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EVALUATING THE PERFORMANCE OF HYDROLOGICALMODELS IN RUNOFF SIMULATION:A CASE OF MERSARIVER WATERSHED, AWASH BASIN, ETHIOPIA

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ENGINEERING HYDROLOGY PROGRAM

MSc Thesis on:

EVALUATING THE PERFORMANCE OF HYDROLOGICAL MODELS IN RUNOFF SIMULATION: A CASE OF MERSA RIVER WATERSHED, AWASH BASIN, ETHIOPIA

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EVALUATING THE PERFORMANCE OF HYDROLOGICAL MODELS IN RUNOFF SIMULATION: A CASE OF MERSA RIVER WATERSHED, AWASH BASIN, ETHIOPIA

BY:

DESALE KASSA

The thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering Hydrology.

Advisor; Dr. Hanibal Lemma

September, 2022

Bahir Dar, Ethiopia

DECLARATION

This is to certify that the thesis entitled "***Evaluating the Performance of Hydrological Models in Runoff Simulation; a Case of Mersa River Watershed, Awash Basin, Ethiopia***", submitted in partial fulfillment of the requirements for the degree of Master of Science in **Engineering Hydrology** under **Faculty of civil and water resource engineering,** Bahir Dar Institute of Technology , is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Desale Kassa Miretie	____________	_June, 2023___
Name of the candidate	signature	Date

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Approval of thesis for defense result

I hereby confirm that the changes required by the examiners have been carried out and incorporated in the final thesis.

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As members of the board of examiners, we examined this thesis entitled "*Evaluating the Performance of Hydrological Models in Runoff Simulation; a Case of Mersa River Watershed, Awash Basin, Ethiopia*" by **Desale Kassa Miretie**. We hereby certify that the thesis is accepted for fulfilling the requirements for the award of the degree of Masters of Science in Engineering Hydrology.

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ABSTRACT

Numerous hydrological modeling studies have been carried out in several basins with various climatic, land-use, soil, and geological conditions. The applied models have different structure to simulate discharge. conducting comparative analyses of models and identifying better models which represent realistic simulation is important for proper development and management of water resource for the watershed.

The main objective of this study is to conduct comparative analysis of rainfall-runoff modeling using HEC-HMS and PED-W Models and its relative strength to simulate discharge for Mersa River watershed. A successive seventeen years (1996-2012) hydro-meteorological data were used for comparisons of these models. For this study's comparison of these hydrological models, hydro-meteorological data analysis, sensitivity analysis, calibration, and validation were completed.

From the parameters of PED-W model hill side area and maximum water storage were very highly sensitive parameter for runoff estimation in the selected watershed. These parameters were very flexible when changing its value. The HEC-HMS model's most sensitive parameters were surface maximum storage, SMA maximum infiltration and SMA soil storage. These sensitive parameters were grouped under the loss model.

The model efficiency measurement techniques were Nash Sutcliff efficiency (NSE), coefficient of determination (R^2) and root mean square error (RMSE).

The corresponding value of the PED-W and HEC-HMS models during daily calibration period were, (0.666, 0.664), (0.705, 0.695) and (1.31, 0.6) of NSE, R^2 and RMSE value respectively. Similarly for validation period were (0.55, 0.542), (0.674, 0.555) and (1.61, 0.7) of NSE, R^2 and RMSE value respectively. Based on these objective function outputs PED-W model had better performance.

Key word: Mersa Watershed, HEC-HMS, PED-W

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LIST OF ABBREVIATION

ANN	Artificial Neural Network.
ARNO	Arno River model
CN	Curve Number
DEM	Digital Elevation Model
DMC	Double mass curve
ET_O	Reference Evapotranspiration
GFMFS	Galway River Flow Modeling and Forecasting System
GIS	Geographical Information System
HBV	Hydrological Byrans avdeling for Vattenbalans model
HEC-HMS	Hydrologic engineering center for Hydrological modeling system
IHACRES	Identification of unit hydrograph and Component from Rainfall Evaporation and Stream flow
LPM	Linear Perturbation Model
LULC	Land use land cover
PED-W	Parametric Efficient semi distributed watershed model
PET	Potential Evapotranspiration
NSE	Nash-Sutcliffe model efficiency index
REFH	Revitalized Flood Hydrograph
R^2	Coefficient of determination
RMSE	Root Mean Square Error
SCS	Soil Conservation Service
SLM	Simple Linear Model

1. INTRODUCTION

1.1 Background

Establishing rainfall- runoff relationship is a fundamental focus of hydrologic modeling from its simple form unit hydrograph to further complex model based on fully dynamic flux equation. Rainfall-runoff model have been under a continuous state of development. Model used in the earlier day did not integrate the different phase of the hydrological cycle. Instead, they implemented simple mathematical relationship between precipitation and certain attributes of final catchment response. However, runoff estimation is normally based on rainfall-runoff process (Hundecha Hirpa, 2005). But the applications of models are different due to the fact that catchments are heterogeneous; In this regard comparative studies in modeling would enable to identify suitable model for understanding hydrological processes better and prediction of environmental changes.

Many research has been conducted in our country utilizing different hydrological models to simulate the relationship between rainfall and runoff. Accurately predicting catchment runoff and the responses of watershed characteristics to rainfall events are the main issues left to hydrological models. It might be challenging to select the best model among the many that are available for a given task because each modeler tends to highlight the advantages of their method (Johnson et al., 2003). Therefore, comparative based evaluation studies are needed to assess the structural validity, and limitations of watershed models and to provide a basis for selecting a model that will perform adequately in a specific application (Johnson et al., 2003).

Different models selection criteria have been presented in various types of literature; however, for this study, the choice of the used hydrological model is mostly based on its performance, availability, application, and required input data. The two models selected for comparative analysis of rainfall-runoff modeling for the selected watershed are HEC-HMS and PED-W models.

This research will be conducted in Mersa river watershed it is found in Awash River basin with the aim of identifying better model in predicting discharge in terms of model conceptualization, parameterization and capturing the response mode of the daily hydrographs during the wet and dry seasons.

1.2 Statement of the Problem

A rainfall runoff model is useful for analyzing catchment behavior that is none linear. As we know, there are numerous rainfall and runoff models that are used for various catchments with various climatic conditions. But identifying of models which represent realistic simulation for the catchment is important for proper management of water resources.

In the country, there are large number of hydrological modeling works has been conducted in different basins under different climate, land use, soil, geology and topographical setting (Taffese, 2011; Temesgen, 2019; Tulu, 2011) among many other studies. The applied models have different structure to simulate discharge. Their ability in simulating discharge in a comparative approach has not yet been explored. Furthermore, identifying better model conceptualization, parsimony issue, identifiably of parameters and predictive ability are key points in understanding catchment behavior at various Spatial- temporal scales. Comparative modeling studies thus would enable to gain an insight about the weakness and the strength of the models in capturing the various response mode of the hydrograph by evaluating the credibility of the model through better process representation, parsimony, identifiably and uncertainty assessment.

The main difficulty in hydrological modeling is expressing a catchment's response in terms of its state variables and characteristics. This necessitates finding a solution to the "closure problem," which requires defining the conditions under which the indeterminate system of balance equations can be closed (Reggiani et al., 2000). A major obstacle to this challenge is the lack of appropriate measuring techniques, which hampers the identification of the mechanisms underlying the rainfall runoff transformation (Beven, 2006). To circumvent this problem, internal catchment behavior has to be inferred by other means.

In general, comparative model assessments to understanding the relation between rainfall and runoff and to identify the dominant hydrological processes in the Mersa watershed are crucial for a variety of reasons. For instance, efficient planning and management of water resources will make it easier to predict extremes and the consequences of coupled changes in land use and climate on stream flow availability.

1.3 Objectives

Main objective

The main objective of this study is to conduct comparative analysis of rainfall-runoff modeling using HEC-HMS and PED-W Models and its relative strength to simulate discharge for Mersa River watershed.

Specific objectives

- To evaluate the performance of each hydrological models based on the model efficiency measurement techniques.
- To estimate simulated discharge in Mersa river watershed

1.4 Research Question

- Which model perform well based on the model efficiency measurement techniques?
- Which hydrological model is better in simulating the discharge at the watershed outlet?

1.5 Significance of the Study

Hydrological model development and use are essential components of future water resource management and planning. As a result, this study is used for the integrated management of water resources planning and implementation in Mersa river watershed. Estimating simulated discharge on the stream have a great significance to design different water related structures in the watershed. This study is important to control runoff by planning and implementing different watershed conservation measures.

1.6 Scope of the Study

The performance of the PED-W and HEC-HMS models was largely examined in this work in order to more accurately simulate Mersa stream flow and to compare the candidate models. This study used from 1996-2012 GC hydro-meteorological data for model comparisons proposes, and the result and conclusion have been drown based in this time series data only.

1.7 Thesis Organization

The thesis was organized in to five chapters. Chapter one is an introduction part which has background of the research, problem statement, the purpose of the research, significant and scope of the document. Chapter two is the literature review part and it includes the hydrology, hydrological models' classification, worked research on the selected model's approach and model set ups were briefly discussed. Chapter three presents the materials and methodology part of the research. It includes, with the study area, data availability and its quality analysis, conceptual frame work of the research, modeling of each utilized models, sensitivity analysis, calibration, validation and model performance evaluation techniques were briefly described. In chapter four the results and discussion of each model's sensitivity, calibration validation and model comparison were briefly described. Chapter five describes the conclusion and recommendation.

2. LITERATURE REVIEW

2.1 Hydrological Process

When precipitated water is intercepted by plants, the rain continues some of the precipitation's overland flow over the ground surface, infiltrates the earth and flows through the soil as subsurface flow, and empties into streams as surface runoff. This process is known as hydrology. The infiltrated water may percolate deeper to recharge groundwater, later emerging as spring, and seeping into streams to form surface runoff and finally flowing into the sea or evaporating into the atmosphere as the hydrological cycle continues (Tsegaw, 2019).

According to (Edwards et al., 1983), the major components of the hydrological process are interception and infiltration (loss), Evaporation Runoff. The first part of the hydrological cycle to directly return to the atmosphere is interception. It blows on 'rough' canopies in an aerodynamic manner as a result of the high wind speed. Infiltration is the physical process involving the movement of water through the boundary area where the raindrops interfaces with the soil. Normal soil texture and structure, initial soil moisture content, decreasing water concentration as water moves deeper into the soil, filling of the pores in the soil matrices, changes in the soil composition, and swelling of the wet soils that in turn close soil cracks all affect the infiltration rate (Edwards et al., 1983).

In terms of the hydrological cycle and the water balance, evaporation and transpiration is the second largest component. It is a process that involves returning moisture to the atmosphere and is influenced by various circumstances (Edwards et al., 1983).

Runoff is flowing from a drainage basin or watershed that appears in surface streams. The flow is made up partly of precipitation that falls directly on the stream and partly it get from lateral flow. There are three types of runoff: groundwater runoff from deep percolation through the soil horizons, subsurface runoff that penetrates the surface soils and travels laterally towards the stream. Surface runoff flows over the land surface and through channels. A portion of the subsurface flow enters the stream rapidly, but the remainder may take some time to mix with the stream's water. The total runoff is formed when all of the component flows enter the stream. Stream flow, also known as direct runoff or base flow, is the term used to describe the entire amount of runoff that enters stream channels.

Generally, (Chiew et al., 1993), describe that the hydrological cycle is the central focus of any hydrological metrological study and the hydrological process has no beginning and end the process occurs continuously. It is noted that through the concept of the hydrologic cycle seems simple, the phenomena are very complex and multiple it is not just one large cycle but it is rather many interrelated cycles of continental regional local extent. The major achievement and objectives of the rainfall-runoff modeling are thus to study a part of the hydrological cycle namely the land phase of the hydrological cycle on a catchments scale. Then the problem becomes to express the runoff from the catchments as a function of the rainfall and other catchments characteristics (Tsegaw, 2019).

2.2 Hydrological Model

There are a variety of reasons, according to (Beven, 2011), why it is necessary to simulate the rainfall-runoff process in hydrology. which is mostly because of the limits of hydrological measurement methods. We are not able to measure everything we would like to know about hydrological systems. In fact, we have, only a limited range of measurement techniques and a limited range of measurements in space and time (Keith, 2002). On the other side, the primary objective of hydrological modeling is relatively often to generate a long representative time series of stream flow volumes from which water supply schemes and civil structures can be designed(Hughes, 1995; Mwelwa, 2004). For efficient and dependable design decisions to be made, longer stream flow time series is essential. Therefore, flow time series data have to be generated with sufficient accuracy through the use of hydrological models (Ido, 2008).

Precipitation turns into channel flow through a very intricate physical mechanism. The representation of watershed processes with a hydrological model is a frequent approach. Governmental organizations, academic institutions, and commercial businesses have created a wide range of hydrological models. They deal with a wide variety of alternatives for process simulation, varying degrees of complexity and data needs, and varying levels of technical support and training. Their application also depends on the forecasting objective, geographical and environmental factors, as well as institutional capabilities. Therefore, the selection of a "best choice" model needs to be based on a systematic approach (Sibanda, 2015).

2.3 Classification of hydrological Models

To help explain and discuss the capabilities, advantages, and disadvantages of hydrological models, these characteristics or classifications are typically used. Hydrological models have been categorized in a variety of ways based on the criteria of interest, but there is no universal approach for doing so (Tsegaw, 2019)

Some literature classifies hydrological models broadly into two categories. Physical and mathematical model, physical models are a representation of the real system. Further, physical model is categorized as scale and analog model. There are various uses of the physical model in engineering and science. The Mathematical model expresses the system behavior by a set of equations, together with logical statements expressing relationships between variables and parameters. Further, mathematical model is classified as theoretical, empirical and conceptual models. Theoretical, empirical and conceptual model further can be classified linear, non-linear, steady, non-steady, lumped, distributed, deterministic and stochastic models (Gupta et al, 2015).

The deterministic models can be broadly classified into three categories based on the degree of approximation of the physical processes and their scale of representation by existing physical laws. Which is System-based (black box) models, Quasi-physical (lumped) conceptual models, and Physically-based distributed models.

i. System-based (block box) models

Regression equations are an example of a black box model that doesn't try to explicitly depict the actual processes. Instead, they use studies of concurrent input and output time series to develop mathematical equations and establish links between the components of the physical processes. Simple Linear Model (SLM), Linear Perturbation Model (LPM), and Neural Network Model, among others, are examples of system-based models.

ii. Quasi-physical (lumped) conceptual models

The conceptual model approach to rainfall-runoff modeling lies intermediate between physically based models and black box models. Generally, the term "conceptual" is used to describe models which rely on a simple arrangement of a relatively small number of interlinked conceptual elements, each representing a segment of the land phase of the hydrological cycle. The most commonly used element in a conceptual model is a storage component. Each such storage usually has one input and one or more outputs and is used to represent basin storage such as surface detention, soil moisture etc. Linear reservoirs and channels are generally used for routing purposes. Conceptual modeling basically consists of a set of rules which govern the moisture flow from one element to another. Conceptual models were initially developed to model small homogeneous areas. Examples of lumped conceptual models include Soil moisture accounting (SMAR), ARNO, Stanford watershed model, and HBV Models, etc.

iii. Physically-based distributed models

The physical processes are explained by nonlinear partial differential equation (PDE) with appropriate numerical methods. The hydrological processes are resolved at finer grid networks and time intervals and require high resolution data and more computing effort and time. The distributed models, attempt to account for the spatial variability in the physical characteristics of a catchment. These models make use of information about topography, soil type and patterns and changes of vegetation.

