow method in the HEC-HMS model, the recession method was selected.

3.9.2.3. Transform model

The models transform the excess precipitation into a direct runoff (Guduru *et al.*, 2023). The HEC-HMS model allows direct runoff modelling with eight different methods: SCS unit hydrograph, Clark unit hydrograph, Snyder unit hydrograph, user-specified s-graph, user-specified unit hydrograph, the ModClark quasi distributed linear transform, kinematic wave, and 2D diffusion wave. It is a parametric model that is based on the average Unit Hydrograph (UH) derived from runoff and rainfall data of several small agricultural watersheds in the United States (Tassew *et al.*, 2019). The SCS proposed the Unit Hydrograph (UH) model, and it is included in the HEC-HMS program. The lag time (T_{lag}) is the only input for this method. The Soil Conservation Service (SCS) provided an equation for estimating the watershed lag, which was defined as the time in hours from the center of mass of the excess rainfall to the peak discharge (Richard H. McCuen, 1998). According to Singh (2003), the SCS unit hydrograph method was used to compute lag time for each basin. It can be stated as follows:

$$T_{lag} = \frac{L^{0.8} * (S+1)^{0.7}}{1900y^{0.5}} \dots\dots\dots (16)$$

Where, T_{lag} is basin lag time (hr), L = length from sub-basin outlet to divide along longest drainage path (ft), y is the mean slope of the basin (%), S is potential maximum retention (in) after runoff begins. This S can be expressed in terms of average curve number as:

$$S = \frac{1000}{CN} - 10 \dots\dots\dots (17)$$

Where: CN is the average curve number for each sub-basin. By substituting the above equation, it becomes;

$$T_{lag} = \frac{L^{0.8} * (\frac{1000}{CN} - 9)^{0.7}}{1900y^{0.5}} \dots\dots\dots (18)$$

Therefore, by using the above (equation 18), in the HEC-GeoHMS the hydrologic parameter menu has assigned lag time for each sub-basin. In the attribute table menu bar, the calculated lag time was populated.

USACE (2000b) provides general recommendations for choosing a direct runoff method. These includes the availability of information for calibration and parameter estimation, appropriateness of the model assumptions, and user preference and experience. The kinematic wave method is a data intensive conceptual direct runoff model based on a finite difference approximation of the shallow water equations.

The ModClark method can only be used in a spatially distributed the HMS model. In this study, among the remaining four unit hydrograph-based direct runoff methods available in the HEC-HMS, the Clark unit hydrograph (Clark, 1945) method was used for transform modeling direct runoff and sediment yield resulting from individual storm events (Straub *et al.*, 2000; Sabol, 1988; Nelson *et al.*, 1999; Fleming and Neary, 2004). The technique is particularly valuable for unusually shaped watersheds, and for application to watersheds containing several different physiographic areas (Sabol, 1988).

The Clark unit hydrograph method represents two key processes in the transformation of excess rainfall to runoff: translation and attenuation. Translation is based on a synthetic time–area histogram and the time of concentration, T_c . The time-area histogram specifies the basin area contributing to flow at the outlet as a function of time. Attenuation is modeled with a linear reservoir (USACE, 2001). The reservoir represents the aggregated impacts of all basin storage, S_t . The average outflow from the reservoir during a period t is (USACE, 2000):

$$O_t = C_A * I_t + C_B * O_{t-1} \dots\dots\dots (19)$$

Where, it is the average inflow to storage at time t , and C_A and C_B are routing coefficients given by:

$$C_A = \frac{\Delta t}{S_t + 0.5\Delta t}, \text{ and } C_B = 1 - C_A \dots\dots\dots (20)$$

Where, Δt is the computational time step.

The time of concentration is computed by the following equation.

$$T_c = 2.2 * \left(\frac{L * L_c}{\sqrt{\text{slope}}^{10-85}} \right)^{0.3} \dots\dots\dots (21)$$

Where, T_c is the time of concentration (hrs), L is the longest flow path (mi), L_c is the centroidal flow path (mi), Slope₁₀₋₈₅ is the average slope of the flow path represented by 10 to 85 percent of the longest flow path (mi).

According to the HEC-HMS model 4.3 manual, the ratio of storage coefficient, R and time of concentration, T_c ($R/(R+T_c)$) tends to be fairly constant for the watershed. For this study area assuming the constant to be 0.65, then the storage coefficient R is;

$$\frac{R}{T_c + R} = 0.65 \text{ or } R = \frac{13}{7} * T_c \dots \dots \dots (22)$$

3.9.2.4. Routing model

Runoff routing is a procedure to envisage the alterations in characteristics of flood wave as a temporal function at one or more points along a channel (Tewolde and Smithers, 2006). Runoff routing and hydrograph generation are the key elements of a hydrological model (Yousuf *et al.*, 2022). The Muskingum method, which was developed by (McCarthy, 1939) is a popular lumped flow routing technique. Muskingum model is very easy and popular to use, but the parameters include in this model are not physically based and thus are difficult to estimate. Further, the model is based upon assumptions that often are violated in natural channels. An extension, the Muskingum-Cunge model, overcomes these limitations. For capturing the sediment load in a reach, it is very necessary to represent the river network like natural channels. In this regard, Muskingum-Cunge can surely give a better calibration of sediment load.

The model is based upon solution of the following form of the continuity Equation 23, (with lateral inflow, q_L , included):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_L \dots \dots \dots (23)$$

And the diffusion form of the momentum Equation 24:

$$S_f = S_o - \frac{\partial y}{\partial x} \dots \dots \dots (24)$$

Combining these and using a linear approximation yields the convective diffusion Equation 30 (Miller *et al.*, 2010).

$$\frac{\partial Q}{\partial t} + c \frac{\partial Q}{\partial x} = \mu \frac{\partial^2 Q}{\partial x^2} + c q_L \dots \dots \dots (25)$$

Where c = wave celerity and μ = hydraulic diffusivity. The wave celerity and the hydraulic diffusivity are expressed as Equation 26 and Equation 27:

$$c = \frac{dQ}{dA} \dots \dots \dots (26)$$

and,

$$\mu = \frac{Q}{2BS_o} \dots \dots \dots (27)$$

Where B = top width of the surface. A finite difference approximation of the partial derivatives yields Equation 28:

$$O_t = C_1 I_{t-1} + C_2 I_t + C_3 O_{t-1} + C_4 (q_L \Delta x) \dots\dots\dots (28)$$

The coefficients are in Equation 29 to 32,

$$C_1 = \frac{\frac{\Delta t}{K} + 2X}{\frac{\Delta t}{K} + 2(1-X)} \dots\dots\dots (29)$$

$$C_2 = \frac{\left(\frac{\Delta t}{K}\right) - 2X}{\frac{\Delta t}{K} + 2(1-X)} \dots\dots\dots (30)$$

$$C_3 = \frac{2(1-X) - \frac{\Delta t}{K}}{\frac{\Delta t}{K} + 2(1-X)} \dots\dots\dots (31)$$

$$C_4 = \frac{2\left(\frac{\Delta t}{K}\right)}{\frac{\Delta t}{K} + 2(1-X)} \dots\dots\dots (32)$$

The parameters K and X are (Cunge, 1969; Ponce and Yevjevich, 1978):

$$K = \frac{\Delta x}{c} \dots\dots\dots (33)$$

$$X = \frac{1}{1} \left(1 - \frac{Q}{BS_o c \Delta x} \right) \dots\dots\dots (34)$$

But c , Q and B change over time, so the coefficients C_1 , C_2 , C_3 and C_4 must also change. The program re-computes C_1 , C_2 , C_3 and C_4 at each time step, Δt and Δx using the algorithm proposed by (Ponce, 1986).

$$\Delta X = c \Delta t \dots\dots\dots (35)$$

$$\Delta X < \frac{1}{2} \left(c \Delta t + \frac{Q_o}{BS_o c} \right) \dots\dots\dots (36)$$

Here, Q_o = reference flow, computed from the inflow hydrograph as Equation 37.

$$Q_o = Q_B + \frac{1}{2} (Q_{peak} - Q_B) \dots\dots\dots (37)$$

Where, Q_B = base flow and Q_{peak} = inflow peak

3.9.3. Meteorological model

Precipitation for runoff modeling is the meteorological model which would be used in this study in the HEC-HMS (USACE, 2009). The sub-basin meteorological model can be matched with the sub-basin in the basin model by using the name of the sub-basin. Precipitation is the most important component in a meteorological model which is the driving factor for watershed responses; as a result, a substantial effort is expended to compute the meteorological model to obtain spatially and temporally distributed precipitation input data. There are ten methods used for meteorological model those are available in the HEC-HMS model.

For this study, from the various method in the HEC-HMS model, the gage weights method was selected for modeling rainfall data. The gage weight of the sub-basin is equal to the area of the sub-basin that passes through the polygon divided by the area of the polygon. The sub-basin precipitation time series data can be obtained by multiplying the gage weight by gage precipitation for each sub-basin.

3.9.4. Time series data entry model

HEC-HMS model requires precipitation gage, evapotranspiration gage, discharge gages and sediment load gage time series data for simulation of runoff and sediment yield respectively. After the rainfall-runoff model was set up, the observed stream flow data and sediment load data was entered into the discharge gage and sediment load gage to be compared to the simulated runoff and sediment data. The daily observed stream flow and sediment load was used model for model calibration and simulation. For the precipitation data, the daily rainfall of each station was entered into the precipitation gage under the time series data model. The depicted weight for each rainfall station in the Mille River watershed was divided by using Thiessen's Polygon method. The average rainfall for each sub-basin was calculated using Thiessen's Polygon Method and entered it into the precipitation data.

3.9.5. Control specification model

Control specification is used to control when the simulation starts and stops, as well as what time interval is used in the simulation, even though it does not contain much parameter data.

3.9.6. Paired Data

Hydrologic models often require the use of paired data to describe inputs that are functional in form (US Army Corps of Engineers, 2024). Functional data defines a dependent variable in terms of an independent variable. For most cases, the function must be monotonically increasing which means it only increases and never decreases. The paired data examples like diameter-percentage functions, river cross sections, gradation curve, unit hydrographs and stage-discharge curves and etc. The program separates different types of paired data with different data types. Paired data only has to be entered one time. The data are part of the project and can be shared by multiple sub-basin or meteorological models.

3.10. Soil Erosion and Sediment Yield Model

3.10.1. Surface Erosion Method

The HEC-HMS model can estimate sediment loads due to stream flow and soil erosion, affecting stream dynamics and reservoirs.

However, it requires calibrated and validated precipitation-stream flow model, soil data, land use data, and sediment grain sizes for the modified universal soil loss equation (MUSLE) equation estimation. The MUSLE (Williams, 1975), is a mathematical model used in soil science and hydrology to estimate soil erosion. It was developed as an extension and modification of the original Universal Soil Loss Equation (USLE).

The MUSLE takes into account factors such as land use, topography, soil erodibility, and climate conditions to predict the potential erosion rate in a particular area. The modifications to the original USLE equation changed the formulation to calculate erosion from surface runoff instead of precipitation. In the HEC-HMS model, soil erosion and sediment yield can be computed for each hydrological response units caused by rainfall and runoff with the MUSLE (Modified Universal Soil Loss Equation) (Williams, 1975) using the following equation 38:

$$Sed_i = 11.8(Q_{surf} * q_{peak})^{0.56} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} \dots\dots\dots (38)$$

Where, 11.8 is the unit conversion factor, Sed is the sediment yield (ton/day), Q_{surf} is the surface runoff volume (mm/ha), q_{peak} is peak runoff rate (m^3/s), A_{hru} is the area of HRU (ha), K_{USLE} is the soil erodibility factor, C_{USLE} is cover and management factor, P_{USLE} is support practice factor, LS is a topographic factor.

There are seven parameters required to input for the erosion and sediment yield model. These parameters were estimated based on terrain, land use, and soil type of the catchment are as follows:

3.10.1.1. Soil erodibility factor (K)

Soil erodibility factor describes the resistance to soil erosion and is depends on soil properties, organic matter content (OM), bulk density, particle size, and shape, (Addis and Klik, 2015; Duiker *et al.*, 2001). The value of K factor ranges from 0 to 1, with 0 indicate the least vulnerable to soil erosion and 1 indicate the high vulnerability to soil erosion (Gwapedza *et al.*, 2018). It is the expression of the intrinsic resistance of soil particles for the removing and transporting power of rainfall.

$$K_{USLE} = f_{csand} * f_{ci-si} * f_{orgc} * f_{hisand} \dots\dots\dots (39)$$

Where, f_{csand} is factor that lowers the K indicator in soil with high coarse-sand content and higher for soils with little sand, f_{ci-si} is gives low soil erodibility factors for soils with high clay-to-silt ratios, f_{orgc} is reduces K values in soils with high organic carbon content, f_{hisand} is lowers K values for soils with extremely high sand content.

3.10.1.2. Topographic factor (LS)

The slope factor is a combination of slope length and slope steepness. The length and steepness of a slope affect the total sediment yield from the area and is accounted by the LS factor in USLE model. In this study, the approach developed by the (Moore and Burch, 1986) is used to compute the LS factor.

$$LS = \left(\frac{\text{Slope length}}{22.13} \right)^{0.6} * \left(\frac{0.01745 * \sin \theta}{0.0896} \right)^{1.4} * 1.4 \dots\dots\dots (40)$$

Where, slope length is flow accumulation*cell size of DEM (30m) resolution and θ is slope.

3.10.1.3. Land and management cover (C)

The cover factor (C) defines the impact of vegetation on soil erosion. A higher value of cover factor indicates the most vulnerable to soil erosion and vice-versa. Generally, the value ranges from 1 to 0.1. The value of cover factor for the bare ground is 1 which is more vulnerable to erosion whereas, C for thick vegetation cover or fully mulched land is 0.1 which is significantly low vulnerable to erosion, the C factor for the forest with the dense tree is 0.0001 (Scharffenberg *et al.*, 2010).

3.10.1.4. The soil practice factor (P)

The soil support practice factor accounts for the managing practices which reduces the wearing away potential of run off by their pressure on drainage patterns, runoff velocity, runoff concentration and hydraulic forces exerted by the runoff on the soil surface. It describes the effect of the specific soil conservation practices, the best management practices, which includes the agricultural practices of terracing, strip cropping, contouring and the urban practices of the silt fence, settling basins and hydro seeding. The values of the soil practice factor decreases by adopting these preservation practices as they diminish the runoff rate and volume of the catchment and support the deposition of sediment on the mount slope surface. For this study area the practice factor of sub-basins were estimated using the contouring and slope relationship given in Table 12 below.

Table 12. The support practice factor is according to the cultivation method and slope (Shammi Haque, 2018).

No	Slope (%)	Contouring	Strip cropping	Terracing
1	0 - 7.0	0.55	0.27	0.10
2	7.0 – 11.30	0.60	0.30	0.12
3	11.30 – 17.60	0.80	0.40	0.16
4	17.60 – 26.80	0.90	0.45	0.18
5	> 26.80	1.00	0.50	0.20

3.10.1.5. Exponent

The exponent in erosion is used to distribute the sediment load into a time series sedigraph. The small value flattens the sedigraph compared to the hydrograph while a large value heightens the sedigraph. The sediment load can be calculated by using a power function (Pak *et al.*, 2015) is shown in equation (41). The value of exponent is generally range from 0.5 to 1 (Pak *et al.*, 2015).

$$C_t = K^i * Q_t^b \dots\dots\dots (41)$$

Where, C_t = sediment concentration at time t , K^i is constant calculated from runoff, Q_t is discharge from the sub-basin. b = exponent entered by a user. Based on previous studies function (Pak *et al.*, 2015), the value of exponent $b = 0.75$ was used for the erosion model.

3.10.1.6. Gradation curve

When using the erosion and sediment transport components in the HEC-HMS model, a gradation curve is a required input for some of the specific methods. For the surface erosion methods, the bulk sediment discharge, which includes all grain sizes, is computed for each sub-basin element. The gradation curve defines the distribution of the total sediment load into grain size classes and sub-classes at each sub-basin outlet. It is defined as a percentage function in the paired data manager.

3.10.2. Sediment transport potential method

The sediment transport capacity of the flow can be derived from the flow parameters and sediment properties. The transport potential functions for calculating the amount of sediments that can be carried by the stream flow. Type is non-cohesive (NC) or cohesive (CO), Method is Excess Shear (ES), Stream Power (SP) or Regression (RE).

Table 13. Methods for reach for transport potential function (Scharffenberg *et al.*, 2006).

Methods	Type	Method	References
Ackers-White	NC	SP	Ackers-White, 1973
Engelund-Hansen	NC	SP	Engelund-Hansen, 1967
Laursen-Copeland	NC	ES	Laursen, 1958; Copeland and Thomas, 1989
Meyer-Peter Muller	NC	ES	Meyer-Peter Muller, 1948
Toffaleti	NC	RE	Toffaleti, 1968
Wilcock	NC	ES	Wilcock and Crowe, 2003
Yang	NC	SP	Yang, 1984
Krone Parthenaides	CO	-	Krone, 1962; Parthenaides, 1962

Then, Engelund Hansen from the above Table 13 would be applicable for all reaches as, in FAP 24, this equation has been found as prediction formulae having a high level of accuracy for Mille River watershed. The generalized form of Engelund Hansen in Equation 42;

$$G = K * \left(\frac{0.05 * W * V_2 * h_{1.5} * S_{1.5}}{(s-1)^2 * D * \sqrt{g}} \right) \dots\dots\dots (42)$$

Where, G is the volumetric sediment transport rate (m³/s), K is the calibration coefficient (=1 for standard equation), W is the width of flow (m), V is the water velocity (m/s), h is the flow depth (m), S is the water surface slope (m/m), s is the specific gravity of sediment (dimensionless), D is the sediment diameter (mm), g is the acceleration due to gravity (m/s²).

3.10.3. Sediment Routing Method

The following methods are available in the HEC-HMS model for sediment method for reach: There are, Fischer's dispersion, linear reservoir, Muskingum, Uniform equilibrium and Volume Ratio. For this study, from the various sediment routing method in the HEC-HMS model, the Volume Ratio method was selected.

Table 14. The estimated values for modeling surface erosion and sediment yield routing.

