JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRAGUATE STUDIES

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

CHAIR OF HYDROLOGY AND HYDRAULIC ENGINEERING

MASTER OF SCIENCE PROGRAM IN HYDRAULIC ENGINEERING

HYDROLOGICAL MODELING USING OBSERVED AND SATELLITE PERCIPITATION DATA: THE CASE STUDY OF WABE WATERSHED, OMO-GIBE RIVER BASIN, ETHIOPIA.

BY

ABEL GIRMA ANJULLO

A THESIS SUBMITTED TO THE CHAIR OF HYDROLOGY AND HYDRAULIC ENGINEERING OF JIMMA INSTITUTE OF TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN HYDRAULIC ENGINEERING.

FEBRUARY, 2024

JIMMA, ETHIOPIA

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ADVISOR: Dr.-Inj. KENENI ELIAS (PhD)

CO-ADVISOR: Mr. SEWEMHON SISAY (MSc)

FEBRUARY, 2024

JIMMA, ETHIOPIA

DECLARATION

I hereby declare that this Master Thesis entitled" HYDROLOGICAL MODELING USING OBSERVED AND SATELLITE PERCIPITATION DATA: THE CASE STUDY OF WABE WATERSHED, OMO-GIBE RIVER BASIN, ETHIOPIA." It is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

Abel Girma Anjullo	______________	______________
Name of the student:	Signature	Date of submission

This thesis has been submitted for examination with my thesis approval as a university advisor.

Advisor: Dr.-Inj. Keneni Elias (PhD):	___________________	_____________
Name	Signature:	Date of submission

Co-Advisor: Mr. Sewemehon Sisay (MSc)	_______________	_______________
	Signature	Date of submission

THESIS APPROVAL SHEET

This is to certify that the thesis entitled "hydrological modeling using observed and satellite precipitation data in Wabe watershed, Omo-Gibe River basin, Ethiopia" is the work of Abel Girma and we here by recommend for the examination by Jimma Institution of Technology in partial fulfillment of the requirements for degree of masters of science in hydraulic engineering.

By Abel Girma	________________	_____________
	Signature	Date
1. Keneni Elias (PhD)	__________________	_____________
(Main Advisor)	Signature	Date
2. Mr. Sewemhon Sisay	_________________	_____________
(Co- Advisor)	Signature	Date

As members of the Examining Board of the Final MSc Open Defense, we certify that we have read and evaluated the thesis prepared by: Mr. Abel Girma entitled: Hydrological modeling using observed and satellite precipitation data in Wabe watershed, Omo-Gibe River basin, Ethiopia. We recommend that it be accepted as fulfilling the thesis requirement for the degree of Master of Science in Hydraulic Engineering.

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ABSTRACT

Precipitation is the most significant atmospheric input to land surface hydrological models. But the rainfall stations are scarce and distributed unevenly, making it difficult to collect precipitation data, which leads to insufficient the simulation of hydrological processes. Alternatives such as satellite-based rainfall estimates can be useful. There are several satellite-based datasets accessible for use in modeling; however, selecting the most accurate and reliable satellite product that should be well matched to the intended area should be considered. Therefore, there is a need to evaluate the accuracy of satellite rainfall product. The aim of this research is hydrological modeling using observed and satellite (GPM_IMERG and CHIRPS) precipitation data for Wabe watershed. Both continuous statistical and hydrologic modeling approaches were used for the performance evaluation from the most representative rain gauge for five stations at daily and monthly time steps. Intercomparison between satellite rainfall product and observed data were done using point to grid method by selecting five representative meteorological stations. For continuous statistical evaluation, CHIRPS is performed better than GPM_ IMERG for daily and monthly timescales in detecting and estimating rainfall for the basin. The performance of HEC-HMS model was evaluated using, Net-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), a coefficient of determination (R^2) and Percent Bias. The model Calibration and Validation results of observed station showed (NSE = 0.55, R^2 = 0.571, RMSE = 0.7, PBIAS = -0.64) and (NSE = 0.58, R^2 = 0.6, RMSE = 0.7, PBIAS = -6.71), throughout the periods respectively. For CHIRPS, the model Calibration and Validation results showed (NSE = 0.532, R^2 =0.51, RMSE = 0.5, PBIAS = 2.48) and (NSE = 0.51, R^2 = 0.547, RMSE = 0.6, PBIAS = 12.04), throughout the periods respectively; whereas for that of GMP_IMERG the model Calibration and Validation results showed (NSE = 0.5, R^2 = 0.516, RMSE = 0.6, PBIAS = 8.33) and (NSE = 0.44, R^2 = 0.458, RMSE = 0.7, PBIAS = 11.08) throughout the periods, respectively. The study shows that the HEC-HMS model is satisfactory in hydrological modeling. However, the finding indicated that observed rainfall is more suitable than Satellite Rainfall for hydrological modeling of wabe watershed. The research outcome is more important to policy planner for efficient water resource management.

Key word: *CHIRPS, GPM-IMERG, HEC-HMS, SCS-CN, SCS-UH, Wabe Watershed*

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ACRONYMS AND ABBREVIATIONS

ANN	Artificial neural networks
CHIRPS	Climate Hazard Infrared Precipitation with Station
CMORFH	Climate Prediction Center Morphing Method
DEM	Digital Elevation Model
GIS	Geographical Information Systems
GPM-IMERG	Integrated Multi-Satellite Retrieval for Global Precipitation Measurement
HEC-HMS	The Hydrologic Engineering Center Hydrologic Modeling System
HEC-GEOHMS	Hydrologic Engineering Center-Geospatial Hydrologic Modeling System
HSPF	Hydrological Simulation Program-Fortran
LULC	Land Use Land Cover
MOWR	Ministry of Water Resources
MOWIE	Ministry of water, irrigation and electricity
MMS	Modular Modeling System
NASA	National Aeronautics and Space Administration
NOAA	National Ocean Atmospheric Administration
PERSIANN	Precipitation Estimation from Remote Sensed Information Using Artificial Neural Network
QGIS	Quantum Geographical Information System Rainfall
SCS-CN	Soil Conservation Service Curve Number
SRE	Satellite rainfall estimation
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
TAMSAT	Tropical Applications of Meteorological Satellites
TRMM	Tropical Rainfall Measuring Mission
UH	Unit Hydrograph
USGS	United States Geological Survey
WHO	World Metrological Organization

1. INTRODUCTION

1.1 Background

High temporal and spatial resolution rainfall data are essential input for any hydrological model to predict river flow. However, due to the high cost of establishing and maintaining infrastructure, ground-based precipitation measurements are often sparse, unevenly distributed, poor in terms of data quality, temporally inconsistent, and impossible to access in time. This is especially true in countries that are developing (Kawo et al., 2021; Dinku *et al.*, 2018).

Obtaining impressive and continuous ground-based precipitation measurement in such developing regions can be challenging due to data quality and inconsistence in instrumentation and ground-based limitation of data. To address this limitation, high resolution satellite-based precipitation product has emerged as promising alternative (Herath and Wijesekera, 2021).

The performance of satellite rainfall products varies with region, elevation, and season. They are also exposed to errors due to temporal resolution, instrument, algorithm, revisit time gaps, and the indirect relationship between remotely sensed signals and rainfall rate. Therefore; it's very important to evaluate the accuracy of these estimates. It is commonly known that satellite rainfall values are only estimates that need to be thoroughly validated. Two categories can be used to classify the validation attempts. First, the satellite rainfall estimates are directly compared to ground-based radar estimations and rain gauge networks (Bitew *et al.*, 2012 ; Gebremichael, 2010).

The second includes evaluating satellite rainfall predictions in a hydrological modeling framework for their capacity to predict stream flow rate. The satellite rainfall estimates are assessed as a driving input variable in a hydrologic model, taking into consideration a particular application (Bitew *et al.*, 2012).

Nowadays, numerous high-resolution satellite-based rainfall products have been developed and studied to assess their effectiveness. Integrated Multi-Satellite Retrieval for Global Precipitation Measurement (GPM_IMERG) is one of the satellite-based rainfall products. Numerous researchers have assessed GPM_IMERG rainfall products with observed rainfall data and with other satellite-based rainfall products (Kawo et al., 2021; Tang et al. 2016).

CHIRPS dataset is available in two sets of spatial resolutions i.e., 0.05° × 0.05° and 0.25° × 0. 25° for it provides daily, pentad, decadal, and monthly precipitation from 1981 to the present (Funk *et al.*, 2015).

In this case the rainfall data sets and the modeling activities were used to characterize and determine performance of input precipitation data and high-resolution satellite rainfall products (CHRIPS and GPM_IMERG).

HEC-HMS model of the Wabe Watershed, using observed and satellite precipitation data presents an interesting area for further investigation. One potential research gap could be the availability, quality of observed and satellite precipitation data. Conducting uncertainty analysis within the HEC-HMS model framework can help identify sources of uncertainty and quantify their impact on model outputs.

The aim of this study is to evaluate the performance of observed and satellite precipitation data (CHIRPS and GPM_IMERG) as input for runoff simulation in Wabe watershed. Both rain gauge and satellite rainfall products, and the stream flow were simulated using the HEC-HMS hydrological model

1.2 Statement of problem

Rainfall is extremely variable in mountain areas, and distribution change can take place quickly and over small distances. Other issues include gathering data from the existing surface observation network distribution and conducting ground survey rain gauge stations do not always adequately represent the weather occurring over watershed, because they can be far from the watershed of interested and can have gaps in their data series or recent data are not available. The Wabe watershed is one of the many Ethiopian watersheds that are exposed to these problems.

Satellite derived rainfall has as alternative option to indirectly retrieve rainfall estimation that can be used as a reliable alternative or complement for hydrological modeling and forecasting in the watershed. However, satellite precipitation products have a systematic bias. its quality needs to be evaluated before to use for different application. All satellite rainfall estimates are not suitable for all the areas. Their suitability and performance vary from region to region therefore a requirement to quantity their uncertainty should be considered before selecting the acceptable product for the region. The problem addressed in this study envisages that they can be used as a reliable alternative or complement for hydrological modeling and forecasting in the watershed. This study intends to evaluate the performance of two widely used, high resolution satellite rainfall data set (CHIRPS and GPM_IMERG) and Ground observation for simulating stream flow modeling in Wabe watershed. Due to this performance evaluation against the rain gauge observed rainfall data and satellite rainfall product is vital in order to enhance their accuracy.

1.3 Objective

1.3.1 The General objective

The general objective of this research is the hydrological modeling using observed and satellite precipitation data in Wabe watershed, Omo-Gibe River basin

1.3.2 The specific objective

- To compare satellite rainfall product with ground-based rain gauge rainfall
- To simulate rainfall-runoff by satellite rainfall products and gauged station data over the watershed.
- Assess the performance of HEC-HMS using ground gauge and satellite rainfall data

1.4 Research questions

1. Can high resolution satellite rainfall product accurately estimate rainfall compared to ground-based rain gauge rainfall observation over Wabe watershed?
2. What are the valuable model runoff simulation results that are simulated using satellite and ground gauge stations rainfall data?
3. How is the performance of HEC-HMS in assessing satellite and ground gauge station rainfall data?

1.5 Scope of the study

The study is bounded by the Wabe watershed, and its scope has been limited to meet its stated objectives. Consequently, the hydrological modeling of watershed using observed and satellite (GPM_IMERG and CHIRPS) for spatial resolution (0.1°×0.1°and 0.05°×0.05°) used for daily precipitation data for the period of (2005-2020). The study was to determine an accurate satellite rainfall evaluated by statistical continuous performance evaluation matrix, which is then simulated in the watershed using the HEC-HMS model. This study was used to point to grid approach where satellite rainfall estimates are extracted for each gauge location and satellite rainfall are generated and compared.

1.6 Significance of the study

The significance of this study, entitled “The hydrological modeling of watershed using observed and satellite precipitation data in Wabe watershed, Omo-Gibe River basin, Ethiopia” can be summarized as follows

1. It enhances hydrological understanding that offers flow data for the state of irrigation and hydroelectric project in the cascade of omo-gibe project area. This understanding is vital for effective water resource management, flood prediction climate change adaptation.
2. Policy Recommendation: based on the study outcome policy makers and water resource management authorities can formulate policies that consider the use of satellite-based precipitation data. Integrating such data into policy decision can lead to more efficient and informed water management strategies.
3. The goal of this research is to determine the capacity and limitations of satellite rainfall data as input into a hydrological model for runoff simulation in the Wabe Watershed, using CHIRPS and GPM-IMERG satellite rainfall products.
4. Scientific contribution: the study's evaluating methodology and the finding will add to the body of scientific knowledge on the accuracy and suitability of satellite derived precipitation data for hydrological modeling. It may lead to advancement in remote sensing techniques and contribute to further research in similar contexts.

1.7 Organization of this thesis

The paper is organized into five chapters: Chapter one is an introduction part where the background, statement of the problem, objectives of the study, research questions, scope of the study and significance of the study are discussed. In chapter two, review of related literatures encompassing the topics of rainfall runoff process in a watershed, rainfall-runoff modeling, HEC-HMS application in Ethiopia, the selection of satellite rainfall products, application of high-resolution satellite rainfall products in hydrological modeling is presented.

In Materials and Methods chapter, Description of the study area, hydro metrological data, model inputs data analysis and preparation, hydrological model selection criteria, model performance evaluation are elaborated. The fourth chapter describes with the result and discussion which includes satellite rainfall products versus rain gauges, stream flow modeling, satellite rainfall simulation of stream flow and overall discussion. The stream flow modeling includes sensitivity analysis, calibration and validation of stream flow simulation, and the performance evaluation of the model. Finally, in section five, conclusion and recommendations of the study are provided.

2. LITERATURE REVIEW

2.1 Rainfall-runoff relationship and Hydrological model

Runoff occurs when parts of the landscape is saturated or impervious. Basically, there are two types of concepts which are responsible for runoff generation. These are the infiltration excess runoff and the saturation excess runoff. In the infiltration-excess runoff concept, it is assumed that the overland flow occurs only when the rainfall intensity is greater than the infiltration rate at the soil surface. The second type of runoff generation also occurs where the soil surface is saturated and any further rainfall, even at low intensities, generates runoff that contributes to stream-flow (Balvanshi and Tiwari, 2014).

2.2 Rainfall-runoff modeling

A hydrologic system model is a mathematical approximation of a real system, with measurable hydrologic variables serving as its inputs and outputs and a set of equations connecting them. A system transformation is a crucial idea in the model structure (Chow, 1988). The modeling of flood events, the monitoring of water levels under various water conditions, and the forecasting of floods are only a few of the many applications for which rainfall-runoff models are applied (Jia *et al.*, 2009).

Many river basins through the world have employed hydrological models to gain a better understanding of the hydrological processes and the availability of water resources. Today, hydrological models are crucial for evaluating and projecting river basin water availability due to climate change, which is necessary for creating adaptation strategies (Choularton et al., 2019).

A model is a representation of a certain real-world event that includes all of its essential components. It fits both the qualitative and quantitative model categories. In research and engineering, a model's capacity to generate numerical value is its most crucial feature. A quantitative model must be used to determine physical parameters that are expensive to test in the field. A model is often categorized or classified in order to more effectively explain and discuss its capabilities, strengths, and limitations. Based on the pertinent criteria, rainfall-runoff models have been grouped in a variety of ways, but there isn't a single consistent approach to do so. In an effort to group rain fall runoff models according to both their unique approaches and distinctive characteristics, hydrologists have done so (Arnold et al., 2001).

In general, stochastic and deterministic hydrological models can be distinguished. In contrast to deterministic models, which do not produce randomness, stochastic models will result in some degree of randomness in their outputs. Within the deterministic models, three types of models are distinguished based on spatial discretization. In rainfall-runoff modeling, models are characterized as lumped, semi-distributed models account for spatial variability of topography, geology, soil type and land use within a catchment. These models use grid layers with elements. For every hydrological component that defines watershed dynamics in theory, there is a different mathematical model included in this model. The model uses a number of models to explain every aspect of the runoff process, including alternative models to account for cumulative losses, the model for base flow, channel flow, direct runoff, and runoff volume calculation.

2.3 HEC-HMS

In the United States, the Federal Emergency Management Agency uses the HEC-HMS model for floodway determinations, and it is currently widely accepted for many official purposes (Scharffenberg et al., 2018). The HEC-HMS model's capabilities include physical description of watersheds, meteorological descriptions, hydrologic simulations, parameter estimation, simulation analysis, future flow forecasting, sedimentation, and water quality. The watershed is represented using a basin model, and the processing moves from the upstream to the downstream components. In a physical watershed, infiltration, surface streamflow, base flow, hydrologic routing, water impoundment, and diversion structures are all simulated; rainfall, evapotranspiration, snowmelt are taken place in the meteorological model; whereas starting date and time, ending date and time, and a time interval are taken place in the control specifications (Herath and Wijesekera, 2021).

2.4 HEC-HMS Application in Ethiopia

HEC-HMS is a numerical and semi-distributed hydrologic model developed by the United States Army Corps of Engineers [USACE 2010]. It is applied in several watershed of the in Ethiopia for runoff simulation. A number of studies carried out in various locations with varying watershed attributes demonstrated the efficacy of the HEC-HMS model in runoff modeling.

In a region of Ethiopia, the HEC-HMS model was calibrated and verified, and its performance was assessed using combinations. SCS-CN of loss and SCS-UH transfer methods Gebre (2015). HEC-HMS hydrological model can be used to model the upper Blue Nile River basin catchments for better assessment and prediction of simulation of the hydrological responses

To account for the loss, runoff estimation, and flow routing, Soil Conservation Service Curve Number (SCS-CN), Soil Conservation Service Unit Hydrograph (SCS-UH) and Muskingum methods were used respectively the model. According to this paper, sub-basin decentralization was less sensitive to the HEC-HMS model than HRU defining thresholds. The comparison of the observed and simulated hydrographs and the model performance and their correlation showed that the model is appropriate for hydrological simulations in the Gilgel Abay Catchment (Tassew et al.,2019).

(Sewmehon and Tolera, 2021) applied the HEC-HMS model to accurately estimate the Gilgel Gibe watershed's peak discharge and daily runoff. As a result, the model is advised for the Gilgel Gibe watershed's continuous runoff simulation. The Gilgel Gibe watershed will benefit from the study's efficient use of water resources and watershed management. Additionally, it can serve as a guide or input for any upcoming hydrological studies in the neighboring poorly or not at all gauged watershed.

2.5 The Selected Satellite Rainfall Products

Hydrological modeling employing satellite technology is particularly useful in developing countries with inadequate stream gauging stations and meteorological stations.

Selection of Satellite Precipitation product Findings from most researchers and scholars above reveals that the GPM-IMERG and CHIRPS relatively well performed and gives a better spatial and temporal distribution of precipitation in the Ethiopia river basin region (Koshuma *et al.*, 2021).Therefore, GPM-IMERG and CHIRPS_V2 was chosen for this study.

2.5.1 GPM-IMERG

The Integrated Multi-satellite GPM (IMERG) method estimates the quantity of precipitation falling over a broad portion of the Earth's surface using data from numerous GPM satellites. The spatial and temporal resolutions of GPM-IMERG precipitation estimations are 0.1° and 30 minutes, respectively.

The GPM Microwave Imager (GMI) and the Dua-frequency Precipitation Radar (DPR) are the two main sensors carried by the GPM Core Observatory. DPR combined with active radar observation technology provides physical information of cloud precipitation particles from angles (Huang et., 2018).

The accuracy of the dataset can be increased by incorporating in-situ station data, particularly in regions with an absence of surface data. Using a merging method that combines the in-situ station data and satellite-based precipitation estimates is one option to incorporate in-situ station data. The accuracy of the dataset can be increased by using the merging approach to modify the satellite-based precipitation estimates to match the in-situ station data. In terms of improving satellite imagery resolution, GPM_IMERG estimates precipitation across most of the Earth's surface using a spatial resolution of 0.1° x 0.1°. It is crucial that the capabilities of the satellite sensors and the processing techniques used to create the data have an impact on the spatial resolution of the image.

2.5.2 CHIRPS

CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations) is a quasi-global precipitation product with a spatial resolution of 5km (0.05° x 0.05°) with timescales of daily, pentadal (5-day), and monthly. The United States Geological Survey (USGS) and the Climate Hazards Group at the University of California, Santa Barbara have created a quasi-global rainfall dataset that spans more than 30 years (from 1981 to the present). It's a gauge-adjusted dataset, meaning it's computed using weighted bias ratios rather than absolute station values, which reduces the dataset's variability (Dinku *et al.*, 2018).

The CHIRPS technique utilizes a combination of interpolated station data and models of terrain-induced precipitation augmentation. In recent times, comprehensive satellite observation resources, such as NASA and NOAA's gridded satellite-based precipitation estimates, have been utilized to construct high resolution (0.05°) gridded precipitation climatology's These improved climatology's can eliminate systematic bias from satellite-based precipitation fields, which was a crucial method used to create the CHIRPS data set, chirps Version-2, which spans the years 1981 to the near present. To generate gridded rainfall time series for trend analysis and seasonal drought monitoring, Satellite Product integrates data from in-situ stations. In places where surface data is scarce, the accuracy of the dataset is enhanced by the inclusion of in-situ station data.

CHIRPS employs 0.05° resolution satellite imagery to generate gridded rainfall time series 1 in order to improve the resolution of the satellite images. It is crucial to remember that the capabilities of the satellite sensors and the processing techniques used to create the image have an impact on the spatial resolution of satellite imagery.

This product is built with high- resolution and long- period record of rainfall estimates based on infrared cold cloud duration observations. The core objective of CHIRPS is to monitor meteorological hazards especially the droughts events, (Dinku *et al.*, 2018). To overcome uncertainties that may result from scarceness of rain gauge observation, blending station data have been added to CHIRPS to enhance its performance. CHIRPS data are chosen by many scientists as one of the best data used in hydrological studies and monitoring extremes weather events especially over African continent. CHIRPS is believed to give a good caption in mountainous areas,(Funk *et al.*, 2015); (Dinku *et al.*, 2018). CHIRPS_2 satellite rainfall result was less affected by elevation variation; it showed less difference for mountainous areas

2.6 Application of high – resolution satellite rainfall products in hydrological modeling

Hydrological modeling has been used in a variety of studies to simulate streamflow and evaluate the capability of satellite rainfall products. Following is a summary of some studies that assessed how well satellite rainfall products performed in hydrological simulations: These studies showed the value of satellite rainfall products for hydrological modeling applications.

Table 2.1 Studies on the performance of satellite rainfall products through hydrological Modelling

No	Satellite Rainfall products Evaluated	Hydrological Model Used	Watershed Characteristics	Main results	Reference
1	GPM_IMERG and CHIRPS	HEC-HMS (Ismael, Joseph and Patrick, 2017)	Shabelle basin 297,000 km^2 Ethiopian highland	the study found that the simulated GPM_IMERG product gave better results than the simulated CHIRPS product.	(Hussein and Baylar, 2023)
2	GPM_IMERG and TRMM3B42V7		The Huang-Huai-Hai Plain, with a total area of 3 × 105 km^2 It is located in the eastern coastal region of China	, the accuracy of IMERG is better than 3B42V7 product in the Huang-Huai-Hai Plain.	(Xu *et al.*, 2019)
3	CHIRPS, IMERG and 3b42/3	SWAT (Arnold et al., 1998)	Dhidhessa River and the Blue Nile River which covers a total drainage area of 28,175 km^2	CHIRPS2 dataset performed the best at annual, seasonal and monthly timescales.	(Gizachew and Misgana,2015)
4	GPM IMERG and TRMM 3B42.	SWAT (Arnold et al., 1998)	The catchment of Chenab River covers an area of about 26,000 km2 up to Marala Barrage	IMERG-F is superior to 3B42 by indicating higher R2, NSE and lower percent bias (PBIAS)	(River *et al.*, 2020)
5	GPM IMERG and CHIRPS		A Lake Ziway Basin total basin area of about 7300 km2	While both GPM-IMERG and CHIRPS showed good agreement with ground-observed rainfall data at monthly and seasonal time scales,	(Aster *et al.*, 2021)

3. MATERIALS AND METHODS

3.1 Description of the Study Area

The Omo Gibe River Basin is almost 79,000 km^2 in area and is situated in the southwestern part of Ethiopia, between 4°30' and 9°30' N latitude and 35° and 38° E longitude with an average altitude of 2800masl.