2.4 Hydrologic Model Selection Criteria

According to (Loucks & Van Beek, 2017), the decision to employ an existing model in each project is influenced by the processes that will be modeled, the data that is available, and the data that the model needs. An important practical criterion is whether there is an accessible manual for operating the model program and a help desk available to address any possible problems. The decision to use a model, and which model to use, is an important part of water resources plan formulation. Even though there are no clear rules on how to select the right model to use, a few simple guidelines can be stated by Elko were:

- ✓ Define the problem and determine what information is needed and what questions need to be answered.
- ✓ Use the simplest method that will yield adequate accuracy and provide the answer to your questions.
- ✓ Select a model that fits the problem rather than trying to fit the problem to a model.
- ✓ Whether increased accuracy or increased effort and increased cost of data collection.

- ✓ Required model outputs important to the project and therefore to be estimated by the model
- ✓ Hydrologic processes that need to be modeled to estimate the desired outputs adequately (Is the model capable of simulating single-event or continuous processes?)
- ✓ Availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?)
- ✓ Price (Does the investment appear to be worthwhile for the objectives of the project)

2.5 Model Calibration and Validation

Once a modeling approach or a particular model has been selected, its strengths and limitations should be studied in more detail. The primary step is to set up a plan for testing and evaluating the model. The model can be run under extreme input data conditions to see if the results are as expected. Once a model is tested satisfactorily, it can be calibrated. Calibration emphases on the comparison between model results and field observations. During calibration sensitivity analysis must be done in order to determine the model parameter as well as to get best calibration result.

i. Sensitivity analysis

Sensitivity analysis involves investigating the behavior of the performance of a model in respect of one or more parameters which might be highly sensitive or insensitive to changes in values. A parameter which is insensitive to changes in values, may be kept at a fixed value while carrying out optimization to reduce the effective number of parameters to be optimized, thereby ensuring better convergence to optimum value of the objective function. The sensitivity analysis tool is helpful to model users in identifying parameters that are most influential in governing stream flow response. Sensitivity analysis helps to determine the relative ranking of which parameters most affect the output variance due to input variability (Saltelli et al., 2000).

ii. Calibration

In order to evaluate a hydrologic model's performance, subjective and/or objective evaluations of how well the model's simulated behavior matches observations are needed (Krause et al., 2005). An important principle during calibration is the smaller the deviation between the calculated model results and the field observations, the better the model. This is indeed the case to a certain extent, as the deviations in a perfect model are only due to measurement errors. In practice, however, a good fit is by no means a guarantee of a good model. The deviations between the model results and the field observations can be due to a number of factors (Loucks & Van Beek, 2017) .

iii. Validation

To determine whether or not a calibrated model is 'good', it should be validated or verified. Validation can be carried out for calibrated models as long as an independent data set has been kept aside for this purpose. The model can then be regarded as having been validated, at least for the ranges of input data and field observations used in the validation. If model predictions are to be made for situations or conditions for which the model has been validated, one may have a degree of confidence in the reliability of those predictions (Beek & Elko, 2005).

2.6 Model Performance Criteria

Decisions on the goodness of the estimated model parameters was to a great extent based on measurement of the model performance, collective use of the three efficiency criteria will be considered. The selected performance criteria with their short description and limitation of each efficiency criteria are summarized from (Krause et al., 2005) as follows.

i. Nash and Sutcliffe Efficiency Criteria (NSE)

NES efficiency criteria Proposed by Nash and Sutcliffe (1970) its value lies between $-\infty$ to 1. If the NSE efficiency approach to zero (perfect fit). An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model. The largest disadvantage of this efficiency criterion is that larger values in a time series are strongly overestimated whereas lower values are of minor importance. For the quantification of runoff predictions this leads to an overestimation of the model performance during peak flows and an underestimation during low flow conditions.

ii. Coefficient of Determination (R^2)

Estimates how much of the observed dispersion is explained by the prediction. Its value range lies between 0 and 1 and a value of zero means no correlation at all whereas a value of one means that the dispersion of the prediction is equal to that of the observation. Similar to R is not very sensitive to systematic model over or under prediction especially during low flow periods. A model which systematically over or under predicts all the time will still result in good R values close to 1.0 even if all predictions were wrong (Krause et al., 2005).

iii. Root mean square error (RMSE)

The Root Mean Square Error (RMSE) (also called the root mean square deviation, RMSD) is a frequently used measure of the difference between values predicted by a model and the values actually observed from the environment that is being modeled. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power.

Table 2.1 Efficiency criteria for evaluating model performance

Objective function	Definition	Value for perfect fit
1.Nash and Sutcliffe Efficiency Criteria (NSE)	$1-\frac{\sum(Q_{obs}-Q_{sim})^2}{\sum(Q_{obs}-\overline{Q_{sim}})^2}$	1
Coefficient determination (R)	$1-\frac{\sum(Q_{obs}-\overline{Q_{obs}})^2(Q_{sim}-\overline{Q_{sim}})^2}{\sum(Q_{obs}-\overline{Q_{obs}})^2(Q_{sim}-Q_{sim})^2}$	1
Root mean square error (RMSE)	$\sqrt{\frac{\sum(Q_{obs}-Q_{sim})^2}{No.of\ days}}$	Approach to zero

2.7 Description of the Selected Model

i. HEC-HMS model

The HEC-1 hydrologic model was originally developed in 1967 by Leo R. Beard and other staff members of the Hydrologic Engineering Center, with the U. S. Army Corps of Engineers, to simulate flood hydrographs in complex river basins (Singh, 1982). Since then, the program has undergone a revision: different versions of the model with greatly expanded capabilities have been released. The current version of HEC-HMS and this study used the 4.3 HEC-HMS Version.

The HEC-HMS model is designed to simulate the surface runoff response of a catchment to precipitation by representing the catchment with interconnected hydrologic and hydraulic components. It is primarily applicable to flood simulations (Oleyiblo & Li, 2010).

Hydrologic elements are arranged in a dendritic network, and computations are performed in an upstream-to-downstream sequence. The SI (System International units) system is used for calculations. However, the U.S. Customary system allows you to enter input, examine output in units, and easily convert input results between one unit system and another.

HEC-HMS includes four main components: basin, meteorological, control specifications component, and time series data component. The basin model stores the physical datasets describing the catchment properties and the meteorological model includes precipitation, evapotranspiration, and snowmelt data. Six different historical and synthetic precipitation methods, two evapotranspiration methods, and one snowmelt method are included. The time span of a simulation is controlled by control specifications including a starting date and time, ending date and time, and computation time step. The last component used for controlling time series data such as rainfall, discharge and evapotranspiration data.

HEC-HMS provides a variety of options for simulating precipitation-runoff processes. In addition to unit hydrograph and hydrologic routing options similar to those in HEC-1, HEC-HMS capabilities currently available include: a linear-distributed runoff transformation that can be applied with girded (e.g., radar) rainfall data, a simple "moisture depletion" option that can be used for simulations over extended time periods, and a versatile parameter optimization option. The latest version also has capabilities for continuous soil moisture accounting and reservoir routing operations.

HEC-HMS also includes an automatic calibration package that can estimate certain model parameters and initial conditions, for the given observations of hydro meteorological conditions. It also links to a database management system that permits data storage, retrieval and connectivity with other analysis tools available from HEC and other sources.

ii. PED-W model (parametric efficient semi-distributed watershed model)

For the Ethiopian Highlands, which have a monsoonal climate with a distinct dry and wet season, a straightforward semi-distributed hydrological model was created. In order to expand the model to simulate sediment, (Collick et al., 2009; Tilahun et al., 2013) developed it. The principle of this model was that Hydrological modeling in monsoonal climates is different than in temperate climates where the soil is wet during the dormant season. Therefore, this semi-distributed model took into account that the soils need to reach at critical moisture content before it becomes hydrological active and starts to contribute surface runoff, interflow and starts recharging the aquifer. The amount of rain to reach this threshold moisture content varies throughout the watershed.

This hydrological model was developed based on dividing the watershed in to three regions hillside infiltration, saturated and hillside degraded area, each with its own characteristic moisture content. A separate water balance was run for each of the regions using rainfall and potential evaporation as the major inputs (Collick et al., 2009).

2.8 Previous Studies

Comparison of the ReFH-runoff rainfall model and the HEC-HMS model in the Korean catchment is made by Joo et al. (2014). He discovered that ReFH model shows limitations in the simulation of peak flow, while HEC-HMS shows good simulations and reason out this was due to a lumped concept in the ReFH modeling and the semi-distributed modeling concept of HEC-HMS is important in the peak flow determination. (Abushandi & Merkel, 2013) modeled rainfall-runoff relations Using HEC-HMS and IHACRES for a Single Rain Event in an Arid Region of Jordan expressed that the performance of IHACRES showed some weaknesses, while the flow comparison between the calibrated stream flow result fits well with the observed stream flow in HEC-HMS. The Nash-Sutcliffe efficiency of these two models were 0.51 and 0.88 respectively.

According to (Garland, 2013) studies in two New York catchments (Little Tonawanda Creek and Black Creek), stated that the PED-W model was easier to set up and calibrate and yields comparable results to SWAT. The SWAT model requires a lot of time, forcing factors, and parameters, although PED-W model efficiency during validation period was greater than SWAT model.

PED-W model was calibrated and validated for the three watersheds located in Ethiopian highlands and one watershed located in semi-arid regions. Model validation indicated that daily discharge values were predicted reasonably well with Nash Sutcliffe values for daily discharge ranging from 0.56 to 0.78 (Collick et al., 2009). (Geta, 2020) concludes that from overall model performance PED model was the most appropriate model to predict stream flow followed by HBV and HEC-HMS model, during evaluation of stream flow prediction capability of these model on Anjeni, Gumara, and Main Belles watersheds.

Generally, models' comparison has been conducted to simulate runoff for different purposes. But most of the researches model performance comparison was depending on the result or the outcome of the model. For instance, Aster (2007) and Genene (2006) studies indicate that comparison of the model depends on the output of the model but less consideration to the validity of model structure for better simulate runoff.

HEC-HMS program uses a separate model to represent each component of the runoff process, and each model also has a list (an option) to use different types of model, this indicates that there is a possibility to use the different model combination from each separate model. Even though there is a possibility to use the different model combination from each separate models, most of the conducted research like (Abushandi & Merkel, 2013; Joo et al., 2014) studies used only a single model set up during comparison of HEC-HMS model to the other model, so this leads unsupported decision unless it could be used other model combination from a separate HEC-HMS models basin model component.

Ethiopia has a tropical country, but almost all hydrological models developed in western countries. Such models consider snowmelt for runoff transformation, in contrary, Ethiopian high lands have a semi-humid monsoonal climate, the generation of runoff different from the western country. Therefore, using these hydrological models without first ensuring their structural validity can lead to incorrect conclusions (Collick et al., 2009).

3. MATERIAL AND METHODOLOGY

3.1 Study Area Description

3.1.1 Location

Mersa River is found in western highlands Awash Terminal, the sub-basins of Awash basin. Mersa River originates from mountains drain to the downstream passes in Mersa town. The Mersa town is found in North Wollo, Amhara region, Ethiopia at 495 KM from Addis Ababa and Geographically located at 11°41′ N latitude and 39°39.5′E longitude and 1633m elevation mean above sea level. Mersa is situated along country (Ethiopian) Highway 2 and the highway passes in Mersa river.

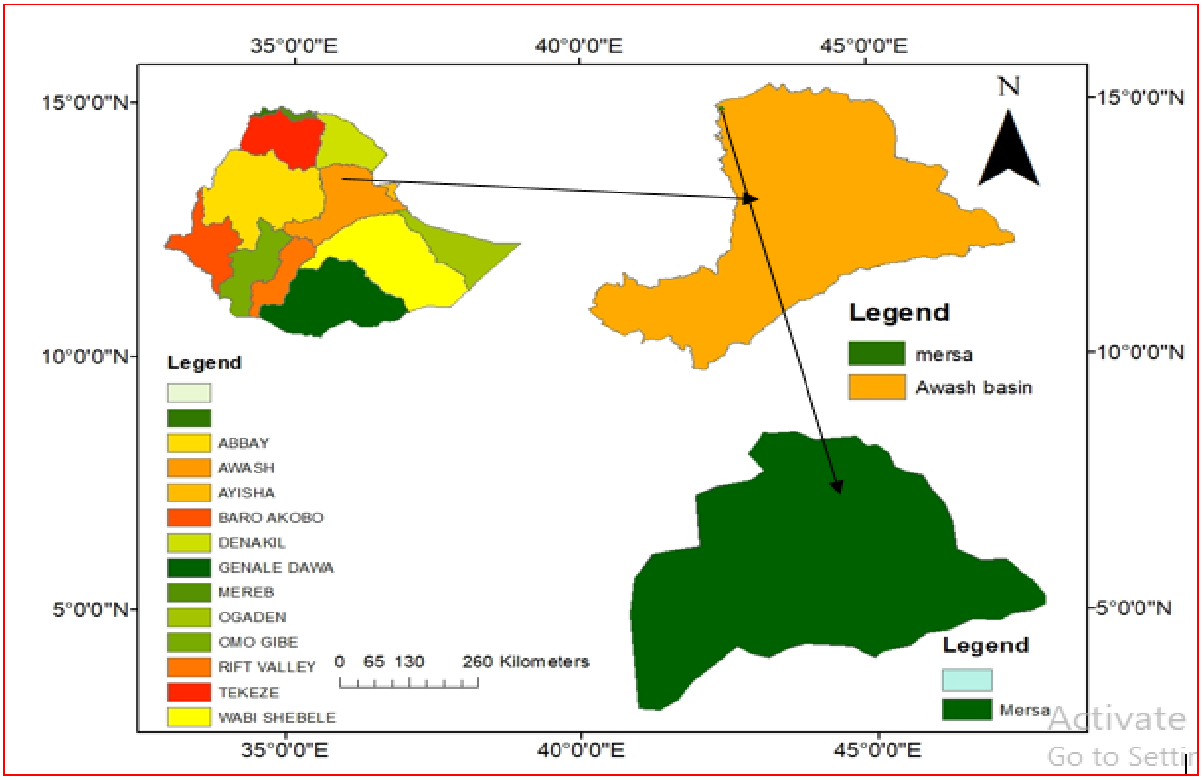


Figure 3.1 Location of Mersa watershed

The watershed is delineated using HEC-GeoHMS that is extension in Arc-GIS (for this thesis ArcGIS 10.4 were used) with 30 m resolution of DEM (digital elevation model). The total area of Mersa watershed is 41.85 km^2. The DEM data was collected from Minster of Water and Energy.

3.1.2 Climate

The minimum and maximum temperature in the watershed is 10^{o}C and 34^{o}C, respectively. The study area is characterized by diverse altitudinal difference and the rain fall pattern is uni-modal with peak rainfall season ranges from end of July up to September and the dry season occurs between October and April. The nature of rainfall is so erratic, short in duration which leads to flash flooding and the district receives average yearly rainfall ranging from 350–1078.9 mm

3.1.3 Topography of the Study Area

The topography of the studying area is characterized by a mountainous and hillsides which has contribution to surface runoff and soil erosion processes. Thus, the topographic effect of the area has a significant effect on the generation of direct runoff from precipitation. The topography varies 1607-3554 m asl.