No.	Parameters	Values
1	Manning's roughness coefficient	0.018 to 0.04
2	Effective river width	4.00 m to 10.00 m
3	Length of the reaches	47,248.087m to 83,765.711m
4	Slope	0.0059 m/m to 0.0178 m/m
5	Surface storage	11.62 mm to 50.80 mm
6	Maximum Infiltration rate	2.48 mm/hr to 6.50 mm/hr
7	Specific gravity (sediment grain)	2.65
8	Clay Density	480.55 kg/m ³
9	Silt Density	1,041.2 kg/m ³
10	Sand and Gravel Density	1,489.7 kg/m ³

3.11. Model Sensitivity Analysis, Calibration and Validation

The main purpose of an interface is to provide connection between the output/input of a calibration program and the model.

3.11.1. Sensitivity analysis

Sensitivity analysis is an investigation of how sensitive the model output is to changes in the parameter values (Wagener *et al.*, 2004). Sensitivity analysis is also a method to determine which parameters of the model have the greatest impact on the model results (Cunderlik and Simonovic, 2004). It ranks model parameters based on their contribution to overall error in model predictions. A local sensitivity analysis was adopted for evaluating the parameters of the continuous model. The final set of the parameters of the calibrated model was considered as a baseline parameter set. It was carried out by selecting one parameter, while keeping all other parameters constant.

The main goal this was to reduce the number of parameters calculated through optimization. The simulation time interval was selected based on the time interval of available data for both model calibration and validation, the bulk of the data was used to calibrate the model. It helps to determine the sensitivity of parameters by comparing the output variance due to input variability. It also facilitates selecting important and influential parameters for a model calibration by indicating the parameters that shows higher sensitivity to the output due to the input variability. The method used to determine the dominant hydrological parameters and to reduce the number of model parameters which was used in calibration. For this reason, sensitivity analysis is a valuable tool for evaluating input parameters in relation to how they affect the model's output. It can be applied to model calibration, validation, and uncertainty reduction (Lenhart *et al.*, 2002).

3.11.2. Model calibration

Model calibration is a process of changing model parameter values until the output of the model satisfactorily corresponds to the observed data (Madsen, 2000). It is also the modification of parameter values and comparison of predicted output of interest to measured data until a defined objective function is achieved. The quantity and quality of the time-series data utilized have a significant impact on the quality of any calibration process (Wagener *et al.*, 2004). The parameters for modification are selected from those identified by sensitivity analysis. The additional parameters other than those identified during sensitivity analysis are used primarily for calibration due to the hydrological processes naturally occurring in the watershed.

Sometimes, it is necessary to change parameters in the calibration process other than those identified during sensitivity analysis because of the type of miss match of the observed variables and predicted variables. For this study, the HEC-HMS model was calibrated with both manually and auto-calibration with the optimization trials available in the HEC-HMS model for optimizing the initial estimates of the model parameters.

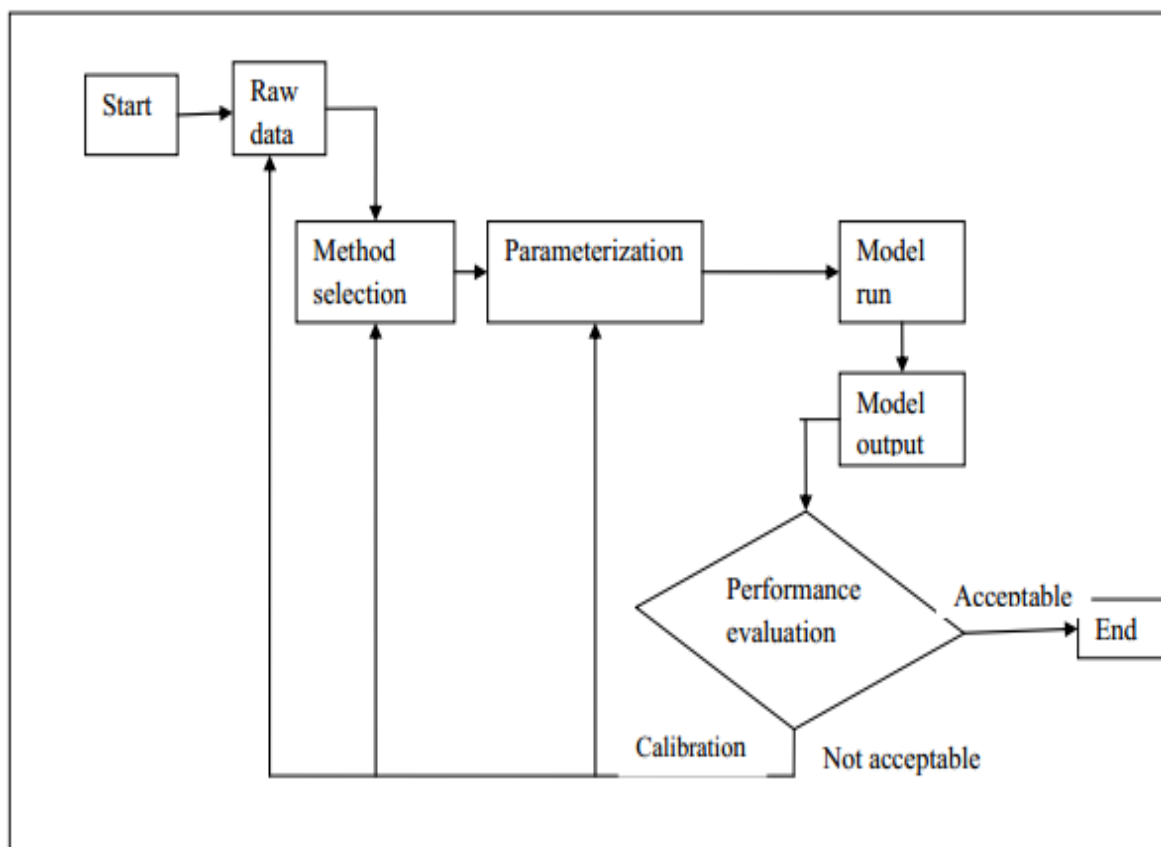


Figure 17. The calibration processes in the HEC-HMS model.

3.11.3. Model validation

Validation is the comparison of the model outputs with an independent data set without making any adjustments. The purpose of model validation is to check whether the model can predict flow for another period range. To utilize the calibrated model for estimating the effectiveness of future potential management practices, the model is tested against an independent set of measured data. As the model's predictive capability is demonstrated as being reasonable in both the calibration and validation phases, the model is used for future predictions under different land use scenarios. The statistical model performance measure will be used in calibration as the percent difference between simulated and observed data (Abbaspour, 2013).

3.12. Model Performance Evaluation

During the calibration and validation phases, methods for goodness-of-fit assessments of model predictions were employed in order to assess the model's performance, including its quality and reliability of prediction in comparison to the observed values. These numerical model performance efficiency are coefficient of determination (R^2), root mean squared error (RMSE), Nash-Sutcliffe efficiency (NSE) and Percent bias (PBIAS) (Moriassi et al., 2007).

3.12.1. Nash-Sutcliffe coefficient (NSE)

The Nash-Sutcliffe coefficient (NSE) measures the efficiency of the model by relating the goodness of-fit of the model to the variance of the measured data (Nash and Sutcliffe, 1970). Its efficiencies can range from $-\infty$ to 1. When the observed mean is a better predictor than the model, the efficiency is less than zero ($-\infty < \text{NSE} < 0$). An efficiency of 1 indicates that the modeled discharge and the observed data match perfectly, while an efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data (Gautam *et al.*, 2019). The evaluation of hydrologic model behavior and performance is commonly made and reported through comparisons of simulated and observed variables. NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. The formula for Nash-Sutcliffe (NSE) is as follows (Nash and Sutcliffe, 1970).

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^n (Q_{obs} - Q_{sim})^2}{\sum_{i=1}^n (Q_{obs} - \bar{Q}_{sim})^2} \right] \dots\dots\dots (43)$$

Where, Q_{obs} is the observed values (m^3/s), Q_{sim} is the simulated values (m^3/s), $\bar{Q}_{obs}$ is mean of the observed values, $\bar{Q}_{sim}$ is the mean of simulated values and n is the number of observations.

3.12.2. Coefficient of determination (R^2)

The coefficient of determination (R^2), provides a measure of how well observed outcomes were replicated by the model. It ranges between 0 and 1 which described how much of the observed desperation is explained by the prediction. A value of zero (0) means no correlation at all; whereas one means that the desperation of the prediction is equal to that of the observation (Nash and Sutcliffe, 1970).

$$R^2 = \left[\frac{\sum_{i=1}^n (Q_{obs} - \bar{Q}_{obs})(Q_{obs} - \bar{Q}_{sim})}{\sqrt{\sum_{i=1}^n (Q_{obs} - \bar{Q}_{obs})^2} \sqrt{\sum_{i=1}^n (Q_{sim} - \bar{Q}_{sim})^2}} \right]^2 \dots\dots\dots (44)$$

Where, $\bar{Q}_{sim}$ is the mean of simulated values, ($\bar{Q}_{obs}$ is the mean of observed values, Q_{sim} is the simulated values (m^3/s), Q_{obs} is the observed values (m^3/s), and n is the number of observations.

3.12.3. Root Mean Squared Error (RSR)

It standardizes the root mean square error (RMSE) using the observation of standard deviation. The optimal value of RSR is 0.0, which presents zero RMSE for perfect model simulation. The lower RSR values present better model performances.

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^n (Q_{i_{obs}} - Q_{i_{sim}})^2}}{\sqrt{\sum_{i=1}^n (Q_{i_{obs}} - \bar{Q}_{i_{sim}})^2}} \dots\dots\dots (45)$$

Where, $Q_{i_{obs}}$ is the observed stream flow data, $Q_{i_{sim}}$ is the simulated stream flow data, and $\bar{Q}_{i_{sim}}$ is the mean simulated stream flow data.

3.12.4. Percent BIAS (PBIAS)

It evaluates the average tendency of the simulated values to be larger or smaller than observed values, as described by (Moriassi *et al.*, 2007). The PBIAS is expressed in percentage; the lower the absolute value of the PBIAS is the better will be the model performance as follows (Gupta *et al.*, 1999). The optimal value of PBIAS is 0.0. The positive values present model underestimation bias, whereas the negative values present model overestimation bias.

$$PBIAS = \frac{\sum_{i=1}^n (Q_{i_{obs}} - Q_{i_{sim}}) * 100}{\sum_{i=1}^n (Q_{i_{obs}})} \dots\dots\dots (46)$$

Where, $Q_{i_{obs}}$ is the mean of observed values (m^3/s), $Q_{i_{sim}}$ is the simulated stream flow (m^3/s), and n is the number of observations.

Table 15. Performance rating for evaluation metrics for a daily time step (Moriassi *et al.*, 2007);

Performance Rating	R^2	NSE	RMSE	PBIAS
Very Good	$0.65 < R^2 \leq 1.00$	$0.65 < NSE \leq 1.00$	$0.0 < RMSE \leq 0.6$	$PBIAS < \pm 15\%$
Good	$0.55 < R^2 \leq 0.65$	$0.55 < NSE \leq 0.65$	$0.6 < RMSE \leq 0.7$	$\pm 15 \leq PBIAS < \pm 20$
Satisfactory	$0.40 < R^2 \leq 0.55$	$0.40 < NSE \leq 0.55$	$0.7 < RMSE \leq 0.8$	$\pm 20 \leq PBIAS < \pm 30$
Unsatisfactory	$R^2 \leq 0.40$	$NSE \leq 0.40$	$RMSE > 0.80$	$PBIAS > \pm 30$
Performance rating for evaluation metrics for a monthly time step;				
Performance Rating	R^2	NSE	RMSE	PBIAS
Very Good	$0.75 < R^2 \leq 1.00$	$0.75 < NSE \leq 1.00$	$0.0 < RMSE \leq 0.5$	$PBIAS < \pm 10\%$
Good	$0.65 < R^2 \leq 0.75$	$0.65 < NSE \leq 0.75$	$0.5 < RMSE \leq 0.6$	$\pm 10 \leq PBIAS < \pm 15$
Satisfactory	$0.5 < R^2 \leq 0.65$	$0.5 < NSE \leq 0.65$	$0.6 < RMSE \leq 0.7$	$\pm 15 \leq PBIAS < \pm 25$
Unsatisfactory	$R^2 \leq 0.50$	$NSE \leq 0.50$	$RMSE > 0.70$	$PBIAS > \pm 25$

3.13. Conceptual Framework

For any research, identifying clear and efficient material and methodology used is crucial for the effectiveness of the study not only from time budget point of view, but also from the quality of the research result expected. The conceptual framework of methodology describing the overall steps were used in the research is presented (Figure 18) as shown below.

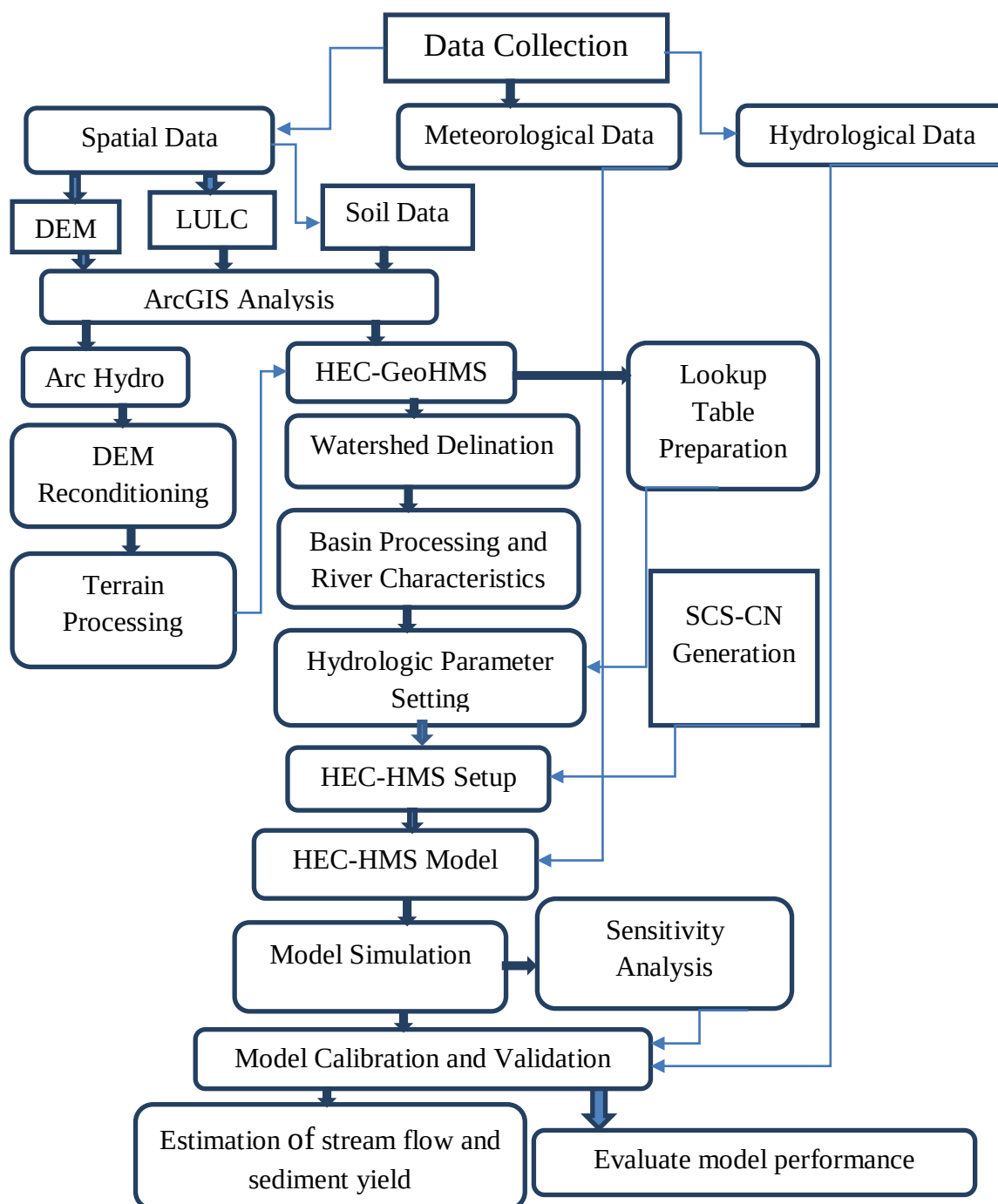


Figure 18. General conceptual framework of the study.

Hence, the weighted CN values were already extracted by the HEC-GeoHMS for each sub-basin. The minimum and maximum weighted curve number values are 84.57 for sub-basin W280 and 92.16 for sub-basin W190 respectively. The CN value is directly proportional to the generation of runoff. The sub-basin with minimum CN value contribute very lower runoff and high infiltration rate whereas, the larger curve number within sub-basin is the higher runoff potential from that sub-basin. Accordingly, the low and high runoff generates from the sub-basin W280 and W190 respectively.

Similarly, the minimum and maximum initial abstraction were 8.14 mm for W290 sub-basin which is high runoff generation and 13.92 mm for W230 sub-basin which generates low runoff. The maximum basin slope is 2.42% found in W320 sub-basin and the minimum slope is 9.26% found in W300 sub-basin. This indicates that sub-basin W320 is the steepest one when compared to the other sub-basins. The lower the sub-basin lag time surface runoff reaches the outlet point very quickly. The minimum and maximum time of concentration were 24.57 hr for W270 sub-basin which indicates the time the runoff reaches the outlet quickly, and 38.71 hr for W220 sub-basin which indicates the runoff reaches the outlet slowly due to the longest flow path of this sub-bas is very high, whereas the minimum storage coefficient is 45.62 for W270 sub-basin, and 71.89 for W220 sub-basin. Storage coefficient was derived from the time of concentration. The watershed parameter for the soil moisture accounting method for the loss model is in the Appendix C, Table 3. The watershed parameters generated by HEC-GeoHMS for the Mille River catchment are shown in Table 16.

Table 16. Watershed parameters generated by HEC-GeoHMS for Mille River watershed.