The fundamental characteristic of the Omo Gibe River Basin is its complex topographic feature. Thus, the basin is divided sharply into the highlands in the northern half of the area and lowlands in the southern half. The northern part of the catchment contains several tributaries emanating from the north-east, of which the largest is the Walga and Wabe rivers. (Gebresenbet, 2015). The Wabe River catchment is located between 08°21′ and 08°30′ N latitude and 38°05′ and 37°49′ E longitude, and the elevation range is between 1062 and 3613 m above sea level and covers a drainage area of about 2005 km^2

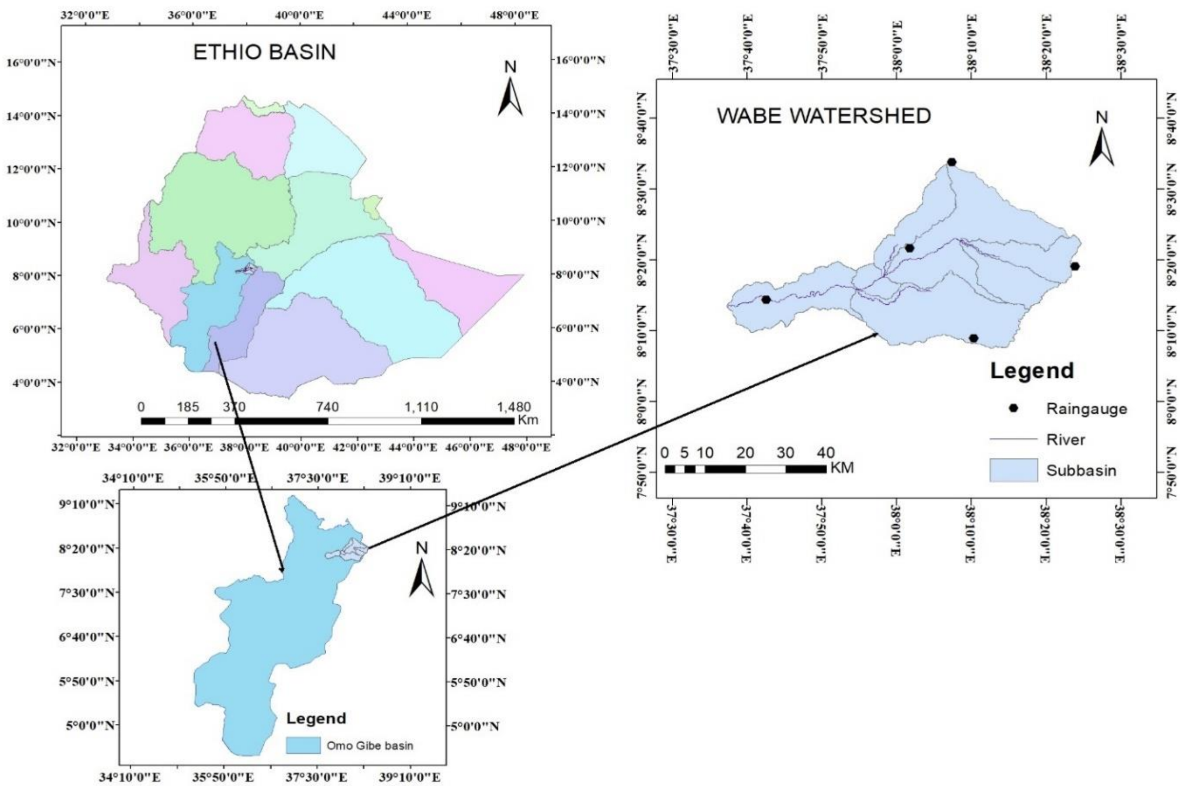


Figure 3.1Map of the study area

3.1.1 Topography

The topography of the Omo-Gibe basin as a whole is characterized by its physical variation. Two-third of the basin in its northern part has mountainous to hilly terrain cut by deeply incised gorges of the Omo, Gojeb and Gilgel-Gibe Rivers. The southern area, which accounts for a third of the basin, is a flat alluvial plain punctuated by hilly geographies. The northern part of the catchment has a number of tributaries. Most of the rivers from the upper part of the catchment drain largely cultivated the land. The Wabe River catchment is one of the tributaries of the Omo-Gibe River basin originating from the northeast part. The source of the Wabe River is the Gurage Mountain chain (Sahle et al,. 2018).

3.1.2 Climate

Omo Gibe River Basin has three distinct climate zones across the watershed in which it follows the country's climate classification, namely, Dega (cool zone), Weyna-Dega (temperate zone) and Kolla (hot zone). During the wet season, the area is under the influence of Atlantic equatorial westerly and southerly winds from the Indian Ocean, producing strong precipitation, mainly due to the Atlantic moisture component.

Omo-Gibe River Basin differs from temperate/hot arid climate properties from southern part of the floodplain to tropical humid of the highlands which include extreme north as well as northwestern part of Omo Basin. Intermediate between these variable climate properties and for the largest part of the basin climate is tropical sub-humid (Asefa and Derje, 2011).

Wabe watershed is characterized by the intermediate climate of tropical sub-humid. In addition, rainfall (RF) in the area varies from over highest values 1210.5 mm and lowest values 991.6 mm per annum in the areas and it is monomials.

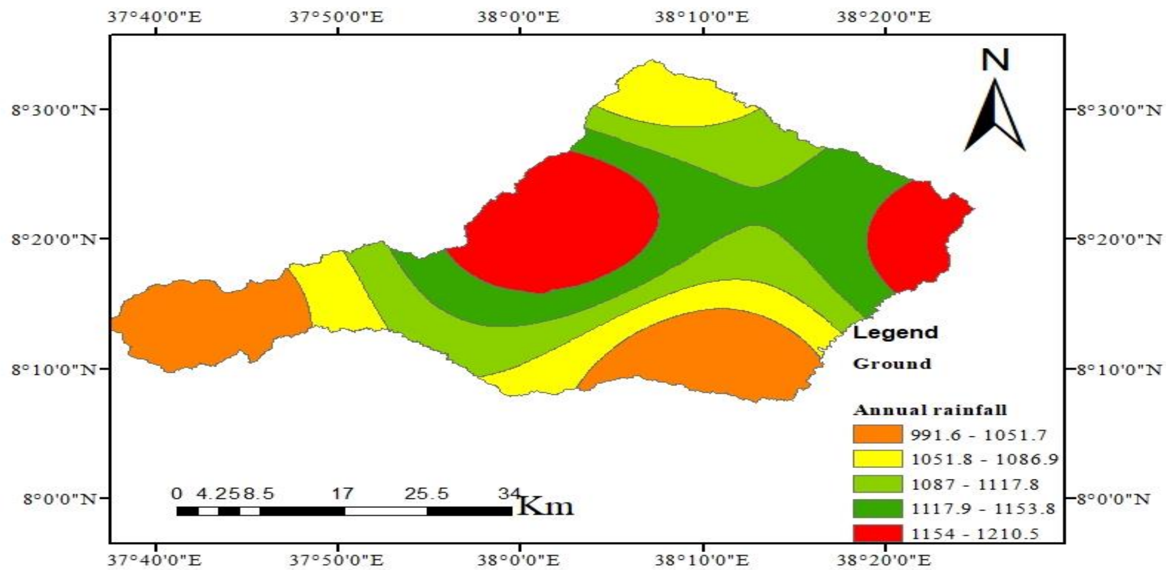


Figure 3.2spatial distribution of mean annual rainfall in wabe watershed

3.2 Spatial Data

3.2.1 DEM

Topography is defined by a Digital Elevation Model (DEM), which describes the elevation of any point in given area at a specific spatial resolution as a digital file. A digital elevation model is needed for raster-based hydrological analysis in a GIS. The DEM used in the study was a (30 by 30 m) made resolution elevation data which were be taken from. Shutter Radar Topography Mission (SRTM) of 30m resolution DEM. it was downloaded from https://earth explorer usgs.gov web page. The DEM was be used to generate percent slope values, to automatically delineate watershed boundary, stream networks, and identify gage outlets.

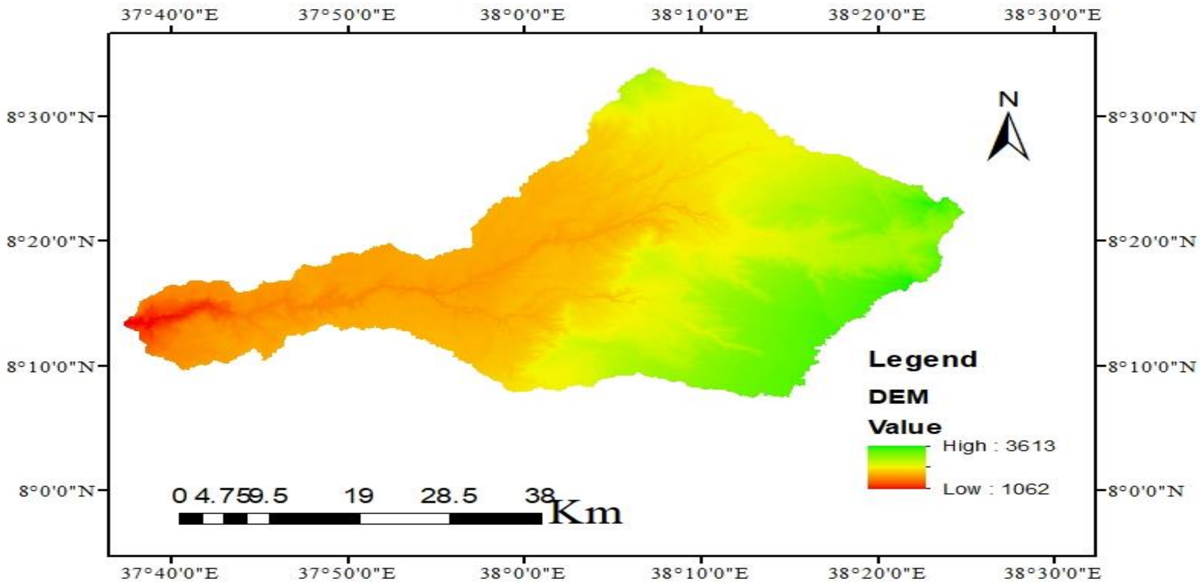


Figure 3.3 Dem of the watershed

3.2.2 Land Use Land Cover/LULC

The LULC is one of the important spatial data that characterizes the catchment. This parameter is dynamic as land use may change both spatially and temporally. The LULC map and datasets were obtained from MWIE. Land use and land covers have a major impact on runoff generation of the watershed. Therefore, land use land cover classification is mandatory to assess the impact of land use land cover change on stream flow.

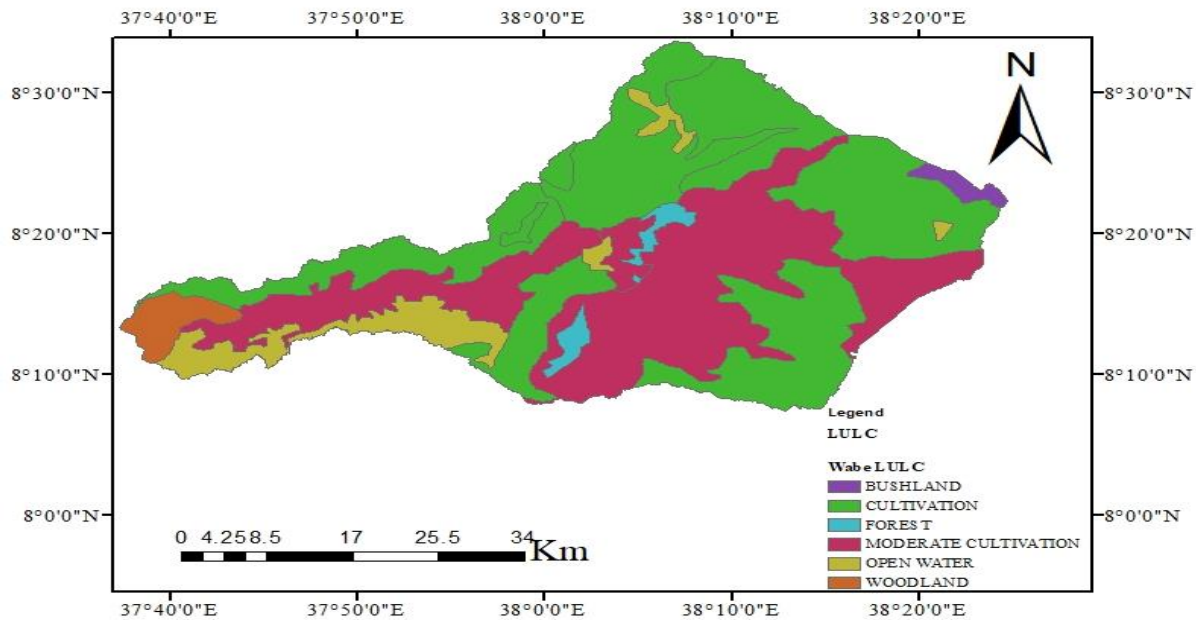


Figure 3.4 Land Use Land Cover Map of the Study Area

3.2.3 Soil type

The hydrological models need soil type of the study area either as the main input or as determining other parameters like curve number. Runoff curve numbers vary with the antecedent soil moisture conditions, defined as the amount of rainfall occurring in a selected period preceding a given storm. The soils of the upper and middle reach of the basin are mainly permeable and well-drained while the valley bottoms have less permeable soils with impeded drainage. As shown in Figure 3.5 below the soil type of Wabe watershed reclassified as four type's loam, clay and sandy loam. The dominant soil types for the study area are clay and sandy loam. Soil type's data in the watershed was obtained from MWIE.

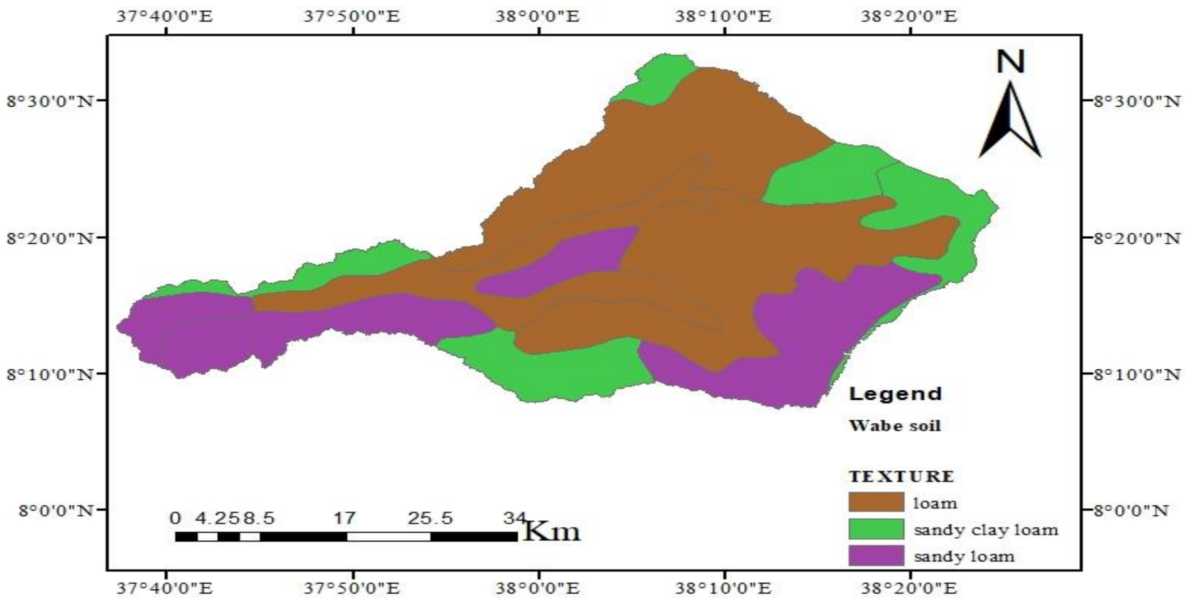


Figure 3.5 Soil map of the study Area (Source: FAO and DSMW)

3.3 Hydro-Meteorological Data

3.3.1 Precipitation data

A watershed's rainfall-runoff relationship must be established using meteorological data. These data were necessary for two purposes in the research. First, the data was utilized to calculate the performance evaluation of satellite product. Second, for the purpose of comparison, the data were input into the HEC-HMS model during the setup and simulated development of the hydrological model. Due to their longer record periods (2005-2020), the Ethiopian National Meteorological Institute provided daily rainfall data for five stations in the study area: Arbuchulule, Butajira, Fato, Dilela, and Welkite. The daily rainfall data from these stations has been analyzed, if there is any missing data.

Table 3.1 Average annual rainfall of selected stations of wabe Watershed

Station	Latitude	Longitude	Altitude	Average annual rainfall
Arbuchulule	8.475	38.52	2434	1054
Dilela	8.38	38.03	2429	1210.534
Fato	8.35	38.25	2520	1180.228
Butajira	8.09	38.22	2074	1029.459
Welkite	8.278	37.772	1888	795.584

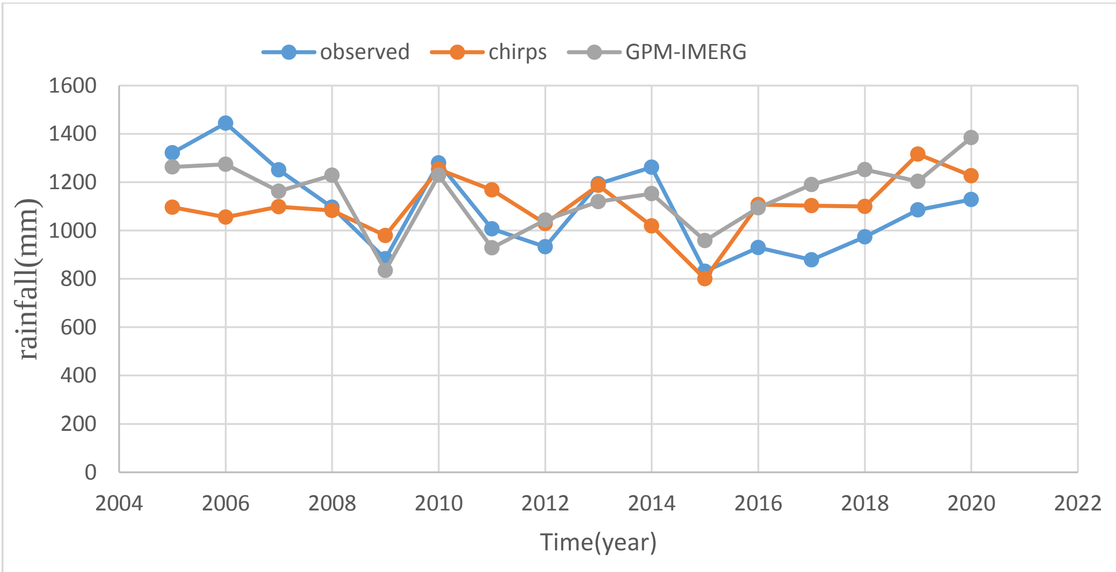


Figure 3.6 Annual average rainfall

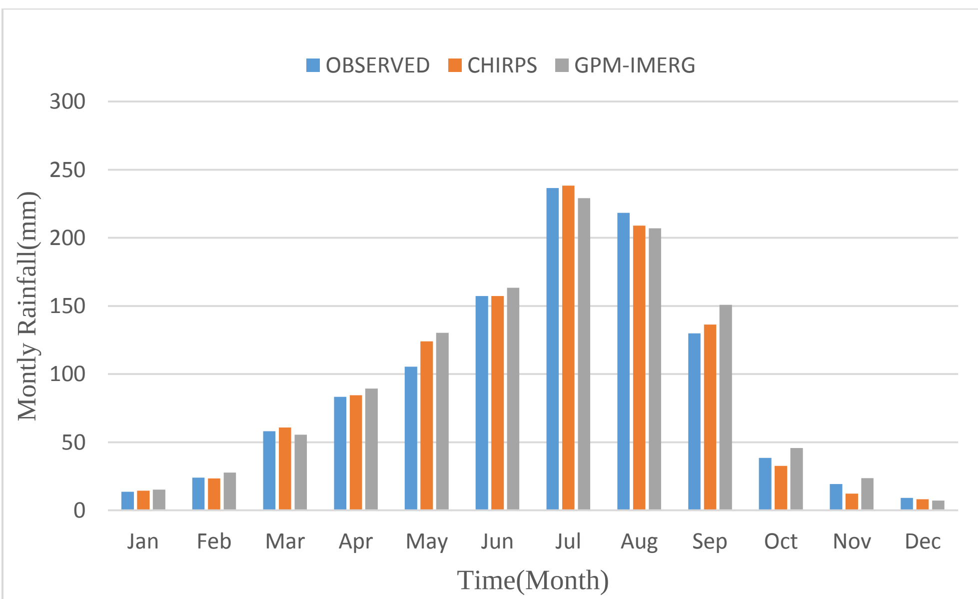


Figure 3.7Monthly average rainfall

3.3.2 Hydrological data

Daily flow data are essential for HEC-HMS simulated result, and for calibration and validation. Relatively long period year from (2005-2015) hydrological daily stream flow data easily collected for wabe catchment was from Ministry of Water, Irrigation and Electricity (MOWIE), Hydrology department.

Table 3.2 Location of the hydrological gauging station (wabe).

River	Gauge station	Latitude (Degree)	Longitude (Degree)	Elevation	Year
Wabe	Wabe	8.23	37.58	2150	2005-2020

Before the data was used it had been checked visually to identify gross error such as inaccurate peak flow, missed recording and flows of constant rate. These were done by filling data using XLSTAT Software. Hence proper data quality checks have been conducted only concentrating toward the objective of the hydrological analysis. This daily stremflow value was used for calibration and validation process. Depending on the extent of calibration and validation, flow data was collected and organized as per the requirement of the HEC-HMS model.

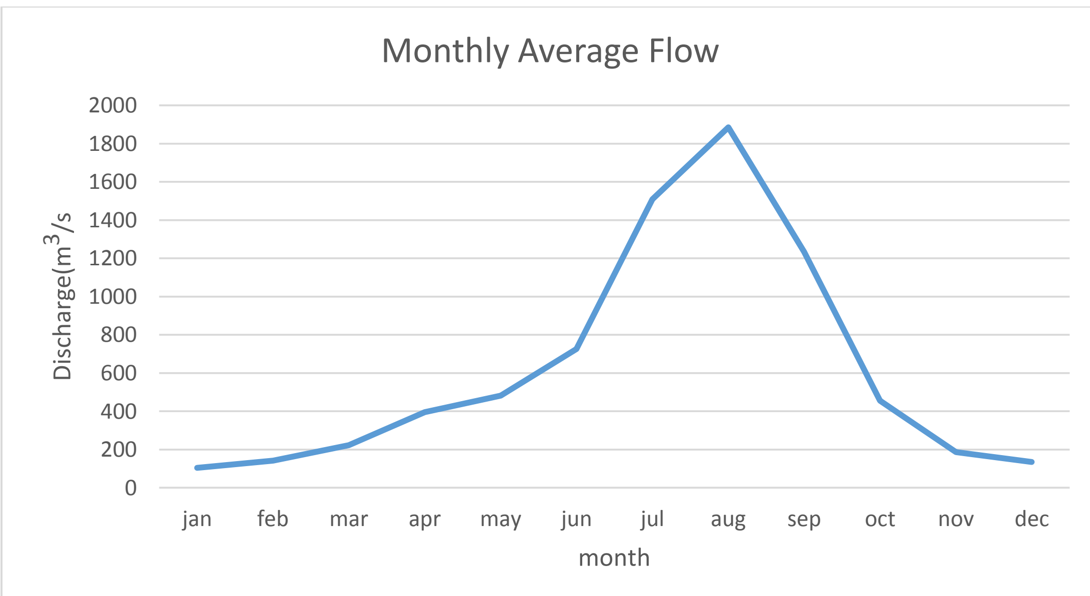


Figure 3.8Mean Monthly Stream Flow at the Outlet

3.4 Satellite Rainfall

High resolution information are also required to improve hydrological models performances and capabilities, whose need of high quality input data with sufficient resolution characteristic is increasing along with the models complexity (Filippucci *et al.*, 2022).