3.1.4 Soil

The soil in Mersa catchment grounded on soil type criteria eutric cambisols, eutric regosols, leptosols and vetric cambisols are earned while according to texture sandy loam and gravel are the greatest coverage in the watershed of Mersa. The soil data was collected from Minster of Water and Energy.

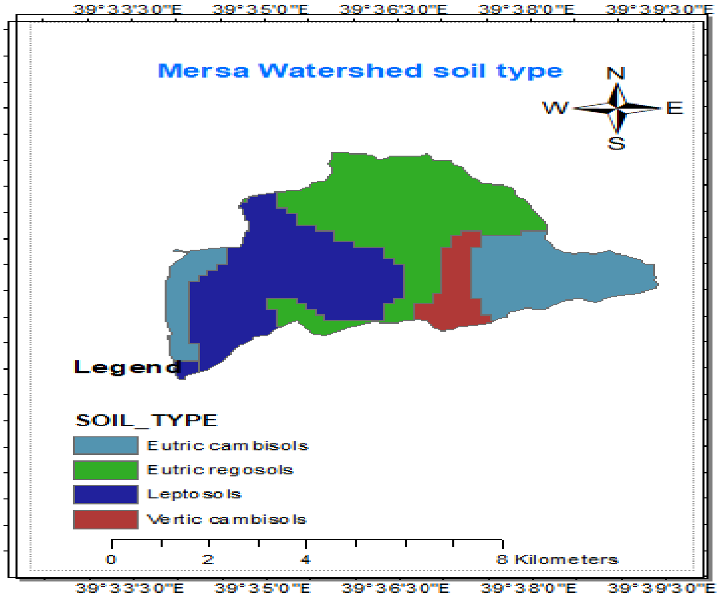


Figure 3.2 Soil map of Mersa watershed

3.1.5 Land Use and Land Cover

The land use data were collected as land cover map from Ministry of Water, Irrigation and Energy. The land use land cover of the study area is mostly covered by cultivated land and Shrub land followed by bare land and woodlands.

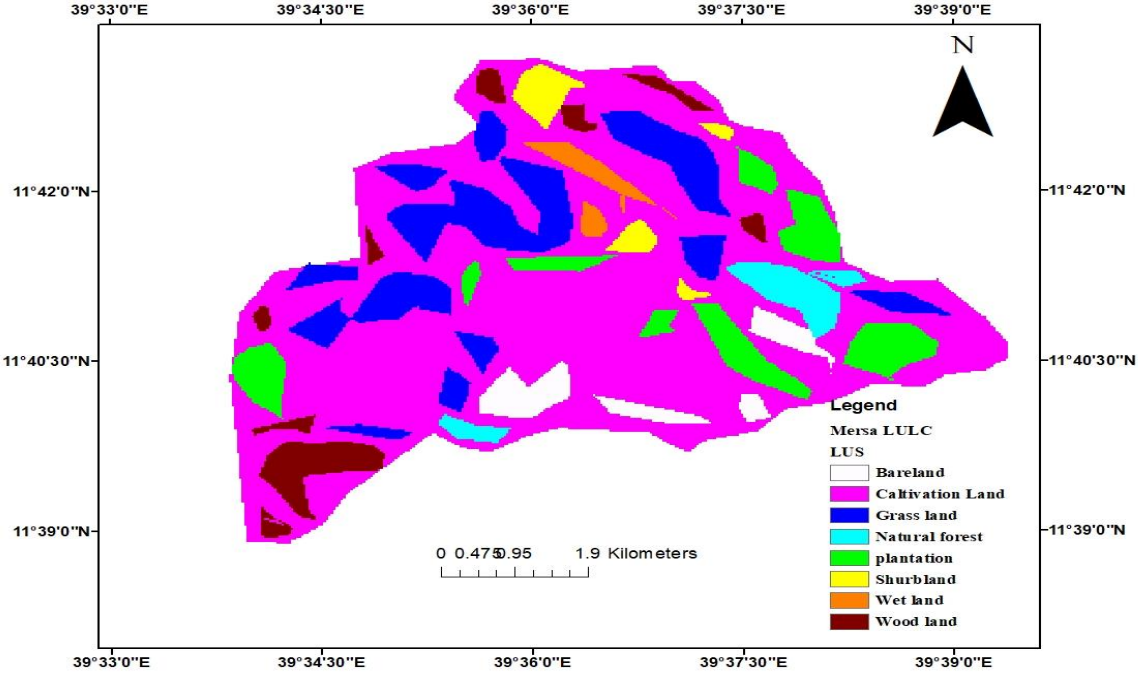


Figure 3.3 Land use and land cover of Mersa watershed

3.2 Data Collection

3.2.1 Hydrology

The flow recorded data is collected from Minster of Water and Energy for Mersa river between 1996-2012 years and the annual maximum mean daily instantaneous flow data taken to estimate the dominant and bank full discharge of the river.

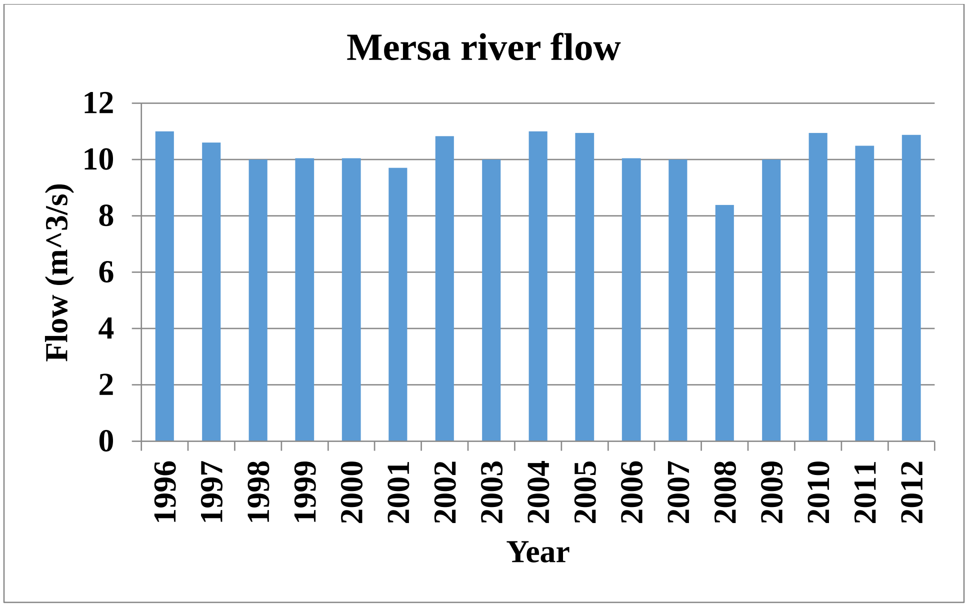


Figure 3.4 Annual maximum mean daily river flow data of Mersa River

3.2.2 Meteorological Data

The meteorological data were collected from National Meteorological Service Agency (NMSA). The data includes; daily rainfall, maximum and minimum daily temperature, wind speed, relative humidity, and sunshine hours of stations.

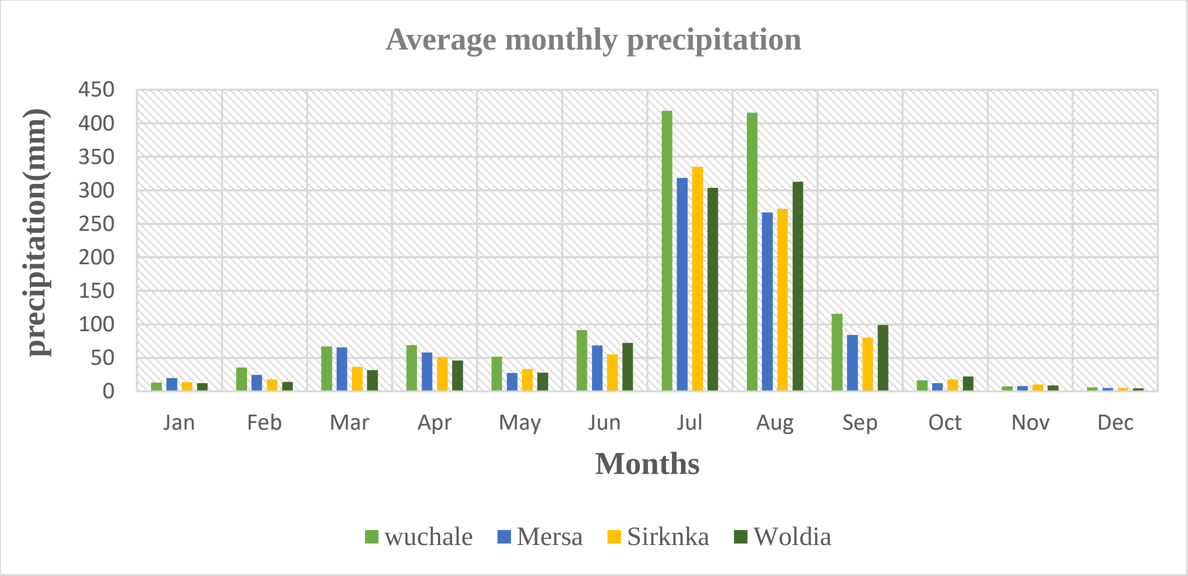


Figure 3.5 Average Monthly Precipitation

3.2.3 Spatial data

i. DEM data

Digital elevation model 30m×30m DEM of Awash basin obtained from the Ministry of water and energy. This data was used to delineate the catchments and extract terrain attributes (drainage line, elevation differences of the study area and watershed characteristics).

ii. Land use land cover and soil data

These data collected from the Ministry of water and energy. The LULC 2008 GC is processed and prepared as a map during the image classification by Ethiopian Ministry of water and energy GIS department. The soil map also prepared on the same year. The land use land cover and soil maps were used to estimate the curve number and input for the HEC-HMS model.

3.3 Data Analysis

After collecting the necessary data's, filling the missed data and check the quality of the hydro-meteorological data were mandatory for valid research. Different data quality methods have been used in different articles, from which some of them were used to check the quality of the collected data.

3.3.1 Filling missed precipitation data

Missed data existed due to lack of appropriate records, shifting of station location, and processing, are a serious problem because they lead inconsistency and ambiguous results that may contradict to the actual situation.

The missing values of precipitation data were filled using the normal ratio method because the annual precipitation of each gauging stations varying above 10%. The Normal ratio method expressed by the following relationship. The missed rainfall data filled using the nearby station.

$$Px = \frac{NX}{N}\left(\frac{P1}{N1} + \frac{P2}{N2} - - - \frac{PN}{Nn}\right) \tag{3.1}$$

Where, Px =Missing value of precipitation to be computed; Nx = Average value of rainfall for the station in question for recording period; N1, N2………Nn= Average value of rainfall for the neighboring station; and P1, P2....Pn = Rainfall of neighboring station during missing period; and N= Number of stations used in the computation.

3.3.2 Estimation of areal precipitation

Mean areal precipitation depth for catchments in the study areas had estimated using the Theisen's polygon method. Out of 4 stations, only 2 stations included in Theison's polygon preparation on Arc-Gis. The method assumes that the recorded rainfall in a gauge is representative for the area half-way to the adjacent gauges. Thiessen polygons are formed around each precipitation station by drawing the perpendicular bisectors of the lines joining adjacent stations. If there are n-number of stations and n-polygons, the average depth of precipitation over the total area (A) is given by:

$$P = \frac{1}{A}\sum_{s=1}^{s=n}(Ps * As) \tag{3.2}$$

Where, P = Areal average rainfall; Ps = Rainfall measured at sub-region; As=Area of sub-region; and A = total area of sub regions.

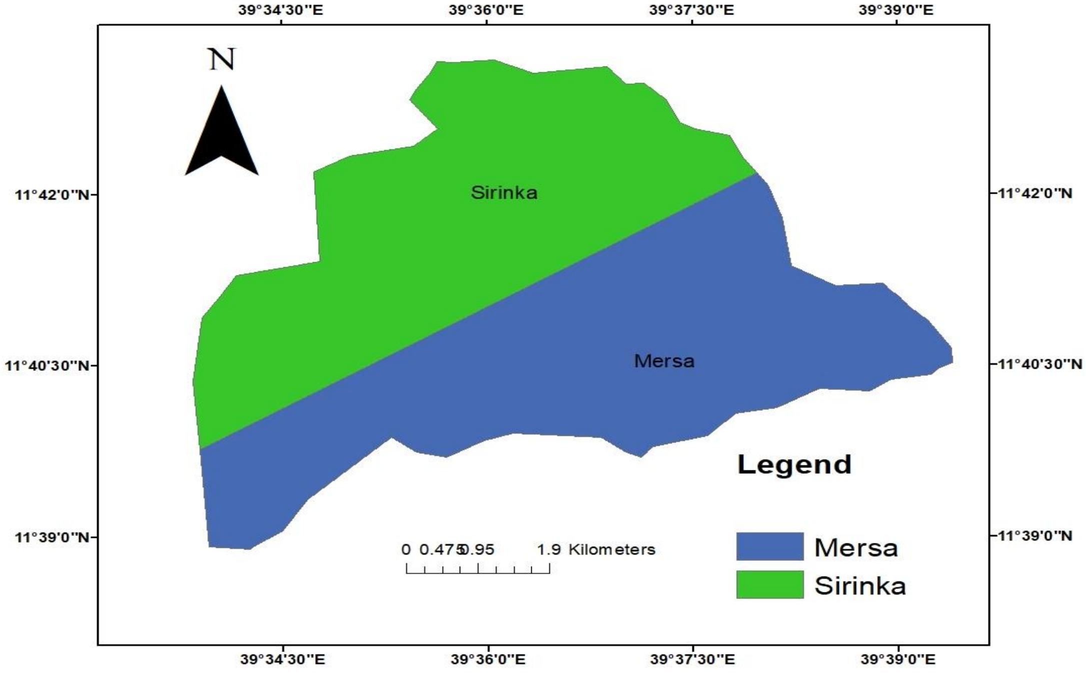


Figure 3.6 Thiessen polygon

3.3.3 Estimation of potential evapotranspiration

Potential Evapotranspiration (PET) is one of the major inputs in rainfall-runoff model. From many evapotranspiration determination methods due to lack of appropriate input data, this study used the Hargreaves PET determination method. The (Hargreaves & Allen, 2003) equation is a well-known temperature-based method for the estimation of daily ETo. This method requires daily maximum and minimum air temperature, and extraterrestrial solar radiation data. The extraterrestrial solar radiation is computed from the information on latitudes of the study site and Julian day of the year. The Hargreaves and Samani (1985) equation are defined as follows:

$$\mathrm{ET_o} = 0.0023(\mathrm{T_{Max}} - \mathrm{T_{Min}})^{0.5}(\mathrm{T_M} - 17.8)\mathrm{R_A} \qquad (3.3)$$

Where ETo is daily reference evapotranspiration (mm day^{-1}); Tmax is daily maximum temperature (^{o}C), Tmin is daily minimum temperature (^{o}C); Tm is daily mean temperature (^{o}C); and Ra is the daily extraterrestrial solar radiation (mm day^{-1})

3.3.4. Data quality checking

i. Double mass curve

One of the methods used in hydro meteorological practice to test the homogeneity of precipitation and runoff records is the use of double mass curve (DMC). The DMC is a plot of the accumulated rainfall data at a station in question against the mean of the cumulative rainfall for a group of surrounding stations for 17 years. DMC analysis had been done after the data at all stations were filled.

If the time series indicates an absence of change in proportionality (i.e., absence of change in the slope of the line) with the period considered, then the time series is assumed to be homogeneous otherwise adjustment is needed by using slop method.