No	Name of Sub-basin	Area (km ²)	Basin Slope (%)	CN	S (mm)	Ia (mm)	TC (hr)	Storage Coeff
1	W190	317.46	5.35	92.16	21.61	4.32	30.071	55.846
2	W220	948.45	7.55	90.22	27.53	5.51	38.713	71.895
3	W230	579.73	6.23	90.76	25.86	5.17	32.369	60.113
4	W270	502.92	2.42	86.35	40.15	8.03	24.566	45.622
5	W280	862.75	2.70	84.57	46.34	9.27	36.364	67.533
6	W290	502.66	2.64	91.25	24.36	4.87	32.212	59.823
7	W300	829.63	9.26	87.41	36.58	7.32	36.022	66.897

4.2. Simulation Results of the HEC-HMS Model

4.2.1. Model sensitivity analysis

Sensitivity analysis was carried out before calibrating the model to save time during calibration. The HEC-HMS model was calibrated (1993-2008) for 16 years by considering 2/3 of the observed flow data and validated (2009-2016) for 8 years by considering 1/3 of observed flow data with a one-day time interval for this research study. To begin the simulation model, the assumed and calculated initial values for the sensitive parameter of the watershed, as shown in the figure 20 by considering the peak change and volume change were first used in the HEC-HMS model. The model considered five flow parameters for analysis of sensitivity for the watershed.

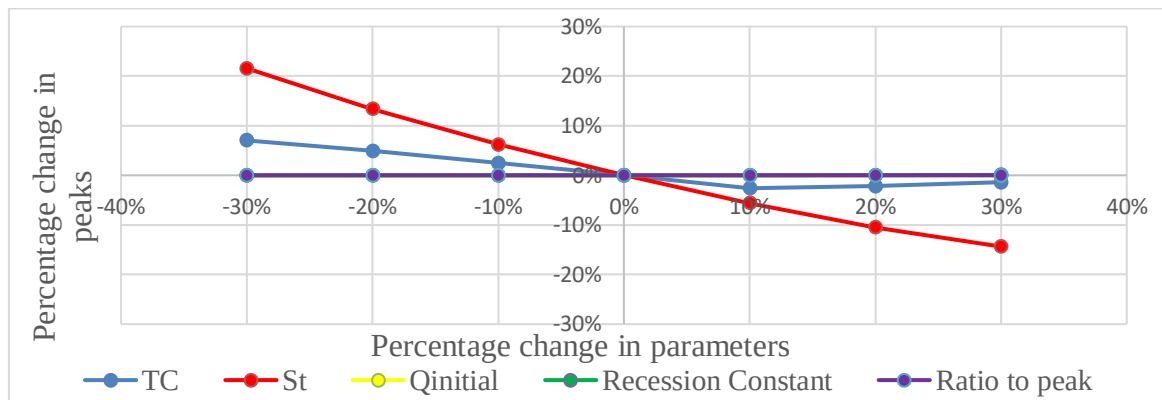


Figure 20. Sensitivity analysis of the model parameters in peak discharge.

In the Figure 20 shows the sensitive parameters are 1st storage coefficient, 2nd time of concentration, where the others are no effect on the peak change. The results showed that with respect to peak, the model was very sensitive to storage coefficient and time of concentration parameters. But, the model was less sensitive for model parameters of ratio to peak, recession constant and initial discharge as shown in Figure 20.

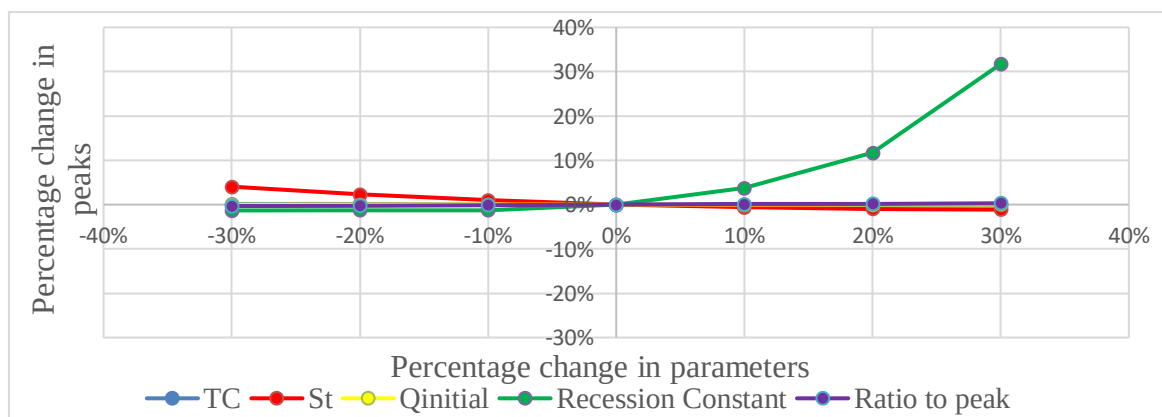


Figure 21. Sensitivity analysis of the model parameters in volume.

In the Figure 21 shows the sensitive parameters are 1st recession constant, 2nd storage coefficient, 3rd ratio to peak, 4th time of concentration, but initial discharge is no effect on changing the volume. The results showed that with respect to volume, the model was very sensitive to recession constant and storage coefficient parameters. But, the model was less sensitive for model parameters of ratio to peak, time of concentration and initial discharge as shown in Figure 21.

4.3. Stream Flow Calibration and Validation

4.3.1. Calibration

Parameter optimization systematically changes model parameter values until the calculated model results agree with the observed data. Optimization of the parameter values was carried out within the allowable ranges recommended by the US Army Corps of Engineers Hydrologic Engineering Center (USACE, 2000). The objective function is a quantitative measure of the goodness of fit between the measured result from the model and the observed flow. The calibrated parameters are adjusted to fit observed data for better output (Dawei Han, 2011). A search method for modifying parameters to minimize objective function value and find optimum parameter value is the secret to automated parameter estimation. The minimum objective function is obtained when the parameter values best able to reproduce the observed hydrograph are found. Based on model storage coefficient (St) and time of concentration (Tc) were the most sensitive parameters.

During the model calibration, the average observed and simulated flows were 10.57 m³/s and 9.82 m³/s, respectively and the model efficiency performances are $R^2 = 0.74$, NSE = 0.65, RSR/RAMSE Stdev = 0.60, and PBIAS = -7.10. The model slightly underestimates the observed flow by -7.10% (Since PBIAS = -7.10, which is very close). This small bias suggests that the model's water balance is reasonably well-calibrated, but there may be minor discrepancies in inputs (e.g., rainfall, evapotranspiration) or parameterization. This result is very close to the findings of (Tadesse, 2022) which concluded that the average observed flow and simulated flows using SWAT model in the same catchment were 11.45 m³/s and 8.05 m³/s, respectively.

Table 17. The initial and optimized values of watershed parameters.

Sub-basin	Recession Constant		Ratio to peak		TC (hr)		Storage Coefficient	
	Initial	Optimized	Initial	Optimized	Initial	Optimized	Initial	Optimized
W300	0.70	0.8972	0.25	0.7730	36.022	32.181	66.897	34.093
W290	0.70	0.8599	0.25	0.6170	32.212	37.285	59.823	43.890
W280	0.70	0.8329	0.25	0.5920	36.364	34.639	67.533	36.698
W270	0.70	0.8671	0.25	0.7931	24.566	26.288	45.622	27.851
W230	0.70	0.7438	0.25	0.6771	32.369	33.079	60.113	35.043
W220	0.70	0.7971	0.25	0.4191	38.713	34.471	71.895	36.522
W190	0.70	0.76912	0.25	0.36284	30.071	30.653	55.846	37.756

The optimization result of the minimum and maximum optimized values of these parameters is shown in Table 18.

Table 18. The minimum and maximum optimized value of the parameters.

No	Model Parameters	Minimum optimized value	Maximum optimized value
1	Time of concentration (hr)	26.288	37.285
2	Storage Coefficient	27.851	43.89
3	Recession constant	0.7438	0.8972
4	Ratio to peak	0.4191	0.7931

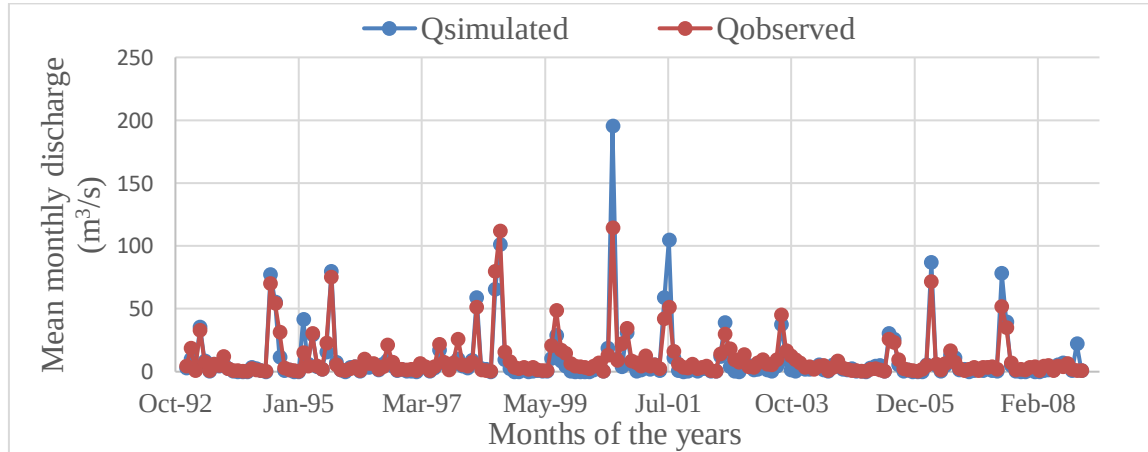
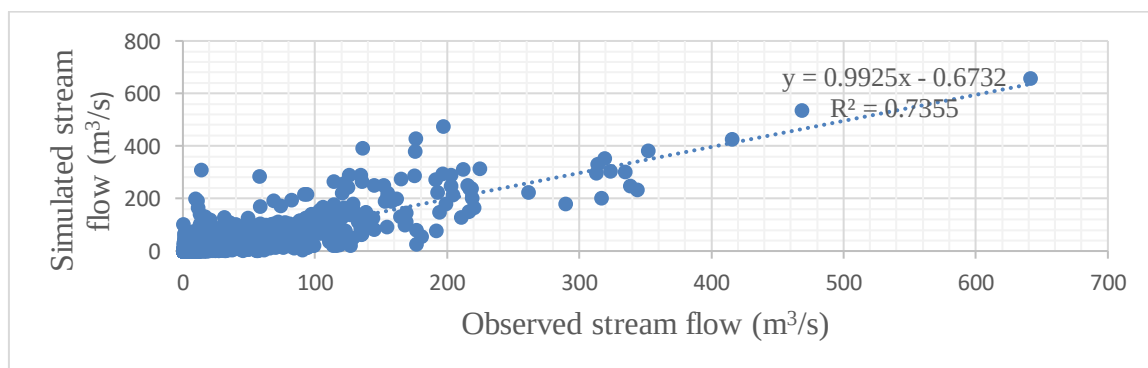


Figure 22. The simulated and observed flow comparison during calibration.

Figure 23. The coefficient of determination (R^2) of the stream flow during calibration.

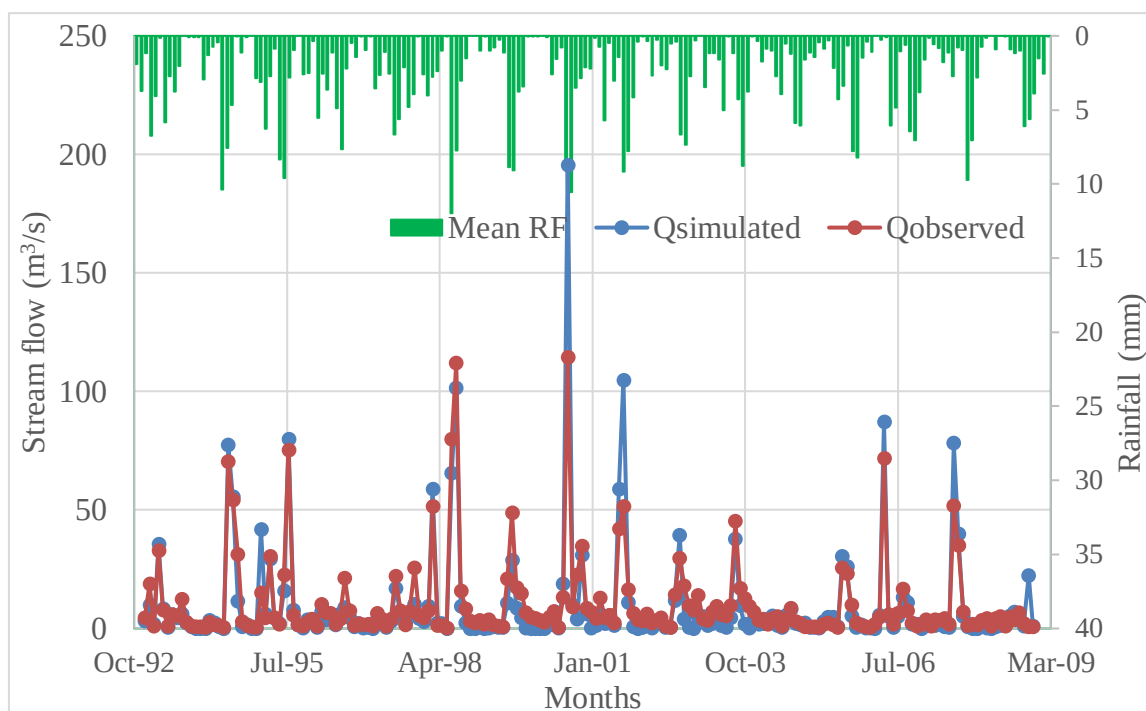


Figure 24. The rainfall-runoff with observed runoff relationship during calibration period.

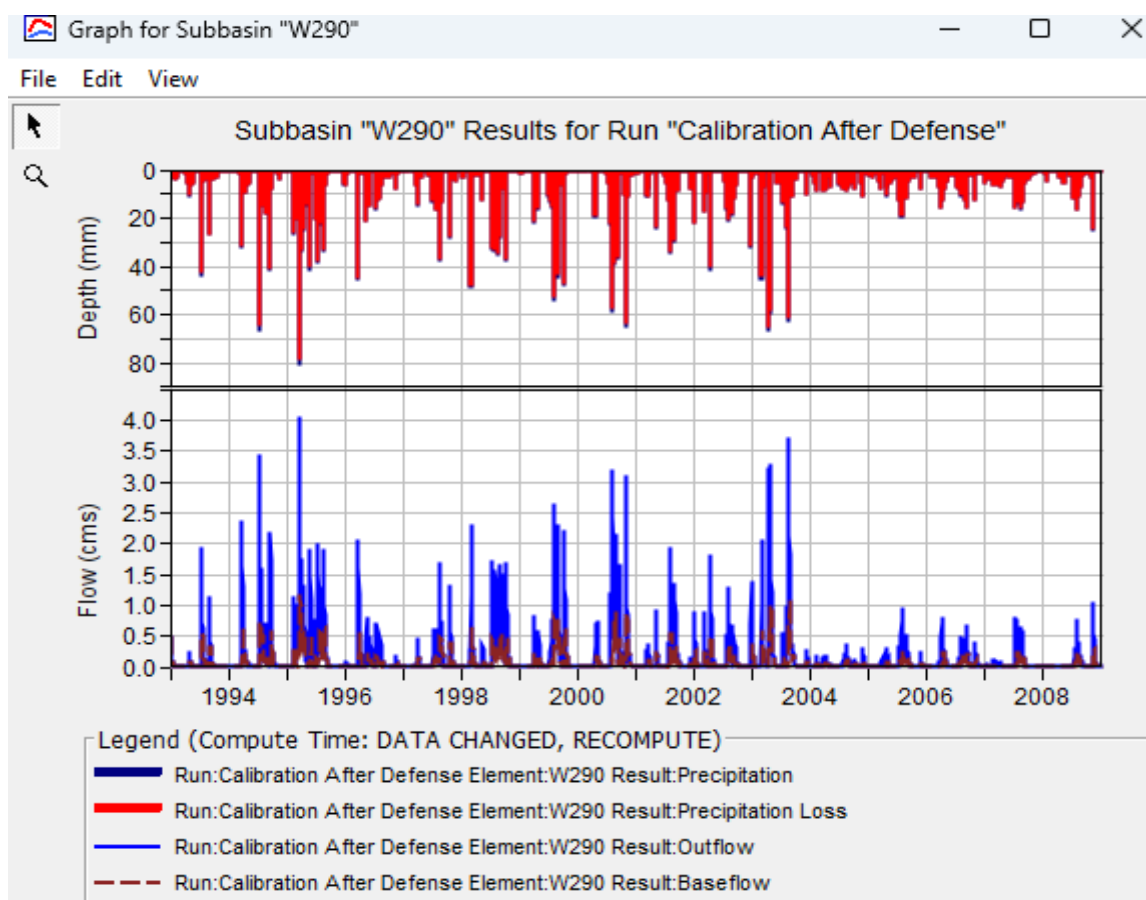


Figure 25. The rainfall-runoff with observed runoff relationship during calibration period for W290 sub-basin.

4.3.2. Validation

After the calibration was completed and all model parameters were optimized, the simulated runoff should be compared to the observed runoff using the same parameters that were used for model calibration during model validation. The model is validated directly using the parameter values obtained from model calibrations. The observed flow data from January 1, 2009, to December 31, 2016, was used for model validation in this study. The validation period was chosen based on the availability of recorded data as well as the sample's freshness. During the model validation, the average observed and simulated flows were $12.53 \text{ m}^3/\text{s}$ and $14.26 \text{ m}^3/\text{s}$, respectively and the model the model performance for stream flow like R^2 , NSE, RSR, and PBIAS are 0.84, 0.69, 0.60, and +14.18 respectively. The model overestimates observed flow by +12.13% (since $\text{PBIAS} = +14.18\%$, which is close). This result is very close to the findings of (Tadesse, 2022) which concluded that the average observed and simulated flows by using SWAT model were $14.0 \text{ m}^3/\text{s}$ and $15.63 \text{ m}^3/\text{s}$, respectively. The simulated and observed runoff hydrographs show little difference, as shown in Figure 26.