Satellite observations yield precipitation data with uniform spatial coverage; however, because of the indirect nature of the relationship between the observations and precipitation, the data contains non-negligible random errors and biases.

The two satellite rainfall estimates were used in this investigation were CHIRPS 2.0 and GPM_IMERG these datasets were selected for a number of reasons, such as the fact that they are the most recent products that have been found to perform well in recent studies; they have also high spatial resolution and are gauge-adjusted products. SREs have become more accurate, consistent, spatiotemporal resolution, and covered.

3.4.1 CHIRPS

This study employed the most recent version of CHIRPS (version 2), which uses more station data, the CHIRPS dataset is available in two sets of spatial resolutions i.e., 0.05° × 0.05° and 0.25° × 0. 25° for it provides daily, pentad, decadal, and monthly precipitation from 1981 to the present. This study employed the most recent version of Climate Hazards Group Infrared Precipitation with Station Data Version 2 (CHIRPS v2.0) are a product delivered from the combination of remotely sensed and ground observations. The core objective of CHIRPS is to monitor meteorological hazards especially the droughts events, (Dinku et al., 2018). To overcome uncertainties that may result from scarceness of rain gauge observation, blending station data have been added to CHIRPS to enhance its performance. CHIRPS data are chosen by many scientists as one of the best data used in hydrological studies and monitoring extremes weather events especially over African continent. CHIRPS is believed to give a good caption in mountainous areas, (Funk et al., 2015); (Dinku et al., 2018). CHIRPS_2 satellite rainfall result was less affected by elevation variation, it showed less difference for mountainous areas In this study, a CHIRPS dataset with a spatial resolution of download from 0.05°×0.05°and a daily time scale, which was freely (https://data.chc.ucsb.edu/products/CHIRPS-2.0/)

3.4.2 GPM_IMER

The Integrated Multi-satellite GPM (IMERG) method estimates the quantity of precipitation falling over a broad portion of the Earth's surface using data from numerous GPM satellites. The spatial and temporal resolutions of GPM-IMERG precipitation estimations are 0.1° and 30 minutes, respectively.

The GPM Microwave Imager (GMI) and the Dua-frequency Precipitation Radar (DPR) are the two main sensors carried by the GPM Core Observatory. DPR combined with active radar observation technology provides physical information of cloud precipitation particles from angles (Huang et., 2018).

Three product kinds are offered by IMERG: the post-real-time "Final Run" product, the near real-time "Early Run" and "Late Run" products. While the second product is not provided until 18 hours after the data retrieval time, the first product is available 6 hours after. About four months later, the Global Precipitation Climatology Centre (GPCC) product for bias correction is also included in the "Final Run" product, which is available for public. In this study, the latest final run IMERG daily version 6 was used (1st January 2005 to 30th December 2020) which are obtained from the Giovanni earth data https://giovanni.gsfc.nasa.gov/giovanni

Table 3.3 Summary of the two Satellite Rainfall Products selected for the study

Satellite Product	Temporal Coverage	Spatial Coverage	Spatial Resolution	Temporal Resolution	Source
CHIRPS-2.0	1981-present	Near-Global (50°N-50°S, 0°- 36^{0}E	0.05°	Daily	http://chg.geog.ucsb.edu/data/chirps/
GPM IMERG V6	2000-present	60°N-60°S	0.1°	Daily	https://giovanni.gsfc.nasa.gov/giovanni/and

3.5 Software's Used for Extraction of Satellite Rainfall

Net-CDF is a set of software libraries and machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data. It is also a community standard for sharing scientific data. The Uni-data Program Centre supports and maintains Net-CD programming interfaces for C, Java, and FORTRAN. Programming interfaces are also available for Python, QGIS, IDL, MATLAB, R, C++, Ruby, and Perl. Data in Net-CDF format is: Self-Describing, portable, scalable, append able, sharable and achievable. QGIS was used to extract and export the rainfall data in to excel for the study area and period for satellite rainfall estimates.

Table 3.4 Summarize of Data Types and its Sources

NO	Data type		Source of data
1	Spatial data	DEM	USGS
		SOIL MAP	MWIE
		LULC MAP	MWIE
		Satellite rainfall	NASA
			NASA
2	Hydrological data	Stream flow	MWIE
3	Meteorological data	Rainfall Gauge station	NMA

Table 3.5 Hydrological model software

No	Materiel and tools	Function	Source
1	QGIS 3.18	Used to extract satellite rainfall data for HEC-HMS input data	Student Trial License
		Raster calculation and fix scale line error of the map	
		Geo-referencing, rectification, rasterization, and other various spatial analysis	
2	Arc-GIS10.2	Once data is available in the GIS, they can be extracted, combined with other data,	Student Trial License
		Preparation of location of the project area, map of the catchment of the study, and database generation	

3	Arc-hydro	DEM to delineate watershed,	Https://www.usace.army.mil/so f tware/hecgeohms/downloads.aspx
		Sub-watersheds, stream network and drainage patterns of a basin	
		Results from terrain processing will be used to create input files for many hydrologic models using HEC- Geo HMS	
4	HEC-Geo-HMS 4.8	Create sub basins,	Https://www.usace.army.mil/so f tware/hec-geohms/downloads.aspx
		Longest and centroid flow paths, basin centroid and other watershed properties	
		Parameters such as slope and length are assigned to flow lines and basins.	
		Uses spatial analyst tools to convert geographic information into parameters for each of the basins and flow lines.	
5	HEC-HMS 3.8	For estimation of peak discharges	Https://www.usace.army.mil/so f tware/hechms/downloads.aspx
		Computes runoff volume by computing the volume of water	
		Then the model were be checked for calibration and validation.	
6	Microsoft Excel	Rearranging of input data	
7	R-studio 4.2	Filling Missing rainfall and discharge data	
8	Xlstat2014	For data quality testing (Homogeneity test and trend analysis) of meteorological and flow data	
9	Mendeley Desktop	✓ To arrange all journals used in this Thesis. ✓ To insert Citation for all Journals	Https://www.mendeley.com/
10	Google Earth Pro.	Metrological and gauge stations, to cross check the land use features	Google earth

3.6 Data Analysis and preparation

Finding biases and systematic errors in the data, such as modifications to the measuring instruments or gauge location, can be aided by a quality evaluation. can help identify errors and inconsistencies in the data, including missing numbers, that could affect the accuracy of the data. In the ideologies of hydrology, data must be stationery, consistency, homogeneous and free from trend when we use it for frequency analysis and hydrological modeling (Dhamen and hall,2006).

3.6.1 Estimating Missing Precipitation

The precipitation missed data filled by the multiple imputation method achieves the most accurate result. The missed data was filled by R studio version R4.2.0 using Multivariate Imputation by chained equation (MICE) using with multiple packages. table 3.6 shows package used to fill missing meteorological data of the study area.

Table 3.6 software and package

Software	Type of package	Purpose
R programming	MICE	Filling missed data

3.6.2 Consistency Test

Rainfall data reported from a station may not be always consistent over the period of observation of rainfall record. A second problem occurs when the catchment rainfall at rain gages is inconsistent over a period and thus adjustment of the measured data is necessary to provide a consistent record. Through checking consistency of individual stations, the data qualities with regard to possible temporal variations or errors been investigated by double Mass curve.

Double Mass Curve: For each observed meteorological data set (in this case, rainfall data), a double mass curve is plotted for each station to assess the consistency of the data series across several stations (Searcy and Hardison, 1960). Figure 3.9. shows a curve where the total values of a particular station's variable are compared to the total average values of related variables from other stations during the same time period. As long as there is a constant ratio in the relationship between the variables, the graph shows a straight line.

Regression from nearby stations will be used to adjust values if any slope change or break in the plotted data (precipitation) is found (Searcy et al., 1960).

$$\mathrm{Pcx} = \mathrm{Px} * \frac{\mathrm{Mc}}{\mathrm{Ma}} \tag{3.2}$$

$$\mathrm{Ma} = \frac{\Delta \mathrm{Po}}{\Delta \mathrm{P}} \tag{3.3}$$

$$\mathrm{Ma} = \frac{\Delta \mathrm{Pa}}{\Delta \mathrm{P}} \tag{3.4}$$

where, Pa= Corrected precipitation at any time period

Po= Original recorded precipitation at time period

Ma= Corrected slope of the double mass curve, and

Mo= Original slope of the double mass curve

A straight line is shown between the accumulation precipitation of all station and the cumulative precipitation of individual station during the reference period and the fitted linear regerassion equation is R^2(0.996, 0.9916, 0.9982, 0.9983, 0.9964) in Arbulacw, Butajira, Fato and Welkite it shows there is more data agreement in the 16 year at all stations.

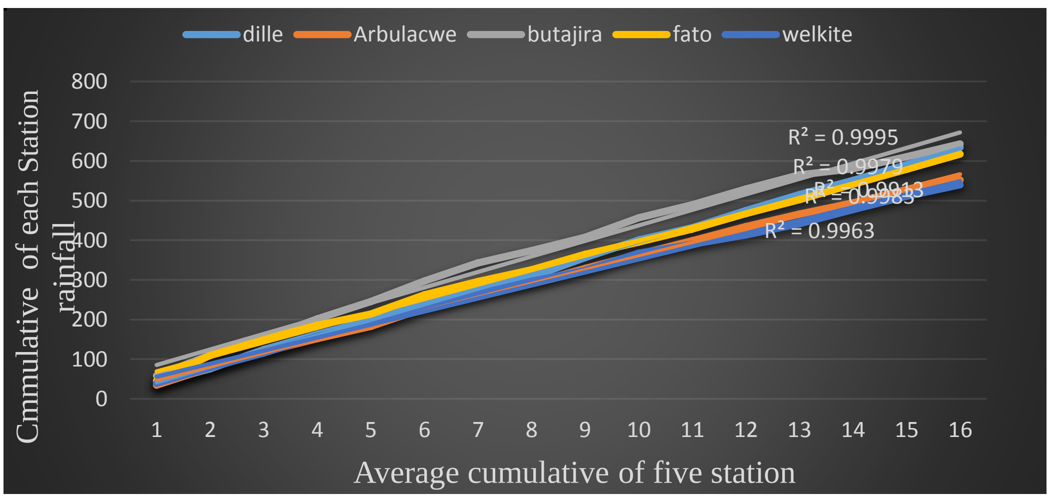


Figure 3.9 Mass curve for consistency check

3.6.3 Checking Homogeneity of Meteorological Stations

Homogeneity analysis is used 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 alterations to land use and relocation of the observation station. The homogeneity test of time serious may be classified into two groups as absolute method and relative method. In the first method, the test applies to each station separately. In the second method, the neighboring (reference) stations are also used in testing (Wijngaard et al., 2003).

Pettit's test was used to determine if the station's annual total precipitation time series was homogeneous.The Pettit test (Pettitt, 1979) is a non-parametric test that is based on the Wilcoxon test. It is also derived from the U-test for Mann-Whitney. The ranks r_1....rn of theY_1......Yn are used to calculate the statistics:

$$Xk = 2\sum_{i=1}^{k} ri - k(n+1) \quad k = 1 \dots\dots n \qquad (3.5)$$

The statistical homogeneity test was conducted using Addinsoft's XLSTAT 2015 software. Using Pettit's tests, the homogeneity of the watershed's annual total precipitation time series was evaluated. The analysis produced the annual maximum precipitation values for each station in the Wabe Watershed. Each method's results were assessed at a 95% significance level in order to identify any in homogeneities. Since the computed p-value is higher than the significance level alpha=0.05, the data are homogeneous. The results, which are displayed in table 3.7 below, showed that the observed annual maximum precipitation of each station were homogenies.

Table 3.7 Homogeneity test

Watershed	Variables					
		RF	RF	RF	RF	RF
	Parameter	Arbuchulule	Dilela	Fato	Butajira	Welkite
	K	40.0	18	35	34	44
	T	2016	2012	2007	2014	2010
	p-value(Two-tailed)	0.201	0.266	0.39	0.46	0.1
Wabe	Alpha	0.05	0.05	0.05	0.05	0.05

Theissen polygon approach is the most generally used method, and it was utilized in this study. By eliminating differences in their spacing over the basins, all measuring gauges are given weights depending on their areal coverage of the watershed. The percentage contribution of each rainfall stations across the watershed computed results were as follows.

Table 3.8 Percentage contribution of Rainfall Stations and weighted factor

Station	Area(km^2)	Weight of station	Weight factor(%)
Arbuchulule	194.09	0.09	9
Dilela	841.338	0.44	44
Fato	250.1908	0.12	12
Welkite	257.377	0.12	12
Butajira	461.958	0.23	23
Total	2005.6	1	100

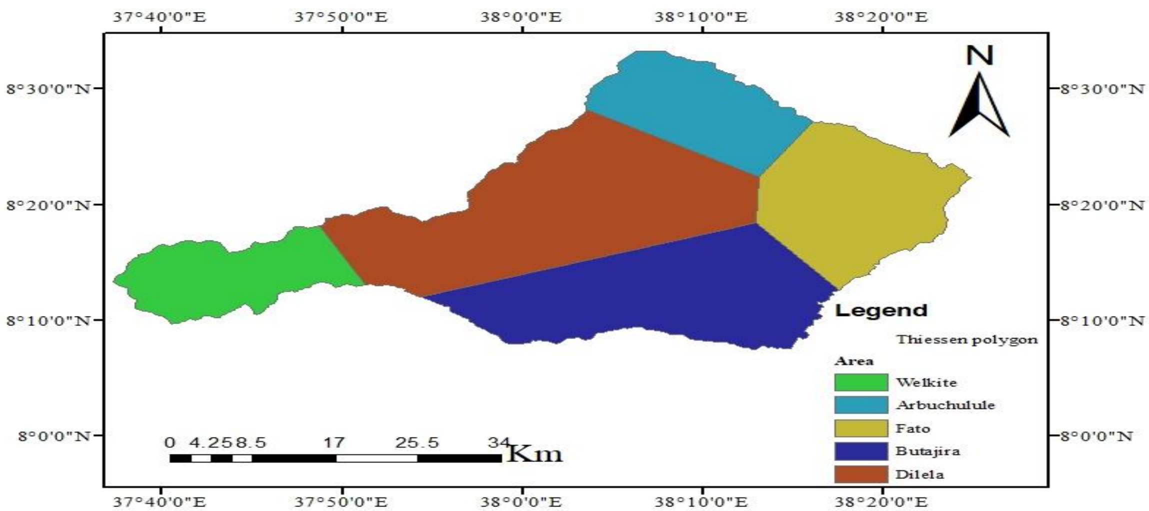


Figure 3.10 Thiessen Polygon of Wabe Watershed Stations

3.7. Data Processing

3.7.1. Digital Elevation Model Data Processing

The DEM data was previously conditioned and in GCS-WGS-1984 raster format. It was transformed into a Universal Transverse Mercator (UTM) projection raster form for hydrologic modeling purposes using ArcGIS software, taking into account the study area's zone, which is Africa, UTM Zone_ 37N. The study area's expected digital elevation model was specifically clipped.

3.7.2. Curve Number Grid Preparation

Soil Conservation Service-Curve Number (SCS-CN) was employed to account for runoff potential variability across the watershed. It described the potential for surface runoff generation as a function of soil type and land use. Land use and soil types all contribute to the curve number, (Mishra and Singh., 2013). As a result, the curve number grid was created by combining land use and hydrologic soil group data and constructing a lookup table which determining curve number grid value.

i. Land Use Data Processing

Land Use (LU) information is mandatory for generation of Curve Number lookup table. Hence accurate identification of LU has a major impact on output of runoff generation. Land use data was available in the form of GCS to WGS-1984 raster form Ethiopia's Ministry of Water, and Energy with DEM (30 m x 30 resolution). As a result, it should be changed into Universal Transverse Mercator (UTM) projection raster form by considering zone of the study area which is Adindan-UTM Zone 37N by using ArcGIS tools. Then, it was reclassified and converted to polygon shape file maps using raster to polygon function

ii. Soil Data Processing

Here after, the soil data was clipped to fit in the extent of study area. To compute Curve Number, soil data should contain information of hydrologic soil groups. Hydrologic soil groups are groups of soils having similar runoff potential under similar storm and conditions. Hydrologic soil group is a parameter that defines the tendency drainage of soil, (Brain, 2003). The hydrologic soil group designation can be either A, B, C, or D. Soil type ‘A’ has high infiltration rate; soil type ’B’ has moderate infiltration rates; soil type ‘C’ has low infiltration rate whereas soil type ‘D’ has very low infiltration rate, (Hafidi., 2014). In contrary to this runoff condition of hydrological soil group increases from ‘A’ to ‘D’. Factors that determine soil groups were soil texture, structure, drainage condition, soil types and even the location of the soil.

iii. Merging of Soil and Land Use

After merging, as previously stated, the study area's LU and soil class were prepared in shape file format, which was critical for Curve Number generation. The data was then combined using ArcGIS using the Arc hydro union tool.

iv. Creating Curve Number Look-up Table

Curve number look up table is the most fundamental input table for Curve Number grid generation and created by using create table function of ArcGIS tool. The CN value of the watershed was determined by using the United States Soil Conservation Service now called the Natural Resources Conservation Service- Runoff Curve Number method. The curve number grid in this study was created using HEC-GeoHMS and combined feature class soil and land use, as well as the lookup table (CN LookUp). These values were only used as an initial input to the HEC-HMS model before optimization, and the model employed the final calibrated model that could fit the objective function in this study.

The Soil Conservation Service-Curve Number table gives Curve Number based on both LU and Hydrological Soil Group. The merged land use and soil data, sink filled DEM and Curve Number lookup table were the input for HEC-GeoHMS to generate Curve Number and it was generated using generate grid function of HEC-GeoHMS. The weighted Curve Number value of each sub-basin are needed in basin model for simulation process and these weighted Curve Number values over sub-basins of watershed were computed using Arc tool box, Geoprocessing, Zonal of statistical mean values from, ArcGIS tools.

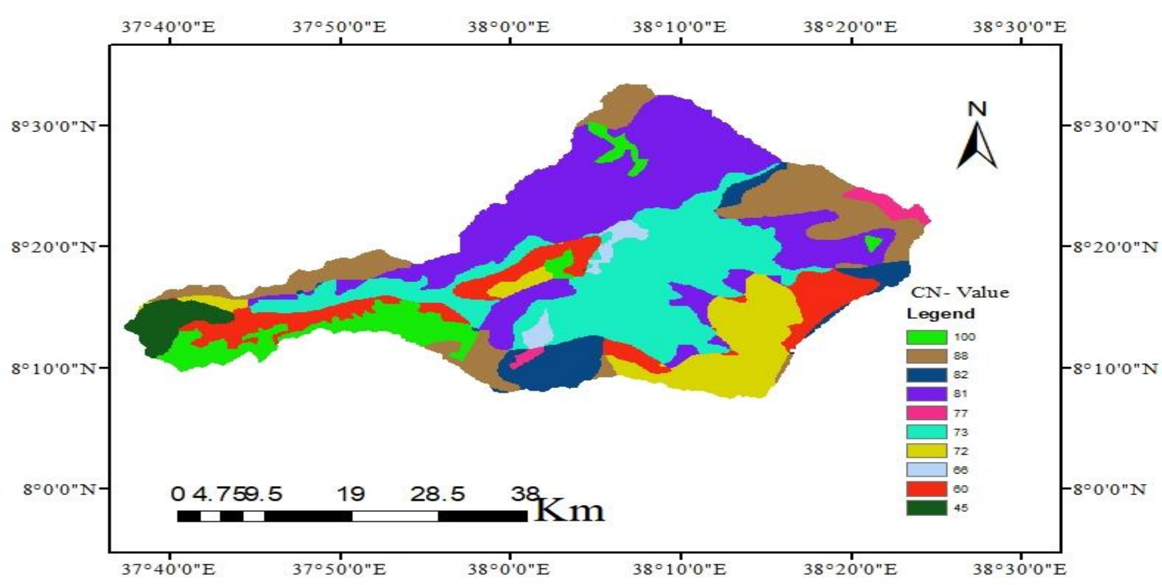


Figure 3.11Curve Number generated of the Catchment Study Area

Creation of Basin Model To run the model, it is necessary to create basin in the HEC-GeoHMS, (Ahn, Gordon and Merry., 2014). The basin model was created using HEC-GeoHMS software functionality within the ArcGIS environment. The first step in creating the basin model was to delineate the stream network and the watershed boundaries of area of interest. This process is commonly referred to as terrain pre-processing and is entirely based on the Digital Elevation Model. The process of generating input parameters for basin model were expressed below in details.

3.8 HEC HMS Model selection criteria

A various of factors can be considered when selecting the best hydrological model for a given situation. Due to the fact that each project has unique needs and requirements, these criteria are always projected dependent. Additionally, some criteria are dependent on the user, making them subjective. There are four standard, essential selection criteria that are dependent on the project and must always be addressed

- The model is easily and publicly available, and it reproduces the main hydrological processes in the watersheds with less demand on input data.
- Can supply a good deal of the required outputs, such as run-off volume, peak flow rate, and flow timing estimation.
- Availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?)
- Different researchers and journal papers have shown and tested that the model is calibrated and simulated on the Omo-Gibe River basin with excellent results.

3.9. HEC-HMS Model

Hydrologic Engineering Centre-Hydrological Modeling System (HEC-HMS) developed by United States Army Corps of Engineer is a very flexible and efficient hydrological model for rainfall-runoff process from watershed. HEC-HMS model has become very popular and widely adopted in many hydrological studies due to its ability to simulate runoff both in short and longtime (Visweshwaran, 2017).

3.9.1. HEC-HMS Basin Model Development

Basin model, Meteorological model, and control specification are the three key model components in the HMS model. The basin model is made up of many catchment parameters such as river reach, basin area, junction, outflows, and so on. That means; W1, W2, W3, W4, W5,W6,W7 and R1, R2, R3, R4, R5, R6, Sink or River outlet are included in this research basin model, where W and R stand for Sub-basins and River Reaches respectively.

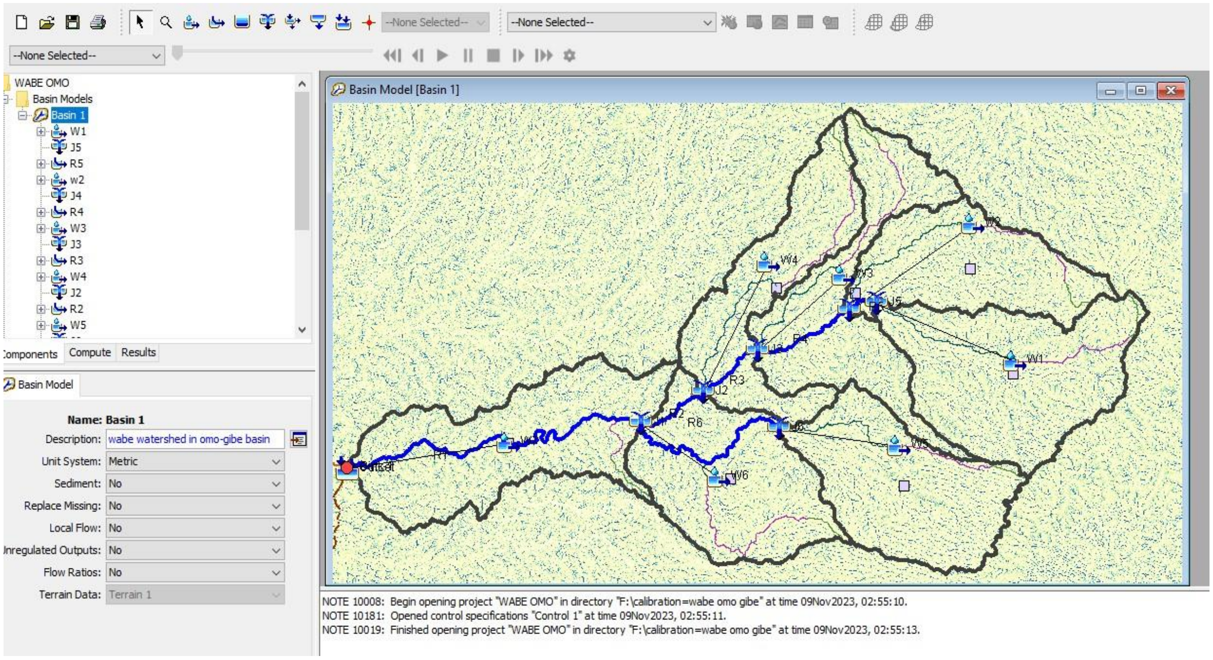


Figure 3.12 HEC-HMS basin model representation of Wabe Watershed

3.9.2. HEC-HMS Model Processing

The first phase of hydrological modeling was HEC-HMS model set-up. HEC-HMS model setup has four main model components such as basin model, meteorological model, control specification and input data. The observed precipitation and discharge data were used to create the meteorological model. A meteorological model method like Gage weights was used in this thesis.

