**Jimma University**

**School of Graduate Studies**

**Jimma Institute of Technology**

**Faculty of Civil and Environmental Engineering**

**Hydraulic Engineering Program**

# Estimation of Probable Maximum Precipitation: A Case Study on Lower to Middle Awash River Basin, Ethiopia.

**By**

**Tekalign Yerango**

A Thesis submitted to the school of Graduate studies of Jimma University in partial fulfillment of the requirements for the degree of Master of Science in Hydraulic Engineering.

January, 2020

Jimma, Ethiopia

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Advisor: Dr. Zeinu Ahmed (PhD)

Co-Advidor: Birhan Tekuame (MSc)

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Jimma, Ethiopia

# DECLARATION

I, **Tekalign Yerango** declare that this thesis is my own original work and it is not been presented for a Degree in any other University.

Tekalign Yerango

Signature

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Date

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# CERTIFICATION

As a thesis research supervisor, I hereby certify that I read and evaluated this thesis prepared under my guidance by **Tekalign Yerango**, entitled **"Estimation of probable maximum precipitation; a case study on Lower and Middle Awash Basin, Ethiopia".** I recommend that it be submitted as in partial fulfillment of requirement for the degree of master's science.

Main Advisor; Dr. Zeinu Ahmed (PhD)

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Co-Advisor; Birhan Tekuame (MSc)

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# APPROVAL PAGE

This thesis entitled **“Estimation of Probable Maximum Precipitation: a case study on middle to lower awash river basin, Ethiopia”**. Submitted by **Tekalign Yerango Gebremariam** is approved and accepted as a partial fulfillment of the requirements for the degree of Master of Science in Hydraulic Engineering at Jimma Institute of Technology.

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# AKNOWLEDGEMENTS

At the beginning, I would like to thank my almighty God who makes me start and helped me to finish it successfully.

I would like to express my gratitude fro the depth of my heart Dr. Zeinu Ahmed who served as my thesis supervisor for his encouragement, guidance as well as constructive and helpful comments from the commencement, until the end of the study.

I would like to express my sincere gratitude to my advisor Mr. Birhan Tekuame (MSc) for his valuable guidance, constructive comments, timely feedback, and professional expertise during the preparation of this thesis.

I would like to deliver my special thanks Mr. Seife Belete (MSc) for his time and guidance to the R- programming for the extraction of reanalysis data.

I also acknowledge Mr. Tarekegn Dejen (MSc) and Mr. Chala Hailu (MSc) for their time, encouragement and availability when I needed them.

My special thanks go to Ethiopian national meteorological service agency (NMSA) and respective officials, team leaders and staff members who provided me valuable meteorological data free of charge and their hospitality.

I am very greatful to ministry of education (MOE), Mizan-Tepi University and to Jimma institute of technology school of civil and environmental engineering for allowing me to take part in the master program.

I would like to give gratitude from the depth of my heart to my parents who raise me and make me who I am today.

Finally, I would like to express my warm feeling of appreciation and thank to my friends who helped me n all stages especially to Alayu Befkadu, yaekob getahun, yoseph and my class mate Makeso Lambamo. Thanks all of you for your help and encouragement to finalize my duties successfully.

# ABSTRACT

*Probable maximum precipitation (PMP) is theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size of storm area at a particular geographical location at a particular time of year. The PMP helps for the design of a civil structure appropriately in the study area. The PMP for rainfall stations in Ethiopia have been estimated by Herhfield's statistical method with frequency factor determined by the Hershfield's chart. But different studies show that the vale of frequency factor founded from the chart was not reliable for PMP estimation for country like Ethiopia having variable climating condition. Therefore, the main purpose of thse study was to evaluate the frequency factor obtained from the hershfield's chart and to provide reliable estimate of PMP using insitu and global land data assimilation system (GLDAS) reanalysis global precipitation products for middle to lower Awash River basin (MLAWB) and evaluate PMP value of reanalysis global precipitation products with the insitu PMP value. The Hershfiled's empirical formula and chart method were applied for Km and PMP calculation. R-studio 2012, MATLAB-2013 and ARCGIS are tools applied to work with the input data. The study shows both insitu and GLDAS reanalysis product for 1 day, 2 days and 3 days the Km and PMP value are not more than 5 and 222 repectively and GLDAS reanalysis precipitation product is adequately capture PMP with respect to the the insitu PMP result in the study area for stations such as Dupty, Combolcha-1, Nazret, Mojo, Metehara, Meiso, Koka dam and Awash 7 kilo within 0.6 and 25% of deviations. The rest of the stations in the basin such as Assebeteferi, Combolcha-2, Gewane, Haik, and Kemise are not adequately captured by GLDAS reanalysis precipitation produt PMP value with respect to the stations insitu PMP value and the reanalysis precipitation product for these stations is not practical unless it is improved by minor and major data improvemet techniques. Comparison of the PMP value using the new Km in MLAWB and the chart value for insitu data exhibit differences in between 128 to 307% which is very much exagurated. This result confirmed the Hershfield's chart overestimated PMP value which has far reaching consequences in total cost of dam and spillway projects in the study area. The average ratio of PMP value to 10,000 years return period quantiles for insitu and GLDAS reanalysis precipitation product for the study area was found tobe 2.0 and 1.81 respectively. This shows GLDAS reanalysis product is adequately captured the result of average ratio value of the insitu data.*

**Key Words**; *Graphical method, Isohyatal map, Km, MLAWB, PMP, Statistical method, Reanalysis*

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# ACRONYMS

| | |
|---|---|
| CDA | Canadian Dam Association |
| CLM | Community Land Model |
| ECMWF | European Center for Medium-range Weather Forecast |
| GESDISC | Godard Earth Science Data and Information Service Center |
| GIS | Geographic Information System |
| GLDAS | Global Land Data Assimilation Systems |
| GRDC | Global Run- off Data Center |
| GSFC | Godard Space Flight Ceter |
| HDISC | The hydrology Data and Information Service Center |
| HSB | Hydrologic Science Branch |
| LIS | Land Information System |
| L-MRD | L- moment Ratio Diagram |
| MLAWB | Middle to Lower Awash Basin |
| NRC | National Research Center |
| NWP | Numerical Weather Prediction |
| PMP | Probable Maximum Precipitation |
| PMF | Probable Maximum Flood |
| VIC | Variable Infiltration Capacity |
| WMO | World Meteorological Organization |
| WWDSE | Water works design and supervision enterprise |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

The need for the development of water resources has become of considerable importance in watersheds in Ethiopia with a view to ensuring sufficient potable and industrial water supplies, providing irrigation for food production and flood control. As a result, large amounts of money are invested each year for the construction of different water resources projects such as dams, storage reservoirs, etc (WWDSE, 2010). Probable maximum precipitation, (PMP) is a common way to synthesize corresponding probable maximum floods in short data case for the design of the previous mentioned water resources projects. The probable maximum precipitation, (PMP) is defined as the greatest depth of precipitation for a given duration that is meteorologically possible over a given station or specified area (WMO, 1986).

Procedures for determining the PMP are admittedly inexact: results are estimated and a risk statement has to be assigned to them. In the PMP approach, by no means, it is to make zero risk in reality (Koutsoyiannis, 1999).

To estimate the PMP in a place, a variety of procedures based on the location of the project basin, availability of data and other consideration have been proposed (WMO, 1986). Most of them are based on the metrological analysis where as some are based on statistical analysis.

Apart from being extremely large flood magnitude, the procedure adopted in the country is based on graphical Hershfield’s estimation procedure (WMO, 1986). As a result, the cost of the dam construction in the country is high due to extremely high cost of spill way.

Therefore, the purpose of this study focuses on evaluation of maximum frequency factor ($K_m$) embedded in Hershfield’s frequency equation of PMP using historical daily rainfall (in-situ data) reanalysis global precipitation products and refine $K_m$ values that would represent the middle and lower Awash sub-river basin.

The procedure given by Hershfield (1961) was used to develop the new $K_m$ and the results compared with the existing work. For the reanalysis of global precipitation, this study selects Global Land Data Assimilation Systems (GLDAS). It fulfills the criteria’s to be the source of global precipitation data for the study area (Vincenzo, 2008). Then the new $K_m$ and PMP for the middle to lower awash sub-river basin was estimated.

### 1.2 Statement of Problem

Ethiopian river basins are rainfed and their discharge capacity fluctuates seasonally based on rain fall distribution over the areas (Awulachew, 2007). This situation directly affects utilization of the river for different purposes like application of different engineering practices. And estimation of reliable PMP value is very important for design and construction of water resources structures. In this study, the selected study area (the middlen to lower Awash River basin) is highly flood affected area. This will cause socio-economic crisis. Reliable estimate of the rainfall depth for the study area is very significant for the future design and operation of water and soil conservation structures and spillways (WWDSE, 2008).

Due to lack of properly established probable maximum flood (PMF) procedure, professionals and practitioners tend to use the Hershfield's graphical procedure to estimating the PMP and converting in to PMP. This method apparently is not well tested in the country and created debates. As water works design and supervision enterprise (WWDSE, 2010), the PMP value estimated by Hershfield (1973) for Ribb and Megech dam design and for Gumera irrigation project, the design report of WWDSE (2008) shows the frequency factor (K) value taken as a constant of 15. Later Hershfield found that use of $K_m = 15$ was not appropriate. According to some research outputs in China and Romania (Desa et al., 2003) and some other countries, the graphical procedure was found to overestimate the actual values. Therefore, adjustment of the value of the frequency factor and use of reanalysis for global precipitation products is essential for estimation of reliable PMP value for local study area.

Thus, the purpose of this study focuses on evaluation of the frequency factor ($K_m$) embedded in Hershfield's frequency equation of PMP using historical daily rainfall (in-situ data) and reanalysis global precipitation products and refine ($K_m$) values that would adequately represent the middle and lower Awash sub river basin and on estimation of reliable PMP values of the stations in the basin for 1 day, 2 days' and 3 days' durations.

### 1.3.1 General Objective

The main objective of the study is to estimate the PMP for middle and lower awash sub-river basin using daily insitu data and reanalysis global precipitation products.

### 1.3.2. Specific Objectives

1. To estimate the frequency factor ($K_m$) for the study area
2. To estimate point PMP's and their return periods for the considered rain gauge stations in the watershed
3. To compare the frequency factor (Km) obtained from the insitu data and global land data assimilation systems (GLDAS) reanalysis global precipitation product.
4. To develop 1day, 2day and 3day PMP and Km isohyetal maps for the watershed using GIS

## 1.4 Research Questions

1. Is that possible to find out the representative ($K_m$) for the study area?
2. Are the obtained PMPs and their corresponding return periods are in acceptable range?
3. Does the reanalysis global precipitation product capture the PMP values adequately?
4. Can we develop a better regionalized PMP maps assimilated from reanalysis and in-situ product?

## 1.5 Scope of the Study

The scope of this study is to estimate the probable maximum precipitation for the study area from the middle to lower awash basin. The study area covers from the point of the downstream of the koka dam reservoir to the lower part of the basin. Eventhough there are several methods to estimate PMP, this study uses the Hershfield's statistical equation and graphical method for comparison. Global land data assimilation system (GLDAS) is used as a global precipitation data source for reanalysis and evaluation. And regional isohyetal map for the specific study area is made using ARCGIS for both insitu and reanalysis data to show the PMP and frequency factor distribution with in the study area.

## 1.6 Significance of the study

This paper assist practitioners, engineers and hydrologists in developing extreme flood estimates for the major water resources engineering works and projects. It also helps in promoting a relatively uniform approach to developing estimates of the probable maximum flood (PMF) of very low probability for purposes of project design or evaluation and to improve the consistency of the estimates.

The estimated probable maximum precipitation (PMP) for the basin have importantance for various engineering works such as spillway design for dams of the highest hazard category in the study area.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Probable maximum precipitation (PMP)

The PMP and PMF concepts were developed in the USA in the mid-twentieth century as a result of dissatisfaction with empirically or statistically based design flood estimates for major structures, and partly as a response to catastrophic failures. The concepts have since been adopted in many countries for high- hazard dams. Probable Maximum Precipitation (PMP) is defined by the World Meteorological Organization (WMO, 2009). As theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year. The idea is that at a given location with a given climate, an upper bound to precipitation can be estimated by analyzing the meteorology of historic storms and maximizing the key causative factors. Although the PMP has a theoretical excedence probability of zero, meaning that it is so large that it will never be exceeded, this is not the case in reality (Koutosyiannis, 1999). Consequently, a few studies have sought to assign a risk statement to PMP estimates. Estimates of extreme floods have long been used to design the flood-handling facilities of major dams whose failure might cause loss of life or extensive property damage (NRC, 1994).

### 2.1.1 Application of PMP in Spillway Design

The hydrologic problem typically addressed in dam safety analysis is the determination of the capacity of the spillway needed to prevent catastrophic failure of the dam due to overtopping. The PMF is generally accepted as the design inflow for evaluating the spillway when there is potential loss of life due to dam failure in high hazard situations. As per the first edition of Dam Safety Guidelines by the Canadian Dam Association (CDA, 1999) dams are classified into four categories according to the perceived incremental consequences of failure these are very high, high, low and very low dams. The criteria for the design flood as stated in CDA, 1999 are: For very high dams the PMF developed as a result of PMP is mandatory, for high dams the design flood may be selected between the PMF and the 1000-years flood, for low dams the design flood may be selected between the 1000-year and the 100-year floods and for very low dams the design flood selected is less than100-year floods.

The PMF represents an estimated upper bound on the maximum runoff potential for a particular watershed. In some sense, the inherent assumption is that a dam with a spillway designed to pass this flood has zero risk of overtopping.

### 2.1.2 Maximum Observed Point Rainfalls

Some of the largest point rainfalls for selected durations that have been observed are given in the following table. These values, which approach probable maximum precipitation magnitude, are enveloped by the approximate equation (konrad, 1995).

$$P = 422\ T^{0.475} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

Where: P is rainfall in millimeters, and T is duration in hours

Table 1: Worlds greatest point rain falls (Source: Australian Bureau of Meteorology, 2009)

| Duration | Depth (mm) | Location | Date |
|---|---|---|---|
| 1 min | 38 | Barot, Guadeloupe | 26 November 1970 |
| 1h00 min | 401 | Shangdi, Nei Monggol, | China 3 July 1975 |
| 6h | 840 | Muduocaidang,Nei, Monggol, China | 1 August 1977 |
| 24h | 1825 | Foc Foc, La Réunion | 7-8 January 1966 |
| 2 days | 2467 | Aurere, La Réunion | 7-9 April 1958 |
| 3 days | 3130 | Aurere, La Réunion | 6-9 April 1958 |
| 7 days | 5003 | Commerson, La Réunion | 21-27 January 1980 |
| 31 days | 9300 | Cherrapunji, India | 1-31 July 1861 |
| 1 year | 26461 | Cherrapunji, India 1861 | August 1860-July |
| 2 years | 40768 | Cherrapunji, India | 1860-1861 |

### 2.1.3 World Meteorological Organization (WMO) Guidelines for Estimating PMP

According to "Manual on Estimation of Probable Maximum Precipitation (PMP)" (WMO, 2009), six methods of PMP estimation currently exist. These are Local method: The observed maximum storm is used to estimate PMP, Transposition method: An extraordinary large storm close by is transposed to the watershed area, Combination method: Two or more storms in the area are combined to produce a sequence of artificial storms with long duration. This method can be applied in large watersheds and requires meteorological expertise, inferential method: A simplified physical equation describing the 3-Dspatial structure of a storm is created. This method can be applied in medium to large watersheds and requires upper meteorological measurements in the area, generalized method: Observed rainfall is separated into convergence and orographic rainfall in a large meteorologically homogeneous region. The method is time consuming and expensive and requires a large dataset of long-term rainfall measurements in the area. However, the results are likely to be of high accuracy and Statistical method (proposed by Hershfield, USA): The hydrological frequency analysis method is applied on data from several rain gauges, in combination with the regional generalized method. The area should be smaller than 1000km$^2$ and meteorologically homogeneous.

For very large watersheds the following two methods are also applied such as the major temporal and spatial combination method Hydro-meteorological methods are applied on the part of PMP that has the larger temporal and spatial influence on PMF, while the common correlation method and flood distribution method are applied on the part of PMP with smaller influence. The method combines temporal and spatial conditions and the storm simulation method based on historical floods Hydrological watershed models are applied in producing a storm with the potential to create an observed historical flood, and PMP is estimated by maximizing moisture.

In addition, a number of techniques for adjusting PMP estimates to orographic regions exist. In some cases, it is recommended to estimate areal precipitation using more than one method in order to obtain thorough hydrological estimates, especially in ungagged catchments like the mountain areas (WMO, 2009).

## 2.2 A Criteria for Selecting Statistical method

The various methods used for estimating probable maximum precipitation amounts are classified into three major groups. These are; Statistical approach, Physical approach and Empirical approach

### 2.2.1 Statistical Aproach

In the statistical aproach the estimates of PMP are drived from frequrncy analysis of the annual maximum rainfall series for different durations. Statistical method for estimating PMP has been developed by Hershfield (1961, 1965) based on a general frequency equation given by Chow (1951). The use of statistical method in different countries ha s shown that the computed PMP estimates is closely comparable to those obtained by meteorological method.

