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**Modeling Rainfall-Runoff Dynamics Using HEC-HMS: Case of Gololcha
Watershed**

A Thesis Submitted in Partial Fulfillment of the Degree of Master of Science in
Hydraulic Engineering

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Bale Robe, Ethiopia

DECLARATION STATEMENT

I hereby declare that the Thesis titled, **Modeling Rainfall-Runoff Dynamics Using HEC-HMS: Case of Gololcha Watershed** is my original work.

I confirm that this thesis has not been submitted elsewhere in any form for funding, academic evaluation, or any other purpose. Any materials or ideas from other sources have been properly cited and acknowledged.

I affirm that this thesis complies with all ethical standards and guidelines outlined by the institution, and I take full responsibility for its content.

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ABSTRACT

Accurate simulation of rainfall–runoff processes is essential for flood prediction and sustainable water resources management, particularly in watersheds that exhibit high seasonal variability in streamflow. The Gololcha watershed in the Wabe Shebele River Basin of Ethiopia frequently experiences high runoff during intense rainfall events, which leads to flooding in the surrounding areas. Understanding the hydrological response of the watershed is therefore important for effective flood risk mitigation and the planning of hydraulic structures. The main objective of this study was to model the rainfall–runoff process of the Gololcha watershed and evaluate the performance of the HEC-HMS model for streamflow simulation and peak flood estimation. Daily rainfall and streamflow data for the period 2000–2020 were used together with a 12 × 12 m Digital Elevation Model, land use/land cover, and soil maps to derive the physical characteristics of the watershed. Missing rainfall data were filled using XLSTAT by linear regression of a nearest neighbor approach was applied to fill the missing data, and areal rainfall was computed by the Thiessen polygon method. HEC-GeoHMS was applied to delineate the watershed and generate model parameters such as sub-basins, stream network, curve number, and lag time. The Soil Conservation Service Curve Number method, SCS Unit Hydrograph, monthly constant baseflow, and Muskingum routing method were used for loss estimation, runoff transformation, baseflow simulation, and channel routing, respectively. Model calibration and validation were carried out using observed streamflow data. The model performance was evaluated using Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS). The results showed good agreement between observed and simulated flows, with NSE values of 0.809 and 0.845, R^2 values of 0.813 and 0.92, and PBIAS values of 11.97% and 14.08% for calibration and validation, respectively. Flood estimation based on 24-hour rainfall for different return periods indicated that peak discharge increases from 106.8 m³/s for the 2-year return period to 630.3 m³/s for the 500-year return period, revealing the high flood potential of the watershed. Overall, the study confirms that the HEC-HMS model is a reliable tool for rainfall–runoff simulation and design flood estimation, and the results provide valuable input for flood risk management and watershed planning in the study area.

Keyword: Rainfall-Runoff, HEC-HMS, HEC-GeoHMS, Performance, Gololcha watershed.

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ACRONYMS AND ABBREVIATIONS

a.m.s.l	above mean sea level
DEM	Digital Elevation Model
DMC	Double Mass Curve
ECDF	Empirical Cumulative Distribution Function
EMA	Ethiopian Mapping Agency
GIS	Geographic Information System
Geo-HMS	Geospatial Hydrologic Modeling System
HEC-HMS	Hydrologic Engineering Centers Hydrological Modeling System
IWRM	Integrated Water Resource Management
IDD	International Disaster Database
KW	Kinematic Wave
LPM	Linear Perturbation Model
LULC	Land Use Land Cover
MoWIE	Ministry of Water, Irrigation and Electricity
NMSA	National Meteorological Service Agency
NSE	Nash-Sutcliffe Efficiency
PDM	Probability Distributed Models
RSR	Observations Standard Deviation Ratio
SCS-CN	Soil Conservation Service Curve Number
SLM	Simple Linear Model
SMA	Soil Moisture Accounting
SNNPRS	Southern Nation Nationalities and people's Regional States
SWAT	Soil and Water Assessment Tools

CHAPTER 1

INTRODUCTION

1.1 General Background

Surface runoff refers to that part of rainwater which reaches oceans, lakes, rivers and other water bodies after leaving soil through infiltration, evaporation and other forms of loss. This runoff is another significant part of the hydrological cycle, consists of plays an essential role in flood prevention, water resource management, and environmental protection. The strength and time over which rain falls; its spatial dispersal from the point of impact, vegetation cover, surface type (roads/buildings), and other variables that encourage its creation are some of the many factors influencing how much water from a storm becomes surface runoff:.

Modeling of rainfall runoff is a basic component of hydrology that is important in water resources planning and design. As an important tool in flood control, irrigation development, reservoir management, and design of hydraulic structures in spatially and temporally variable rainfall regimes, it is a key component of hydrology. Rainfall is characterized by significant temporal and spatial variability in Ethiopian agricultural-based economies. During the last decades the increased surface runoff and peak discharges are due to the climate change, land and land cover change, deforestation, and increased population density. All of these drivers are responsible to alter the hydrological cycle and consequently to intensify the hazards of floods, surface runoff, and land degradation. Rainfall runoff modeling in catchment areas is of critical importance.

Runoff estimation requires understanding of the interactions between meteorological variables, terrain characteristics, and the physical characteristics of the soil and land cover. The complexity of these interactions, direct measurement of runoff for every rainfall event is often impossible. Instead, hydrologic modeling has created as an effective approach to simulate rainfall-runoff processes and predict runoff volumes under different environmental condition. The relationship between precipitation and surface runoff can be effectively evaluated using hydrological models(Tassew et al. 2019).

In both gauged and ungauged watersheds, hydrologic models are frequently used to estimate stream flow and simulate the conversion of precipitation into runoff. Among all hydrological models, HEC-HMS is highly valued for its flexibility and moderate data needs and for its capability to mimic various hydrological processes. For operational use of this model, various parameters of watersheds

like land use/cover, type of soils, slope, and drainage patterns can be obtained through GIS technology.

In Ethiopia, several research works have successfully applied the HEC-HMS method in rainfall-runoff modeling in different rivers' catchment areas. For example, the simulated streamflow results of the HEC-HMS model in the Gilgel Abay watershed of the Upper Blue Nile Basin were in good agreement with observed data. The agreement demonstrates that the model is dependable for estimating rainfall-runoff and conducting hydrological analyses in watersheds with similar characteristics(Tassew et al. 2019). In a similar study conducted in the Katar Watershed, the application of HEC-HMS produced satisfactory agreement between measured and simulated streamflow, demonstrating its suitability for rainfall-runoff modeling and other hydrological investigations(Geyisa Namara et al. 2020). Additionally, hydrological simulations can be used to perform tasks other than flood forecasting. The tasks include flood estimation and watershed management(Tassew et al. 2019). Overall, all the above research has verified that HEC-HMS is an effective model in hydrological modeling under various hydro-climatic conditions of Ethiopia.

Despite these successes, there is evidence that most of the previous HEC-HMS studies in Ethiopia were on the Abay, Awash and Rift Valley river basins while very limited research occurred on the Wabe Shebele River Basin. Wabe Shebele River Basin, Gololcha watershed has recently faced the variability of rain and land use change. This may alter runoff produced and increase flooding risk. Unfortunately, there is no detailed information on the runoff processes and watershed hydrological response. No study has been done in particular on the watershed by calibrating and validating using the long-term hydro-meteorological data available the HEC-HMS model. It negatively impacts confidence in flood forecasting, hydraulic structure designing, and water resources planning. A comprehensive study of the Gololcha watershed is therefore deemed vital to improve the awareness of its hydrological behavior and facilitate effective water resource management.

The study simulated the rainfall-runoff process in the Gololcha watershed of the Wabe Shebele River Basin using the HEC-HMS model by using rainfall and streamflow data collected from 2000 to 2020. Results of this study can be applied to water resource planning and management of Gololcha watershed; design of hydraulic structure; flood forecasting. In addition to this, the study will increase the existing hydrological knowledge on Wabe Shebele River Basin as there is limited rainfall-runoff modeling analysis conducted on the Wabe Shebele River Basin.

1.2 Statement of the Problem

For planning water resources to be effective, there is a need to have a deep understanding of how water runoff behaves in a watershed. Estimation of runoff is essential in defining measures that can sustain water development projects, including measures to mitigate water problems (Zegele and Melesse 2018). There are various watersheds, like the Gololcha Watershed, that exhibit changes in runoff patterns due to both natural and anthropogenic factors.

During rapid development, land use planning and land management are also important issues in controlling surface runoff since they can exacerbate it by reducing land cover, depleting nutrients in soils, deteriorating water quality in rivers, and increasing impervious surfaces (Choudhary et al. 2014). The Gololcha watershed communities are still highly exposed to flooding and droughts, at times without the means or plans to prepare to mitigate their effects. Their high dependence on farming activities makes them highly vulnerable to environmental changes, including temperature, rainfall, humidity, and sunlight patterns. Peoples are not aware of the peak discharge, runoff, or how land use changes affect the watershed communities. It is difficult to develop effective watershed management plans without this information, making the communities highly exposed to flooding, land degradation, and water shortages.

There is also an insufficient of information about predictive tools for future hydrological conditions in the watershed, making it difficult to develop effective watershed management plans. For instance, it is difficult to develop effective infrastructure or mitigate flooding in the Gololcha watershed communities without information regarding future flooding patterns.

This model is used in the evaluation of various scenarios in relation to land use and climatic variations. By estimating flood peaks and describing the process of runoff and its response to rainfall events, it is possible to generate vital data for effective decision-making in water resource management.

1.3 Objective

1.3.1 General Objective

This study's primary goal was to model the Gololcha watershed's rainfall-runoff dynamics.

1.3.2 Specific Objective

The following specific goals were established for the study's key indicators in order to achieve the overall goal: -

- To evaluate the performance of the HEC-HMS model in simulating rainfall-runoff processes for the Gololcha Watershed.
- To model the rainfall-runoff interactions to understand the hydrological response of the watershed to rainfall events.
- To predict peak flood discharges for different return periods to support flood risk assessment and management.

1.4 Research Question

This study addresses the following research questions:-

- How accurately does the HEC-HMS model simulate rainfall-runoff processes in the Gololcha Watershed?
- What is the hydrological response of the Gololcha Watershed to varying rainfall events?
- What are the predicted peak flood discharges for different return periods, and how can these predictions inform flood risk assessment and management in the Gololcha Watershed?

1.5 Scope of the study

The Gololcha watershed, a sub-watershed of the Wabe Shebele River Basin, is where the research study area is situated. The current study used the HEC-HMS model to simulate rainfall and runoff in order to determine the amount of stream flow and runoff in the Gololcha watershed. Rainfall, streamflow, digital elevation, land use, land cover, and soil were among the data used in this study.

The study was conducted during a period when data was both available and consistent, with the accuracy of the results being determined using selected statistical measures. To allow for a thorough spatial investigation of runoff patterns, the watershed was split up into sub-basins.

Surface runoff data were used in this study; groundwater flow, sediment transport, reservoir operations, and potential changes brought on by shifting land use and climate were not taken into account. The reliability of output from HEC-HMS depends on how good the input data is and on assumptions made regarding processes such as loss estimation, runoff transformation, base flow, and flow conveyance through channels.

1.6 Significance of the study

The primary contribution of the study is the provision of important information on peak river discharge and watershed runoff. Such data is of great use to both government and non-governmental organizations in planning and constructing future structures in the watershed. Therefore, the application of hydrological modeling is essential for assessing and predicting water availability within the watershed. It is clear that knowledge of the link between rainfall and runoff at different scales in Wabe watershed regions.

Investigating water balance, managing water resources, conserving land and water, hydraulic infrastructure like irrigation and hydropower, and even flood control would all benefit from the Shebele River Basin.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Rainfall–Runoff Modeling

Rainfall–runoff modeling is a key hydrological approach used to represent the transformation of rainfall into surface runoff within a watershed. The impracticability of monitoring all hydrologic processes spatially and temporally; models have been adopted to predict the process by which precipitation inputs are changed to varying flows at the outlets of a watershed. This is crucial for efficient administration of water resources, lowering the risk of flooding, and designing hydraulic structures correctly(Beven 2012).

The ability of the rainfall-runoff model is dependent upon its ability to represent the relationship between climatic inputs and features of watersheds. Runoff generation is initiated by climatic factors such as rainfall intensity, duration, and spatial-temporal distribution; the distribution of rainfall into infiltration and surface runoff components is greatly influenced by watershed characteristics such as soil texture, land use/land cover, slope, and storage capacity(Beven 2012). The rate of infiltration, which in turn influences the creation of surface, subsurface, and base flows in the streams, is determined by the texture of the soil.

Hydrological models vary with regard to their consideration of spatial variation, which is inherent to watershed characteristics. A ‘lumped’ model depicts the whole watershed as a single, homogenous unit, while a ‘fully distributed’ model depicts regional heterogeneity in watershed features. A ‘semi-distributed’ model represents the watershed as several units or sub-basins. In the ‘semi-distributed’ model, spatially averaged physical characteristics are used, allowing for realistic simulation with a moderate amount of data (Devia et al., 2015)

Semi-distributed hydrological models are commonly applied in engineering studies because they consider important spatial variations within a watershed, including differences in slope, land use, soil properties, and channel characteristics, while requiring less input data compared to fully distributed models(Devia et al., 2015). The semi-distributed technique is extensively used for both research and practical reasons because it depicts the main mechanisms of runoff generation for each sub-basin level and enhances the simulation of runoff generation in relation to the period of generation.

2.2 Hydrological Processes in Rainfall–Runoff Modeling

The fundamental foundation on which rainfall runoff modeling is based is essentially underpinned by the fundamental hydrological processes, which form the basis on which the simulation of the watershed's response to rainfall can be effectively addressed. These processes are essentially fundamental in underpinning the rainfall runoff processes through the development of a hydrological pathway. The watershed's response to rainfall can be addressed in terms of climatic inputs and other hydrological characteristics. In order to replicate the rainfall-runoff process and analyze the behavior of runoff under various hydrological conditions, hydrological models are created that reflect the various hydrological routes(Beven 2012).

When rainfall reaches the ground, a portion is intercepted by vegetation and returns to the atmosphere through evaporation before it can contribute to runoff. The remaining rainfall either infiltrates into the soil or becomes part of the overland flow that contributes to surface runoff. The rainfall infiltration and overland runoff essentially depend on the rainfall intensity-soil infiltration capacity relationship. Runoff will be hortonian in conditions when rain-fall intensity exceeds the rate at which it can infiltrate into the ground, saturation excess runoff occurs when the soil profile is saturated to its full capacity and will not be able to infiltrate further rain-fall(Chow et al. 1988). The texture, antecedent moisture, vegetation, and land management techniques that regulate the quantity of rainfall contributing to surface runoff all have an impact on soils, which are crucial for infiltration (Dingman 2015).

Evapotranspiration is identified as a key water loss phenomenon in the hydrological cycle and accounts for significant losses of water available for stream flow. One method of water loss from surfaces (soils, water bodies, and plants) is evapotranspiration. This phenomenon is usually regulated by environmental conditions. This process results in great loss of precipitation in the tropical and semi-humid areas, which affects the surface runoff yield. Therefore, this process is usually considered as an input or through soil moisture accounting in hydrological models to ensure water balance in a watershed (Allen et al. 1998).

The resulting runoff generated within a catchment enters the channel via a number of flow paths. Surface runoff causes a swift hydrological response and adds to peak flow, whereas subsurface flow and groundwater flow add to base flow during dry spells. Catchment features including slope, drainage density, geometry, and land cover enormously effect on the rate and volume of these

components. These factors also influence the travel time of water from the catchment to the outlet, thereby affecting the shape of the resulting hydrograph(Pechlivanidis et al., 2011).

Loss methods, transform functions, baseflow representation, and channel routing are key components of semi-distributed hydrological models such as HEC-HMS, which are used to simulate the rainfall–runoff process(Feldman 2000).

2.3 Rainfall–Runoff Relationship

Rainfall and runoff are hydrologically related; this means rainfall can be converted to runoff and flow through a watershed's drainage system. The process is affected by both meteorological and catchment factors. Not all rain is converted to runoff since some is lost to interception, infiltration, and evapotranspiration. The concept is essential for hydrological modeling since the amount of rain that is effective in converting to runoff will determine the volume of flow that will be simulated by a hydrological model(Tamer et al. 2025).

Effective rainfall must be estimated using loss abstraction methods prior to hydrological modeling. One of the widely used techniques for estimating rainfall excess is the Soil Conservation Service Curve Number (SCS-CN) method and this approach determines runoff based on factors such as soil characteristics, land use, and antecedent moisture conditions. Owing to its simple application and minimal data requirements, it is extensively utilized in rainfall–runoff prediction studies (Khattab et al., 2025). For physically based infiltration estimation, the Green Ampt model represents the infiltration process using soil hydraulic parameters and has been shown to effectively simulate infiltration dynamics under rainfall conditions, closely relating to Richards' equation solutions (Nie et al.,2017).

The effective rainfall distribution is the one used in watershed for rainfall to become run-off. By understanding this distribution, can simulate accurately the shape and characteristics of the hydrograph generated from runoff within a watershed. The link between rainfall and stream flow is frequently shown using methods like unit hydrographs and kinematic wave approaches in a variety of rainfall-runoff modeling methodologies. The procedures reflect that storage in catchment and channels influence the Hydrological response of watershed to rain fall (Khadka et al., 2018). Some research has showed that distribution and amount of rainfall, slope, drainage density and other characteristics of watershed highly affect watershed response to storm. For accurate flood forecasts and efficient use of water resources, these elements are crucial. Thus, it is essential to comprehend the link between rainfall and runoff for hydrological analysis and modeling applications.

2.4 Hydrological Models for Rainfall–Runoff Simulation

Hydrological models are applied commonly for simulating the response of a watershed to rainfall and other associated hydro-meteorological inputs. These models provide quantitative information on surface runoff, river discharge, and flood peaks(Beven 2012). Lumped, semi-distributed, and fully distributed hydrological models differ from one another in terms of their spatial features. Although lumped models are simpler to deal with, they may not accurately reflect local features since they treat the watershed as a single unit(Chathuranika et al. 2022). Fully distributed models need a lot of input data, but they allow for the representation of geographical differences within the catchment by dividing a watershed into many grid cells.

In order to simulate geographical variations in soils, land use patterns, and climate regimes, semi-distributed hydrological models split a watershed into many sub-basins. At the same time, these models demand fewer data inputs compared to fully distributed hydrological models, thus making them very convenient for undertaking various hydrological studies. The widely used semi-distributed hydrological models HEC-HMS and the Soil and Water Assessment Tool have shown great promise in modeling watershed hydrological processes. They are useful instruments for rainfall–runoff analysis because they offer a trustworthy depiction of hydrological behavior within a watershed(Alemu et al. 2023).

The data accessibility, watershed characteristics, and the particular goals of the research all play a role in the choice of hydrological model. Semi-distributed conceptual models, such as HEC-HMS, are widely used to simulate rainfall-runoff processes because they may incorporate a variety of base flow, transformation, and rainfall loss techniques while maintaining ease of computing(Tassew et al. 2019).

The semi-distributed modeling technique, which integrates remote sensing and GIS for improved spatial analysis and parameter estimates, is supported by current research, nevertheless. Models such as SWAT and HEC-HMS are commonly used to examine the impact of land use change on run-off within the tropics and semi-arid zones. This reflects the model’s applicability, flexibility and portability(Odey and Cho 2025). If the data from rainfall and stream flow observations are used to calibrate these models, they can perform better. Put differently, hydrological models offer a framework for comprehending how watersheds react to specific climate and land use change scenarios. Selecting an appropriate model is always based on data requirements, model complexity,

computational requirements, and accuracy of simulation. Semi-distributed conceptual models like HEC-HMS are deemed suitable for watershed study (Tassew et al., 2019).

2.4.1 Types of Hydrological Models

Hydrological models are frequently categorized according to how they handle spatial variability. The models might be lumped, semi-distributed, or completely distributed. The watershed is treated as a homogenous unit in the lumped models. Though the idea is advantageous for ease of implementation, it does not take into consideration the heterogeneity of the watershed (Devia et al. 2015). In fully distributed models, watershed is discretized into grid cells to adequately represent hydrological processes (Abbott and Refsgaard 1996). These models still need more accurate data and more powerful computing to work well. Semi-distributed models strike a balance between the two approaches. They break the watershed into smaller sub-basins, which lets parameters vary across different areas but keeps the calculations simpler (Scharffenberg 2000).

Hydrological models can be categorized according to their spatial properties or approach. Empirical models use observed data, e.g., unit hydrographs, which are useful for ungauged basins. Conceptual models simulate watershed processes through conceptualizations of hydrological processes, while physically based models use detailed processes with catchment characteristics and hydrologic laws (Whitfield 2007). Semi-distributed conceptual models, e.g., HEC-HMS, are popular models that allow users to combine methods using loss, transform, and routing methods in flexible ways with moderate data requirements (Tassew et al. 2019).

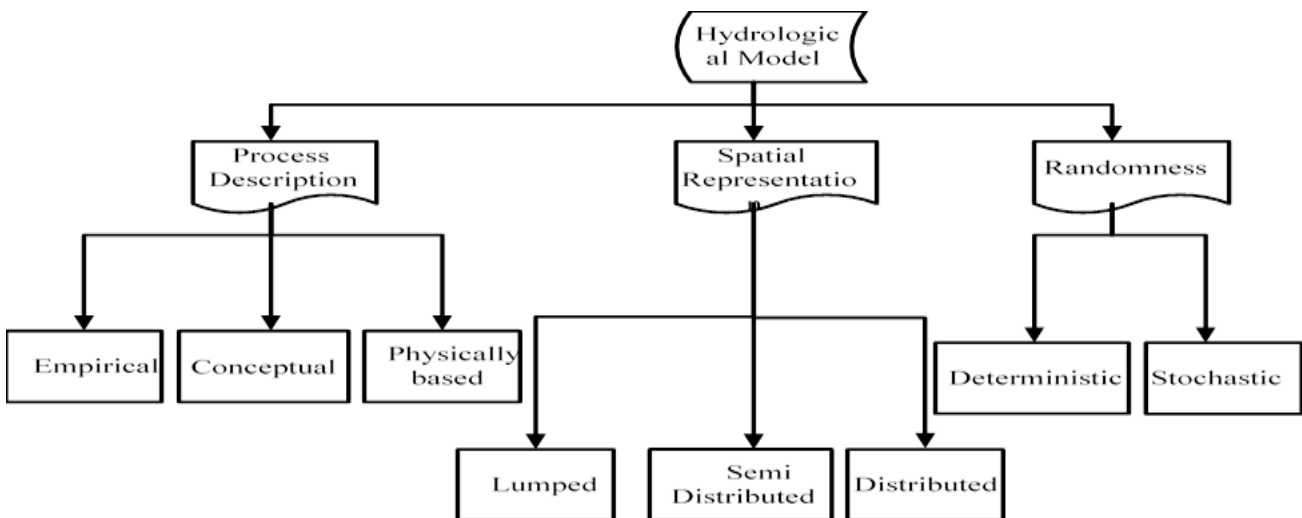


Figure 2.1: Hydrologic Model Classification

2.4.2 Selection Criteria for Hydrologic Models

Different hydrological models exist with various levels of complexity while requiring different data types and producing different results when operating with particular watershed scenarios. Among the widely applied hydrological models are HEC-HMS, SWAT, MIKE SHE, and TOPMODEL, which are frequently employed for rainfall–runoff and watershed simulations. The three methods in their study present positive and negative elements, which have been discussed in previous research (El-Bagoury and Gad 2024; Odey and Cho 2025).

HEC-HMS functions as a semi-distributed, physical process-based hydrological model, which proves useful for general rainfall–runoff modeling applications that require adaptation to various environments. The model can achieve the two loss methods, which is SCSCN, and Green Ampt, whereas the model can implement the runoff transformation, the separation of base flow and routing procedures. The software provides free access through its user-friendly design, supporting GIS functionality, making it a preferred hydrological modeling solution for areas with limited data availability (Scharffenberg 2000).

SWAT (The Soil and Water Assessment Tool) is a semi-distributed hydrological model designed to simulate long-term effects of water resources management, land use practices, hydrological model designed for use in long-term water management impacts, land use impacts, sediment and nutrient transport at the watershed scale. However, the information in it about effects of land-use practices on soil and water processes is highly useful; nonetheless, data used for this methodology is hard to obtain for basins lacking gauging stations (Zhang et al. 2009).

MIKE SHE is a physically based, distributed model that simulates hydrological processes in detail, capturing variations at a fine spatial scale. It can account for complex surface-subsurface interactions, snowmelt processes, and urban drainage. However, its large data and computational requirements make it less suitable for rapid studies (Devia et al., 2015).

TOPMODEL a hypothetical, semi-distributed hydrological model that emphasizes topographic influences on runoff processes. It is best suited for small to medium-sized catchments strongly affected by topography. Its inability to account for complex processes such as channel routing and heterogeneous land use makes it less suitable for large catchments (Odey and Cho 2025).

Therefore, HEC-HMS is a balanced option for the research study since it requires moderate data; It is applicable to a range of watersheds and can be integrated with GIS tools to assist in estimating model parameters. From the comparison of the models, HEC-HMS is obviously the best option for the research project. The SWAT and MIKE SHE models have detailed representations of hydrological processes but are less suitable for the study due to their data and computational requirements.

Several important factors were responsible for selecting the HEC-HMS model to carry out the analysis in this study.

- The model is freely available online and in the public domain.
- This model is physically based and simulates several hydrological components using easily available data.
- It can be utilized to assess the global impacts of land cover and land-use changes.
- The model operates with ArcGIS, facilitating efficient management of spatial data.
- It can be seamlessly combined with tools for sensitivity analysis, assessment of uncertainty and calibration.

2.5 Overview of the HEC-HMS Model

The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) is a physically based, semi-distributed model that was developed by U.S. Army Corps of Engineers. It is designed to simulate rainfall-runoff transformations from small catchments to river basins (Tassew et al., 2019). It can simulate of main hydrologic processes, which include rainfall losses, runoff production, base flow addition, and channel routing. The flexibility of this modeling system lies in its ability to choose from different methods in simulating each process, depending on the data and objectives (USCAE 2000).

HEC-HMS has two operational modes: event-driven mode and continuous mode. The model is therefore suitable for simulating flood forecasting, water resource planning, hydropower studies, and impact studies of climate change (Abushandi and Merkel 2011). The event-driven mode of operation is particularly useful in simulating short-term storm events, whereas the continuous mode of operation is useful in simulating long-term hydrologic responses to changing climate conditions (Yu and Zhang 2023). Because of the model is adaptability, simplicity, and relatively minimal data needs, which suitable for many hydrological studies, it has been widely used across the world.

2.5.1 ArcGIS and Arc-Hydro Tools

The Spatial input data for hydrological analysis are prepared using ArcGIS, which enables watershed delineation and the extraction of stream networks and key hydrological parameters such as flow direction, slope, and drainage area (USCAE 2000). The Arc-Hydro tools are used in conjunction with ArcGIS and are designed to automate the extraction of sub-basin and stream characteristics from DEM. These are vital tools in ensuring that accurate input files are generated for HEC-HMS simulations.

2.5.2 HEC-GeoHMS

HEC-GeoHMS is an extension of ArcGIS that facilitates the extraction and conversion of watershed spatial characteristics into parameters compatible with HEC-HMS for hydrological modeling applications (Fleming and Doan, 2013). The model utilizes DEM, land use data, and soils maps to calculate the parameters, such as curve numbers, time of concentration, and basin lag.

2.5.3 HEC-HMS Model Setup

The setup of the HEC-HMS model involves choosing meteorological inputs, configuring watershed model, and determining the control rules to guide the simulation. In estimating loss estimation, users can select any model like SCS-CN or Green-Ampt. The runoff transformation process usually employs unit hydrographs like Clark or SCS-UH. The model of base flow is usually exponential or linear recession curves. The routing of channels in HEC-HMS is usually Muskingum or kinematic wave routing, depending upon the purpose of the model (Tassew et al., 2019). This model makes it possible to simulate rainfall-runoff processes effectively across different catchment conditions.

2.5.4 Integration with GIS

Hydrological parameters may be examined with more geographical detail and watershed behavior can be more clearly seen when the HEC-HMS model is combined with GIS technology. The model also makes it possible to evaluate different scenarios, such as how runoff generation within a watershed is affected by changes in land use and climatic variability (El-Bagoury and Gad 2024). The Combination of HEC-HMS with GIS simplifies the process of handling data, ensures consistency in handling data, and accelerates the process of parameter extraction.

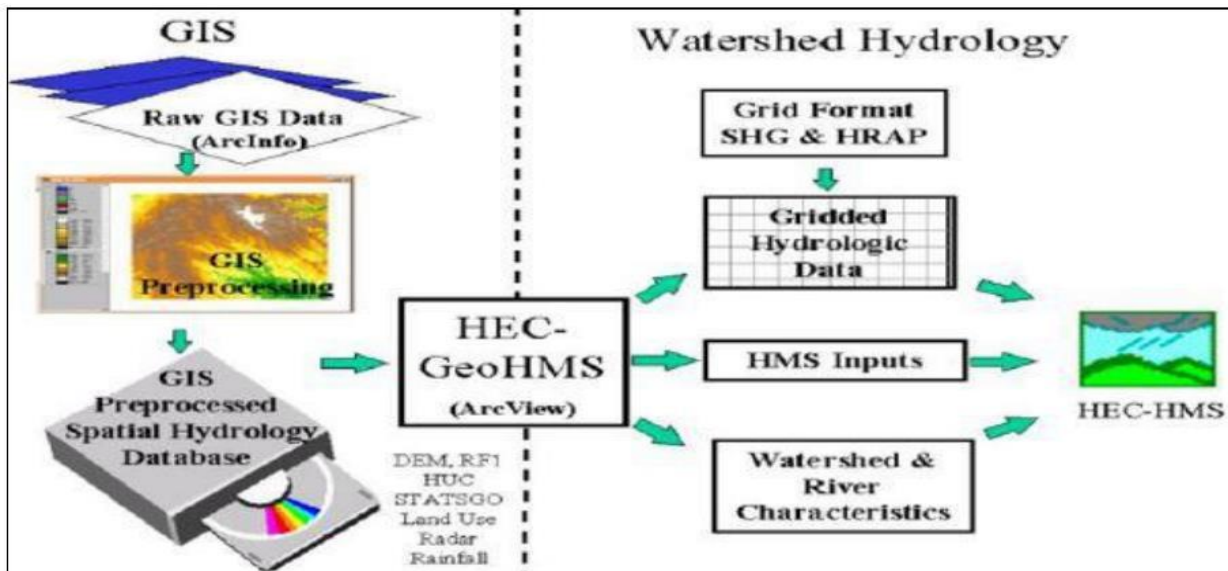


Figure 2. 2: Conceptual representation A conceptual illustration of how GIS, HEC-GeoHMS, and HEC-HMS are integrated in hydrological modeling applications(Fleming, M. & Doan, K. 2013).