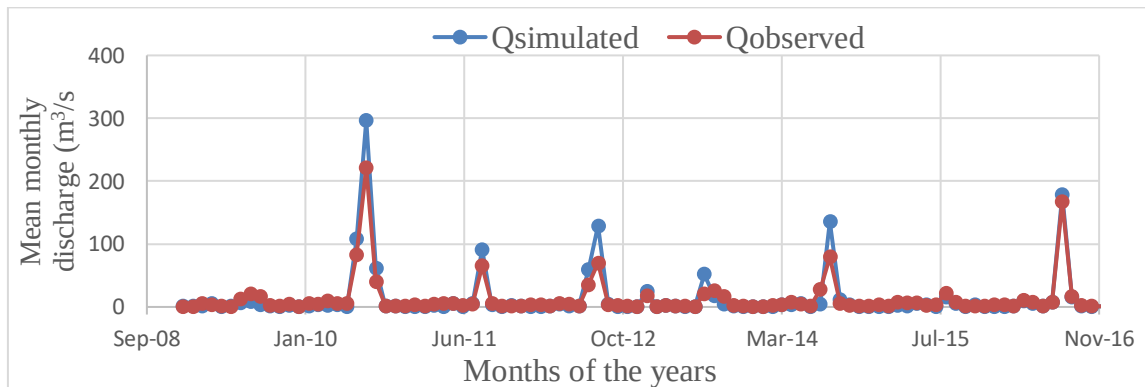


Figure 26. The simulated and observed flow comparison during validation.

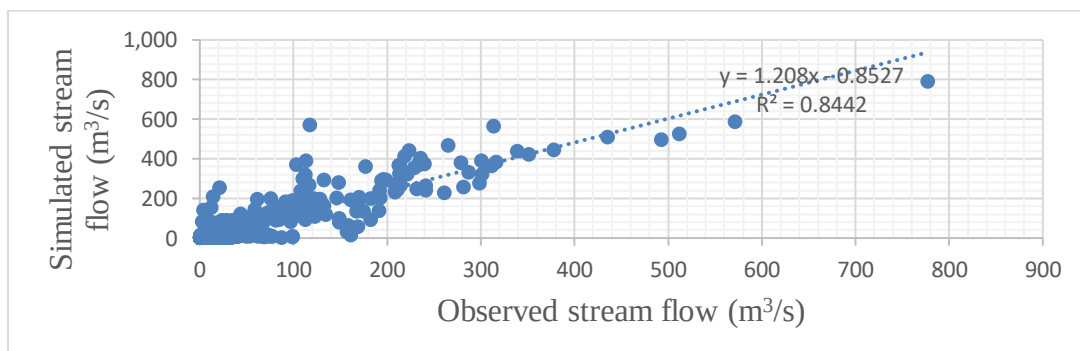


Figure 27. The coefficient of determination (R^2) of the stream flow during validation.

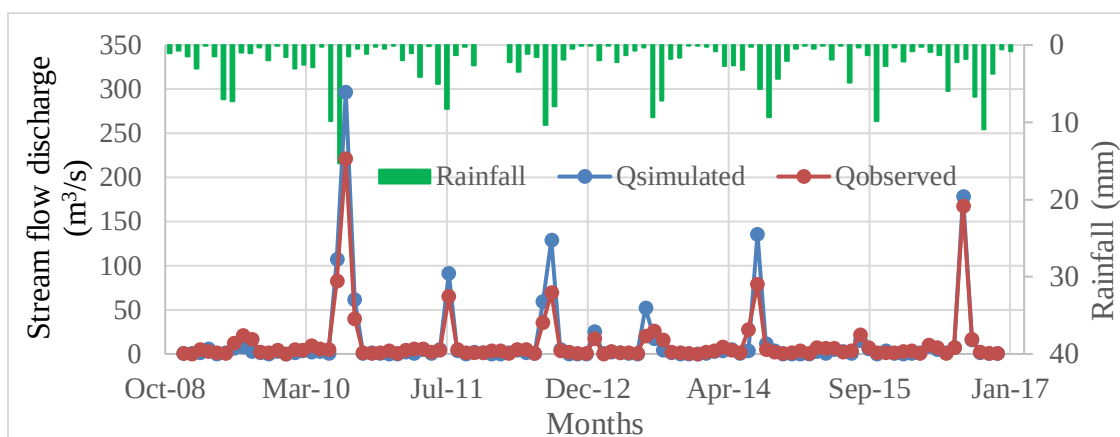


Figure 28. The rainfall-runoff with observed runoff relationship during validation period.

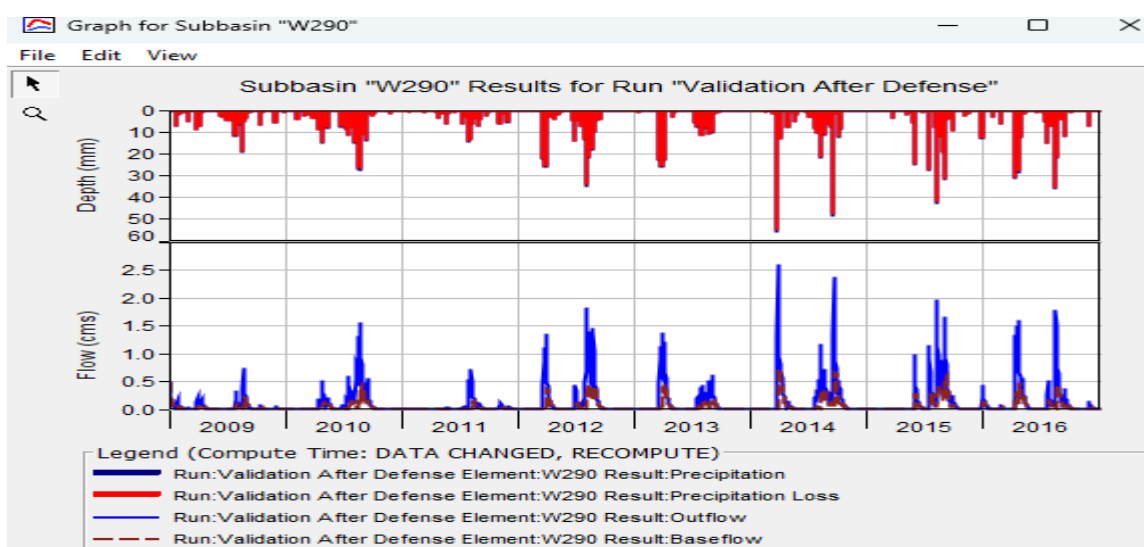


Figure 29. The rainfall-runoff relationship during validation period for W290 sub-basin.

Table 19. Model performance statistics for calibration (1993-2008) and validation period (2009-2016) of the Mille River watershed.

Periods	Observed Mean	Simulated Mean	Model Performances			
	Flow (m³/s)	Flow (m³/s)	R²	NSE	RSR	PBIAS
Calibration	10.57	9.82	0.74	0.65	0.60	-7.10
Validation	12.53	14.26	0.84	0.69	0.60	+14.18

From the calibration and validation result it's visible that both the observed and simulated stream flow values were relatively close to each other, and also by visually inspection and comparing the simulated and observed hydrograph shows very good relation. Therefore, the concept of the Rainfall-runoff modeling for the Mille River watershed was successfully performed well. Again, all the performance evaluation criteria proof the simulation under the recommended ranges that leads the objective of modeling.

4.4. Sediment Yield Calibration and Validation

The sensitivity analysis for sediment yield is carried out by changing one parameter whereas the other parameter remain constant. During this sensitivity analysis the practice factor (LS) is the more sensitive parameter whereas the erodibility factor (K) is the low sensitive parameter. Once the sediment sensitive parameters were identified during sensitivity analysis, calibration process took place. Similar to flow, the model was calibrated for sediment yield from 1993 to 2008. Sediment yield calibration and parameters adjustment continued iteratively until simulated and observed sediment yield fitted. Sediment yield validation conducted with sediment data for the periods 2009 to 2016 without further adjustment of calibration fitted parameters. The model efficiency of predicting the sediment yield and uncertainty of its prediction for calibration and validation was checked through model performance evaluation criteria and model uncertainty measures. The values for developing the soil erosion USLE watershed parameters are illustrated in Table 20.

Table 20. The soil erosion USLE watershed parameters.

No.	Sub-basins	K factor	LS factor	C factor	P factor	Exponent
1	W190	0.3037	1.2563	0.309	0.55	0.65
2	W220	0.2831	1.4673	0.233	0.60	0.65
3	W230	0.2748	1.177	0.205	0.55	0.65
4	W270	0.2314	0.4262	0.177	0.55	0.65
5	W280	0.2552	0.4692	0.164	0.55	0.65
6	W290	0.1946	0.3644	0.476	0.55	0.65
7	W300	0.268	1.7749	0.441	0.60	0.65

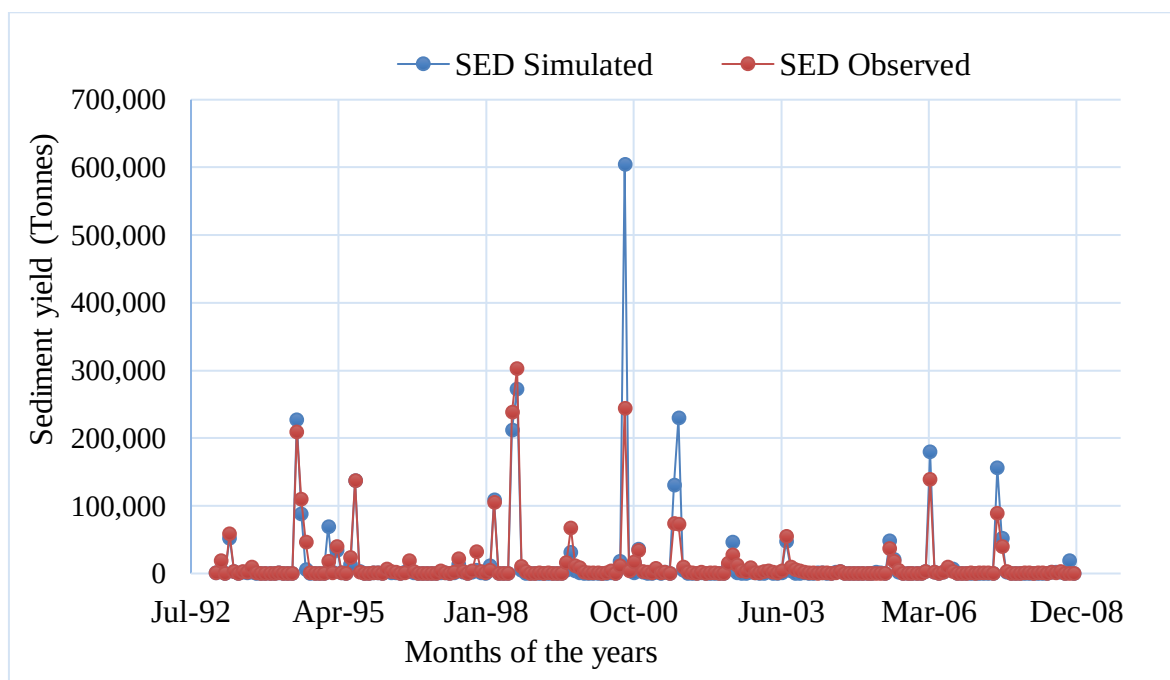


Figure 30. The simulated and observed sediment load comparison during calibration.

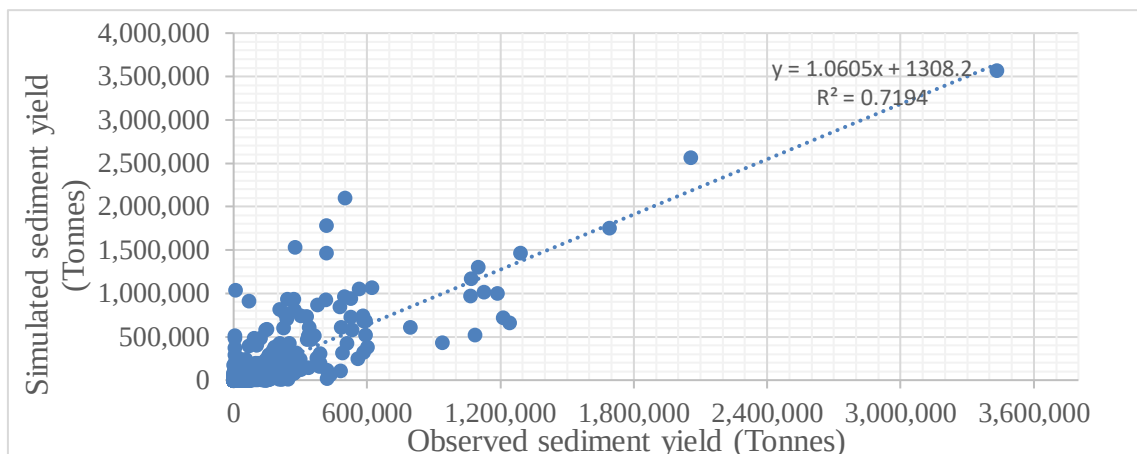


Figure 31. The coefficient of determination (R^2) of the sediment load during calibration.

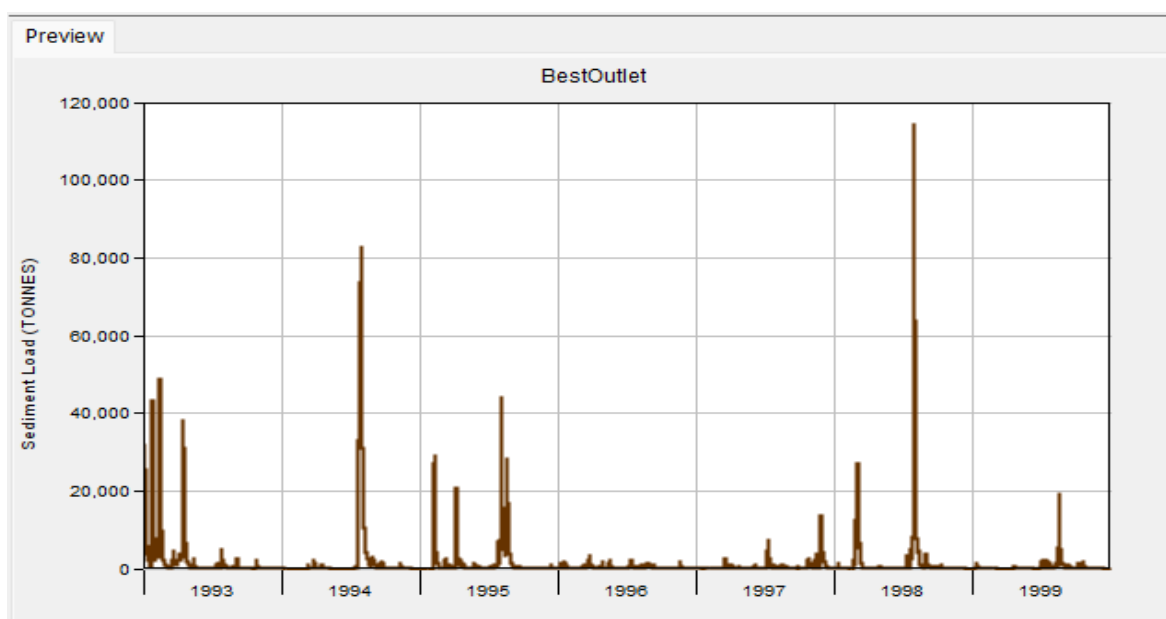


Figure 32. The sediment load graph during calibration processes from 1993 to 2008.

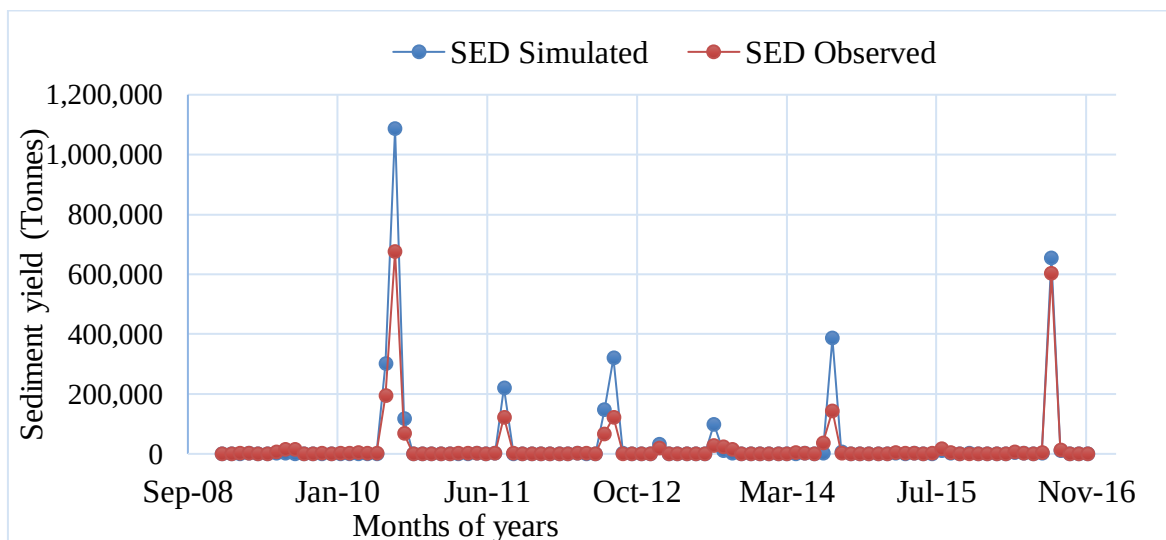


Figure 33. The simulated and observed sediment load comparison during validation.