WMO (2009, et. al) has suggested this method for estimating PMP for stations having long period of daily rainfall data. Considering this, many countries have employed the statistical method extensively for estimating PMP for stations having a long period of rain fall records (Myers 1967; Bruce and Clark, 1966; Rakhecha et al., 199, 1994). The statistical method is useful when there is insufficient meteorological data to apply the other methods.

### 2.2.2 Physical Aproach

The physical aproach is primarily concerned wih the estimation of probable maximum precipitation, which can be defined as the theoretical highest precipitation amount which is physically possible over a locality for a given duration. Values of PMP are therefore dependent on the humidity content of the air and maximum efficiency of release. Values of PMP are usually estimated by the physical method of storm transposition and maximization described by Bruce and Clark (1966, p. 230-233) or by the use of storm models such as the hurricane model used by the US Weather Bureau to make generalized estimates of PMP for Puerto Rico and the Virgin Islands (US Weather Bureau, 1961).

The storm model approach uses physical parameters, such as surface dew point, height of storm cell, and inflow and outflow, to represent the precipitation process (Collier and Hardaker 1996).

Storm transposition involves translating observed storm characteristics from one or more gauged locations to the location where the PMP estimation is required (typically an ungauged location). Storm maximization consists of adjusting observed precipitation amounts upward to account for maximum atmospheric moisture convergence. Generalized PMP methods are often developed by maximizing and translating classes of storms over a broad region; storm classification in turn is based on the storm type, and storm efficiency defined as the ratio of maximum observed rainfall to the amount of perceptible water in the storm column (Collier and Hardaker 1996). Physical methods of estimating the PMP are rather complex and require meteorological data which are often not available. They also make several assumptions which may not always be valid (Bruce and Clark, 1966).

### 2.2.3 Empirical Approach

The empirical approach to the estimation of extreme rainfalls utilizes the available data just like the statistical approach. The US Weather Bureau has carried out some studies utilizing data on heavy rainfall occurrences extracted from autographic records. From these, an enveloping curve can be drawn to show the maximum rainfall likely to be obtained in any given time. The reliability of such estimates obviously depends on the duration and quality of rainfall records as well as the number of gauges involved especially if a catchment is being considered.

***The statistical approach*** is often found to be quick and reliable and is therefore often preferred to the physical or empirical approach to the estimation of extreme rainfall. But the statistical method demands that the assumptions underlying the particular distribution function used be satisfied and the sample size used to be large.

### 2.3 Probable Maximum Precipitation (PMP) by Statistical Methods

Hershfield (1961, 1965) based on a general frequency equation given by Chow (1951) suggested that PMP for a station can be estimated from the following equation:

$$PMP = \overline{Xn} + Km\ \sigma_n \quad \text{......} \quad [2.2]$$

Where: $\overline{Xn}$ and $\sigma_n$ are the mean and standard deviation for a series of n annual maximum rainfall values of a given duration respectively.

Km; is the frequency factor and is the largest of all the calculated K values for all stations in a given area. The value of K is calculated using the following equation:

$$K = \frac{(X_1 - \overline{X}\,n\text{-}1)}{\sigma_{n-1}} \quad \text{..........} \quad [2.3]$$

Where; $X_1$, $X\overline{n}\text{-}1$ and $\sigma_{n-1}$ are the highest, mean and standard deviation respectively excluding the $X_1$ value from the series. In a survey of more than 2700 stations world over, Km values as calculated from equation 2.3 vary from less than 3 to a highest value of 14.5. Hershfield adopted the highest value rounded to 15 for estimating PMP,

$$\text{I.e. } PMP = \overline{X}\,n + 15\ \sigma_n \quad \text{..........} \quad [2.4]$$

Later Hershfield found that use of Km =15 was not appropriate. He noted that K varies inversely with mean annual maximum rainfall at any station and presented a chart for determining Km for 5-min, 1-h, 6-h, and 24-h durations of mean annual maximum rainfall as shown below.

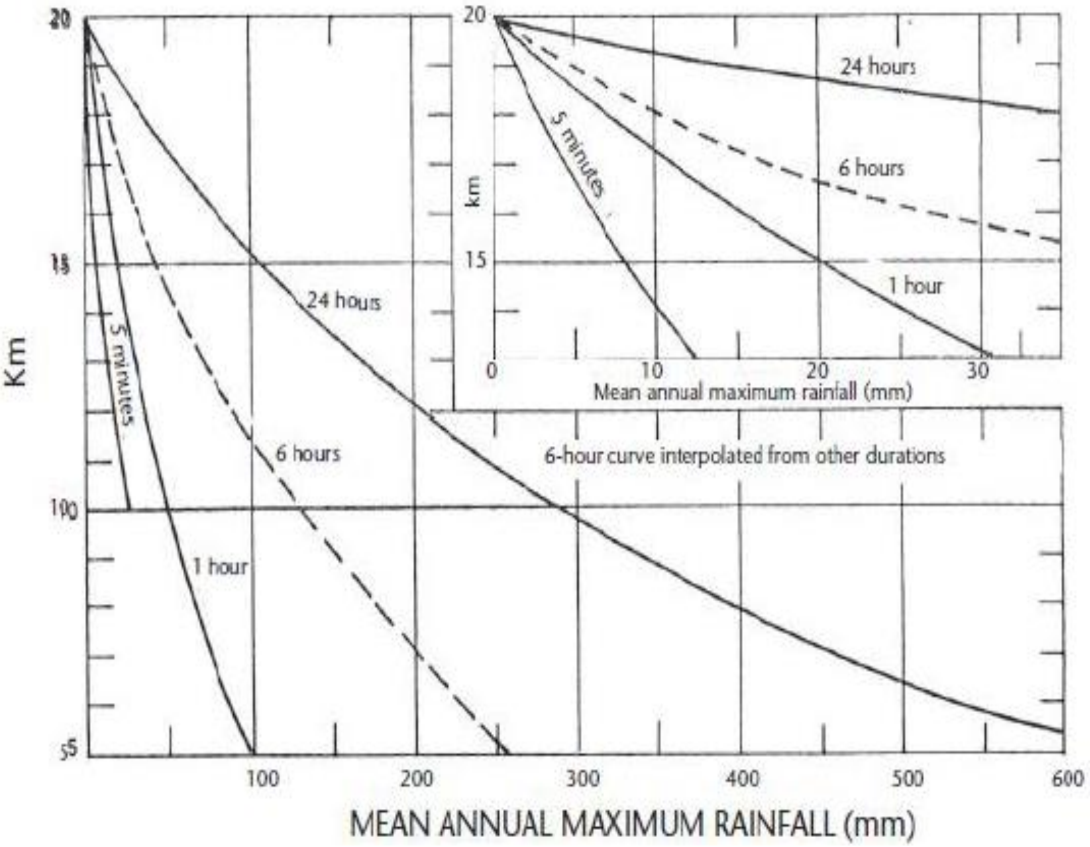

Figure 2.1: The Hershfield's chart for determination of frequency factor Km (Abenezer,2016)

The curves of Figure 2.1 are based on observed data from 2700 stations 90 percent of which were in the United States, where observations were at least daily for a period of at least 10 years. As a matter of fact, there are several measurements of rainfall in the United States made at locations other than where there are official gauges that exceed the PMP values calculated from this statistical procedure, Riedel (1977). Computation of Km for Canada (McKay, 1965) indicated a maximum value of 30 associated with a mean annual maximum 24-hours rainfall amount of 15mm. Similar research project within the Austrian Academy of Sciences (Nobilis et al., 1990) using a series of the annual daily maximum precipitation at

504 observation stations are investigated by using the method of Hershfield (WMO, 1986) for PMP-estimation the results show that according to the Hershfield method for some stations PMP amounts are evaluated which are far below the observed values. The method is found to be inadequate for series with "outliers" because the factor of Hershfields chart for used for determination of K values is a function of the average values.

The research outputs of countries like China and Romania also showed that that their frequency factor (Km) value varies between 6 and 8.5 for their respective countries and rejected the Hershfields chart as it over estimates the PMP. (Desa et al. (2001) and M.N. Desa et al. (2003) and NIHWM, Bucharest, ROMANIA) Desa et al. (2001) and M.N. Desa et al. (2003) employed the Hershfield method to find out the appropriate frequency factor that can give reliable PMP values for stations in Malaysia for practical application. They analyzed the series of the annual daily maximum rainfall amounts for stations in Selangor and Kelantan states and obtained the appropriate frequency factors of 8.7 and 7.4 respectively. These values are applied to calculate the PMP values in these two study areas. In view of the above-mentioned problems and resent research outputs, the Hershfield's chart might not give reliable frequency factor estimates world over. It was therefore felt that an appropriate Km value based on historical data of particular study area might give better estimates of PMP than Hershfield's chart.

## 2.4 Frequency Distribution and Analysis

The primary objective of frequency analysis is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions (Chow et al., 1988). Data observed over an extended period of time in a river system are analyzed in frequency analysis.  The data will be assumed to be independent and identically distributed.  The flood data will be considered to be stochastic and may even be assumed to be space and time independent.

Further, it will be assumed that the floods have not been affected by natural or manmade changes in the hydrological regime in the system. In practice, the true probability distribution of the data at a site or a region is unknown. The assumption that data in a given system arise from a single-parent distribution may be questionable when data from large watersheds are analyzed. In such cases, more than one type of rainfall or flow may contribute to extreme events in a region. However, for the analysis to be of practical use, simpler distributions are often used to characterize the relation between flood magnitudes and their frequencies. The performance of distributions is evaluated by using different statistical tests. Quite often, many assumptions made in flood frequency analysis may be invalid. At any rate these assumptions have been questioned and discussed extensively (Kleme, l987a; Kleme, l987b; Yevjevich, 1968).

Some of the distribution models which are recommended by WMO for annual maximum data series are exponential distribution (EX), pearson three distribution (PIII)(Foster, 1924), log pearson three distribution (LP3)(USWRC, 1967), extreme value type one distribution (EVI) and Weibul distribution (Cunane, 1989).

## 2.5 Reanalysis Global Precipitation Product

The reanalysis dataset is technology based which are used for data generation instead of observed data. There are different types of dataset based on their area of application such as: Snow Cover (SC) used to generate the snow cover data, Global Runoff Data Centre (GRDC) for River mean daily Discharge Data, ECMWF Forcing for meteorological data, European Center for Medium-Range Weather Forecast (ECMWF) and Global Land Data Assimilation System (GLDAS). Each of the dataset including the datasets which are not explained are used as input and output data instead of observed data. Reanalysis makes use of data assimilation systems designed for weather forecasting.  It uses a single model and analysis method for a consistent re-analysis of past observations.

### 2.5.1 Selection Criteria for Global Data Source for Reanalysis Data

The world climate research program (WCRP) was established in 1980 to persue two maor scientific objectives. These are, determine the extent to which climate can be predicted and determine the extent of human influence on the climate system.

Accurate precipitation data are critical for hydrologic prediction, yet outside the developed world insitu networks are so spars as to make alternative methods of precipitation estimation is essential (Nathal V., Andrew W. Wood, and Dannis P.L., 2007). Some of such alternative precipitations product that would be adequate to drive Hydrologic prediction models at regional and global scales is evaluated in this study. Accordind to the the world climate research program, the precipitation products are developed the underlying assumptions and sampling and processing procedures, their spatial and temporal resolutions, and the potential source of errorsand anomalies in the records (Arnold and Vincenzo, 2008).

Table 2.2 shows the areal coverage, the time coverage, the time scale and space scale of some selected global precipitation products.

Table 2.2: Comparion of global precipitation products (Arnold and Vincenzo, 2008)

| Data source | Space scale | Time scale | Area coverage | Time coverage |
|---|---|---|---|---|
| GLDAS | $0.25^0$ | Daily | Global land | 1948-2014 |
| GPCC guage analysis | $2.5^0$ | Monthly | Global land | 1986-present |
| CAMS+GHCN guage analysis | $2.5^0$ | Monthly | Global land | 1979-1985 |
| OPI | $2.5^0$ | Monthly | Gobal land | 1979-1987 |

Since the global reanalysis data needed for this study is precipitation data on a daily basis time scale, GLDAS fulfill all the criterias having having higher spatial resolution as shown in the table 2.2.

### 2.5.2 Global Land Data Assimilation System (GLDAS)

Global hydrological data such as soil moisture and evaporation are crucial for understanding the land surface process and the atmospheric general circulation modeling for climate simulation and weather forecasting. The Hydrologic Sciences Branch (HSB) at NASA's Goddard Space Flight Center (GSFC) has collected a series of surface hydrological data sets in order to enable a better understanding of the global hydrospheric cycle. These data sets include field measurements, parameters simulated from land surface models, and products derived from many satellite instruments (Rodell et al., 2004).

NASA is mandated by Congress to make its data and products available to the broader user community. The Hydrology Data and Information Services Center (HDISC) was developed as part of the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) to archive and support data products generated by the GSFC HSB. HDISC is a portal to a hydrology-specific, on-line, easy-access archive and distribution system, employing data analysis and visualization, data sub setting, and other user-requested techniques for better science data usage. HDISC provides convenient access to hydrology data and information from various land surface models. The first products hosted are outputs from the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004). The HDISC has the capability to support more hydrology data products and more advanced analysis tools. The goal is to develop HDISC as a data and services portal that supports weather and climate forecast, and water and energy cycle research.

Objectives: The goal of the Global Land Data Assimilation System (GLDAS) is to ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface states and fluxes (Rodell et al., 2004a).

Background: GLDAS drives multiple offline (not coupled to the atmosphere) land surface models, integrates a huge quantity of observation-based data, and executes globally at 2.5° to 1 km resolutions, enabled by the Land Information System (LIS) (Kumar et al., 2006). Currently, GLDAS drives four land surface models: Mosaic, Noah, the Community Land Model (CLM), and the Variable Infiltration Capacity (VIC). GLDAS products include land surface state (e.g., soil moisture and surface temperature) and flux (e.g., evaporation and sensible heat flux) parameters. For example, the total evapotranspiration for April 1979 is the average 3-hour mean rate of evapotranspiration over all the 3-hour intervals in April 1979.

## 2.6 Previous Studies in Ethiopia

Several related studies have been conducted in Ethiopia on maximum frequency fator and probable maximum precipitation at different duration for a given area. According to “Estimation of probable maximum precipitation in upper awash basin” (Birhan, 2017), the maximum frequency factor for upper awash basin was 6.2. This value was obtained from 30 years of recorded rainfall data for 11 rainguage stations with in the watershed using Hershfield’s statistical method. In this study it was concluded that the PMP value obtained using Hershfield’s chart maximum frequency factor deviated around 54% from the PMP value obtained from the Hershfield’s frequency equation which clearly indicates the Hershfield’s chart is overestimated (Birhan, 2017).

Also, the maximum frequency factor (Km) obtained using Hershfield’s statistical method was 11 for upper Blue Nile basin (Abenezer, 2016). The study used 30 years of recorded rain fall data for 104 rainguage stations with in the watershed and the obtained PMP value for both insitu and reanalysis global precipitation product was not more than 875. Global land data assimilation system (GLDAS) precipitation product was adequately capture PMP with respect to the in-situ PMP result in upper Blue Nile basin. As compared between the Hershfield's statistical Km and Km from Hershfield's chart for both insitu and reanalysis global precipitation data, the value from Hershfield's chart exhibit up to 96.4% of deviations and this result confirmed that the Hershfield's chart is Overestimated (Abenezer, 2016).

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Study area description

The Awash River is a major river of Ethiopia. Its course is entirely contained within the boundaries of Ethiopia and empties into the chain of interconnected lakes that begins with Lake Gargori and end with lake Abbe on the border with Djibouti, some 100 kilometers from the gulf of Tajura. The awash rises south of mount Warque, west of Addis Ababa in the woreda of Dandi, close to the town of Ginchi, west shewa zone Oromia. After entering the bottom of the Great Rift Valley, the Awash flows south to loop around mount zuqualla in an easterly then north easterly direction before entering Koka reservoir (Awulachew, 2007).

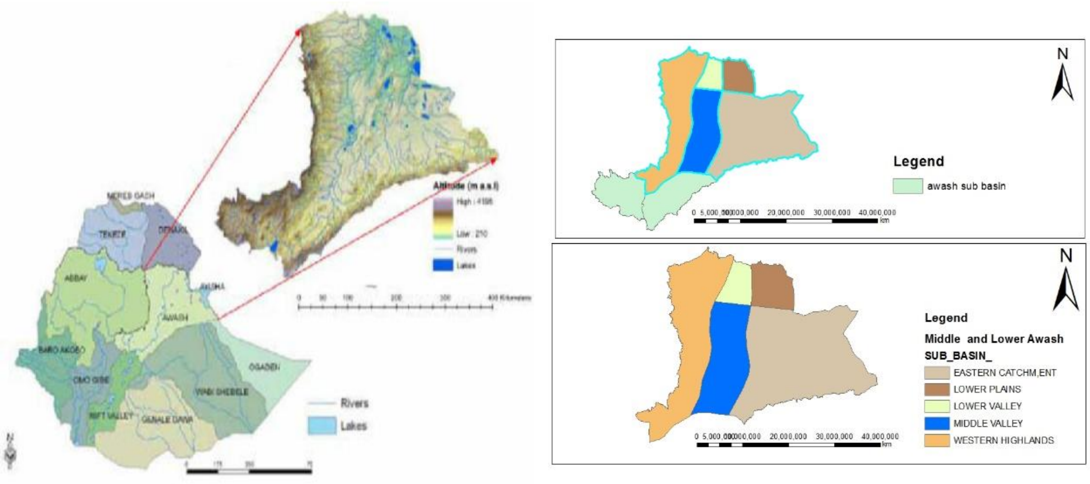

Fig. 3.1: Location of the study area (the middle to lower awash river basin)

The study area covers the middle and the lower part of the Awash River basin. It contains five subriver basins; middle valley, western highlands, eastern catchments, lower plains and lower valley as shown in the figure above. The total watershed area covers 98,800km$^2$ of the total area of the Awash River basin which is 110,000km$^2$.