2.6 HEC-HMS Model Setup

The Hydrologic Engineering Center Hydrologic Modeling System (HEC HMS) is a hydrological model that is commonly used to simulate rainfall runoff processes in watershed analysis(Choudhari et al., 2014). This model has often been used for simulating stream flow in different climatic conditions ranging from humid, tropical, sub-tropical, and arid climates for analyzing stream flow(Abushandi and Merkel 2011). In addition, the model is commonly used to evaluate how climate variability and climate change affect streamflow in watershed systems(Joo et al., 2014).

How accurately the HEC-HMS model may work varies from storm event to storm event. Using the same physical parameter values for different storm events can influence the simulation results, since these parameters may not remain constant under varying hydrological conditions(Abushandi and Merkel 2011).

The HEC-HMS system includes several components for hydrological analysis, such as rainfall–runoff simulation, open channel flow routing, loss estimation, and runoff transformation, along with parameter estimation tools. To generate the final output results, the HEC-HMS simulation procedure combines the basin model, meteorological data, control parameters, and run choices(Choudhari et al., 2014).

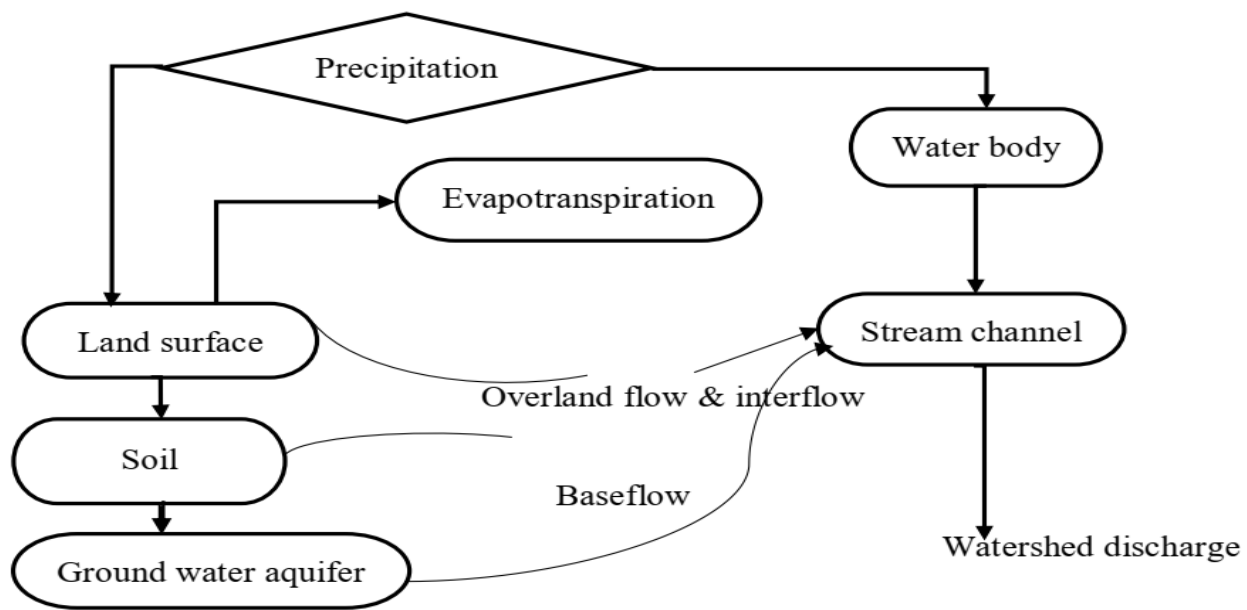


Figure2.3: HEC HMS representation of runoff process(Ayenew, Y. 2016).

2.7 Flood Forecasting

The natural process of water overflowing and flooding dry ground is known as flooding. Floods are widely recognized as one of the most common and costly natural disasters worldwide. Natural disasters such as floods have both an economic cost and a loss of life cost. Floods result in economic losses and loss of life. The floods also affect the socio-economic activities in the world (Pathak et al. 2017).

Flood forecasting can be defined as a methodological approach for predicting floods by utilizing the available river basin data for determining the intensity, time, and duration of floods. Statistical properties of the long term annual maximum stream flow records such as average value, standard deviation, skewness are commonly analysed in hydrology by using flood frequency analysis (Subramanya 2009).

Different probability distribution functions are applied in flood frequency analysis for selecting a most suitable model for predicting extreme flood events. Some of these probability distributions are: Generalized Pareto, Gumbel Maximum, Normal, and Log-Pearson Type III distributions (Chow et al., 1988; Subramanya 2009).

Rainfall is considered a primary influencing factor in controlling runoff generation and flood events across a watershed. The temporal and spatial distribution of rainfall plays a significant role in controlling the hydrological cycle in a basin, which in turn controls flood events in a basin.

The HEC-HMS model and probability distribution functions were used in this study's flood frequency analysis. The Ethiopian Roads Authority Drainage Design Manual for Region RR-A3, which offers rainfall and hydrological data for flood estimation in Ethiopia, was the source of the hydrological data used in the research(ERA 2013).

2.8 Review of Previous Studies

A semi-distributed, physically based modeling system designed to simulate rainfall-runoff dynamics across several watersheds is called the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS). According to (Xu, C.Y. 2002), the performance of HEC-HMS model is closely related to the choice of loss methods, runoff transformation methods and base flow separation method. (Padala Raja Shekar 2021) The Garang Watershed in Indonesia was a successful application of the HEC-HMS hydrologic model. In this paper exponential recession method was used for baseflow separation, SCS-UH method for rainfall-runoff transformation, SCS-CN method for losses and Lag routing method for simulating rainfall-runoff process.

Results showed accuracy of the HEC-HMS model in rainfall-runoff simulation. In Sri Lanka HEC-HMS model to the Kalu Ganga river basin (H.K. Nandalala, U.R Ratnayake 2010) used and said that simulation using Clark's transformation with Muskingum routing approach simulated well the hydrological events and found the HEC-HMS models suitability for watershed hydrology modeling. In the context of Malaysia, (Jabbar, et al. 2021) implemented HEC-HMS for the Cameron Highlands basin and found that the use of SCS-CN for losses, SCS-UH for rainfall–runoff transformation, and Muskingum routing provided accurate simulations of hydrological processes in tropical highland environments.

The HEC-HMS integrated with GIS and remote sensing data, (Patel.2018) applied to Tapi River basin, India accurately predicted flood events which are directly relevant for disaster management in South Asia. In USA, there is also a number of studies applying HEC-HMS model for simulation of severe rainfall for urban storm water runoff management, particularly in Texas(Fang et al. 2007). HEC-HMS was used for snowmelt runoff simulation in Alpine rivers in Europe and it indicated a strong dependence on the site-specific model calibration as a result of different climate and geographic conditions(Griessinger et al. 2016).

In Ethiopia, there is an increasing trend in the application of HEC-HMS in recent years, mainly because of its free use and GIS capability. For example, in Gilgel Abay watershed demonstrated, there was good agreement between observed and simulated discharges between SCS-CN loss method combined with Muskingum routing and applicable in highlands watersheds(Tassew et al. 2019). Similarly, in the Gilgel Gibe watershed, continuous simulation showed high performance of the model in estimating daily discharge, thus making it applicable in water resources planning (Fanta et al. 2021).

In the Awash River watershed, hydrological modeling was performed using HEC-HMS and shown to be applicable in analyzing hydrological response under different climatic conditions (Belay et al. 2022). Likewise, in the Omo-Gibe watershed, flood prediction was improved using this model, which was shown to be applicable in estimating peak discharges in ungauged watersheds (Woldegebrael et al. 2022).

Despite its extensive application in different parts of Ethiopia, most of the applications have focused on large and well-gauged watersheds. Moreover, few applications have focused on small and medium-scale watersheds. The amount of information is limited on rainfall-runoff model of Gololcha Watershed which is a sub basin of the Wabe Shebelle River basin.

As it is evident that the result from rainfall-runoff model plays an important role in watershed management, in design of hydraulic structure and flood estimation, there is thus a tremendous deficiency in hydrologic data base. Thus, by running the HEC-HMS model on the Gololcha Watershed, this work aims to close the current gap.

2.9 Research Gaps

Hydrological rainfall-runoff models have been successfully used to represent stream flow in river basins all over the world, and some knowledge gaps exist in this regard in Ethiopia regarding study area and methodology. Many previous researches on hydrology of Ethiopia were concentrated on large river basins of Upper Blue Nile and Omo Gibe river mainly due to the availability of data needed for calibration of model easily. The model, HEC-HMS was found to be capable of simulating the runoff process under varying hydro climatic regimes(Fanta et al., 2021; Tassew et al., 2019). However, small to medium-sized watersheds, particularly in the Wabe Shebelle River Basin, have not been given much attention with regard to rainfall-runoff model development.

For instance, many of the earlier works have concentrated on rough runoff estimates without the use of geospatial techniques for the characterization of watersheds in an integrated manner. GIS-based parameterization for the derivation of spatially distributed hydrological inputs has not been appropriately used in the Gololcha watershed. Watershed behavior is very sensitive to spatial variation in landuse, soil, slope, drainage, therefore omitting this variable can create uncertainties in the prediction of runoff and make the results meaningless(El-Bagoury and Gad 2024).

Furthermore, the literature on hydrological modeling in Ethiopia has largely focused on the application of models and the validation of models, with little emphasis on event-based rainfall-runoff modeling for the estimation of flood in the region. The problem of acquiring hydro-meteorological data and its impact on the parameterization, calibration, and validation of models has not been appropriately addressed in the Gololcha watershed, in the Wabe Shebelle Basin region of Ethiopia. This represents a significant gap in understanding hydrologic processes.

As of the present, no investigation employing the HEC-HMS model for the rainfall-runoff simulation has been conducted in the Gololcha Watershed. This inhibits access to reliable design discharges, flood estimates, and water resources planning information. The goal of this study are met by using GIS and HEC-HMS modeling tools to extract information from the watershed, simulate the rainfall-runoff processes, and understands how the watershed responds hydrological using existing hydro-meteorological information. The Gololcha Watershed, which is a part of the Wabe Shebelle River Basin, is expected to benefit from the investigation's findings in terms of flood estimation, hydraulic structure design, and efficient water resources management.

CHAPTER 3

MATERIALS AND METHODS

3.1 Description of study area

The Gololcha Watershed is located within the Wabe Shebelle River Basin in Ethiopia, at approximate coordinates of 7.23° latitude and 40.38° longitude. Covering an area of 7,163 km², the watershed is an important sub-basin of the Wabe Shebelle system. The Gololcha River, a right-bank tributary of the Wabe Shebelle River, flows through the semi-arid western part of the basin(Awass 2009). The river originates from highland plateaus located east of Gasera town, at elevations exceeding 2,678 meters above sea level. From its source, the Gololcha River flows eastward, receiving approximately 1,100 mm of precipitation annually, and descends gradually through the Gololcha area until it reaches the wide plains of Sawena Woreda, around 1,500 meters above sea level. This journey from the highlands to the lower plains reflects significant changes in elevation and terrain, which influence the river's flow characteristics, runoff generation, and overall hydrological behavior within the watershed. Figure 3.1 shows the location of the Gololcha Watershed within the Wabe Shebelle River Basin in Ethiopia.

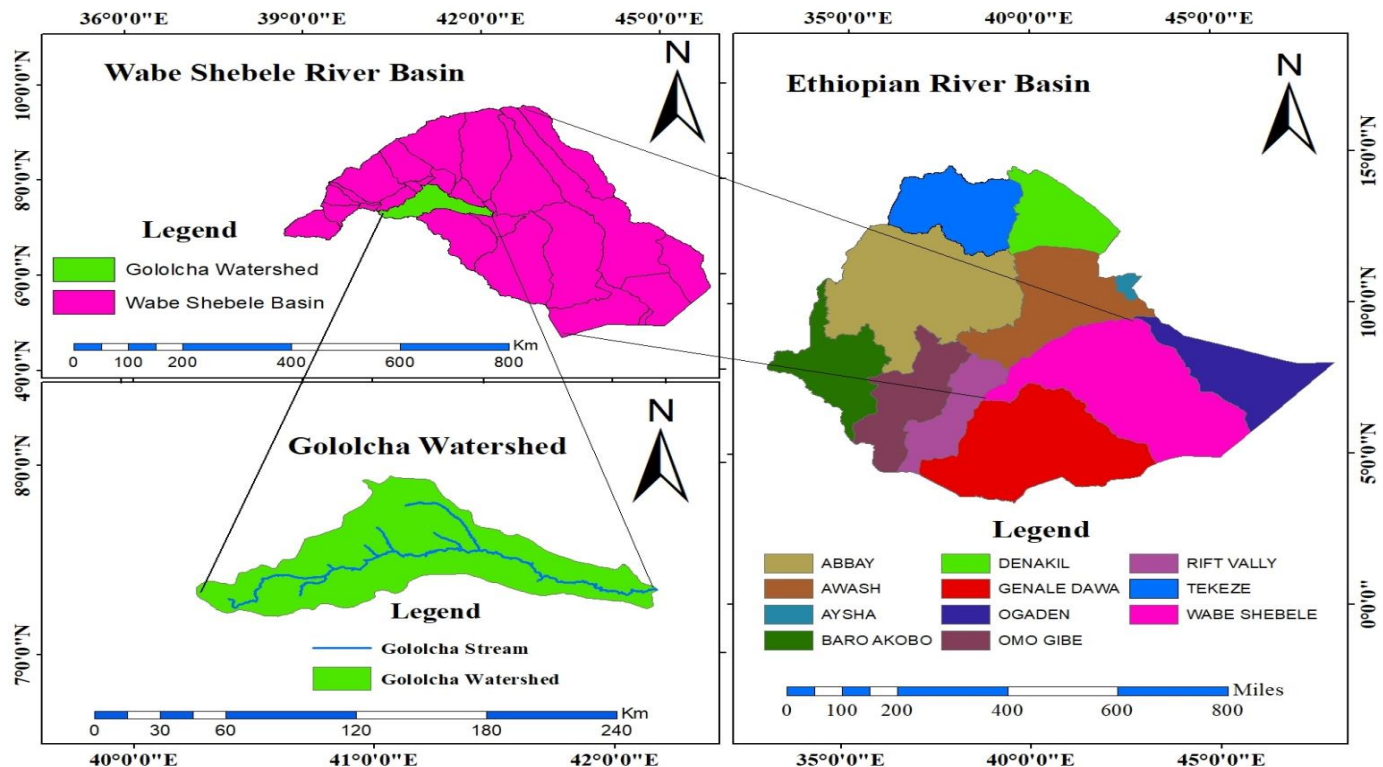


Figure3.1: Map of Study Area (Gololcha Watershed)

3.1.1 Rainfall Characteristics

Gololcha Watershed is like other places in Ethiopia when it comes to rain. It has two rainy seasons. The first one is called the Belg season. This happens from March to May. At this time it starts to rain more and it usually rains the most in April and May. The Gololcha Watershed gets an amount of rain throughout the Belg season. This is significant for the Gololcha Watershed because it helps get agriculture started and makes the soil moist again. The Belg season is a deal, for the Gololcha Watershed.

Kiremt season, which runs from June to September, is the main rainy season. In this season, it rains very intensively. July and August receive the heaviest rain. Most of the rain occurs in the watershed during the Kiremt season due to the northward movement of the ITCZ. As the ITCZ moves northward, strong hydrologic responses occur in the watershed, including increased surface runoff resulting from the high intensities. Hydrologic responses include increased surface runoff due to heavy rainfall.

The other months outside the Belg and Kiremt seasons are dominated by dry months, and this implies that rainfall in the watershed is not consistent throughout a year. The Bega season is from October to February. It is very dry with not much water available. The amount of rain that falls in this area is different in places. For example Jara station gets 983.1 mm of rain every year while Gololcha station gets around 1,066.5 mm. This demonstrates that the amount of rain that falls in the Bega watershed is not the same. The Bega watershed has hills and valleys that affect the weather. This is why some places get more rain than others. The rain that falls in the Gololcha catchment is very important for the Bega season. The Bega season needs rain to fill up the rivers and to help farmers grow crops. The Bega season also needs rain so that people, in the region have water.

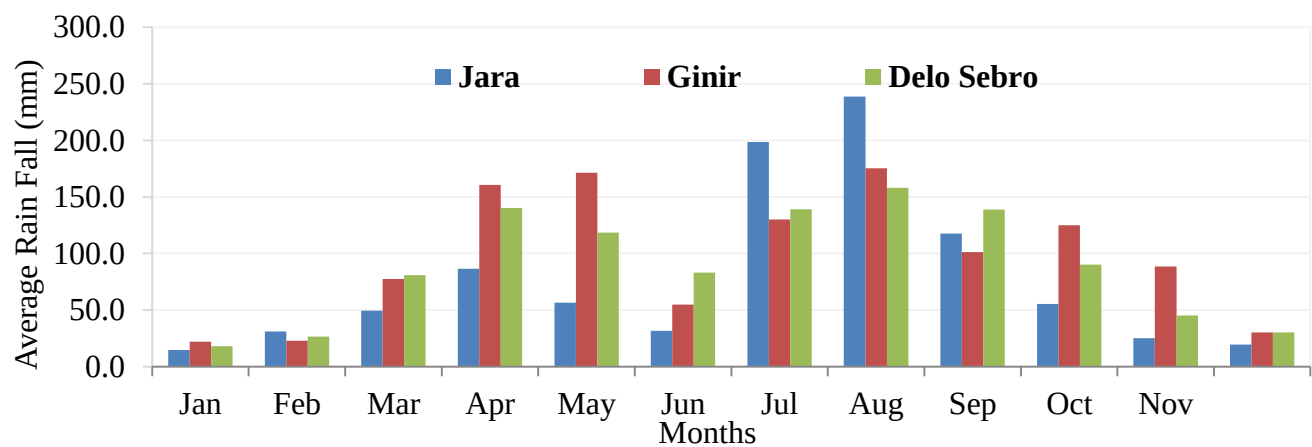


Figure3.2: Average monthly precipitation in Gololchaa Watershed.

3.1.2 The Gololcha Watershed Climate Features

The Gololcha watershed has a climate that is mostly defined by two seasons. The study area experiences two rainy seasons: the longer rainy season called Kiremt, usually from July to November, and the shorter rainy season known as Belg. The time span from December to March is considered as dry. On the other hand, parts of the Gololcha Watershed receive rain during the Belg season, which lasts from mid-March to mid-June. The climate of the study area shows variation at different heights. The highlands tend to be cooler and wetter than the lowlands. To develop the region responsibly, it is important to understand its climate so that the environment is preserved and resources are used carefully. Understanding the climate of the Gololcha watershed is important for responsible management of its natural resources.

3.2 Data Sources and Modeling Tools

3.2.1 The type and source of data

This study was purely based on secondary data only. The researcher did not collect any primary data through measurement or surveys from the field. The data used was from reliable sources of governmental agencies and the internet. In the analysis of the Gololcha watershed; various categories of spatial and hydro-meteorological information were used. The datasets which were utilized in this research were obtained from various respected organizations and publications. Topographical information as a Digital Elevation Model and soils information, flow of stream and land use/land cover were mainly obtained from the ministry of water and energy. The data of Rainfall was from Ethiopian National Meteorological Agency. Since the research was done with recorded and published data and so relying on secondary information source for data, consistency and reliability of the research was assured.

Table 3.1: Type of Data and their Sources

Data types	Data sources	Scale/period
DEM	Website: https://vertex.daac.asf.alaska.edu/ , 12.5mx12.5m	12.5mx12.5m
Soil data	Ministry of Water, and Energy (MoWE)	2020
LULC	Ministry of Water, and Energy (MoWE)	2020
Rainfall Data	National Meteorological Service Agency (NMSA)	1990-2020
Stream Flow	Ministry of Water, and Energy (MoWE)	2000-2020

3.2.1.1 Metrological Data

Rainfall records were used as direct hydrological inputs into HEC-HMS models to establish the rainfall-runoff mechanisms within Gololcha watershed. Records of rainfall were required in order to model the rainfall runoff response of the watershed, and thus the calculation of runoff generation. The period of records was 2000-2020, and the records were derived from Ethiopian National Meteorological service agency. The three stations namely Delo Sebro, Ginir and Jara were chosen since they are relatively closer to the Gololcha watershed and applicable for study area. The rainfall stations can be shown in and near the study area by the Figure 3.3.

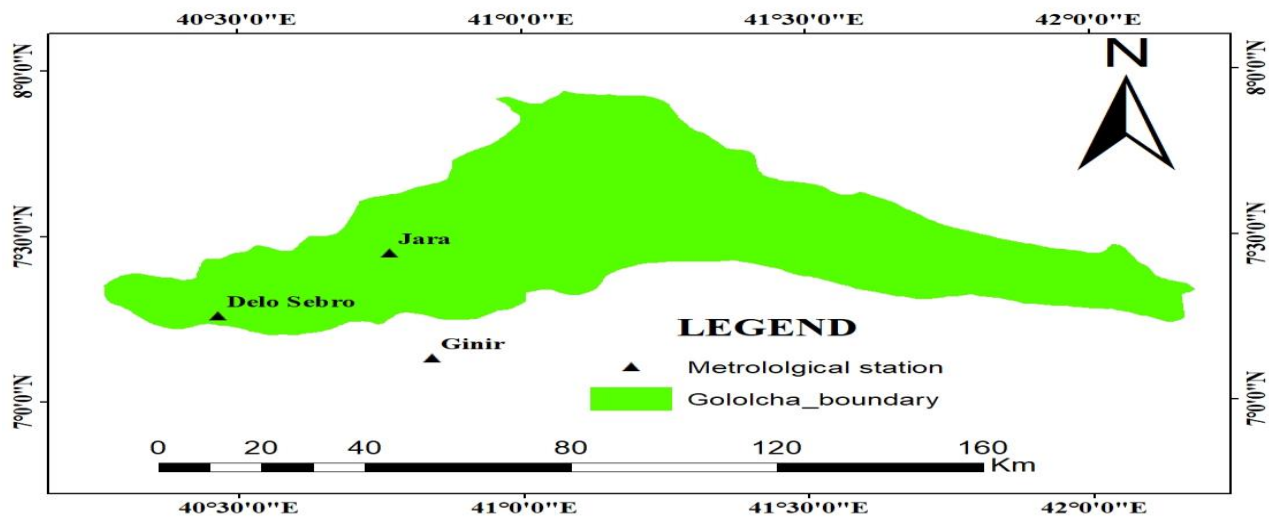


Figure3. 3: Position of meteorological stations of Gololcha watershed.

Table 3.2: Meteorological gauge Stations, Elevation, position of data

S.NO	Name	Elevation	Latitude	Longitude
1	Ginir	1941	7° 8' 00"	40° 48' 25"
2	Delo Sebro	2171	7° 15' 41"	40°27'52"
3	Jara	1960	7° 27' 0"	40° 46' 0.1"

3.2.1.2 Hydrological Data

Hydrological data was a crucial element in the analysis of Gololcha watershed runoff characteristics. In this study, daily discharge data was obtained from Gololcha river gauging station which lies at a latitude of 71955 N and longitude of 415830 E. The Ethiopian Ministry of Water and Energy provided the stream flow records utilized in the study for the years 2000–2020. Using these data, the HEC-HMS model was calibrated and validated to determine the watershed hydrological response. Figure 3.4 shows location of the Gololcha River Gauging Station.

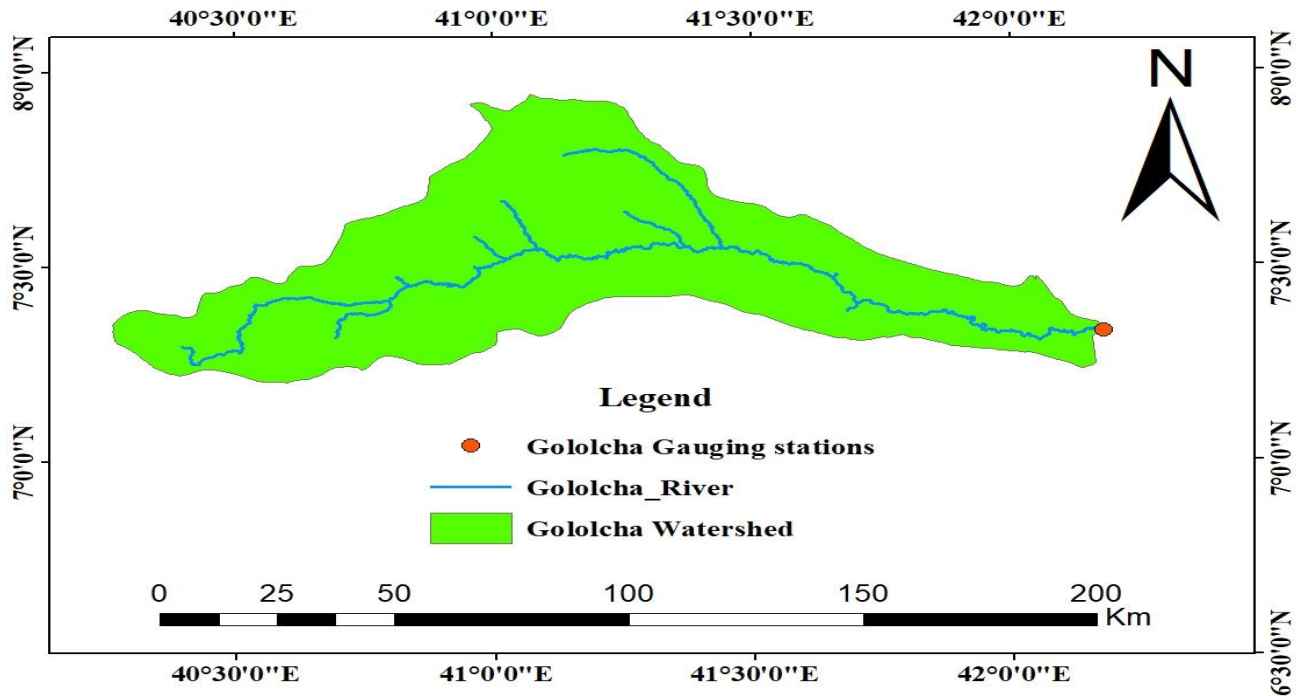


Figure 3.4 Gololcha stream flow gauging station

3.2.2 Software and Tools Used for Hydrological Modeling.

The hydrological model for simulating the rainfall-runoff processes and examining the watershed characteristics in the Gololcha region was developed using a collection of specialist software tools. These tools were effective for spatial analysis, hydrological modeling, statistical analysis, and data management during the entire project.

For geospatial analysis and the delineation of the watershed region, ArcGIS along with Arc Hydro Tools and HEC-GeoHMS was utilized. This group of tools was effective for extracting the basin parameters and preparing the required inputs for the hydrological model.

For handling the data during the hydro-meteorological inputs and also for data quality management, Rainbow was utilized. For statistical analysis using EasyFit for probability distribution identification during the flood frequency analysis, the tool was utilized. During the identification of data gaps and also for statistical analysis, XLSTAT and Microsoft Excel were utilized. For managing the reference data using the citation tool, Zotero was utilized.

Table3.3: Software applied for simulation of rainfall runoff.

No.	Software	Uses
1	ArcGIS 10.3.1	To generate a CN grid plan and study area
2	Arc Hydro tools	For train pre – processing
3	HEC – GeoHMS	For Background, basin model and watershed parameter preparation
4	HEC HMS 4.12	For Rainfall – Runoff Simulation, and flood frequency analysis for the different return period
5	Rainbow	To test the homogeneity of the data set
6	Excel and XLSTAT 19	For data preparation, adjustment, and providing data for the software.
8	Zotero	Used to insert bibliography and references
9	Easy fit test	To know the best – fit flood Probability distribution

3.3 Evaluation of Data Quality

3.3.1 Analysis of Hydro-Meteorological Data

3.3.1.1 Gap Filling in Meteorological and Stream flow Records

In hydrology, one of the problems that we encounter is the issue of missing data. Missing data is normally caused by factors such as broken measurements, changes in measurement points, or errors in recording or handling the data. In case these missing data points are not properly addressed, it could have an adverse effect on the precision of the analysis and reliability of the modeling results. Before conducting the analysis, the rainfall data obtained from the selected stations were carefully examined to ensure their continuity and consistency. During this process, missing data points were identified in the datasets of the three stations selected for the analysis.

These missing data points need to be handled suitably before the data is used for any rainfall-runoff modeling or any other hydrological analysis. To counter the missing data points, XLSTAT software, a statistical add-in specifically for Microsoft Excel, was used. XLSTAT is statistical software package consisting of a broad set of data analyzing, modeling and data processing tools. The program is commonly used for analysis of various types of datasets and to perform advanced statistical calculations. Functions that helps to identify the outliers, homogeneity test, trend detection, manage missing values according to the type of dataset are also included in XLSTAT.