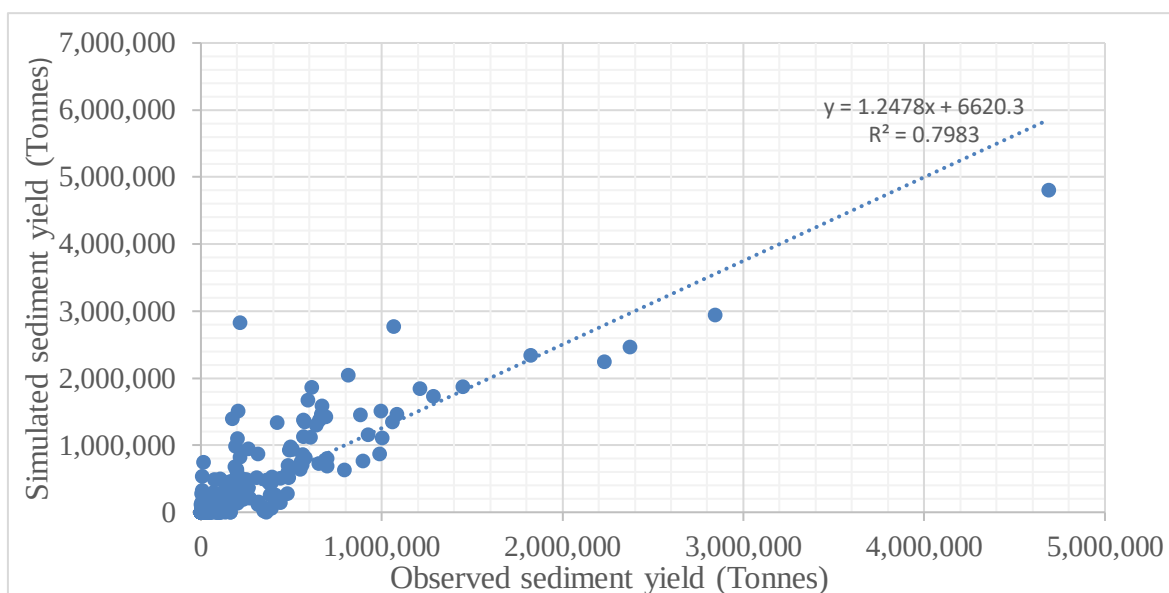


Figure 34. The coefficient of determination (R^2) of the sediment load during validation.

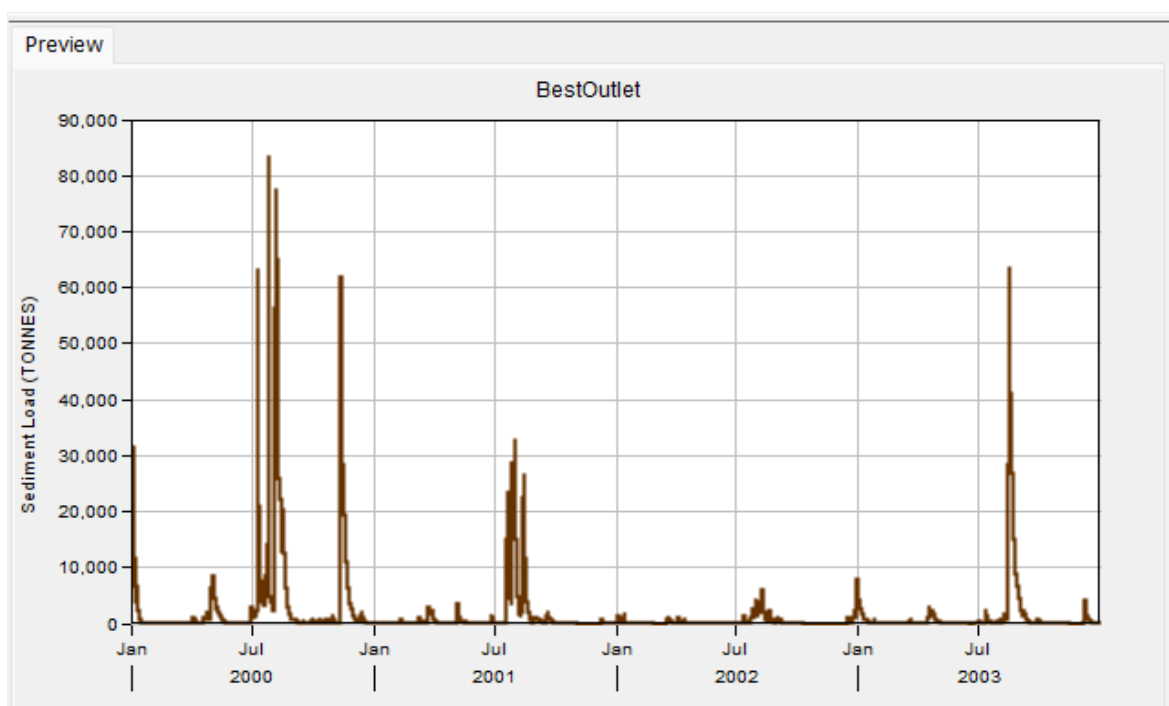


Figure 35. The sediment load graph during validation processes from 2009 to 2016.

Table 21. Model performance statistics for calibration (1993-2008) and validation period (2008-2016) for sediment yield of the Mille River watershed.

Period	Observed mean sediment yield(Ton)	Simulated mean sediment yield(Ton)	Model Performance			
			R^2	NSE	RSR	PBIAS
Calibration	13,695.37	15,809.59	0.72	0.56	0.67	-15.50
Validation	23,605.98	35,942.24	0.80	0.54	0.68	-

From Figure 30 and Figure 33 above it was observed data for both sediment graphs during calibration and validation period has the same characteristics and shape, but they are different in their magnitude. Also the above sediment graphs showed that the model slightly overestimated sediment yield from the watershed in most of the year and underestimated in some years. Average annual sediment yield from Mille River watershed after calibration and validation at Mille gauging station was total sediment loading 18.36 ton/ha/year of 1993 to 2016.

Table 22. The comparison between the mean monthly observed and simulated stream flow and sediment yield of the HEC-HMS model results during the calibration and validation.

Descriptions	Period	Observed	Simulated	R ²	NSE	RSR	PBIAS
Stream flow (m3/s)	Calibration	10.57	9.82	0.74	0.65	0.60	-7.10
	Validation	12.53	14.26	0.84	0.69	0.6	+14.18
Sediment yield (ton)	Calibration	13,695.37	15,809.59	0.72	0.56	0.67	-15.50
	Validation	23,605.98	35,942.24	0.80	0.54	0.68	-

In general the HEC-HMS model performed very well for both the stream flow and sediment yield estimation when the whole data period was considered, but some discrepancies were displayed for the model runs of individual years which shows the need to parameterize the models according to the varying seasons and thus, seasonal parameterization of the model but out of the scope of this study, might improve the performance of the model. From the observed data, the annual rate of sediment yield ranges from 0.74 ton/ha/year to 64.73 ton/ha/year respectively, with the average value of 13.85 ton/ha/year of the Mille River watershed. The results of the simulated sediment yield by the model showed that the annual rate of sediment yield were ranges from 0.65 ton/ha/year to 102.65 ton/ha/year respectively, with the average value of the annual sediment yield computed was 18.36 ton/ha/year. This indicated that, for the Mille River watershed the simulated sediment yield by the model were greater than the observed sediment load values. The average annual of sediment yield of Tendaho sub-basins ranges between 26.66 ton/ha to 0.02 ton/ha (Tilahun et al., 2017). (Hurni, 1989) had conducted a research to estimate the rate of soil erosion for Ethiopia and found that the range of tolerable soil loss level for various agro-ecological zone of Ethiopia from 2 to 18 tons/ha. The average simulated sediment yield in this study area was found to be in the tolerable rate as indicated above, whereas the maximum values was above the tolerable rate. The sediment yield from a given watershed is dominantly related to rainfall and runoff, soil erodibility, slope length and steepness, cropping and management of the soil and land, and any supporting practices implemented to prevent the erosion.

Table 23. Sub-basins base period sediment yield variations in Mille River watershed.

No.	Sub-basins	Area (km ²)	Sediment load (ton/ha)
1	W190	317.46	3.32
2	W220	948.45	7.71
3	W230	579.73	13.00
4	W270	502.92	3.16
5	W280	862.75	1.52
6	W290	502.66	0.19
7	W300	829.63	11.82

In addition, the results indicate that more severe erosion occurred in the lower and middle parts of the watershed. This shows that soil erosion was a serious phenomenon in the different sub-basins in the study area during the observed time periods. During the observed time period, the maximum sediment load occurred in sub-basin W230 and the minimum sediment load occurred in the sub-basin W290 and also some sub-basins showed some increment in sediment yield from time to time and such impacts occurred due to the increase in precipitation amount in combination with the land use/land cover change, soil and slope combination of the sub-basins. Kefalew *et al.*, (2003) indicate that the Lower Awash sub-basin was highly affected by flood and soil erosion year to year. The flow versus sediment yield of the Mille River catchment was drawn in the following Figure 36;

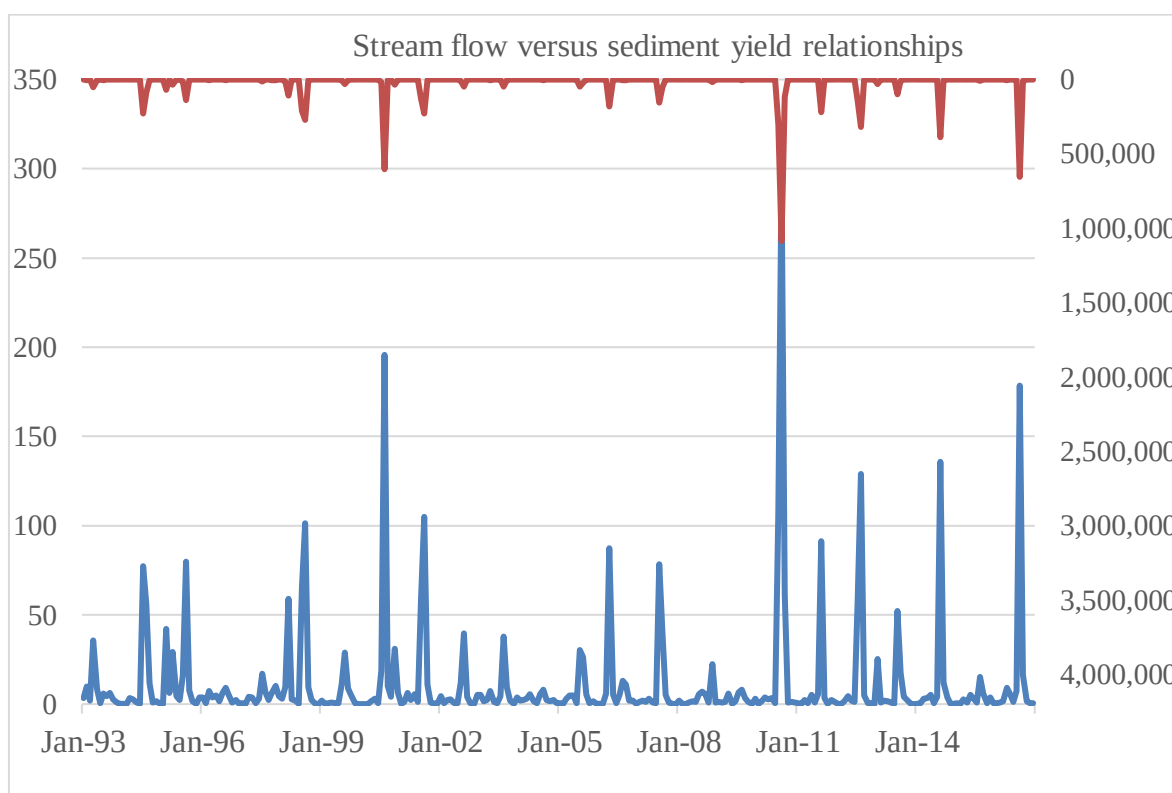


Figure 36. Flow versus sediment yield relationships of the watersheds.

4.5. Discussion of the HEC-HMS model results

The study indicates the successful utilization of the HEC-HMS model in the estimation of stream flow and sediment yield within the Mille River watershed, Lower Awash sub-basin. HEC-HMS model adopted for the estimation of the amount stream flow and sediment yield of the Mille River watershed data demanding conceptual model which must be calibrated and validated well for the accurate estimation of runoff and sediment yield and the data involved in the model requires careful observation to achieve high level of accuracy but for this study all the data was obtained from secondary data sources from various organizations.

In this study observed stream flow data, which is used for the calibration and validation purpose, at the outlet of the watershed was restricted to the year of 1993 to 2016 and the average annual stream flow and average annual sediment yield of 11.42 m³/s and 18.36 tons/ha/year for the calibration and validation period of 1993 to 2016, 9.82 m³/s and 12.85 ton/ha/year for the years 1993 to 2008 and 14.26 m³/s and 29.38 ton/ha/year for the years 2009 to 2016 respectively at the outlet of the watershed. The Nash-Sutcliffe efficiencies (NSE) and coefficient of determination (R^2) of the model indicates well to very good model performances. The modeling in this study was conducted according to daily rainfall and daily observed stream flow basis, which is again the maximum limit for the HEC-HMS model because the model cannot accept the monthly data and above and it, is recommended to check the modeling of the Mille River watershed using the HEC-HMS conceptual model by incorporating hourly rainfall and discharge data. The sediment yield results of the HEC-HMS model is not displayed in tabular form as runoff discharge, it is only in graphical form and this has resulted in approximations in the analysis of sediment yield as well.

A previous study by (Abebe and Gebremariam, 2019) on modeling runoff and sediment yield of the Kesem dam watershed, Awash River Basin, Ethiopia has also confirmed that good land use/land cover has positive effects on the reduction of runoff and sediment yield. The spatial distribution of the sediment sources shows that very low and low sediment yield (less than 11 ton/ha) in the watershed was generated from sub-basin W190, W220, W70, W280 and W290. These sub-basins are covered by woodland followed by forestry crops. The highest contributor of sediment yield (greater than 11 ton/ha) are sub-basin W230 and W300 located in the middle and lower parts of the watershed respectively. Cultivated crops characterize these two sub-basins. Ebabu *et al.* (2022) reported that land cover types and support practices largely control the magnitude and variability of soil erosion.

The results of the study in the Lake Hawassa watershed, Ethiopia by Degife *et al.* (2021) also shows, those areas covered by agroforestry, forest, and woodlands had the highest sediment retention capacity while bare land and built-up area had the lowest retention capacity. This revealed that human activities in the higher slopes were the main driving factor of sediment yield.

Vanwalleghe (2017) described as human-induced land use change results in much faster net erosion rates which concede with the findings of this study. In general, areas that have good vegetation cover around the upper parts of the watershed are characterized by lower sediment yield and sloping agricultural lands are the dominant sources of higher sediment yield. This implies that agricultural lands need the application of effective management practices whereas; the existing woodlands and forest coverages are enough to retain soil loss. The study indicated that sediment yield is more sensitive to land use classes revealing areas under minimal disturbances are not a significant source of erosion and areas under extensive agriculture are the sources of high erosion. Several studies also show that land use/land cover can be controlled erosion by covering the soil surface with the canopy and reducing the mechanical action happening at the soil surface by intercepting the raindrop (Du *et al.*, 2022). This is in line with research findings from a different area that show that sub-watersheds produce a large portion of a watershed's overall sediment yield, which is lower on forested terrain (Tripathi *et al.*, 2003; Degefe and Bewket, 2011).

Overall, it is believed that the result of this study can give the basic information on the context of surface runoff and sediment yield in the watershed for the corresponding the rainfall events, which are in turn significant for the planning and designing of appropriate watershed management activities and formulating the suitable management strategies reducing the problems of the soil erosion by water and flood risks in the lower parts by managing the surface runoff and sediment yield generated in the watershed.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary and Conclusions

Hydrological studies are necessary and important for water and environmental resources management. In this thesis, hydrological model of Mille River watershed were developed using the HEC-HMS model for the estimation of stream flow and sediment yield of the watershed and was successfully calibrated from 1993-2008 years and validated from 2009-2016 years on the daily continuous time period. The overall model efficiencies was given by Nash-Sutcliffe Efficiency (NSE) criteria are 0.65 and 0.69 for the stream flows and 0.56 and 0.54 for the sediment yield respectively, for the calibration and validation time periods, indicating a good model fit performances. The coefficient of determination (R^2) for the calibration period and for the validation period of stream flow 0.74 and 0.84 and sediment yield was found to be 0.72 and 0.80, respectively, indicating a good model fit. And also the values of RSR and PBIAS were 0.60 and -7.10 during calibration period for flow and 0.60 and +14.18 during validation period for flow respectively and for sediment yield 0.67 and -15.50 during calibration period and 0.68 during validation period, respectively.

The calibration and validation results of the model showed that the model was able to simulate the climatic variables (precipitation and temperature) which follow the same trend with the observed one. According to the hydrological analysis carried out, time of concentration and storage coefficient were the most sensitive parameters affecting the runoff estimation and the soil practice factor and land and management factor were the most sensitive parameters affecting the sediment yield estimation of the Mille River watershed.

Due to the lack of observed stream flow in the outlet of the catchment for the years 2017 to 2022, the HEC-HMS model can be used to model stream flow and sediment yield in the Mille River watershed from the years 2017 up to 2022 by using the parameters found in the calibration and validation period.

The conclusion can be drawn undoubtedly from this research that the research questions in the order they have affirmed in the above chapter of this study have been answered comprehensively and the HEC-HMS model simulates the average annual stream flow and average annual sediment yield of 11.42 m³/s and 18.36 tons/ha/year for the calibration and validation period of 1993 to 2016 respectively, at the outlet of the watershed (Mille guaging station). From the results of this thesis, one can conclude that the HEC-HMS model can estimate well both the stream flow and sediment yield of the Mille River watershed.

Finally, the methodologies developed in this research can also be applied in other ungauged catchment and regions with similar physical characteristics. We suggest further studies in the study watershed to generate more detailed information for modeling work by reviewing the efficiency of meteorological and hydrometric measurements (which were poor in quality and quantity during the study) to establish the optimal number of stations and their adequate distribution. The output of this study not indicates the impact of land use land cover modification on the surface runoff and sediment yield in the watershed.