## 3.2 Procedure of New Km Development

The Hershfield method is used to find out the appropriate frequency factor that can give reliable PMP values for stations in the study area for practical application. But here the annual maximum rainfall amounts series of the stations found in the study area is used for the analysis. This involves standardizing the residual (maximum rainfall minus mean of annual maxi ma) by dividing it by the standard deviation to obtain the frequency factor as indicated in equation 2.2. The frequency factor is analogous to the normal deviate or reduced variate when normally distributed or extreme-value data will be analyzed, respectively. After determining the appropriate Km values for the study area different adjustments have to be carried out for the maximum observed events before using them for subsequent calculations.

### 3.2.1 Adjustment of Mean and Standard deviation for Maximum Observed Events

Extreme rainfall amounts of rare magnitude or occurrence, such as with return periods of 500 or more years, are often found to have occurred at some time during a much shorter period of record. Such a rare event, called an outlier, may have an appreciable effect on the mean and standard deviation of the annual series. The magnitude of the effect is less for long records than for short, and it varies with the rarity of the event, or outlier. This has been studied by Hershfield (1961) using the hypothetical series of varying length, and the following figures were made to show the adjustments to be made to mean and standard deviations to compensate for outliers.

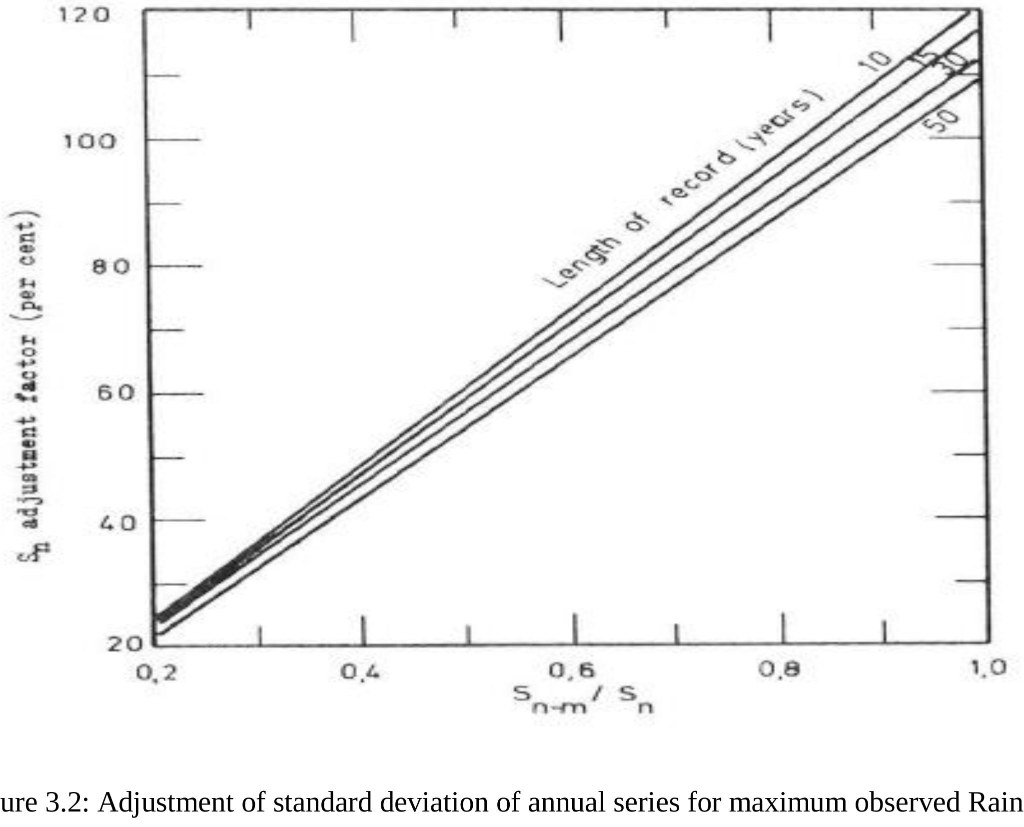

Figure 3.2: Adjustment of standard deviation of annual series for maximum observed Rainfall (Hershfield, 1961b) (Abenezer, 2016).

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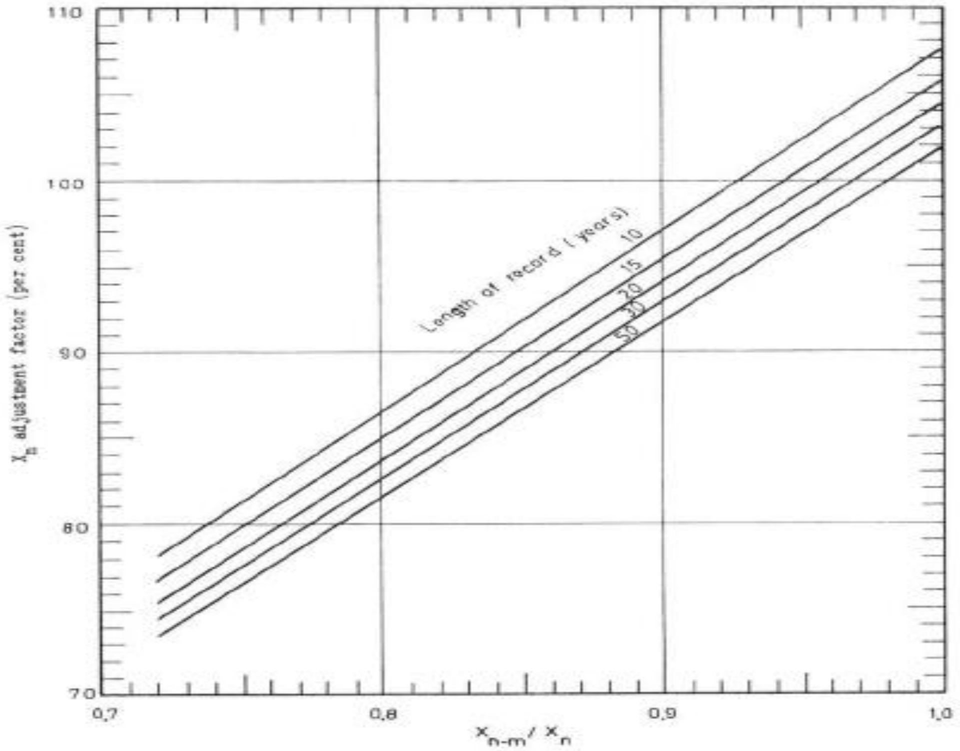


Figure 3.3: Adjustment of mean of annual series for maximum observed rainfall (Hershfield, 1961b) (Abenezer, 2016).

In the figures, X̄n-m and Sn-m refer, respectively, to the mean and standard deviation of the annual series computed after excluding the maximum item in the series. It should be noted that these relationships consider only the effect of maximum observed event. No consideration will be given to other anomalous appearing observations.

### 3.2.2 Adjustment of Mean and Standard Deviation for Sample Size

The mean and standard deviation of the annual series tend to increase with length of record, because the frequency distribution of rainfall extremes is skewed to the right so that there is a greater chance of getting a large than rainfall extreme as length of record increases. Figure 3-4 shows the adjustments to be made to the mean and standard deviation for length of record. There were relatively few rainfall records longer than 50 years available for evaluating the effect of sample size, but the few longer records available indicated adjustment only slightly different from that for the 50-year records.

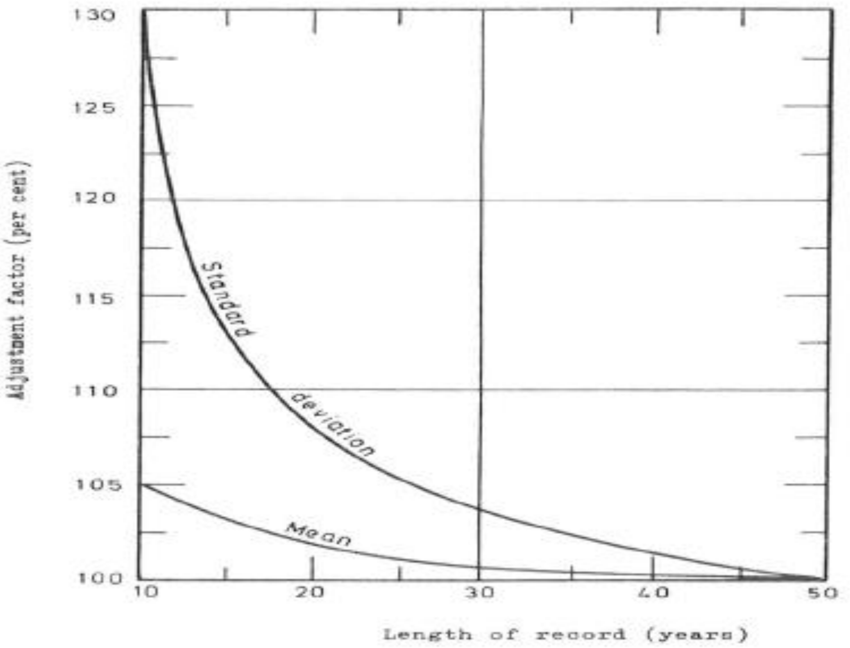


Figure 3.4: Adjustment of mean and standard deviation of annual series for length of record (Hershfield, 1961b) (Abenezer, 2016).

### 3.2.3 Adjustment of Data for Fixed Observational Time Intervals

Rainfall data are usually published for fixed time intervals, 08:00-08:00(daily), 06:00-12:00 (six-hourly), and 03:00-04:00 (hourly). Such data rarely yield the true maximum amounts for the indicated durations. For example, the annual maximum observational-day amount is very likely to be appreciably less than the annual maximum amount determined from intervals of 1440 consecutive minutes unrestricted by any particular time. Similarly, maxima from fixed six-hourly and hourly intervals tend to be less than maxima obtained from 360 and 60 consecutive one-minute intervals, respectively, unrestricted by fixed beginning or ending times.

Studies of thousands of station-years of rainfall data indicate that multiplying annual maximum hourly or daily rainfall amounts for a single fixed observational interval of one to 24 hours by 1.13 will yield values closely approximating those to be obtained from an analysis of true maxima (Hershfield, 1961a). Lesser adjustments are required when maximum observed amounts are determined from two or more fixed observational intervals (Weiss, 1964; Miller, 1964). Thus, for example, maximum six and 24-hour amounts determined from six and 24 consecutive fixed one-hour increments require adjustment by factors of only 1.02 and 1.01, respectively.

### 3.3 Frequency Distribution and Analysis

The primary objective of frequency analysis is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions (Chow et al., 1988). Data observed over an extended period of time in a river system are analyzed in frequency analysis. The data are assumed to be independent and identically distributed. The flood data are considered to be stochastic and may even be assumed to be space and time independent. Further, it is assumed that the floods have not been affected by natural or manmade changes in the hydrological regime in the system. In practice, the true probability distribution of the data at a site or a region is unknown. The assumption that data in a given system arise from a single-parent distribution may be questionable when data from large watersheds are analyzed. In such cases, more than one type of rainfall or flow may contribute to extreme events in a region. However, for the analysis to be of practical use, simpler distributions are often used to characterize the relation between flood magnitudes and their frequencies. The performance of distributions is evaluated by using different statistical tests. Quite often, many assumptions made in flood frequency analysis may be invalid. At any rate these assumptions have been questioned and discussed extensively (Kleme, l987a; Kleme , l987b; Yevjevich, 1968). The distribution models which are recommended by WMO for annual maximum data series (Cunnane, 1989) are listed below.

1. Normal distribution (NOR)
2. Two parameter Log-Normal distribution (LN2) (Hazen, 1914)
3. Three parameter Log Normal distribution (LN3)
4. Exponential distribution (EX)
5. Two parameter Gamma distribution (G2) (Moran, 1957)
6. Pearson three distribution (PIII) (Foster, 1924)
7. Log Pearson three distributions (LP3) (USWRC, 1967)
8. Generalized extreme value distribution (GEV) (Jenkinson, 1955)
9. Extreme value type one distribution (EVI)
10. Weibul distribution (W) (Wu & Goodridge, 1959)

11. The five parameter Wakeby distribution (WAK5) (Houghton, 1977)

12. The four parameter Wakeby distribution (WAK4) (Houghton, 1977)

13. The generalized Pareto distribution (GP)

14. Logistic Logistic distribution (LLg) (Ahmed et al, 1988)

15. Generalized Logistic distribution (GLg)

### 3.3.1 Moments of Distributions

Moments about the origin or about the mean are used to characterize probability distributions. Moments about the origin are the expected values of powers of a random variable. In frequency analysis the two popular moments these are conventional moments and L-moments.

#### 3.3.1.1 Conventional Moments

For a given distribution, conventional moments can be expressed as functions of the parameters of distributions. It follows that the higher order moments can be expressed as functions of lower order moments. The method of moments has been one of the simplest and conventional parameter estimation techniques used in statistical hydrology. In this method, while fitting a probability distribution to a sample, the parameters are estimated by equating the sample moments to those of the theoretical moments of the distribution. Even though this method is conceptually simple, and the computations are straight-forward, it is found that the numerical values of the sample moments can be very different from those of the population from which the sample has been drawn, especially when the sample size is small and/or the skewness of the sample is considerable.

#### 3.3.1.2 L-Moments

Recently, Hosking (1990) has defined L-moments, which are analogous to conventional moments, and can be expressed in terms of linear combinations of order statistics. Basically, L-moments are linear functions of probability weighted moments (PWMs).

The following are advantage of L-moments Cunnane (1989).

- Compared to method of moments, L-moments can characterize a wide range of distributions

- Sample estimates of L-moments are so robust that they are not affected by the presence of outlier in the dataset and are less subjected to bias in estimation L-moments yield more accurate estimates of the parameters of a fitted distribution.

The following L-Moments are defined in Cunnane, 1989.

$\lambda_1 = L_1 = M100$

$\lambda_2 = L_2 = 2M110 - M100$

$\lambda_3 = L_3 = 6M120 - 6M110 + M100$

$\lambda_4 = L_4 = 20M130 - 30M120 + 12M110 - M100$

The 4 L-Moments ($\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$) are all derived using the 4 PWMs. Other useful ratios are L-CV ($\tau_2$), L-Skewness ($\tau_3$) and L-Kurtosis ($\tau_4$).

L-CV is similar to the normal coefficient of variation (CV). The standard equation for CV = standard deviation/mean, and shows how the data set varies. The larger the CV value, the larger the variation of the data set from the mean. For example, in arid regions that receive few storm events, the variation will be large, as one storm will deviate greatly from the low mean.

$\tau_2 = L_2/L_1$ (L-Cv)……………………………………………………….[3.1]

L-Skewness is a measure of the lack of symmetry in a distribution. If the value is negative, the left tail is long compared with the right tail, and if the value is for GEV frequency

For GEV frequency analysis, a positive L-Skewness value is desired, as we are interested in the extreme events that occur in the right-side tail of the distribution.

$\tau3 = L3/L2$ (L-Skewness)………………………………………………….[3.2]

L-Kurtosis is difficult to interpret, however is often described as the measure of "Peaked ness" of the distribution (Hosking, 1997). L-kurtosis is much less biased than ordinary kurtosis.

$\tau4 = L4/L2$ (L-Kurtosis)………………………………………………..[3.3]

Where, L1 = measure of location

$\tau2$ = measure of scale and dispersion (LCv)

$\tau_3$ = measure of skewness (LCs)

$\tau_4$ = measure of kurtosis (LCk)

### 3.3.2 Method of Parameter Estimation

Numerous parameter estimation procedures have been proposed and studied in order to investigate their performance for various distributions (GUO, 1990). In the past only the ordinary methods of moments (MOM) was mentioned for parameter estimation. It should be noted that MOM, PWM and MLM are the most efficient method of parameter estimation available.

#### 3.3.2.1 Method of Moments (MOM)

It is one of the most commonly used methods of estimating parameters of a probability distribution. The estimated parameters of a probability distribution function are obtained by equating the moments of the sample with the moments of the probability distribution function. It provides simple calculations, but higher order moment estimates are biased (Wallis, et. al. 1974). Parameter estimation by MOM is known to be biased and inefficient especially with three parameter distributions. Method of moments (MOM) is a relatively easy parameter estimation method. Unfortunately, MOM estimates are usually inferior in quality and generally not as efficient as the ML estimates especially in the case where the distributions have a large number of parameters. This is due to the fact that higher order moments are more likely to be highly biased in relatively small samples.