For a quantitative dataset, XLSTAT gives various methods to deal with the missing observation such as deleting the missing values, imputation using mean, using nearest neighbor method. In this study nearest neighbor method has been employed for missing data imputation for both rainfall and stream flow data because this provides good estimation of missing values according to the nearest neighbors.

3.3.1.2 Consistency Analysis of Data

The problem of ensuring consistency in time series data is just as significant a contribution to reliable modeling results as the maintenance of data where there are gaps. The most significant problem facing hydrologists in this case is the estimation of missing precipitation data. This problem usually appears when there is non-uniformity in rainfall records at a specific station in a given time. Rainfall data recorded by different gauges within a watershed may not be exactly alike.

In a consistent set of data, the characteristics should not change with time, while inconsistency in the set of data results from changes in the set's characteristics. This can be ascertained graphically, where the trend line should be straight in a consistent set of data, indicating the need for corrections if the line is not straight. Inconsistencies in rainfall records may result from a number of influences. Consistency of rainfall records from the three stations was assessed using the double mass curve (DMC) method. This indicates that the stations' data consistency was quite good. Figure 3.4 illustrates that the cumulative rainfall at all locations is closely related to the average of all stations, implying a strong consistency and the individual plots for each of the stations are provided in Appendix 1.

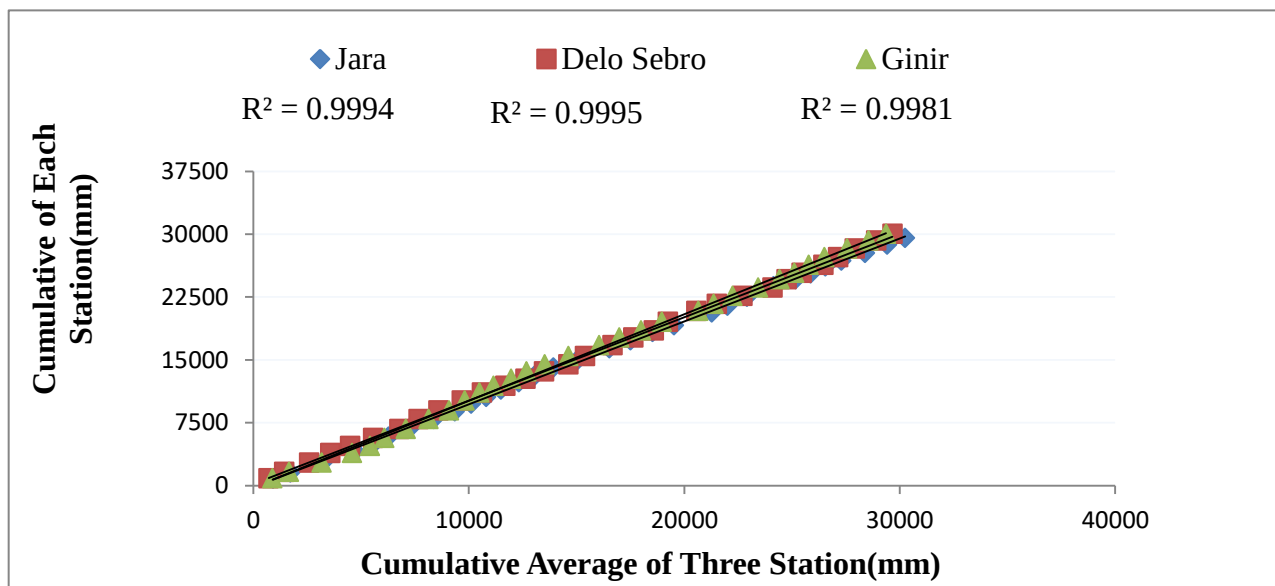


Figure3.4: Assessment of Rainfall Data Consistency Using Double Mass Curve

3.3.1.3 Assessment of Rainfall Data Homogeneity

The homogeneity of group stations must be examined in order to choose representative meteorological stations and fill in missing rainfall data. To identify data variability, the homogeneity test is necessary. Measurements made consistently using the same method, with the same equipment, in the same setting, at the same time, and in the same location were considered to be uniform. Several methods are available to test the homogeneity of rainfall data, and Rainbow software which measures cumulative deviation from the mean was chosen for the study.

Rainfall data are considered consistent or homogeneous, when the cumulative deviations remain small and the maximum deviation is close to zero. In order to test it on the current analysis the use of Rainbow software is considered.

The software would confirm that the precipitations records are homogenous and from the same statistical population, a necessary assumption for a consistent frequency analysis. The homogenous test could be expressed with the equation below:

$$S_k = \sum_{i=1}^k (Y_i - \bar{Y}) \dots \dots \dots 3.1$$

Where; $K = 1, 2 \dots n$, Y_i = time series precipitation data, $\bar{Y}$ = average of precipitation data, $\bar{Y}$ = cumulative deviation and K = number of years. Changes in the average are easily detected when plotting the SKs (also known as a residual mass curve). SK = i increases and decreases for a record, Y_i above normal and Y_i below normal, respectively.

The datasets will not pass the test for homogeneity at the 90%, 95% and/or 100% level if the cumulative deviation is above any of the parallel horizontal lines (reference) shown in the figure. This investigation was performed and the probability of rejecting the homogeneity of the dataset was obtained through using the homogeneity statistics menu. Figure 3.5 illustrate of yearly summary of the Ginir homogeneity assessment. Appendix-2 includes figure 2.1) includes the stations of other homogeneity test

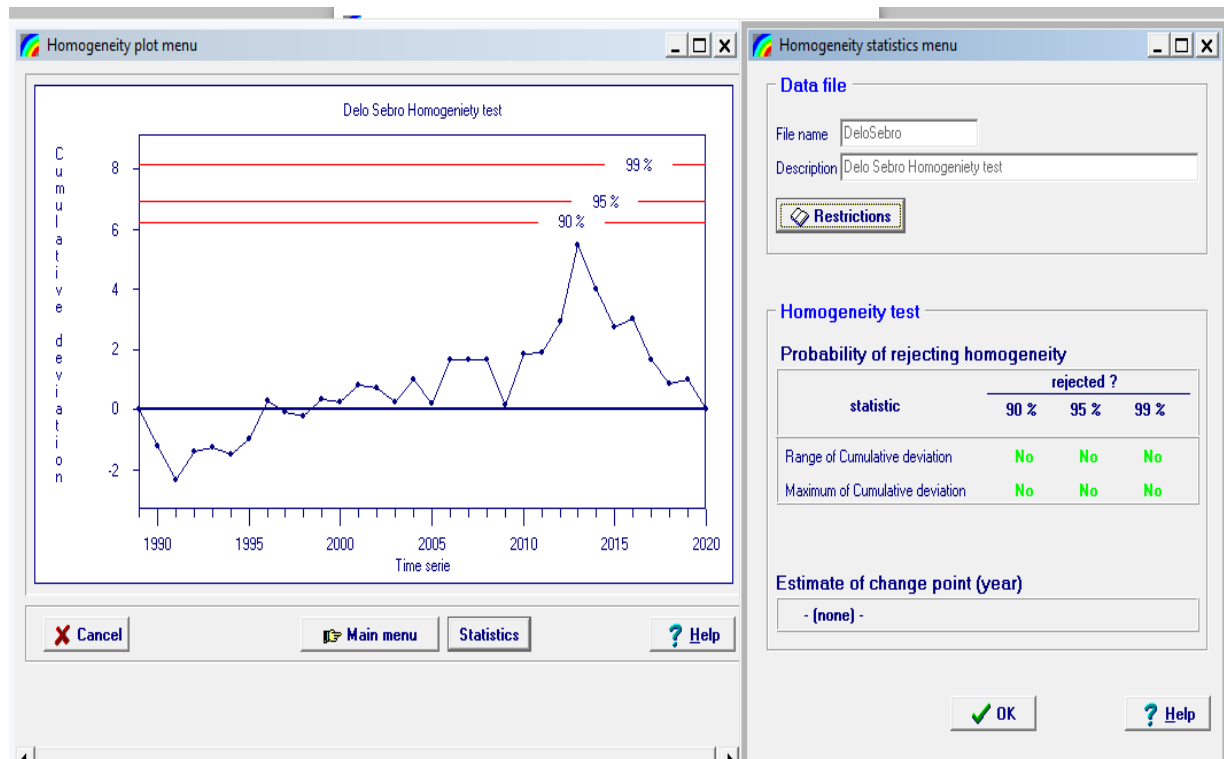


Figure3.5: Assessment of Rainfall Data Homogeneity at Delo Sebro Station

3.3.1.4 Estimation of Areal Rainfall from Point Measurements

Rainfall recorded at particular points represents the precipitation at a specific point, which may not accurately reflect the average rainfall over an entire watershed. Hydrological modeling, including rainfall–runoff simulation, requires areal rainfall, which is the spatially averaged precipitation over a watershed or sub-basin.

Converting point rainfall to areal rainfall is essential for hydrological analysis and runoff estimation. There are several different methods for interpolating from that single, local measurement to an average value for the whole watershed. The choice of the method of estimation of areal rainfall depends on the nature of the data, quality of data and required accuracy. Thiessen polygon method was employed in this study for determining areal average rainfall from the point data. Rainfall data from two points in the watershed and another two points outside the watershed were incorporated into the analysis to cover the entire spatial area. As a result, if there are many rainfall gauging stations close to and beyond the watershed's boundary, the Thiessen polygon approach is required (Legesse 2009).

To compute areal precipitation, use the Thiessen polygons method's equation:

$$P_{\text{Total}} = \frac{A_1}{A_{\text{total}}} * P_1 + \frac{A_2}{A_{\text{total}}} * P_2 + \dots + \frac{A_n}{A_{\text{total}}} * P_n \dots \dots \dots 3.2$$

Where: A_{total} = total area, $A_1, A_2 \dots \dots A_n$ = Area of each station, P = Precipitation, P_o = the sum of precipitation for five meteorological stations.

Applying Thiessen polygon approach, weight for the contribution of each rain station over a sub-basin was determined based on the area associated with its polygon. The time series of rainfall for each sub-basin was then generated by calculating the weighted sum of data from individual rain stations with the computed polygon weights. Using ArcGIS version 10.3.1, the influence area of each rainfall station was developed by drawing the perpendicular bisectors between the stations. Each rainfall station was weighted by its percentage cover which was derived from the polygon it enclosed. The method of Thiessen polygons was employed to determine the mean areal rainfall over the watershed. This method gives weight to each station on the basis of its area.

$$R_{\text{areal}} = \sum_{i=1}^n \frac{A_i R_i}{A_t} \dots \dots \dots 3.3$$

Where A_i is the area of each sub basin, R_{areal} is the areal average of rainfall, and R_i is the rainfall of each sub – basin

Thiessen polygon method is used to find the sub-basins influenced by each rainfall station and the weight gage of each rainfall station as shown in the Table 3.4 and Figure 3.6.

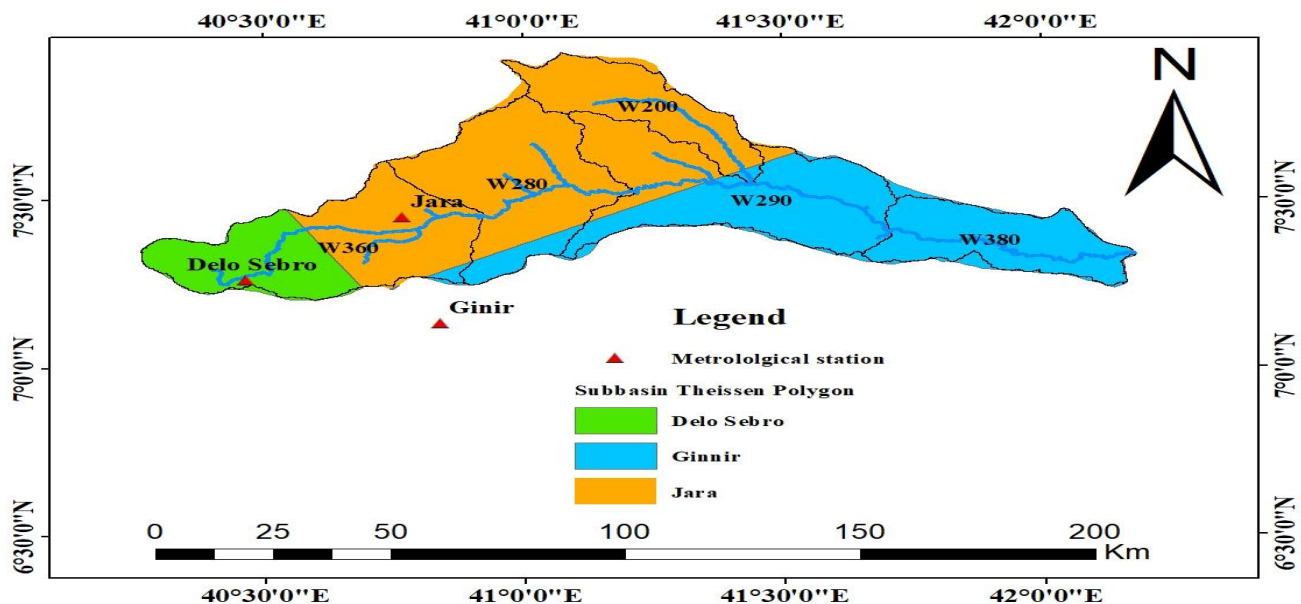


Figure3. 6: Thiessen Polygon Distribution for Sub-basins of the Gololcha Watershed.

Table3.4: Thiessen Polygon Weights for Rainfall Stations in the Gololcha Watershed

Sub basin name	Precipitation Stations	Total Area of Sub basi (Km2)	Area of met station in the basin in (km2)	Gauge Weight
W200	Jara	851.83	841.01	0.9873
	Ginir		10.82	0.0127
W280	Jara	1557.8	1467.45	0.942
	Ginir		90.35	0.058
W290	Jara	1788.3	1425.28	0.797
	Ginir		363.03	0.203
W360	Delo sebro	1753.3	788.985	0.45
	Ginir		73.64	0.042
	Jara		890.68	0.508
W380	Ginir	941.80	941.80	1

3.3.2 Spatial Data Analysis

3.3.2.1 Classification of Land Use-Land Cover (LULC)

Land Use and Land Cover (LULC) is a spatial data set describing different classifications of land use within the particular region. The maps are mostly produced through image classification, where data is often based on images obtained from the Ethiopian Ministry of Water and Energy (MoWE). LULC data plays a vital role in the use of hydrological models, especially considering the impact these maps have on the water cycle mechanisms, including evaporation, transpiration, rainfall interception, and runoff. In addition, LULC data is used to compute curve numbers to forecast the watershed behavior ensuing from rainfall events.

In the Gololcha watershed, the dominant LULC classes include the Open Shrub land, which covers 56.32% of the area, followed by the Open Grassland class, which covers 15.11%; the Closed Shrub land class covers 14.23%, while the Annual Cropland covers 10.17%. The Sparse Forest class covers 2.31%, while the remaining area is comprised of other minor classes, covering 1.86%. This is spatially represented in Figure 3.7 below for a clear understanding of the different classes in the in Gololcha watershed which is created by using Spatial Data of 2020 from Ethiopia Ministry of Water and Energy.

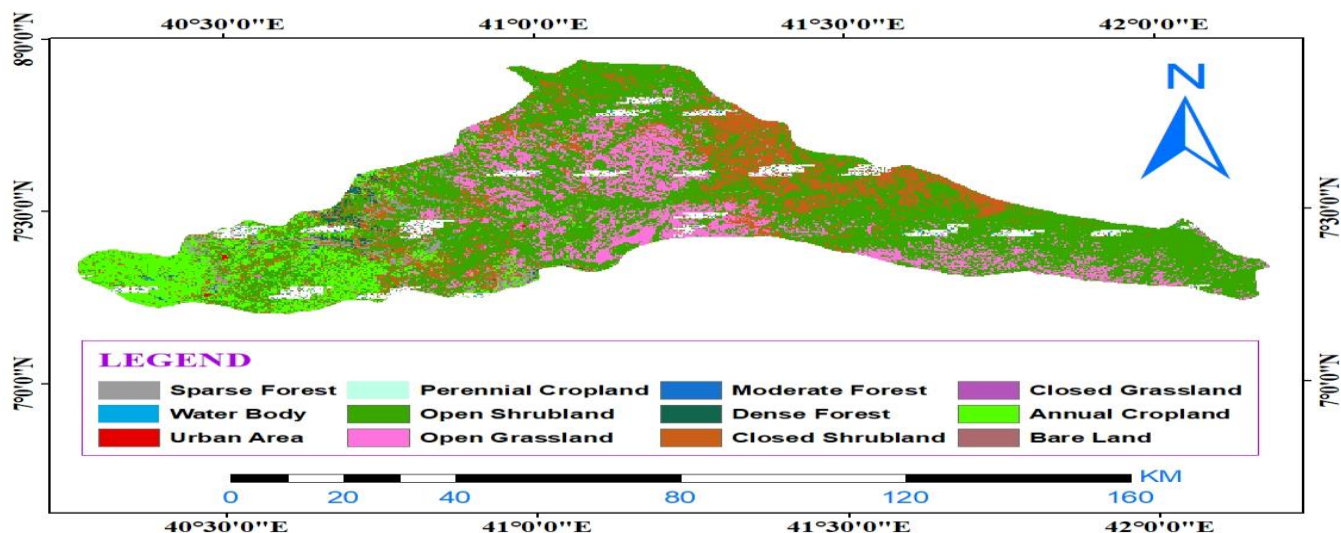


Figure3. 7: Gololcha Watershed Spatial Spreading of LULC.

Table3.5: Area and Percentage of LULC of the Gololcha Watershed

S. NO	Land use – land cover	LULC Area(km ²)	Covered (%)
1	Open Shrubland	3872	56.32
2	Open Grassland	1039	15.11
3	Closed Shrubland	978	14.23
4	Annual Cropland	699	10.17
5	Sparse Forest	159	2.31
6	other minor land cover	128	1.86

3.3.2.2 Soil type

Soil is essential factor in determining Curve Numbers (CN) for hydrological modeling. For the purpose of this work, soil data was retrieved from the Ethiopian Ministry of Water and Energy (MoWE). The Gololcha Watershed has seven main types of soils. The soils are mainly composed of Cambisols, which cover 51.17% of the area, followed by Vertisols, Leptisols, and Calcisols, which cover 18.87%, 14.67%, and 8.19%, respectively and the remaining 6.36 are covered by different soils.

Table 3.6: Distribution of Soil Types in the Gololcha Watershed.

S. No	Types of soils	Covered Area (%)
1	Cambisols	51.28
2	Vertisols	18.87
3	Leptisols	14.69
4	Calsisols	8.19
5	Arenosols,luvisols &fluvisols	6.96

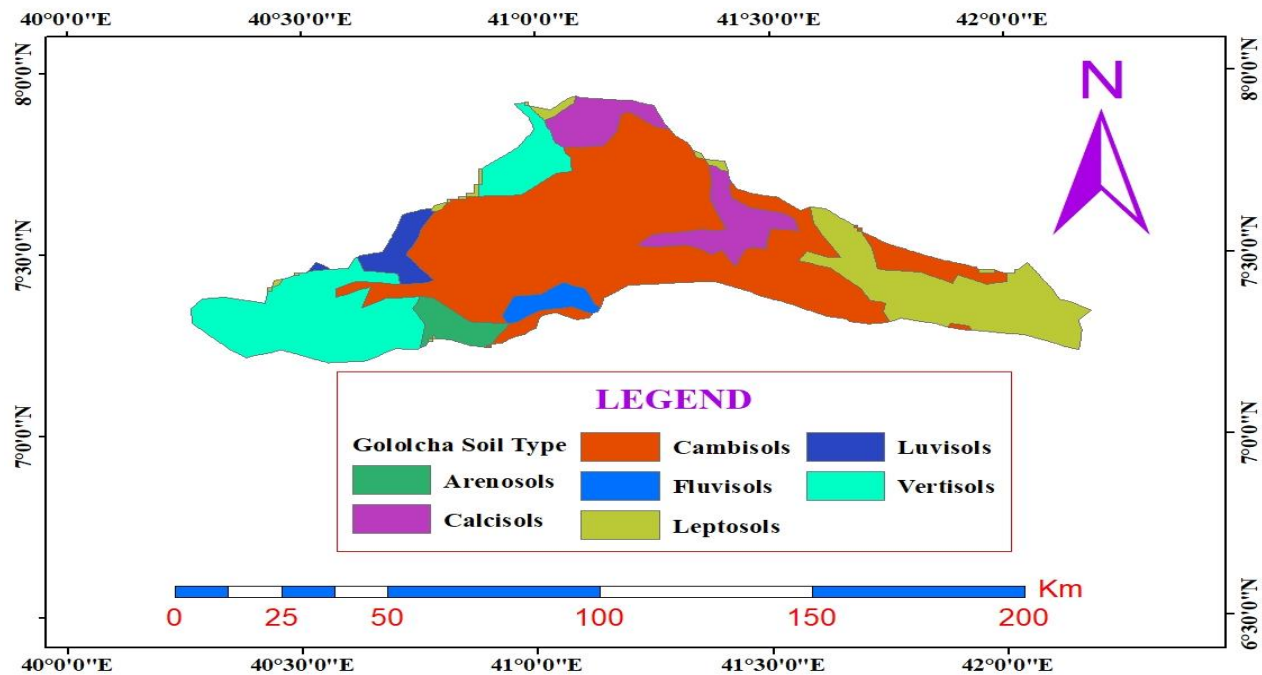


Figure 3.8: Gololcha Watershed major Soil Classes

3.4 Curve Number Generation

The parameter controlling computation of direct runoff for the SCS method is the Curve Number (CN) as outlined by the method of the U.S. Department of Agriculture. The CN value measures the runoff potential of a watershed in terms of precipitation amount versus runoff volume and is controlled predominantly by hydrological soil group, land use, land cover, and antecedent soil moisture condition. Tables are constructed by SCS which aid in predicting the CN value for a given land use, land cover, and soil group. Weighted CN values are used when the watershed is composed of multiple soil and land cover types.

The Curve Number (CN) may be manually obtained through tables, but Geographic Information System (GIS) technology is highly effective for increasing efficiency and accuracy. In the present study, the spatial data management was performed using ArcGIS software, along with HEC-GeoHMS. The technique adopted is displayed in the Fig.3.9. The technique begins with processing soil data, classification of soil data into hydrologic group, land use and land cover classification, combining processed data with filled DEM and generation of the CN table. Later soil data and land use polygons were overlaid. This process then leads to computation of weighted CN for the watershed.

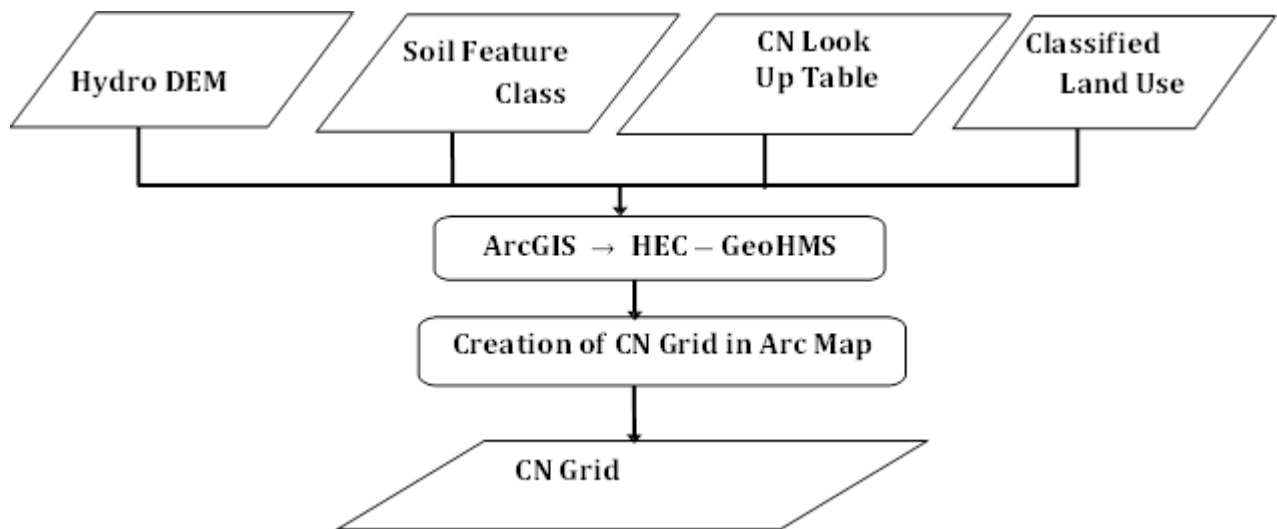


Figure3. 9 : Flowchart for CN Grid Development in ArcGIS

3.4.1 Land Use and Land Cover Data Processing

Accurate LULC data is very necessary to the creation of the CN lookup table since the real conditions of the land surface are highly determinant of the hydrological simulation. It is noted that the accuracy of the CN values is affected by the land use category; hence, careful preparation of the LULC data is considered to be a very important step when carrying out the simulation. The LULC raster data used in this research was of $12.5 \text{ m} \times 12.5 \text{ m}$ in the GCSWGS1984 coordinate system. For spatial data, it was reprojected to WGS1984UTMZone37N through 'Project' tool of ArcGIS, reclassified and re-projected in polygon through 'Raster to Polygon'.

3.4.2 Hydrologic Soil Group Classification

The borders were trimmed to the boundaries of the area under study after the soil layers were added. The soil data were reclassified into Hydrologic soil group which was required for Curve Number estimation. These groups classify the soils based on their infiltration capacity or potential to generate runoff under similar rainfalls and moisture levels. This classification represents a fundamental parameter for hydrological modeling.

Hydrological soil groups are a classification of soils according to their infiltration rates as well as their capacity to produce runoff. Soils can be classified into four different hydrological soil groups. These four hydrologic soil groups can be categorized as A, B, C, and D. The soils in the A group have the highest infiltration rate and the least potential for runoff, the soils in the B group have a moderate infiltration rate and a moderate potential for runoff, the soils in the C group have a low infiltration rate and a significant potential for runoff, and the soils in the D group have a very low infiltration rate and a significant potential for runoff.

Classification of soil into different hydrologic groups relies on a few soil characteristics such as texture, structure and drainage. Using the various attributes mentioned in the previous paragraph, a hydrological soil group can be allocated to a given soil type. Table 3.7 provides an overview of the hydrological soil group categorization for the soils in the research region. Additionally, the appendix displays the software's results that incorporate the complete dataset.

Table 3.7: Classification of Hydrologic Soil Groups by Type of Soil

NO	Group of Soils	Unit_name	Txt_USDA	HSG
1	Arenosols	Cambic Arenosols	Sand	A
2	Calcisols	Haplic Calcisols	Loam	B
3	Calcisols	Petric Calcisols	Sandy Clay Loam	C
4	Cambisols	Chromic Cambisols	Clay Loam	D
5	Cambisols	Eutric Cambisols	Loam	B
6	Fluvisols	Eutric Fluvisols	Loam	B
7	Leptosols	Lithic Leptosols	Clay Loam	D
8	Leptosols	Rendzic Leptosols	Loam	B
9	Luvisols	Chromic Luvisols	Sand clay loam	C
10	Vertisols	Eutric Vertisols	Clay(light)	D

3.4.3 Integration of LULC and Hydrologic Soil Group for CN

The Union tool in ArcGIS was used to connect the hydrologic soil group, land use, and land cover in order to compute the Curve Number. First LULC data was reclassified and then hydrologic soil groups was assigned to various soils and joined with LULC data, then both became a single spatial layer. The hydrologic soil group (A, B, C, D) along with the LULC class were found in the attribute table of this shape file. From this composite shape file Curve number values for watershed was calculated.

Table 3.8: Curve Number (CN) Values for Different LULC–HSG Combinations

No	Types of LU/LC	Hydrological Soil Groups(HSG)			
		A	B	C	D
1	Annual Cropland	67	78	85	89
2	Bare Land	77	86	91	94
3	Closed Grassland	39	61	74	80
4	Closed Shrub land	43	65	76	82
5	Dense Forest	30	55	70	77
6	Moderate Forest	36	60	73	79
7	Open Grassland	49	69	79	84
8	Open Shrub land	57	73	82	86
9	Perennial Cropland	59	74	83	87
11	Sparse Forest	43	65	76	82
12	Water Body	98	98	98	98
10	Urban Area	77	85	90	92

3.4.4 Creating CN Lookup Table

A curve number (CN) look-up table was developed to determine a suitable value for the CN over the various land use/land cover types and soil hydrologic soil groups for use in the rainfall runoff modeling process. Standard CN values from SCS-CN procedure overlaid with the land use/land cover types and hydrologic soil groups mapped over the study area. Each land use/land cover type was mapped to the appropriate hydrologic soil groups and a value for the CN for that combination was assigned on the basis of tables recommended by the SCS-CN. This was later translated into an input file that could be referred to by the model to associate the relevant CN number with different land uses and soil type.

Table 3.9: Curve Number (CN) Lookup Table

Table							
Export_Output							
OID	LUVALUE	DESCRIPTIO	A	B	C	D	
0	1	Annual Cropland	67	78	85	89	
1	2	Bare Land	77	86	91	94	
2	3	Closed Grassland	39	61	74	80	
3	4	Closed Shrubland	43	65	76	82	
4	5	Dense Forest	30	55	70	77	
5	6	Moderate Forest	36	60	73	79	
6	7	Open Grassland	49	69	79	84	
7	8	Open Shrubland	57	73	82	86	
8	9	Perennial Cropland	59	74	83	87	
9	11	Sparse Forest	43	65	76	82	
10	12	Water Body	98	98	98	98	
11	10	Urban Area	77	85	90	92	

In the concluding stage, the CN grid raster file and the HEC-GeoHMS parameter estimate tool were utilized to determine the curve number. The curve number may be found and the weighted curve number for the sub-watershed can be calculated using the parameter estimation tool. The calculated curve number was then appended to the attribute table of the sub-watershed.