5.2. Recommendations

Based on the results and the knowledge gained during the study, the following recommendations are made;

1. The sediment gauging stations in this watershed are recorded small number of sediment data. Hence, it is better to increase number of recorded time and number of hydrological stations to get better result.
2. For this study, input data (hydro-meteorological data) collected from the concerned offices and authorities were used to simulate the HEC-HMS model in the study watershed. In order to improve the model performance, it is highly recommended that the hydrometric and meteorological gauging stations should be improved both in quality and quantity.
3. The identified critical sub-basins showed of serious vulnerability to erosion and generate a huge amount of sediment at the outlet of the watershed and this can endanger the service life of Tendaho dam reservoir which is found just downstream of the outlet. Thus it needs urgent sustainable management practices. In addition to this, integration of terracing and contouring have shown effective way of sediment reduction from the catchment hence necessitates applying in combination.
4. Possible discrepancy of the computed sediment output data is expected as the HEC-HMS displays the results in graphical form and the calibration and validation of the sediment in this study is done by approximation of the output graphical sediment data in a monthly basis and it is better if the model displays the results of sediment in tabular format.
5. Sediment reduction practices such as grassed waterway, filter strips, terracing and contouring were developed in this research work. In order to improve the sediment reduction in the Mille River watershed additional management practices should be established from the HEC-HMS model management operation or other soil and water conservation measures should be introduced.
6. The local government of the watershed should implement the green legacy to reduce the soil erosion due to high surface runoff generated in the Mille River watershed.

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7. APPENDICES

Appendix A, Table 1: Corrected monthly rainfall (mm) of Bati meteorological station.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	89.9	102.6	0.0	243.0	114.9	5.3	203.5	32.5	67.5	77.0	0.0	0.0
1994	0.0	2.3	64.6	28.9	18.1	15.2	330.5	204.8	106.3	0.0	42.6	5.6
1995	0.0	46.5	101.2	136.1	87.3	31.3	269.9	352.0	110.6	14.6	0.0	35.0
1996	98.4	0.0	145.0	74.4	124.7	15.2	182.7	212.1	63.7	0.0	49.2	1.7
1997	33.4	0.0	140.2	30.1	10.7	52.3	217.9	136.8	37.7	149.1	211.1	0.0
1998	43.5	81.4	86.4	42.9	31.9	0.0	285.5	168.3	68.7	30.5	0.0	0.0
1999	42.3	0.0	10.4	24.0	7.7	0.0	265.2	231.7	125.5	111.9	3.2	0.0
2000	0.0	0.0	9.7	36.4	54.9	32.2	265.7	270.9	89.8	82.8	144.7	126.5
2001	5.9	12.7	230.2	24.4	78.7	38.8	281.7	172.2	106.9	6.0	0.0	24.3
2002	61.5	4.1	84.0	54.0	9.6	0.0	155.6	186.4	68.9	8.3	0.0	188.5
2003	40.2	14.7	31.8	159.4	1.6	26.4	119.5	337.4	103.0	0.0	0.0	89.8
2004	24.7	58.8	54.9	147.4	44.7	50.3	169.7	217.2	43.9	21.2	12.0	12.9
2005	39.7	6.7	82.3	101.6	70.9	8.8	285.9	222.8	41.1	16.5	33.1	0.0
2006	15.5	2.5	168.7	202.8	6.2	10.3	193.1	211.3	102.6	31.1	0.0	20.4
2007	47.9	9.1	19.9	100.0	4.3	16.4	328.4	184.4	101.6	8.4	4.2	0.0
2008	56.5	0.0	0.0	20.1	57.2	55.4	181.2	149.9	100.5	74.5	119.4	0.0
2009	27.7	31.8	26.0	56.4	2.0	61.7	228.9	229.4	41.3	35.2	16.3	8.1
2010	0.0	15.5	153.8	51.9	37.9	0.0	242.3	475.2	26.6	9.5	27.2	0.0
2011	30.8	0.0	42.2	19.1	110.1	3.7	185.4	260.0	50.3	0.0	95.5	0.0
2012	0.0	0.0	0.0	73.6	26.7	28.4	330.4	235.2	54.8	0.0	0.0	0.8
2013	38.4	0.0	36.2	37.0	38.7	4.8	328.9	248.3	74.4	37.5	0.1	0.0
2014	9.3	25.3	82.2	63.0	125.4	7.9	181.0	362.7	148.2	106.0	6.1	0.0
2015	8.7	0.7	106.8	0.0	161.0	6.2	40.9	385.1	127.8	4.2	92.3	13.5
2016	0.0	20.6	0.0	231.1	57.5	72.5	214.5	415.0	161.1	0.0	13.2	0.0
2017	0.0	125.4	39.9	46.5	110.9	21.9	138.2	213.0	115.5	23.1	0.0	19.6
2018	31.3	0.0	160.8	160.8	28.2	75.4	299.0	262.1	89.3	68.0	70.6	0.0
2019	0.0	6.3	0.4	91.9	116.2	60.4	196.2	170.4	112.5	23.2	154.4	17.2
2020	23.5	10.0	26.6	85.3	127.1	28.7	279.9	333.0	182.7	2.5	10.5	0.0
2021	1.9	39.9	1.6	53.2	73.0	21.1	273.4	262.6	154.4	31.4	10.7	0.0
2022	16.9	2.7	35.4	99.6	22.8	109.6	205.9	246.3	73.0	28.0	0.0	21.0

Appendix A, Table 2: Corrected monthly rainfall (mm) of Haik meteorological station.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	45.20	63.30	110.1	185.2	219.7	9.00	222.3	150.5	158.9	47.90	0.00	10.3
1994	6.60	0.30	135.2	61.3	38.30	25.80	374.3	285.3	183.8	1.50	38.70	2.90
1995	0.00	27.90	92.40	234.2	77.40	22.50	227.1	347.9	87.10	43.50	0.00	74.9
1996	33.90	33.60	259.7	89.0	130.3	49.90	229.8	382.7	87.10	4.30	59.40	0.00
1997	44.60	0.00	119.4	122.8	60.40	100.8	301.7	253.8	105.7	161.5	133.8	0.00
1998	93.40	146.9	25.70	130.2	45.30	0.00	509.8	291.2	159.9	48.10	0.00	0.00
1999	38.00	4.50	38.80	19.10	6.00	24.00	363.8	324.8	155.9	122.2	0.00	0.00
2000	0.00	0.00	1.40	158.7	66.70	40.70	419.1	408.4	156.2	72.60	39.90	76.8
2001	6.00	41.60	171.1	24.30	165.2	87.20	384.5	347.1	198.9	10.20	0.60	7.20
2002	92.58	20.60	76.20	99.00	44.80	39.40	337.7	325.8	121.0	23.41	0.00	72.0
2003	45.80	57.30	97.20	130.4	4.10	54.30	209.6	236.6	160.2	2.00	29.80	53.4
2004	7.30	12.40	166.2	97.70	9.60	54.50	255.0	255.1	114.6	57.30	62.80	11.4
2005	18.80	12.90	86.60	246.1	139.1	29.50	310.1	308.5	73.30	4.30	35.30	0.00
2006	6.20	3.00	189.0	141.9	59.10	27.60	325.0	193.0	156.0	49.10	0.70	25.7
2007	18.80	87.20	55.80	74.98	30.60	46.60	344.0	291.3	82.80	37.90	3.70	0.00
2008	0.00	0.00	2.00	33.10	34.60	26.30	261.7	221.2	196.7	51.60	88.60	0.00
2009	49.00	28.80	73.00	116.4	1.00	82.90	297.3	282.8	65.60	52.60	9.30	77.4
2010	0.00	86.90	103.6	129.3	117.3	11.70	544.9	617.6	44.40	32.50	73.40	13.1
2011	17.30	4.50	66.60	45.00	210.4	13.00	236.3	356.9	46.80	12.10	44.20	0.00
2012	0.00	0.00	128.3	95.00	43.90	65.80	427.5	290.3	64.80	21.00	0.00	3.00
2013	35.70	2.40	95.80	13.80	31.20	22.10	382.8	266.3	72.20	92.00	3.60	0.00
2014	12.90	24.30	108.3	89.50	87.20	16.70	274.0	369.9	100.8	94.90	13.10	4.00
2015	19.40	4.80	82.00	2.20	191.0	18.00	61.70	268.8	66.40	20.80	75.20	22.4
2016	9.20	29.00	97.70	106.6	111.4	77.70	286.1	362.1	115.1	53.90	41.40	0.00
2017	0.00	118.5	160.3	49.3	207.3	16.60	207.3	364.7	139.0	55.40	3.20	0.00
2018	17.60	75.60	24.10	132.3	9.40	122.4	283.4	325.2	117.8	54.30	51.80	0.00
2019	0.00	26.20	108.0	151.6	108.1	65.26	217.5	252.2	152.9	31.80	179.1	16.9
2020	9.80	17.50	88.70	123.1	86.40	35.30	289.0	319.7	168.6	22.00	26.20	0.00
2021	1.48	26.63	2.07	70.61	136.4	15.60	303.4	383.1	238.1	46.31	9.07	0.00
2022	22.40	4.07	46.21	65.88	9.84	117.4	215.1	313.2	97.26	43.72	5.82	32.3

Appendix A, Table 3: Corrected monthly rainfall (mm) of Mersa meteorological station.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	77.70	202.1	21.70	285.6	108.1	0.00	191.6	109.4	154.6	100.8	0.00	0.70
1994	1.44	4.60	88.30	42.20	18.30	8.20	347.6	314.5	176.7	0.00	38.90	0.90
1995	0.00	190.4	74.80	246.4	105.7	22.60	355.3	305.8	99.40	46.30	0.00	173.0
1996	140.8	1.90	179.7	109.1	126.4	45.50	90.70	226.1	87.50	45.90	34.00	2.70
1997	27.10	0.00	121.7	121.5	47.00	113.5	190.3	191.2	83.00	189.9	76.80	0.00
1998	145.1	168.3	159.8	81.80	24.00	0.90	449.1	321.8	65.70	64.60	0.00	0.00
1999	31.83	1.50	46.40	28.60	10.90	96.50	312.1	350.5	112.1	110.5	0.00	0.70
2000	0.00	0.00	0.00	57.50	49.70	12.20	258.2	386.1	106.3	116.2	36.50	38.70
2001	2.00	18.00	206.0	3.00	80.50	24.80	303.3	271.6	124.5	25.00	2.40	5.50
2002	129.6	0.00	40.20	59.80	5.90	3.50	227.8	253.7	87.60	0.00	0.00	104.7
2003	43.40	18.10	43.60	167.8	0.00	40.00	121.8	284.9	124.2	1.80	8.20	45.00
2004	56.70	27.90	68.70	152.2	2.70	17.00	190.0	155.5	0.60	36.50	68.40	19.90
2005	30.85	8.81	54.50	84.30	143.2	27.80	214.1	322.0	32.60	18.00	38.00	0.00
2006	4.30	1.60	279.5	137.1	41.20	24.20	158.7	327.8	127.1	89.30	12.70	11.10
2007	18.00	68.50	40.80	97.20	44.10	33.10	336.2	256.3	98.80	30.60	4.50	0.00
2008	43.20	0.00	0.00	42.80	33.70	22.60	200.8	221.1	115.3	40.10	43.40	0.00
2009	35.10	6.40	52.70	137.6	3.20	9.50	233.8	268.5	1.60	28.80	3.80	127.8
2010	0.00	49.80	75.40	75.70	148.6	5.20	264.4	546.4	65.80	6.90	18.10	13.40
2011	7.90	0.00	112.2	44.00	130.3	0.00	116.8	243.6	37.90	13.10	122.7	0.00
2012	0.00	0.00	75.50	177.8	56.30	61.20	342.7	265.0	77.90	33.70	0.00	0.00
2013	141.2	2.50	67.70	73.00	6.40	9.30	290.4	230.0	43.50	54.20	0.40	5.10
2014	2.30	28.30	81.30	116.8	138.7	1.60	138.3	241.3	167.1	10.70	28.00	0.00
2015	21.90	0.00	21.50	0.00	173.3	10.30	22.90	354.3	86.20	8.24	61.18	44.43
2016	13.04	32.43	45.43	228.1	70.68	44.70	215.1	368.1	107.6	12.19	25.69	0.00
2017	0.00	89.65	96.49	58.13	112.7	13.60	256.9	552.8	136.8	47.40	9.90	0.00
2018	27.30	42.17	48.60	225.1	8.70	96.00	239.8	453.4	77.60	66.50	108.2	1.60
2019	0.00	65.10	81.60	131.9	94.03	54.50	91.00	100.8	167.2	27.67	155.9	14.66
2020	52.20	17.50	73.70	109.8	29.60	42.40	281.1	285.0	91.80	9.70	49.90	5.54
2021	1.60	23.17	1.80	61.43	118.6	13.57	263.9	333.3	208.3	40.29	9.34	0.00
2022	28.55	3.54	40.20	57.31	8.56	102.2	187.2	294.5	86.41	38.04	5.06	28.10

Appendix A, Table 4: Corrected monthly rainfall (mm) of Mille meteorological station.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	2.30	8.50	0.00	18.30	13.50	0.40	52.60	13.00	38.40	0.90	0.00	0.00
1994	0.00	0.00	64.00	8.80	11.30	0.00	171.9	48.00	60.60	0.00	3.50	0.00
1995	0.00	30.60	139.7	87.00	57.50	25.80	122.6	99.90	7.20	0.00	0.00	5.70
1996	5.80	0.00	48.60	1.90	30.90	15.50	66.14	41.90	0.00	7.05	15.70	0.89
1997	0.00	0.00	10.20	17.40	2.10	9.70	48.30	72.70	0.20	45.40	0.80	0.00
1998	4.90	9.30	59.20	2.40	12.70	0.00	138.6	128.20	52.60	39.00	0.00	0.00
1999	0.00	0.00	23.20	16.70	5.40	0.00	64.90	165.50	17.20	57.60	0.00	0.00
2000	0.00	0.00	0.00	46.00	0.00	0.00	99.10	180.20	43.60	77.40	13.50	0.00
2001	0.80	0.00	39.90	0.00	24.80	1.10	80.00	118.30	27.90	0.00	0.00	6.80
2002	22.0	0.00	39.00	45.70	0.00	0.00	28.10	80.70	22.00	0.00	0.00	32.8
2003	0.00	46.90	6.40	139.4	0.00	10.70	37.70	197.10	24.70	0.00	0.00	9.30
2004	9.22	9.48	25.58	42.63	5.37	12.85	62.77	69.09	17.79	13.73	16.29	5.07
2005	10.1	2.89	26.19	43.20	37.40	7.34	88.83	94.91	16.16	6.22	14.40	0.00
2006	2.35	3.49	63.59	59.69	11.41	5.57	66.59	82.91	40.46	16.78	1.30	6.47
2007	10.1	18.56	12.72	31.22	9.01	10.26	111.6	78.57	30.11	9.86	1.42	0.00
2008	3.30	0.00	0.14	3.10	9.90	0.40	56.90	39.20	2.40	2.50	33.90	0.08
2009	9.90	6.72	20.23	32.72	0.52	5.50	32.60	38.20	0.00	6.77	5.10	0.88
2010	0.00	4.50	5.40	31.60	19.80	11.37	55.70	128.30	29.10	3.40	0.00	0.00
2011	0.00	0.00	0.00	4.50	11.40	0.70	33.80	92.65	14.69	2.17	33.71	0.00
2012	0.00	0.00	78.50	40.51	2.10	20.40	69.20	150.20	12.00	0.00	0.00	0.00
2013	0.00	0.00	78.50	23.50	3.00	0.00	53.70	87.90	1.50	0.00	0.00	0.00
2014	0.00	0.00	57.30	21.30	4.90	0.51	67.56	101.57	94.35	21.30	0.00	0.00
2015	0.00	0.00	1.90	0.16	31.00	1.30	28.60	144.40	23.30	0.00	0.80	13.0
2016	4.00	10.62	0.00	131.5	0.20	0.00	34.60	112.60	17.40	0.00	7.20	0.00
2017	0.00	37.40	26.60	16.00	0.20	0.00	15.50	207.50	58.10	7.10	0.00	0.00
2018	0.00	13.81	21.12	54.45	6.11	8.90	106.0	96.60	0.00	21.44	29.22	0.36
2019	0.00	12.40	19.38	43.19	30.79	18.59	50.88	58.02	50.85	9.06	51.04	4.80
2020	8.68	0.00	55.00	36.50	12.50	10.44	92.94	102.60	43.83	4.76	10.09	1.81
2021	0.33	7.59	0.59	20.12	38.85	1.10	51.20	137.96	77.70	14.80	2.34	0.00
2022	5.16	1.16	0.13	0.00	0.00	33.45	34.80	102.37	27.15	12.46	1.66	9.20

Appendix A, Table 5: Corrected monthly rainfall (mm) of Sirinka meteorological station.