#### 3.3.2.2 Method of Maximum Likelihood (MML)

The maximum likelihood method (MLM) is often regarded as the most efficient method. This is because it provides the smallest sampling variance of the estimated parameters which leads to the smallest sampling variance of the estimated quantiles compared to other methods. MLM has disadvantages in some particular cases, such as the Pearson type III distribution where the optimality of the MLM is only asymptotic and small sample estimates may lead to estimates of inferior quality (Bobée et al., 1993). Another disadvantage is that MLM often gives biased estimates. However, these biased estimates can be corrected. Furthermore, MLM might be hard to compute especially if the number of parameters is large. This will in turn make it hard and might also be impossible to obtain ML estimates of small samples.

Estimation by the Maximum Likelihood (ML) method involves the choice of parameter estimates that produce a maximum probability of occurrence of the observations. The parameter estimates that maximize the likelihood function are computed by partial differentiation with respect to each parameter and setting these partial derivatives equal to zero and finally solve the resulting set of equations simultaneously. The equations are usually complex that can only be solved by numerical techniques. As a result of this difficulty, the solution set may not properly find, Rao & Hamed (2000).

#### 3.3.2.3 Method of Probability Weighted Moments (PWM)

The probability weighted moments (PWM) method, Greenwood et al., (1979); Hosking (1986) gives parameter estimates comparable to the ML estimates. In fact, in some cases the estimation procedures are much less complex and thus less complicated since the computations are simpler than that of ML estimates. Landwehr et al., (1978) stated that the parameter estimates from small samples using PWM are sometimes more accurate than the ML estimates. Parameter estimates are obtained in this method, as in the case of MOM, by equating moments of the distributions with the corresponding sample moments of observed data. For a distribution with k parameters, the first k sample moments are set equal to the corresponding population moments.

The resulting equations are then solved simultaneously for the unknown parameters. Parameter estimation by PWM, which is relatively new, is as easy to apply as ordinary moments (MOM), is usually unbiased and is almost as efficient as ML. Indeed, in small samples PWM may be as efficient as ML. With a suitable choice of distribution PWM estimation also contributes to robustness and is attractive from that point of view. Another attraction of the PWM method is that it can be easily used in regional estimation schemes (Roa & Hamed 2000).

### 3.4 Conceptual work flow chart

The following figure shows the general work flow summary of this study.

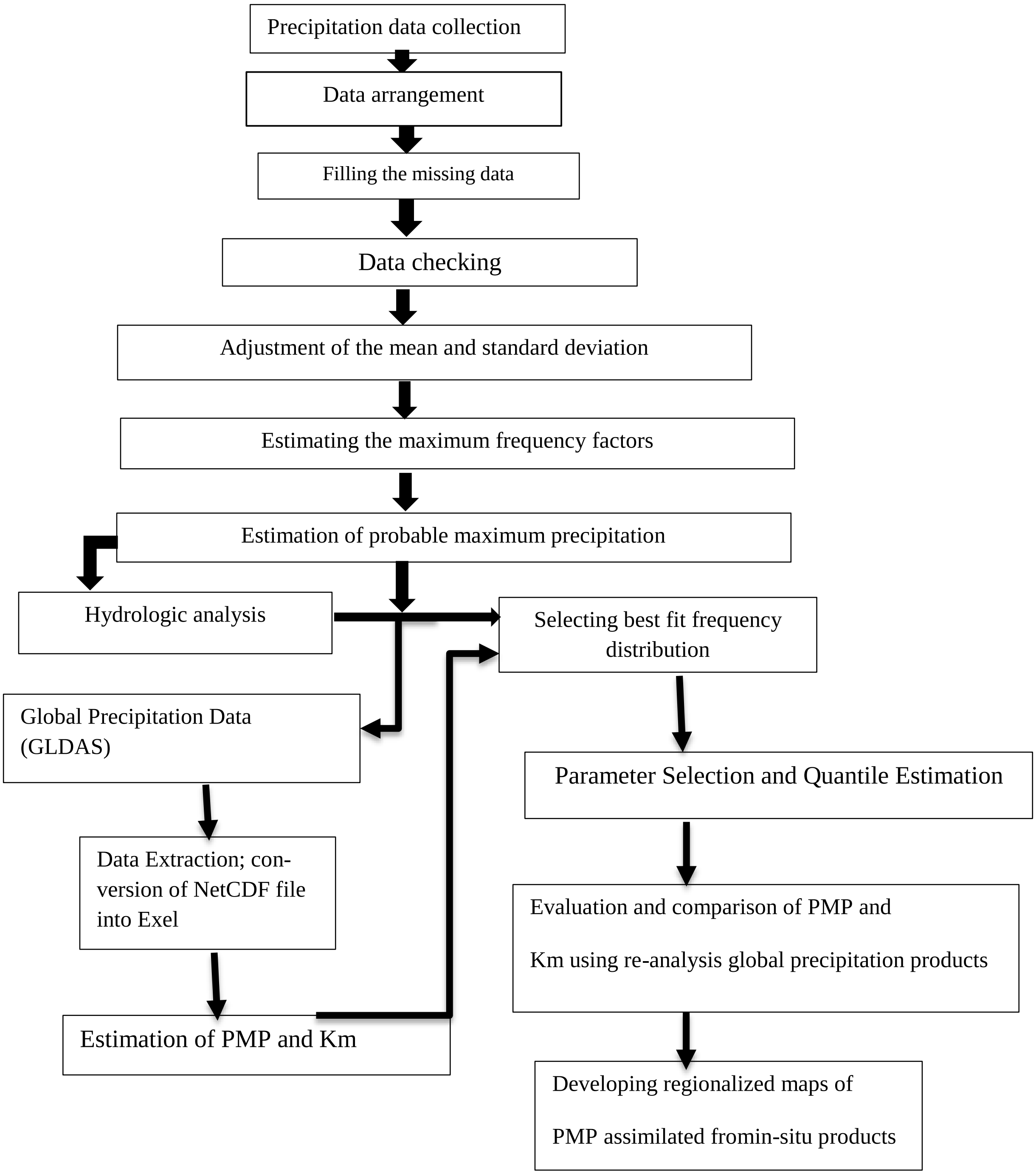


Figure 3.5: The general work flow summary of the study

### 3.5 Materials Used

To work with the input data and get the expected out put, the following materials were used.

I. MS excel spread sheet
II. XLSTAT 2018
III. MATLAB 2013
IV. R-STUDIO 2012
V. ARC GIS 10.4.1

- MS excel spread sheet was used to calculate the statistical parameters of hydrological data that will use from near by station.
- XLSTAT 2018 was applied to data arrangement, filling the missing data and for checking the data quality.
- MATLAB 2013 was used for curve fitting and selection of distribution functions
- R- STUDIO 2012 was applied for conversion of reanalysis global precipitation product in to excel format which was previously in the form of netcdf file. It was not possible to procede the similar steps done on the insitu data with this procedure. The it was essential to convert the netcdf file format into excel by R-programming.
- ARCGIS 10.4.1 was used to specify the location of the study area, for showing the distribution of the ranguage stations over the study area and to develop the regionalized PMP and Km distribution maps assimilated from reanalysis and in-situ product.

### 3.6 Data Availability and Analysis

### 3.6.1 Rainfall Data Source

The in situ daily rainfall data was collected from Ethiopian national meteorological service agency for rainguage stations in the selected study area. Since GLDAS was selected by hving high special resolution and larger time scale coverage (vicenzo, 2008) to be the source of reanalysis precipitation data and then annual maximum of reanalysis data were taken from Global Land Data Assimilation System (GLDAS) from the NASA earth data web site.

### 3.6.2 Data Availability

There are more than 36 stations in the in the middle and lower Awash River basin. Even though the number of stations reaches to the above-mentioned number, the distributions along the sub basins like Meteorological data are cluster to some of the basin. Here in this paper 13 rainfall stations for 1-day, 2- & 3-days durations are collected and analyzed. And the annual maximum for 1 day, 2 & 3 days of the in-situ data prepared from the daily rainfall data and shown in Appendix.

The existing meteorological stations below the koka reservoir along with the study river basin used as a source of precipitation data. Rainfall data for a series specified decades was obtained from the national meteorological agency (NMA). Metrological stations which are actively recording the daily data in the basin's tributaries will be used as a source of daily rainfall data. Table 3.1 shows the existing metrological stations which are active since 1962, according to their time of installation.

Table 3.1: Existing meteorological stations in the study area for insitu data source

| St. No. | Station Name | Latitude | Longitude | Elivation |
|---|---|---|---|---|
| 1 | Assebetefri | 9.0725 | 40.8715 | 1792 |
| 2 | Awash 7 Kilo | 8.983333 | 40.15 | 923 |
| 3 | Combolcha-1 | 11.083899 | 39.717633 | 1857 |
| 4 | Combolcha-2 | 9.433333 | 42.1167 | 2122 |
| 5 | Dupty | 11.723 | 41.01 | 376 |
| 6 | Gewane | 10.15 | 40.633 | 568 |
| 7 | Haik | 11.305316 | 39.680205 | 1985 |
| 8 | Kemisse | 10.716667 | 39.833333 | 1450 |
| 9 | Koka Dam | 8.46933 | 39.1542 | 1618 |
| 10 | Meiso | 9.233333 | 40.75 | 1400 |
| 11 | Metehara | 8.858667 | 39.919 | 944 |
| 12 | Mojo | 8.60533 | 39.108167 | 1763 |
| 13 | Nazret | 8.55 | 39.283333 | 1622 |

Figure 3.6 shows Distribution of rainfall stations over the middle to lower Awash River basin

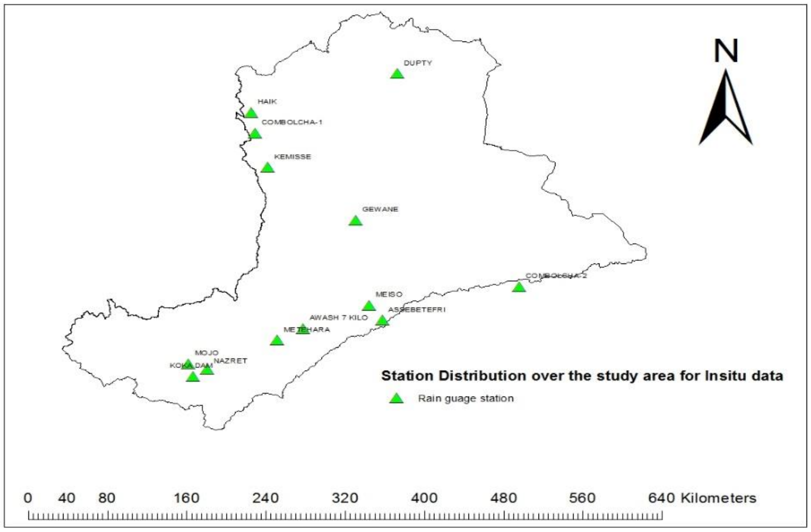


Figure 3.6: Distribution of Rainfall stations over the middle and lower Awash River basin.

The reanalysis data of GLDAS that contains the available stations by the grid size of 0.25 by 0.25 degree of longitude and latitude. The station distribution on the reanalysis map for GLADS shown on Figure 3.7.

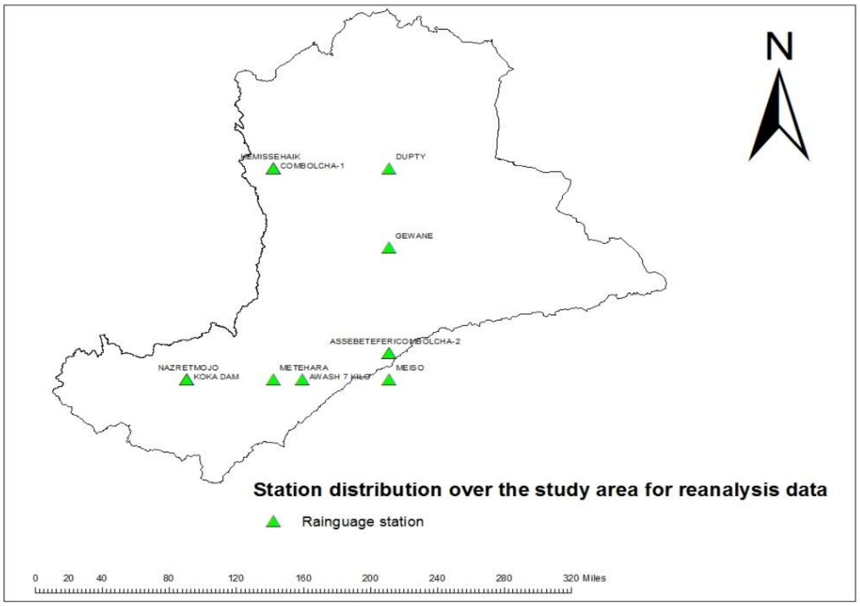


Figure 3.7: Rain fall Station Distribution for 0.25 by 0.25 grid box GLDAS Reanalysis data

### 3.6.3 Gauge Stations for the Respective Sub Basin of Middle to Lower Awash Basin

Table 3.2 shows the summary of Hydro-meteorological networks in the Middle to lower Awash River basin.

Table 3.2: Summary meteorological networks in lower to middle awash river basin

| No. | Subbasin | Number of guage stations |
|---|---|---|
| 1 | Eastern catchment | 1 |
| 2 | Lower plains | 1 |
| 3 | Lower valley | 1 |
| 4 | Middle valley | 4 |
| 5 | Western highlands | 6 |
| Total | | 13 |

### 3.7 Data Quality Control

In order to get good results, the qualities of the data should be investigated though different methods of checking. Under flood frequency analysis the following tests, are commonly used, such are test for Outliers, homogeneity, and independence of data which are discussed by Bobee and Ashkar (1991).

### 3.7.1 Testing for Outliers

An outlier is an observation that deviates significantly from the bulk of the data, which may be due to errors in data collection, or recording, or due to natural causes. The presence of outliers in the data causes difficulties when fitting a distribution to the data. Low and high outliers are both possible and have different effects on the analysis. The Grubbs and Beck (1972) test (G-B) may be used to detect outliers. In this test the quantities XH and XL are analyzed using the following equations.

$$X_{H} = \exp(\bar{X} + K_{NS}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3.4]$$

$$X_{L} = \exp(\bar{X} - K_{NS}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3.5]$$

Where: X and S are the mean and standard deviations of the logarithm of the annual rainfall peaks, respectively, and Kn is detected and Kn, is the G-B statistic tabulated for various sample sizes and significant levels by Grubbs and Beck (1972). At 10% significant level, the following approximation proposed by Pilon et al. (1985) is used.

$K_N = -3.62201 + 6.28446N^{1/4} - 2.49835N^{1/2} + 0.49146N^{3/4} - 0.037911N$....................[3.6]

Where; N is the sample size

The result of the outliers' test for in-situ data for 1-day duration of rainfall depths for Assebeteferi station indicated in Table 3.3

Table 3.3: Outlier test result for Assebeteferi station for 1-day duration annual maximum series insitu data

| Mean | STDEV | Limmiting value | | Data Range | |
|---|---|---|---|---|---|
| | | Upper (XH) | Lower (XL) | Max | Min |
| 1.758603911 | 0.137424277 | 8.167725308 | 6.63081E-07 | 131 | 36.4 |

`

The extreme rainfall events not necessarily bounded by these limits but these tests will help to sort out the exaturated values from the series that might be due to reading error or other errors.

### 3.7.2 Test for data consistency

It is usually assumed that all the peak magnitudes in the AM series are mutually independent in the statistical sense. This assumption is usually justified. A hydrologic time series is stationery if it is free of trends, shifts or periodicity (cyclicity) which implies that the statistical parameters of the series, such as the mean, variance, and autocorrelation structure do not change over time (Maidment, 1993).

The statistical analysis for dependence is carried out for all the 1-day durations of in-situ rainfall record with in each station.

The double mass curve, scattering graph, is used to check the stations data consistency and stationarity. Figure 3.8 shows the data consistency test result for Combolcha-1 station's one day duration annual maximum rainfall.