The weighted curve number can potentially be determined using the following formula:

$$CN = \sum_{i=1}^n \frac{A_i C_i}{A} \dots \dots \dots 3.4$$

where : CN = weighted curve number, C_i = curve number for the i th polygon, A_i area with curve number C_i .

The explanation for the connection between runoff and rainfall is that the boundaries of the curve number (CN) parameter are well defined between 0 and 98. If the $CN = 0$ with $S = \infty$, the surface is completely prioritized/preliminary, with all the rainfall being completely abstracted with minimal runoff and a high infiltration rate. Once the curve number generation procedure described above was completed, the curve number is as shown in Figure 3.10.

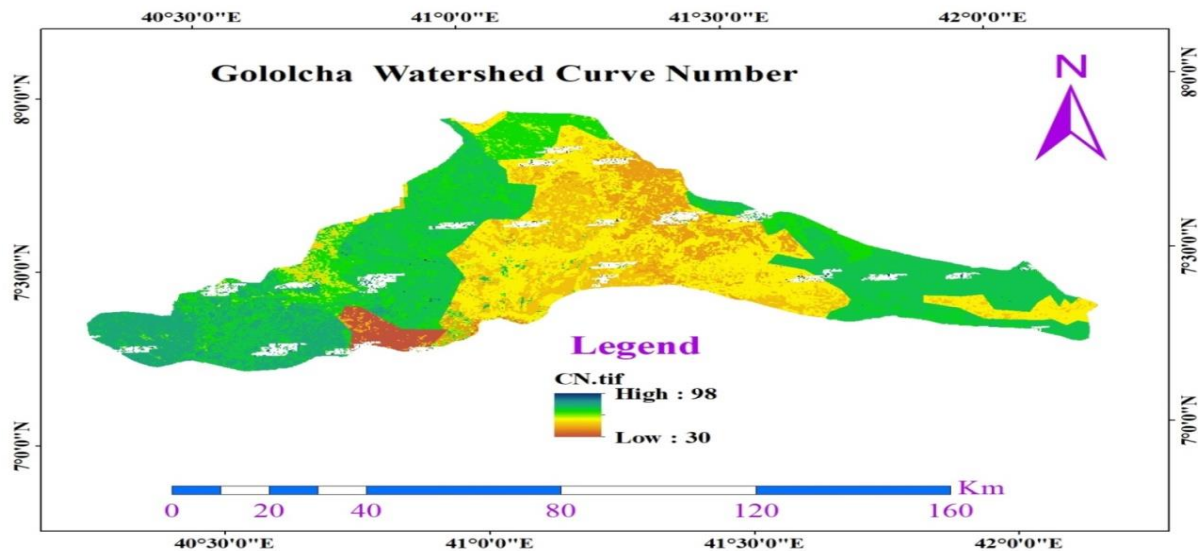


Figure3. 10: Generated Curve Number (CN) Grid for the Gololcha Watershed

3.5 HEC-HMS Basin Model Development

Hydrologic Modeling System (HEC-HMS) is a semi-distributed, physically-based conceptual model which is created by the Hydrologic Engineering Center to simulate rainfall-runoff processes in a watershed or basin. It can describe infiltration, surface runoff, baseflow, channel routing, reservoirs and other hydrological processes by utilizing meteorological inputs and it can be applied at various scales from small urban and natural catchments to a large river basin.

To generate a basin model under HEC-HMS, one has to input background information, sub-basin parameters, meteorological data, and gauge data. The preparation of these inputs often involves GIS-based tools like HEC-GeoHMS, which help extract terrain and hydrologic parameters needed for accurate simulation of rainfall-runoff processes (Fleming, M. & Doan, K. 2013).

3.5.1 Preprocessing of Watershed Terrain Using Arc Hydro Tools

The first one is the terrain processing, the boundary of watershed have been defined by utilizing DEM. The smoothing of the input terrain is done by re-conditioning the DEM, followed by DEM preprocessing, where the drainage network is extracted and the sub-basins are created.

It is important to note that before any of the available tools in the HEC-GeoHMS is executed, all the preprocessing steps are done in an appropriate order. The workflow consisted of various hydrological processes: identifying and partitioning the streams, dividing catchments into a grid, processing the catchments polygon layer, classifying and processing drainage lines and points. Other processes: sink filling, flow direction, flow accumulation and slope. Drainage lines are shown in Figure 3.11. An extensive description of the preprocessing results is given in Appendix 3.

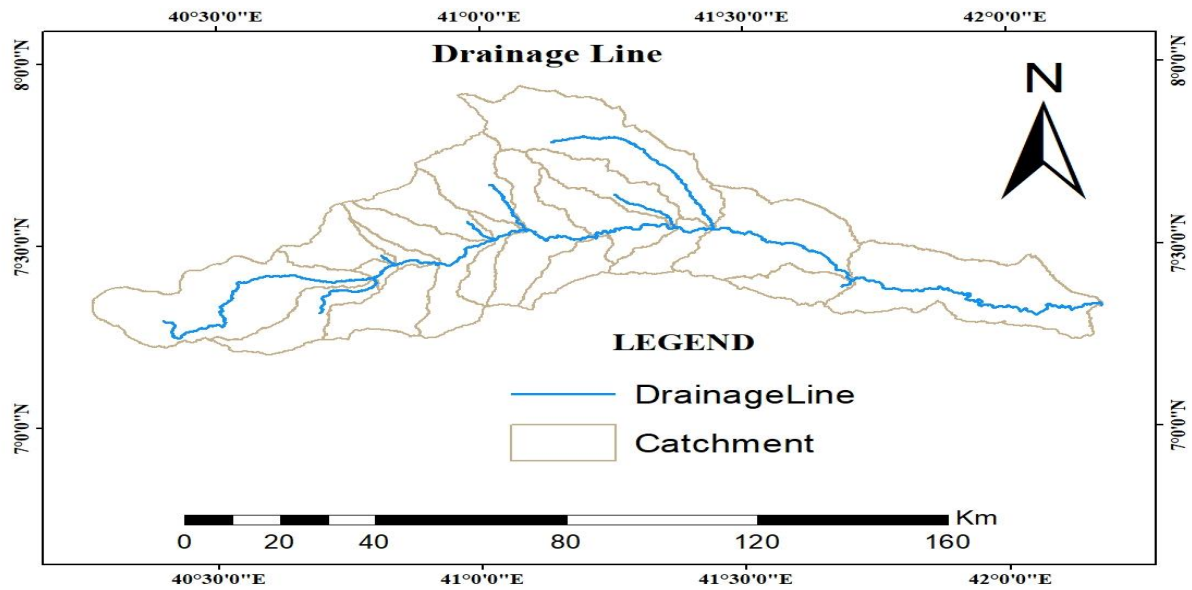


Figure 3.11: Gololcha Catchment Terrain pre-processing output by using Arc Hydro Tools

3.5.2 HEC-GeoHMS Hydrologic Processing for Basin Modeling

HEC-GeoHMS is a geospatial hydrology application that can be used by engineers and hydrologists to effectively study and model watershed characteristics. As an extension of ArcGIS, it has the functionality to show the visualization of spatial elements, the delineation of a watershed area and stream elements, documentation of watershed characteristics, and hydrological report generation. Using a Digital Elevation Model (DEM), HEC-GeoHMS can derive various hydrological parameters including basin and river slopes, river length, longest flow path, basin lag time, and Curve Number (CN), which are essential for hydrological analysis and modeling (Fleming, M. & Doan, K. 2013). The HEC-GeoHMS application has a wide variety of different functions that can be done through the different menu options available.

The basin model for this study was derived by following the established procedure (Merwade, . 2012). The DEM, soil, and land use/land cover datasets were first gathered, and then processed, arranged, and ready for additional examination. Preprocessing was done with the use of Arc Hydro Tools to enhance the DEM data with regard to hydrological modeling. Creating HEC-HMS project files was carried out with the use of a project setup menu included in HEC-GeoHMS, with the inclusion of terrain preprocessing results into the model. Basin processing activities involved the calculation of various physical or geometric properties, such as the length of the streams, upstream and downstream elevations, river slope, as well as various properties for the sub-basins, including the longest flow path, centroid, centroid elevation, centroid flow length, and basin slope.

Using the HEC-GeoHMS tool, the hydrological parameters were calculated. The Curve Number (CN), surface storage, lag time, and concentration time were among these factors. At this point, the gage file, the project file, the hydrological model, the basin model, the meteorological model, and the backdrop shape file were all constructed. Moreover, Thiessen polygons were created in order to compute gage weights using utility files. After processing all of these steps in HEC-GeoHMS, various outputs such as background shape file with various elements such as basin model, meteorological model, gage model, etc., are exported into HEC-HMS. These files served as inputs for subsequent hydrological analysis (Figure 3.12).

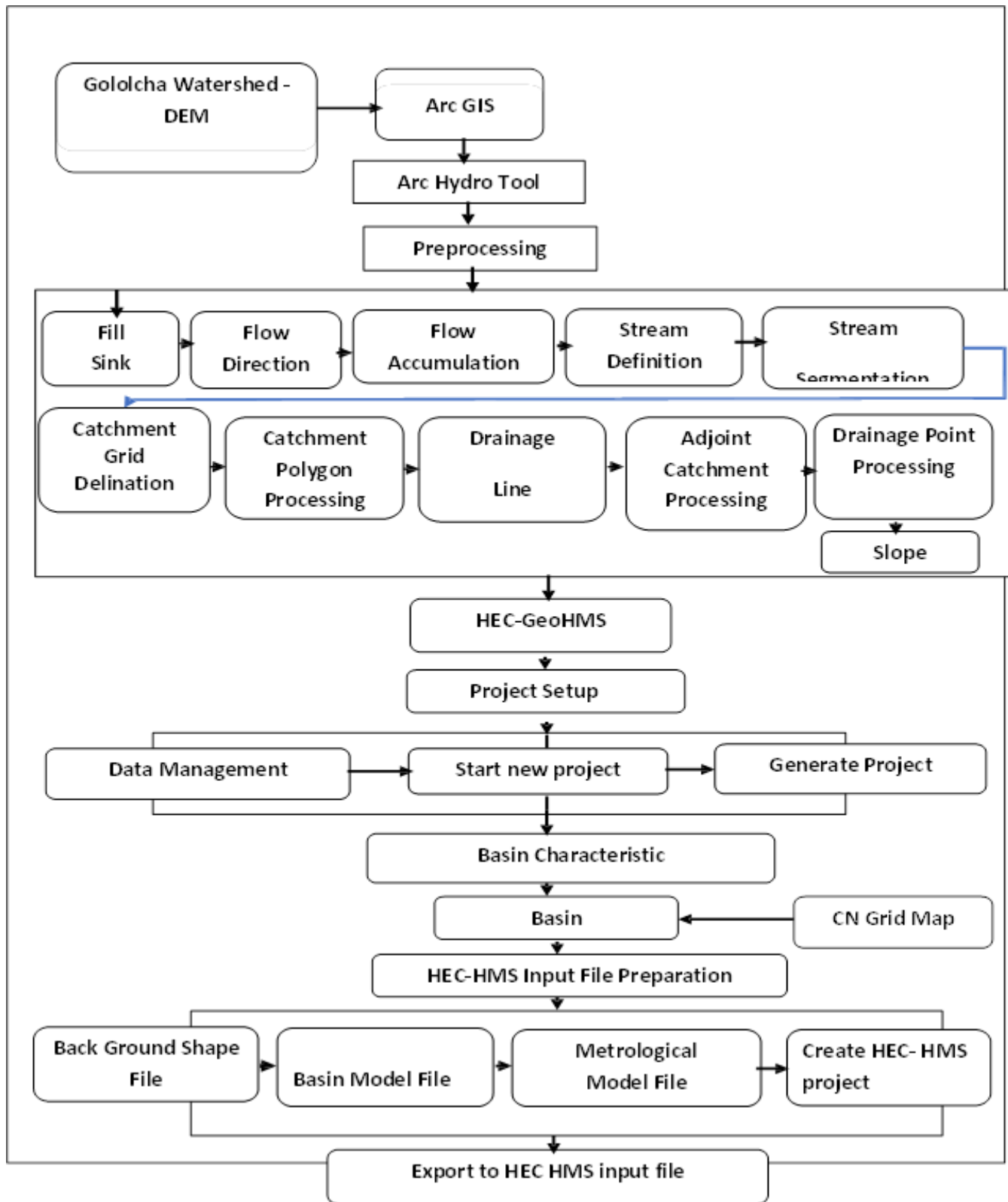


Figure 3.12: Workflow for Preparing Input Data in HEC-HMS

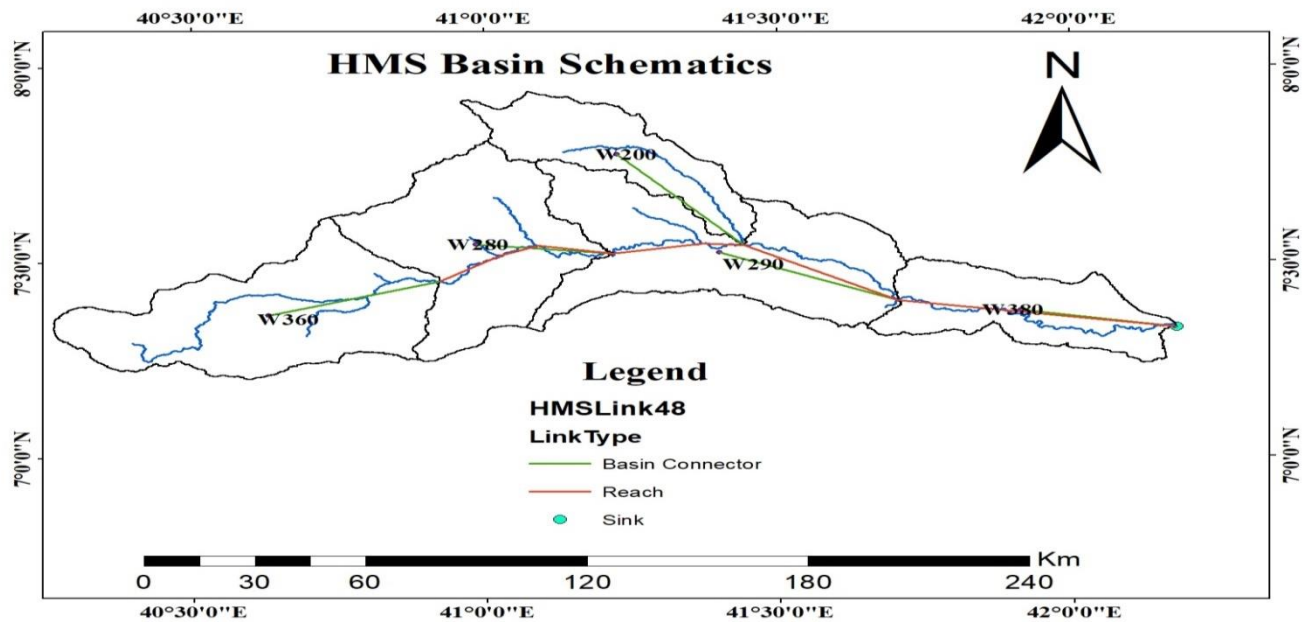


Figure3.12 : Background Map and Basin Elements Generated by HEC-GeoHMS

3.6 HEC-HMS Hydrological Model for Rainfall–Runoff Simulation

HEC-HMS is able to simulate both short- and long-term hydrologic processes including characteristics of catchment; the rainfall-runoff process over the Gololcha Watershed was modeled using HEC-HMS. The sub-basins of the watershed were determined by HEC-HMS model. Also the sub-basins were assigned the hydrologic parameters. The necessary meteorological data and stream flow have been used to run the simulation processes accurately. The necessary files have been prepared to run the simulation processes. These files include the basin model file, the meteorological model file, and the gage files. In fact, it has been extensively used for various hydrological studies across the globe due to its popularity, ease of use, and effectiveness, as mentioned in the study by the (USCAE 2000). It also offers a number of tools for simulating the hydrological cycle by using a number of basic modules, each representing a different component.

3.6.1 Model Setup and Simulation of HEC-HMS

The procedure of the hydrological modeling starts with the construction of the HEC-HMS model consisting of four sub-elements namely basin model, meteorological model, control specifications and inputs to the model. The meteorological model was generated using recorded rainfall and stream flow records using Gage Weight and Frequency Storm methods, taking care of spatial and temporal distribution of rainfall over the watershed. Control specification was used to determine the simulation framework which was set for hourly intervals from January 01 1987 to December 31 2017.

The meteorological and basin models and the control specification together used for the purpose of conducting the hydrological modeling simulation of the watershed. The main run-off-generating processes such as direct run-off volume and base flow are separately simulated.

3.6.2 HEC-HMS Basin Model Configuration

At the center of the HEC-HMS model is the watershed model that depicts the movement of water across the watershed. In essence; it maps out the watershed drainage system using hydrologic components like sub-basins, reaches, and junctions, showing how they are interconnected. In this study, the three components were enough to describe the watershed's hydrological processes.

The basic objective of the basin model was to transform meteorological input data into the stream flow leaving the watershed. This was achieved by simulating the rainfall–runoff process through four main stages: estimating losses, transforming rainfall into direct runoff, simulating base flow, and routing the flow through the stream network. Each stage represents a different part of the water cycle. The methods used in each stage have been designed to represent the special behavior of the watershed. Loss of rainfall in this study was estimated using SCS Curve Number method. Runoff directly generated was obtained using SCS Unit Hydrograph method. Base flow was modeled using recession method whereas channel flow routing was modeled using Muskingum method. These four methods are described in subsequent subsections:

3.6.2.1 SCS-CN Loss method

Rainfall loss prior to the generation of surface runoff within the watershed was calculated using the SCS-CN loss method. The SCS-CN loss method models interception and surface storage losses along with losses due to infiltration by taking into account the land use/land cover, hydrologic soil group, and antecedent moisture condition to determine a CN value. This CN value shows the runoff generating potential of a watershed: a larger CN value means less infiltration capacity and greater runoff generating potential and a smaller CN value means greater infiltration capacity and less runoff generating potential.

The CN value in HEC-HMS determines the initial abstraction and effective rainfall that contributes to direct runoff. After the rainfall amount has surpassed the initial abstraction, it will become runoff and flow over the land surface. The method allows for a fairly reliable and simplistic method for estimating rainfall loss in situations where little to no hydrologic data is available.

The method is applied in a variety of different hydrological models because of its ease of use, practicability, and ability to take into account many different physical properties of a watershed, and it fits well in the context of a semi-distributed model such as HEC-HMS. The Curve Number, ranging from 0 to 100, indicates the soil's ability to infiltrate water and its corresponding runoff potential. The general equation for the curve number method is:

$$Q = \frac{(p - I_a)^2}{(P - I_a + S)} \dots \dots \dots 3.5$$

Where: Q = runoff (mm), P = depth of rainfall (mm), I_a = initial abstraction, S = maximum Potential retention (mm).

Initial abstraction (I_a) represents all the losses occurring before the start of surface runoff. This includes the intercepted precipitation, stored precipitation in depressions, evaporation, and infiltration. As this first abstraction is soil type and land-use dependent it is regarded as a highly variable parameter. This can be approximated by the following equation:

$$I_a = 0.2S \dots \dots \dots 3.6$$

Substituting I_a in equation 3.5 produces a unique runoff quantity by combining S and P. The equation for rainfall connections is:

$$Q = \frac{(p - 0.2S)^2}{(P + 0.8S)} \text{ If } P > 0.2S \text{ and } Q = 0, \text{ If } P < 0.2S \dots \dots \dots 3.7$$

The theoretical maximum retention (S, in mm) ranges from 0 to ∞ and represents the maximum amount of rainfall that can be retained by the watershed before runoff begins. Its value depends on the soil and land cover characteristics and is related to the Curve Number through the following equation.

$$S = \frac{254000}{CN} - 254, \dots \dots \dots 3.8$$

Where: CN = is a function of LULC, soil type, hydrologic soil group, and antecedent moisture condition (AMC) is an important element in the SCS – CN approach.

CN values range from nearly 30 for highly pervious and infiltrated soils to nearly 100 for water surfaces such as rivers and lakes (Mokhtari et al., 2016).

When soils and land uses vary within the watershed, the overall runoff potential of the watershed is expressed in terms of a weighted Curve Number (CN), as shown in Equation 3.9.

$$S = \frac{CN_i * A_i}{A_t}, \dots \dots \dots 3.9$$

Where A_i is defined as the area of the sub – basin, A_t is defined as the total watershed area, and CN_w is defined as the weighted curve number for the sub – basin.

3.6.2.2 Rainfall–Runoff Transformation Method

The SCS Curve Number method is frequently employed to estimation the quantity of direct runoff produced due to rainfall events, due to the ease of application and lower data demands. In this method, runoff is determined by means of the Curve Number (CN) which are the variables of hydrological characteristics (soil group, land use, cover type, land slope). A value of CN is an integer between 0 and 100, representing the overall runoff potential of a watershed. The smaller the value of CN, the greater the infiltration capacity and lesser the surface runoff, and the larger the value of CN, the lesser the infiltration capacity and greater the possibility of surface runoff. This method is considered useful for hydrological modeling in areas where data is scarce because it can be easily calculated based on GIS data availability. It can be phrased as follows.

$$T_{Lag} = \frac{L^{0.8}(S + 1)^{0.7}}{1900Y^{0.5}} \dots \dots \dots 3.10$$

Where: T_{Lag} = basin lag time (minutes), L = length from sub-basin outlet to divide along the longest drainage channel (km), y = basin mean slope (%), and S = Potential maximum retention once runoff begins.

This S may be stated in terms of average curve numbers as follows:

$$S(mm) = \frac{254000}{CN} - 254 \dots \dots \dots 3.11$$

Where: CN = average curve number for each sub – basin. By substituting the above equation, it becomes.

$$T_{Lag} = \frac{L^{0.8}(\frac{254000}{CN} + 253)^{0.7}}{1900Y^{0.5}} \dots \dots \dots 3.12$$

3.6.2.3 Base flow Contribution Method

Base flow refers to the part of the stream flow that is derived from groundwater and other time-delayed water sources. This flow is what maintains the stream flow during dry periods when no rainfall is occurring. In hydrological modeling, the different components of the base flow are calculated to represent the stream flow response of the catchment. In the current study, constant monthly base flow method implemented in the HEC-HMS model is employed.

This method is the best used in catchments where long-term stream flow records are available. This method allows the calculation of base flow values that remain constant for any given month of the year. The method is implemented by extracting the minimum discharge values for any given month

from the available historical stream flow records. These minimum discharge values are used to represent the constant base flow for the respective months.

3.6.2.4 Hydrologic Routing Method

Flow routing is an essential constituent of hydrological models, as it accounts for the flow of runoff in the river channels and streams of a watershed. For this study, Muskingum technique was used as an effective tool of channel routing, which describes the characteristics of runoff as they move downstream. This method accounts for storage effects within river reaches, making it suitable for medium- to large-scale catchments like the Gololcha watershed. The Muskingum method is commonly used in hydrologic studies because it is simple to apply and provides reliable predictions of downstream hydrographs (Chow et al. 1988; Singh. 2003). Using input from sub-basin runoff and base flow, the method distributes flow through the drainage network, providing an accurate representation of stream flow at the watershed outlet. Muskingum routing technique requires two parameters to be defined. In this case, K represents the travel time for the reach and X is a coefficient used in weighting the relationship between inflow and outflow in the channel routing.

3.6.3 Meteorological Data Modeling

The meteorological model provides rainfall and climate inputs that drive runoff in the watershed. For the Gololcha watershed, observed precipitation and stream flow data from selected stations were used. Gage weights and frequency storm analysis ensured that spatial and temporal variability in rainfall was accurately represented. Meteorological model works in combination with the basin model to simulate stream flow, forming the basis for hydrological analysis and flood estimation (Singh. 2003; USCAE 2000).

Control Specifications for Hydrological Simulation

The time parameters of the simulation are also part of the control specifications, the parameters being simulation start time, simulation end time and the simulation step size. Although not numerous, these parameters are very important for making sure the simulation model works well. This is because the model specifications ensure that numerical errors are eliminated. In addition, the model specifications ensure that the model works at regular intervals. This is critical in the management of long-term simulations as well as the management of short-duration storm events. This is most important to ensure good calibration of the hydrological model.

Time Series Data Preparation

Simulation of runoff and calibration of HEC-HMS model involves time series data. In this work daily rainfall from three meteorological stations i.e. Delo Sebro, Ginir and Jara were used as model inputs. Thiessen polygons were used to obtain the weighted rainfall values, which represent the mean precipitation values over each sub-watershed within the Gololcha watershed.

Daily stream flow data was also gathered at the outlet of the watershed in order to confirm and validate the model's predictions. The rainfall and stream flow data was weighted and entered into HEC-HMS in order to estimate what the actual stream flow was for the watershed.

3.6.4 Hydrological Simulation

The hydrological simulation of watershed is performed by coupling basin model, meteorological model and control specifications in HEC-HMS. By the coupled models, the response of watershed to the rainfall event is simulated. The input rainfalls data is provided by the meteorological model, the basin model provided the watershed physical conditions and the control specification provides the duration of simulation. With the models coupled, the model performs the rainfall runoff transformation simulation. With the simulation results obtained, the outputs are analyzed in different format. Through the basin map and watershed explorer, we can see the result of simulation clearly.

3.7 Estimation Flood

Flood prediction is one of the significant aspects in the hydrological research and is concerned with the estimation of the discharge that may be expected in the river as a result of heavy rainfall. Reliable estimation of flood discharge is of considerable significance in the design and planning of hydraulic structures. The accuracy of flood forecasting relies largely on two factors: availability of hydrological and meteorological data and adequacy of the technique adopted for the analysis. Therefore, selection of the flood forecasting technique depends on the basis of data, nature of catchments and application of the study.

3.7.1 Estimation of Flood Using the HEC-HMS Model

In this study, the frequency storm method using HEC-HMS was applied to predict the magnitude of the floods. This technique employs statistical rainfall data to develop design storms that can be used to simulate flood events. This method takes into consideration the most important characteristics of storms, including rainfall depth, duration, intensity, likelihood of occurrence, and distribution of rainfall across the watershed.

The selected rainfall depths for Flood Analysis are corresponding return periods: 2, 5, 10, 25, 75, 100, 200, 500 years. The rainfall distribution in Ethiopia is divided into 8 regions following the classification of the Ethiopian Road Authority. The rainfall has been determined for the study area to be classified as Rainfall Region Three (RR-A3) according to the ERA drainage design manual. From the classification above rainfall depths for the specified return periods were selected from the ERA drainage design manual and applied as the input for HEC-HMS model.

Using the equation (3.17) the rainfall depths were found and summarized in Table 3.10. The rainfall values were then applied as the input data to HEC-HMS for flood discharge prediction from rainfall depths determined.

Table 3.10: Estimated Rainfall Depths (mm) Corresponding to Selected Return Periods (ERA 2013)

Region Classification ERA	24 hrs. Rainfall depth (mm) vs frequency (yr.)							
	2	5	10	25	75	100	200	500
RR – A1	50.3	66.02	76.28	89.13	98.63	108.06	117.48	130
RR – A2	51.92	65.52	74.45	85.7	94.07	102.45	110.91	122.27
RR – A3	47.54	59.61	67.66	77.92	85.62	93.34	101.13	111.58
RR – A4	50.39	63.83	72.28	82.55	89.97	97.2	104.32	113.38
RR – B1	58.87	71.26	79.29	89.35	96.84	104.37	112.02	122.41
RR – B2	55.26	69.95	79.68	92.03	101.29	110.61	120.07	132.87
RR – C	56.52	71.04	80.54	92.52	101.48	110.5	119.66	132.06
RR – D	56.23	76.84	90.37	107.46	120.23	133.05	146	163.44
Note: RR – Rainfall Region								

Using Table 3.10, where rainfall depth over a 24-hour period is given along with rainfall duration, we can derive the ERA equation, as shown below:

$$R_{RT} = \frac{t(b+24)^n}{24(b+t)^n} \dots\dots\dots 3.17$$

Where: R_{Rt} = Rainfall depth ratio R_t : R_{24} , R_t = Rainfall depth in a given duration 't', R_{24} = 24hr Rainfall depth, b and n are constant coefficient in which $b = 0.3$ and $n = (0.78 - 1.09)$ and t = Rainfall duration. For this study the value $n = 1$ used, to calculate the 24 – hr depth for each return period.

3.7.2 Flood Frequency Analysis Using Probability Distribution Functions

Flood frequency analysis was performed using various probability distribution functions to assess extreme flood magnitude and probability of events. Easy Fit is a software working on stand-alone and Excel environment (Mehrannia and Pakgohar 2014), analyzes data and ranks probability distributions using established goodness-of-fit tests. Five probability distributions (General Extreme Value (GEV) distribution, General Pareto distribution, Log Pearson Type III distribution, Gumbel Max distribution and Gamma (3P) distribution) were used in analyzing extreme flood events in the watershed. These distributions were selected for ease of application, computational simplicity and general use in hydrological and flood frequency studies.

EasyFit which is commonly used for goodness of fit of different statistical distributions and analysis of hydrological data was used. To determine the best fit for the chosen probability distributions, 3 goodness of fit test were carried out: Kolmogorov-Smirnov test, Anderson-Darling test and Chi-Squared test. Goodness of fit test results shown in table 3.11 was analyzed in order to find the best distribution to fit to the outlet discharge data of the watershed. Maximum annual stream flow data for the Gololcha watershed, spanning 21 years (2000–2020), was analyzed. It was found that a general Pareto distribution fit well with the flood data. Thus the general Pareto distribution was chosen as the best distribution and used to estimate flood magnitude for each return period.