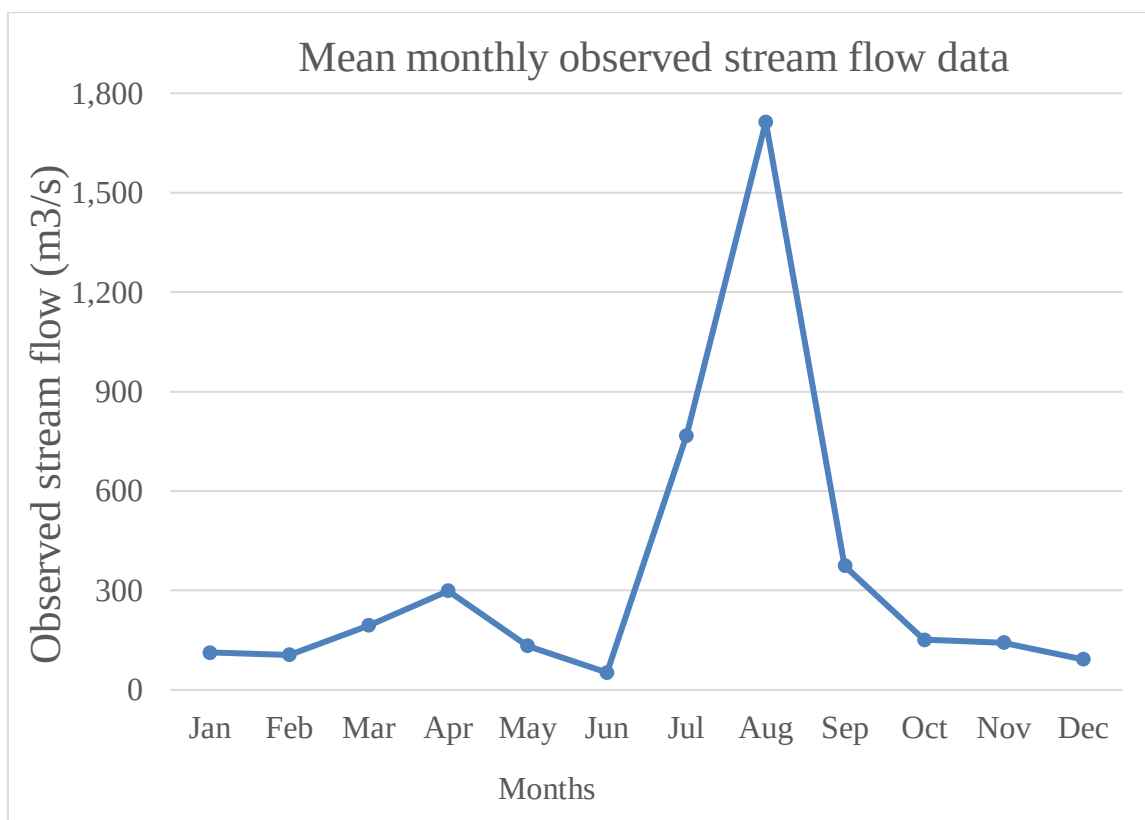
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	29.40	87.30	29.20	152.4	64.00	0.00	152.2	134.2	140.5	93.30	0.00	11.40
1994	0.00	0.00	74.60	52.20	37.90	0.00	300.1	413.2	115.0	1.70	44.40	5.80
1995	0.00	125.8	62.00	273.2	32.10	44.3	268.8	289.9	69.90	24.60	0.00	108.2
1996	78.60	1.70	157.7	115.9	199.0	72.3	113.0	263.8	60.30	37.10	51.50	6.30
1997	32.50	3.80	227.9	85.69	71.50	99.2	206.9	184.3	96.30	320.5	106.0	0.10
1998	115.2	118.9	114.8	63.50	36.10	0.00	367.5	334.4	73.50	57.00	0.00	0.00
1999	47.40	0.00	32.00	46.00	16.80	15.7	375.0	394.8	97.20	164.4	14.50	4.00
2000	0.30	0.00	15.90	69.70	33.90	35.2	338.3	338.5	85.20	126.8	49.70	115.7
2001	6.90	21.70	237.6	10.40	30.00	32.8	274.7	247.8	91.90	28.20	4.90	5.40
2002	87.60	6.20	47.00	71.60	0.60	7.90	229.5	285.3	134.0	16.80	0.00	94.70
2003	65.20	60.40	68.40	115.5	4.90	36.9	166.6	276.3	103.2	0.00	10.80	48.30
2004	22.10	11.00	37.90	119.4	4.20	36.5	166.4	225.6	68.70	58.50	63.50	17.90
2005	32.00	7.80	99.00	116.7	114.6	26.7	283.8	323.3	55.60	36.30	71.10	0.00
2006	1.60	36.20	145.2	244.2	40.40	8.30	157.0	283.7	117.8	38.60	2.60	23.00
2007	35.60	73.30	44.40	108.1	35.10	33.8	363.7	246.4	83.90	48.20	5.00	0.00
2008	42.80	0.00	0.00	27.10	33.90	46.9	132.5	341.2	134.3	49.90	132.7	1.00
2009	12.20	15.10	103.4	98.90	0.00	16.4	197.9	179.5	12.50	50.90	27.70	153.4
2010	2.80	32.70	98.30	84.00	103.4	0.00	338.7	103.4	39.60	8.10	28.64	10.80
2011	26.00	1.00	67.90	35.30	118.1	0.00	161.1	289.5	45.00	2.90	145.5	0.00
2012	0.00	0.00	85.10	154.1	39.30	70.6	384.7	252.9	76.70	14.40	0.40	1.50
2013	60.30	4.90	28.00	81.40	17.40	9.40	306.0	286.1	49.53	56.30	14.20	5.00
2014	25.20	21.80	79.70	115.7	196.1	7.80	248.8	273.5	165.6	78.30	51.80	3.20
2015	16.00	0.40	32.40	0.00	106.4	15.0	31.70	313.5	73.10	10.30	74.10	105.1
2016	32.50	49.70	98.40	160.3	122.5	30.0	268.7	351.8	97.10	1.90	30.40	0.00
2017	0.00	0.00	122.4	89.90	147.6	5.80	121.0	387.2	148.0	40.90	6.40	0.00
2018	16.50	61.80	7.30	146.1	26.40	93.5	172.5	389.1	119.3	72.70	126.2	2.80
2019	0.00	57.50	61.80	163.0	58.10	48.6	122.2	199.9	197.5	29.70	140.1	10.10
2020	19.10	12.60	73.90	188.4	87.80	22.5	292.2	320.3	92.60	26.90	39.40	16.90
2021	2.16	1.40	1.83	64.00	157.7	13.8	332.9	287.5	213.4	40.99	11.14	0.00
2022	22.29	4.10	81.40	60.73	0.00	82.2	227.0	283.4	92.20	45.30	10.30	33.10

Appendix A, Table 6: Consistency test analysis of rainfall data of Mille River watershed.

Year	Mean Annual Cumulative of all stations	Mean Cum. of Sirinka	Mean Cum. of Mille	Mean Cum. of Mersa	Mean Cum. of Haik	Mean Cum. of Bati
1993	890.54	893.90	147.90	1252.30	1222.40	936.20
1994	1776.04	1938.75	516.00	2293.94	2376.40	1755.10
1995	2958.80	3237.48	1092.00	3913.64	3611.30	2939.60
1996	3920.54	4394.68	1326.37	5003.94	4971.00	3906.70
1997	4966.01	5829.43	1533.17	6165.93	6375.50	4926.00
1998	6065.71	7110.33	1980.07	7647.03	7826.01	5765.10
1999	6981.50	8318.13	2330.57	8748.66	8923.11	6587.04
2000	8038.40	9527.33	2790.37	9810.06	10363.61	7700.64
2001	8995.23	10519.63	3089.97	10876.64	11807.46	8682.44
2002	9842.77	11500.83	3360.27	11789.44	13059.94	9503.34
2003	10709.17	12457.33	3832.47	12688.24	14140.64	10427.14
2004	11485.02	13289.03	4122.34	13484.34	15244.54	11284.85
2005	12417.54	14455.93	4469.97	14458.51	16509.04	12194.25
2006	13380.46	15554.53	4830.59	15673.11	17685.34	13158.74
2007	14245.92	16632.03	5154.02	16701.21	18759.02	13983.34
2008	14963.45	17574.33	5305.85	17464.21	19674.82	14798.04
2009	15730.80	18442.23	5464.99	18373.01	20810.92	15562.84
2010	16775.58	19292.67	5754.16	19642.71	22585.62	16602.74
2011	17528.50	20184.97	5947.79	20471.21	23638.72	17399.79
2012	18414.94	21264.67	6320.71	21561.31	24778.32	18149.69
2013	19205.44	22183.20	6568.81	22485.01	25796.22	18993.99
2014	20186.12	23450.70	6937.60	23439.41	26991.82	20111.09
2015	20907.43	24228.70	7182.06	24243.57	27824.52	21058.29
2016	21947.45	25472.00	7500.18	25406.54	29114.72	22243.79
2017	22944.97	26541.20	7868.58	26780.97	30436.32	23097.79
2018	24034.28	27775.40	8226.57	28175.94	31650.22	24343.29
2019	24970.37	28863.90	8575.59	29160.23	32959.76	25292.39
2020	25953.59	30056.50	8954.75	30208.44	34146.06	26402.22
2021	26895.70	31183.43	9307.32	31283.70	35378.73	27325.32
2022	27672.42	32125.40	9534.85	32163.29	36351.97	28186.58

Appendix A, Table 7: The monthly observed stream flow data at the outlet of Mille River watershed.

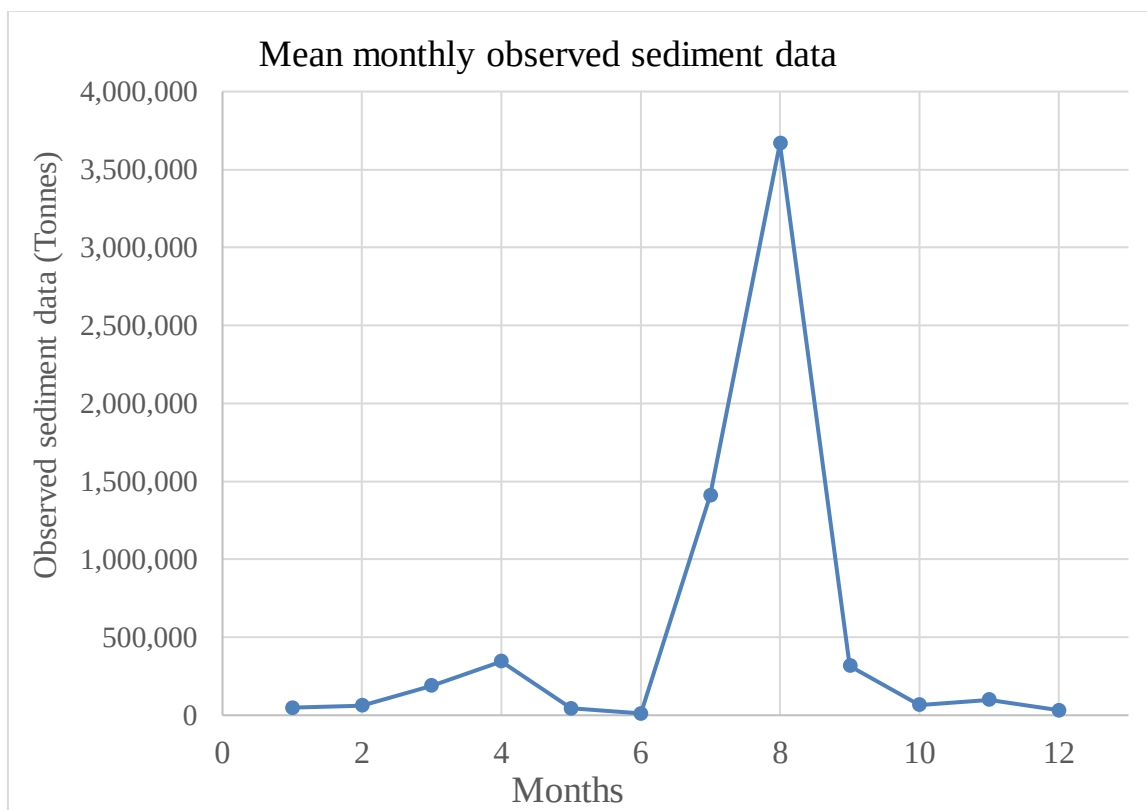
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	141.03	529.21	31.81	991.42	240.76	35.02	183.84	164.13	373.35	87.28	29.18	24.64
1994	22.19	13.12	85.1	45.55	39.88	19.89	2184.8	1686.07	941.47	88.6	39.33	28.78
1995	14.94	421.71	142.15	914.98	138.82	56.13	703.96	2332.77	169.04	47.82	33.14	85.21
1996	124.73	31.84	315.51	203.18	199.26	61.01	128.75	661.16	227.51	45.03	65.14	47.47
1997	58.98	30.54	205.32	119.8	36.7	125.88	685.46	236.57	48.39	225.82	773.41	176.8
1998	142.69	209.17	1600.65	41.7	40.19	8.67	2479.29	3472.79	481.6	259.52	100.13	72.36
1999	110.31	56.61	114.56	52.76	36.22	28.04	654.66	1516.59	519.11	462.51	202.24	147.54
2000	132.11	100.26	82.29	144.01	225.99	18.84	408.34	3553.59	278.54	701.8718	1045.31	270.89
2001	214.37	122.72	402.4	139.53	177.21	75.45	1305.3	1603.04	491.72	197.36	114.87	98.82
2002	196.14	66.22	111.61	138.85	35.73	18.03	447.4	924.87	543.62	303.93	233.05	433.58
2003	127.02	99.3	215.3	286.33	183.61	165.02	301.19	1408.24	509.89	391.73	284.05	219.56
2004	112.03	118.19	60.58	133.29	156.38	31.27	117.65	271.06	89.77	67.17	28.39	24.77
2005	21.85	12.89	59.63	72.59	49.59	20.05	798.66	719.12	296.65	75.71	39.19	28.56
2006	14.69	55.81	152.06	2159.79	187.12	53.65	202.88	516.41	226.48	77.28	32.65	56.77
2007	114.2	29.86	118.51	108.18	131.26	61.01	1608.75	1090.16	207.51	45.03	56.14	47.47
2008	112.03	125.19	30.58	133.29	156.38	31.27	148.65	121.06	202.77	67.17	28.39	24.77
2009	21.85	12.89	168.63	95.15	39.59	20.05	385.66	651.12	509.65	75.71	39.19	128.56
2010	14.69	143.81	142.06	281.79	177.12	163.65	2572.88	6866.41	1206.48	47.28	32.65	57.77
2011	114.2	29.86	141.51	177.18	180.26	61.01	128.75	2021.16	167.51	45.03	56.14	47.47
2012	118.03	112.19	30.58	152.29	153.38	31.27	1098.65	2161.06	109.77	62.17	28.39	24.77
2013	541.85	12.89	88.63	42.59	39.59	20.05	635.66	806.12	486.65	75.71	39.19	28.56
2014	14.69	55.81	112.06	235.79	132.12	53.65	862.88	2466.41	166.48	67.28	32.65	57.77
2015	114.2	29.86	228.51	197.18	199.26	61.01	110.75	682.16	227.51	45.03	56.14	47.47
2016	100.03	112.19	30.58	312.29	236.38	31.27	228.65	5195.06	504.77	67.17	28.39	24.77



Appendix A, Figure 1. The Mean monthly observed stream flow of the Mille River watershed.

Appendix A, Table 8: The mean monthly sediment data at the outlet of Mille River watershed.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	43,630.65	524,667.46	3,753.33	1,773,564.39	102,003.5	4,237.20	94,490.09	74,624.37	303,312.48	23,257.35	2,669.99	2,012.72
1994	1,680.18	744.79	27,148.78	7,648.75	5,562.87	1,420.11	6,495,381.01	3,398,533.13	1,385,444.5	23,487.93	5,020.42	2,624.11
1995	883.62	498,094.18	50,020.66	1,205,751.13	41,820.81	8,876.40	749,648.69	4,244,908.77	56,953.20	6,025.41	3,226.72	22,520.29
1996	35,285.46	3,236.43	221,706.32	82,173.35	73,195.50	11,821.74	44,581.92	586,245.73	104,363.51	5,908.43	13,029.53	5,719.68
1997	9,672.14	3,037.02	116,265.88	35,107.32	4,399.13	60,815.90	688,776.60	82,843.75	8,333.84	127,129.38	967,527.50	107,482.09
1998	38,571.27	142,250.43	3,269,198.8	7,754.43	6,509.60	364.99	7,400,339.70	9,385,930.84	318,311.10	97,226.15	19,705.88	11,288.53
1999	23,299.44	8,187.88	32,383.52	8,151.04	3,850.42	2,472.00	512,017.57	2,079,943.63	345,285.78	258,605.21	61,965.27	35,876.84
2000	29,967.62	19,961.84	14,127.97	46,438.63	128,169.3	1,284.42	356,073.32	7,572,423.74	117,256.23	536,705.32	1,018,343.5	101,400.48
2001	70,383.62	29,060.35	236,806.83	36,777.70	58,219.35	12,776.96	2,295,599.43	2,275,792.96	293,105.52	59,522.74	24,443.47	18,752.66
2002	68,522.71	10,522.23	25,320.61	48,414.01	4,624.77	1,203.74	483,146.05	857,580.34	382,628.58	119,207.51	77,216.86	258,707.69
2003	29,252.30	22,781.28	85,568.71	128,036.96	52,285.80	44,184.72	124,464.48	1,708,139.58	279,820.89	182,756.36	107,214.08	75,902.96
2004	25,145.39	29,731.98	18,793.93	36,598.27	43,055.72	3,307.68	36,421.12	106,026.34	19,682.08	11,719.02	2,543.12	2,029.64
2005	1,639.68	724.98	11,565.51	20,007.21	9,906.53	1,438.52	1,163,245.60	563,069.48	147,219.25	16,983.64	5,001.29	2,598.10
2006	860.83	12,448.88	79,991.78	4,172,825.41	72,353.85	8,112.90	77,854.17	291,480.04	95,747.46	19,966.74	3,145.63	8,942.14
2007	28,022.79	2,959.66	32,264.73	25,326.90	32,023.10	11,821.74	2,764,096.05	1,237,465.97	83,807.34	5,908.43	9,196.33	5,719.68
2008	25,145.39	33,157.89	3,533.41	36,598.27	43,055.72	3,307.68	55,660.95	37,269.66	91,424.69	11,719.02	2,543.12	2,029.64
2009	1,639.68	724.98	69,159.86	33,544.06	5,527.54	1,438.52	215,161.12	487,006.68	442,037.65	16,983.64	5,001.29	50,092.93
2010	860.83	68,961.78	50,004.21	132,892.37	67,620.98	64,501.69	6,024,399.75	20,958,418.43	2,024,039.9	5,913.31	3,145.63	9,179.57
2011	28,022.79	2,959.66	42,102.46	61,365.04	63,710.92	11,821.74	44,581.92	3,810,761.40	58,100.43	5,908.43	9,196.33	5,719.68
2012	27,525.71	28,050.40	3,533.41	45,156.94	41,936.27	3,307.68	2,066,368.29	3,787,764.65	30,176.25	9,926.42	2,543.12	2,029.64
2013	601,134.2	724.98	27,950.32	6,907.52	5,527.54	1,438.52	861,145.90	727,937.10	476,245.97	16,983.64	5,001.29	2,598.10
2014	860.83	12,448.88	29,470.41	99,544.24	37,604.80	8,112.90	1,109,283.50	4,462,909.19	61,052.79	15,112.39	3,145.63	9,179.57
2015	28,022.79	2,959.66	99,508.13	79,078.46	73,195.50	11,821.74	32,188.20	548,958.44	104,363.51	5,908.43	9,196.33	5,719.68
2016	20,530.50	28,256.10	3,533.41	176,733.59	89,514.65	3,307.68	137,554.28	18,718,070.42	384,750.24	11,719.02	2,543.12	2,029.64