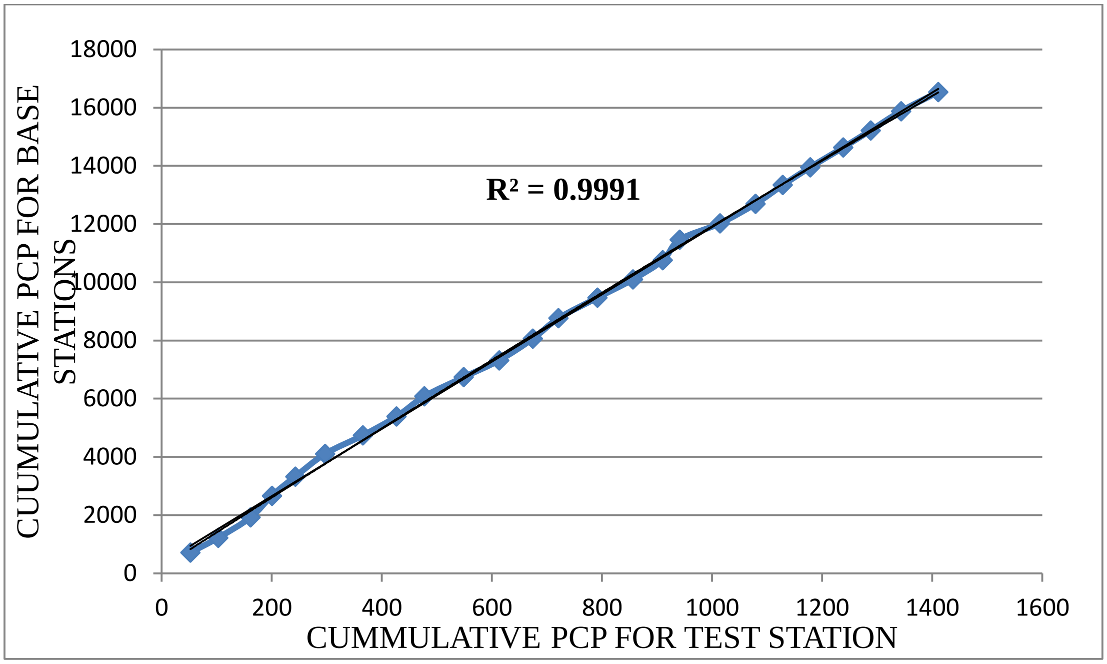


Figure 3.8: gragh of double mass curve for data consistency test

The $R^2$ value is greater than 0.95, as shown in the figure above, so that the data is consistent and stationary.

### 3.7.3 Homogeneity Test for the Data Series

The use of a longer series in the estimation of PMP is appropriate only if they show no significant increasing or decreasing trends. The presence or absence of trends in the annual maximum rainfall series for the 13 rainfall stations used were investigated using the Mann-Kendall rank statistics test. In this test two samples of size p and q with $p \leq q$ are compared. The combined data set of size $N = p + q$ is ranked in increasing order. The Mann-Whitney (1947) (M-W) test considers the quantities V and W in Equation. 3.7 and 3.8

$$V = R - [P\ (P+1)]/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [3.7]$$

$$W = p*q - v \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [3.8]$$

Size N), and V and W are calculated from R, p, and q. V represents the number of times an item in sample 1 follows an item in sample 2 in the ranking. Similarly, W can be computed for sample 2 following sample 1.

The M-W Statistic U is defined by the smaller of V and W. When $N > 20$ and $p, q > 3$, and under the null hypothesis that the two samples came from the same population, U is approximately normally distributed with mean; Umean = $(p+q)/2$, variance var (U);

$Var\ (U) = [(p*q)/(N^3(N-1))]*[((N^3-N)/12)-\sum T]$……………………………[3.9]

Where T= J3 - J /12 and J is the number of observations tied at a given rank. T is summed over all groups of tied observations in both samples of size p and q.

The statistic u= $(U - Umean) / [Var\ (U)]^{1/2}$ is used to test the hypothesis of homogeneity at significance level α by comparing it with the standard normal variate for that significance level.

For no trend in the data series, this value should lie within the limits of ± 1.96 at the 5% level of significance. The test by Mann-Kendall showed that no significant trend in the annual maximum rainfall values exists at all of stations. Hence, the annual maximum rainfall series for all the stations are treated as homogeneous for subsequent calculation.

Table 3.4: Homogeneity test result For Assebeteferi Station for 1-day duration insitu data

| Mann-Kendall's rank statistics test result (WMO, 1966) | | Remark |
|---|---|---|
| Station name | Assebeteferi | |
| Sample size | 25 | |
| Sample 1 (p) | 12 | |
| Sample 2 (q) | 13 | |
| Number of observations tied (J) | 4 | |
| Sum of the tied | 15.666 | |
| *Var (U)* | 333.9267 | Using equation 4.5 |
| Standard test result for 5% significant level (u) | 0.684045 | < 1.96 |

As shown in the table 3.4, the standard test for Assebeteferi station for 5% significant level was found to be less than 1.96 therefore no significant trend in the annual maximum rainfall values exist. Hence, the annual maximum rainfall series for the station is treated as homogeneous for subsequent calculation.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 Determination of Frequency Factor (K) Value Using Hershifield's Statistical Method for MLAWB

Following the same procedure explained in section three and using the statistical values of the stations in the basin the frequency factor K for each rainfall station was computed by using equation 2.2, Hershfield (1961, 1965).

Table 4.1: The proedure for computing K value for insitu 1-day duration for Assebeteferi station

| Year | Rainfall depths of 1 day durations in (mm) | Rainfall dapth(Xn-1) in mm Excluding 131mm rainfall depth |
|---|---|---|
| 1986 | 131 | |
| 1987 | 81.2 | 81.2 |
| 1988 | 90.4 | 90.4 |
| 1989 | 47.6 | 47.6 |
| 1990 | 59 | 59 |
| 1991 | 38.2 | 38.2 |
| 1992 | 77.5 | 77.5 |
| 1993 | 50.4 | 50.4 |
| 1994 | 52 | 52 |
| 1995 | 54.4 | 54.4 |
| 1996 | 36.4 | 36.4 |
| 1997 | 73.5 | 73.5 |
| 1998 | 68.9 | 68.9 |
| 1999 | 73 | 73 |
| 2000 | 45 | 45 |
| 2001 | 60 | 60 |
| 2002 | 46.7 | 46.7 |

| | | |
|---|---|---|
| 2003 | 48 | 48 |
| 2004 | 44.3 | 44.3 |
| 2005 | 86.2 | 86.2 |
| 2006 | 39 | 39 |
| 2007 | 66.5 | 66.5 |
| 2008 | 41 | 41 |
| 2009 | 54.4 | 54.4 |
| 2010 | 45 | 45 |
| | | |
| | Max X1 | **131.00** |
| | Mean of Xn-1 | 57.44 |
| | ST.Dev. Of Xn-1 | 16.03 |
| | Frequency factor | 4.59 |

Table 4.1 shows the calculted value of frequency factor for Assebetefri station using Hershfield's statstical equation ( equation 3.2), Hershfield (1961, 1965). 25 years of insitu data at the station was used. The adjusted mean and standard deviation (Hershfield, 1961b) are input for the empirical formula. And the resulted frequency factor (K) value for Assebeteferi station using Hershfield's statistical method is 4.59. The distribution of K values for the 13 rainfall stations of in-situ 1-day duration are given in table 4. 2.

Table 4.2: The frequency factor K values for insitu 1-day duration of the meteorological station in MLAWB

| **Station Name** | **K** |
|---|---|
| Assebeteferi | **4.59** |
| Awash 7 Kilo | 4.08 |
| Combolcha-1 | 1.69 |
| Combolcha-2 | 2.17 |
| Dupty | 4.17 |
| Gewane | 1.69 |
| Haik | 3.31 |

| | |
|---|---|
| Kemisse | 4.06 |
| Koka Dam | 2.82 |
| Meiso | 2.42 |
| Metehara | 2.13 |
| Mojo | 2.58 |
| Nazret | 3.02 |

Table 4.2 shows results of the frequency factor values for the 13 ranguage stations in the water shed of insitu data for 1-day duration. As of table 4.1, the same procedure was applied for the other 12 stations in the watershed. As seen in table 4.2, the maximum of all the values is 4.59 which is at Assebeteferi station. Hence, the value of the maximum frequency (Km) factor for insitu data of 1-day duration using Hershfield's statistical method is 4.59.

## 4.2 Determination of Frequency Factor (K) Values Using Hershfield's Chart

A sample station was taken and the Hershfield's chart was used to determine the frequency factor. Since the mean of the annual maximum rainfall series at Assebeteferi station for insitu 1-day duration is 54.11mm, the frequency factor corresponding to the mean from Figure 2.1 (Hershfield's chart) is 16.5.

### 4.2.1 Comparison of K value obtained from Hershfield's chart and by Using Statistical Method

Table 4.3: Frequency factor obtained by Hershfield's statistical and graphical method for insitu 1-day duration for the study area

| Station No. | Station Name | Km by Hershfield's statistical Method | Km by Hershfield's Chart | Remark |
|---|---|---|---|---|
| 1 | Assebetefri | 4.59 | 16.5 | Km by chart method is obtained from the chart given on figure 2.1 |
| 2 | Awash 7 Kilo | 4.08 | 17.1 | |
| 3 | Combolcha-1 | 1.69 | 16.6 | |
| 4 | Combolcha-2 | 2.17 | 16.9 | |
| 5 | Dupty | 4.17 | 18 | |

|  |  |  |  |  |
|---|---|---|---|---|
| 6 | Gewane | 1.69 | 16.5 |  |
| 7 | Haik | 3.31 | 16.45 |  |
| 8 | Kemisse | 4.06 | 16.45 |  |
| 9 | Koka Dam | 2.82 | 17.15 |  |
| 10 | Meiso | 2.42 | 16.65 |  |
| 11 | Metehara | 2.13 | 17.25 |  |
| 12 | Mojo | 2.58 | 16.95 |  |
| 13 | Nazret | 3.02 | 16.5 |  |

Table 4.3 comparison between the Hershfield's chart frequency factor and the Hershfield's statistical frequency factor values for 1-day duration insitu data of the ranguage stations in the study area. The K value using Hershfield' chart is obtained from figure 2.1 and it is inversely proportional the mean maximum annual rainfall of the rainguage stations. When the mean annual rainfall is smaller the frequency factor value tends to the maximum value for 24-hour duration of rainfall which is 20 from the chart.

Generally, the mean of maximum precipitation for the majority of stations in the study area for the indicated duration is found to be less than 100 mm; therefore, there corresponding frequency factors from the chart ranges from 16 to18 which is more than twice of the estimated Km in the above-mentioned procedure and this causes overestimation**.**

### 4.3 Probable Maximum Precipitation (PMP)

In view of the mentioned problems in the methodology part and recent research outputs, the Hershfield's chart might not give reliable frequency factor estimates world over. It was therefore felt that an appropriate Km value based on in-situ and reanalysis product of particular study area would give better estimates of PMP than Hershfield's chart.

Table 4.4: Procedure for PMP estimation at Assebeteferi station for insitu 1-day duration

| | Station Name | Assebeteferi | | |
|---|---|---|---|---|
| No. | Description | Symbol | Values | Remarks |
| 1 | Sample Size | N | 25 | 9.0275N,40.8715E and 1792m Alt. |
| 2 | Mean(mm) | Xn | 60.38 | |
| 3 | Standard Deviation(mm) | σn | 21.51 | |
| 4 | Mean after Excluding the maximum rainfall depth from the series(mm) | Xn-1 | 57.44 | |
| 5 | Standard deviation after Excluding the maximum rainfall depth from the series(mm) | σn-1 | 16.03 | |
| 6 | The ratio of 5 and 3 | Xn-1/Xn | 0.95127 | |
| 7 | The ratio of 6 and 4 | σn-1/σn | 0.7451 | |
| 8 | Adjustment of mean for the maximum observed series (see section 2) | From fig(2.2), | 0.89614 | |
| 9 | Adjustment of mean for length of record (see section 2) | From fig (2.4) | 0.8716 | After Hershfield,1961,b |
| 10 | Adjustment of standard deviation for the maximum observed series (see section 2) | From fig(2.3) | 0.85418 | |
| 11 | Adjustment of standard deviation for length of record | From fig(2.4) | 0.83451 | |
| 12 | Adjusted mean(mm) | adj. mean | 54.113 | |
| 13 | Adjusted stdev(mm) | adj.stdev | 18.37125 | |
| 14 | Frequency factor | km | **4.59** | See section 4.2 |
| 15 | 1-day probable maximum precipitation(mm) | 1-day PMP | 138.4358 | |
| 16 | 24 hrs probable maximum precipitation(mm) | 1.13*daily PMP | 156.4325 | After Hershfield,1961,b |

Table 4.4 shows procedure for estimation of PMP using Hershfield's statistical method for insitu data

For 1-day duration. The table shows the result for the calculated PMP value using equation 2.2, Hershfiel (1961, 1965) for Assebeteferi station in the watershed. Using the adjusted mean and standard deviation (Hershfield, 1961b), the resulted PMP value for the station is 156.4 mm. similar procedure was applied to get the PMP values for the ranguage stations in the watershed of insitu data at different durations.

### 4.3.1 Estimation of PMP Using Hershfield's Chart and Compering the Result with the computed PMP of Hershfield's Frequency Equation

So far, practitioners in Ethiopia have been using the Hershfield's chart for estimation of PMP (WWWDSE, 2008). Here in this study estimation of PMP were made using the chart's Km values to elaborate the discrepancy of the results from the results obtained in the above procedures. See the following table for in situ 1-day data.

Table 4.5: Comparison of the resulted PMP with PMPs from the graphical methods

| IN-SITU 1 DAY DURATION | | | | | | | |
|---|---|---|---|---|---|---|---|
| Station No. | Station Name | Xm | Adjusted Mean | Adjusted Standard deviation | PMP by statistical method | PMP by Grapical Method | Percent of Deviation (%) |
| 1 | Assebetefri | 131 | 54.11 | 18.37 | 156.43 | 357.24 | **128.37** |
| 2 | Awash 7 Kilo | 122.1 | 47.72 | 20.12 | 146.70 | 391.70 | 167.01 |
| 3 | Combolcha-1 | 73.2 | 52.44 | 12.13 | 82.43 | 253.86 | 207.97 |
| 4 | Combolcha-2 | 81.6 | 50.69 | 14.99 | 93.98 | 303.99 | 223.47 |
| 5 | Dupty | 90.8 | 37.90 | 13.93 | 108.46 | 288.72 | 166.20 |
| 6 | Gewane | 89.5 | 54.07 | 22.29 | 103.66 | 421.88 | **306.99** |
| 7 | Haik | 104.2 | 56.55 | 15.43 | 121.64 | 310.42 | 155.20 |
| 8 | Kemisse | 114 | 55.45 | 15.58 | 134.21 | 311.73 | 132.27 |
| 9 | Koka Dam | 100.8 | 46.49 | 21.20 | 120.20 | 410.03 | 241.12 |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| 10 | Meiso | 98 | 51.11 | 21.14 | 115.48 | 403.14 | 249.10 |
| 11 | Metehara | 68.1 | 43.48 | 12.02 | 78.11 | 250.81 | 221.10 |
| 12 | Mojo | 94.9 | 49.79 | 19.01 | 111.66 | 371.94 | 233.09 |
| 13 | Nazret | 104.8 | 54.39 | 18.06 | 123.19 | 352.42 | 186.07 |

The PMP obtained using the new K value and the chart K values for the stations in the basin shown above table confirms that the PMPs obtained using the K from the chart is greater than range between **128** and **307** % of the PMP obtained using the new K value.

This exaggerated difference of PMP as a result of difference in new Km and the Chart's Km has far reaching consequence in the total cost of dam projects when dam design is considered based on PMF. Therefore, high attention should be provided for the estimation of Km values because, Km constant is sensitive in the estimating PMP. As seen the results of similar studies in other parts of the country (Abenezer et. al., 2016), the result in this study shows that Hershfield's chart is overestimative than the Hershfield's statistical method.

### 4.3.2 The Rainfall Frequency Analysis

Rainfall frequency analysis is a methodology which comprises data preparation, selection of frequency distribution, method of parameter estimation and computing rainfall quantiles for different durations. In order to compare some of the present study results a 1day, 2 and 3 days PMPs with the 10,000 years return period rainfall events this procedure is required.

#### 4.3.2.1 Selection and Evaluation of Parent Distributions for the Rainfall Data

Frequency distributions can be described by their moments. The two most commonly used moment ratio diagrams: The Conventional Moment Ratio Diagram (MRD) and the L-moment Ratio diagram (LMRD) which is used to select the parent distribution of a particular station which helps for the estimation of the rainfall events of different recurrence intervals using different parameter estimation methods.

Figure 4.1 indicates the graph of L-MRD and the candidate distributions for in-situ 1-day duration annual maximum rainfall at Assebeteferi station. The same analysis could be applied to fit the best distribution to each station data.