The control specifications determine the time pattern for the simulation. Accordingly, the control specification for this simulation was (01Jan 2005 to 31 Dec 2020) with daily time step. To run the system, the basin model, the meteorological model, and the control specifications were combined. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff, and models of base flow.

3.9.2.1Basin model

Data that depicts the physical system of the understudied area is contained in the basin model. The user can edit the descriptive data, which is imported from GIS or typed manually.

These details contain a description of the hydrologic components that make up the basin model, details on their connections, and parameter values for the hydro components. Sub basins, reaches, junctions, sources, sinks, reservoirs, and diversion are some of these hydrologic components. It is possible to "drag-and-drop" icons on a schematic display to construct a basin model. With single element or global editors, the element data can be changed. There are seven different sorts of hydrologic features that make up a basin model: sub basin, routing reach, junction, reservoir, diversion, and source.

3.9.2.2 Meteorological Models

Information regarding meteorological components such as temperature, precipitation evapotranspiration, sunshine, humidity, and snowmelt is defined in meteorological model. HEC-HMS provides variety of options to define each meteorological element

Rainfall can be estimated remotely, either from ground-based weather radars or from satellite. Radars are active devices, emitting radiation at wavelengths ranging between 1 and 10 cm, and receiving the echo from targets such as raindrops. Satellite observations yield precipitation data with uniform spatial coverage; however, because of the indirect nature of the relationship between the observations and precipitation, the data contains non-negligible random errors and biases. I used ground and satellite based precipitation data.

3.9.2.3 Control Specifications

The Control Specifications specify time-related details for a simulation, such as the beginning and ending dates and the computation time interval. The starting and ending dates, times, and time (computation) interval are determined by control specifications. The time step for HEC-HMS model calibration for the catchment is divided into different time steps as for calibration, simulation and verification.

i. Loss Model

The runoff volume is often calculated by the loss models in HEC-HMS by subtracting the precipitation from the volume of water that is intercepted, infiltrated, stored, evaporated, or transpired. In this study, the direct runoff from a particular or design rainfall was estimated using the Soil Conservation Service Curve Number loss method.

It is superior to other approaches in a number of ways, including: It relies only on the curve number, which is a function of the soil type and land use/cover, which are the main characteristics of a watershed that produce runoff. It is a straightforward conceptual method for the estimation of the direct runoff amount from a storm rainfall event and is well supported by empirical data. For HEC-HMS, the SCS-CN loss approach was adopted (Sardoii *et al.*, 2012).

.

The SCS-CN model assumes that the accumulated rainfall-excess depends upon the cumulative precipitation, soil type, land use and the previous moisture conditions as estimated in the following relationship (Feldman, 2000).

$$Pe = \left(\frac{(P - Ia)}{(P - Ia + S)}^{2} \right) \quad (3.6)$$

Where Pe is the accumulated precipitation excess at time t (mm); P is the accumulated rainfall depth at time t (mm); Ia is the initial abstraction (initial loss) (mm) and S is the potential maximum retention (mm), a measure of the ability of a watershed to abstract and retain storm precipitation. In the curve number method, the runoff is directly proportional to the precipitation with an assumption that the runoff is produced after the initial abstraction of 20% of the potential maximum storage.

Equation 2.2 was found to be an approximate representation of Ia through studies of many small agricultural watersheds. The following equation makes the assumption that 20% of the rain is absorbed prior to the start of direct runoff and the remaining 80% is absorbed post-runoff (Heshmatpoor, 2009).

Ia=0.2S (3.7)

The maximum retention, S, and watershed characteristics are related through an intermediate dimensionless parameter, the curve number (CN) as:

$$S = 25400 - \frac{(\mathbf{254*CN})}{\mathbf{CN}} \quad (3.8)$$

where CN is the SCS curve number used to represent the combined effects of the primary characteristics of the catchment area, including soil type, land use, and the previous moisture condition.

ii. The Transform Model

The HEC-HMS transform prediction models simulate the process of the excess precipitation's direct runoff onto the watershed and convert it to point runoff. The Soil Conservation Service Unit Hydrograph model will be used in this study to convert too much precipitation into runoff. The Unit Hydrograph (UH) model was proposed by the SCS and is a part of the HEC-HMS program (Kirpich, 1940). Unit hydrograph can be defined as the runoff hydrograph produced from excess rainfall of unit depth occurring over the watershed.

This should be a composite curve number that represents all of the different soil group and land use combinations in the sub basin.

This method was chosen because it required less input data than other approaches, and different researchers' recommendations for modeling excess rainfall were covered in various literature reviews and composite curve number that represents all of the different soil group and land use combinations in the sub basin.

The lag time (Tlag) is the single input for the transform method and is calculated for each watershed based on the time of concentration Tc, as follows:

$$Tlag=0.6*TC \qquad (3.9)$$

where, Tlag and Tc are in (minutes)

Kirpich's formula,(Gebre (2015)), can be used to determine the period of concentration based on basin parameters such as topography and reach length

$$Tc = 0.0195 * L0.77 - S - 0.385. \qquad (3.10).$$

where, L is the reach length of the main river in (m), and S is the slope of the main river in (m/m).

iii. Base flow method

Theoretically, the sub-basin element represents infiltration, surface runoff, and interactions between subsurface processes. The actual subsurface calculations are carried out by a sub basin-contained base flow technique. No base flow separation method was used in this study, because the area is largely covered by agricultural crops.

iv. Routing Model

Due to the effects of channel storage, flood runoff is dampened as it passes through the channel reach. The HEC-HMS routing models take this attenuation into consideration. McCarthy (McCarthy, 1938) created the common lumped flow routing approach known as the Muskingum method. To determine the outflow hydrograph at the downstream end of the channel reach from the inflow hydrograph at the upstream end, the Muskingum routing approach offers a straightforward approximation.

In this model, two parameters, X and K, required calibration. A dimensionless weight, or constant coefficient with a range of 0 to 0.5, is represented by the factor X, which also expresses the proportionate impact of flow on storage levels. Assume that the calibration process corrected the initial value of the calibration parameters, which was 0.1. A time unit parameter called K has a range of one to five hours. It is related to the intervals between discharge peaks (US Army Corps of Engineers., 2008).According to Subramanya, (2008)and Chang (2009), the Muskingum flood routing method uses equation 3.11 as below.

$$S = K [x * I + (1 - x) Q] \qquad (3.11)$$

where, I, in the equation(3.11), is the inflow, Q is outflow, ds is change in storage, S is storage, K is flood wave traveling time, x is weighting coefficient of discharge. Mathematically, K is given as equation 3.12

$$K = \frac{L}{Vw} \qquad (3.12)$$

where; Vw denotes the flood wave velocity, which is 1.5 times the average velocity, and L is the reach length

Table 3.9 Summery of model setup of HEC-HMS at study area

Hec-HMS runoff processer	Method
Loss	SCS-CN
Transform	SCS unit hydrograph
Routing	Muskingum

SCS-CN, SCS Unit hydrograph, Muskingum method was chosen because it required less input data than other approaches, and also because of its simplicity, accuracy, availability for the HEC-HMS modeling.

3.10 Sensitivity analysis

Sensitivity analysis: Using the meteorology model, a simulation run determines the precipitation-runoff reaction in the basin model. The time period and time interval are specified in the control specifications. The computation of a simulation run requires the presence of all three elements.

The HEC-HMS model's parameters that contribute most to the variability of streamflow are identified using parameter sensitivity analysis (SA), which should be calibrated. It assigned a ranking to model parameter based on their contribution to the overall model predict error. In this study five parameters such as curve number, initial abstraction, lag time, Muskingum k and Muskingum x was used

The simulation time interval will be 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. HEC-HMS model was be calibrated and validated using a total 16 years with a one-day time interval.

The model output or objective function.in order to minimize the number of parameters that require optimization, sensitivity analysis were performed prior to the calibration and validation process.

3.11 Calibration and Validation

3.11.1 Model calibration

Hydrological modeling includes calibration as a key component, which aims to optimize the match between measured and simulated discharge. For the chosen catchments, the model's calibration for the catchment representation was done.

The value of each parameter found in HEC-HMS was specified to use the model for estimating runoff volume by use of satellite and gauge rainfall. Model calibration is the process of adjusting selected model parameters values and other variables in the model in order to match the model outputs with the observed values.

A total of 16 years of hydrological data was used, spanning 2005 to 2014, with the 10 years being used for calibration in the study. During optimization from the objective functions, peak weighted root means square error (PWRMSE) was selected because, it is ameasure of the comparison of the magnitude of the peak, volume, and time of the peak of the the simulated and measure hydrograph.

3.11.2 Model validation

In order to verify the consistency of the model's performance in continuous runoff simulation, a lengthy duration of observed flow is preferred for model calibration and validation.

Model validation is the process of testing the model ability to simulate observed data, other than those used for the calibration, within acceptable accuracy. During this process, calibrated model parameter values were be kept constant. The degree of variance between computed and observed hydrograph is used as a quantitative measure of the match. Validation data for the selected watersheds in the wabe Basin was collected in between (2015 and 2020).

3.12 Evaluation of HEC- HMS Model Performances

The daily simulated runoff with the actual stream flow at the catchment's outlet, was determined calibration and validation performance of the HEC-HMS. According to statical parameter there are four criteria for model evaluation that were adopted for this study, namely, NSE, R^2, RMSE and PBIAS.

3.12.1 Nash-Sutcliffe efficiency (NSE)

Nash-Sutclife efficiency (NSE) is used to access the overall agreement of the shape of the simulated and observed stream flow time series. if the NSE value is 1, the model daily stream flow are identical to the observed daily stream flow (or perfect fit). while if the NSE value is less than zero, the model simulation are poorer than merely using the mean observed daily stream flow as he stream flow estimate for each days. NSE can expressed as

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Qobs - Q\,sim)^2}{\sum_{i=1}^{n} (Qobs - \overline{Q}\,sim)^2} \qquad (3.13)$$

3.12.2 Root Mean Square Error

The average error between observed and simulated discharge measured by RMSE. The model performance improves as the RMSE value approaches zero, resides are the individual difference between observed and simulated values. RMSE can expressed as

$$\text{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}(\text{Qobs-Q sim})^2}{n}} \tag{3.14}$$

3.12.3 Percent of Bias (PBIAS):

It compares the simulated data's average tendency to the matching observed data, (Gupta et al., 1999). PBIAS has an optimum value of 0. A positive score suggests underestimation, while a negative value shows overestimation (Gupta et al., 1999).

$$PBIAS = \left[\frac{\sum_{i=1}^{n} Qob - Qsim}{\sum_{i=1}^{n} \text{Qob}}\right] \tag{3.15}$$

3.12.4 Coefficient of Determination (R^2)

It described the properties of the variance in measured and simulated data. Has a value range of R^2 is 0 to 1. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation. The fact that only the dispersion is quantified is one of the major drawbacks of R^2 if it is considered alone (Krause et al., 2005) R^2 has been widely used for model evaluation expressed as

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Qobs - \overleftarrow{Q}obs)\,(Qsim - \overline{Q}sim)}{\left(\sum_{i=0}^{n}(Qobs - \overline{Q}\,obs)^2\right)^{1/2}\quad\left(\sum_{i=0}^{n}(Qsim - \overline{Q}\,sim)^2\right)^{1/2}}\right]^2 \tag{3.16}$$

3.13 Comparison of Satellite rainfall products versus rain gauges

There are two widely used techniques for assessing satellite rainfall products: grid to grid (interpolated grid to satellite grid) and point to grid (point-based). Individual gauge station-based rainfall is compared with grid-based satellite and reanalysis rainfall data in point-based comparison methods, whereas in grid-to-grid comparison The gauge-based observed rainfall is then analyzed after being interpolated to the same resolutions as the chosen grid-based satellite and reanalysis rainfall outputs. A high density of uniformly networked gauge stations covering the area makes the grid-to-grid technique of evaluation suitable.

Estimates of precipitation from satellite rainfall products are particularly useful in areas where there are few ground observations. The accuracy and usefulness of these products, however, may be affected by the underlying assumption of pixel-based precipitation, which is uniform rainfall within a satellite gride.

Assumption of the variable of precipitation in the gride is the same. due to this point to gride precipitation is uniform rainfall within satellite pixel it can have an impact on the accuracy and usefulness of these product.

The point to grid approach is the most effective way to assess each satellite and reanalysis rainfall product independently utilizing their native resolution in locations with a sparsely distributed and small number of rain gauge stations and complicated terrain. for this study, the point-to-grid approach was used.

Continuous statistical indices were used in the current study to assess the accuracy of the satellite rainfall products. Continuous statistical indicators assess how well the satellite rainfall product performs in calculating the total amount of precipitation over a period of time. Based on the computation of the mean error (ME), mean absolute error (MAE), Pearson correlation (R), Nash-Sutcliffe efficiency coefficient (NSE), root mean square error (RMSE), and Pbias were used. The cumulative rainfall was evaluated as follows:

Table 3.10 Performance ratings for recommended statistics (Hussain et al., 2021)

Performance Ratings	NSE	R2	PBIAS
Very good	$0.75<NSE\leq1$	$0.85<R2\leq1$	$PBIAS< \pm10$
Good	$0.65<NSE\leq0.75$	$0.7<R2\leq0.85$	$\pm10\leq PBIAS< \pm15$
Satisfactory	$0.5<NSE\leq0.65$	$0.6<R2\leq0.7$	$\pm15\leq PBIAS< \pm20$
Acceptable	$0.4< NSE\leq0.5$	$0.4< R2\leq0.6$	$\pm20\leq PBIAS< \pm25$
Unsatisfactory	$NSE\leq0.4$	$R 2\leq 0.4$	$PBIAS\geq\pm25$

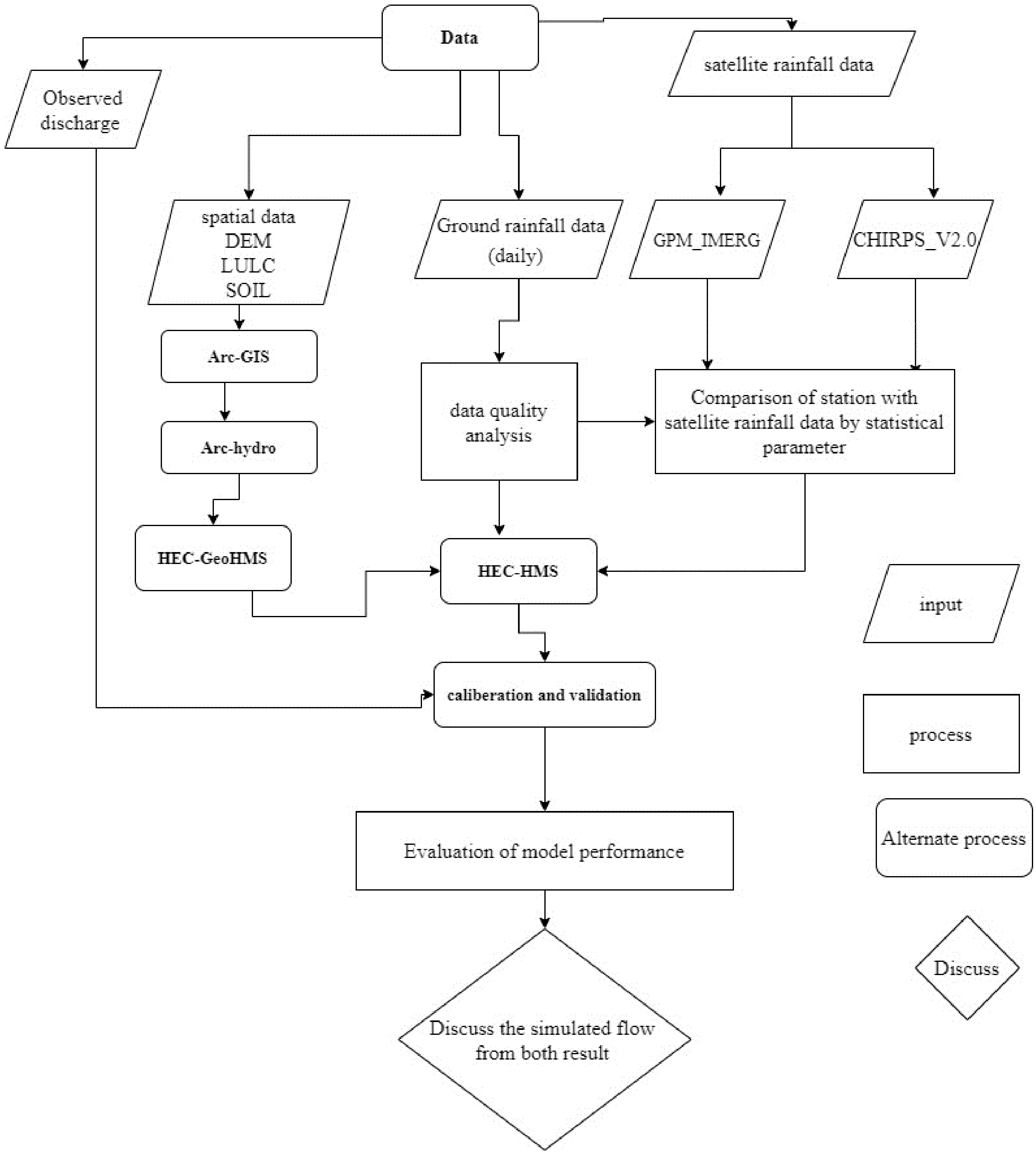


Figure 3.13 Flow chart for model simulation

4. RESULTS AND DISCUSSIONS

4.1. Comparison of Satellite Rainfall Products with Ground Station Data

The comparisons of satellite rainfall data with ground-station were made on daily and monthly time scales using graphical and statistical parameters as presented in the following section

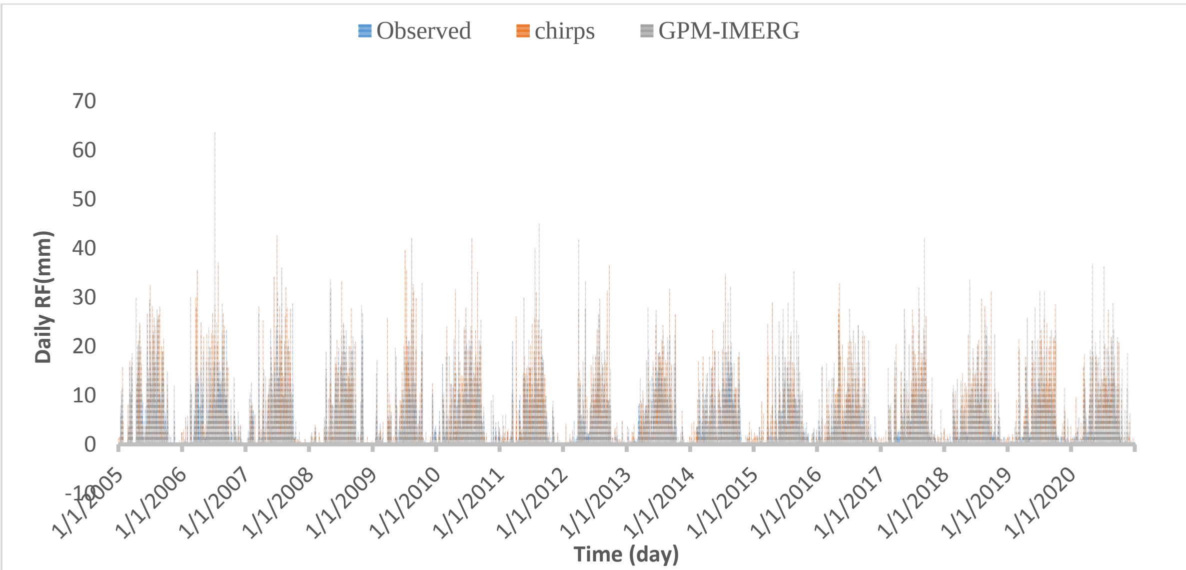


Figure 4.1Daily comparison of Satellite rainfall products and Stations (2005- 2015) time Series

4.2 Based on the provided statistical evaluation

4.2.1 Temporal resolution for daily time scale

Based on these statistics (Table4.1), we can observe that for Arbuchulule Station, CHIRPS Satellite Rainfall has the highest mean value. For Dileile Station and Welkite Station, GPM_IMERG satellite rainfall has the highest mean value. In Butajira Station, the station's rainfall data has the lowest mean value, followed by CHIRPS Satellite Rainfall and GPM_IMERG satellite rainfall. The percent difference between the mean of GPM_IMERG satellite rainfall and guage rainall is 5.02%. The percent difference between the mean of CHIRPS Satellite Rainfall and gauge Rainfall is 2.07%. Therefore, CHIRPS Satellite Rainfall is relatively closer to gauge rainfall in terms of mean percent value.

Table 4.1 Summary statistics of daily stations and satellite rainfall product

Arbulaculule Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	2.88	5.359	1.857					
CHIRPS	2.8	7.2	2.52	3.79	59.27	7.6	-0.58	0.08
GPM-IMERG	2.92	6.234	2.12	3.33	44.65	6.68	1.09	0.11

Dilele Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	3.31	6.73	2.03					
CHIRPS	3.09	7.17	2.3	4.19	71.54	8.45	-6.9	0.11
GPM-IMERG	3.31	6.913	2.11	3.7	61.14	7.81	-1.72	0.1

Fato Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	3.232	6.32	1.956					
CHIRPS	3.08	6	2	4.27	72.83	8.53	-6.3	0.06
GPM-IMERG	3.09	6.627	2.13	3.87	60.51	7.7	-4.36	0.078

Wellkite Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	2.82	5.624	2					
CHIRPS	3.299	7.18	2.1	4	63.95	7.99	14	0.058
GPM-IMERG	3.36	7.1	2.13	3.85	61.14	7.85	16.28	0.07

Butajira Stations	MEAN	STDV	CV	MEA	MSE	RMSE	PBias	R^2
OBSERVED	2.716	6	2.23					
CHIRPS	2.74	7.33	2.67	3.87	71.61	8.4	1.09	0.04
GPM-IMERG	3.03	6.5	2.15	3.64	59.27	7.69	10.26	0.066

Table 4.2 Summary of mean daily

Stations	MEAN	STDV	CV	MEA	MSE	RMSE	PBias	R^2
OBSERVED	2.99	3.844	1.28					
CHIRPS	3	4.7	1.57	2.77	24.12	4.91	0.69	0.23
GPM-IMERG	3.06	4.74	1.54	2.65	22.99	4.79	4.47	0.266

According to Table 4.1 and Figure 4.2 on a daily time scale The MAE was low in comparison to the daily average rainfall for both SREs. The lower MAE values 3.79 in the Arbulaculule station suggest that there were small random errors in the CHIRPS estimates for all five of the selected stations. Then also Arbulaculule station there are small random errors in the GPM_IMERG (3.33) estimates for all five stations, the station having a lower MAE value of 3.33, respectively.

A smaller RMSE value indicates that the satellite is performing better in terms of accuracy . For CHIRPS and GPM_IMERG, Arbulaculule (7.6, 6.68) and Welkite(7.99, 7.88) are the regions is performing well in terms of accuracy, as their RMSE values are smaller than the other station. On the other hand, Dellile, Fato, and Butajira are the regions where CHIRPS is performing relatively poorly in terms of accuracy, as their RMSE values are higher than the other station.