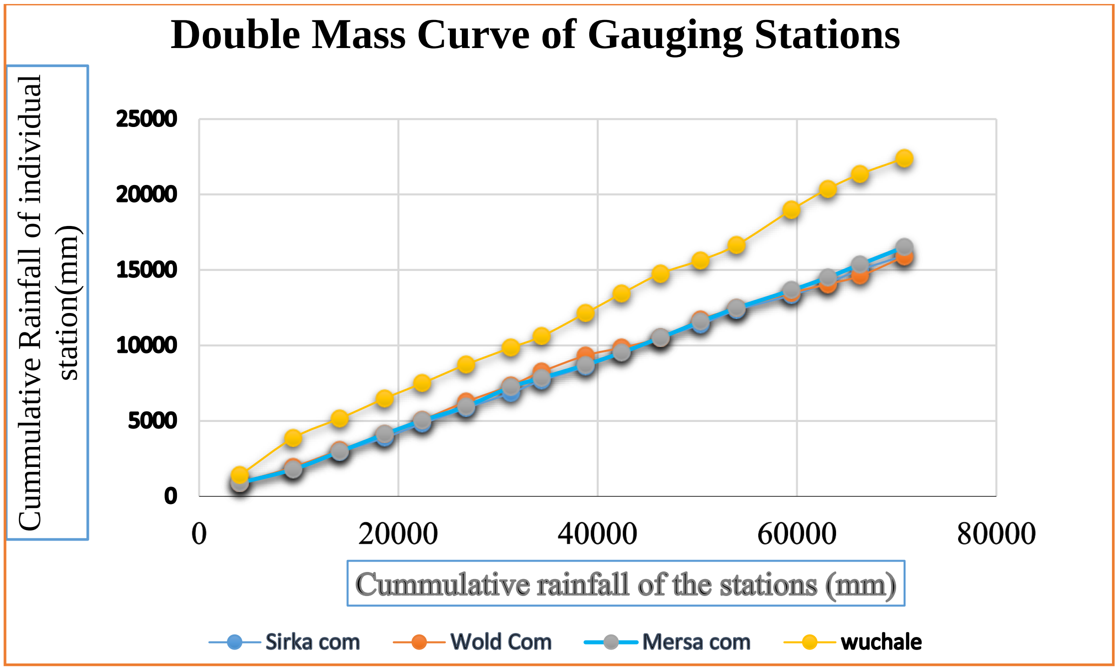


Figure 3.7 Double mass curve of gauging stations

ii. Non-Dimensional Homogeneity Test

The homogeneity of the selected gauging stations monthly rainfall records has been determined by non-dimensional sing equation:

$$Pi = \frac{\overline{Pi}}{\bar{p}} \tag{3.4}$$

Where: Pi=Non dimensional Value of P for the month I; $\overline{Pi}$ = Over years averaged monthly precipitation for the station I; and $\overline{P}$ = the over years average yearly precipitation of the stations.

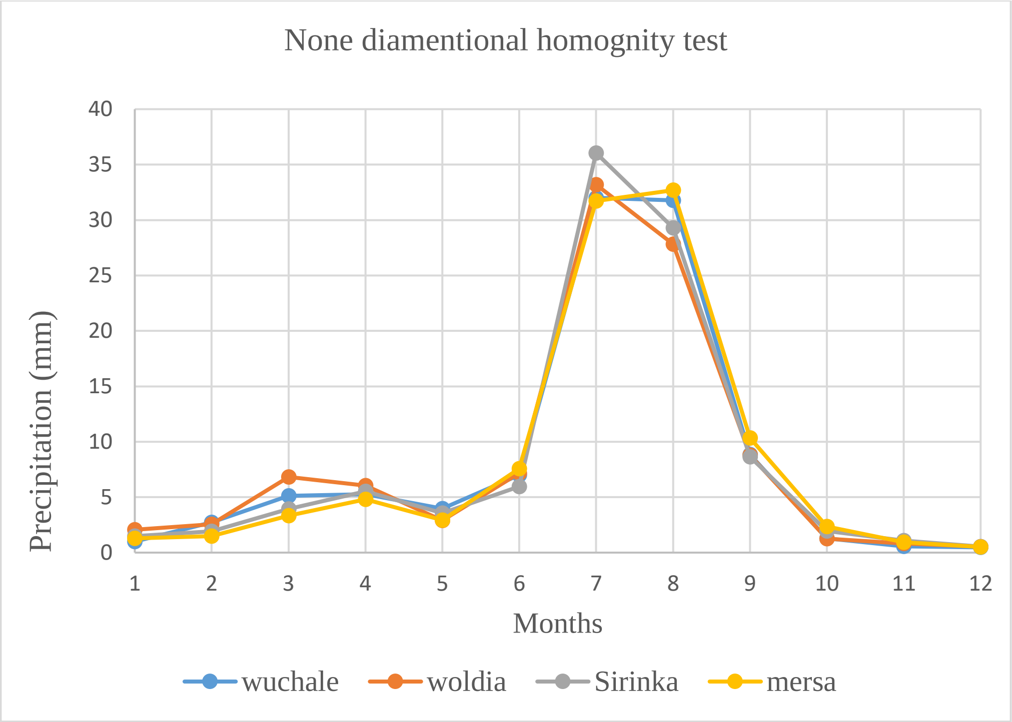


Figure 3.8 non-dimensional homogeneity test

3.4 Conceptual frame of the study

Time series data were organized using the relevant data formats for each model following a thorough study of the meteorological and hydrological data. The next step was splitting data for two-thirds of them for calibration and one third for validation, Sensitivity analysis, Calibration, and Validation has been achieved. The following figure stated that the overall flow chart of this study bingeing from input data preparation up to model comparison.

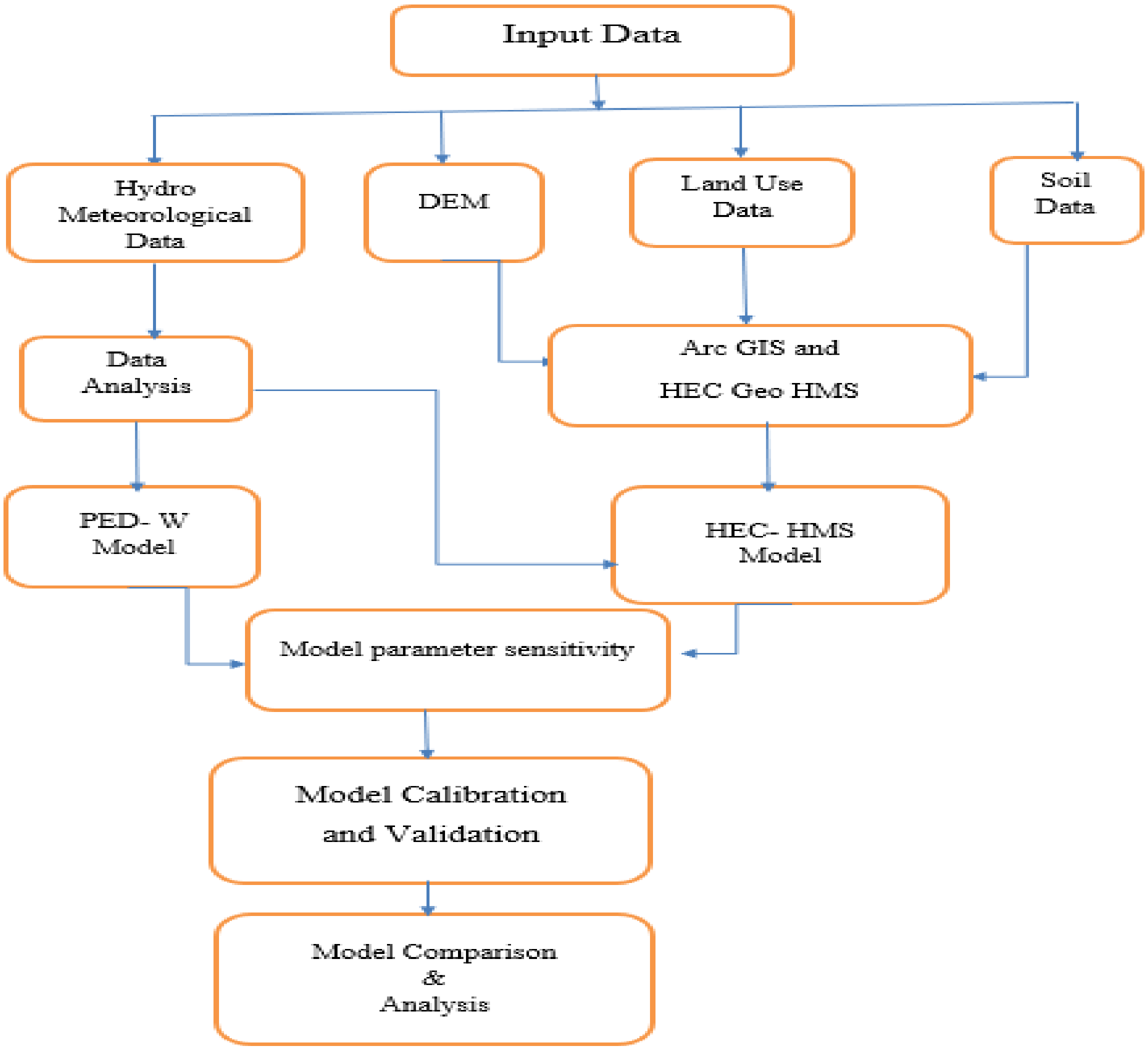


Figure 3.9 Flow Chart of the study

3.5 Watershed model structures

i. Based on input data requirement

HEC-HMS may or may not utilize daily evapotranspiration as an input, it depends on the method employed on loss models while PED-W model used daily representative precipitation and evapotranspiration at watershed level to simulate stream flow. Event modeling cannot use Evapotranspiration as an input, but continuous modeling such as Deficit constant and soil moisture accounting model used Evapotranspiration as an input to simulate stream flow. All model used observed stream flow for model optimization on the outlet of the watershed. Solely HEC-HMS model used land use land cover as an input during Curve number estimation. The HEC-HMS model used either sub-basin or watershed level evapotranspiration and daily representative rainfall.

ii. Based on parameter representation

a. Loss model

PED-W and HEC-HMS model have used the loss model, to simulate excess rainfall. PED-W model simulate calculate loss from hillside degraded and saturated area. Soil moisture holding capacity (Smax) was a basic parameter used to calculate excess rainfall during PED-W model simulation. The PED-W model assumes that runoff can occur after the soil has reached its field capacity. The HEC-HMS model has been used to simulate excess rainfall using a variety of loss models. Basically, these separate models divided into two, event modeling and continuous modeling. SCS curve number and Initial constant loss models are event-based models, but one layer deficit and constant loss models; and three-layer SMA models are continuous modeling’s. Each loss model has a number of parameters used to calculate loss.

b. Groundwater flow model

In order to calculate groundwater flow, the PED-W model used a different water balance equation. PED-W model solely takes into consideration base flow from the infiltration area on the hillside. Excess water drains to the groundwater or travels laterally through the soil profile after reaching saturation in the hillside infiltration regions. Parameters used for simulation of base flow in PED-W model are groundwater base flow maximum storage (BSmax), groundwater half time (t 1⁄2), interflow (τ*). Whereas the HEC-HMS model has different types of base flow models. From which recession base flow model is an event or multiple event-based models, linear reservoir base flow model works well for continuous modeling and linear reservoir model use mass balance equations routing infiltrated water into the channel.

c. Direct runoff transfer model and Routing model

Direct runoff transferer and open channel routing methods are available in the HEC-HMS model. SCS unit hydrograph utilizes just lag parameters from the HEC-HMS model's direct runoff transfer methods. HEC-HMS model open channel routing method, simple attenuation

(X) and lag time or Muskingum (K) are parameters used in Muskingum routing model. PED-W model has only groundwater routing method it doesn't have a distinctive open channel routing method.

iii. Based on spatial representation of model

Three distinct areas hillside degradation region, hillside infiltration area, and saturation area are identified by the PED-W model. The PED-W model is characterized as a conceptual semi-distributed model and each parameter differs in each fractional area because for each area it employs a different unique water balance equation to simulate surplus rainfall.

A variety of models are available under the HEC-HMS model, a physical semi-distributed model, to simulate direct runoff, base flow, and routing open channel flow. Some of these models have initial lumped models, whereas the others have dispersed models. HEC-HMS model generally semi distribute model means the single watershed divided into interconnected sub-basin so each individual parameters varies in each sub-basin.

iv. Based on process formulation and optimization

a. Water balance equations

According to Thornthwaite-Mather (1955) water balance equations were employed in the PED-W model. The fundamental idea behind this calculation for the water balance was that any excess precipitation would flow either as runoff or as a lateral flow in the soil profile once it had satisfied the soil's required water holding capacity. Most of the time this method is known as saturation excess.

A water balance equation was utilized in each individual basin model in the HEC-HMS model. Three-layer SMA loss models and the one-layer Deficit Constant Rate models employ the water balance equation to simulate runoff volume, but the other models are event-based models that are used to mimic a single storm. One layer Deficit constant rate and three-layer SMA loss models used an empirical equation to simulate runoff volume.

b. Searching method

To calibrate the optimum parameter PED model used only manual calibration method. HEC-HMS model used both manual and automatic calibration method.

3.5.1 HEC-HMS model structure

HEC-HMS can be used to simulate a single watershed or a system of multiple hydrologically interconnected watersheds. Like any physically-based hydrologic model, HEC-HMS simulates most of the key hydrologic processes at the watershed level. The HEC-HMS model requires different datasets including a Digital Elevation Model (DEM), weather data, soil type, and land use.

Arc-Gis Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) and the Arc Hydro extension in ArcView were used as the first stage in manipulating HEC-HMS. In order to create a stream network and estimate CN, HEC-GeoHMs used to outline the physical characteristics of the watershed from DEM data and land use land cover map as inputs. For the HEC-HMS model, HEC-GeoHMS was used to prepare a meteorological model, produce an input file in the form of sub-catchment borders, and estimate the SCS CN and SCS unit hydrograph lag time (USACE, 2009).