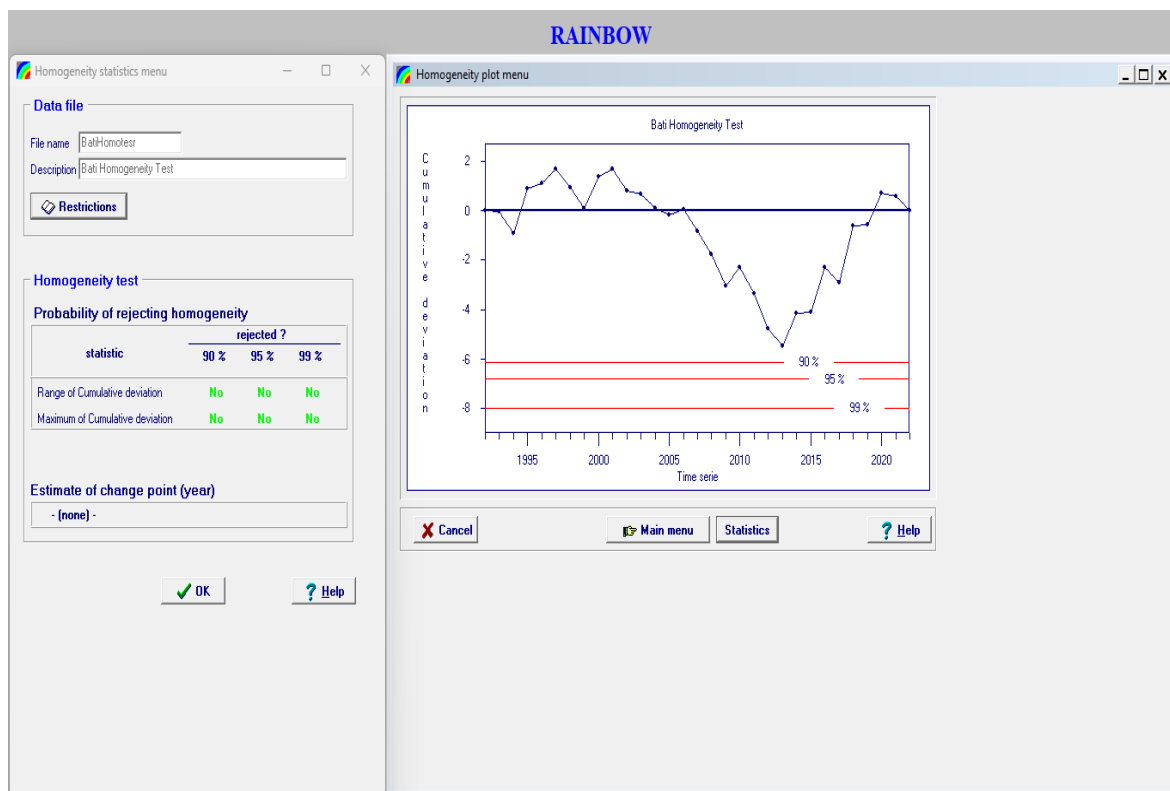
Appendix A, Figure 2. The mean monthly observed sediment data of the Mille watershed.

Appendix A, Table 9: Sediment data collected for the development of rating curve.

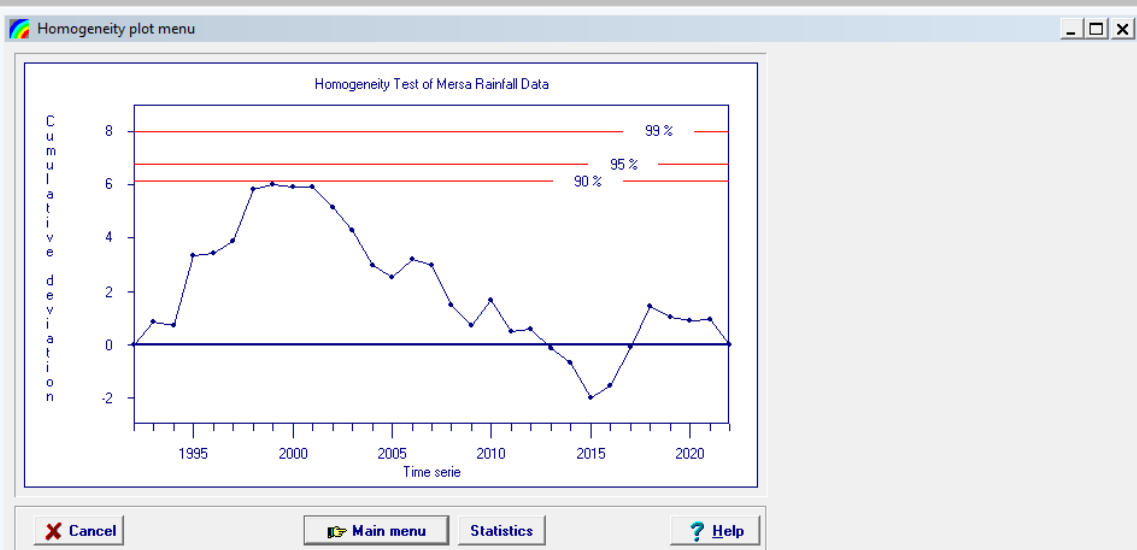
River Name	Basin Name	Stream Flow (m3/sec)	Sediment Concentration (mg/l)	Sediment Load (Metric ton/day)
Mille	Awash	14.387	25538.38	31745.14615
Mille	Awash	14.387	25696.23	31941.35951
Mille	Awash	14.387	25788.63	32056.21611
Mille	Awash	15.796	4652.17	6349.16252
Mille	Awash	15.796	4571.43	6238.970635
Mille	Awash	15.796	4500	6141.4848
Mille	Awash	15	4218.75	5467.5
Mille	Awash	15	4033.33	5227.19568
Mille	Awash	15	4000	5184
Mille	Awash	9.02	2500	1948.32
Mille	Awash	9.02	2500	1948.32
Mille	Awash	9.02	2677.42	2086.588374
Mille	Awash	1.098	2565.56	243.3874936
Mille	Awash	1.098	2662.37	252.5715873
Mille	Awash	1.098	2726.36	258.6421394
Mille	Awash	0.834	489.75	35.2902096
Mille	Awash	0.834	521.67	37.59028819
Mille	Awash	0.834	575.65	41.47995744
Mille	Awash	0.451	892.83	34.79037091
Mille	Awash	0.818	670.1	47.35945152
Mille	Awash	0.818	679.2	48.00259584
Mille	Awash	0.818	717.74	50.72641805
Mille	Awash	0.711	322.58	19.81621843
Mille	Awash	0.711	304.35	18.69634224
Mille	Awash	34.993	39726.49	120108.8792
Mille	Awash	34.993	40522.86	122516.6204
Mille	Awash	34.993	32455.26	98125.0773
Mille	Awash	9.418	8295.83	6750.442968
Mille	Awash	9.418	8201.57	6673.742173
Mille	Awash	9.418	8283.81	6740.662111
Mille	Awash	29.99	5839.21	15130.18724
Mille	Awash	29.99	6243.43	16177.57624
Mille	Awash	29.99	5627.5	14581.61784
Mille	Awash	11.258	1301.35	1265.811693
Mille	Awash	11.258	1295.93	1260.539707
Mille	Awash	11.258	1316.22	1280.275611
Mille	Awash	8.032	456.85	317.0378189
Mille	Awash	8.032	464.48	322.3327703
Mille	Awash	8.032	502.80	348.9255014
Mille	Awash	7.029	21697.59	13177.06791
Mille	Awash	7.029	22407.24	13608.04233
Mille	Awash	7.029	22464.00	13642.513
Mille	Awash	28.287	36483.71	89166.07049

Mille	Awash	28.287	32716.04	79957.89707
Mille	Awash	28.287	41106.50	100464.1545
Mille	Awash	71.263	32014.35	197116.2971
Mille	Awash	71.263	26828.72	165187.7343
Mille	Awash	71.263	26479.35	163036.6202
Mille	Awash	47.565	26100.00	107260.9776
Mille	Awash	47.565	26347.55	108278.313
Mille	Awash	47.565	28677.64	117854.0882
Mille	Awash	306.069	2185.60	57796.79671
Mille	Awash	306.069	53245.00	1408030.033
Mille	Awash	306.069	37055.69	979914.0657
Mille	Awash	763.033	39225.94	2586011.329
Mille	Awash	764.033	40879.71	2698569.861
Mille	Awash	765.033	42999.85	2842240.687
Mille	Awash	46.942	1073.24	4352.834772
Mille	Awash	46.942	13972.06	56667.72446
Mille	Awash	46.942	18379.18	74542.0724
Mille	Awash	65.590	3822.58	21662.46912
Mille	Awash	65.590	7200.00	40802.2272
Mille	Awash	65.590	4000.00	22667.904
Mille	Awash	58.911	17483.87	88991.33175
Mille	Awash	58.911	15944.44	81155.77098
Mille	Awash	58.911	1029.41	5239.604665
Mille	Awash	39.134	16189.78	54740.52148
Mille	Awash	39.134	1486.49	5026.086691
Mille	Awash	39.134	1132.35	3828.676455
Mille	Awash	24.877	18822.58	40456.74148
Mille	Awash	24.877	13932.43	29945.98608
Mille	Awash	24.877	2914.29	6263.895657
Mille	Awash	91.320	2957.14	23331.97654
Mille	Awash	91.320	13561.64	107001.9906
Mille	Awash	91.320	17814.29	140555.6032

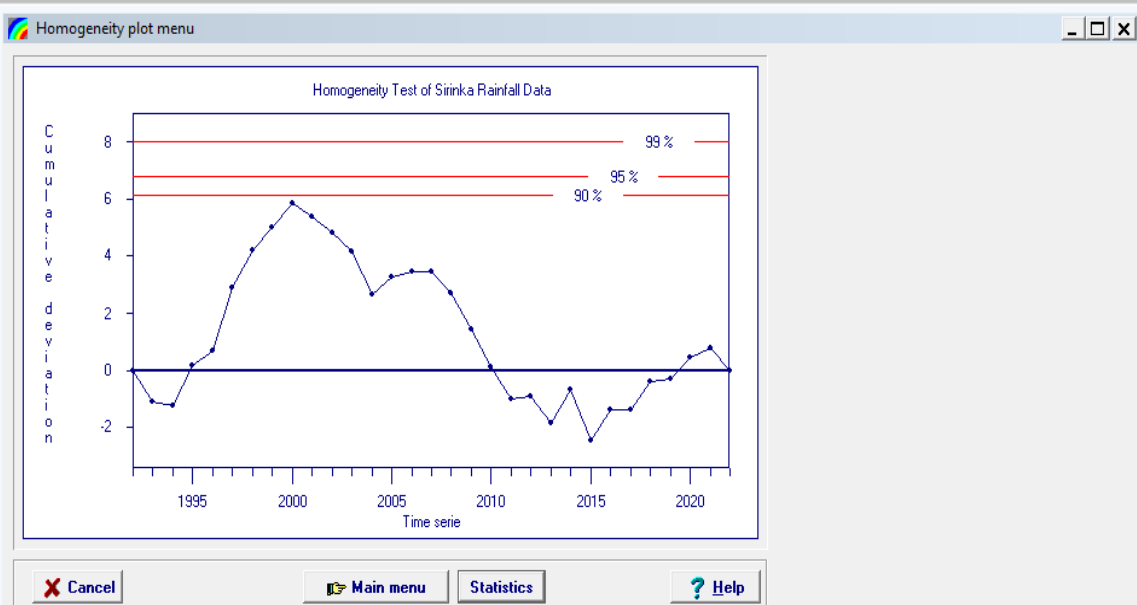
Appendix B, Figure 1-4: Homogeneity test and statistics of meteorological station rainfall data.



RAINBOW



RAINBOW

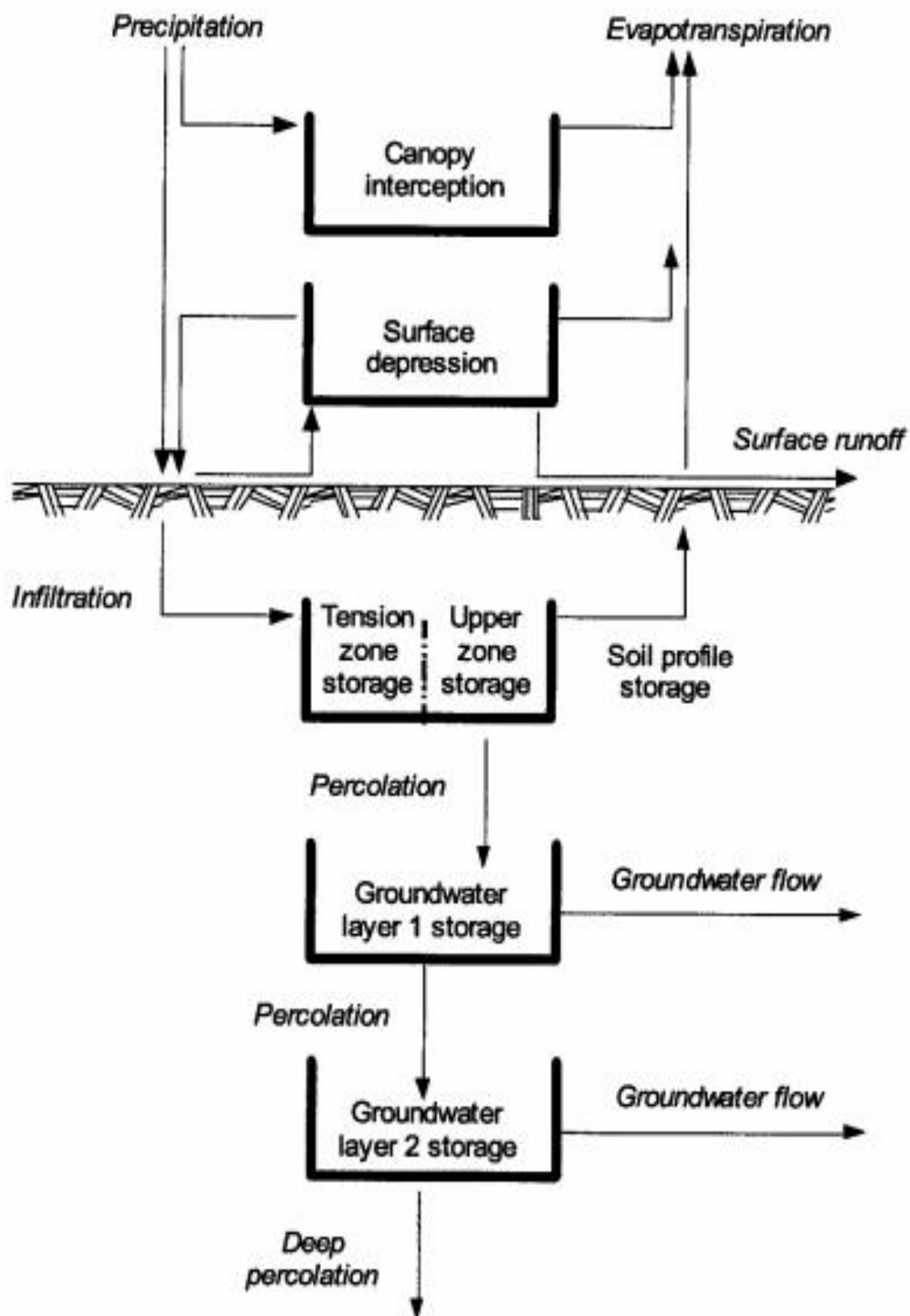


Appendix C, Table 1: The maximum surface storage (mm) is estimated with the slope (%) of the catchment surface, as the table below;

Maximum surface storage (mm) is estimated with the slope (%) of the catchment surface, as the table below;			
No	Surface depression	Slope (%)	Maximum Surface storage (mm)
1	Paved impervious area	NA	3.2 - 6.4
2	Steep, smooth slope	>30	1
3	Moderate to gentle slope	0-30	12.7 - 6.4
4	Flat, Furrowed land	0-5	50.8

Appendix C, Table 2: The maximum canopy simple method used in HEC-HMS model, as the table follows.

Maximum canopy simple method used in HEC-HMS as the following table;			
No	Type of Vegetation	Max. Canopy (mm)	SCS land use class
1	Species of vegetation is not directly known	1.27	Small grain, straight row, good condition
2	Grasses and deciduous trees	2.032	Brush, fair condition + Pasture, fair condition
3	Coniferous trees	2.54	Pinyon, good + fair + bad condition
4	Water Bodies	0	Other classes



Appendix C, Figure 1. The conceptual representation of soil moisture accounting (SMA) loss method.

Appendix C, Table 3. The soil moisture accounting (SMA) loss method parameters.

Sub-basin	Soil (%)	GW1 (%)	GW2 (%)	I (mm/hr)	Impervious (%)	Soil storage (mm)	Tension storage (mm)	Soil percolation (mm/hr)	GW1 storage (mm)	GW1 percolation (mm/hr)	GW1 coeff. (hr)	GW2 storage (mm)	GW2 percolation (mm/hr)	GW2 Coeff. (hr)
W300	9.21	5	5	6.50	2.81	56.768	10.408	1	0.18	1	150.78	6.52	1	250.96
W290	8.86	5	5	2.48	2.91	56.537	12.229	1	0.29	1	150.78	10.76	1	250.96
W280	9.87	5	5	5.29	2.32	54.032	10.611	1	0.17	1	150.78	6.27	1	250.96
W270	9.65	5	5	3.85	2.60	53.671	12.688	1	0.29	1	150.78	10.76	1	250.96
W230	9.76	5	5	5.58	2.48	56.119	11.406	1	0.25	1	150.78	9.33	1	250.96
W220	9.93	5	5	5.85	2.54	56.541	12.222	1	0.15	1	150.78	5.70	1	250.96
W190	9.90	5	5	5.76	2.76	56.797	11.292	1	0.46	1	150.78	17.04	1	250.96