Table 3.11: Summary of Goodness-of-Fit Tests for Selected Statistical Distributions Using Easy Fit 5.6

S No.	Distributions	Kolmogorov		Anderson Darling		Chi – square	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.11819	5	0.4623	2	2.0444	1
2	Gen. Pareto	0.08739	1	0.24103	1	1.1486	4
3	Gumbel Max	0.13547	4	0.54874	4	2.2841	2
4	Log – Person 3	0.12425	3	0.44756	3	2.4053	4
5	Gama(3p)	0.12585	2	0.48988	5	2.478	3

3.8 Separation of Base Flow and Surface Flow Using SepHydro - Hydrograph Separation Tool

In this study, the SepHydro-Hydro Separation Tool has been used to separate surface flow (SF) from base flow (BF). The stream flow information for Gololcha Watershed was obtained from HEC-HMS which is commonly used hydrological rainfall-runoff model. The hydrograph data were converted into a continuous data set. The data was input into SepHydro. SepHydro automatically performs a hydrograph separation technique which separates the slow responding baseflow from the quick responding surface runoff. In the process of hydrograph separation, a number of parameters such as the recession coefficient (α) and the Base Flow Index (BFI_{max}) were modified to better simulate the watershed features such as slopes, soil types and groundwater contributions. The tool analyzes the hydrograph to determine the amount of flow contributed by groundwater and separate it from the fast-response surface flow, which is contributed by rainfall or precipitation.

After the hydrograph separation, hydrographs were generated for base flow and surface flow, which were then analyzed over the study period to determine trends, peak flows, and seasonal variations. Separating the total flow into base flow and surface flow by the technique of hydrograph separation, with the base flow representing the slow-moving water and the surface flow representing the fast-response water. The base flow, which moves through the channel at any given time step, can be mathematically represented by:

$$Q_b(t) = \frac{\alpha \cdot Q_b(t-1) + (1-\alpha) \cdot Q(t)}{1+\alpha} \dots \dots \dots 3.18$$

Where $Q_b(t)$ the base flow at time t , $Q(t)$ is the total stream flow and α alpha is the recession constant controlling the response rate.

After separating the flows, we then plot the hydrographs for the base flows and surface flows to see how they contribute to the total flows. This also helps us to better understand how the watershed hydrological functions. It is important to differentiate between surface runoff and groundwater inputs to the overall stream flow for managing the water resources and prediction of the flood accurately. In Gololcha watershed it is necessary to determine the proportion of surface run-off and groundwater for watershed performance, especially in the event of floods and water availability.

3.9 Assessment of HEC-HMS Model Performance

Evaluating a hydrological model's performance requires careful consideration of its accuracy, consistency, and flexibility. The analysis is used to compare how accurately the model predicts to the values measured in terms of accuracy of prediction of the hydrograph peaks time and of the runoff volume. There were 4 evaluation criteria implemented in order to carry out the analysis: Nash-Sutcliffe Efficiency, Coefficient of Determination, Root Mean Square Error, and percent Bias.

Nash-Sutcliffe Efficiency (NSE)

Nash-Sutcliffe Efficiency is another widely used statistical criterion to measure hydrological model performance. It is defined as the amount of variation of the residuals compared with the variation of the observations. In simple terms, the measure shows to what extent the model could predict the discharge better than just simply taking the average observation.

The NSE is calculated using the formula:

$$NSE = 1 - \frac{\sum(Q_{obs(t)} - Q_{sim(t)})^2}{\sum(Q_{obs} - Q_{sim})^2} \dots \dots \dots 3.19$$

Where, NSE is Nash Sutcliffe Efficiency $Q_{obs(t)}$ is observed discharge at time t, $Q_{sim(t)}$ is simulated discharge at time t and Q_{obs} is average observed discharge.

The NSE index (Nash and Sutcliffe efficiency) quantifies the accuracy with which the model results agree with the measured values. The possible range of NSE is from -infinity to 1 and the best agreement of results to the runoff data is achieved with $NSE=1$. A Nash-Sutcliffe Efficiency of 0 is equal to how well we would have performed if we simply used the average of observed data as a proxy, and negative numbers imply model inadequacy. When negative values, then you are seeing that the model is performing poorly because what you actually observe is better than what you are seeing through the simulation. Common evaluation metrics that are typically acceptable are: Nash-Sutcliffe Efficiency >0.5 for acceptable; >0.65 for good fit (Moriasi et al. 2007; Nash and Sutcliffe 1970).

Coefficient of Determination (R^2)

The coefficient of determination, or R^2 , measures how good the results from the simulation match up with a trend established by what was actually seen or observed. R^2 measures how well the results from the observation match up in a straight-line fashion with the results from the simulations.

R^2 can range from 0 to 1, where a low number indicates no relationship at all, while a number closer to 1 indicates a match between the results from observation and the results from the simulations. For hydrological modeling research, an R value > 0.6 is acceptable which represents acceptable agreement between the observed and simulated data (Moriassi et al. 2007).

The formula for calculating R^2 is:

$$R^2 = \frac{[(\sum_{i=1}^n Q_{sim(t)} - \bar{Q}_{sim})(\sum_{i=1}^n Q_{obs(t)} - \bar{Q}_{obs})]^2}{\sum_{i=1}^n (Q_{sim(t)} - \bar{Q}_{sim})^2 \sum_{i=1}^n (Q_{obs(t)} - \bar{Q}_{obs})^2} \dots \dots \dots 3.20$$

Where, R^2 is coefficient of determination, Q_{obs} and Q_{sim} are observed and simulated discharge
 $\bar{Q}_{obs}$ and $\bar{Q}_{sim}$ are mean observed and simulated discharge at the time

Root mean square error (RMSE)

The Root Mean Square Error (RMSE) is one of the most used statistical measure to assess the disagreement between simulated and observed runoff values. It is never negative and the minimum value is one that show the higher agreement between simulated and observed value, hence the more accurate is the model. Larger errors are given more weight when evaluating model performance since the RMSE calculation squares the differences between observed discharge (Q_{obs}) and simulated discharge (Q_{sim}) (Singh. 2003).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Q_{obs(t)} - Q_{sim(t)})^2} \dots \dots \dots 3.21$$

RMSE values are always greater than or equal to zero, and values closer to zero indicate better model performance (Singh. 2003).

Percent Bias (PBIAS)

A statistical metric called Percent Bias (PBIAS) is used to assess how comparable the simulated and actual data are on average. It shows the degree and direction of bias; a perfect match is shown by a value of zero, but overestimation and underestimation are indicated by positive and negative values, respectively. According to (Moriassi et al., 2007), a positive PBIAS value shows that the model tends to underestimate observed flow, whereas a negative PBIAS value suggests an overestimation.

The formula for PBIAS is:

$$PBIAS = \left[\frac{\sum_{i=1}^n (Q_{obs} - Q_{sim})}{\sum_{i=1}^n Q_{obs}} \right] \dots \dots \dots 3.22$$

Where, Q_{obs} and Q_{sim} are observed and simulated discharge;

In general, the accuracy of the results of a simulation in a watershed is determined using performance metrics, with RSR, NSE, and PBIAS identified as key metrics for evaluation purposes. These metrics provide a framework for determining the extent to which the results of the simulation match the observed results in the stream flow process.

Table 3.12: Guidelines for Assessing Hydrological Model Performance(Moriasi et al. 2007).

Performance rating	Very good	Good	Satisfactory	Unsatisfactory
NSE	$0.75 \leq \text{NSE} \leq 1$	$0.65 \leq \text{NSE} \leq 0.75$	$0.5 \leq \text{NSE} \leq 0.65$	$\text{NSE} \leq 0.5$
R^2	$0.85 \leq R^2 \leq 1$	$0.7 \leq R^2 \leq 0.85$	$0.6 \leq R^2 \leq 0.6$	$R^2 < 0.6$
RMSE	$\text{RMSE} < 0.5$	$0.5 < \text{RMSE} \leq 0.6$	$0.6 < \text{RMSE} \leq 0.7$	$\text{RMSE} > 0.7$
PBIAS	$\text{PBIAS} \leq \pm 10\%$	$\pm 10\text{PBIAS} < \pm 15$	$\pm 15\text{PBIAS} < \pm 25$	$\text{PBIAS} \geq \pm 25$

3.9.1 Analysis of Model Sensitivity

A Sensitivity analysis is performed to show how the simulation behaves under slight perturbations of model parameters. Such an analysis will highlight which parameters contribute the most to watershed response. This is because, by deliberately modifying each input and monitoring the change in the output, we can determine the relative importance of each parameter and rank them accordingly. This process helps to focus calibration on the most influential parameters and improves the efficiency and reliability of the modeling procedure.

Curve Number (CN), initial abstraction (Ia), lag duration, Muskingum storage coefficient K, and Muskingum weighting factor X were the five variables selected for sensitivity analysis. Each of the parameters was varied within its physically realistic range, and the sensitivity of the parameter to the simulated discharge at the Gololcha watershed outlet was studied. Parameters with significant effects on the hydrograph, With respect to peak flow rate and volume, were identified as highly sensitive, whereas those with less significant effects were identified as moderately sensitive.

Performing sensitivity analysis offers a distinct insight into the hydrologic processes that most significantly affect watershed behavior. It also aids in simplifying the model calibration by concentrating precise modifications on the most sensitive parameters. Less sensitive parameters are adjusted as necessary, depending on differences between actual and simulated flows.

This method increases calibration effectiveness and boosts the overall dependability of the hydrological model. An essential tool for hydrological modeling that improves calibration, validation, and model confidence is sensitivity analysis (Beven 2012; El-Sayed and Zumwalt 1991).

3.9.2 Calibration and Adjustment of HEC-HMS Model Parameters

The process of calibrating a model involves adjusting its parameters within a physically viable range in order to create the best match between the simulated and observed hydrograph. It entails a methodical adjustment of critical parameters until the gap between calculated and observed discharge is reduced. The results of a hydrological model are largely a function of the accuracy of the calibration procedure, which is also a function of the model type, and reliability of input data, and accuracy (Vaze et al., 2010).

The optimization manager in HEC-HMS is used to find optimal parameter values for the simulated to observe data to best fit each other automatically. This is done through an objective function that assesses the fit quality between the two hydrographs. The criterion function (in terms of minimization) calculates the most suitable parameter set minimizing the discrepancy between observed and simulated data (USCAE 2000). Amongst all the objective functions present in the literature, Peak Weighted Root Mean Square Error (PWRMSE) is chosen as the objective function for this work. The reason behind choosing the PWRMSE as objective function is that PWRMSE places greater emphasis on the error occurring at peak discharge and peak runoff. HEC-HMS has two methods of optimizing the objective function: the Univariate Gradient method (UG method) and Nelder-Mead method.

The UG method is to change one parameter and hold others as constant, but the Nelder-Mead method uses a downhill simplex algorithm and the changes of all the parameters can make the result converge to optimal values at a quicker rate, thus all the parameters change and move simultaneously. Thus the results were obtained using Nelder-Mead method with PWRMSE as objective function.

3.9.3 Validation and Assessment of HEC-HMS Model Performance

Model validation helps as to what extent the HEC-HMS model configuration accurately represents real-world hydrological processes for a specific application. During the validation, the model is executed with another set of data, different from the calibration set, while keeping the previously determined model parameters constant.

The simulated discharges accuracy is tested and compared to the observations using statistical methods like Nash-Sutcliffe Efficiency, Root Mean Square Error and Coefficient of Determination are used to define the proximity of the observed to simulated ones in order to assign confidence in the appropriateness of model for both hydrological analysis and flood forecasting application.

3.10 Conceptual Framework of the Study

In this section described the conceptual framework of the study, which represents rainfall-runoff and flood characteristics of Gololcha watershed based on the HEC-HMS model. The procedure included data collection, preparation of spatial data using GIS techniques, watershed delineation, and parameter estimation, application of hydrologic model, calibration, validation, and flood frequency analysis.

Various data such as rainfall, stream flow, DEM, LULC and soil were collected and prepared in to hydrologic model parameters such as sub-basins, stream network, HSG, CN. The parameters were applied to hydrologic model and simulated discharge was calibrated and validated using observed discharge data, then flood frequency analysis performed by various probability distribution functions and flood for different return periods estimated. The below Fig 3.13 describes the flow of study procedure in the watershed.

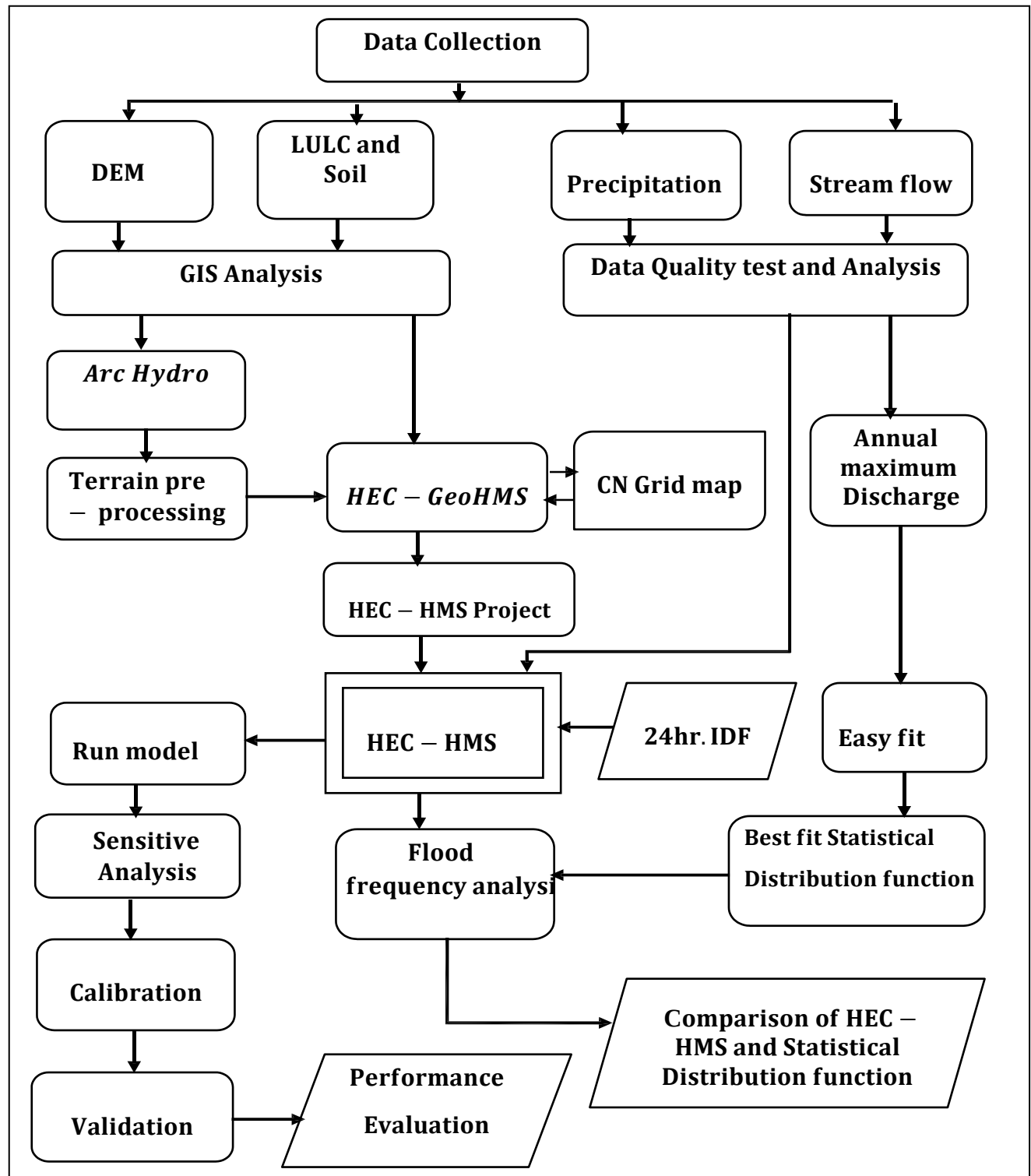


Figure 3.13: Conceptual Framework of the Study of the Gololcha watershed.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Physical Characteristics of the Watershed

The physiographic condition of the Gololcha watershed, which was adopted in this study is represented in the figure below. The watershed boundaries and the drainage network were obtained using ArcGIS and HEC-GeoHMS with DEM, which are also processed through Arc Hydro extension. From which five sub-basins, seven reaches and six junctions were identified in the Gololcha watershed. Figure 4.1 clearly indicates that, this physical map could be useful in defining basin model, meteorological model, gauge data, time series data and control specification, which are required in simulation of rainfall-runoff modeling. The basin model prepared by HEC-GeoHMS is the aggregate representation of main constituents of the watershed namely sub-basin, reach, junction, outlet that help in the simulation of rainfall runoff transformation, which include loss, precipitation-runoff transform, base flow and channel routing.

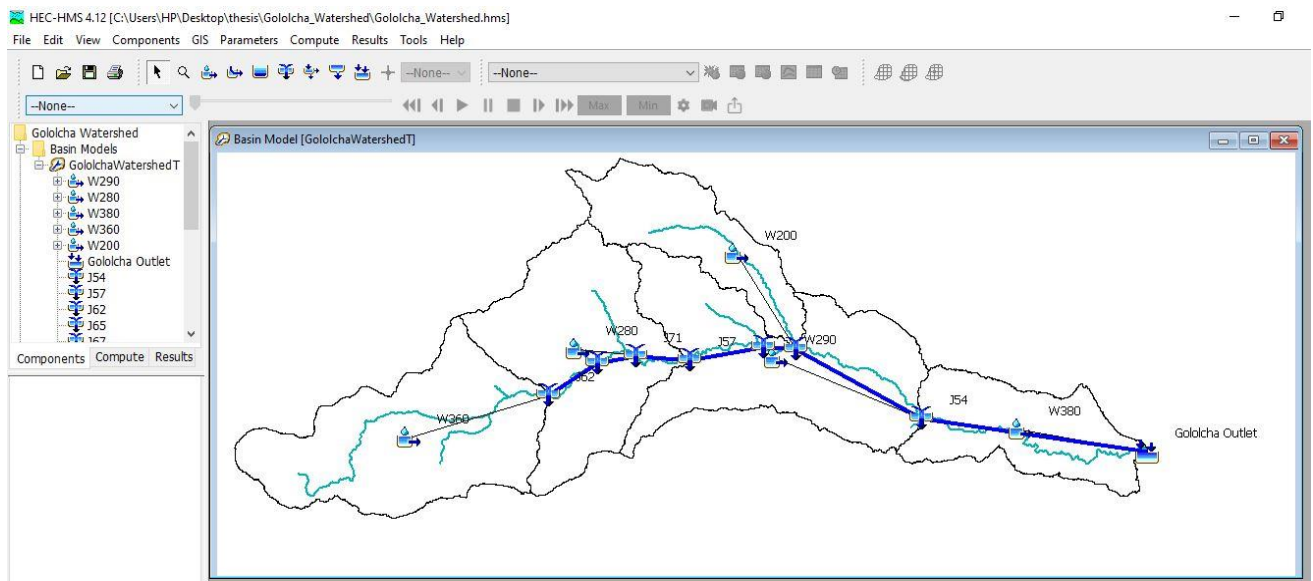


Figure 4. 1: Gololcha Watershed Geographic Location

In this study, HEC-GeoHMS was applied to derive important watershed characteristics from the spatial datasets. Model parameters that were needed to set up the model to simulate the runoff: Watershed Area, Curve number, Lag time, and Initial abstraction were need to run the model.

SCS Curve Number (SCS-CN) was applied in HEC-HMS model to calculate losses in rainfall, and the produced excess rainfall was then converted into the direct runoff using SCS Unit Hydrograph (SCS-UH) method. Flow routing along river channels was then simulated using Muskingum routing method with K and X routing coefficients. The K and X values were estimated from the characteristics of the watershed.

4.2 Watershed Characteristics and Derived Parameters

The important physical and hydrological parameters for Gololcha watershed derived for modeling were also presented. Curve Number (CN), basin lag time, watershed area, slope, maximum retention capacity (S) and initial abstraction are the factors considered. The value of curve number varies all over the watershed based on the type of landuse and the soil types. In the area the curve number is ranging from approximately 30 for the forested/dense vegetative land cover to 98 for water and very impervious areas.

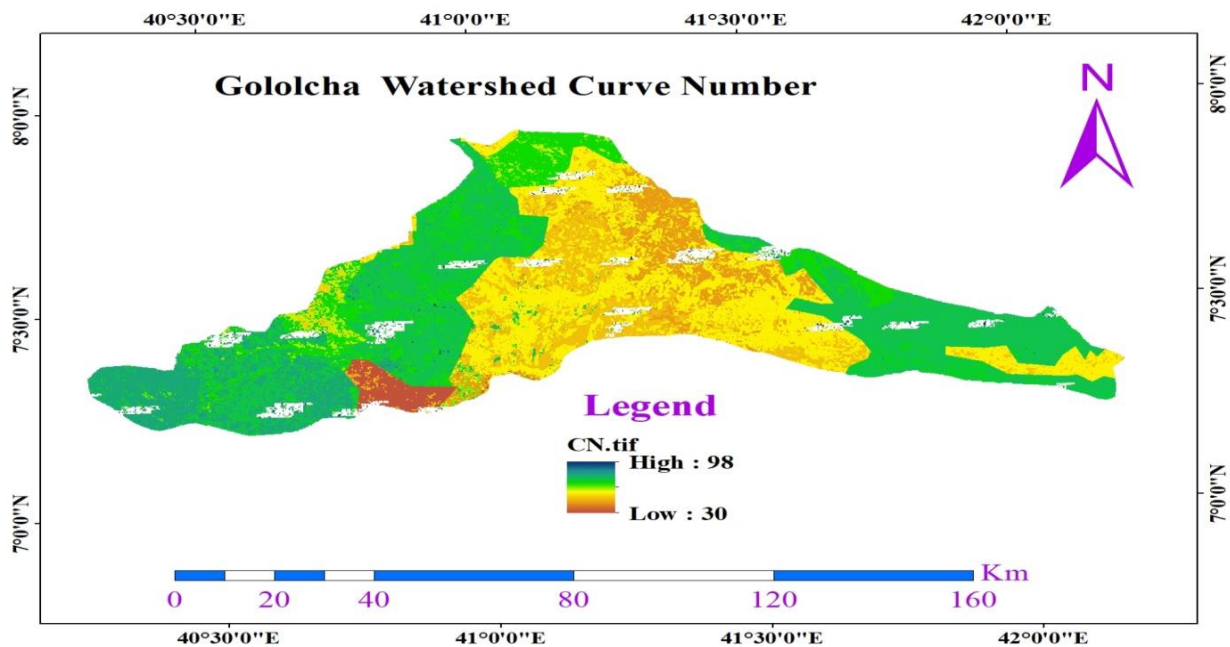


Figure4.2: Curve Number grid map of Gololcha watershed.

To accurately simulate rainfall runoff, each of the sub-basins needs a unique value of Curve Number (CN). CN was calculated for the watershed by HEC-GeoHMS and weights were given for each watershed. The range had a maximum of 83.08 and a minimum of 72.76. W290 and W360 have the lowest and the highest weighted CN values, respectively.

The importance of CN in contributing to run-off and Sub-basins with high values of the CN, like W360, yield greater amounts of runoff compared to those with low CN values, like W290, which yield lower volumes of runoff due to their high rates of infiltration. Figure 4.3 shows the distribution of CN Values for each sub-basin which is determined by Arc-Gis integrated with HEC-GeoHMS.

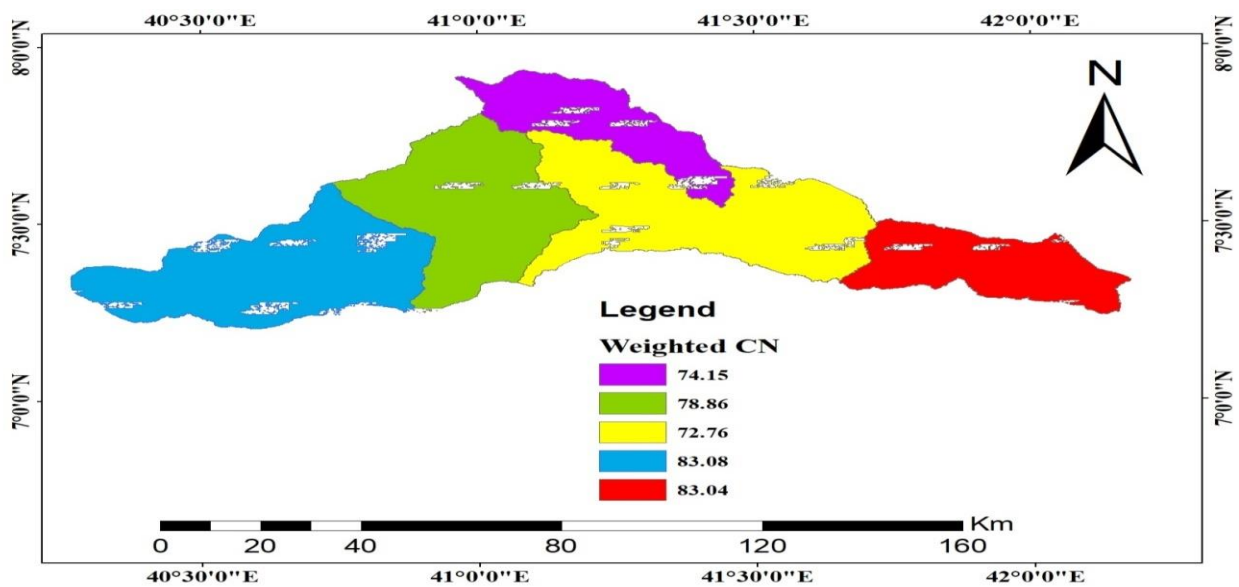


Figure4. 3 : Gololcha watershed Weighted Curve Number map

The begin of abstraction values varied between the sub-basins; with W290 indicating a minimum of 10.35 mm and W360 shows a high of 19.02 mm. This shows that W360 contributes to a greater runoff compared to W290. The lag time for the Sub basin varies between 105.73 and 253.74 hours, a shorter lag periods allowing surface runoff to reach the outlet more quickly. Table 4.1 provides information on the watershed's characteristics of Gololcha watershed

Table 4.1: Physical Characteristics of the Gololcha Watershed Created Using HEC-GeoHMS

Name	Area (Km ²)	Sub Basin Slope	Basin Lag	CN	Potential maximum Retention (S)(mm)	Initial Abstraction (mm)I = 0.2S
W200	851.8	0.020	253.74	74.15	88.57	17.71
W280	1557.8	0.067	105.73	78.86	68.11	13.62
W290	1788.3	0.066	174.27	72.76	95.12	19.02
W360	1753.3	0.025	211.50	83.08	51.73	10.35
W380	941.8	0.012	249.81	83.04	51.87	10.37

4.3 Model Simulation Result

From the HEC-HMS results, it is clear that the outlets of the Gololcha watershed are subject to the peak discharge, which is up to 907.2 m³/s. Table 4.2 shows the discharge of water from each of the sub-basins on a daily basis and the river reach into which they drain, showing the varied effects of different areas on the water discharge.

Out of the sub-basins, the discharge of water from W280 is the highest, while that from W200 is the lowest due to their unique characteristics. The total water volume and rate at which it flows to the outlets vary from one sub-basin to another. River depth increases from the outlets, according to the HEC-HMS results.

Table 4.2: Peak Simulated hydrological results for each sub-basin and river reach

Hydrologic Element	Drainage Area(Km2)	Peak Discharge (m3/sec)	Time of Peak	Volume(MM)
W290	1788.3	266.2	3 September 2006, 24:00	11839.79
W280	1557.8	273.0	3 September 2006, 24:00	12067.72
W380	941.8	128.9	11 May 2006, 24:00	12851.26
W360	1753.3	203.1	3 September 2006, 24:00	10553.42
W200	851.8	140.6	3 September 2006, 24:00	12158.29
Gololcha Outlet	6893.0	907.2	3 September 2006, 24:00	11741.59
J54	5951.2	882.5	3 September 2006, 24:00	11566.02
J57	3311.1	475.7	3 September 2006, 24:00	11265.83
J62	1753.3	203.1	3 September 2006, 24:00	10553.42
J65	4162.9	616.1	3 September 2006, 24:00	11448.43
J67	3311.1	474.3	3 September 2006, 24:00	11265.81
J70	1753.3	201.9	2 September 2006, 24:00	10553.40
J71	1753.3	202.0	3 September 2006, 24:00	10553.39
R40	3311.1	475.5	3 September 2006, 24:00	11265.81
R50	3311.1	474.3	3 September 2006, 24:00	11265.81
R80	1753.3	202.0	3 September 2006, 24:00	10553.39
R90	1753.3	202.7	3 September 2006, 24:00	10553.36
R130	1753.3	201.9	2 September 2006, 24:00	10553.40
R150	4162.9	616.3	3 September 2006, 24:00	11448.42
R170	5951.2	883.2	3 September 2006, 24:00	11565.98

4.4 Calibration and Validation Model

4.4.1 Model Calibration

The calibration was performed on the HEC-HMS model by adjusting parameters so that the simulated flow was as close as possible to the observed stream flow. The primary goal of the calibration was to match the observed and simulated stream flow as closely as possible. For instance, the actual peak discharge for the Gololcha watershed is 180.8m³/s, while the HEC-HMS model's predictions show that the peak discharge is 153.2 m³/s. The actual peak discharge occurred on September 3, 2006, while the HEC-HMS model's predictions show that the peak discharge occurred a couple of days later on September 5, 2006.

Although July and August have the highest values of precipitation, the HEC-HMS output has highest values of discharge in September. It is because of the delay of the hydrologic cycle between precipitation and runoff. The time difference between precipitation and runoff depends on watershed conditions, soil moisture condition before precipitation, and runoff process. The runoff does not always have the same timing as precipitation.