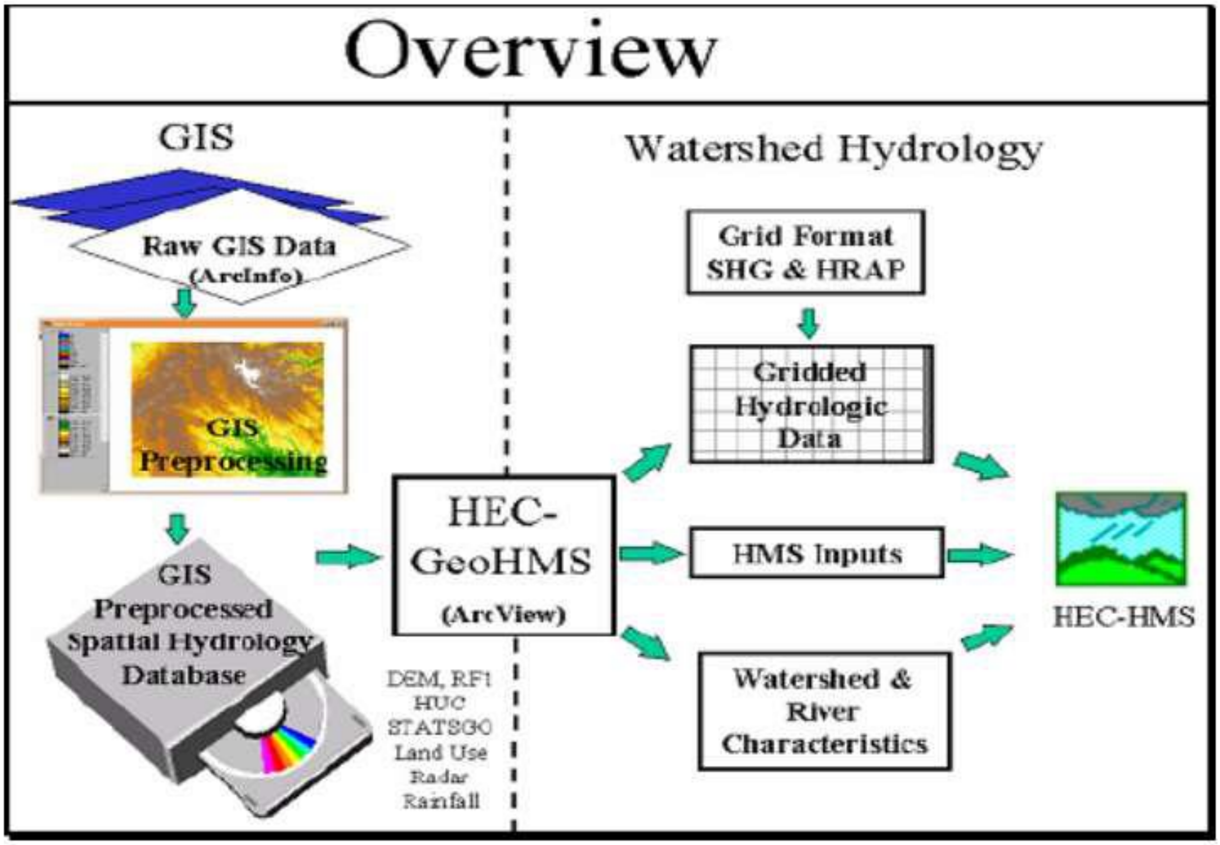


Figure 3.10 Overview of GIS, HEC-GeoHMS and HEC-HMS (USACE, 2009)

The basin model, meteorological model, control, specification, and time series models are the four main model components of the HEC-HMS model. Each part of the runoff process is represented by a different model under the basin element in the software. However, careful consideration had to go into the model selection for stream flow simulation. For the case of this study two and above models have been applied from each sub basin models, based on their acceptable model combination of previous studies and availability of data. Hence, all loss model has not used for all transform methods (HEC-HMS, 2000). The appropriate model combination for Mersa watershed was listed in table 3.1.

Basin model:

Under basin model the hydrological process splits in to sub basin element, Reach element and junction element.

i. Sub-basin element

At the sub-basin level, HEC-HMS model recognized no inflow and only outflow always accounted. Excess rainfall and base flow are the two sources of producing outflow at the sub-basin level. To represent interception and evapotranspiration, one way is to employ the canopy approach. Another way to take into consideration water stored in surface depressions is through the surface component. The selection of the loss method determines the use of the surface component and canopy component; all loss models may employ these components. 2000 (HEC-HMS).

a. Canopy method:

Choosing the canopy technique to reflect how the plant canopy intercepts precipitation and draws water from the soil, and choosing the combined form to account for evapotranspiration loss caused by the presence of plants in the watershed. This approach is frequently combined with a continuous loss model. The Simple and Dynamic Canopy Method was offered under the canopy method. The dynamic canopy technique is more advantageous if the crop coefficient and canopy storage capacity alter over time.

b. Surface method:

Surface storage used to account the ground surface water (groundwater), where water may accumulate in surface depressions. This method is important to the area where depression storage for an agricultural field can be quite large if conservation tillage practice used. This method used different option to calculate surface maximum storage. Simple surface method is used with a combination of continuous model.

c. Loss model:

A number of loss methods are available under loss model, from which some of them are.

- Initial and constant-rate loss model
- The deficit and constant-rate loss model
- The SCS curve number CN loss model
- The Green and Ampt loss model
- Soil Moisture Accounting and Routing model

This study employed the SCS curve number, Deficit and constant, and Soil Moisture Accounting (SMA) loss model from the aforementioned runoff volume model.

i. Initial and constant-rate loss model

The basic concept regarding to this loss model is that the maximum rate of precipitation loss f_c constant through the event. The excess Pe_t during time interval is given by

$$Pe_t = \begin{Bmatrix} p_t - f_c & if\ p_t > f_c \\ 0 & otherwice \end{Bmatrix} \qquad 3.5$$

An initial loss l_a is added to the model to represent interception and depression storage. The parameters l_a and constant loss rate are fitted parameter but there is an option to calibrate within the given boundary provided on HEC-HMS model.

ii. The deficit and constant-rate loss model

The program includes a quasi-continuous variation on the initial and constant model of precipitation losses; the model different from the initial and constantan loss model in the initial recovery after a prolonged period of no rainfall. The moisture deficit tracked continuously computed as the initial abstraction volume less precipitation volume plus recovery volume during precipitation free periods. The recovery rate could be estimated as the sum of the evaporation rate and percolation rate. To account the loss between precipitations the soil dries out and canopy extract soil water this loss model used canopy method and surface method. To determine the parameters, it has to be directly fitted or calibrated within the boundary condition.

iii. The SCS curve number loss model:

The SCS-CN method accounts for most of the runoff-producing watershed characteristics, such as soil type, land use, hydrologic condition, and antecedent moisture condition, using the following formula:

The soil conservation service SCS curve number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture, using the following equation.

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \qquad 3.6$$

Where P_e= accumulated precipitation excess at time t; p = accumulated rainfall depth at time t, I_a the initial abstraction (initial loss); and S= potential maximum retention.

$I_a = 0.2S$

Therefore, the cumulative excess at time t is

$$Pe = \frac{(P-0.2S)^2}{P+0.8S} \qquad 3.7$$

The increment excess for time interval is computed as the difference between the accumulated excess at the beginning of the period. The maximum retention, (S), and watershed characteristics are related through an intermediate parameter, the curve number (commonly abbreviated CN) as

$$S = \begin{cases} \frac{1000-10CN}{CN} & (foot-poumd\ system) \\ \frac{25400-254CN}{CN} & (SI) \end{cases} \qquad 3.8$$

CN values range from 100 (for water bodies) to approximately soils with high infiltration rate. The CN for a watershed can be estimated as a function of land use, soil type, and antecedent watershed moisture. For watershed that consist of several soil type and uses, a composite CN is calculated as

$$CN_{composite} = \frac{\sum \text{AiCNi}}{\sum Ai} \qquad 3.9$$

In which CN = the composite CN used for runoff volume computation; i= an index of watershed subdivision of uniform land soil type; CN= the CN for subdivision; and A_i= the drainage area of subdivision i. on this study CN easily calculated by using Geo-HMS extension tool on Arc-GIS.

iv. Soil moisture accounting model (SMA)

This loss model combined a canopy and surface technique with three layers to reflect the dynamic water movement in the soil. The model represented how water is flowing through and was stored on vegetation, in the soil profile, and in the ground layers. 2000 (HEC-HMS).

a. Storage component

This component accounts for water loss due to canopy interception, surface storage, soil profile storage, and groundwater storage. The soil profile storage represents water stored on the top layer of the soil. In the SMA model round water layer may one or two layers. Loss from groundwater storage is either due to groundwater percolation from one layer two another or too deep percolation to the aquifer. The latter loss is not accounted in the SMA model, because lost from the system is not modeled.

b. SMA flow component

Flow component represents flow in to, out and between storage volumes, flow component considered in SMA model are all processes undertaken in the hydrologic cycle. The water that passes through the canopy water already in surface storage infiltrate down into the soil SAM model calculated as

$$PotSoilInfil = MaxSoilInfil - \frac{CurSoilStore}{MaxSoilStore} MaxiSoilInfil \qquad 3.10$$

Where, $PotSoilInfil$ = potential soil infiltration; $MaxSoilInfil$ = maximum infiltration rate; $CurSoilStore$= volume in the soil at the beginning of time step, and $MaxSoilStore$ =the maximum volume of soil storage.

If the water available for infiltration exceeds this calculated infiltration rate it contributes to surface storage or generate surface runoff. Infiltrated water fills the soil pores or saturated excess water percolates through the soil layer profile or deep into the ground. The rate of potential soil percolation calculated as;

$$PotSoilPerc = MaxSoilPerc\left[\frac{CurSoilStore}{MaxSoilStor}\right]\left[1 - \frac{CurGwStore}{MaxGwStore}\right] \qquad 3.11$$

Where, $PotSoilPerc$= potential soil percolation; $MaxSoilPerc$=user specified maximum percolation rate; $CurSoilStore$= the calculated soil storage at the beginning of time step; $MaxSoilStor$= user specified maximum storage for the soil profile; $CurGwsSore$= the calculated ground water storage for the upper ground water layer in beginning of time step; and $MaxGwStore$= user specified maximum groundwater storage for groundwater layer one.

The minimum and the available potential volume contributes to ground water volume and expressed by:

$$PotGwPerc = MaxGwPer\left[\frac{CurGwStore}{MaxGwStore}\right]\left[1 - \frac{CurGwStore}{MaxGwStore}\right] \qquad 3.12$$

Where, $PotGwPerc$= potential groundwater percolation; $MaxGwPerc$=user specified maximum percolation rate; $CurGwstore$= the calculated ground water storage for the groundwater layer 2; and $MaxGwStore$= user specified maximum groundwater storage for groundwater layer2

SMA model also determines percolation directly from soil profile to deep aquifer by

$$PotSoilInfil = MaxsoilInfil - \frac{CurSoilStore}{MaxSoilStore}\ And \qquad 3.13$$

$$PotPercGw = MaxPercGw - \frac{CurGwStore}{MaxGwStore} \qquad 3.14$$

The water exceeds from infiltration rate and over flow surface storage accounts as surface runoff. Groundwater flow is the sum of groundwater flows from each ground layer at the end of time interval. Expressed by

$$GwFlow_{t+1} = \frac{ActSoilPerc + CurGw_iStore - PotGw_iperc - \frac{1}{2}GWFlow_t * Time\ stepe}{RoutGw_iStore + \frac{1}{2}Timstep} \qquad 3.15$$

Where $GwFlow_{t+1}$ and $GWFlow_t$ = ground water flow at the beginning of time interval *t* +1and *t* respectively; $ActSoilPerc$= actual percolation from the soil profile to the groundwater layer; $PotGw_iperc$= potential percolation from the groundwater layer *i*;

$RoutGw_iStore$= ground water flow routing coefficient from ground water storage i; and $Timstep$= the simulation time step.

The last flow component of SMA model used potential evapotranspiration. It accounts loss of water through canopy interception, surface depression and soil profile and estimated as

$$AcEvapsoil = PotEvapSoil * f(CurSoilStore, MaxTenStore) \qquad 3.16$$

Where $AcEvapsoil$= the calculated ET from the soil storage; $PotEvapSoil$= the calculated maximum potential ET; and $MaxTenStor$ the user specified maximum storage in tension zone of soil storage. $f\,(.)$ indicates function.

The number of parameters used in this model is greater than other loss model parameters. It is difficult to determine by direct fitting method. So, calibration was done to get optimum parameters.

d. Direct runoff models:

The direct runoff method represents the actual surface runoff, which is achieved by a transform method contained within the sub-catchment. From eight of direct runoff modeling, this study used SCS UH model, Clark UH and Snyder UH model.

i. SCS UH model:

The Soil Conservation Service (SCS) proposed a parametric UH model; the basic concepts and equations at the heart of the SCS UH model is a dimensionless, single-peaked UH: time of peak (T_P) is determined by.

$$T_P = \frac{\Delta t}{L} + t_{lag} \qquad 3.17$$

In which Δt = the excess precipitation duration (which is also the computational interval in HEC-HMS); and t_{lag} = the basin lag, defined as the time difference between the center of mass of rainfall excess and the peak of the UH. The parameter lag has to be determined directly by fitting calibration technics but Geo-Hms extension method easily determined an initial value.

ii. Clark's unit hydrograph:

Clark’s model drives a watershed UH explicitly representing two critical processes in the transformation of excess precipitation to runoff. The translation or movement of the excess from its origin through the drainage to the watershed outlet and attenuation or reduction of the magnitude of discharge as the excess is stored through the watershed.

The model began continuity equations

$\frac{ds}{dt}=I_{t-O_t}$ 3.18

In which ds/dt =time of change of water storage at time t, I_t=average inflow to the storage at time t; and O_t= out flow from storage at time t.

With the linear reservoir model, storage at time t is related to the out flow as:

$S_t=RO_t$ 3.19

Where R = constant linear reservoir parameters combining and solving the equation using the simple finite difference approximation yield.

$O_t=C_AI_t+C_BO_{t-1}$ 3.20

Where C_A *and* C_B = routing coefficient calculated from

$C_A=\frac{\Delta t}{R+0.5\Delta t}$ 3

.21

$C_B=1-C_A$ 3.22

The average outflow during period of t is

$\bar{O}=\frac{O_{r-1}+O_t}{2}$ 3.23

iii. Snyder unit hydrograph:

Is a synthetic unit hydrograph method. The original data support computing the peak flow as a result of a unit of precipitation. Latter equation was developed to estimate the time base of hydrograph and the width at 50% of peak flow. This indicated that it cannot compute all ordinate of the hydrograph. The other step creates Clarke hydrograph in such a way that the Snyder properties are maintained. Snyder unit hydrograph parameters are estimated through the direct fitting method but not have stream data at the sub-basin level, so the lag parameter and peaking ratio had directly calibrated within the given boundary condition.

e. Base flow model:

A Base flow model represents the subsurface model which is interacted with infiltration and surface runoff process. The actual subsurface runoff is calculated by base flow method contained within the sub-catchment. A total of three different base flow methods includes in the program. From which the exponential recession model and the linear reservoir model applied for soil moisture accounting loss model.

i. Linear reservoir:

This model used in conjugation with moisture accounting loss model. The main concept is to simulate the storage and movement through the reservoir method. The principle of this method is the model follows conservation of mass principle. The parameters used in this method was estimated through calibration.

ii. Exponential Recession Model:

This model defines the relationship of $Q_{t,}$ the base flow at any time t to an initial value as:

$$Q_t=Q_0k^t \qquad 3.24$$

Where Qo = initial base flow (at time zero); and k= an exponential decay constant.

ii. Reach element

A reach element conceptually represents a segment of stream or river. There are six routing methods in the HEC-HMS. Each of the methods implements a hydrological routing methodology as compared to a hydraulic approach that implements the full unsteady flow equations.