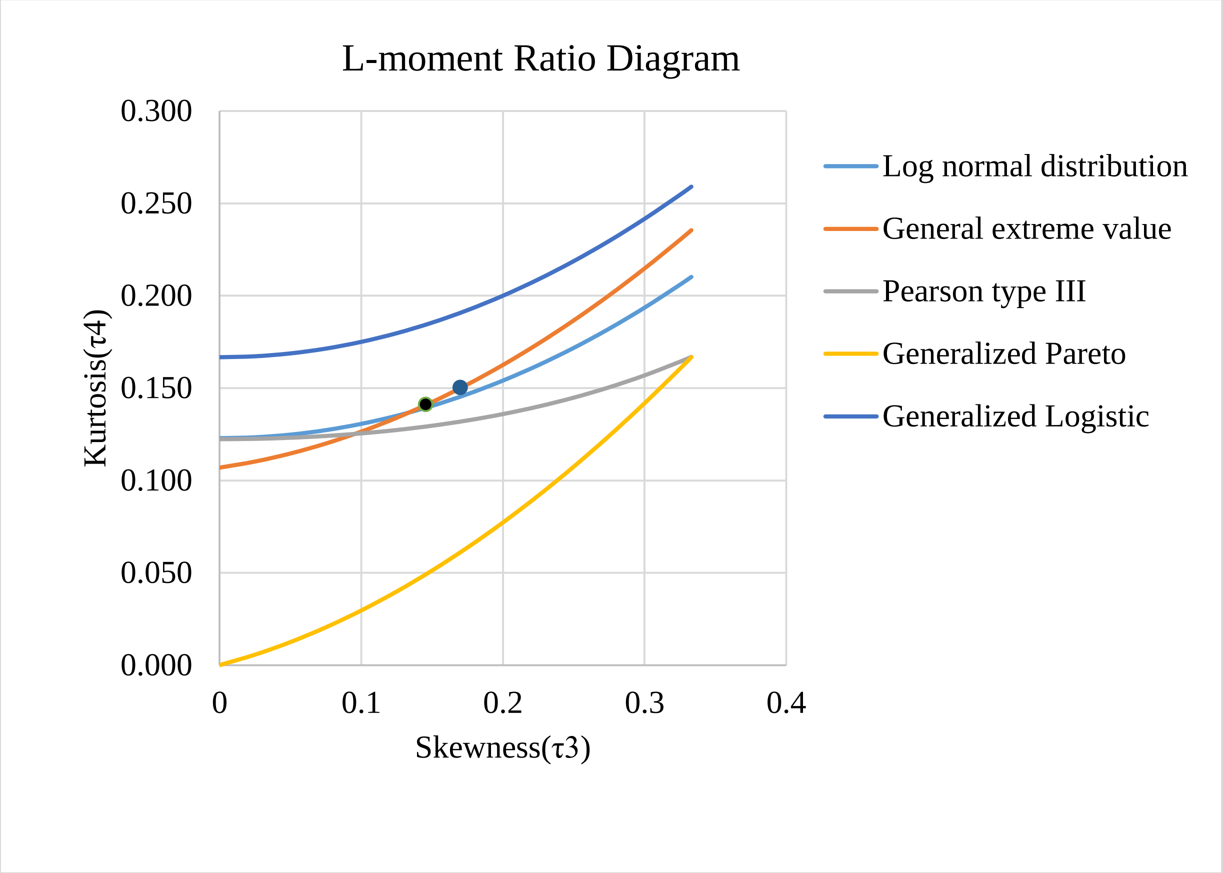


Figure 4.1: L-MRD for 1-day in-situ rainfall depth at Assebeteferi station

Estimates based on L- moments are generally superior to standard moment-based estimates. L- moments are analogous to conventional moment ratios (Hosking, 1990). The values of the ratios are calculated using different equations for each distribution type. The graph of skewness versus kourtosis (L- moment ratios) is known as L- moment ratio diagram (LMRD). And the distribution that approaches or passes through the points on the graph is selected as best distribution function for the station. As shown in figure 4.1, GEV is selected as best fit Candidate distribution for Assebeteferi Station. Similar procedures have been applied for the the other ranguage stations with in the water shed to select best fit distribution functions.

#### 4.3.2.2 Parameters Selection and Quantile Estimation

Using standard error of estimate (SEE), the fitted Parameter estimation methods were selected and then computed the quantile estimates ($X_T$) corresponding to different return periods. The standard error of estimate (SEE) for annual maximum rainfall of In-situ 1-day duration in the different return periods for Assebeteferi station are shown in table below.

Table 4.6: Standard error test for for different parameter estimation methods for fitted distributions for Assebeteferi station

| Method of Parameter Estimation | Standard Errors of Estimates for the indicated return periods in years | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2 | 10 | 50 | 100 | 200 | 500 | 1000 | 10000 |
| GEV/MOM | 1.21568 | 1.3599 | 1.7625 | 2.1135 | 2.5758 | 2.7221 | 3.0165 | 3.2283 |
| GEV/MLM | 1.59143 | 1.8791 | 2.4743 | 3.2013 | 3.7867 | 3.9315 | 4.2071 | 4.3516 |
| GEV/PWM | 1.58761 | 1.7962 | 2.2915 | 2.9761 | 3.4744 | 3.5751 | 3.7375 | 3.9165 |

Quantiles of different return periods were estimated using the parameters with smallest standard error of estimate for the best fitted distributions. The best fitted candidate distributions of in-situ 1-day rainfall durations and the method of parameters and quantiles estimator for all stations in the basin are shown in table 4.7.

Table 4.7: Best fitted distributions and methods of parameter estimations for insitu 1-day duration

| St. No. | Station Name | Fitted Distribution and method of parameter Estimation |
|---|---|---|
| 1 | Assebeteferi | GEV/MOM |
| 2 | Awash 7 Kilo | GEV/MLM |
| 3 | Combolcha-1 | PIII/MOM |
| 4 | Combolcha-2 | GEV/MOM |
| 5 | Dupty | GEV/MOM |
| 6 | Gewane | GEV/MOM |
| 7 | Haik | PIII/MLM |
| 8 | Kemisse | PIII/MOM |
| 9 | Koka Dam | PIII/MOM |
| 10 | Meiso | GEV/MOM |
| 11 | Metehara | GEV/MOM |
| 12 | Mojo | GEV/MOM |
| 13 | Nazret | GEV/MLM |

As the shown-on table 4.7, for the in-situ 1-day duration the candidate distribution of the available stations in the study area were General Extreme Value (GEV) and Pearson (III).

Among various frequency distributions, the generalized extreme value (GEV) theory has been recently applied in hydrological studies by many researchers, to determine extreme rainfall values associated with large return periods (Koutsoyiannis, 1999, 2004; Lee and Maeng, 2003; Haktanir, 2004; Michele and Salvadori, 2005). Based on this recommendation and the fitted distribution as shown on table 4.7, the generalized extreme value (GEV) distribution is used for both 2 & 3 days' in-situ and 1 day, 2- & 3-days' reanalysis precipitation product to estimating quantiles of different durations.

Table 4.8: Estimated quantiles of different durations for Assebeteferi station

| Return Period (years) | Estimated Quantiles for the indicated durations of in-situ rainfall, depth (mm) at Assebeteferi station | | |
|---|---|---|---|
| | 1-day | 2-days | 3-days |
| 2 | 56.87 | 73.49 | 88.40 |
| 10 | 88.40 | 107.31 | 124.84 |
| 50 | 116.05 | 136.97 | 156.79 |
| 100 | 127.74 | 149.50 | 170.29 |
| 200 | 139.38 | 161.99 | 183.75 |
| 500 | 154.75 | 178.47 | 201.51 |
| 1000 | 166.36 | 190.93 | 214.92 |
| 10000 | 204.91 | 486.74 | 259.47 |

As seen on the results of table 4.8, quatiles are estimated upto 10000 years of return periods. National research council recommends estimation of quantiles up to $10^9$ years of return periods (NRC, 1994). Recent related researches in our country (Abenezer, 2016; Birhan, 2017) have estimated quantiles of their specific study areas up to 10000 years of return periods. Based on similar reaserch trends and recommendations rainfall quantiles for this study area were calculated upto 10000 years of return periods as shon on table 4.8.

## 4.4 Evaluation and Comparison of Km and PMP with Reanalysis Products

### 4.4.1 Evaluating the Frequency factor (K) Values of the reanalysis products for a sub basin of LMAWB

As shown in Table 4.2 most of the K values for 1-day duration were less than 5.0. Thus, the highest value of (Km) for the in-situ 1-day duration was found to be 4.59 or approximately 5 in the study area which is the required frequency factor of the study area for the in-situ 1-day annual maxima series. For durations of 2 and 3 days of the in-situ data the frequency factors Km values are found to be 5.09 and 4.03 respectively. The table 4.9 shows the number of stations which occurred in the given k value range for 1-day duration of both in- situ and reanalysis products.

Table 4.9: Number of stations for a given K value range for 1-day duration MLAWB

|  | Number of Stations for the computed K value |  |  | Captured Reanalysis |
|---|---|---|---|---|
| Data Source | K<3 | 3<K<5 | K<5 | Product for k<5 |
| In-Situ | 7 | 6 | 13 | GLDAS |
| GLDAS | 7 | 6 | 13 |  |

As shown on table 4.9, the of number of station's k values in a sub basin are less than 5 and compered the k value of a sub basin of reanalysis product result with the in-situ result. The results are the values of frequency factors for each station within the water shed Hershfield's statistical method. Those K value ranges include for both in-situ and GLDAS reanalysis global precipitation data for 1-day, 2-days and 3-days durations. The results on table 4.9 shows us a sub basin of MLAWB GLADS reanalysis product is adequately captured the k value range with respect to in-situ result.

### 4.4.2 Computed Maximum Frequency Factor (Km) Values Using Hershfield's Frequency Equation for a Sub Basin of LMAWB.

The maximum frequency factor (Km) that represents the study area was computed using Hershfield's statistical method for both in-situ and GLDAS reanalysis global precipitation product for the study watershed. The result is shown on table 4.10.

Table 4.10: Frequency factor (Km) values for a sub basin of LMAWB using Hershfield's frequency equation

| | Km for 1 Day | | Km for 2 Day | | Km for 3 Day | |
|---|---|---|---|---|---|---|
| Station Name | In-situ | GLDAS | In-situ | GLDAS | In-situ | GLDAS |
| Assebeteferi | **4.59** | 2.13 | **5.09** | 2.63 | 2.41 | 2.03 |
| Awash 7 Kilo | 4.08 | 3.14 | 3.37 | 3.38 | 3.06 | 3.16 |
| Combolcha-1 | 1.69 | 3.96 | 2.50 | 2.82 | 2.14 | 3.09 |
| Combolcha-2 | 2.17 | 2.13 | 1.58 | 2.63 | 2.37 | 2.03 |
| Dupty | 4.17 | 3.89 | 4.80 | 3.06 | 3.50 | 2.22 |
| Gewane | 1.69 | 1.82 | 2.74 | 3.14 | 3.13 | 3.27 |
| Haik | 3.31 | **3.96** | 2.68 | 2.82 | 2.67 | 3.09 |
| Kemisse | 4.06 | **3.96** | 4.10 | 2.82 | 3.79 | 3.09 |
| Koka Dam | 2.82 | 2.73 | 3.60 | 3.99 | 3.60 | 4.6 |
| Meiso | 2.42 | 2.95 | 3.34 | **4.17** | **4.03** | **5.01** |
| Metehara | 2.13 | 3.41 | 2.74 | 2.23 | 3.38 | 3.09 |
| Mojo | 2.58 | 2.73 | 2.56 | 3.99 | 2.65 | 4.6 |
| Nazret | 3.02 | 2.73 | **5.09** | 3.99 | 3.94 | 4.6 |

As seen in the results shown on table 4.10, the maximum value of the frequency factor for both insitu insitu and GLDAS reanalysis global precipitation data was 5.1. it is smaller value as compared with the results obtained in other parts of the country; 11 for upper Blue Nile basin (Abenezer, 2016) and 6.1 for upper Awash basin (Birhan, 2017). This result show that the maximum frequency factor value depends on the annual maximum rain fall depth. The middle to lower Awash basi is arid and semi arid region (Awulachew, 2007). Thus, the annual rain fall depth is smaller than the other reasearched areas mentioned above. For this reasonand as discussed on table 5, the estimation using Hershfield’s chart for the study area was highly exaggurated and overestimated.

### 4.4.3 Evaluating the Maximum Frequency factor Km and PMP Using Hershfield’s Frequency Equation for a Sub Basin of LMAWB.

The table 4.11 shows the computed Km and PMP value using Hershfield’s equation for both in-situ and reanalysis data for different duration in the study area.

Table 4.11: Km and PMP result for insitu and reanalysis data

| Data Source | Durations | | | | | |
|---|---|---|---|---|---|---|
| | 1-Day | | 2-Day | | 3-Day | |
| | Km | PMP (mm) | Km | PMP (mm) | Km | PMP (mm) |
| INSITU | 4.59 | 156.43 | 5.09 | 181.00 | 4.03 | 214.23 |
| GLDAS | 3.96 | 69.73 | 4.17 | 180.22 | 5.01 | 221.82 |
| **Maximum of K & PMP** | **4.59** | **156.43** | **5.09** | **181.00** | **5.01** | **221.82** |

As shown on table 4.11 for both in-situ and reanalysis data for 1 day, 2 & 3 days the Km and PMP (mm) value not much more than 5.1 and 222 respectively for MLAWB. The table also shows GLADS precipitation product adequately captures PMP with respective to the in situ PMP result. The estimated PMP value for the insitu and reanalysis products and its percent of deviation for a sub basin of MLAWB shown in the table 4.12

Table 4.12: PMP values for LMAWB using Hershfield's frequency equation and its percent of deviation for 1-day duration

| PMP (mm) Value Using Hershfield's Frequency Equation for a sub basin of MLAWB for 1-day duration | | | | | |
|---|---|---|---|---|---|
| Station name | Insitu | GLDAS | | | Percent of Deviation |
| Assebeteferi | 156.43 | 71.35 | | | -119.25 |
| Awash 7 Kilo | 146.70 | 117.91 | | | -24.41 |
| Combolcha-1 | 82.43 | 69.73 | | | -18.22 |
| Combolcha-2 | 93.98 | 71.35 | | | -31.72 |
| Dupty | 108.46 | 107.84 | | | -0.57 |
| Gewane | 103.66 | 72.13 | | | -43.72 |
| Haik | 121.64 | 70.49 | | | -72.55 |
| Kemisse | 134.21 | 70.49 | | | -90.39 |
| Koka Dam | 120.20 | 98.37 | | | -22.19 |

| | | | | | |
|---|---|---|---|---|---|
| Meiso | 115.48 | 95.95 | | | -20.36 |
| Metehara | 78.11 | 62.15 | | | -25.69 |
| Mojo | 111.66 | 98.37 | | | -13.51 |
| Nazret | 123.19 | 98.37 | | | -25.24 |

As a result, in table 4.12 above, stations; Dupty, Combolcha-1, Nazret, Mojo, Metehara, Meiso, Koka dam and Awash 7 kilo captured by GLDAS reanalysis product with in 25% of deviation. But the rest of the stations in the basin; Assebeteferi, Combolca-2, Gewane, Haik and Kemisse are not adequately captured by the reanalysis product PMP values with respect to the stations insitu PMP value.

## 4.5 Comparing the PMP Values with the 10,000 years Return Period Quantiles in the Study Area

According to Hershfield (1962), the magnitude of point PMP at an individual station should normally not exceed three times the Highest Observation Rainfall from a long period of rainfall data. Although the PMP has a theoretical exceedance probability of zero, meaning that it is so large that it will never be exceeded, this is not the case in reality. Consequently, a few studies have sought to assign a risk statement to PMP estimates. The National Research Council (NRC) estimates the return period of the PMP in the United States as between $10^5$ and $10^9$ years (NRC 1994). Taking these in to consideration the PMP obtained for different stations in the study area compared with their corresponding rainfall Quantiles for T=10,000 years. The ratio of the PMP values to the T=10,000 years' rainfall Quantiles varies from 1.27 to 2.82 for both in-situ and reanalysis data of different durations.

Table 4.13: The ratio of PMP to the 10000 years return period event

| Durations | Insitu | GLDAS |
|---|---|---|
| 1 Day | 2.13 | 1.84 |
| 2 Day | 1.96 | 1.80 |
| 3 Day | 1.91 | 1.80 |

As per the upper mentioned table the ratio of PMP to the 10,000 years return period quantiles for in-situ, and GLADS data in the study area are 2.13 and 1.84 respectively. This shows GLADS reanalysis precipitation product captured the result of average ratio of PMP to the

10,000 years return period quantiles of the in-situ data. And the estimated quantiles with respect to their return periods were in acceptable range.

### 4.6 Construction of k and PMP Contour Maps for LMAWB

Continuous phenomena like precipitation can be graphically represented as contour maps, which are maps in which a set of isolines are interpolated between points of known value. Interpolation is necessary to obtain a spatial pattern because precipitation data typically come in the form of points. However, there are problems of interpolating data between irregularly spaced points of known value. The inverse distance weighting (IDW) is one of the methods to address the upper mentioned problem. IDW lays a grid on top of the input or control points and estimates values at each grid point as a function of distance to each control point. Then the technique interpolates between the grid points. The control points are weighted as an inverse function of their distance from the grid points. As shown in figures below the K and PMP contour maps for the in-situ 1-day durations using Hershfield's equation and chart in the study area were constructed using Arc-GIS environment. The inverse distance weighting (IDW) method is used to construct the isolines between two station PMP values.