During calibration parameters of the watershed were varied in order to obtain the best performance for HEC-HMS model. The calibrated parameters were Lag time, Curve number, Initial abstraction, and Muskingum parameters K and X, and these were clustered to the following sets for conducting the sensitivity analysis: the sensitivity of parameters influencing the runoff most in HEC-HMS calibration were found to be: Curve Number (CN), Time lag / Time of concentration, Recession constant of base flow, Initial abstraction (Ia). After adjustment of these parameters, the HEC-HMS was able to best simulate observed stream flow in order to conduct runoff simulations for the Gololcha watershed.

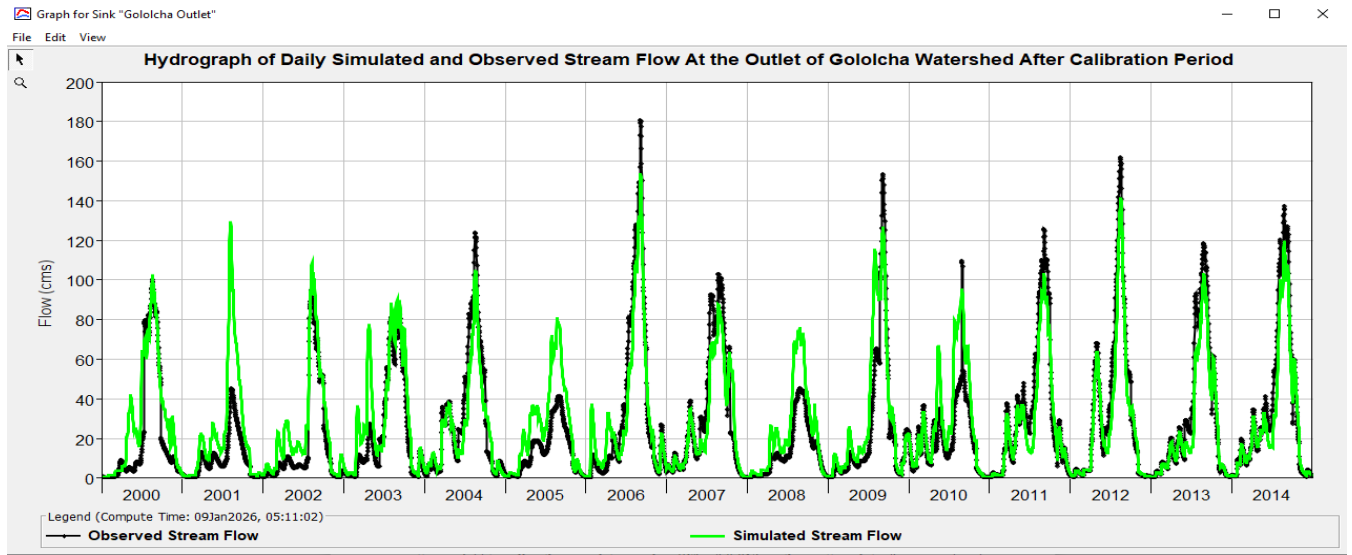


Figure 4. 4: Stream flow Calibration Performance of the HEC-HMS Model

Figure 4.4 presents the observed and simulated stream flow hydrograph at the watershed outlet of Gololcha after calibration of the model. Also, at calibration stage, simulated discharge was almost identical to the observed hydrograph, which indicated that both low and high flow stages were well represented by the simulated hydrograph.

Below figure 4.5 showing comparison of observed and simulated stream flow in the calibration period; it clearly shows the good match with correlation coefficient (R) value 0.813 of differences between observed and simulated stream flow values.

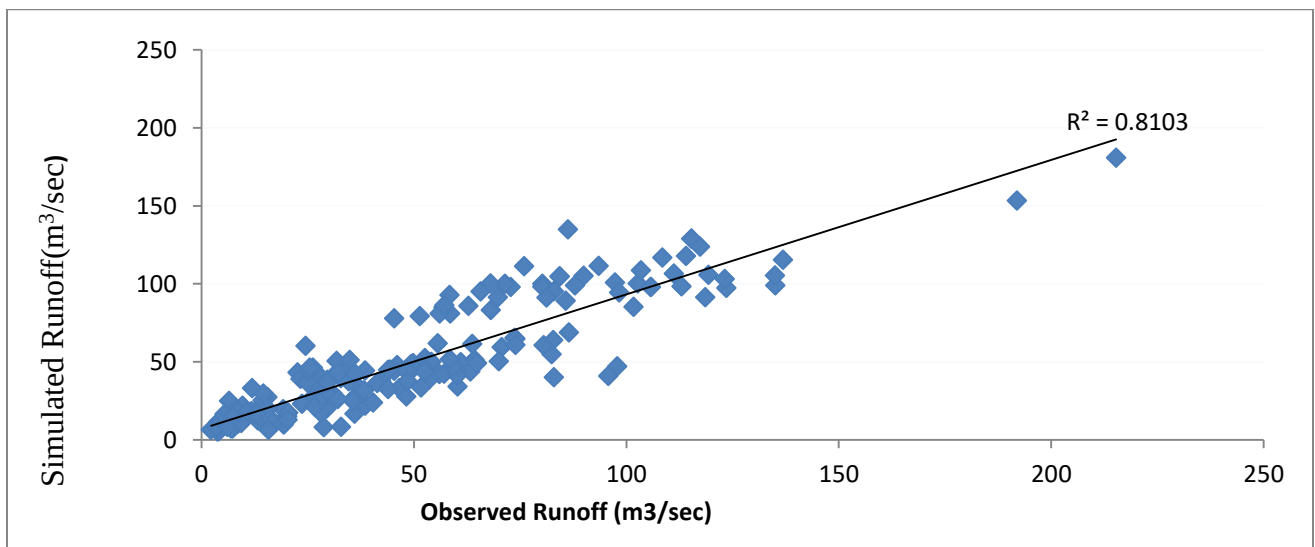


Figure 4.5: Correlation of observed flow after calibration.

4.4.2 Model Validation

The reliability of the calibrated HEC-HMS model is demonstrated by the validation findings, which show that the model's primary parameters are within acceptable bounds. Figure 4.6's comparison of the simulated and observed hydrographs for the Gololcha Watershed demonstrates how effectively the model captures the low and peak flows. The HEC-HMS model well captures the hydrological behavior of the watershed, as evidenced by the strong correlation between the simulated and observed stream flow values during the validation period.

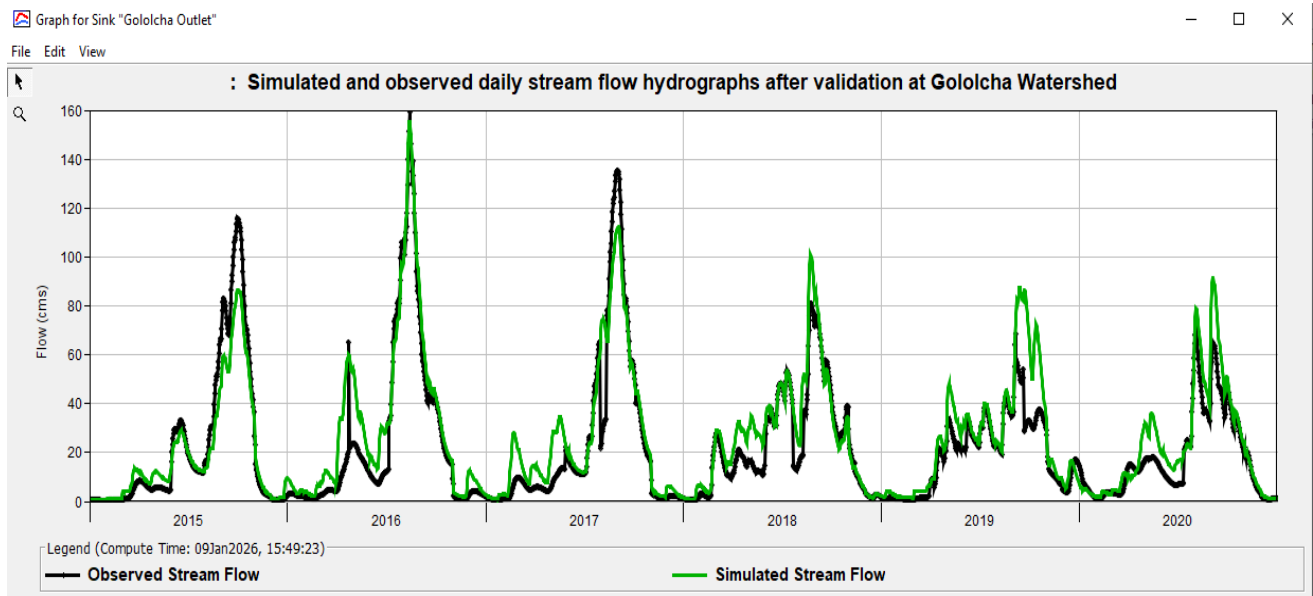


Figure4.6: HEC-HMS model validation hydrographs for the Gololcha watershed

Observed and simulated streamflow shows a strong agreement during validation period. So the graph plot for observed streamflow against simulated streamflow is shown in Figure 4.7. Similar to the calibration time, the watershed outlet streamflow hydrograph is well simulated by HEC-HMS as that it indicates the watershed hydrologic behavior in Gololcha Watershed.

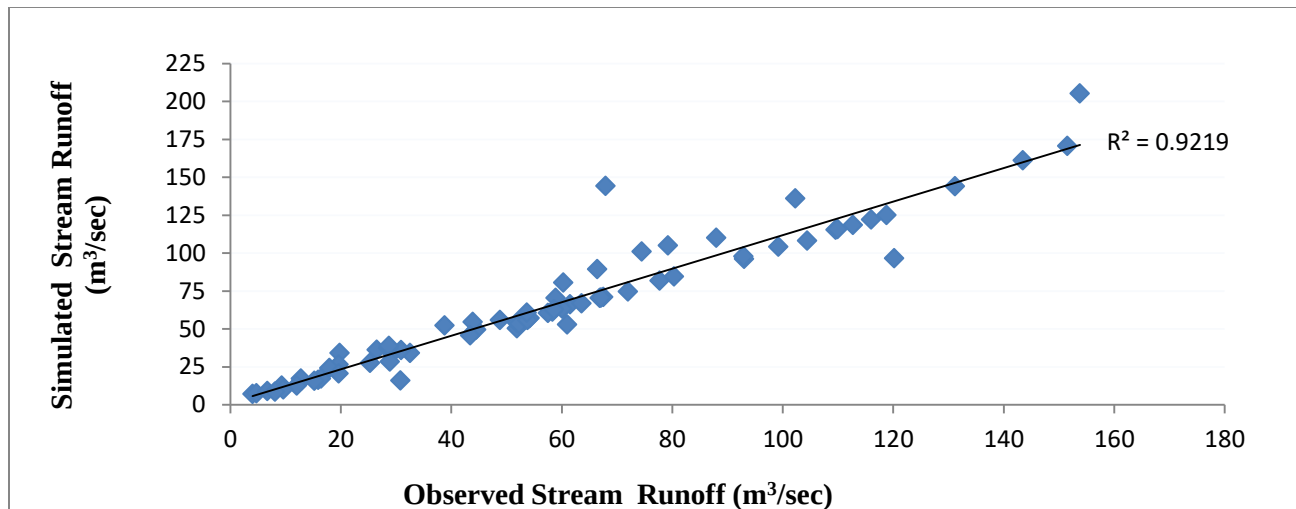


Figure 4.7: Validation of simulated stream flow against observed stream flow

4.5 Model Performance evaluation

The efficiency of the HEC-HMS model was tested with three common performance statistics. The most popular statistical measures for model performance are: Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Error (RMSE), and Coefficient of determination (R). Statistical criteria to measure watershed simulation model accuracy as per the definition of criteria of performance: Nash-Sutcliffe efficiency (NSE), coefficient of determination (R) and Root mean square error (RMSE). Performance is considered excellent if NSE and R values are between 0.75 to 1.0 and RMSE values between 0 to 0.5 (Moriassi et al., 2007).

For validation period, an RMSE was found to be 0.4, whereas for calibration period, an RMSE value was found to be 0.5. The calculated results are well correlated with each other, also fall within the acceptable limits, which implies that the simulation performed by the HEC-HMS model for Gololcha watershed is reasonable for simulating hydrological processes. In other words, it shows that hydrological processes are being adequately represented by the model.

It is observed that both during the calibration and validation period the model is functioning reliably and consistently through the entire period. From the above, it can be inferred that, given the rainfall inputs, the HEC-HMS configuration utilized is adequate in simulating daily stream flow for Gololcha watershed. Peak flood events are well simulated in model simulation; the relationship between observed and simulated flows shows high consistency.

Table 3.3: Summary of Calibration and Validation Results for HEC-HMS

Performance Rating	After calibration	After validation	Remark
Nash – Sutcliffe Efficiency	0.809	0.845	Very good
Root Mean Squared Error	0.4.	0.4	Very good
Coefficient of determination	0.813	0.92	Very good
Percent of Bias	11.97	14.03	Good

4.6 Rainfall-Runoff Relationships

Relationships between rainfall and runoff can also be used to understand the process through which rainfall in a watershed is converted to surface runoff. Various factors affect rainfall and runoff relationships.

These factors include soil characteristics, land use, topography, vegetation, and climate. The principal elements and determinants to be considered in rainfall-runoff relationships are briefly summarized in the table that follows. This study examines the rainfall and runoff relationship using validated data. As illustrated by Figure 4.8, there is a definite correlation between rainfall within a watershed and its runoff.

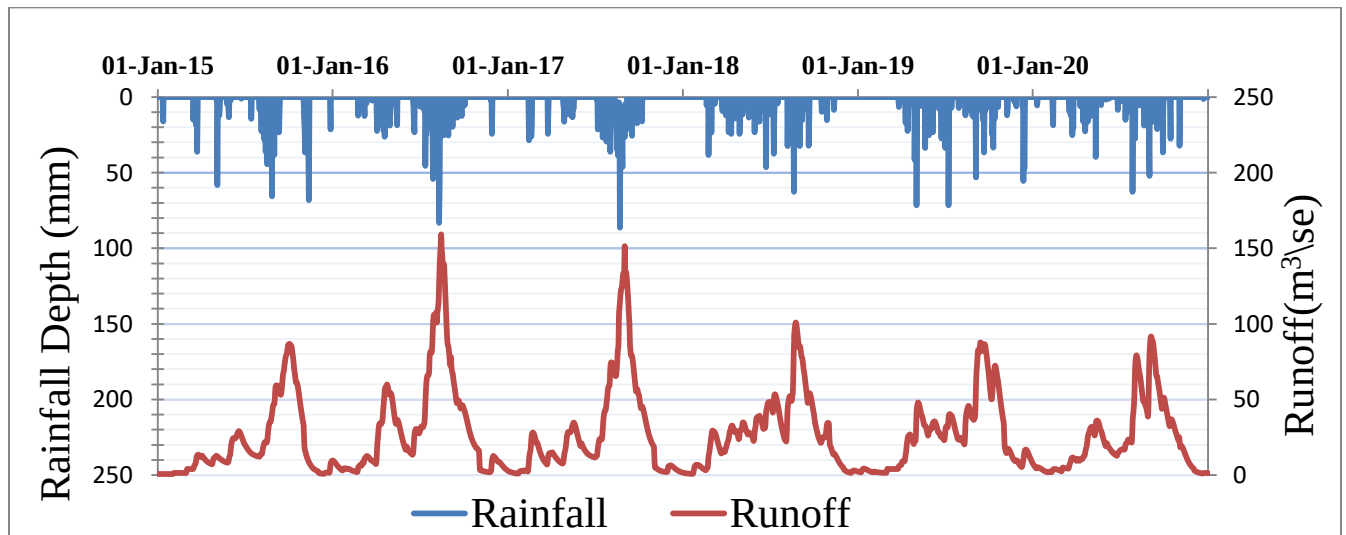


Figure 4.8 Watershed Rainfall-Runoff relationships for the validated data

4.7 Flood Prediction for Different Return Periods

4.7.1 Flood Simulation Using HEC-HMS for Different Return Period

Using the IDF curves provided in the drainage design manual of the Ethiopian Roads Authority the rainfall depths for specified return periods were determined for storm durations of 0.083, 0.25, 1, 2, 6, 12 and 24 hours. The design rainfalls determined were then input to HEC-HMS to simulate the flood response of the Gololcha Watershed.

The longest storm duration at which the greatest rainfall depth occurred was 24 hours for all the return periods selected. This finding is consistent with the features of Rainfall Region Three (RR-3), where deeper rainfall is usually associated with longer storm durations.

Higher surface runoff from deeper rains results in bigger peak flows at the watershed outflow. Table 4.4 below shows the rainfall depths calculated for all return intervals and durations. The rainfall depths were then used in deriving the design flood values, which is required during flood risk analysis and the design of hydraulic structures in the watershed.

Table 4.4: Rainfall Depth (mm) for Various Return Periods for Gololcha watershed

Rainfall intensity duration(hr.)	Rainfall Depth (mm) versus Return Periods (yrs.)							
	2	5	10	25	50	100	200	500
0.083	10.46	13.12	14.89	17.15	18.85	20.54	22.26	24.56
0.25	21.88	27.43	31.14	35.86	39.40	42.96	46.54	51.35
1	37.03	46.43	52.70	60.69	66.68	72.70	78.76	86.90
2	41.86	52.48	59.57	68.60	75.38	82.92	89.04	98.24
3	43.76	54.87	62.28	71.72	78.81	85.92	93.09	102.70
6	45.84	57.48	65.24	75.14	82.56	90.01	97.52	107.60
12	46.96	58.88	66.83	76.97	84.58	92.20	99.90	110.22
24	47.54	59.61	67.66	77.92	85.62	93.34	101.13	111.58

Table 4.5 displays the predicted peak discharges at the outlet of the Gololcha Watershed for 24 hour storms of varying return periods from 2-500 years. A clear pattern of increasing peak discharge with increasing return period can be observed. This increase in return periods causes greater rainfall depth in the watershed. In turn, this causes the discharge to increase. In other words, it was determined that rainfall with a depth of 47.54 mm resulted in a peak discharge of 106.8 m/s in a 2-year return time.

The corresponding peak discharge increased dramatically in relation to return time. For the 25-year return time, peak discharge was calculated to be 302.5 m/s; it increased to 449.1 m/s in the 100-year return time. The largest peak discharge, 630.3 m/s, occurred in relation to the 500-year return time, with a corresponding rainfall depth of 111.58 mm. The enormous rise in peak discharge values for large return periods reflects that extreme precipitation events caused the excess runoff, since infiltration loss is extremely small.

The results obtained in this research are in line with the results obtained in many Ethiopian watersheds using the HEC-HMS model. The findings from the Gilgel Abay watershed and other parts of the Upper Blue Nile Basin also indicate that longer return periods produce considerably higher peak discharge values (Aliye et al., 2020; Fanta et al., 2021). The results obtained in this research confirm that higher return periods result in significantly higher values of peak discharges in the Gololcha watershed.

The difference between the results obtained for moderate return periods and extreme return periods is very high. Peak discharge values increased from 302.5 m³/s for a 25-year return period to 449.1 m³/s for a 100-year return period, demonstrating that flood damage extends beyond simple structural damage. Additionally, it is anticipated that future flood damages brought on by land use and climate change variability will raise peak discharge values. The Gololcha watershed with the goal of reducing flood damages. From the flood risk management perspective, flood damages due to flood events with return periods of 500 years are considered to be minimum in the Gololcha watershed. Additionally, increased flood damage will result from changes to future land use and a changing climate.

Table 3.5: Rainfall and Peak Flow for various returns period

S. No	Return Period	24 hr. storm(mm)	Peak flow (m3/s)
1	2	47.54	106.8
2	5	59.61	176.5
3	10	67.66	227.1
4	25	77.92	302.5
5	75	85.62	379.6
6	100	93.34	449.1
7	200	101.13	523.2
8	500	111.58	630.3

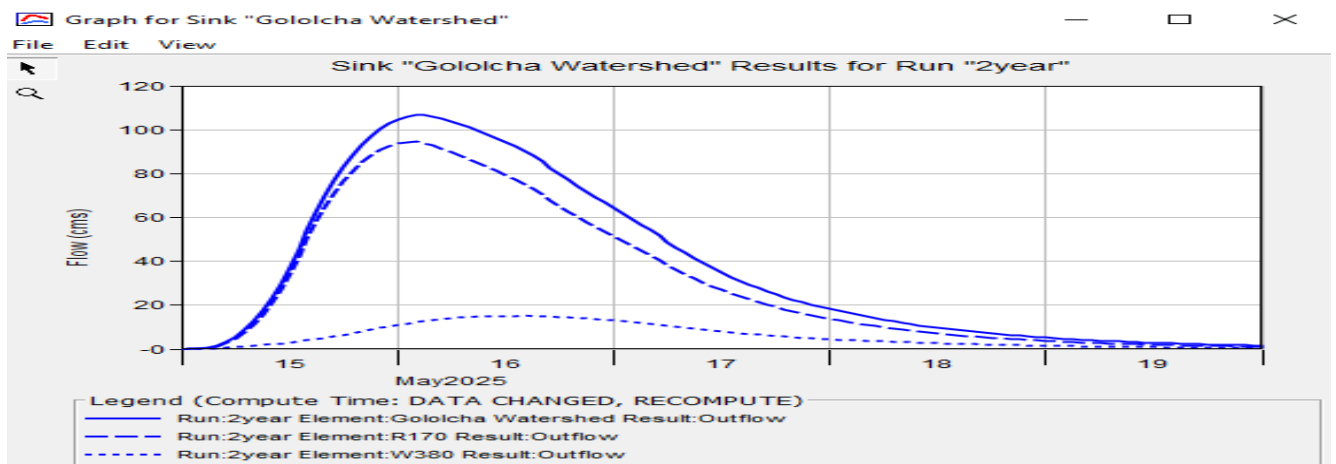


Figure4.8: 2-Year Storm Flow Hydrograph of Gololcha Watershed

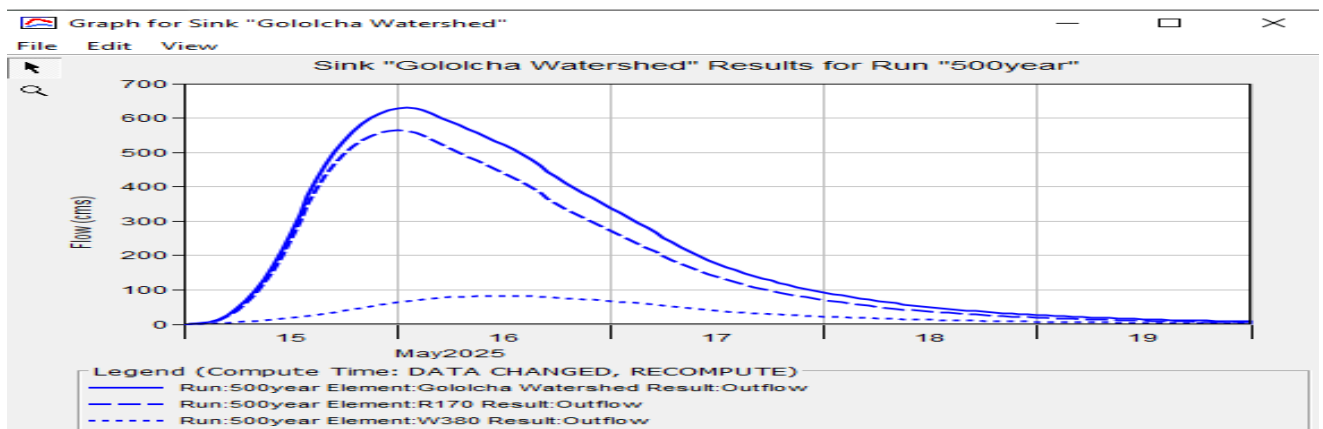


Figure4.9: 500 Year Storm Flow Hydrograph of Gololcha Watershed

The storm flow hydrographs for 2 yr return period and 500 yr return period derived using HEC-HMS shown in Figure 4.7 and 4.8 below. The rest of the return periods of 5, 10, 25, 50, 100, 200 and 500 year can be seen at Appendix-4.

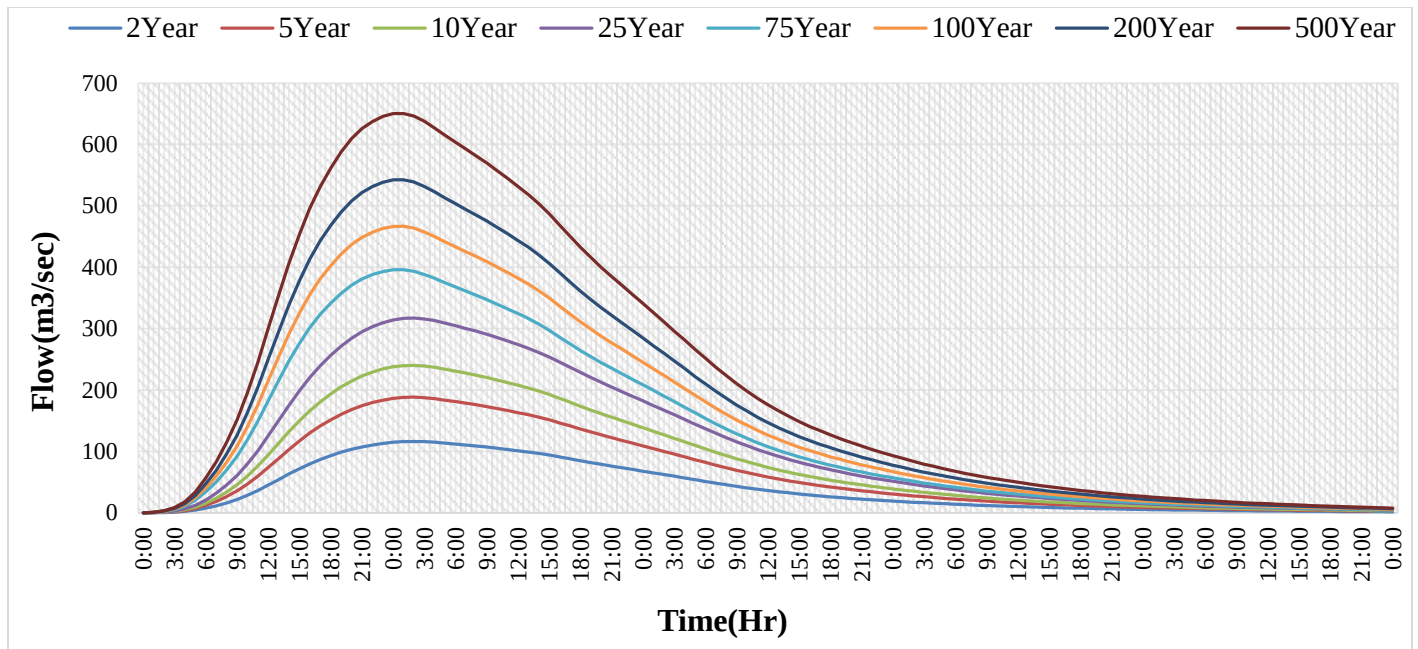


Figure 4. 10: Peak flood magnitudes in the Gololcha watershed simulated using HEC-HMS.

4.7.2 Evaluation of HEC-HMS Result with other Frequency Analysis Methods

The results of maximum discharge from HEC-HMS and those obtained from statistical method (frequency analysis) for Gololcha Watershed. Statistical analysis was used to check which statistical distribution fits the data and using GEV distribution and GPD.

The topic in this case was the comparison of the calculated max flood magnitude for each return period, shown in fig 4.11. The return periods derived from HEC-HMS and the results from the easy fit were compared.

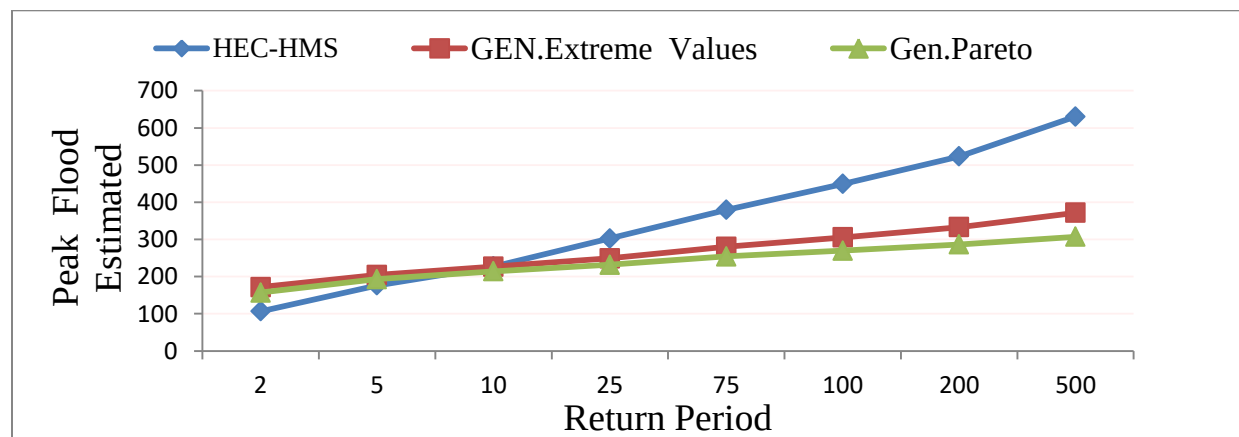


Figure 4.11 estimated flood by HEC-HMS and Statistical methods

Table4.6: Peak Flood Estimates from HEC-HMS and Statistical Methods

Return period	Discharge (m ³ /s)		
	HEC – HMS	Gen. Extreme Value	Gen. Pareto
2	106.8	171.4	156.8
5	176.5	204.12	193.3
10	227.1	226.752	214.1
25	302.5	249.16	231.8
75	379.6	280.19	254.0
100	449.1	305.63	269.7
200	523.2	332.95	286.4
500	630.3	371.70	307.2

In all return periods, Table 4.6 shows that the flood frequency analysis of HEC-HMS uniformly estimates higher peak discharges than General Extreme Value (GEV) and General Pareto (GP) models. For example, at the 500-year return period, HEC-HMS predicts 630.3m³/s, while GEV and GP predict 371.7 m³/s and 307.2 m³/s, respectively. These higher estimates indicate that HEC-HMS uses a conservative modeling approach, which is advantageous for designing vital flood control infrastructure, such as dams, spillways, and levees, thereby reducing the risk of major failures.