Table 3.1 HEC-HMS routing model selection criteria

If it is true…	…. Then consider this model
No observation hydrological data available for calibration	Kinematic wave; Muskingum-cunge

Significant back water will influence discharge hydrograph	Modifies puls
Flood wave will go out of bank, in to floodplain	Muskingum-cunge with 8- point cross section
Chanel slope >0.002	Any
Chanel slop from 0.002 to 0.0004 and $\frac{T_s u_o}{d_0} \geq 171$	Muskingum-cunge, modified puls and Muskingum
Chanel slope$<$ $0.0004\ and\ Ts_o \frac{g}{d_o} \geq 30$	Muskigum-cunge
Chanel slope$<$ $0.0004\ and\ Ts_o \frac{g}{d_o} \leq 30$	Non

Based on the criteria of the above table and availability of data required the Muskingum routing model was suitable for the selected catchment.

i. Muskingum model:

Muskingum routing model basically uses simple finite difference approximation of the continuity equation.

$$\frac{I_{t-1}+I_t}{2} - \frac{O_{t-1}+O_t}{2} = \frac{S_t - S_{t-1}}{\Delta t} \qquad 3.25$$

The storage in the reach is modeled as the sum of prism storage and wedge storage. The volume of prism storage is the outflow rate, *O* multiplied by the travel time through the reach *K,* the volume of the wedge storage is a weighted difference between in flow and out flow multiplied by travel time *K* thus the Muskingum model define the storage.

$$S_t = KO_t + (KXI_T - O_t) = K[XI_t + (1 - X)O_t] \qquad 3.26$$

Where k = the travel time of the flood wave through routing reach and x= dimensionless weight (0$\leq x \leq$ 0.5)

The quantity $xI_t+(1-x)O_t$ is a weighted discharge. If storage in the channel is controlled by downstream condition. Such that storage and outflow are highly correlated. Then $x=0.0$ then $S=KO$ this is reservoir model. *If* $x=0.5$ equal weight is giving inflow and out flow.

If the above equation is substitute in the first equation it gives

$$Qt=\left(\frac{\Delta t-2kx}{2k(1-x)+\Delta t}\right)I_t+\left(\frac{\Delta t+2kx}{2k(1-x)+\Delta t}\right)I_{t-1}+\left(\frac{2k(1-x)-\Delta t}{2k(1-x)+\Delta t}\right)Q_{t-1} \quad 3.28$$

3.5.2 PED-W model structure

PED-W model have been executed on the excel spreadsheet format. To execute PED-W model the first step was determine point rainfall and average evaporation by using Thiessen's polygon method and arrange the rainfall, evaporation and stream flow data on the daily and monthly time series data in vertical format. The second step is calculating watershed area by using DEM data on Arc-GIS. The rest have been achieved sensitively analysis, calibration and validation.

Theoretical background of the model; the model used the water balance model based on Thornthwaite-Mather (1955) procedure.

$$S_s(t) = S_s(t-\Delta t) + [P - E_a - R - P_{erc}]\Delta t \quad 3.29$$

Where P is precipitation (LT^{-1}), E_a is actual evapotranspiration (LT^{-1}), $S_s(t)$ is water storage in soil profile at time t at some distance L above the restrictive layer, $S_s(t-\Delta t)$ is water storage at previous time step at L above restrictive layer, R is saturation excess runoff (LT^{-1}), P_{erc} is percolation to the subsoil (LT^{-1}), Δt is time step (T)

During wet periods when the rainfall (P) exceeds potential evapotranspiration (E_p), ($P<E_p$) the actual evaporation (E_a), is equal to the potential evaporation (E_p),

Actual evaporation when precipitation, P, is below potential evaporation E_P, ($P<E_p$) for the time step is described by

$$E_a = E_P\left[\frac{S_r(t)}{S_{r\,max}}\right] \quad 3.30$$

Where, $S_r(t)$ is soil moisture at time t for root zone, $S_{r\,max}$ is field capacity moisture content for the permeable hillside and saturated moisture content for runoff areas. $S_{r\,max}$ varies according to soil characteristics (e.g., porosity bulk density) and soil layer depth.

Soil moisture is then computed according to Steenhuis et al. 2009 it described in exponential form based on the previous time steps soil moisture:

$$S_r(t) = S_r exp\left[\frac{(P-E_p)\Delta t}{S_{rmax}}\right] \qquad 3.31$$

When P<E_P

In this simplified model, direct runoff occurs only from the runoff contributing area, when the soil is saturated from bottom valley saturated area and degraded area. Recharge and interflow originate from the remaining hill slopes. It is assumed that the surface runoff from these areas is minimal. In the overland flow contributing areas when rainfall exceeds evapotranspiration and fully saturates the soil, any moisture above saturation becomes runoff, and the runoff, R, can be determined by adding the change in soil moisture from the previous time step to the difference between precipitation and actual evapotranspiration, e.g

$$R = S_{r\ t-\Delta t} + (P - E_A)\Delta t \qquad 3.32$$

$S_{r\ t}$ =$S_{r\ Max}$

The base flow reservoir acts as a linear reservoir and its outflow, BF, and storage, BS_t, are calculated when the storage is less than the maximum storage, BS_{max} as:

$$BS_f(t) = BS_f(t-\Delta t) + \left[P_{erc} - BS_f(t-\Delta t)\right]\Delta t \qquad 3.33$$

$$BF_t = \frac{BS_t[1-exp[1-\alpha\Delta t]]}{\Delta t} \qquad 3.34$$

Where α is the half-life of the aquifer (the time it takes for half of the volume of the aquifer to flow out without the aquifer being recharged). When the maximum storage, BS_{max}, is reached then:

BS_t=BS_{max}

$$BF_t = \frac{BS_{tmax}[1-exp[1-\alpha\Delta t]]}{\Delta t} \qquad 3.35$$

Interflow originates from the hill slopes with the slope of the landscape as the major driving force of the water. Under these circumstances, the flow decreases linearly (i.e., a zero order reservoir) after a recharge event.

$$Q_{if}(t) = \sum_{\tau=1}^{\tau \leq \tau^*} 2P^*{}_{erc}(t-\tau)\left[\frac{1}{\tau^*} - \frac{\tau}{\tau^{*2}}\right], \tau \leq \tau^* \qquad 3.36$$

The total interflow, $Q_{if}(t)$ at time t can be obtained by superimposing the fluxes for the individual events. Where τ^* is the duration of the period after the rainstorm until the interflow ceases, $Q_{if}(t)$is the interflow at a time t, and Perc*t-τ is the percolation on t-τ days. Model outputs include daily runoff, interflow, and base flow according to the type and proportion of area under consideration within the watershed.

4. RESULT AND DISCUSSION

4.1 PED-W Model output

4.1.1 PED-W model calibration and validation

a. PED-W model calibration:

PED-W model used eleven years (1996-2006) of hydro-metrological data for calibration from a total of seventeen years of time series data. PED-W model calibration was done manually by adjusting the initial values of parameters until best fit has obtained, and the parameter set with the highest Nash Sutcliff efficiency, R^2, and the lower RMSE should be selected. The output for daily simulation of PED-W model fits 0.666, 0.705, and 1.31 of NSE, R^2 and RMSE value respectively.

The optimum parameters of the PED-W model were 0.1, 0.11, and 0.7 of saturated, degraded, and hillside recharge frictional area respectively. Their maximum water holding capacity at root depth (Smax) of these friction areas were 600, 400, 70 mm respectively. These indicate, on saturated and hillside degraded area the runoff generates after 600mm and 400mm effective rainfall to satisfy both soil water storage and evapotranspiration conception. On the other hand, the hillside recharge area has required 70 mm effective precipitation to reaches its field capacity and to contribute runoff as an interflow and base flow.

Generally, the sum of the fractional area was not greater than one, but the result of this study indicates the total area was less than one which is 0.91. A portion of land (0.09) was not contributed runoff as a surface or base flow the reason was this area may contribute deep to groundwater or other watersheds as interflow or base flow.

The optimum parameters of PED-W model used to control subsurface flow were the maximum ground reservoir storage capacity (linear reservoir BS max), (τ^*) interflow, and t1/2 or 0.69/α base flow half time becomes 60 mm, 7 days, and 14 days respectively. This result shows that the time to reduce the volume of the base flow reservoir to half under no recharge conditions was 14 days, and the duration of the period after a single rainstorm until interflow ends up to 7 days means the hillside contribute interflow for 7 days after the storm occurs.

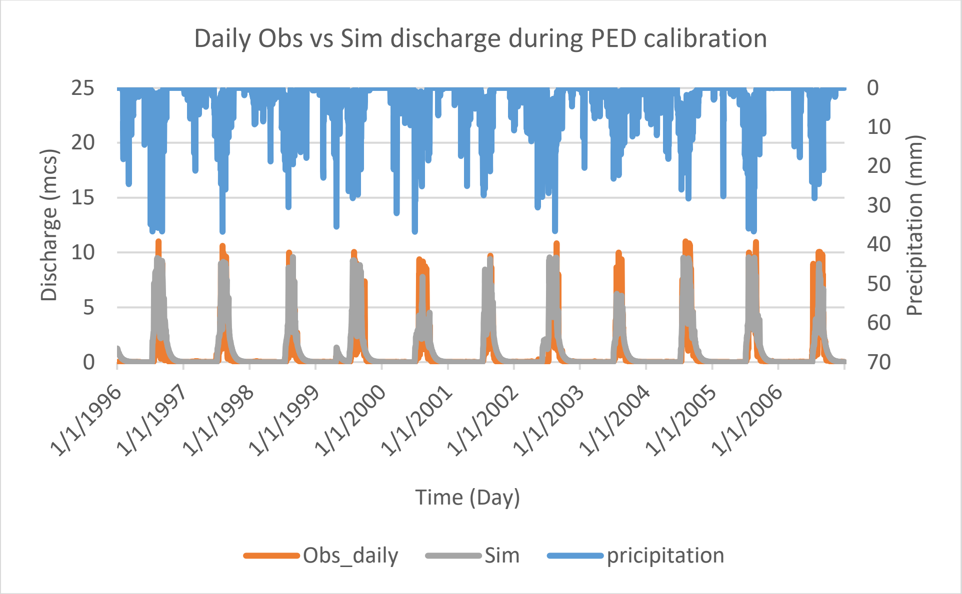


Figure 4. 1 Daily simulated and observed discharge of PED model during calibration

b. PED model validation:

The PED-W model validation method includes keeping the values of all calibrated parameters while only changing the data time steps. The output of all the objective functions parameters which are Nash Sutcliff efficiency (NSE), coefficient of determination (R^2) and root mean square error (RMSE) were 0.55, 0.674, and 1.61 respectively.

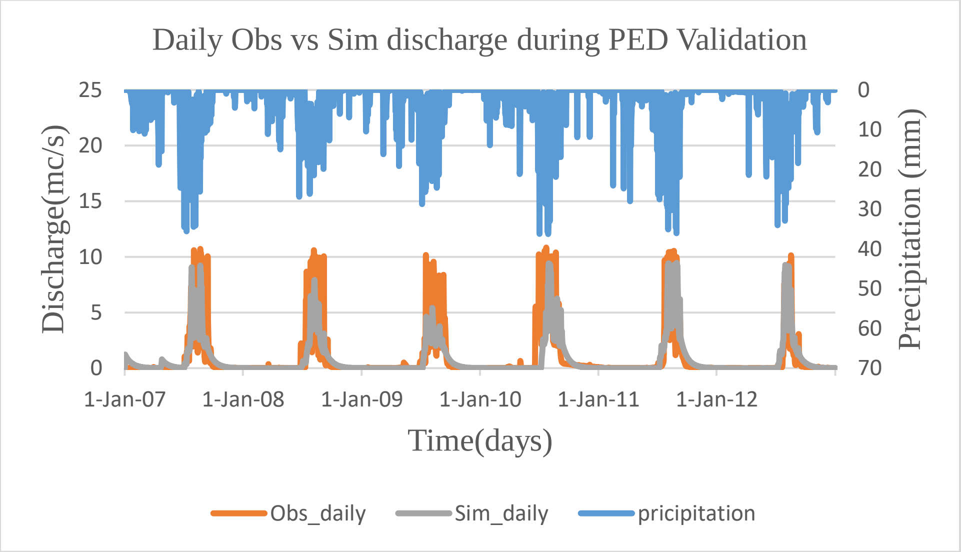


Figure 4.2 Daily observed and simulated discharge of PED-W mode during validation period

4.1.2 PED-W model Sensitivity Analysis

PED-W model has nine parameters and those were optimized with manually. The distribution of the three fractional areas saturated, degraded, and permeable (AS, AD, and AH) with the correspondent water storage capacities (Smax, i) and in the subsurface flow parameters BS max of GW (Maximum Storage), Base flow half-life (t1/2) and Interflow (τ*) runoff parameters. PED-W model has done with directly by adding ±10 % of each parameter separately, and the other parameter kept constant while checking the other parameter sensitivity. Among the nine parameters PED-W model the hillside infiltration and maximum water storage were the most sensitive parameter. The following figure illustrated that changing the value of recharged area by +10% to ± 50% the NSE value reduces from (0.666-0.42), The other parameters are relatively constant throughout the calibration period, with the exception of the hillside infiltration area (Smax).

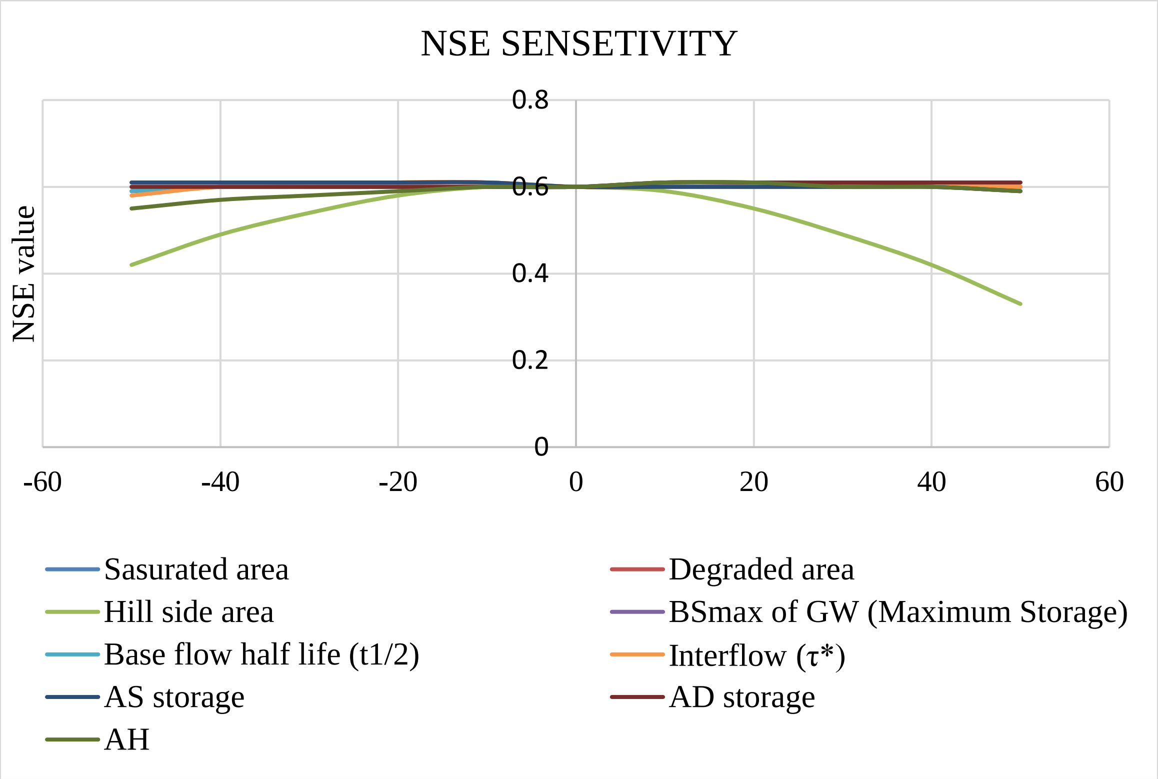


Figure 4. 2 PED model parameters sensitivity analysis

4.2 HEC-HMS Model Results

HEC-HMS model has four major model components these are basin model, meteorological model, control specification model and time series model. Under basin model this study divides the watershed into three sub-basins and one reach by taking into account the entire area of the watershed. Under time series dataset such as rainfall, evaporation and stream flow gauges also arranged according to the available data and number of sub-basins. As shown in the figure below, a graphic representation of sub-basins, a reach, a junction, and an outlet were prepared using Arc GIS, HEC-GeoHMS extension, and Arc Hydro extension.