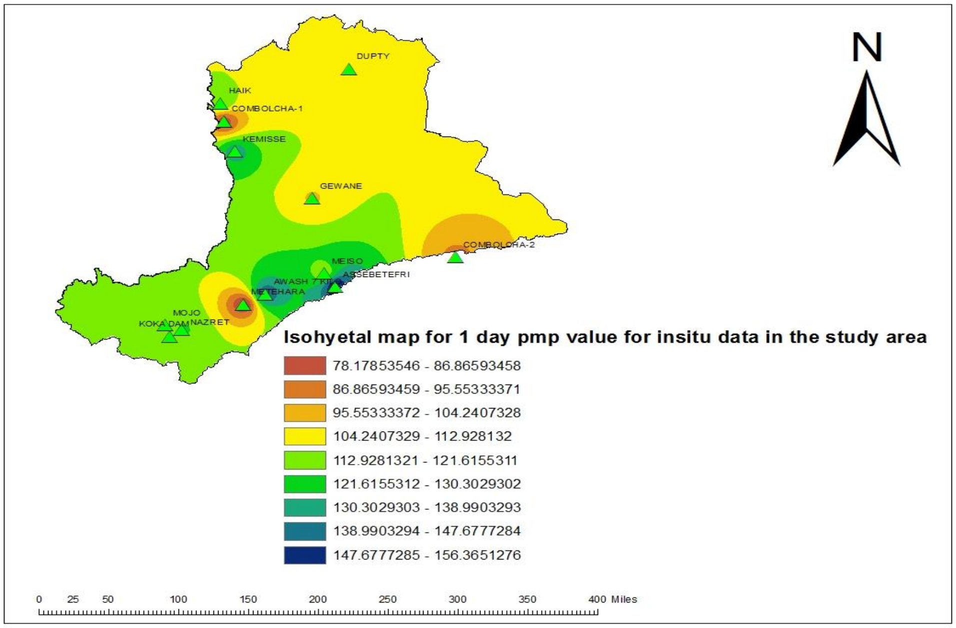
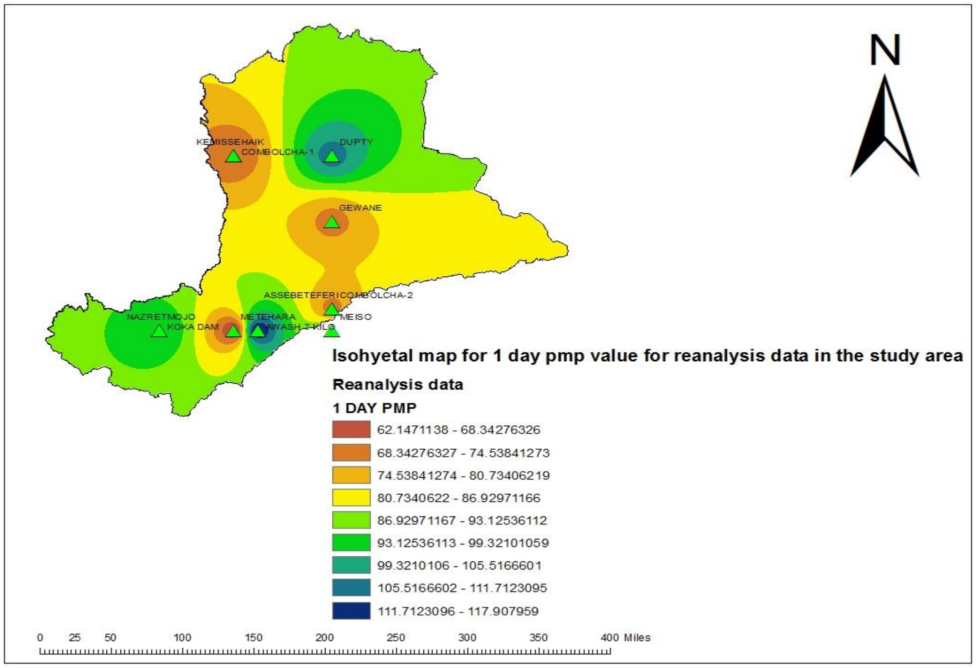


Figure 4.2: PMP (mm) Contour Maps of Middle to Lower Awash for in-situ 1-Day Durations using Hershfield's frequency equation



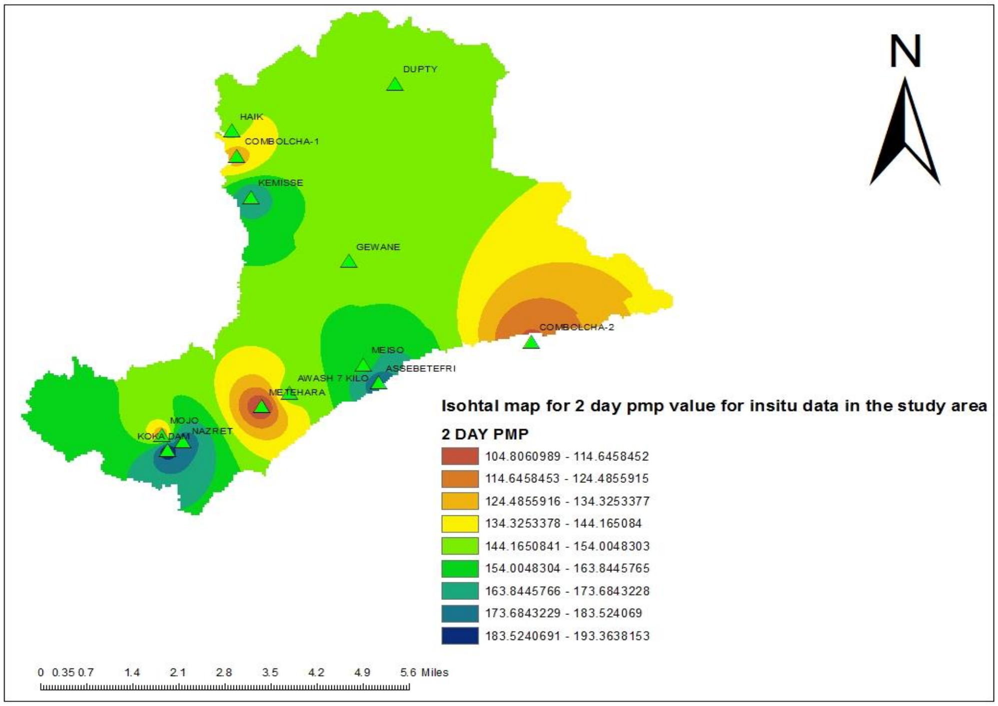


Figure 4.3: PMP (mm) Contour Maps of Middle to Lower Awash for in-situ 2-Day Durations using Hershfield's frequency equation

Figure 4.4: PMP (mm) Contour Maps of Middle and Lower Awash for in-situ 3-Day Durations using Hershfield’s frequency equation

The upper mentioned K and PMP contour map shows the spatial distributions of PMPs over Middle to Lower Awash basin. Data from these maps used to characterize the PMP over the Middle to Lower Awash Basin. The PMP contour maps for the reanalysis products using Hershfield’s equation and the K for both the isitu and the reanalysis products using Hershfield’s equation of different durations are sited in the *Appendix I*.

# CHAPTER FIVE

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

Reliable estimation of probable maximum precipitation over a point or an area for a different duration that are expeted to occur, is a very much important for hydrometeorology. These estimates are of considerable importance to hydrologists for calculating the probable maximum flood (PMF) for planning, design and and risk assessment of hydrological structures such as flood controlling structures upsteam of populated areas and spillways on large dams.

The purpose this study was to evaluate the frequency actor (Km) embedded in Hershfield's frequency equation of PMP using insitu and GLDAS reanalysis product and refine Km value that would adequately represent the lower and middle awash basin and to evaluate the reanalysis products of K and PMP values of MLAWB for 1-day, 2-days and 3-days durations.

In this study, 13 stations for 1-day, 2-days and 3-days durations were used to estimate new PMP on the basis of Hershfield's statistical procedure. The result obtained by comparing the Km value from Hershfield's statistical method and the Hershfield's chart was deviated up to 3 time's larger (300% deviation) than K value obtained from Hershfield's statistical equation. The K values obtained from the chart are between 15 and 19, the maximum Km value obtained using statistical method for both insitu and reanalysis data of 1 day, 2 day and 3-day durations are limited to 5.1. The maximum frequency factor for the study area is 5.1 using Hershfield's statistical method.

In comparison of insitu and GLDAS reanalysis data for 1 day, 2 day and 3-day durations PMP and Km values are not more than 222 and 5.1 respectively. And GLDAS reanalysis product is adequately capture PMP with respect to the insitu PMP result for stations such as Dupty, Combolcha-1, Nazret, mojo, Metehara, Meiso, Koka dam and Awash 7 kilo in the study area within 0.6 and 25 percent of deviation. The rest of the stations in the selected study area such as Assebeteferi, Combolcha-2, Gewane, Haik and Kemisse are not adequately captured by GLDAS reanalysis precipitation product PMP value with respect to the station insitu PMP value and the reanalysis product for these stations is not practical for hydrological analysis.

The result of comparison between the values of PMP obtained by Hershfield's chart and Hershfield's statistical procedure confirmed, the Hershfield chart overestimated PMP value which has far reaching Consequences in the total cost of dam and spillway projects in the study area when design is considered PMF.

The average ratio of PMP value to 10000 years return period quantiles for insitu and GLDAS reanalysis precipitation product for the study area was found to be 2.0 and 1.81 respectively which is less than aximum ratio value 3 (Hershfield, 1962). This shows GLDAS reanalysis product is adequately captured the result of average ratio value of the insitu data and the estimated quantiles for the rainguage stations with respect to their return period was in acceptable range.

# RECOMMENDATIONS

To have some changes on similar researches and encouragements to the researchers, the following recommendations are necessary.

Since, we have plenty of water resources, further researches should be conducted on the rest of the basins of Ethiopia for fixing the country's reliable maximum frequency factor (Km).Researches and studies related to this issue must be encouraged to to save the loss of huge amount of water resources project costs due to unreliable estimation of PMP. Since, meteorological data is an input for such studies the way of data recording system should be moderniandzed and the data should be easly accessible to any concerned researchers.Since the development of the probable maximum flood (PMF) is a powerful tool for practical purposes of water resources developments like in design of spillway to avoid the overtoping of dams as a result of river flooding, it is advisable to develop the PMF for the study area and for the country as well.

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# APPENDIXES

## Appendix-A:

Table A-1: Data test results for ode day duration of in-situ data;

| Test of Homogeneity | | | |
|---|---|---|---|
| Station Name | Statistics | Critical Test Statistics | Remark |
| Assebeteferi | 0.697591 | 1.96 | Homogeneous |
| Awash 7 Kilo | 0.728189 | 1.96 | Homogeneous |
| Combolcha-1 | 1.259701 | 1.96 | Homogeneous |
| Combolcha-2 | 0.797763 | 1.96 | Homogeneous |
| Dupty | 0.684311 | 1.96 | Homogeneous |
| Gewane | 0.855017 | 1.96 | Homogeneous |
| Haik | 0.707673 | 1.96 | Homogeneous |
| Kemisse | 1.045302 | 1.96 | Homogeneous |
| Koka Dam | 0.6721613 | 1.96 | Homogeneous |
| Meiso | 0.8492077 | 1.96 | Homogeneous |
| Metehara | 0.756534 | 1.96 | Homogeneous |
| Mojo | 0.697591 | 1.96 | Homogeneous |
| Nazret | 0.697591 | 1.96 | Homogeneous |

Table A-2: Data dependency and consistency test

| Data Consistency and Dependency Test | | | |
|---|---|---|---|
| Station Name | $R^2$ value | Critical $R^2$ value | Remark ($R^2 > 0.95$) |
| Assebeteferi | 0.9925 | 0.95 | Independent/Consistent |
| Awash 7 Kilo | 0.9963 | 0.95 | Independent/Consistent |
| Combolcha-1 | 0.9991 | 0.95 | Independent/Consistent |
| Combolcha-2 | 0.9995 | 0.95 | Independent/Consistent |
| Dupty | 0.9978 | 0.95 | Independent/Consistent |
| Gewane | 0.9974 | 0.95 | Independent/Consistent |
| Haik | 0.9988 | 0.95 | Independent/Consistent |
| Kemisse | 0.9983 | 0.95 | Independent/Consistent |
| Koka Dam | 0.9971 | 0.95 | Independent/Consistent |
| Meiso | 0.9984 | 0.95 | Independent/Consistent |
| Metehara | 0.9992 | 0.95 | Independent/Consistent |
| Mojo | 0.998 | 0.95 | Independent/Consistent |
| Nazret | 0.9978 | 0.95 | Independent/Consistent |

# APPENDIX –B:

Table: Available in-situ data for 1day, 2- and 3-days' durations

Assebeteferi

| year | 1-day's | 2-days' | 3-days' |
|---|---|---|---|
| 1986 | 131 | 145.2 | 145.2 |
| 1987 | 81.2 | 82.4 | 107.9 |
| 1988 | 90.4 | 90.4 | 90.4 |
| 1989 | 47.6 | 76.4 | 76.4 |
| 1990 | 59 | 59.4 | 92.3 |
| 1991 | 38.2 | 52.7 | 52.7 |
| 1992 | 77.5 | 77.5 | 96.1 |
| 1993 | 50.4 | 65.4 | 65.8 |
| 1994 | 52 | 99 | 109 |
| 1995 | 54.4 | 74.6 | 95.5 |
| 1996 | 36.4 | 37.5 | 41.7 |
| 1997 | 73.5 | 80.4 | 100.4 |
| 1998 | 68.9 | 87.5 | 94 |
| 1999 | 73 | 86.8 | 88.6 |
| 2000 | 45 | 61.8 | 71.8 |
| 2001 | 60 | 100 | 130 |
| 2002 | 46.7 | 75.1 | 111.3 |
| 2003 | 48 | 51 | 60.4 |
| 2004 | 44.3 | 72.2 | 98.6 |
| 2005 | 86.2 | 123.2 | 133.6 |
| 2006 | 39 | 59.2 | 67.2 |
| 2007 | 66.5 | 78.2 | 116.2 |
| 2008 | 41 | 52 | 81 |
| 2009 | 54.4 | 74.6 | 95.5 |
| 2010 | 45 | 69 | 90 |

Awash 7 Kilo

| Year | 1-day's | 2-days' | 3-days' |
|---|---|---|---|
| 1985 | 60 | 61.3 | 65.2 |
| 1986 | 24 | 35.1 | 37.2 |
| 1987 | 44.2 | 44.2 | 67.6 |
| 1988 | 62.3 | 73.7 | 74.5 |
| 1989 | 66.2 | 71.6 | 93 |
| 1990 | 110 | 110.7 | 136.5 |
| 1991 | 47.1 | 65.1 | 87.8 |
| 1992 | 54.8 | 79.2 | 79.2 |
| 1993 | 64.2 | 82.4 | 109.8 |
| 1994 | 38.9 | 38.9 | 49.2 |
| 1995 | 45.8 | 47.8 | 48.2 |
| 1996 | 122.1 | 125 | 125 |
| 1997 | 50.4 | 70.8 | 85.3 |
| 1998 | 43.3 | 48.7 | 55.7 |
| 1999 | 36.1 | 45.3 | 55.2 |
| 2000 | 30.6 | 38.7 | 48.5 |
| 2001 | 51.5 | 53.7 | 54 |
| 2002 | 31.8 | 33.7 | 46.1 |
| 2003 | 30 | 30 | 42.1 |
| 2004 | 48.9 | 87.1 | 88.9 |
| 2005 | 65.6 | 65.6 | 65.6 |
| 2006 | 58.2 | 68.6 | 68.8 |
| 2007 | 58 | 60.8 | 83.1 |
| 2008 | 39.1 | 44.5 | 46.9 |
| 2009 | 54.4 | 54.4 | 54.4 |

Combolcha-1

| year | 1-day's | 2-days' | 3-days' |
|---|---|---|---|
| 1992 | 52.4 | 61.7 | 71.9 |
| 1993 | 50.7 | 65.7 | 79.8 |
| 1994 | 58.5 | 78.1 | 104.1 |
| 1995 | 38.7 | 53.8 | 64.2 |
| 1996 | 42.7 | 79.8 | 80.3 |
| 1997 | 54.3 | 64.8 | 75.6 |
| 1998 | 68.4 | 86 | 123.5 |
| 1999 | 61.2 | 98.2 | 110.2 |
| 2000 | 50.6 | 65.2 | 92.5 |
| 2001 | 71.6 | 93.1 | 99.8 |
| 2002 | 64.4 | 112.6 | 112.7 |
| 2003 | 60.9 | 64 | 71.9 |
| 2004 | 46.8 | 76.6 | 93.7 |
| 2005 | 70.4 | 73.5 | 90.9 |
| 2006 | 64.8 | 65 | 84.3 |
| 2007 | 54.3 | 70.5 | 80.5 |
| 2008 | 30.5 | 50.7 | 64.5 |
| 2009 | 73.2 | 79.8 | 92.8 |
| 2010 | 64.5 | 96.8 | 107.4 |
| 2011 | 49.8 | 68.4 | 87.6 |
| 2012 | 49.6 | 71.5 | 82.6 |
| 2013 | 60.4 | 74 | 88 |
| 2014 | 49.6 | 91.5 | 100.1 |
| 2015 | 55.1 | 101.6 | 121.2 |
| 2016 | 67.9 | 99.2 | 109.1 |