The variations in the outcomes observed the necessity of calibrating the HEC-HMS model to the specific conditions of the Gololcha Watershed and validating the outcomes using both statistical methods and observed data. Simulated outputs from the HEC-HMS can be combined with the results obtained from the GEV and GP models in flood risk assessment, thus providing an integrated basis for decision-making. Thus, in conclusion, even though HEC-HMS provides a safety-oriented methodology, the integration of HEC-HMS with the results obtained from the GEV and GP models can provide an effective basis for achieving the balance between cost-effectiveness and safety in infrastructure development.

4.8 The SepHydro Hydrograph Tool is used to separate base flow from surface runoff.

4.8.1 Hydrograph Separation Result

Hydrograph separation was carried out through the SepHydro software tool. This tool applies the Eckhardt recursive digital filter. In this study, we used hydrograph separation parameters: $BFI_{max} = 0.40$ and $\alpha = 0.90$. The daily discharge from January 2000 to December 2020 was used for hydrograph separation, which comprised 7,499 daily values. The hydrograph obtained from hydrograph separation effectively separates base flows from total stream flows. Figure 4.11 show hydrograph, base flows are represented in red and total stream flows are represented in blue.

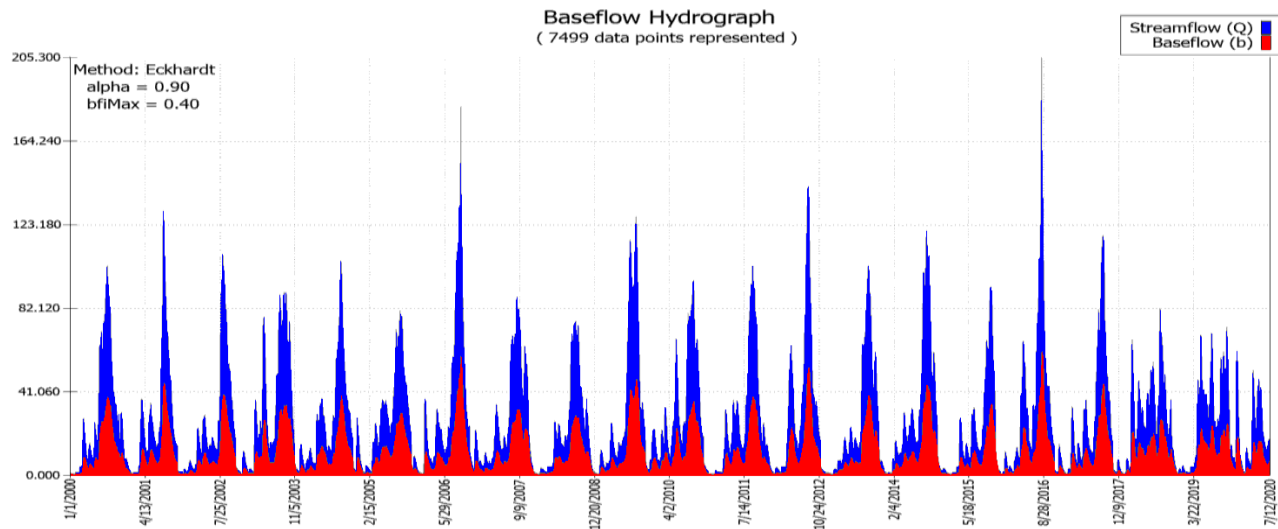


Figure 4.12 Hydrograph-Based Base Flow Separation Using SepHydro

4.8.2 Characteristics of Stream Flow, Base Flow and Surface flow

The hydrograph shows clear peaks during the rainy season due to storm runoff and clear declines in the dry season. The hydrograph thus suggests that groundwater discharge is an important component in maintaining the river's discharge in the absence of rainfall. From the above discussion about the separation of the hydrograph, it can be concluded that the average base flow is $11.11\text{m}^3/\text{s}$, which forms 39.9% of the total discharge. In other words, the discharge from groundwater forms almost two-fifths of the total discharge.

The higher value of baseflow suggests good coupling between the surface and groundwater system. Baseflow is an important part of the stream discharge during the dry periods and during the time when runoff (direct) is less. Surface runoff (quick flow) in this study has been computed by excluding the baseflow part from stream discharge. The mean surface flow was determined to be 16.7m³/s, accounting for 60.1% of the total flow. The above-mentioned surface flow includes direct runoff and quick surface storm flow due to rainfall in the watershed area. The peaks in the hydrograph (Figure 4.12) indicate that surface flow dominates in the watershed area due to the quick hydrological response of the watershed area to rainfall intensity and land covers.

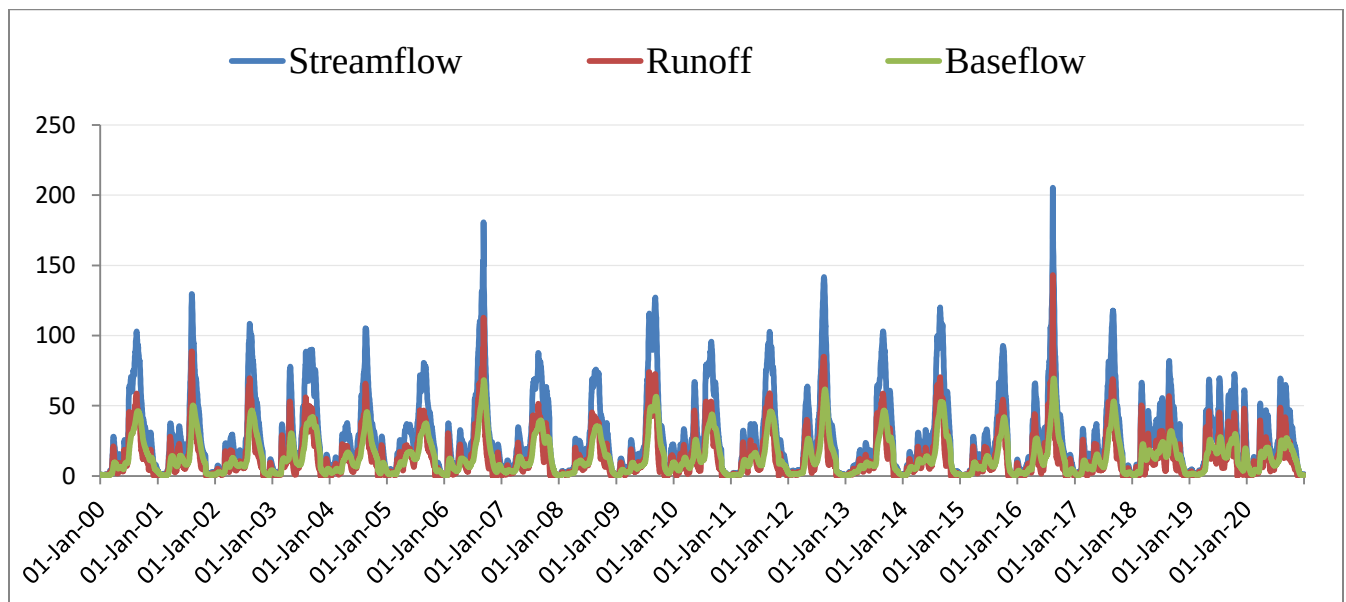


Figure 4.13 Graph of Stream flow, Base flow And Surface flow

Table4.7 Summary of Base flow and Surface flow Results

Component	AverageValue (m ³ /s)	Contribution (%)
Total Stream flow (Q)	27.81	100%
Base flow (BF)	11.11	39.9%
Surface Flow (SF)	16.7	60.1%

5. Conclusion and recommendation.

5.1 Conclusion

This study has successfully simulated the rainfall–runoff process in the Gololcha watershed using the HEC-HMS model. This study has also successfully evaluated the performance of the HEC-HMS model in flood estimation. The primary aim of this study was to simulate the rainfall–runoff process in the Gololcha watershed using the HEC-HMS model. This study has also attempted to evaluate the applicability of the HEC-HMS model in flood estimation. The HEC-HMS model has been developed based on hydro-meteorological data, hydrological characteristics of the watershed, land use/land cover information, and soil data. The rainfall in the study area has been estimated based on the Thiessen Polygon Method. The rainfall values have been considered as input values in hydrological simulation. The performance of the HEC-HMS model has been evaluated through calibration and validation stages. In the calibration stage, the HEC-HMS model has been able to obtain an NSE value of 0.809, R^2 value of 0.813, and PBIAS value of 11.97 %. In the validation stage, the HEC-HMS model has been able to obtain an NSE value of 0.845, R^2 value of 0.92, and PBIAS value of 14.08 %. This indicates a good agreement between the observed values and simulated values. This proves the ability of the HEC-HMS model in simulating the hydrological processes in the Gololcha watershed. The rainfall–runoff simulation has proved the ability of the watershed to produce a rapid response to rainfall. The change in runoff values for the sub-basins was mainly influenced by curve number, lag time, and initial abstraction, which represent the effect of land use, soil, and slope on hydrological response in the watershed. The sensitivity analysis identified these parameters as the most significant in simulating the stream flow. The flood prediction analysis showed that peak discharge increases as the return period increases. The peak discharge values vary from 106.8m³/s for a return period of 2 years to 630.3m³/s for a return period of 500 years, which shows the flood potential in the watershed is very high for extreme values of rainfall. These values are very significant for flood management, design of hydraulic structures, and planning of water resources in the study area. In conclusion, it can be stated that the results from this study show that the HEC-HMS model is a powerful tool for simulating runoff and flood prediction in the Gololcha watershed.

5.2 Recommendation

According on the findings of this study, the following recommendations are forwarded for future or further study:

- Better outcomes were attained based on the modeling work done in the Gololcha watershed's selected catchments. For various hydrological and environmental studies, flow forecasting, future urbanization impact assessment, flood damage reduction, reservoir design studies, and overall systems operation, the simulation findings may thus be utilized directly or in conjunction with other software.
- LULC, topography, soil moisture condition (SMC), and soil type all have a significant impact on the Curve Number (CN) value, which determines flood generation. Therefore, researchers should consider these parameters while determining CN.
- The primary issue with the HEC HMS model is the absence of relevant and high-quality data. To solve this issue, more meteorological stations both inside and outside the basin should be added, and new data recording methods should be taken into consideration. The quality and suitability of the available data are more crucial than anything else when it comes to model calibration and improving model consistency.
- To improve the model's performance in modeling runoff with combinations, it is better to develop the watershed's local and regional curve numbers and find locally valid unit hydrographs rather than depending on tabular standardized curve number values.

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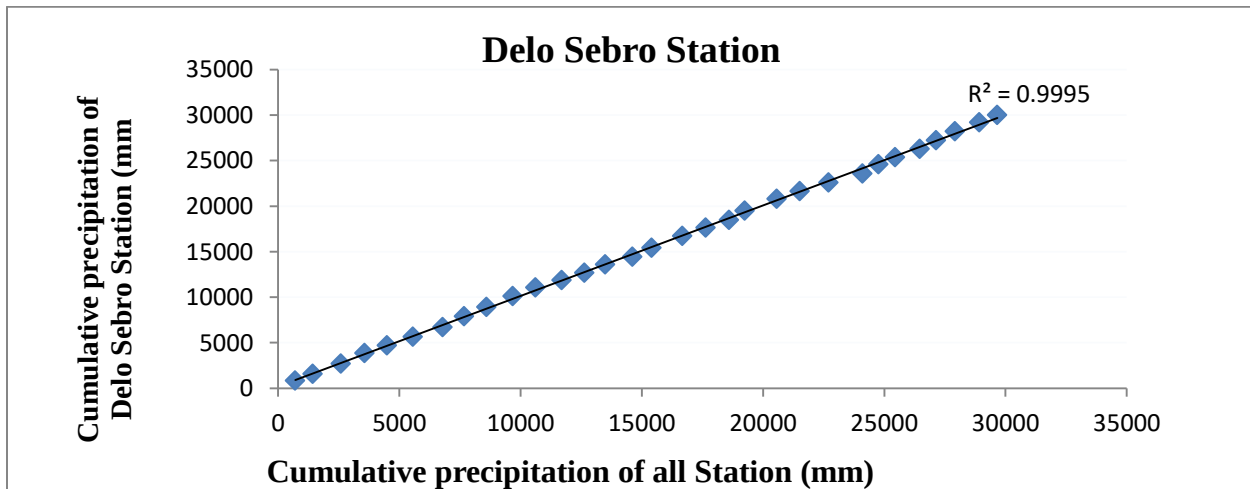
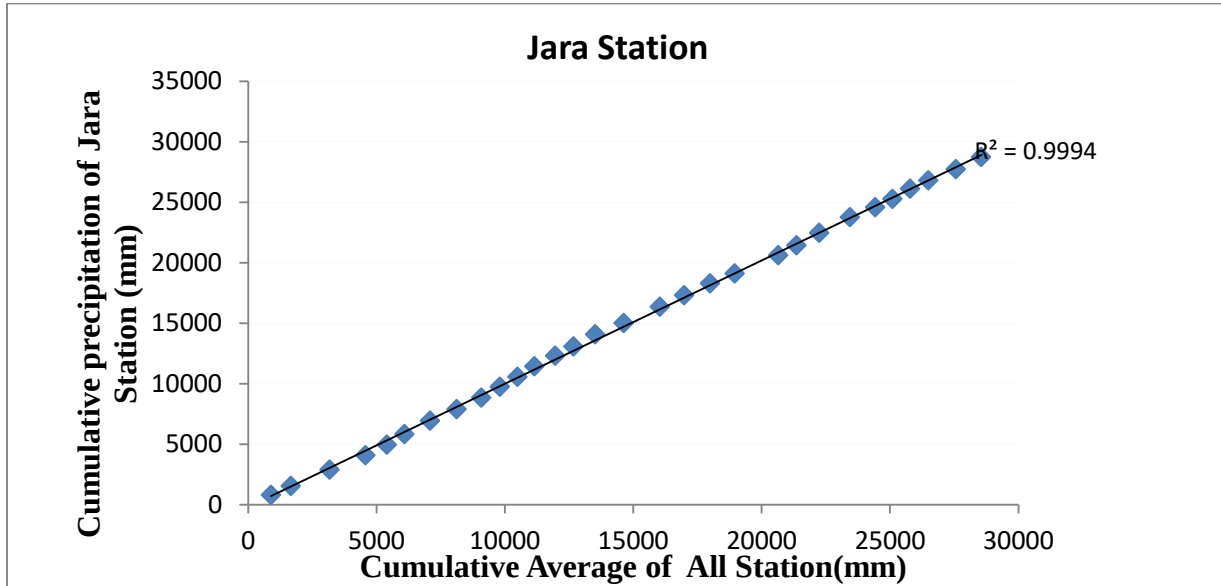
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APPENDIXES

APPENDIX-1: RESULTS OF CONSISTENCY CHECK



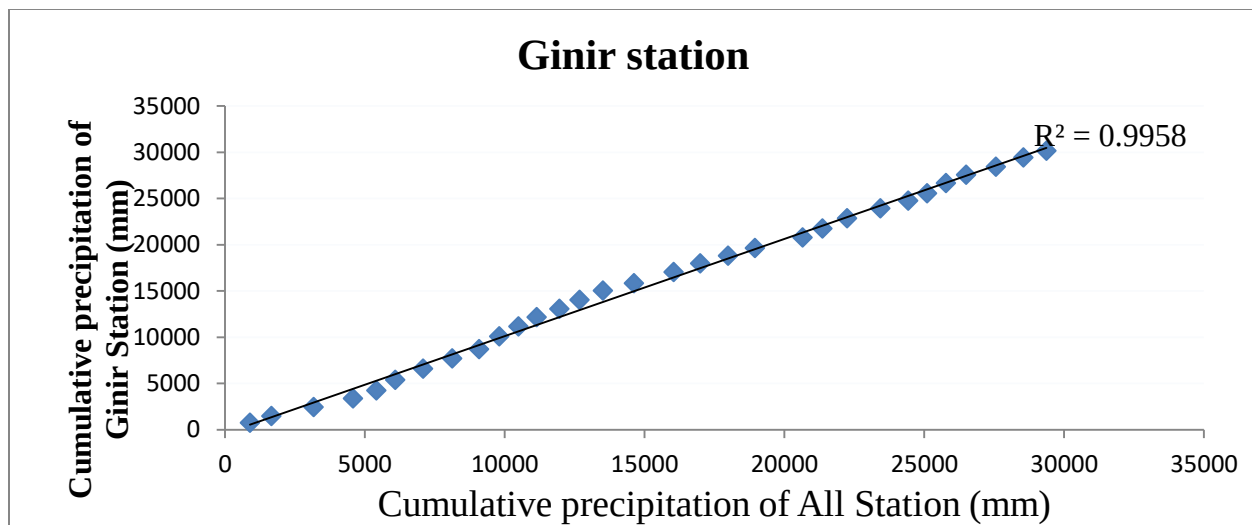
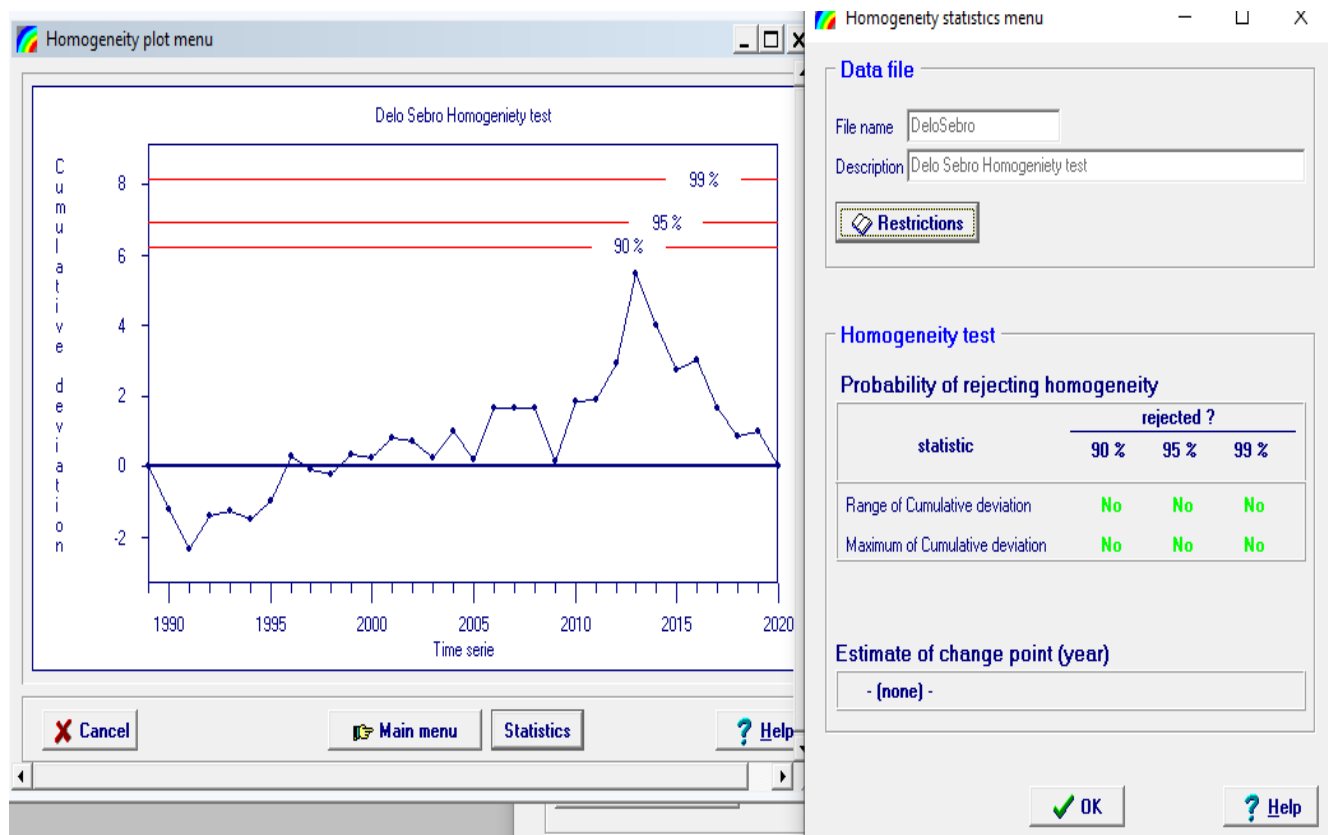


Figure 1.1. Consistency Check Results of Delo Sebro, Ginnir, and Jara Stations, respectively.

APPENDIX-2: RESULTS OF HOMOGENEITY TESTS



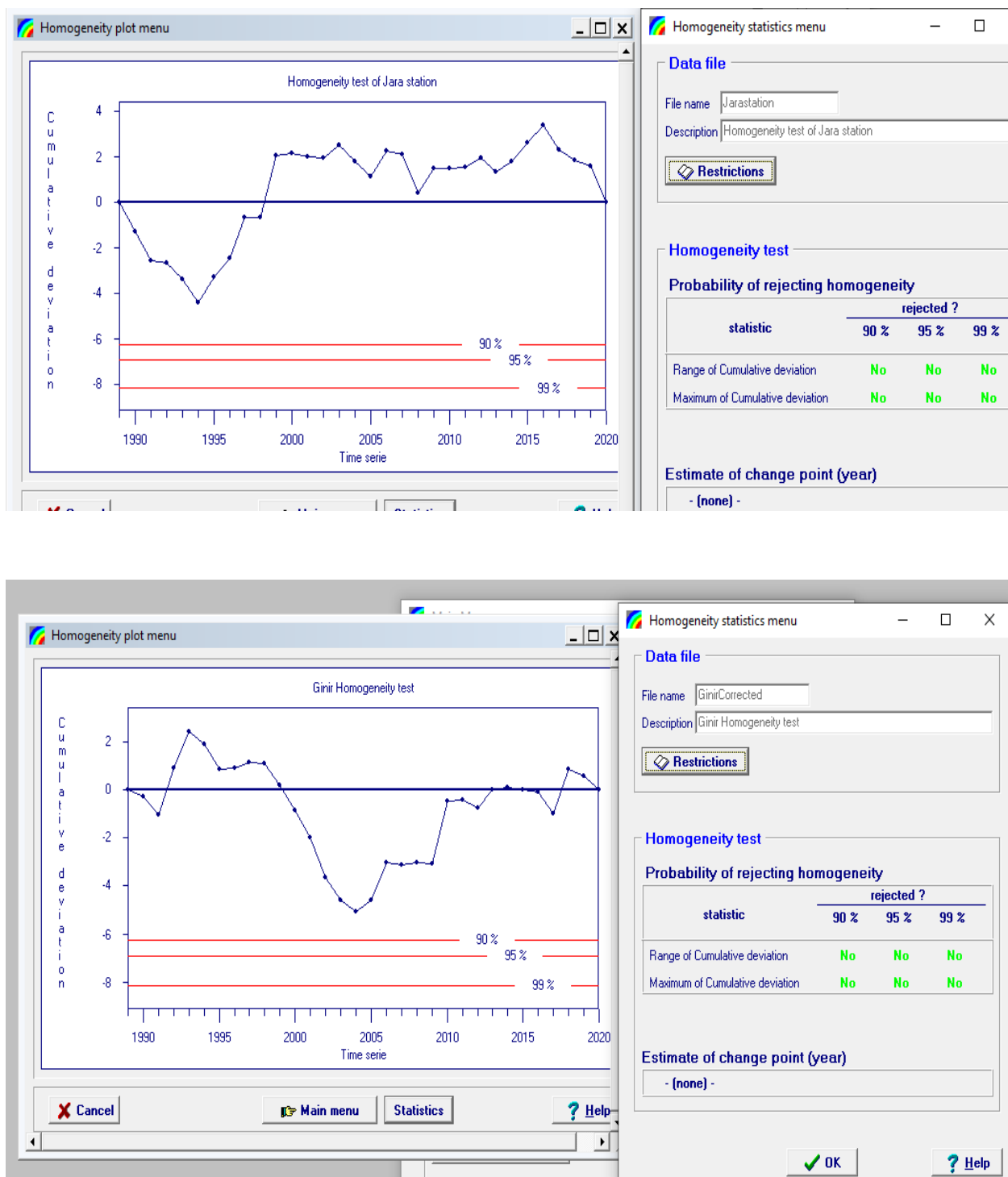
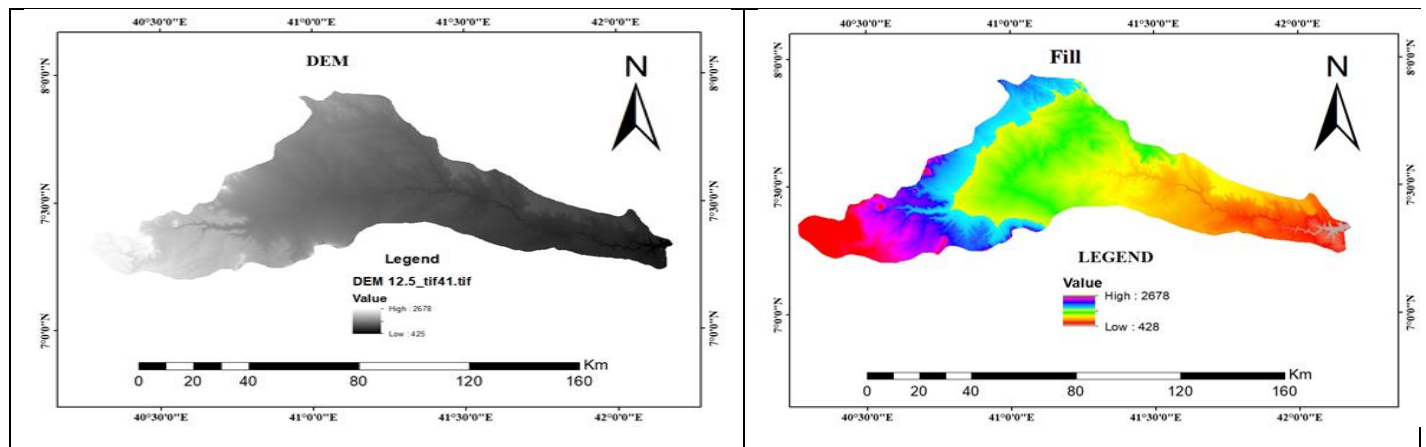
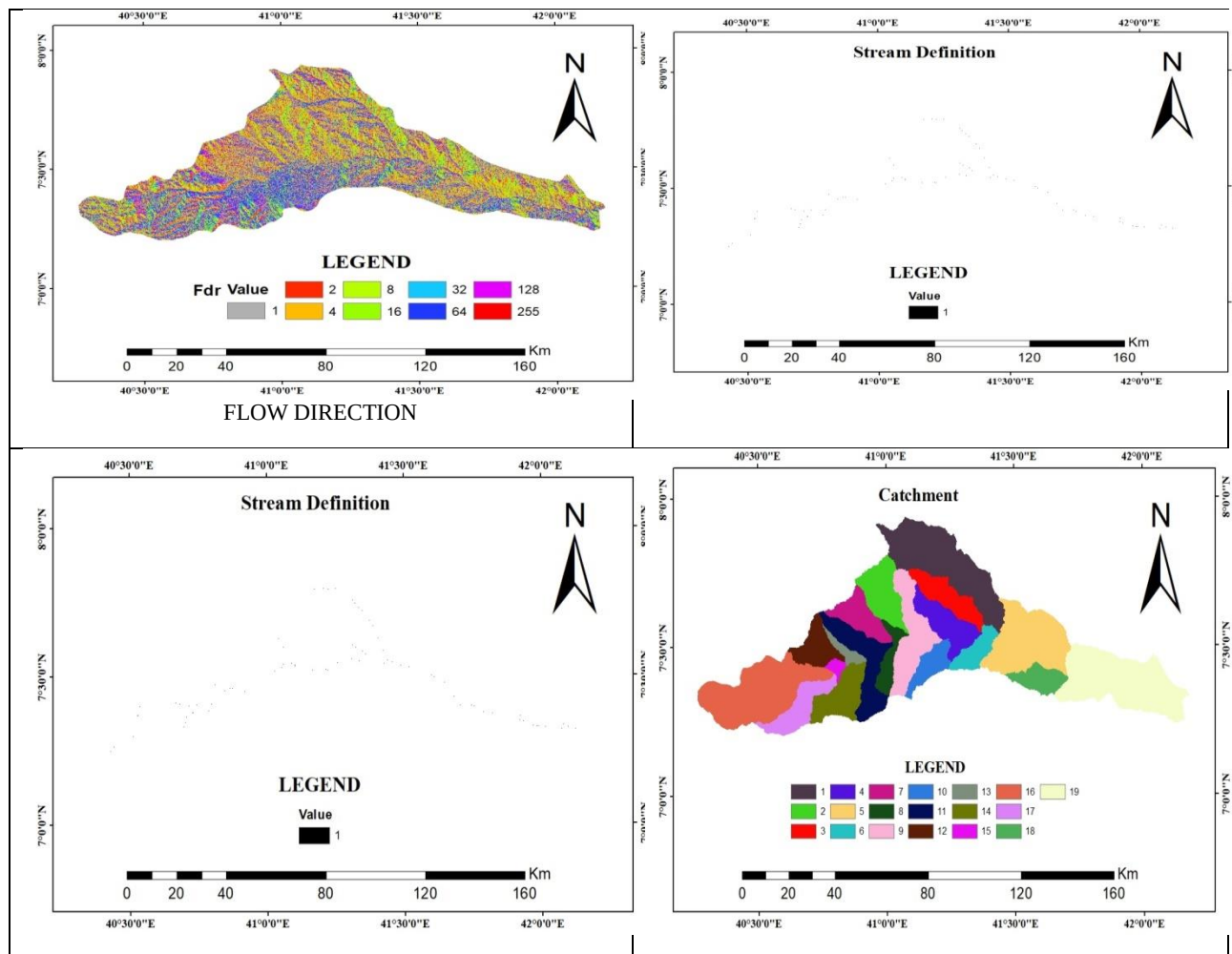


Figure 2.1: Homogeneity test results of Delon Sebros, Ginir, and Jara Stations, respectively.