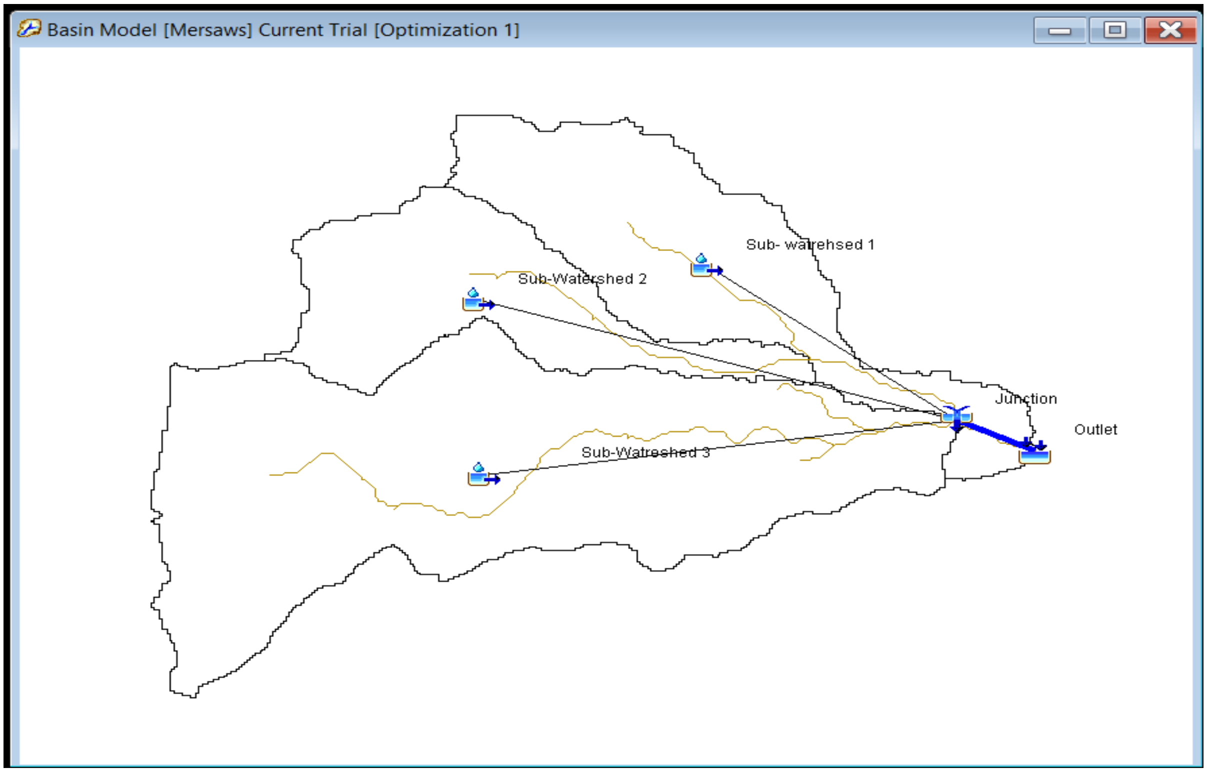


Figure 4. 3 HEC-HMS Basin model of Mersa watershed

HEC-HMS model has different model parameter combinations, for this study the following parameter combinations were applied as shown in the table.

Table 4. 1. The Selected HEC-HMS model Parameter combination

Parameter	Loss model	Transform model	Base flow model	Routing model

Combination parameter	Soil moisture accounting	SCS unit hydrograph	Linear Reservoir	Muskingum

4.2.1 Calibration and Validation of HEC-HMS model

a. Calibration result of HEC-HMS model:

HEC-HMS model calibration was conducted in Mersa watershed outlet for the total of eleven years consecutive daily data (from January 1, 1996 to December 31, 2006) which includes two years of warm up period, (from January 1, 1996 to December 31, 1998). The calibration technique was used; first, the initial values of the selected parameters were provided, and then the simulation was performed until the objective functions became constant with respect to the observed flow. Both automatic and manual calibration methods have been used for calibration.

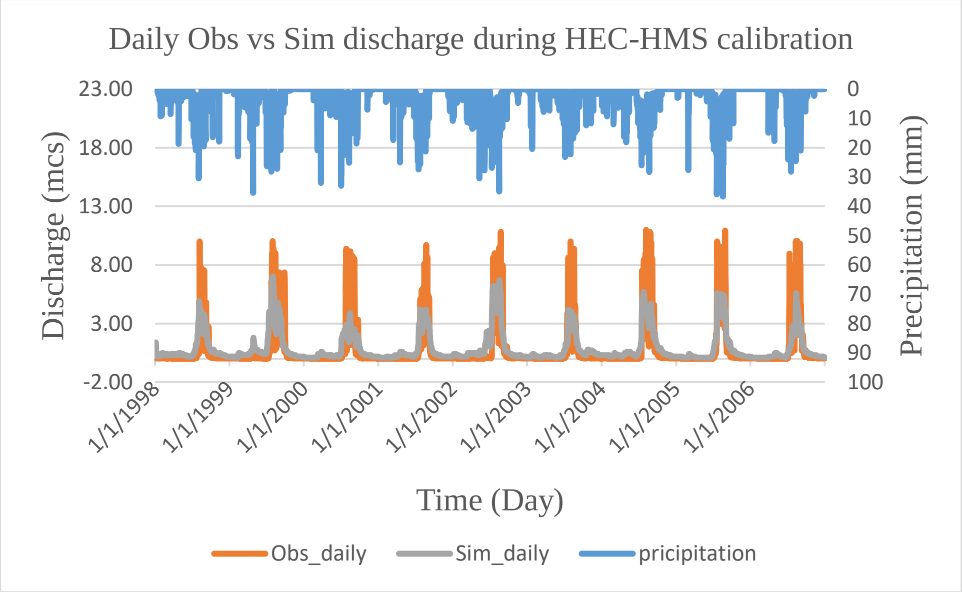
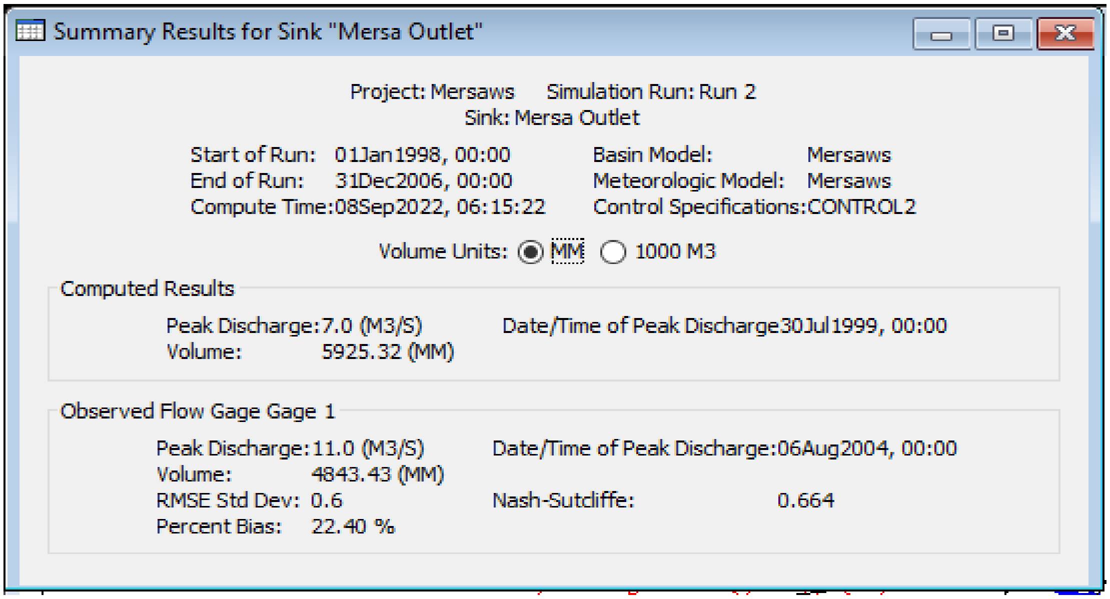


Figure 4. 4 HEC-HMS model simulated and observed discharge relation during calibration

The HEC-HMS calibrated discharges result and the observed flow at the study area's outlet were in good agreement, according to the calibration results using the Nash Sutcliff model efficiency objective function. After thousands iteration was applied, the best calibrated results of the objective functions which are Nash Sutcliff efficiency (NSE), coefficient of determination (R^2) and root mean square error (RMSE) were 0.664, 0.7 and 0.6 respectively.

Table 4. 2. Calibrated HEC-HMS model results



Summary Results for Sink "Mersa Outlet"

Project: Mersaws Simulation Run: Run 2
Sink: Mersa Outlet

Start of Run: 01Jan1998, 00:00
End of Run: 31Dec2006, 00:00
Compute Time: 08Sep2022, 06:15:22

Basin Model: Mersaws
Meteorologic Model: Mersaws
Control Specifications: CONTROL2

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge: 7.0 (M3/S)
Volume: 5925.32 (MM)
Date/Time of Peak Discharge 30Jul1999, 00:00

Observed Flow Gage Gage 1

Peak Discharge: 11.0 (M3/S)
Volume: 4843.43 (MM)
RMSE Std Dev: 0.6
Percent Bias: 22.40 %
Date/Time of Peak Discharge: 06Aug2004, 00:00
Nash-Sutcliffe: 0.664

b. HEC-HMS model validation:

Validation of HEC-HMS model was applied for six years consecutive daily data from January 01/01/2007 up to December 31/12/2012. Applying this required importing validation data and using calibrated parameters with consistent values. For the observed discharges value, the validated discharge findings of the model are best followed.

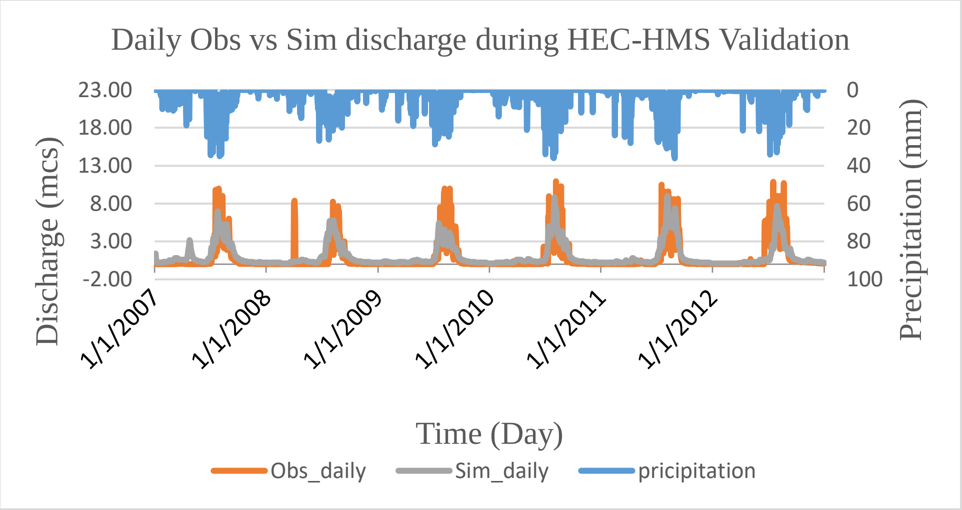
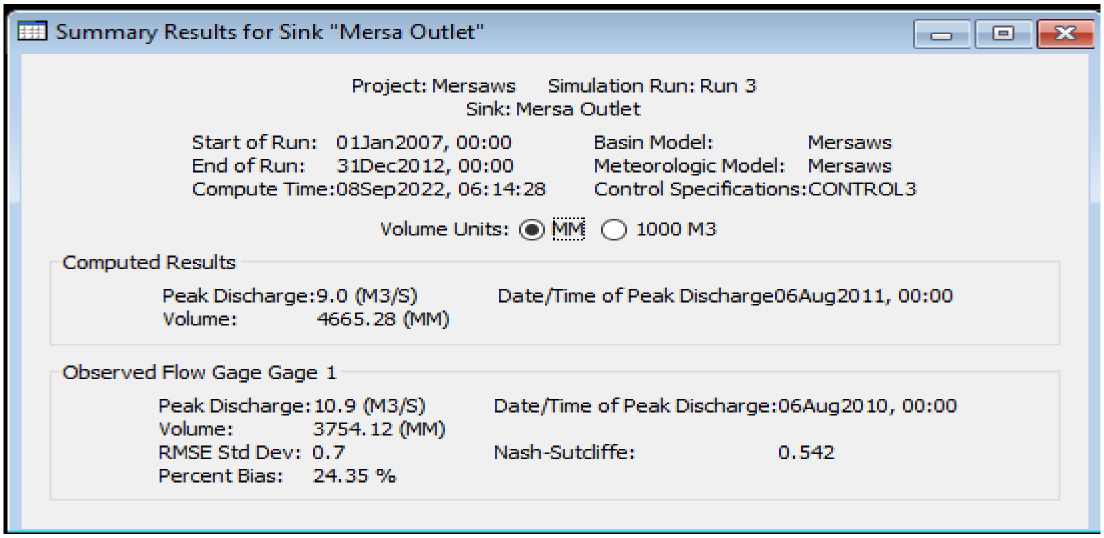


Figure 4. 5 HEC-HMS model simulated and observed discharge relation during Validation

HEC-HMS model validation results of the selected efficiency measurements which are NSE, R^2, and RMSE, were 0.542, 0.555 and 0.7 respectively.

Table 4. 3 Validated HEC-HMS model results



Summary Results for Sink "Mersa Outlet"

Project: Mersaws Simulation Run: Run 3
Sink: Mersa Outlet

Start of Run: 01Jan2007, 00:00
End of Run: 31Dec2012, 00:00
Compute Time: 08Sep2022, 06:14:28

Basin Model: Mersaws
Meteorologic Model: Mersaws
Control Specifications: CONTROL3

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge: 9.0 (M3/S)
Date/Time of Peak Discharge 06Aug2011, 00:00
Volume: 4665.28 (MM)

Observed Flow Gage Gage 1

Peak Discharge: 10.9 (M3/S)
Date/Time of Peak Discharge: 06Aug2010, 00:00
Volume: 3754.12 (MM)
RMSE Std Dev: 0.7
Nash-Sutcliffe: 0.542
Percent Bias: 24.35 %

4.2.2. HEC-HMS model sensitivity analysis

For HEC-HMS model this study divides the watershed into three sub-basins and one reach one junction and one outlet for analysis. HEC-HMS model was capacity to determine the sensitive parameter during automatic optimization methods or manual optimization method, but for convenience, this study used a manual sensitivity method by adding ±10%, ±20%, ±30%, ±40% and ±50% to the parameters and keeping the other parameter constant. The result shown that the most sensitive parameter was surface maximum storage, SMA maximum infiltration and SMA soil storage compared to the other parameter, the other parameters do not cause a significant change. The figure below displays that changing surface maximum storage from 0% to 50% of the NSE (objective function) value varies from 0.66 – 0.62.