As their PBIAS values for daily time scale CHIRPS and GPM_IMERG in Arbuchulule (-0.58, 1.09) and Butajira are the regions where the satellite is performing well, that are close to zero. On the other hand, Dellile(-6.9, -1.72) and Fato(-6.3, -4.36) are the regions where the satellite is underestimating the observed values, as their PBIAS values are negative. Finally, Welkite(14, 16.28) is the region where the satellite is overestimating the observed values, as its PBIAS value is positive

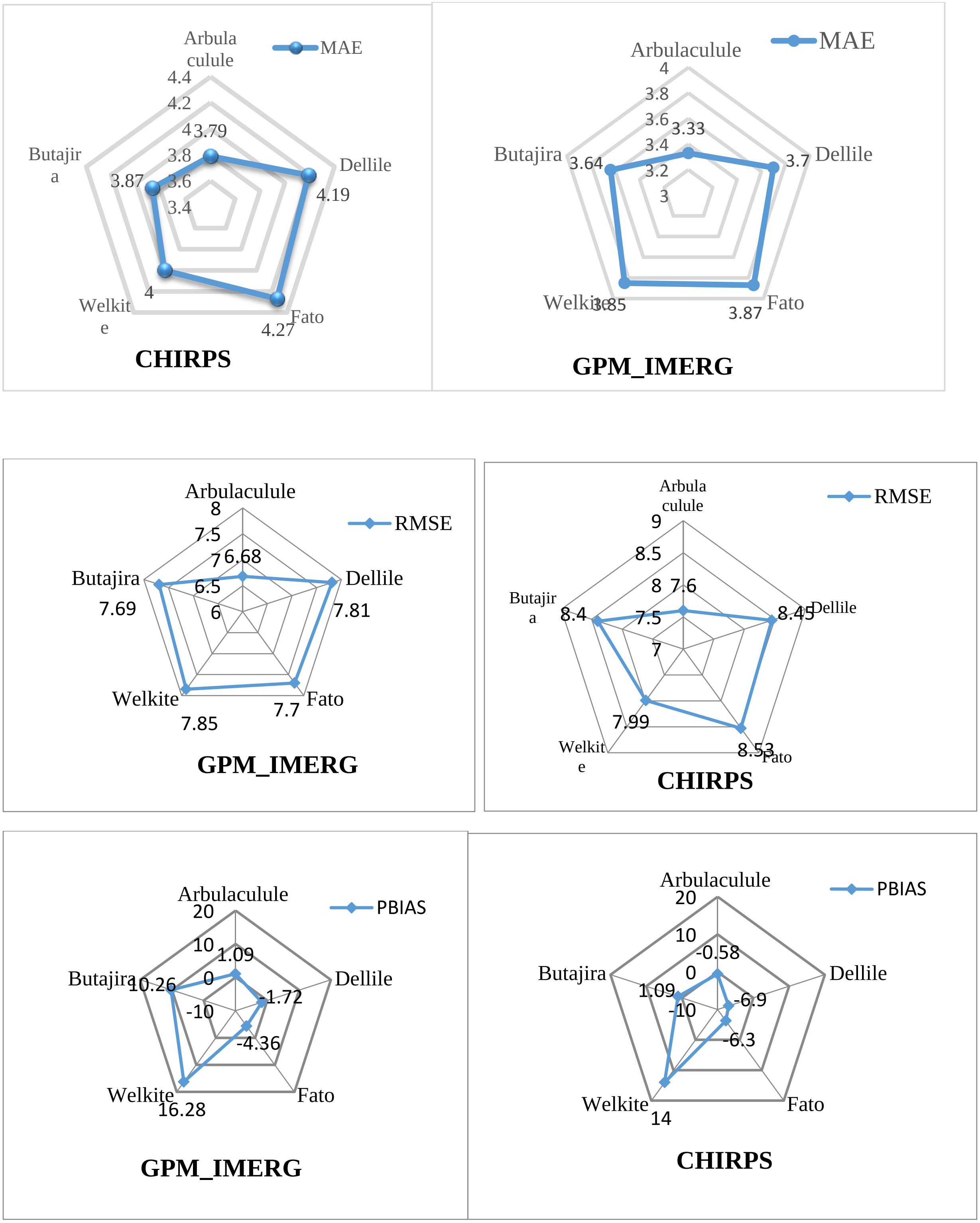


Figure 4.2 The daily (MAE, RMSE, PBIAS,) satellite rainfall of each station in wabe watershed for the period (2005-2020)

Figure 4.3 shows comparison between the satellite rainfall estimates and the rain gauge observations for the wabe watershed from January 2005 to December 2020 on a daily scatter plot. Each station plot (Appendix II) that showes the correlation between satellite rainfall estimates and observed rain gauge estimates. Unsatisfactory correlations (R2 values ranging from 0.23 to 0.32) were found between satellite rainfall values and rain gauge values. as shown by the scatter plot in (Appendix II) a relativily better correlation agreement was observed in Dillel station with GPM_IMERG and CHIRPS, (R=0.1, R=0.11). Compared with all stations, a low correlation with CHIRPS (R=0.045) was shown in Butajira.

The average rain gauge and CHIRPS showed a relatively lower correlation (R2 =0.266) in comparison with GPM_IMERG. Generally, daily satellite rainfall from CHIRPS and GPM IMERG showed relatively poor correlations (R2= 0.32).

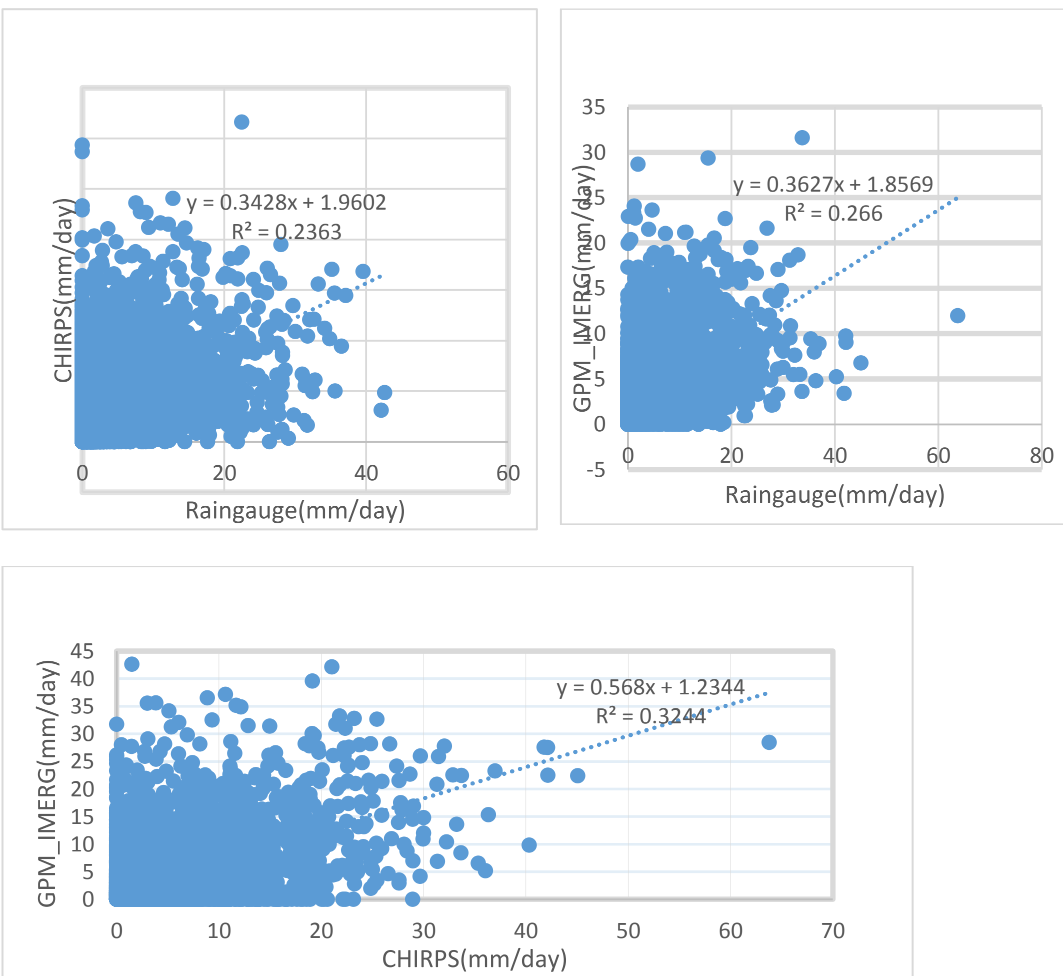


Figure 4.3 Scatter plots of Satellite rainfalls products (CHIRPS AND GPM IMERG) and rain gauge for wabe watershed

4.2.2 Temporal resolution for monthly time scale

As shown the table 4.3 monthly time series mean value in wabe watershed CHIRPS has lower (48.01) and GPM_IMERG has (50). Alower Mean value indicate better performance that CHIRPS has lower mean than GPM_IMERG.

Table 4.3 Summary statistics of monthly stations and satellite rainfall product

Arbulaculule Stations	MEAN	STDV	CV (%)	MAE	MSE	RMSE	PBias	R^2
OBSERVED	45.96	44.43	0.97					
CHIRPS	49.35	45.38	0.919	5.725	65.74	8.1	6.86	0.97
GPM-IMERG	46.778	41.119	0.879	4.69	43.61	6.57	1.74	0.98

Dellile Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	52.85	47.81	0.9					
CHIRPS	51.2	45.7	0.87	5.615	71.73	8.47	-7.08	0.97
GPM-IMERG	52	43	0.827	5.93	75.21	8.67	-1.62	0.97

Fato Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	51.41	44.9	0.874					
CHIRPS	49.25	42.523	0.84	8.21	93.04	9.64	-4.45	0.95
GPM-IMERG	49.39	40.29	0.81	9.78	148.28	12.18	-4.09	0.92

Welkite Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	44.9	37.88	0.844					
CHIRPS	52.59	46.24	0.97	8.1	142	11.92	14.6	0.98
GPM-IMERG	53.74	43.35	0.81	8.98	131.42	11.46	16.45	0.98

Butajira Stations	MEAN	STDV	CV	MAE	MSE	RMSE	PBias	R^2
OBSERVED	43.32	34.11	0.788					
CHIRPS	43.478	32.66	0.745	6.89	82.52	9.08	9.08	0.923
GPM-IMERG	48.478	36.41	0.75	7.07	79.34	8.9	10.64	0.95

Table 4.4 Summary of mean Monthly

Stations	MEAN	STDV	CV	MEA	MSE	RMSE	PBias	R^2
OBSERVED	47.69	41.27	0.86					
CHIRPS	48.016	40.58	0.84	2.42	12.97	3.6	0.58	0.99
GPM-IMERG	50	40.05	0.82	4.28	32.14	5.66	4.54	0.98

Based on the above table4.3 and figure 4.4 monthly for the MAE was small relative to the average monthly rainfall for both the SREs. There were small random errors in the CHIRPS estimates for all the five selected stations, as indicated by the lower MAE values 5.613 in Dillel station. the GPM_IMERG estimates all five station as lower MAE value is 4.69 in Arbulaculule station respectively (Table 4.3)

RMSE for GPM_IMERG and CHIRPS, we can see that the Arbulaculule station has the lowest RMSE value, which indicates that the regression satellite fits the data well for this station. On the other hand, for CHIRPS the Welkite station has the highest RMSE value, which indicates that the regression satellite does not fit the data well for this station.

For GPM_IMERG the Fato station has the highest RMSE value, which indicates that the regression satellite does not fit the data well for this station.

Based on the figure 4.4 and table 4.3 monthly time scale that the CHIRPS and GPM_IMERG in Arbulaculule station (6.86, 1.74) has the lowest PBIAS value of, which indicates that the satellite and observed values are close to each other for this station. On the other hand, the Welkite station (14.6, 16.45) has the highest PBIAS value, which indicates that the satellite values are overestimate.

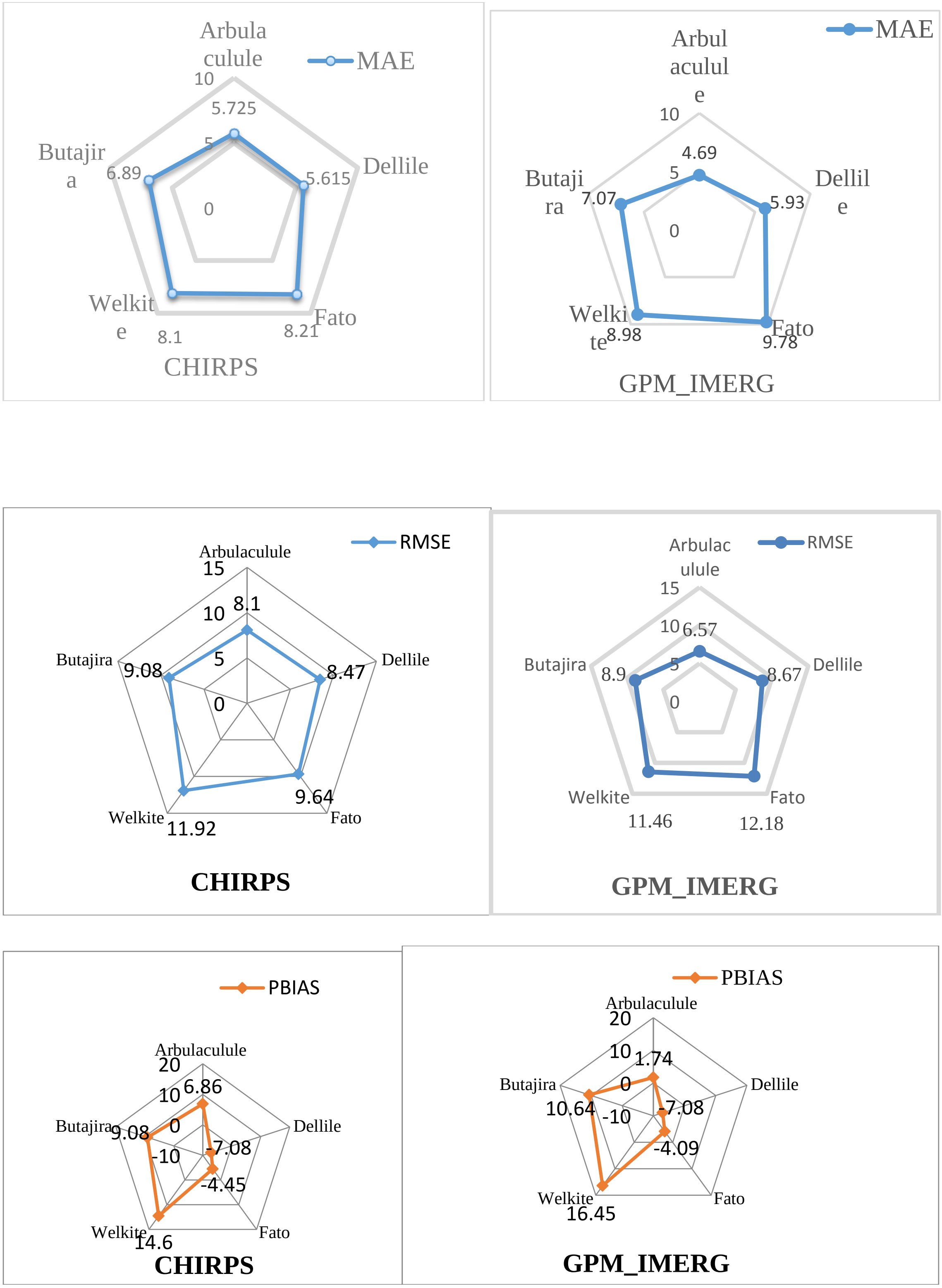


Figure 4.4 The monthly (MAE, RMSE, PBIAS,) satellite rainfall of each station in wabe watershed for the period (2005-2020)

Figure 4.5 showes a comparison of monthly rainfall projections. The correlation between satellite rainfall values and rain gauge was nearly identical at the monthly time scale. which is nearly identical to the correlation found between monthly rainfall values measured by satellite (R values ranging from 0.94 to 0.975). as shown by the scatter plot in (Appendix II) a relativily it is better correlation agreement was observed by Arbulaculule, welkite and dillel with GPM_IMERG and CHIRPS. low correlation (see appendixII) as compare of all station is butajira with GPM_IMERG (R=0.9232) and Fato with GPM_IMERG(R=0.926).

The correlation between CHIRPS and GPM was found to be the highest (R = 0.9922), followed by the correlation between CHIRPS and rain gauge (R=0.992) and the lowest (R=0.983) between the GPM and rain gauge.

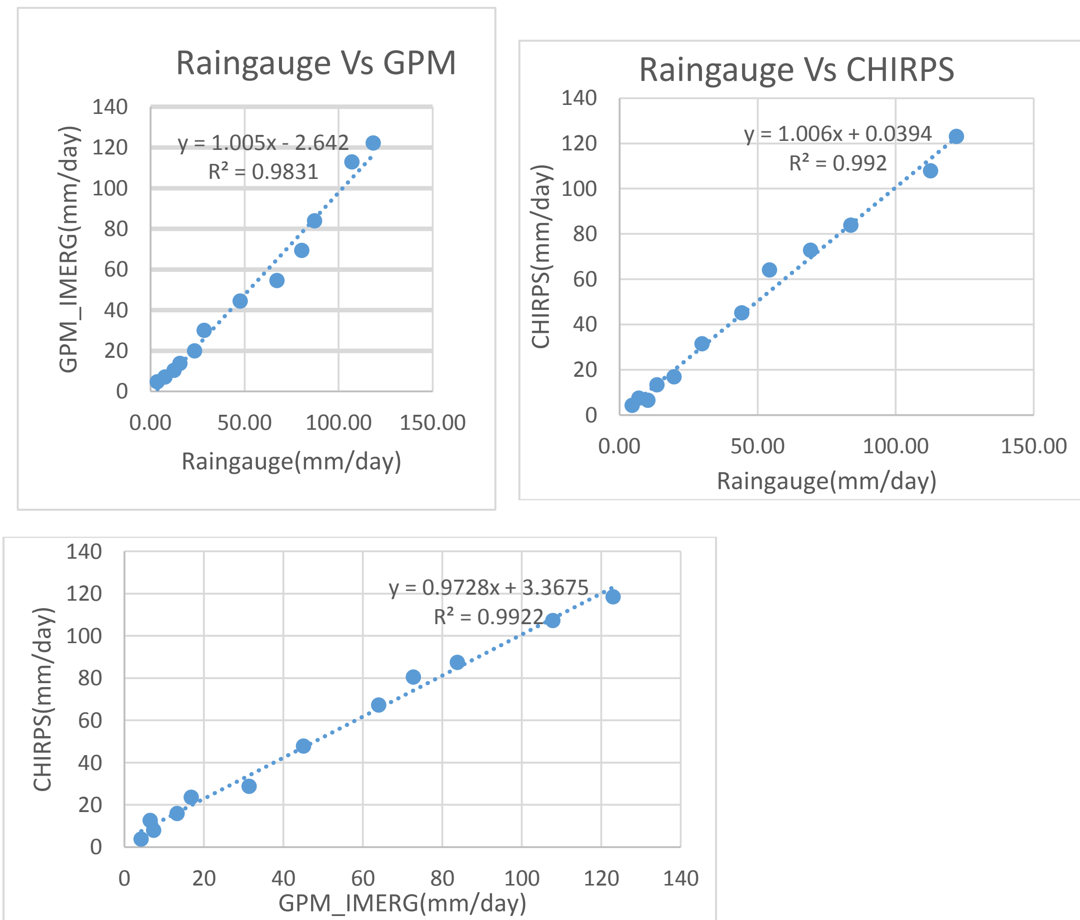
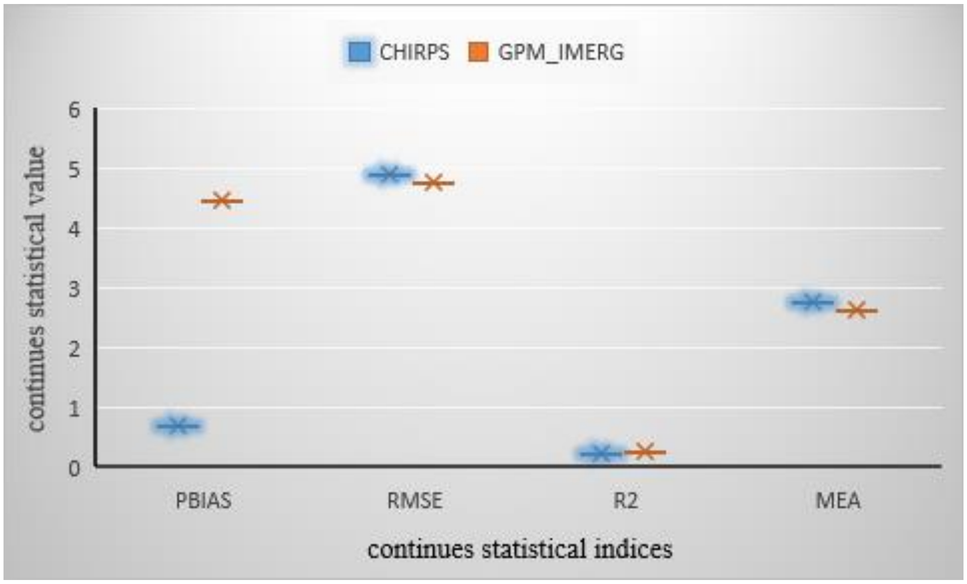
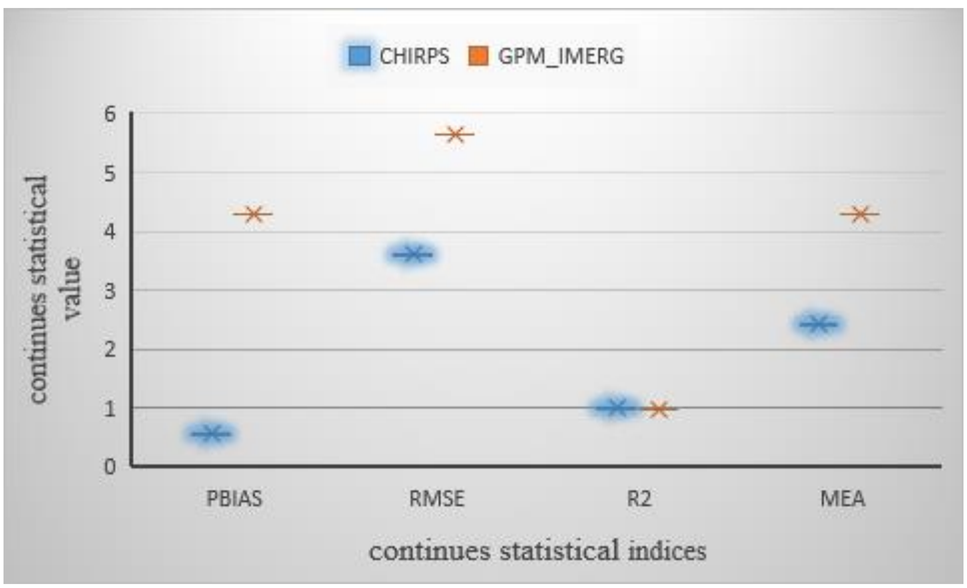


Figure 4.5Scattter plot of monthly rainfall from satellite rainfall products and rain gauge Wabe watershed.



(a)



(b)

Figure 4.6Stastical indices of the SRE for wabe watershed at daily(a) and monthly(b) time scale

According to table 4.5 and figure 4.6 at daily time series of the watershed CHIRPS has a lower PBIAS value (0.69) than GPM_IMERG (4.47) indicating that CHIRPS have a smaller overall tendency to overestimation precipitation compare to GPM_IMERG. GPM_IMERG has a lower RMSE value (4.79) than CHIRPS (4.91), suggesting that GPM_IMERG has a slightly smaller average difference between its estimates and the ground observations.

At monthly time period that CHIRPS has a lower PBIAS value than GPM_IMERG, which indicates that the satellite and observed values are close to each other. The performance evaluation of CHIRPS v2 due to PBIAS asserts that it includes bias correction techniques that are intended to enhance agreement with ground observations, particularly on monthly scales, and gauge data is greater than GPM_IMERG to a more precise match with ground truth on monthly scales.