Table				
LULC and Soil Union				
OBJECTID *	Unit_name	Txt_USDA	HSG	
1	Lithic Leptosols	Clay Loam	D	
2	Cambic Arenosols	Sand	A	
3	Chromic Cambisols	Clay Loam	D	
4	Chromic Luvisols	Sandclay loam	C	
5	Eutric Cambisols	Loam	B	
6	Eutric Fluvisols	Loam	B	
7	Eutric Vertisols	Clay(Light)	D	
8	Haplic Calcisols	Loam	B	
9	Lithic_Leptosols	Clay loam	D	
10	Petric Calcisols	Sandy Clay Loam	C	
11	Rendzic Leptosols	Loam	B	

APPENDIX 3: RESULTS OF TERRAIN PREPROCESSING





APPENDIX-4: HEC-HMS OUTPUT RESULTS

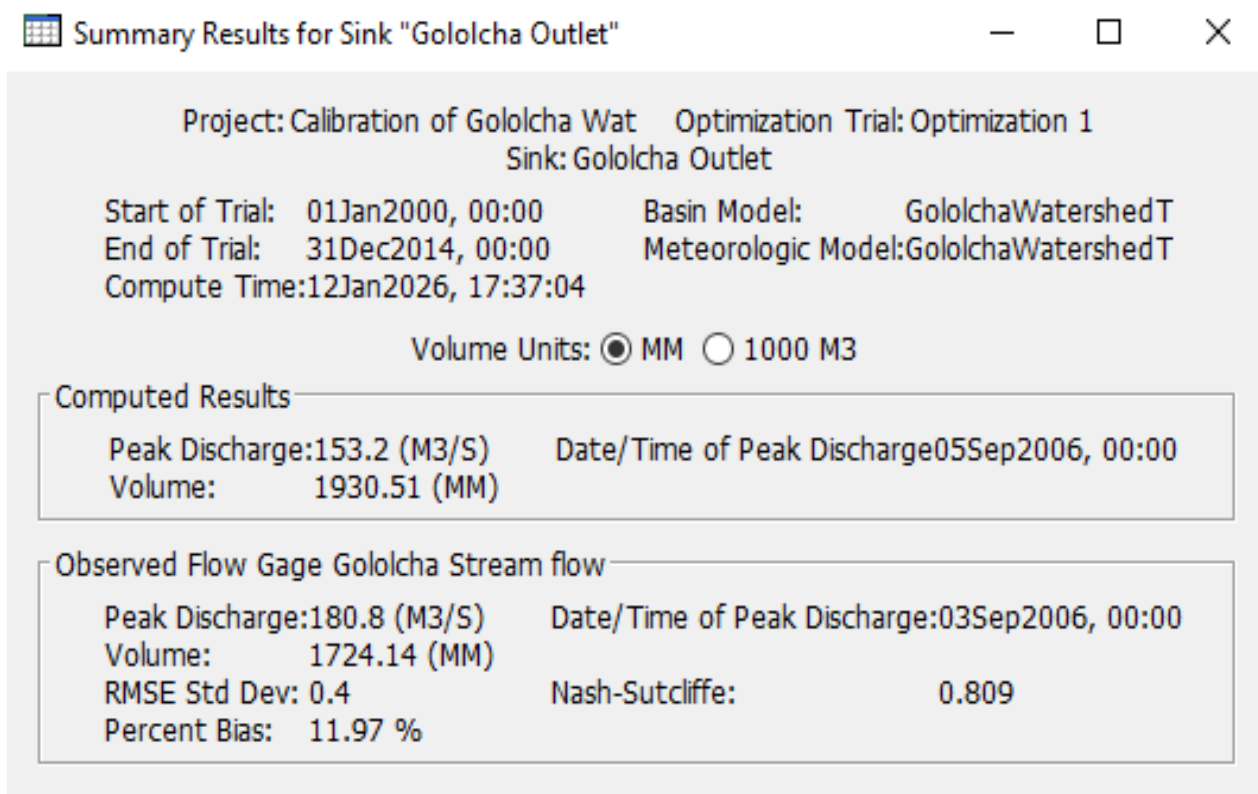
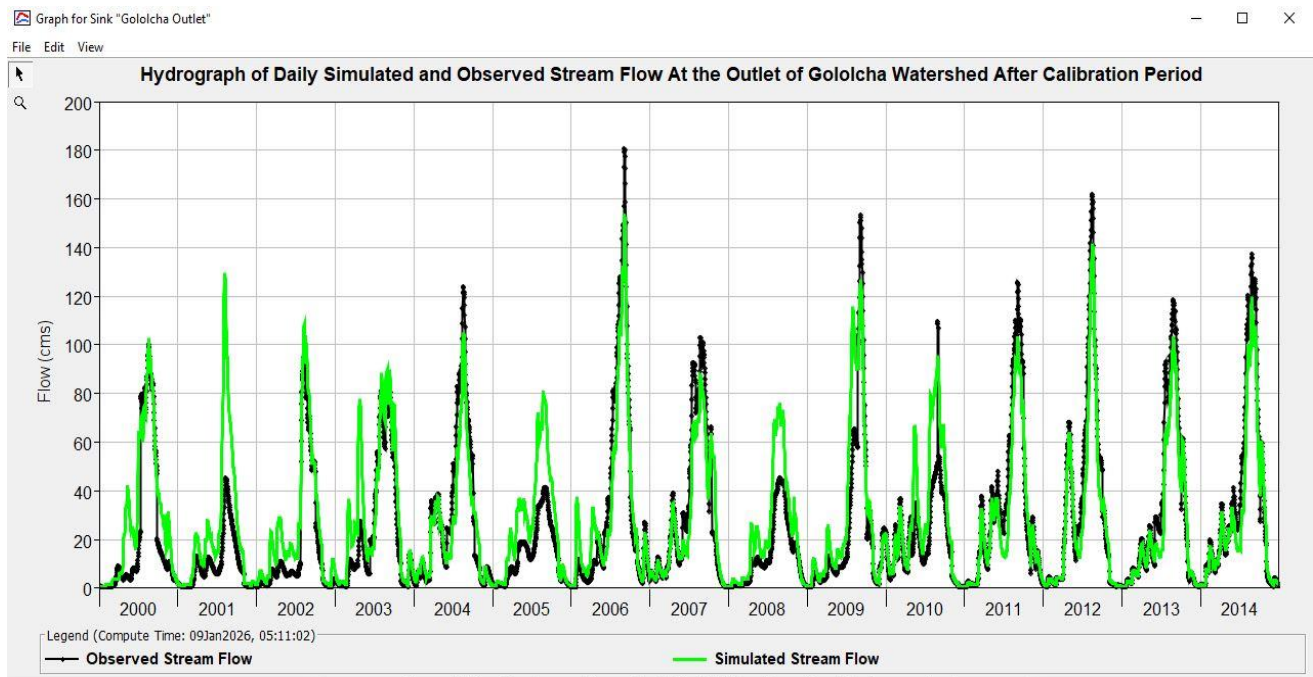


Figure 4.1: Calibration Results of Simulated and Observed Stream flow Hydrograph

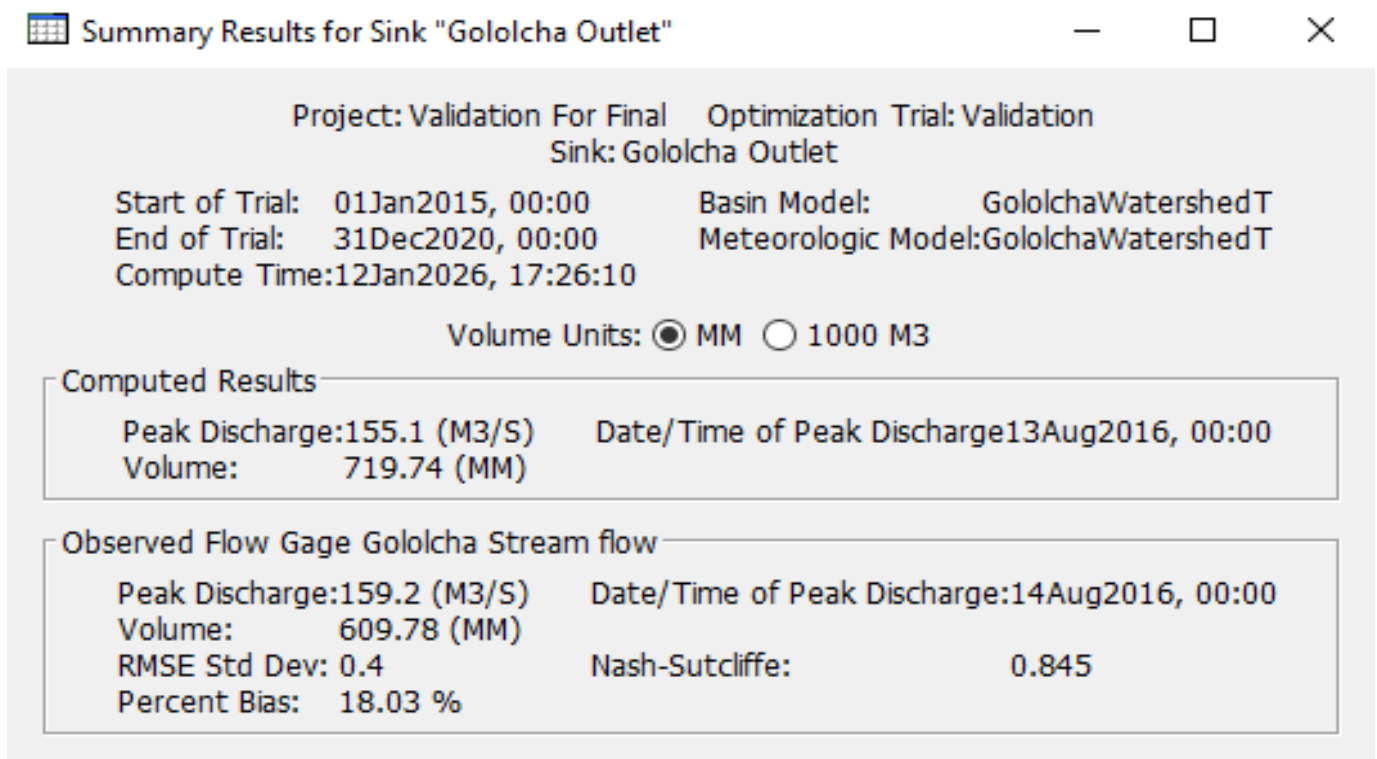
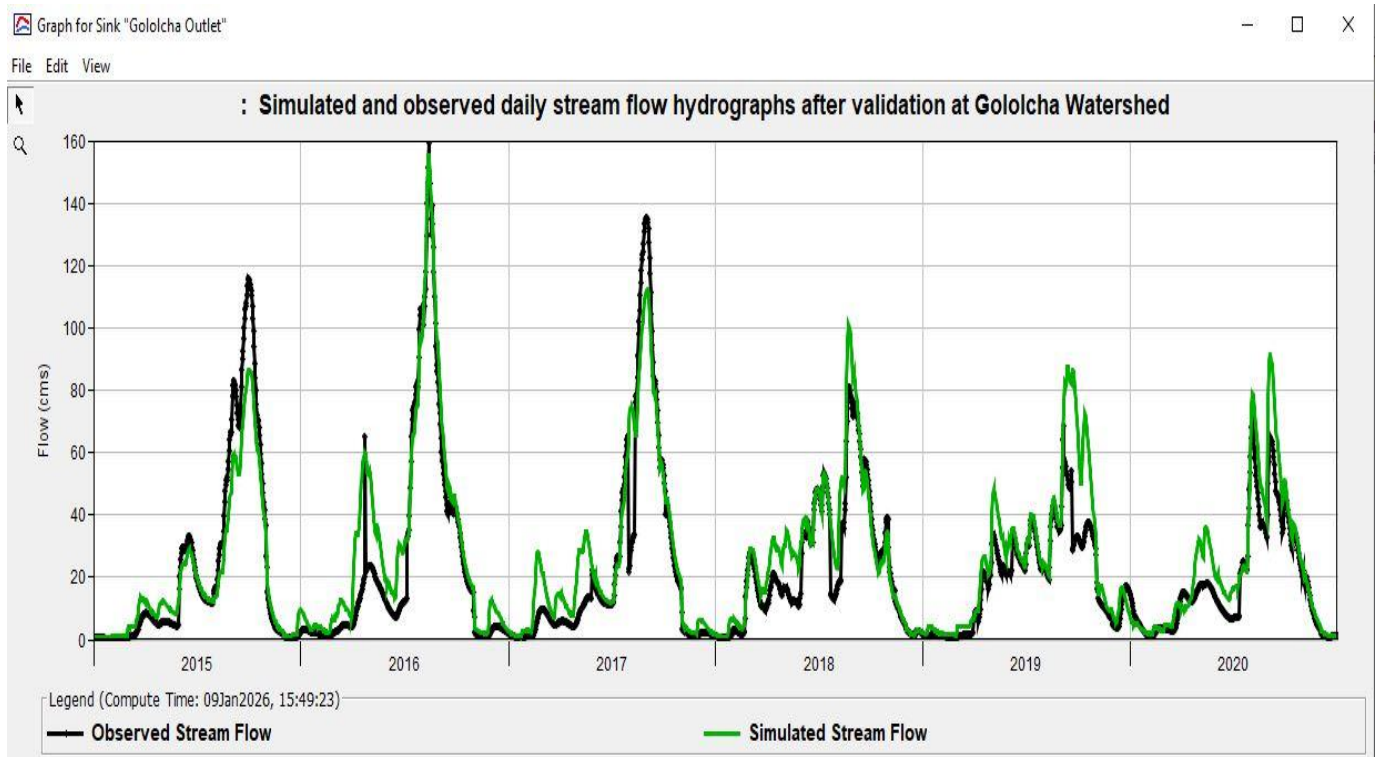


Figure 4.2: Validation Result of Simulated and observed Stream flow Hydrograph

APPENDIX-5: ETHIOPIA RAINFALL REGION

REGION Appendix- 5.1: Ethiopia Rainfall region

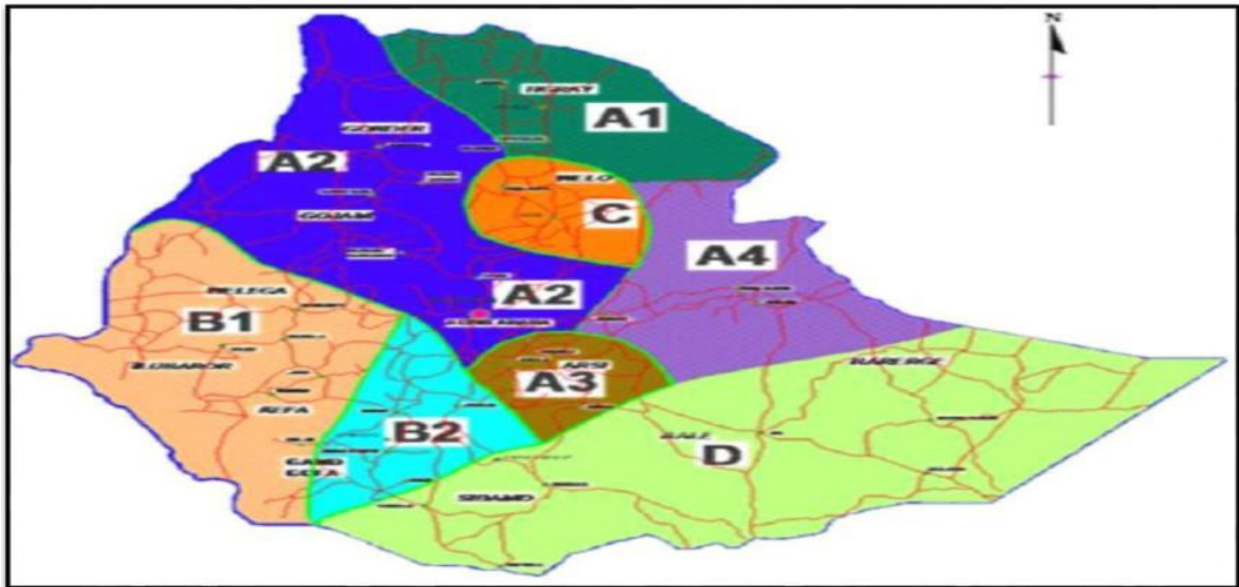


Figure 5..1. Ethiopian Rainfall Regions

Table5.1: Meteorological Stations (years of record through 2010)

Meteorological Region	Station	Years of Record	Meteorological Region	Station	Years of Record
A1	Axum	17	B	Bedele	39
	Mekel e	46		Gore	56
	Maychew	32		Nekempte	40
	Gondar	52		Jima	54
	Debre Tabor	15		Arba Minch	23
A2	Bahir Dar	45	C	Sodo	49
	Debre Markos	55		Awasa	36
	Fitche	44		Kombolcha	57
	Addis Ababa	57		Woldiya	29
	Debre Zeit	55		Sirinka	27
A3	Nazareth	46	D1	Gode	33*
	Kulumsa	43		Kebri Dihar	40
A4	Robe/Bale	29	D2	Kibre Mengist	33
	Metehara	24		Negele	51
	Dire Dawa	58		Moyale	29
	Mieso	42		Yabelo	34

Source: ERA Drainage manual, 2013

APPENDIX- 6: SCS –CN FOR DIFFERENT LU/LC AND HYDROLOGIC SOIL GROUP

Table 6.1: Runoff curve number for urban area

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area ²	A	B	C	D
<i>Fully developed urban areas</i>					
Open space (lawns, parks, golf courses, cemeteries, etc.) ³ :					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) ⁴		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
<i>Residential districts by average lot size</i>					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acre	12	46	65	77	82
<i>Developing urban areas</i>					
Newly graded areas (pervious areas only, no vegetation) ⁵		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c					

¹ Average runoff condition, and $I_a = 0.2S$.

² The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.

³ CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

⁴ Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

⁵ Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4, based on the degree of development (imperviousness area percentage) and the CN's for the newly graded pervious areas.

Table 2.2: Runoff curve number for another agricultural area

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Hydrologic condition	A	B	C	D
Pasture, grassland, or range – continuous forage for grazing. ²	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow – continuous grass, protected from grazing and generally mowed for hay.	–	30	58	71	78
Brush – brush-weed mixture with brush the major element. ⁵	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 ⁴	48	65	73
Woods – grass combination (orchard or tree farm). ³	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. ⁶	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 ⁴	55	70	77
Farmsteads – buildings, lanes, driveways, and surrounding lots.	–	59	74	82	86

¹ Average runoff condition, and $I_a = 0.2S$.

² *Poor*: <50% ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: >75% ground cover and lightly or only occasionally grazed.

³ *Poor*: <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

⁴ Actual curve number is less than 30; use CN=30 for runoff computations.

⁵ CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

⁶ *Poor*: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

APPENDIX- 7 : Rainfall and stream flow data used for study

Table 7.1 Delo sebro station monthly rainfall (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2000	2.5	0	28.5	71.2	68	54.8	86.1	192.7	167.1	161.4	36.4	31.4	900.1
2001	6.4	36.4	84.1	101.4	76.9	71.3	118.9	150	66.5	80.7	46.4	46.4	885.4
2002	48.4	0	82.4	97.1	65.1	60.7	112.5	164	198.4	135.4	16.8	146.4	1127.2
2003	39.6	20.3	17.9	143.6	121.9	149	228.4	78.3	77.1	37.5	91.9	57.6	1063.1
2004	16.7	10	110.6	104.2	17.7	52.2	151.3	149.5	316.3	129.2	80.1	25.4	1163.2
2005	72.4	31.2	56.4	184.7	182.2	71.7	132.6	72.3	129.6	100.2	38.2	0	1071.5
2006	9.2	66.6	155.9	165.2	123.4	89.9	187.6	293	148.1	166.7	4	90.5	1500.1
2007	5.4	13.3	64.2	42.9	69.2	163.6	194.4	180.6	171.1	88.8	25.7	0	1119.2
2008	2	0	37.4	161.8	219.6	113.6	171.1	188.9	127.5	55.5	156.1	0	1233.5
2009	42	0	16.5	171	50.4	30.7	127.4	53	154.3	113.1	32.4	62.4	853.2
2010	0	216.4	228.5	134.7	178.7	88.6	149.8	241.8	167.1	25.8	8.9	0	1440.3
2011	1	7.9	7.2	40.3	177.6	112.2	104.6	124.1	145.6	45.6	82.3	0	848.4
2012	0	0	31.8	127.4	102.7	126.9	96.6	91.7	232.3	69.2	40.1	46	964.7
2013	24.8	0.8	258	204.3	91.2	84.8	152.2	162.1	168.6	104.4	72.5	0	1323.7
2014	0	37.3	189.6	117.8	94.5	28.4	88.4	262.4	108.2	112.7	13.5	0	1052.8
2015	0	0	65.9	35.5	217.6	132.7	85.6	174.1	90.2	87	79.6	0.2	968.4
2016	11.4	8.9	83	285.9	111.2	103.4	165.8	221.6	138.7	62.2	48.1	6.1	1246.3
2017	0	14.8	85.7	78.4	162	29.9	57.8	164.9	217.9	51.6	0	0	863
2018	0	27	108.9	248.7	114	106.4	55.8	146.8	31.7	74.4	46.5	0	960.2
2019	0	0	13.4	101.3	133.9	100.3	249.8	104.1	147.3	80.6	73.8	37.4	1041.9
2020	13	9.9	66.7	346.7	142.4	14.3	108.1	174.4	92.5	20.3	0	16.1	1004.4

Table 7.2 Jarra meteorological station monthly rainfall (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2000	0	0	0	127.7	85.7	161.8	228	361.7	105.3	64.4	61.6	13.7	1209.9
2001	0	0	122.7	7.1	103	10.1	441.8	223	58.4	0	0.9	6.4	973.4
2002	21.3	9.7	55	88	16.2	11	217.9	263.8	89.7	13.5	27.3	0	813.4
2003	4.1	82.6	49	190	76.6	23.7	230.3	259.8	211.5	32.3	0.7	35.4	1087.1
2004	17.3	25	76.4	87.7	20	47.6	172.5	263	70.7	17.5	63.8	0	861.5
2005	9.9	13.4	59	79.3	90	42.5	187.9	218	100.7	19.1	17.4	0	837.2
2006	89.5	5.6	32.1	65.4	15.9	47	227.6	407.1	299.4	24.7	53.2	16.3	1267.5
2007	28	10.6	23.8	79.1	20.5	23.1	214	236.3	103.4	141	3.4	0	883.2
2008	7.1	0	0	50.8	41.4	20.1	183.7	186.3	105.4	74.1	14.2	0	683.1
2009	30.2	3.2	47	4.7	20.9	27.5	364.5	336.2	110	41.8	16.6	73.2	1075.8
2010	10.6	80.8	32.1	55.7	145.8	35.7	187.6	285.4	116.8	12.3	0	0	962.8
2011	4	0	76.4	38.8	107.6	0	77.8	310.6	214.3	8.5	77.7	3.4	919.1
2012	7.5	0	0	198.9	33.8	37.7	261.6	422.3	36	27.1	0	1.3	1026.2
2013	5.6	13.3	35.9	21.9	22.5	13	190.5	312.5	99.5	79.2	8.6	1.7	804.2
2014	17.4	35.3	49.9	50.7	71.2	7.8	200.3	346.9	135.1	85.6	0	6.7	1006.9
2015	0	0	75	0	110.7	3.3	22.7	402.7	54.5	3.5	191	24	887.4
2016	6.6	12.3	19.1	223.1	29.8	60.9	303	480.8	85.3	8.8	28.8	4.5	1163
2017	5.1	95	30.8	41.8	92	0	218.1	498.3	156.6	22.3	14.4	0	1274.4
2018	15.5	143.1	40.3	123.2	75.7	113.6	71.7	209	77.5	55.7	8.5	5.2	939
2019	7.7	0	6.7	131.8	146.6	76.9	126.7	58.7	151.4	115.8	30	123.9	976.2
2020	5.5	24.8	103.5	115.4	57	13	143.4	123.9	89.1	27.5	32.3	1.3	736.7

Table 7. Ginir meteorological station monthly rainfall (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2000	0	0	22	46.5	55	29.7	109.1	289.3	85.7	229	40.8	23.5	907.6
2001	0	0	60.9	1.1	57.3	36.6	66.1	101.3	114.5	182.6	17	22.5	637.4
2002	44.5	0	127.5	6.3	75.6	24.6	133.1	143.5	122	242.9	26	41.1	946.4
2003	1.1	0	10.3	17.1	68.6	53.9	159.8	105.5	32.4	103.3	68.5	93.1	620.5
2004	85.8	0	3.9	0	18.1	2.7	218.9	79.5	93.7	183.9	78.1	76	764.6
2005	6.4	0	57.5	49	89.7	99.5	200.2	190.7	72.5	107.9	233.5	0	1106.9
2006	5.2	31.8	81.1	3.2	16.7	77.6	346.8	404.3	126.8	139.6	82.2	102	1315.3
2007	0	0.3	45.1	21.9	53.4	56.2	263.1	107.5	128.8	132	138.7	0	947
2008	8.7	0	0	40.5	52.3	4.2	220.7	91.2	85.7	294.3	206.8	0	1004.4
2009	38.9	5.6	19.1	5.4	2.7	22.2	245.9	113.1	225.2	159.8	83.4	39	921.3
2010	0	108.8	312	50.2	15	25	315.2	147.8	105.8	181.3	39.5	0	1300.6
2011	3	2	0	39.7	63.3	79.9	109.1	214.6	130.3	145.3	173.9	35.3	961.1
2012	0	0	5.6	2.9	232.2	34	150.8	219.9	284.3	157.3	110.5	46	1197.5
2013	56	0	141.5	94.2	271.2	3.5	285	219	45.4	93.2	157.6	58.6	1366.6
2014	0	0	155.7	14	127.9	5.5	189.5	277.3	125.8	318.2	180.7	0	1394.6
2015	0	0	100.6	14.7	2.5	74.5	114.8	164.8	105.6	287.6	81.1	5.7	946.2
2016	6.5	13.4	30.5	12.5	41	52	279.8	341.8	72.3	203.2	65.4	33	1118.4
2017	0.6	121	54.4	62.1	44.5	42.5	117.4	220.6	75.8	156.2	93.5	0	988.1
2018	0	80	138.3	23.5	8.5	66	232.5	231.5	91.5	197.5	26.3	2	1095.6
2019	0	0	54	85.7	280.1	146	74	302.2	112.5	105	25.8	5	1185.3
2020	35	0	82	43.2	169	63	371.3	265.5	56.3	9.7	7.1	47.6	1102.1

7.4 Mean monthly stream flow data at the outlet of gololcha Watershed.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.48	0.49	3.82	5.54	4.52	8.10	23.81	34.35	28.03	13.99	9.47	3.89
2001	0.95	0.53	6.27	8.35	9.56	7.84	11.25	38.22	22.93	9.24	1.40	0.82
2002	1.64	1.55	5.83	8.70	6.41	6.23	9.05	35.78	26.26	13.71	2.17	1.92
2003	1.71	1.32	9.44	15.02	15.77	6.09	15.16	31.06	31.41	20.49	3.05	3.19
2004	2.17	3.74	4.98	12.45	9.21	5.69	14.62	32.36	22.94	12.01	3.40	5.72
2005	1.19	1.22	5.69	7.97	13.57	10.93	14.49	26.97	25.22	14.35	3.66	1.42
2006	2.84	7.74	2.98	9.18	7.41	6.19	16.98	38.24	45.98	15.76	4.26	5.25
2007	2.37	3.11	2.62	8.94	7.07	6.40	16.76	28.15	27.40	20.56	8.55	0.95
2008	0.63	0.91	1.40	5.60	8.19	6.27	11.40	26.90	24.75	13.00	9.08	1.55
2009	0.90	3.09	2.31	6.88	4.64	6.32	21.13	39.27	39.72	14.75	3.45	1.93
2010	1.31	3.81	9.08	5.69	17.42	9.54	14.28	31.39	29.21	14.82	2.94	0.47
2011	0.53	0.68	5.83	6.52	11.59	10.37	7.47	25.56	35.79	18.87	7.83	4.18
2012	0.91	1.12	1.44	10.25	17.97	6.93	15.98	44.85	24.71	11.88	2.12	0.50
2013	0.46	1.48	3.02	5.32	6.96	6.11	12.99	31.01	30.84	18.77	4.82	0.92
2014	0.79	4.35	4.26	8.73	8.99	9.04	11.42	35.71	37.36	19.36	4.45	1.05
2015	0.40	0.49	3.55	5.68	4.51	10.04	6.55	9.55	24.93	28.00	4.88	0.78
2016	2.44	1.36	3.85	15.22	15.26	7.71	21.21	49.48	23.84	11.77	1.54	3.34
2017	0.70	4.50	5.77	4.43	10.91	6.26	10.99	31.53	34.93	14.76	1.82	1.73
2018	0.75	3.43	15.10	12.80	11.04	14.07	17.70	15.85	22.76	11.33	6.79	1.11
2019	1.20	0.70	1.44	8.88	18.92	14.17	19.14	10.51	18.36	21.59	6.99	3.78
2020	1.51	2.46	5.36	13.20	15.10	6.62	8.40	18.79	19.83	14.13	6.20	0.79
Aver	1.23	2.28	4.95	8.83	10.72	8.14	22.32	30.26	28.44	15.86	4.71	2.16