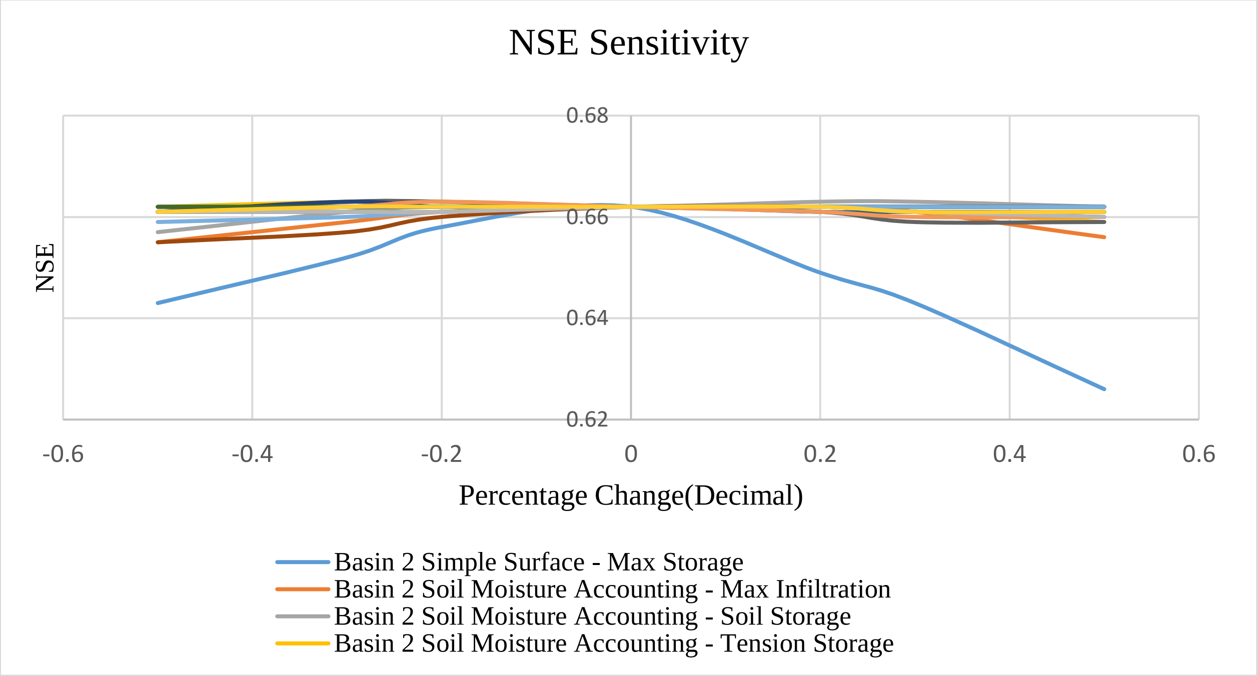


Figure 4.6. HEC-HMS sensitivity analysis under NSE Value

4.3 Comparison of Models

The comparison results of PED-W and HEC-HMS modals based on the objective function have done. PED-W model and HEC-HMS model have different structures and parameters for the discharge estimation systems. But the same daily time series data were used for all the models' calibration and validation. The model efficiency measurement techniques were Nash Sutcliff efficiency (NSE), coefficient of determination (R^2) and root mean square error (RMSE). The following figures illustrate the various efficiency of the models.

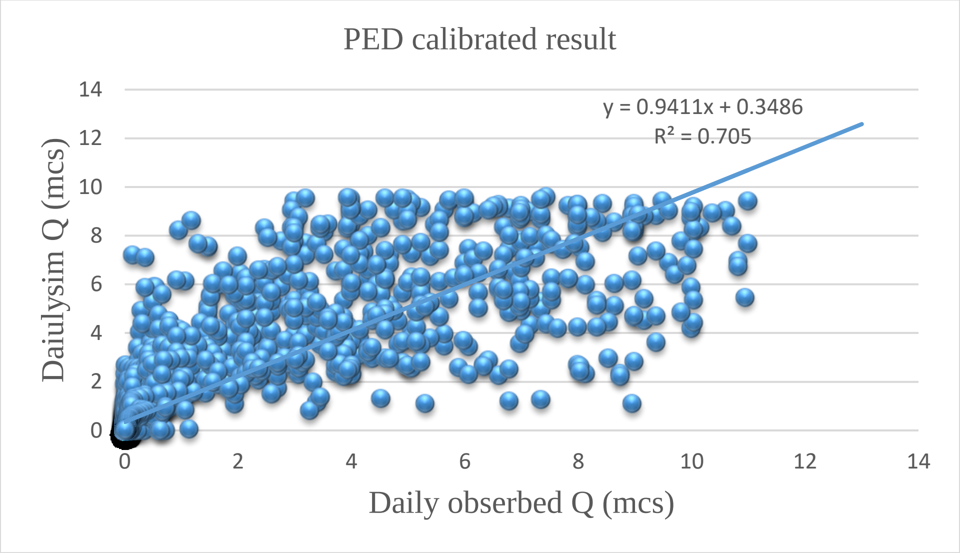


Figure 4.7 Calibrated daily discharge scatter chart for the PED-W model

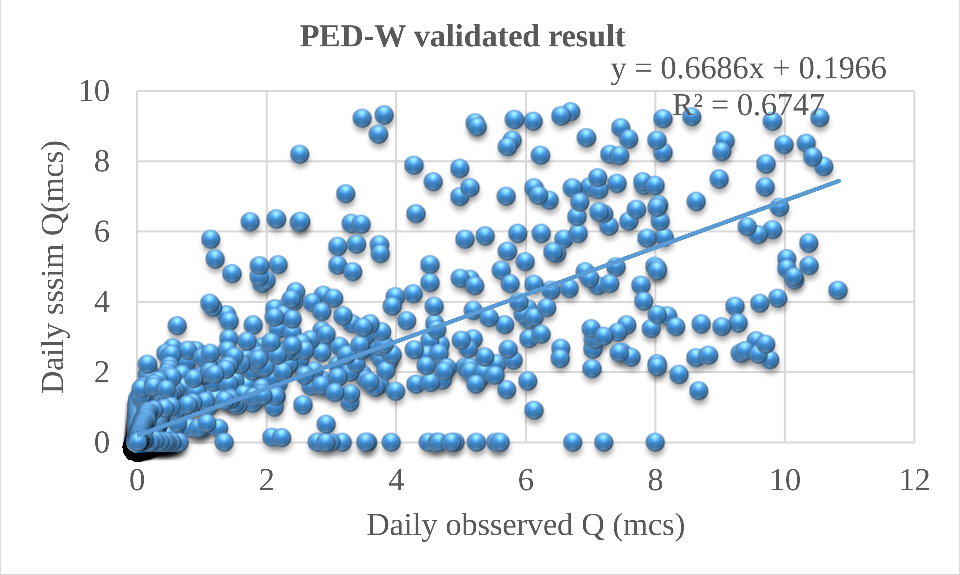


Figure 4.8. Validated daily discharge scatter chart for the PED-W model

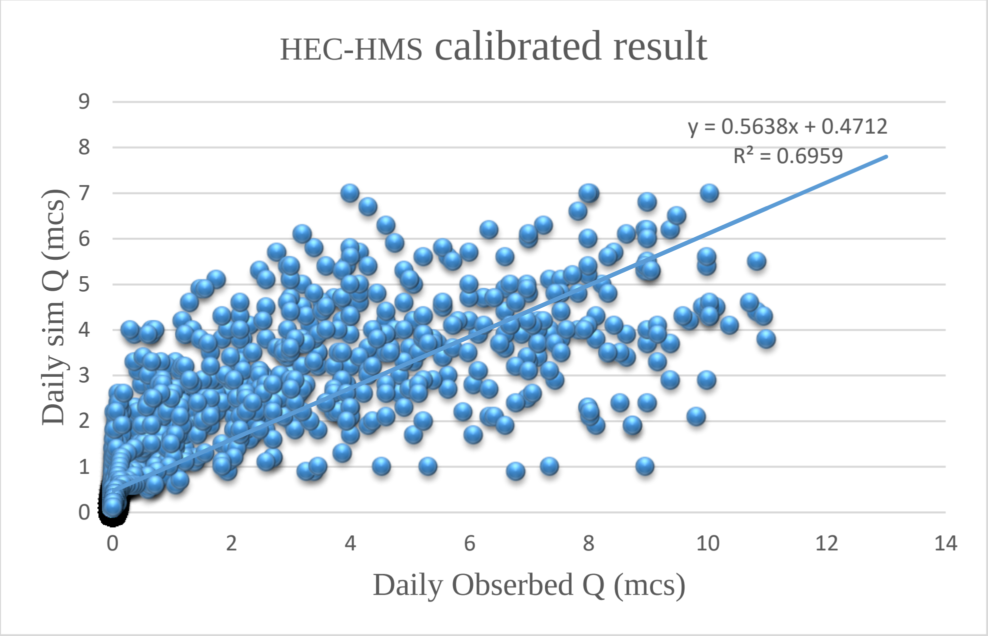


Figure 4.9. Calibrated daily discharge scatter chart for the HEC-HMS model

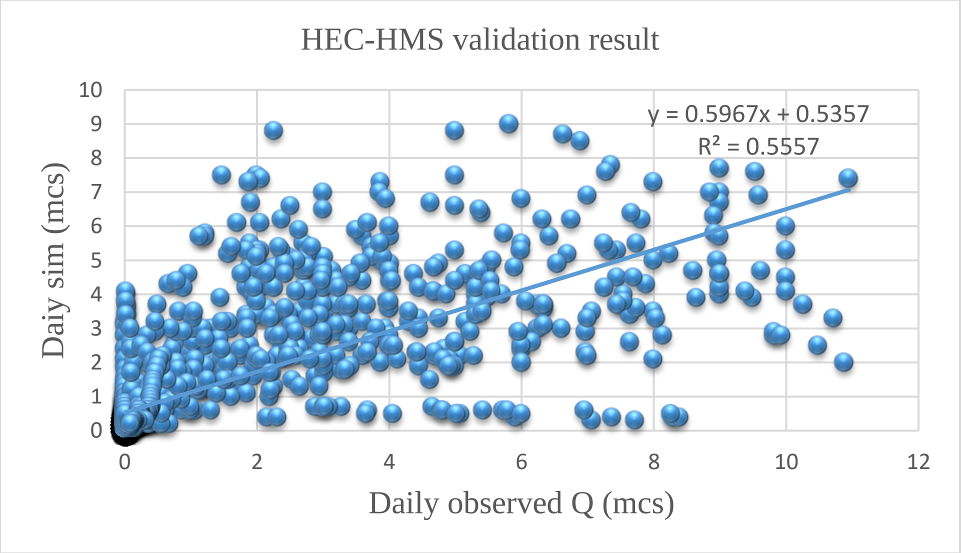


Figure 4.10. Validated daily discharge scatter chart for the HEC-HMS model

Generally, the comparison results of PED-W and HEC-HMS modals based on the objective function Nash Sutcliff efficiency (NSE), coefficient of determination (R^2) and root mean square error (RMSE) were summarized as follows in the table below.

Table 4.4. Summarized objective function result of PED-W and HEC-HMS modals

Period of simulation	Statistical parameters	Daily Simulation	
		PED	HECHMS
Calibration Period	Simulated peak Discharge (m^3/s)	9.588	7
	Observed peak discharge (m^3/s)	11	11
	R^2	0.705	0.695
	NSE	0.666	0.664
	RMSE	1.31	0.6
Validation Period	Simulated peak Discharge (m^3/s)	9.465	9
	Observed peak discharge (m^3/s)	10.834	10.834
	R^2	0.674	0.555
	NSE	0.55	0.542
	RMSE	1.61	0.7

Based on table 4.4 Nash Sutcliff efficiency (NSE) measurements, coefficient of determination (R^2) and root mean square error (RMSE) results from the calibration and validation output PED-W model performs in better way than the HEC-HMS model. And also PED-W model could simulate the better peak flows than HEC-HMS model during calibration and validation time.

PED-W and HEC-HMS models had maximum soil moisture storage capacities of 70–600mm and 14.6–100mm, respectively. This result indicates that the HEC-HMS model soil moisture storage capacity was smaller than PED-W model, because the HEC-HMS model accounted for additional loss for canopy and surface storage.

The PED-W and HEC-HMS models' optimum parameters for maximum groundwater storage were estimated to be 60 mm and 6 mm – 20 mm, respectively. HEC-HMS model optimized the groundwater storage coefficient up to 123 hours on sub-basin level, and the PED-W model groundwater linear reservoir storage base flow half-life 14 days. Interflow end up to 7 days after rainfall stops in PED-W model at the outlet of the watershed. Subsurface flow storage coefficient (lag time) of HEC-HMS model was 60-66 hours at the outlet of each sub basin.

The PED-W model provides a soil moisture balance equation for each fractional area. Hillside degraded area and saturation area were hydrologically active (generate runoff) after field capacity of the soil (maximum water holding capacity) but hillside infiltration area contribute runoff indirectly due to lateral flow and subsurface flow. When the rainfall continues after satisfy evapotranspiration and infiltration the excess rainfall infiltrate into the soil, at this stage PED-W model measure the loss by using the Thornthwaite equation. PED-W model assumes direct runoff contribution areas are saturation fractional area and hillside degraded area whereas hillside infiltration area contributes runoff through base flow and lateral flow. The result indicates that much of the fractional area covered by hillside infiltration area (70%), due to this reason PED-W model generate flows laterally than surface runoff.

From the parameters of PED-W model hill side area and maximum water storage have very high contribution for runoff estimation in the selected watershed. These parameters were very flexible when changing its value. The HEC-HMS model's most sensitive parameter is the sum of soil moisture storage depth and surface storage. This result implies that runoff generation is significantly influenced by the infiltration area, surface storage, and soil storage characteristics of the watershed.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The main objective of this research was to compare the relative strength and validity of the PED-W and HEC-HMS model to simulate a runoff. In this research work seventeen years (1996-2012) hydro-metrological data were used. The calibration was done using (1996-2006) hydro-meteorological data and from (2007-2012) hydro-meteorological data used for validation. The model efficiency measurement techniques were Nash Sutcliff efficiency (NSE), coefficient of determination (R^2) and root mean square error (RMSE). Based on these objective function outputs PED-W model had better performance as the result shown below.

The corresponding value of the PED-W and HEC-HMS models during daily calibration period were, (0.666, 0.664), (0.705, 0.695) and (1.31, 0.6) of NSE, R^2 and RMSE value respectively. Similarly for validation period were (0.55, 0.542), (0.674, 0.555) and (1.61, 0.7) of NSE, R^2 and RMSE value respectively.

Based on simulated discharge from the two models PED-W model could simulate the better peak flows than HEC-HMS model during calibration and validation time.

From the parameters of PED-W model hill side area and maximum water storage were very highly sensitive parameter for runoff estimation in the selected watershed. These parameters were very flexible when changing its value. The HEC-HMS model's most sensitive parameters were surface maximum storage, SMA maximum infiltration and SMA soil storage. These sensitive parameters were grouped under the loss model.

5.2 Recommendation

In this research, the time duration of the study was from 1996 up to 2012 for comparison PED-W and HEC-HMS models. For best accuracy of the predictions long time series data and more model comparison should be tested.

There is need to explore the performance of other hydrologic models for the purpose of comparing watershed behavior and impacts statistics even best simulation result is get from each model.

For further investigation, this study recommended that good quality data have the most critical issue before manipulation of models in order to prevent inaccurate conclusion.

In general, the results of this study will be used to different watersheds management practices and to design water related structures.

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