Overall, For PBIAS and R2, CHIRPS performs better for both daily and monthly time periods. This makes it a better choice if minimizing overall bias and ensuring a strong linear relationship with ground observations is important. For RMSE and MEA, GPM_IMERG has a slight advantage for both daily and monthly data. However, the difference is small, and CHIRPS may still be preferable and the importance of minimizing average error.

According to in this study that when it looked at the above the daily satellite rainfall data may have poor performance as compared to monthly data it may be due to temporal resolution. due to Temporal resolution refers to the frequency at which rainfall data is collected and reported. Daily rainfall data may have more noise and variability compared to monthly data, which can make it more challenging to accurately capture the true rainfall patterns. Monthly data, on the other hand, may have less noise and variability, which can result in better performance. up to this reason in this study monthly data is more performed than daily data.

Table 4.5 Continuous statistical evaluation of average the wabe watershed

SATELLITE PRODUCT	PBIAS	RMSE	R^2	MEA	period
CHIRPS	0.69	4.91	0.23	2.77	daily
GPM_IMERG	4.47	4.79	0.266	2.65	
CHIRPS	0.58	3.6	0.99	2.42	monthly
GPM_IMERG	4.28	5.66	0.98	4.28	

4.3 Hydrological Evaluation

In this section, a HEC-HMS model was driven to simulate runoff using the two daily satellite precipitation products as inputs. Furthermore, the observed streamflow at the study area's outlet was used to calibrate the model. In this study, the hydrological station's daily observed flow was used to assess how well both CHIRPS and GPM_IMERG performed when simulating streamflow. Two precipitation inputs were used to the input HEC-HMS model: CHIRPS and GPM_IMERG data, which were derived from the gauge. The models are able to replicate the observed flow in simulation by varying pertinent sensitive parameters and converge to various parameter intervals.

Important watershed characteristics such as Curve number, basin lag time, watershed area, basin slope, potential maximum retention (S), and beginning abstraction from watershed were determined, as stated under methods. The CN value of the study area was changed throughout time.

But in the simulation, a single CN value is needed for every sub-basin. The weighted CN values for every sub-basin have already been obtained by HEC-GeoHMS. At 70.12 and 83.34, respectively, were the weighted curve number values for the minimum and maximum. Weighted CN values were lowest in sub-basin W3 and highest in sub-basin W4, respectively. The relationship between runoff generation and the Curve Number's value is direct. Low CN sub-basins have high infiltration rates and little runoff As a result, the potential runoff from a subbasin increases with its CN level. This leads to high runoff in W4 and low runoff in W3. There were two different initial abstractions in the W4 and W3 sub-basins: 0.83 mm for the minimum and 8 mm for the maximum. Here are the runoff values produced by W3 and W4 both low and high. With 0.218% basin slope, sub-basin W1 has the highest. Therefore, out of all the sub-basins, sub-basin W1 had the steepest slope. The duration of the basin lag in the study area varied from 7.11 to 16.74 minutes. Surface runoff reaches the exit point very quickly the lower the basin lag time at W1 as shown in Table4.6 below.

Table 4.6 Summary of Watershed parameters generated by HEC-GeoHMS and HEC-HMS for Wabe watershed

Rank	Sub basin	Area	Lag Time (min)	Basin Slope (%)	Weighted CN	Slope (mm)	Ia(mm)
1	W1	344.61	7.11	21.8	78.94	0.21805	0.53
2	W2	236.26	10.36	14.9	80.74	0.14932	0.48
3	W3	269.51	14.53	13.9	70.12	0.13934	0.85
4	W4	244.15	13.54	10.8	83.37	0.10863	0.4
5	W5	283.53	8.31	19.26	73.533	0.19261	0.72
6	W6	284.25	12.08	15.147	75.91	0.15147	0.63
7	W7	344.19	16.74	12.98	76.379	0.12987	0.62

After many iterations, it was found that the travel time through the reach (Muskingum k) and weight discharge coefficient (Muskingum x) was the sensitive parameter as most sensitive flow parameter is CN value. Calibration was done by using these parameters.

Table 4.7initial and optimized value of k and x parameter in the routing reach element

Reach	Muskingum x		Muskingum k, K(hr.)	
	Initial	Optimized	Initial	Optimized
R1	0.16	0.44	120	140
R2	0.42	0.42	125	145
R3	0.3	0.49	100	120
R4	0.42	0.42	90	110
R5	0.2	0.46	81	101
R6	0.47	0.47	125	145

According to the figure 4.7 the CN values of different sub-areas within the watershed influence the overall performance of the HEC-HMS model. The model might be more sensitive to parameter changes during calibration than during validation. This can be helpful for identifying areas where improvements can be made to the model or for understanding the impact of land use changes on streamflow.

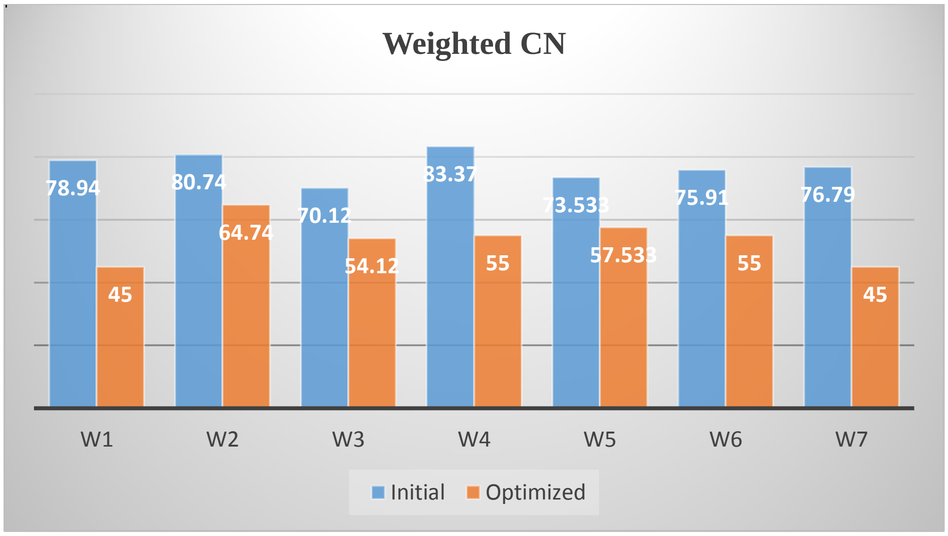


Figure 4.7 Optimization of CN value in the watershed

4.4 Hydrological Modelling Performance

4.4.1 Model Calibration Results

Parameter optimized is a method of systematic changing model parameter values until te calculated model results agree with the observed data. Optimization of the parameter values was carried out within the allowable range recommended by the US Army corps of engineers hydrological engineering center (USCAE, 2000).

Based on the model sensitivity CN, Muskingum K and Muskingum X were the most sensitive parameter. The optimization result of the minimum and maximum optimized values of these parameters shown in table 4.8

Table 4.8 The minimum and maximum optimized value of CN, Muskingum k and x

Model parameter	Minimum optimized value	Maximum optimized value
CN value	45	64.74
Muskingum k	101	145
Muskingum x	0.42	0.49

Hydro-meteorological data that was gathered over a ten-year period was used to perform the flow calibration. During these periods, the observed flow and the predicted daily flow matched well. The models using the rain gauge observations and the CHIRPS and GPM IMERG estimates as the precipitation data attain relatively satisfactory performance during the calibration period NSE = (0.55, 0.532and 0.517), R2= (0.57,0.51and 0.516) PBIAS (-0.64, 2.48 and 8.33) respectively

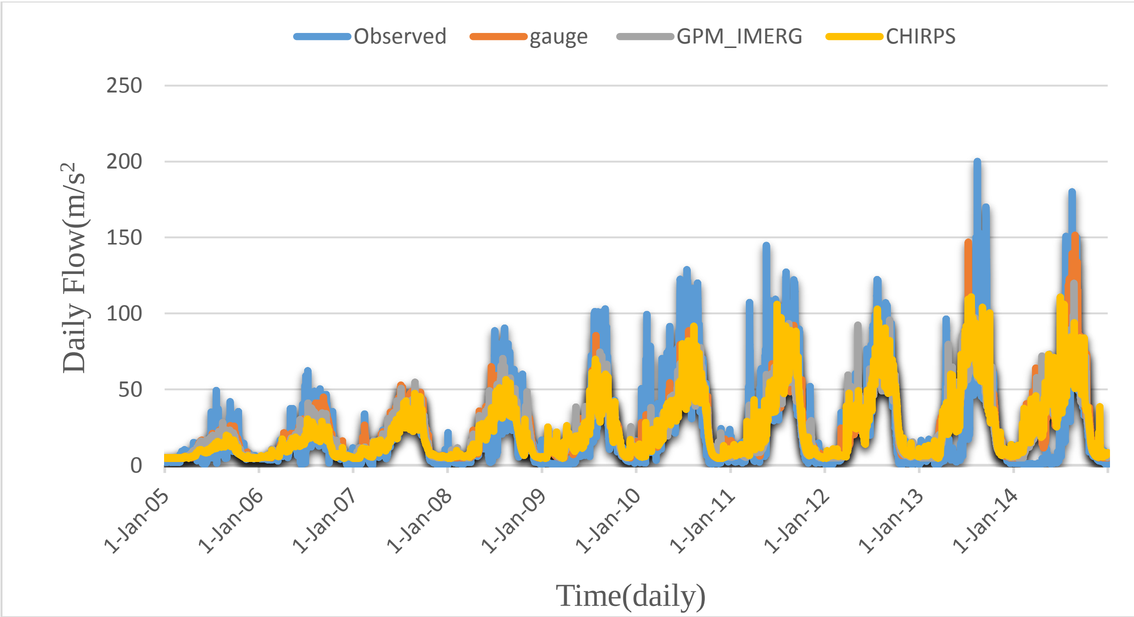


Figure 4.8 The Graph of the Daily Calibrated flow of model output from (2005 - 2014) of time series.

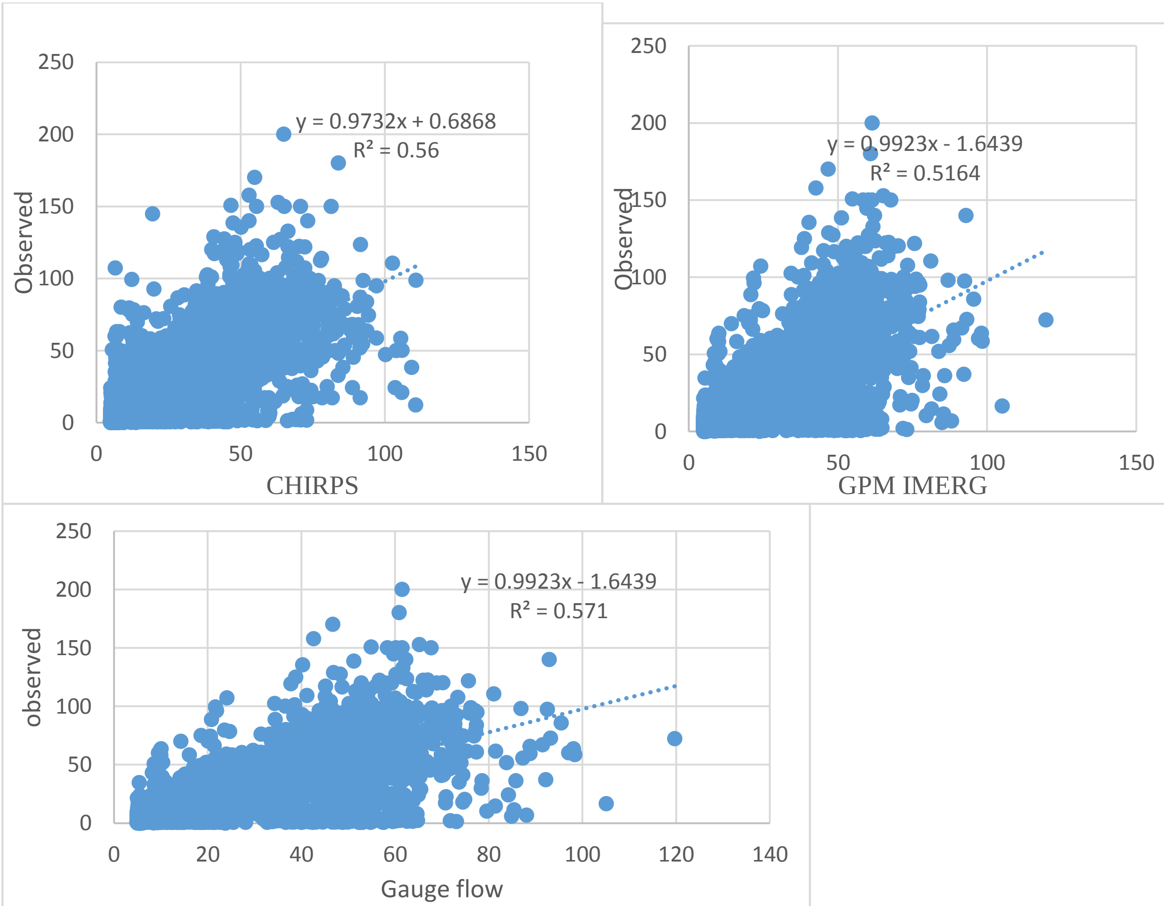


Figure 4.9 Scatter plot of simulated daily stream flow (based on CHIRPS, GPM IMERG and rain gauge rainfall input data) the period of (Jan, 2005 - Dec, 2014)

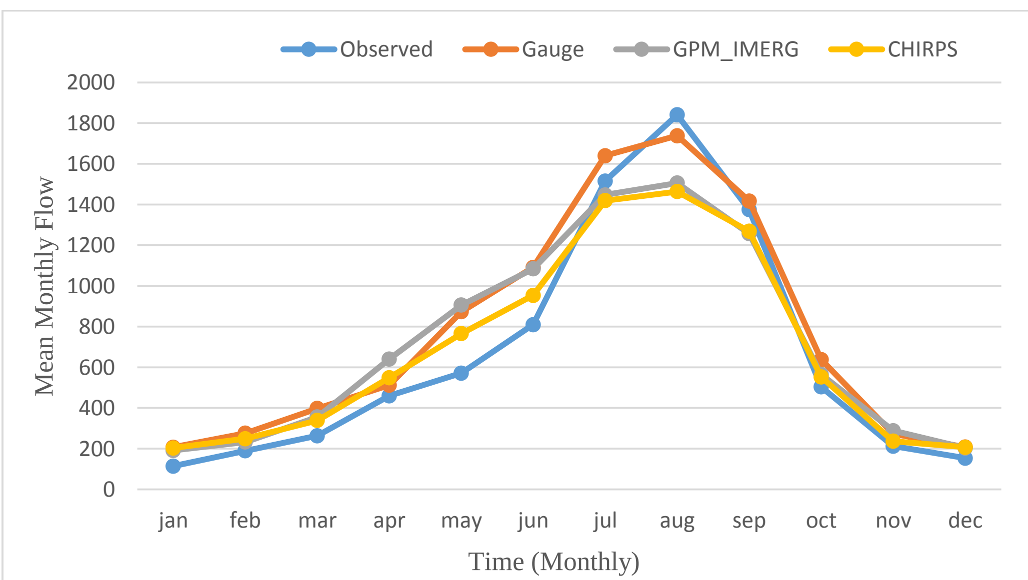


Figure 4.10 Comparison of HEC HMS simulated stream flow during the calibration period

4.4.2 Model Validation Result

The validation the model's performance for six years has been provided for the validation of the HEC-HMS model. The models using the SRE (CHIRPS and GPM IMERG) estimates as the precipitation data attain satisfactory performance during the validation period NSE = (0.58, 0.51 and 0.44), R2= (0.6, 0.54 and 0.458) PBIAS (-6.71, 11.08 and 12.04) respectively

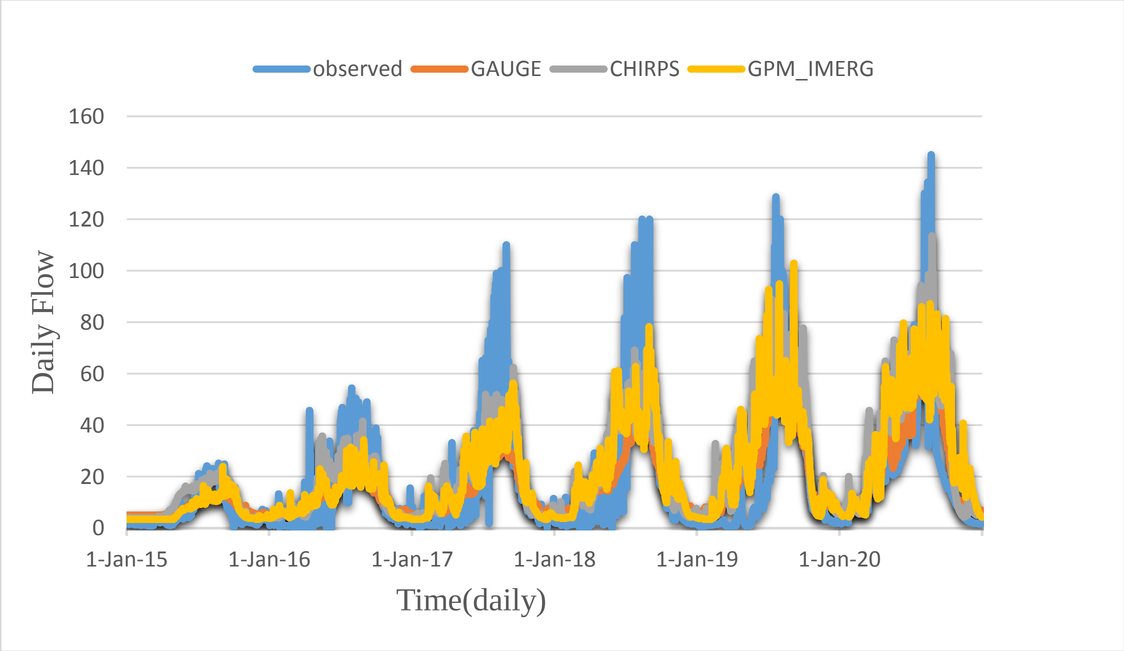


Figure 4.11The Graph of the Daily Validated flow for model output results from (2014 - 2020)

According to the model simulation there could be several reasons why the observed stream flow is greater than the simulated runoff in an HEC HMS model simulation. It may have Data Inaccuracy that calibrating a hydrological model involves adjusting various parameters to match the observed stream flow. However, calibration is often challenging due to the non-uniqueness of parameter solutions and the limited availability of high-quality observed data.

The input data used in the simulation, such as rainfall or land cover information, may not accurately represent the actual conditions at the study area. The HEC HMS model makes certain assumptions and simplifications to represent complex hydrological processes. These assumptions may not fully capture the real-world conditions, leading to differences between the observed and simulated results.

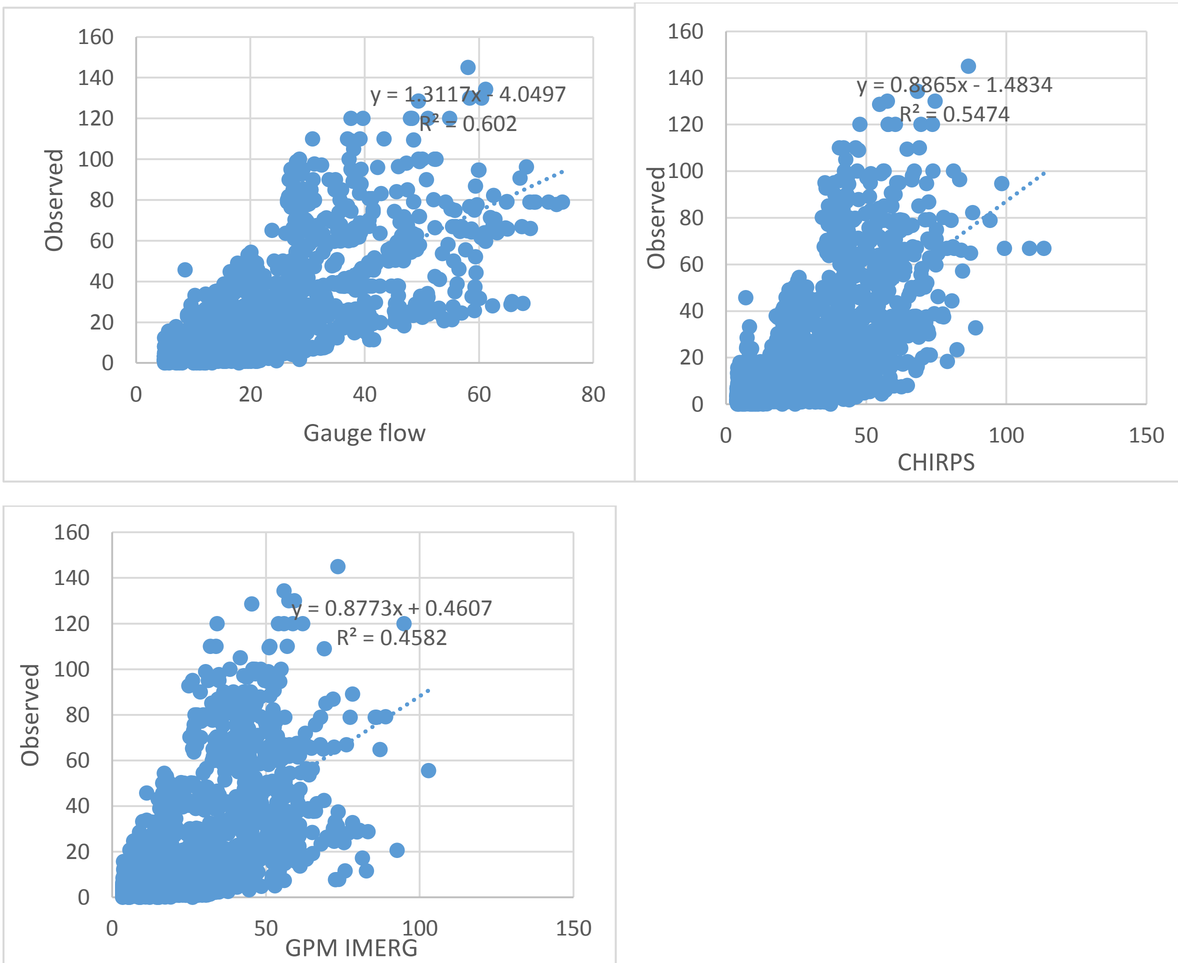


Figure 4.12 scatter plot of simulated daily stream flow (based on CHIRPS, GPM IMERG and rain gauge rainfall input data) the period of (Jan, 2014 - Dec, 2020)

The correlation between simulated and observed flows during calibration and validation time on daily basis is shown in Fig.4.12. The plotted points above the line 1:1 represent an overestimation, while those below that indicate an underestimation. The peak flow points of simulated are under the line 1:1 represent the underestimation of model while low flow points are plotted above line indicating overestimation. the model simulate is well the low flows for low rainfall events during the dry periods. According to Araújo (2006), The model evaluation is satisfactory for validation based on PBIAS. Overall, the magnitude of overestimation varies CHIRPS (2.48%) the smallest positive bias, GPM_IMERG followed by (8.33%), and then gauge (-0.64%) in calibration. For validation period the magnitude of underestimation gauge (-6.7%) and (CHIRPS and GPM_IMERG) overestimation varies (12.04%, 11.08%)

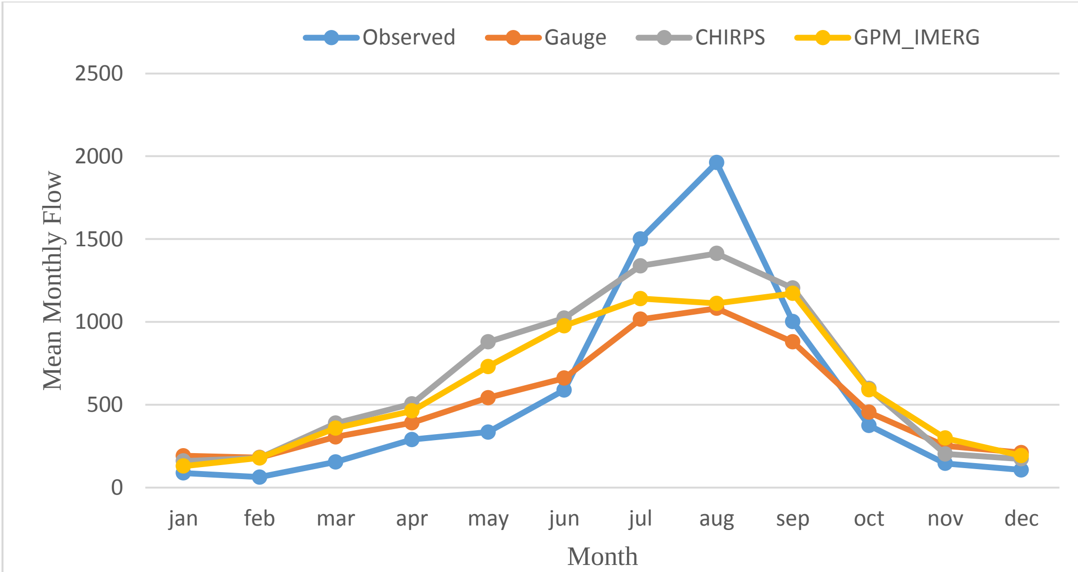


Figure 4.13Comparison of HEC HMS simulated stream flow during the validation period.

Table 4.9 Summary of model performance results at calibration and validation for Ground Station rainfall

	Calibration		
Performance Evaluation	Rain gauge	GPM-IMERG	CHIRPS
NSE	0.55	0.512	0.532
R^2	0.571	0.516	0.51
RMSE	0.7	0.6	0.5
PBIAS	-0.64	8.33	2.48
	Validation		
NSE	0.58	0.44	0.51
R^2	0.602	0.458	0.54
RMSE	0.7	0.7	0.6
PBIAS	-6.71	11.08	12.04

The models using the rain gauge observations, and CHIRPS precipitation data attain satisfactory performance during the calibration (NSE = 0.55 and 0.532, respectively), and validation period (NS = 0.58, and 0.51, respectively), while the performance of the model with the GPM_IMERG is satisfactory performance during calibration (0.512) but for during validation is lower performance (0.44). The highest NSE values are reached when using the rain gauge observations input data during the calibration period and validation period. For the coefficient of determination R^2, during the calibration period, all the models forced by the rain gauge, CHIRPS, and GPM_IMERG data exhibit satisfactory performance. The rain gauge data-forced model exhibits the highest R^2 value (R^2 = 0.602) as compared to GPM_IMERG and CHIRPS, but CHIRPS more performed than GPMS. GPM_IMERG data-forced model does low performance than others especially during validation period (R^2 = 0.44).

Generally based on the above rain gauge has the highest NSE and R^2 value as compare to other, it indicates that it has the best it among the models. It also has the lowest RMSE value, indicating that it has the smallest prediction error. However, it has a negative PBIAS value, indicating that it underestimates the observation on the average.

GPM_IMERG and CHIRPS have similar NSE and R^2 values, indicating that they have comparable it to the data. They also have the same RMSE value, indicating that they have similar predication error. However, during calibration GPM_IMERG has a higher PBIAS value, it indicating that overestimates than the observations value.it has more than CHIRPS. But during validation GPM_IMERG has a lower PBIAS value, that it has less bias than CHIRPS.

4.6. Comparison of Simulated flow of Satellite Products with Stations Results

Table 4.10 Summary for comparison of simulated discharge for satellite products with Stations results

Name of Stations	Sub - Basins	Simulated Discharge Computed (m3 /s)		
		CHIRPS_2.0	GPM_IMERG	Station
Fato	W1	64.6	58	65.7
Dillel	W2	56.5	52.6	55.9
	W3	57.9	53	57.1
Arbulaculule	W4	51.5	53.4	42.8
Butajira	W5	58.8	58	44.1
	W6	57.2	56	43
Welkite	W7	87.6	67.8	65

As seen from the above table 4.10, the results compared that, the highest simulated discharge was computed at wellkite station and CHIRPS satellite rainfall products of (87.6) and the lowest simulated discharge were computed at Arbulaculule station by ground and CHIRPS (42.8:51.5).

4.5. Discussions

The two satellite rainfall products (GPM_IMERG and CHIRPS V2) were studied, and the results showed that the products' performance continues to showing its value for hydrological and water resource studies in wabe watershed.

we can observe that for Arbulaculule Station, CHIRPS and GPM _IMERG Satellite Rainfall has the highest mean value. but Butajira Station, the station's daily and monthly rainfall data has the relatively lowest mean value by CHIRPS and GPM_IMERG satellite rainfall. The average rain gauge and (CHIRPS, GPM_IMERG) showed a relatively same it has poor correlation (R^2 =0.236, 0.266,). The daily satellite rainfall from CHIRPS and GPM_IMERG showed as better than with gauge but it has also relatively poor correlations (R^2= 0.32).

Based on daily statistical evaluation for this study, we can observe that for most stations, the CHIRPS Satellite Rainfall tends to have a smaller percent difference with the gauge rainfall but better than GPM_IMERG satellite rainfall. However, it is important to note that the relative closeness can vary depending on the specific station being considered. Even for studies that concentrate on temporary occurrences like flash floods, daily data might still be preferred. CHIRPS is the satellite product that is performing better in term of accuracy, as its PBIAS and RMSE value smaller than of GPM_IMERG.

The evaluation between CHIRPS, GPM_IMERG and Station rainfall was evaluated and compared at monthly using graphically, statistical parameters and a Pearson's product moment correlation(r)that the results is good. It tells that, the mean ground station, CHIRPS and GPM_IMERG satellite-based rainfall estimates in the Wabe watersheds were almost relatively correlated. For all stations in result section, the intercept value was close to zero which were good correlation performances, and showing that the variance of ground station and satellite-based rainfall estimate products were in slightly good agreement. At monthly rainfall data CHIRPS and GPM_IMERG that PBIAS the two satellite closer to unbiased in its estimation but CHIRPS PBIAS is more unbiased.

The performance evaluation of CHIRPS v2 due to PBIAS asserts that it includes bias correction techniques that are intended to enhance agreement with ground observations, particularly on monthly scales, and gauge data is greater than GPM_IMERG to a more precise match with ground truth on monthly scales.

Applications like drought monitoring, agricultural planning, and hydrological modeling tend to be more concerned with long-term trends and seasonal patterns than with the subtleties of daily variations. It may be more appropriate to use monthly aggregated data.

Overall CHIRPS performed better than GPM IMERG for daily, monthly timescales in detecting and estimating rainfall for the basin. The best of CHIRPS was also reported by previous studies for different parts of world (Katsanos et al., 2016) including basins in Ethiopia ((Bayissa *et al.*, 2017); (Gebremicael *et al.*, 2019)). Better performance of CHIRPS V2 has been attributed to the capability of the algorithm to integrate satellite, gauge and reanalysis products and its high spatial and temporal resolution (Funk *et al.*, 2015). This can be advantageous in capturing rainfall variability in complex terrain where satellite signals might be compromised.

The ME values showed the presence of almost the same level of errors high altitude and lower altitude part of the basin for rainfall estimates. However, Pbias indicating underestimation was observed in the highland part of the basin for CHIRPS and GPM_IMERG. Relatively the Pbias values of both product in the highland and lowland elevation zone were found to be close. however, CHIRPS showed a better performance in the case of Pbias.

CHIRPS incorporate gauge data to improve accuracy, but the availability of gauges in mountainous regions like wabe can be sparse. In welkite station have lower altitude than another station that it has the highest correlation the gauge due to effect of altitude. However, the relatively poor performance that the gauge is too sparse to accurately characterize rainfall variability. In fato station has lower altitude and the correlation is lower as compared to other station. This limited data can hinder the ability of CHIRPS and GPM_IMERG to capture localized variations in rainfall, especially at higher elevations (Funk *et al.*, 2015).

GPM_IMERG's accuracy can still decrease with increasing altitude, especially in complex terrain like the Ethiopian Highlands that wabe watershed also is exposed this problem. This is because microwave signals used by the satellites can be weakened or scattered by mountains, leading to underestimation of rainfall (Hussein and Baylar, 2023).

GPM_IMERG dataset has several limitations that should be considered when the Spatial and Temporal Resolution of IMERG data is relatively coarse around 0.1 degrees to compared CHIRPS V2 (~5 km). This may not capture fine-scale precipitation patterns accurately, especially in regions with complex topography or localized convective systems. GPM_IMERG data may exhibit discrepancies in precipitation estimates between different latitudinal zones. These discrepancies can be attributed to variations in satellite coverage, retrieval algorithms, and the availability of ground-based validation data across different regions. this study showed that the SRE products considered in this study exhibited relatively good rainfall estimation capability for the Wabe Watershed.

HEC-HMS software was used to model the rainfall-runoff simulation while ArcGIS and HEC-GeoHMS were used to handle the spatial aspects of the study area and model development. Ten years of the 16 years of available precipitation and discharge data were used for calibration, and the remaining six years were used for validation. The were calibrated using different precipitation inputs, (i.e., the gauge, CHIRPS, and GPM IMERG data-forced models' calibrated). This was determined by the model evaluation result. Furthermore, the top three simulations for every model are investigated, and the outcomes of the gauge, CHIRPS & GPM IMERG rainfall product HEC-HMS models have ($0.44 < R^2 < 0.6$; $0.44 < NSE < 0.55$; $-6.78 < PBIAS < 12.04$ and $0.5 < RMSE < 0.7$) both calibration and validation.

The hydrological model's evaluation shows the better performance of the gauge-based on model in both calibration and validation phases, exhibiting high NSE values and minimal biases. PBIAS values are slightly negative for calibration and validation period, indicating the model underestimates streamflow. This is a common issue with hydrological models and might be related to factors like model structure, parameterization, or uncertainties in input data.

The HEC-HMS model exhibits satisfactory performance when calibrated and validated using gauge and satellite rainfall data, with NSE, PBIAS, R^2 and RMSE values indicating a good fit to the observed data. The GPM_ IMERG Satellite product, while providing well calibration results, faces challenges in validation, as indicated by lower NSE and R2 values with to the gauge and CHIRPS. Generally, CHIRPS is slightly better than GPM_IMERG. The simulated CHIRPS product outperformed the simulated GPM_IMERG. The positive PBIAS values for both satellite products highlight a consistent overestimation of rainfall.

According to Hussain, et al.,(2021), studied model evaluation guidelines for systematic quantification of accuracy in watershed simulations and stated that, the model to be satisfactory.

Recognize the inherent uncertainties in satellite products due to spatial resolution, retrieval algorithms, and atmospheric conditions. Sparse gauge networks can introduce errors when converting point measurements to gridded estimates, and also Inaccurate or inconsistent data can lead to higher RMSE values impacting RMSE. An RMSE of 0.5 up to 0.7 reflects these limitations.

The study area's geography, soil type, hydrological characteristics, and land use all form the basis of the model and based on the chosen loss, transform, and flow routing methods, the HEC-HMS model's performance was satisfactory in terms of Nash Sutcliffe Efficiency (NSE), coefficient of determination (R2), and RMSE. according to((Kassem and Gökçeku, 2023) ;(Arunkumar, 2023) ; (Hussain, et al, 2021)) the same results reported that HEC-HMS model performance was satisfactory.

This finding was in line with data from other watersheds in Ethiopia, such as the shebele, and ziwey lake basin,(e.g.(Hussein and Baylar, 2023);(Aster *et al.*, 2021)). In all circumstances, the CHIRPS almost outperforms than GPM_IMERG.

Over all result in this study both satellite rainfall shows similar performance, however CHIRPS having slightly better (NSE, R2, PBIAS, RMSE) value during calibration and validation phase.

5. CONCLUSIONS AND RECOMENDATIONS

5.1. CONCLUSIONS

Satellite-based precipitation estimates with high temporal and spatial resolution and large area coverage provides another potential source of data forcing in hydrological models in areas where conventional in situ precipitation measurements are not readily available. To overcome limitation of lacking robust station data, this research study uses some of the available globally gridded high-resolution precipitation datasets to simulate runoff using HEC HMS model. This study aims

Hydrological modeling of watershed using observed and satellite precipitation data for wabe watershed during the period of 2005 to 2020. The findings of this study are as follows:

1. The comparison results of rainfall magnitudes from satellite rainfall products and rain gauges revealed that GPM IMERG and CHIRPS rainfall estimates gave relatively good result at daily, monthly scale for different stations.

2. In terms of the hydrological evaluation, the HEC HMS model was forced by precipitation derived from the gauge, GPM IMERG and CHIRPS data to examine their hydrologic utilities. The model with precipitation data from rain gauges showed satisfactory by R2, NS, RMSE and PBIAS values during both the calibration and validation periods, which means that the HEC HMS model is capable of simulating the streamflow over the study area.

Gauge data prove to be a reliable choice, satellite products like CHIRPS and GPM IMERG exhibit limitations, particularly in accurately predicting rainfall during calibration and validation periods. The CHIRPS data-forced model performs better than the GPM IMERG data-forced model. The overestimation of the input satellite rainfall estimates and the problem of satellite rainfall estimates with systematic errors were the causes of the overestimation of the streamflow simulated by satellite rainfall estimates and the decrease in model performance statistics. The rain gauge rainfall data consistently perform s better than the satellite product in the context of HEC-HMS model evaluation. However, the overestimation of observed in all cases highlight the challenges associated with accurately representing precipitation pattern using these date source, Future studies should explore methods to enhance the accuracy of satellite precipitation products or combine them with other data sources to improve model performance.

Consider possible causes of the disparities, such as the limitations of the HEC-HMS model and date resolution, regional variability, and temporal variability. Although there are inherent limitations in these gridded datasets, applying them to hydrological research in the absence of station data can be beneficial.

Furthermore, in order to minimize errors, satellite precipitation products could be corrected using probable mathematical models. Finally, there are still a lot of uncertainties around the use of satellite precipitation products in hydrological modeling (Xu *et al.*, 2019).

5.2 Recommendations

Based on this research, the following recommendations have been required:

- Despite the improved temporal and spatial resolution of these satellite datasets, much more research is still needed to properly comprehend the numerous sources of errors. In the future, studies should focus minimizing temporal and spatial resolution of satellite datasets evaluated the uncertainties satellite rainfall. I recommended to use point to basin or gride to gride method to Consider the spatial resolution of satellite rainfall data
- More meteorological data must be used in these investigations, and they must cover the entire nation. And also, it is highly recommended to establish good meteorological stations and to have a high quality of streamflow data.
- Future research could focus on exploring advance calibration techniques such as automated calibration, multi-site calibration, sensitivity analysis by changing parameter in to rainfall runoff modeling. Considering the effect of climate change and land use modification in hydrological modeling. And also, Evapotranspiration data can be incorporated into rainfall-runoff modeling
- Understanding the model rainfall simulation capability and want to comparation with both ground and satellite data was evaluated by ground calibration and validated approach, however I recommended used satellite rainfall calibration and validation approach.

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7. APPENDICES

Appendix I List of tables

Tabel 1 Mean monthly rainfall o ground station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2005	52.40	5.80	104.58	138.76	141.04	164.48	228.92	237.74	183.56	45.86	17.72	0.88
2006	7.97	33.53	145.77	186.57	95.30	167.80	322.77	267.77	161.32	31.40	17.25	6.26
2007	15.58	75.14	52.46	69.60	138.64	200.18	247.40	249.47	166.98	28.31	3.58	3.34
2008	1.98	3.42	1.98	48.36	135.90	181.82	255.66	226.26	112.70	44.62	83.40	0.06
2009	34.74	11.32	19.74	25.18	49.85	85.00	226.54	210.86	87.04	89.34	0.28	42.99
2010	14.88	64.37	66.42	118.24	139.53	219.86	252.18	235.95	111.98	13.92	16.18	26.06
2011	8.72	9.99	73.22	43.54	116.28	157.44	180.05	219.44	147.72	20.68	26.10	3.20
2012	2.74	10.80	34.78	97.97	73.61	135.49	237.22	188.33	122.87	13.42	9.40	6.45
2013	10.32	13.83	68.98	106.87	104.56	210.78	275.80	183.00	139.98	67.75	9.84	1.75
2014	7.29	64.20	92.00	37.32	129.20	91.50	302.34	321.25	139.99	75.28	1.12	0.00
2015	2.32	8.85	32.70	25.56	90.40	163.78	166.54	172.78	102.10	35.03	16.81	14.15
2016	26.64	10.12	51.74	100.70	112.16	147.82	178.64	157.18	88.20	23.71	23.90	8.05
2017	0.00	20.12	21.42	56.91	76.31	120.64	197.56	199.17	132.43	28.18	16.24	9.24
2018	9.74	32.26	46.07	74.42	77.96	143.87	221.42	200.95	86.35	37.15	35.27	7.65
2019	9.07	7.43	41.07	87.26	92.43	172.56	243.55	206.30	155.20	37.23	22.82	10.56
2020	14.24	13.02	76.61	114.12	113.27	152.98	246.98	218.46	139.56	23.31	9.91	5.42

Comparison result of average rainfall magnitude over the watershed.

Table 2: Mean monthly rainfall (mm)

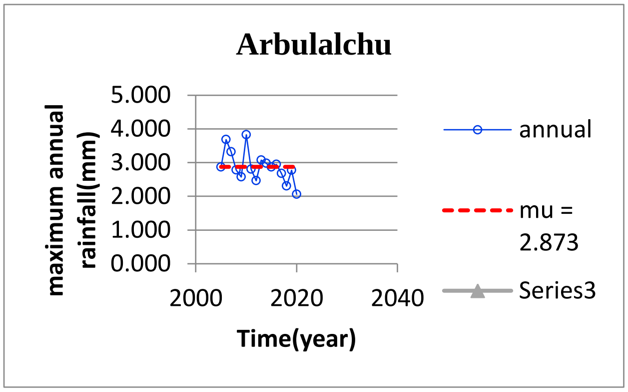
Month	observed	CHIRPS	GPM_IMERG
Jan	13.67	14.29	15.21
Feb	24.01	23.39	27.64
Mar	58.10	60.84	55.51
Apr	83.21	84.55	89.37
May	105.40	123.98	130.24
Jun	157.25	157.21	163.42
Jul	236.47	238.36	229.09
Aug	218.43	209.00	206.93
Sep	129.87	136.42	150.72
Oct	38.45	32.64	45.63
Nov	19.36	12.13	23.59
Dec	9.13	8.18	7.20

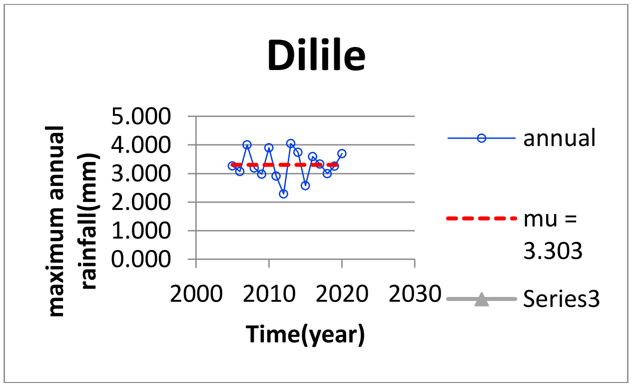
Table 3: Annual rainfall from various rainfall products

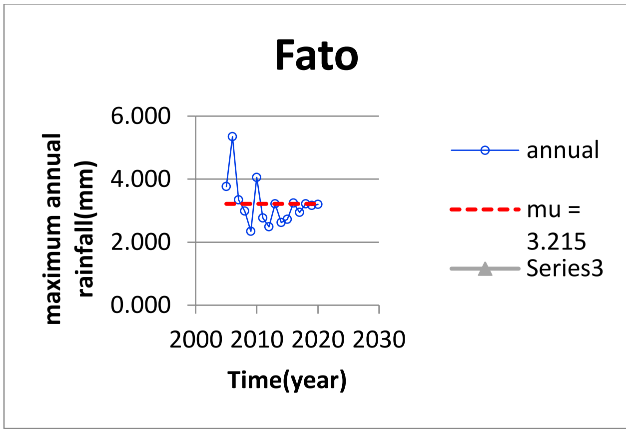
YEARLY	OBSERVED	CHIRPS	GPM-IMERG
2005	1321.74	1096.31	1262.65
2006	1443.72	1054.91	1273.71
2007	1250.69	1097.76	1162.13
2008	1096.17	1082.35	1228.89
2009	882.87	978.83	833.92
2010	1279.56	1252.90	1228.85
2011	1006.38	1168.20	927.72
2012	933.09	1028.29	1043.13
2013	1193.47	1186.51	1119.06
2014	1261.50	1018.39	1151.80
2015	831.02	800.04	957.90
2016	928.86	1107.59	1093.73
2017	878.23	1102.43	1189.37
2018	973.10	1099.44	1252.03
2019	1085.48	1315.32	1203.25
2020	1127.89	1226.74	1384.55

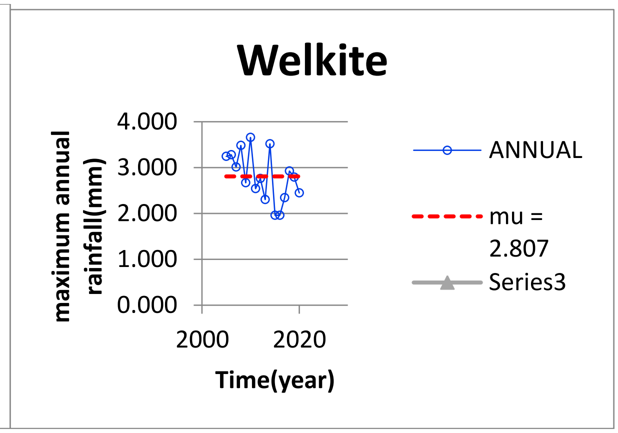
Appendix II. List of figures

Figure 1. Homogeneity test









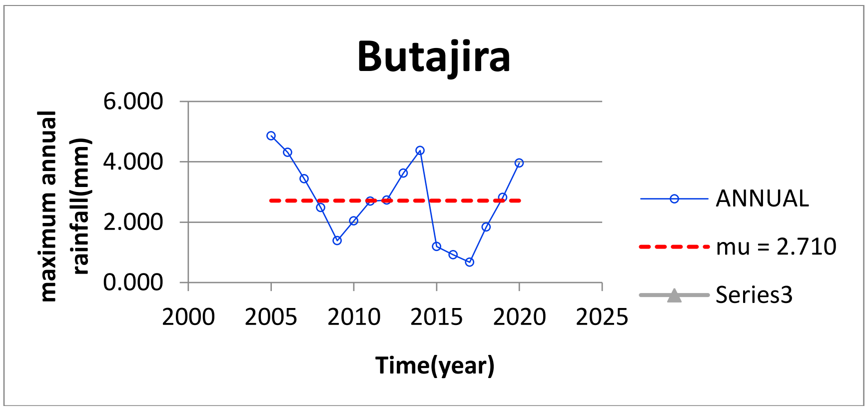
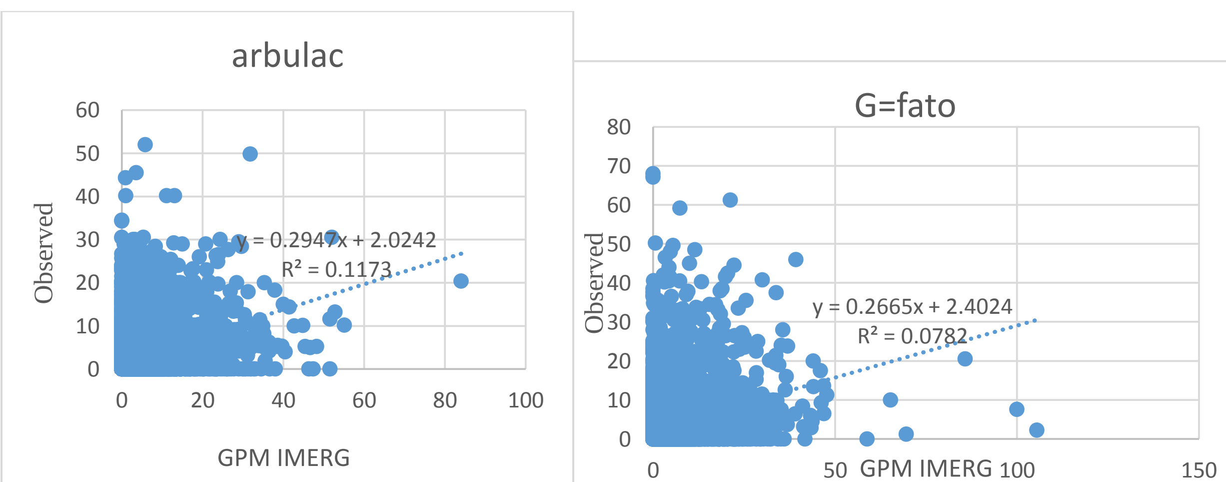
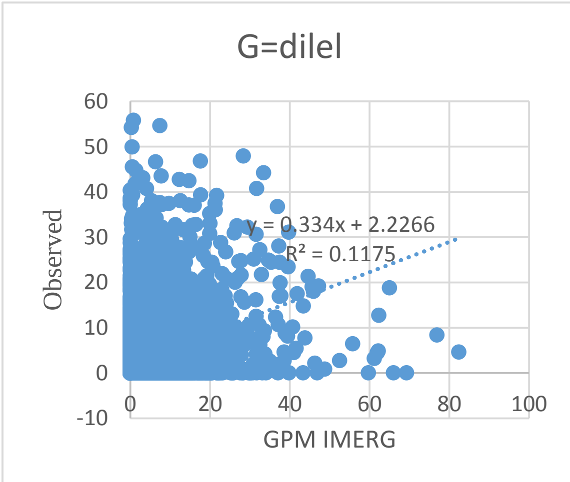
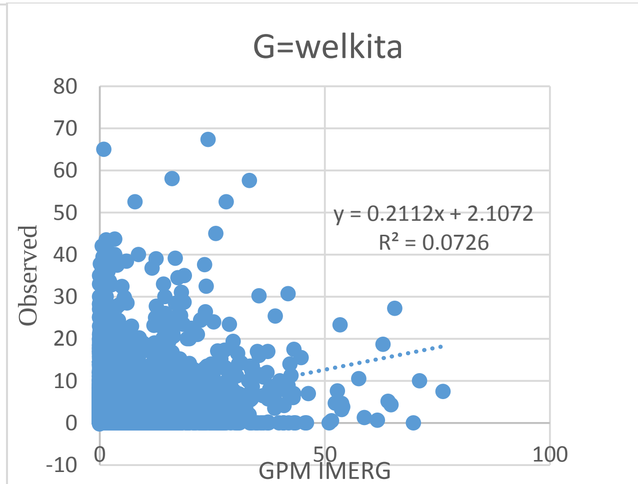
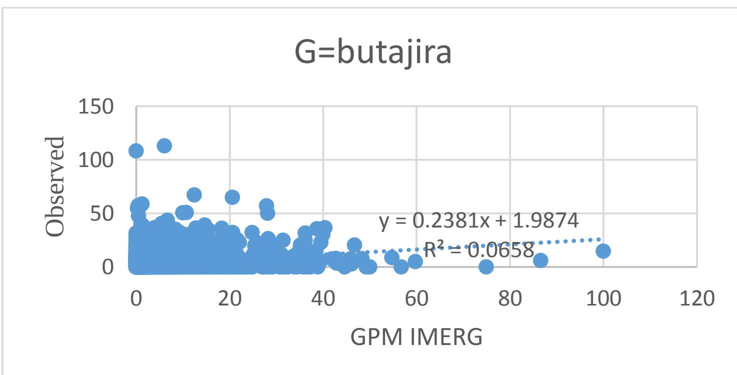


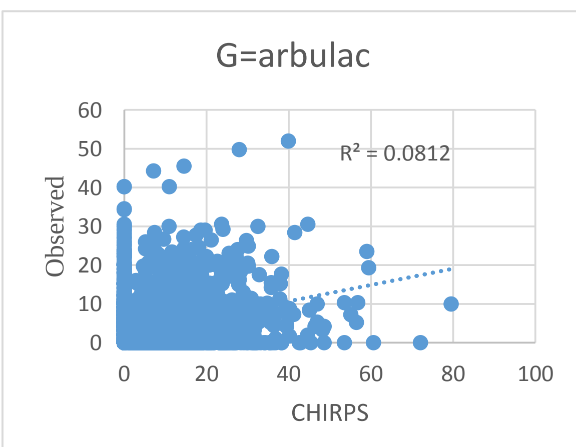
Figure 2. Scatterplots of various biased satellite rainfall and in situ (gauge) daily rainfall measurements in wabe watershed

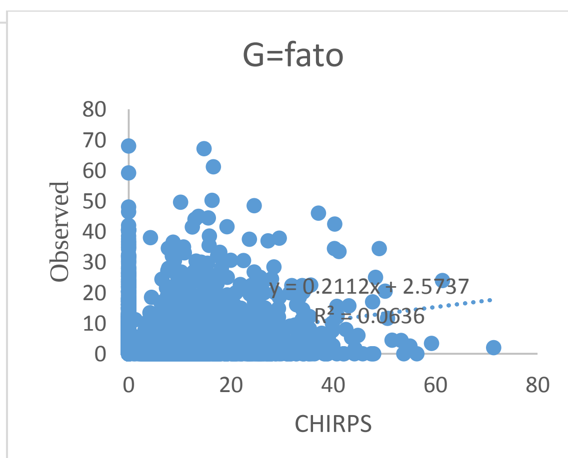



G=dilel
y = 0.334x + 2.2266
R² = 0.1175
Observed
GPM IMERG
60
50
40
30
20
10
0
-10
0
20
40
60
80
100


G=welkita
y = 0.2112x + 2.1072
R² = 0.0726
Observed
GPM IMERG
80
70
60
50
40
30
20
10
0
-10
0
50
100


G=butajira
y = 0.2381x + 1.9874
R² = 0.0658
Observed
GPM IMERG
150
100
50
0
0
20
40
60
80
100
120


G=arbulac
R² = 0.0812
Observed
CHIRPS
60
50
40
30
20
10
0
0
20
40
60
80
100


G=fato
y = 0.2112x + 2.5737
R² = 0.0636
Observed
CHIRPS
80
70
60
50
40
30
20
10
0
0
20
40
60
80

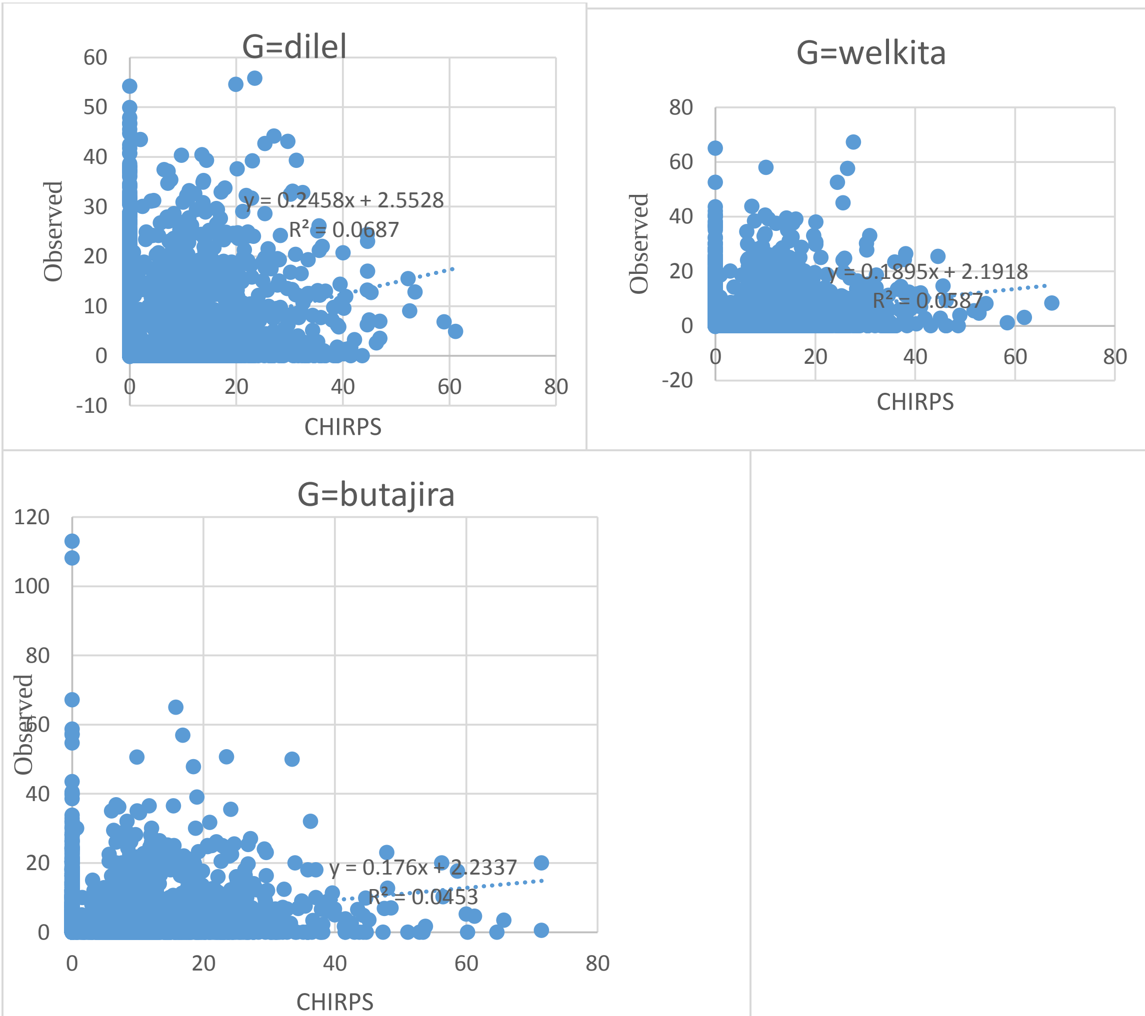
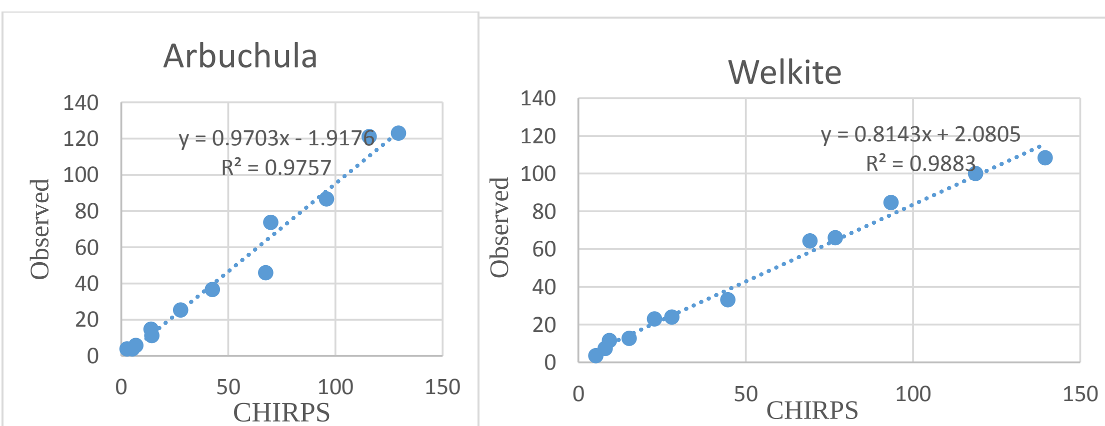
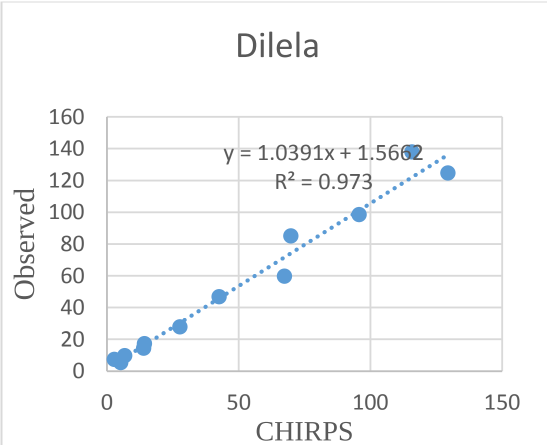
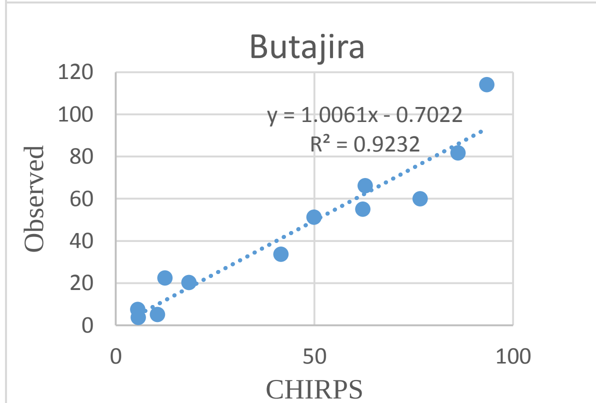
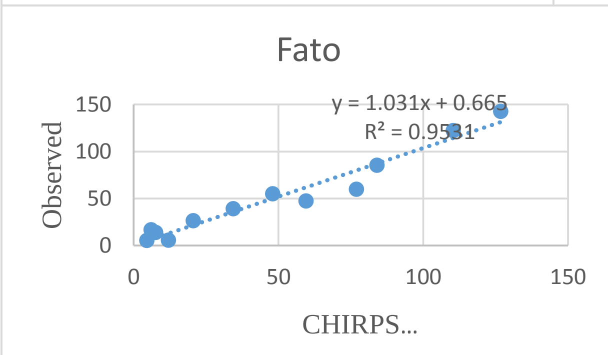


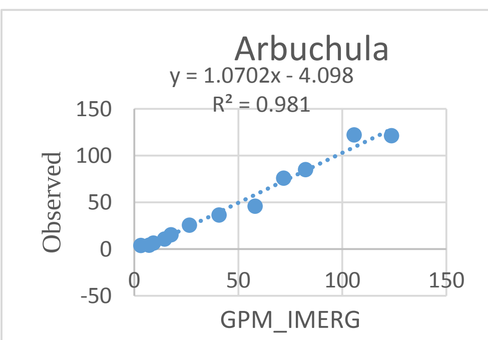
figure 3. Scatterplots of various biased satellite rainfall and in situ (gauge) monthly rainfall measurements in wabe watershed

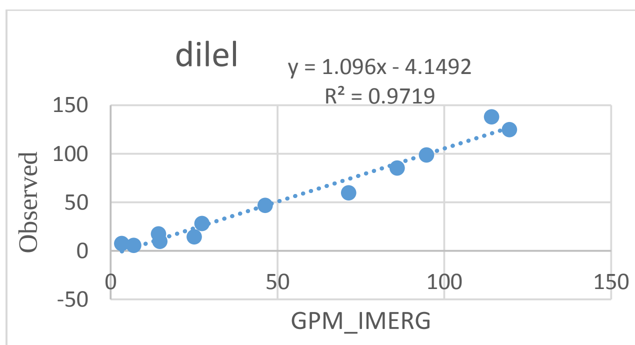


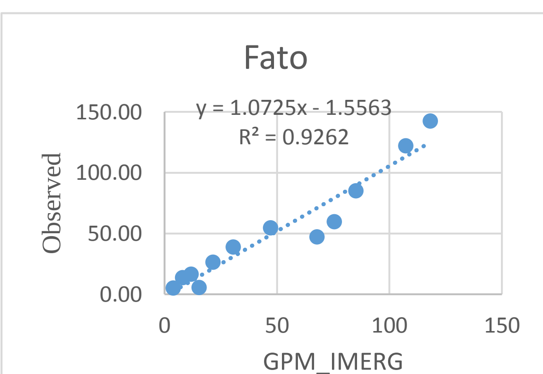

Dilela
y = 1.0391x + 1.5662
R² = 0.973
Observed
CHIRPS
0 20 40 60 80 100 120 140 160
0 50 100 150

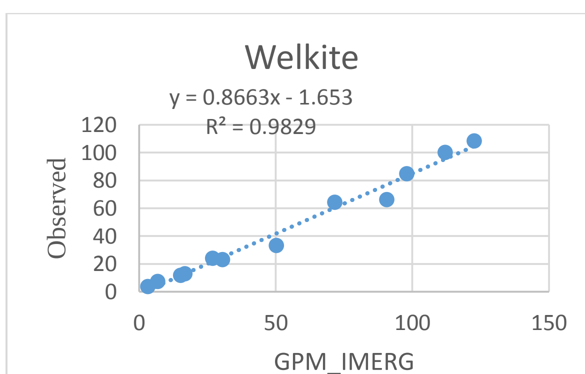

Butajira
y = 1.0061x - 0.7022
R² = 0.9232
Observed
CHIRPS
0 20 40 60 80 100 120
0 50 100


Fato
y = 1.031x + 0.665
R² = 0.9531
Observed
CHIRPS...
0 50 100 150
0 50 100 150


Arbuchula
y = 1.0702x - 4.098
R² = 0.981
Observed
GPM_IMERG
-50 0 50 100 150
0 50 100 150


dilel
y = 1.096x - 4.1492
R² = 0.9719
Observed
GPM_IMERG
-50 0 50 100 150
0 50 100 150


Fato
y = 1.0725x - 1.5563
R² = 0.9262
Observed
GPM_IMERG
0.00 50.00 100.00 150.00
0 50 100 150


Welkite
y = 0.8663x - 1.653
R² = 0.9829
Observed
GPM_IMERG
0 20 40 60 80 100 120
0 50 100 150

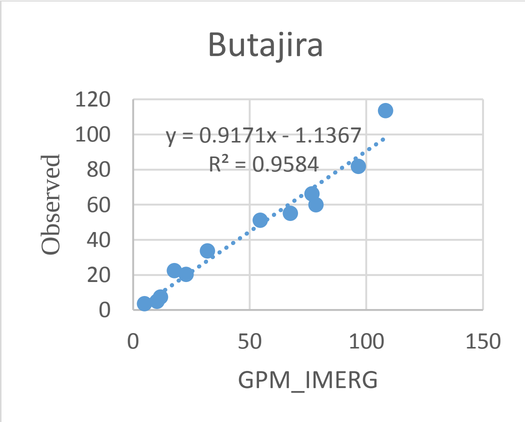


Figure 3 Summary of objective function calibration Results for the model output Results

Appendix II. List of model figures

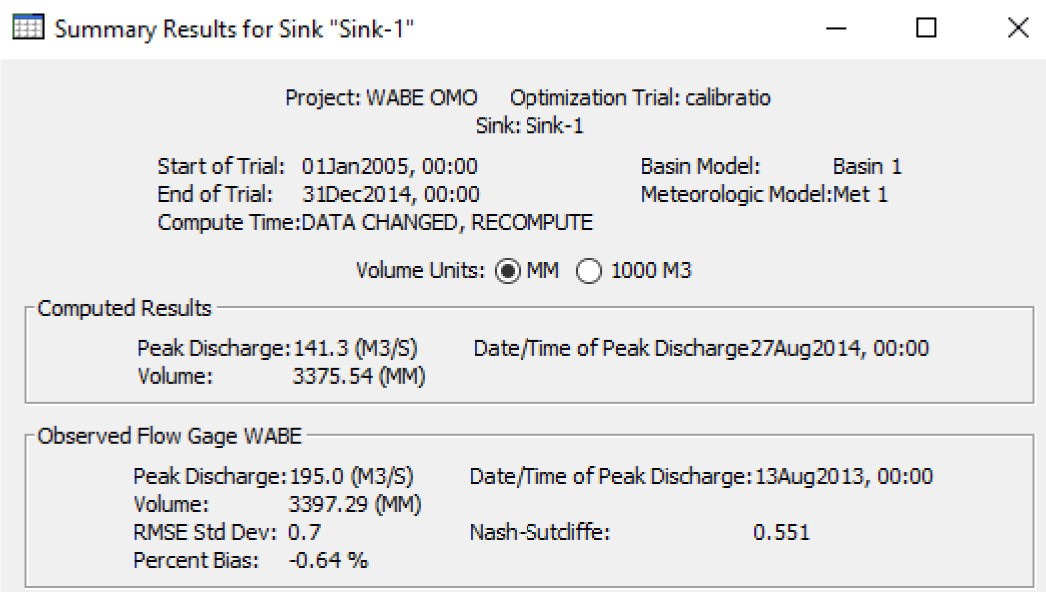


Figure 4 Summary of objective function calibration Results for the model output Results

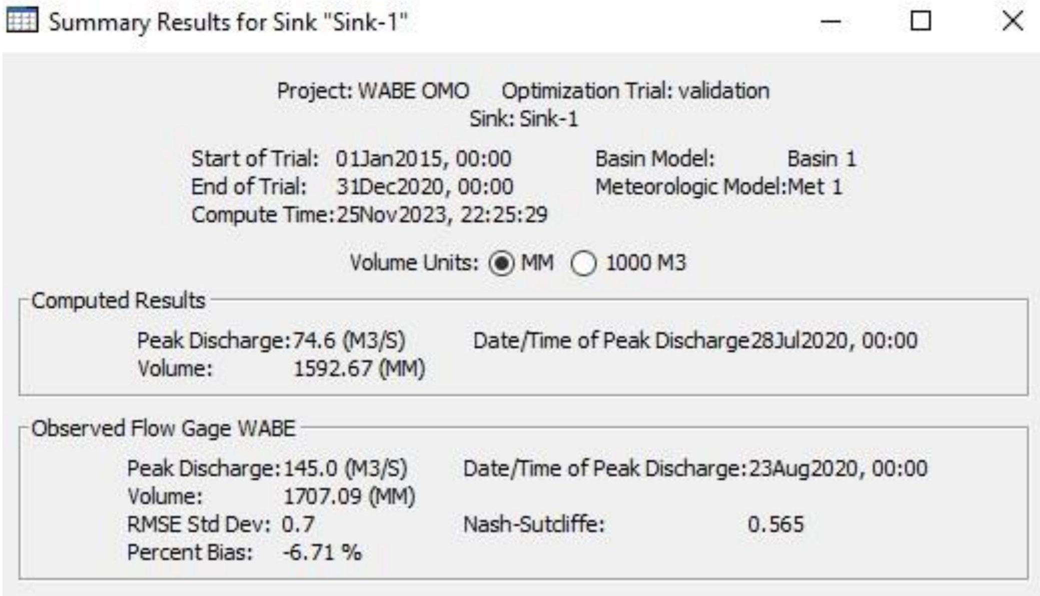


Figure 4 Summary of objective function Validation Results for the model output Results

Subbasin	Longest Flowpath Length (KM)	Longest Flowpath Slope	Centroidal Flowpath Length (KM)	Centroidal Flowpath Slope	10-85 Flowpath Length (KM)	10-85 Flowpath Slope	Basin Slope	Basin Relief (M)	Relief Ratio	Elongation Ratio	Drainage Density (KM/KM²)
W1	40.16555	0.03852	19.51244	0.03167	30.12416	0.02717	0.21805	1597.00000	0.03976	0.52151	0.04936
w2	43.00665	0.03324	21.67460	0.01802	32.25499	0.02425	0.14932	1614.00000	0.03753	0.40329	0.04449
W3	40.89760	0.02547	15.79341	0.01447	30.67320	0.01545	0.13934	1451.00000	0.03548	0.45294	0.05609
W4	44.94715	0.02371	19.49001	0.00957	33.71036	0.01290	0.10863	1087.00000	0.02418	0.39226	0.10073
W5	34.32220	0.04254	17.59877	0.03625	25.74165	0.04839	0.19261	1468.00000	0.04277	0.55358	0.02332
W6	44.16569	0.02705	14.30300	0.01550	33.12427	0.02685	0.15147	1201.00000	0.02719	0.43074	0.11826
W7	55.69467	0.01723	23.12821	0.02653	41.77100	0.01896	0.12987	961.00000	0.01725	0.37587	0.12901