Combolcha-2

| year | 1-day's | 2-days' | 3-days' |
|---|---|---|---|
| 1985 | 40.7 | 60.7 | 66.6 |
| 1986 | 44.2 | 48.4 | 52 |
| 1987 | 64.8 | 90.8 | 127.7 |
| 1988 | 62.2 | 99.1 | 103 |
| 1989 | 56.3 | 98.8 | 107.8 |
| 1990 | 71.6 | 76.1 | 77.5 |
| 1991 | 37 | 49.7 | 61.4 |
| 1992 | 68.5 | 82.7 | 84.6 |
| 1993 | 52 | 65.5 | 66.3 |
| 1994 | 66 | 90.1 | 91.2 |
| 1995 | 64.8 | 85.3 | 92.1 |
| 1996 | 65 | 87.6 | 87.6 |
| 1997 | 38.6 | 38.6 | 38.6 |
| 1998 | 61 | 70.5 | 111 |
| 1999 | 54 | 70 | 87 |
| 2000 | 69 | 71.5 | 87 |
| 2001 | 54.6 | 76.7 | 85.1 |
| 2002 | 33.2 | 42.1 | 53.1 |
| 2003 | 72.6 | 99.3 | 99.3 |
| 2004 | 54.8 | 61 | 93.4 |
| 2005 | 33.9 | 46.9 | 65.5 |
| 2006 | 46.4 | 63.8 | 64.7 |
| 2007 | 81.6 | 83.6 | 108.8 |
| 2008 | 43.7 | 83.6 | 83.6 |
| 2009 | 38.2 | 43.2 | 51.8 |

## Dupty

| year | 1-day’s | 2-days’ | 3-days’ |
|---|---|---|---|
| 1986 | 64 | 122.5 | 122.5 |
| 1987 | 51 | 53 | 53 |
| 1988 | 58.4 | 58.4 | 95.5 |
| 1989 | 32.5 | 36.6 | 39.5 |
| 1990 | 52.2 | 52.2 | 61.9 |
| 1991 | 26 | 26 | 26 |
| 1992 | 33.4 | 33.4 | 33.4 |
| 1993 | 38.4 | 45.6 | 45.6 |
| 1994 | 40.2 | 40.2 | 56.2 |
| 1995 | 36.1 | 36.1 | 43.8 |
| 1996 | 46.8 | 46.9 | 46.9 |
| 1997 | 35.3 | 39.1 | 39.1 |
| 1998 | 90.8 | 96.8 | 96.8 |
| 1999 | 24.9 | 24.9 | 24.9 |
| 2000 | 48.3 | 49.7 | 61.5 |
| 2001 | 31.5 | 31.5 | 32.3 |
| 2002 | 13.5 | 23.6 | 23.6 |
| 2003 | 43.2 | 54 | 84.2 |
| 2004 | 46.2 | 50.4 | 51.9 |
| 2005 | 43.2 | 43.2 | 43.2 |
| 2006 | 35.5 | 39 | 39.8 |
| 2007 | 58.6 | 76.8 | 80.6 |
| 2008 | 22.6 | 45.1 | 46.7 |
| 2009 | 44.5 | 44.5 | 44.5 |
| 2010 | 39.2 | 46.5 | 46.5 |

## Gewane

| year | 1-day’s | 2-days’ | 3-days’ |
|---|---|---|---|
| 1986 | 33 | 43 | 105.9 |
| 1987 | 67.7 | 95.5 | 55 |
| 1988 | 35.3 | 55 | 84 |
| 1989 | 84 | 84 | 153.1 |
| 1990 | 85.7 | 124.2 | 48.7 |
| 1991 | 34.5 | 39.5 | 56.2 |
| 1992 | 38.5 | 52.5 | 52.5 |
| 1993 | 35.3 | 47.2 | 65.5 |
| 1994 | 60 | 65.5 | 93.7 |
| 1995 | 70.6 | 90.2 | 62.5 |
| 1996 | 35.2 | 51 | 91.6 |
| 1997 | 56.6 | 65.2 | 78.1 |
| 1998 | 64.2 | 74.6 | 48.9 |
| 1999 | 48 | 48.9 | 65.5 |
| 2000 | 63.2 | 63.2 | 52 |
| 2001 | 35.7 | 38.3 | 137.1 |
| 2002 | 80.3 | 127.8 | 82.5 |
| 2003 | 65.6 | 79.5 | 82.5 |
| 2004 | 66.2 | 74.1 | 81.5 |
| 2005 | 60.1 | 81.5 | 104.8 |
| 2006 | 89.5 | 89.5 | 102.7 |
| 2007 | 88.4 | 88.4 | 66 |
| 2008 | 40.8 | 45.4 | 51.9 |
| 2009 | 44.5 | 50.6 | 117.4 |
| 2010 | 85.8 | 86.9 | 105.9 |

Haik

| year | 1-day’s | 2-days’ | 3-days’ |
|---|---|---|---|
| 1985 | 72 | 84.6 | 84.6 |
| 1986 | 44.2 | 55 | 55 |
| 1987 | 81.5 | 112 | 112 |
| 1988 | 62.6 | 94.2 | 94.5 |
| 1989 | 42.8 | 49.9 | 49.9 |
| 1990 | 67.4 | 82.2 | 82.2 |
| 1991 | 56.5 | 89 | 89 |
| 1992 | 76 | 91.6 | 91.6 |
| 1993 | 62.7 | 84.6 | 84.6 |
| 1994 | 61.6 | 97.2 | 97.2 |
| 1995 | 52.6 | 73.9 | 73.9 |
| 1996 | 48.4 | 83.5 | 83.5 |
| 1997 | 47 | 71.5 | 71.5 |
| 1998 | 71.6 | 106.9 | 106.9 |
| 1999 | 43.2 | 69.7 | 69.7 |
| 2000 | 56.7 | 100.9 | 100.9 |
| 2001 | 104.2 | 127.5 | 127.5 |
| 2002 | 58.8 | 102 | 102 |
| 2003 | 43.9 | 60.8 | 60.8 |
| 2004 | 70.3 | 93.3 | 93.3 |
| 2005 | 59.4 | 79.9 | 79.9 |
| 2006 | 64 | 96.4 | 96.4 |
| 2007 | 40.6 | 70.2 | 70.2 |
| 2008 | 66.5 | 71.9 | 71.9 |
| 2009 | 91.7 | 97.1 | 97.1 |

Kemisse

| year | 1-day’s | 2-days’ | 3-days’ |
|---|---|---|---|
| 1985 | 50.4 | 71.2 | 77.7 |
| 1986 | 43.3 | 81.9 | 85.3 |
| 1987 | 60.5 | 74.2 | 101 |
| 1988 | 114 | 117 | 122.8 |
| 1989 | 43.4 | 60.9 | 63.7 |
| 1990 | 38 | 53 | 66 |
| 1991 | 48.7 | 75.4 | 83.9 |
| 1992 | 42 | 59.2 | 75 |
| 1993 | 49.7 | 69.4 | 82.3 |
| 1994 | 76.3 | 96.4 | 109 |
| 1995 | 66 | 73.2 | 103 |
| 1996 | 84.2 | 146.1 | 167.8 |
| 1997 | 59.5 | 99.9 | 127.8 |
| 1998 | 69.8 | 98.1 | 107.9 |
| 1999 | 59.7 | 82.8 | 95 |
| 2000 | 81 | 89.2 | 120.8 |
| 2001 | 53.3 | 71.6 | 99.4 |
| 2002 | 62.1 | 79.8 | 97.6 |
| 2003 | 58 | 73.1 | 84.4 |
| 2004 | 39.1 | 62.4 | 76.9 |
| 2005 | 60.7 | 76.8 | 108.4 |
| 2006 | 72.5 | 86.6 | 111.7 |
| 2007 | 56.9 | 86.6 | 111.7 |
| 2008 | 81.8 | 111.9 | 125.4 |
| 2009 | 56.5 | 86.7 | 102.1 |

Koka Dam

| year | 1-day's | 2-days' | 3-days' |
|---|---|---|---|
| 1985 | 37.4 | 66.6 | 77.9 |
| 1986 | 22.4 | 42.4 | 42.4 |
| 1987 | 24.5 | 35.5 | 48.5 |
| 1988 | 58.8 | 60 | 77.7 |
| 1989 | 51.5 | 79.7 | 94.5 |
| 1990 | 100.8 | 100.8 | 151.2 |
| 1991 | 35.3 | 40.6 | 65.7 |
| 1992 | 96.3 | 155.4 | 218.7 |
| 1993 | 87 | 161 | 223 |
| 1994 | 30.6 | 40.9 | 42.2 |
| 1995 | 47.5 | 57 | 67.2 |
| 1996 | 47.5 | 67 | 67.3 |
| 1997 | 56.3 | 75.1 | 78.8 |
| 1998 | 83.5 | 109.5 | 122.7 |
| 1999 | 48.2 | 59.9 | 76.1 |
| 2000 | 54.2 | 79.7 | 102.9 |
| 2001 | 58.4 | 77.4 | 94.6 |
| 2002 | 43.9 | 64.6 | 67 |
| 2003 | 51.4 | 68.1 | 82.3 |
| 2004 | 48.4 | 70.3 | 112.3 |
| 2005 | 35.3 | 53.2 | 58.9 |
| 2006 | 37.3 | 43.5 | 46.1 |
| 2007 | 40.3 | 70.5 | 81.2 |
| 2008 | 40.2 | 66.9 | 79.5 |
| 2009 | 48.7 | 58.9 | 58.9 |

Meiso

| year | 1-day's | 2-days' | 3-days' |
|---|---|---|---|
| 1985 | 42.7 | 59.7 | 89.3 |
| 1986 | 29.3 | 33.7 | 42.6 |
| 1987 | 93 | 134 | 179 |
| 1988 | 85.8 | 85.8 | 87.7 |
| 1989 | 48.8 | 59.3 | 97.6 |
| 1990 | 98 | 125.6 | 125.6 |
| 1991 | 74.3 | 78.6 | 91.6 |
| 1992 | 51.1 | 53.4 | 56.6 |
| 1993 | 40.5 | 61.8 | 67 |
| 1994 | 82.5 | 82.5 | 90.7 |
| 1995 | 32.2 | 32.2 | 35 |
| 1996 | 56.3 | 80.1 | 90.2 |
| 1997 | 79.6 | 94.6 | 124.6 |
| 1998 | 36.3 | 44.7 | 70.7 |
| 1999 | 55.2 | 56.4 | 56.4 |
| 2000 | 51.2 | 61 | 74.9 |
| 2001 | 58.8 | 71 | 71 |
| 2002 | 33.5 | 40.7 | 40.7 |
| 2003 | 57.6 | 64.3 | 78 |
| 2004 | 45.5 | 48.1 | 56.9 |
| 2005 | 49.4 | 61 | 70.7 |
| 2006 | 65 | 71.3 | 112.1 |
| 2007 | 61.6 | 74.6 | 110.6 |
| 2008 | 33.8 | 48.8 | 54 |
| 2009 | 39.2 | 45.4 | 74.7 |

Metehara

| year | 1-day’s | 2-days’ | 3-days’ |
|---|---|---|---|
| 1985 | 58.7 | 60.2 | 62.9 |
| 1986 | 18.6 | 21.1 | 27.2 |
| 1987 | 51 | 51.5 | 57.3 |
| 1988 | 60.7 | 62 | 62.8 |
| 1989 | 38.6 | 38.6 | 55.9 |
| 1990 | 55.1 | 79.2 | 81.2 |
| 1991 | 43.8 | 43.8 | 54.3 |
| 1992 | 57.5 | 58.5 | 70.2 |
| 1993 | 68.1 | 71.2 | 76.6 |
| 1994 | 52.2 | 52.4 | 55.9 |
| 1995 | 39.7 | 53.6 | 53.6 |
| 1996 | 58.5 | 58.5 | 65.3 |
| 1997 | 33 | 48.7 | 51.7 |
| 1998 | 49.5 | 55.4 | 57.2 |
| 1999 | 45.8 | 61 | 61 |
| 2000 | 44.4 | 53.4 | 65.8 |
| 2001 | 36.7 | 36.7 | 43.7 |
| 2002 | 45.4 | 53.1 | 70.1 |
| 2003 | 45.8 | 55.8 | 56.6 |
| 2004 | 59.4 | 83.3 | 84.3 |
| 2005 | 40.7 | 47 | 47 |
| 2006 | 30.7 | 44.9 | 44.9 |
| 2007 | 47 | 90 | 101.4 |
| 2008 | 44 | 56.2 | 59.2 |
| 2009 | 52.4 | 57.8 | 61.5 |

Mojo

| year | 1-day’s | 2-days’ | 3-days’ |
|---|---|---|---|
| 1985 | 65 | 76 | 76 |
| 1986 | 34 | 55.3 | 63.5 |
| 1987 | 48.2 | 58 | 92 |
| 1988 | 44.5 | 65.2 | 87.5 |
| 1989 | 60.6 | 79.1 | 88.9 |
| 1990 | 62 | 62 | 90.5 |
| 1991 | 69.2 | 89 | 113 |
| 1992 | 35.3 | 48.1 | 58.3 |
| 1993 | 47.7 | 72.4 | 88 |
| 1994 | 39 | 46.6 | 65.4 |
| 1995 | 36.2 | 56.4 | 71 |
| 1996 | 45 | 54 | 74.5 |
| 1997 | 54.2 | 61.2 | 71.7 |
| 1998 | 83 | 91 | 105.3 |
| 1999 | 92 | 92 | 109.2 |
| 2000 | 44.8 | 73.1 | 73.1 |
| 2001 | 42.5 | 64.8 | 72.1 |
| 2002 | 46.8 | 64.8 | 72.1 |
| 2003 | 85.1 | 95.6 | 127.6 |
| 2004 | 47.2 | 77.2 | 79.5 |
| 2005 | 56.3 | 84.8 | 101.8 |
| 2006 | 36 | 59.8 | 74.1 |
| 2007 | 38.8 | 60.2 | 76.7 |
| 2008 | 94.9 | 107.1 | 112.5 |
| 2009 | 56.1 | 87.3 | 105.1 |

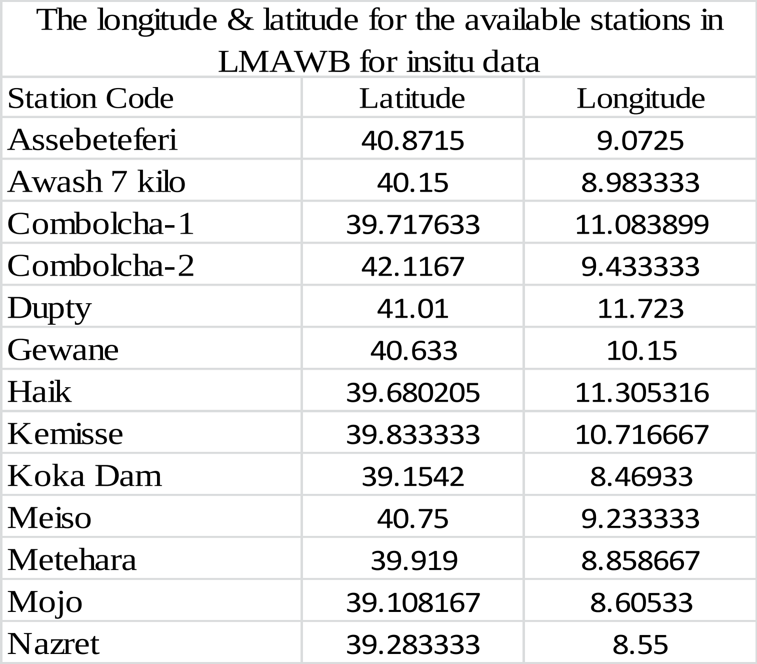
Nazret

**Nazret**

| year | 1-day's | 2-days' | 3-days' |
|---|---|---|---|
| 1985 | 57 | 98 | 102 |
| 1986 | 50 | 78 | 92 |
| 1987 | 44.4 | 65.3 | 86.7 |
| 1988 | 31.2 | 42.9 | 52.9 |
| 1989 | 55 | 58.1 | 58.1 |
| 1990 | 77 | 77 | 93 |
| 1991 | 73.8 | 73.8 | 76.3 |
| 1992 | 41.1 | 70.2 | 72.2 |
| 1993 | 70 | 85 | 125.5 |
| 1994 | 51 | 51 | 85.6 |
| 1995 | 77.5 | 97.7 | 99.8 |
| 1996 | 47.5 | 68.4 | 94.7 |
| 1997 | 61.4 | 68.4 | 94.7 |
| 1998 | 59.8 | 70.8 | 79.3 |
| 1999 | 41.5 | 56.7 | 63.4 |
| 2000 | 99.8 | 152.8 | 153.4 |
| 2001 | 104.8 | 104.8 | 107 |
| 2002 | 48.3 | 50.4 | 62.6 |
| 2003 | 70.4 | 80.4 | 103.6 |
| 2004 | 43.3 | 74.6 | 91.6 |
| 2005 | 42.3 | 54.5 | 69.6 |
| 2006 | 62.8 | 71.2 | 86 |
| 2007 | 55.1 | 62.2 | 89.6 |
| 2008 | 72.5 | 88.2 | 93 |
| 2009 | 54 | 83.4 | 92.8 |

# APPENDIX -C:

Table C-1: The longitude & latitude for the available stations in LMAWB for insitu data



| The longitude & latitude for the available stations in LMAWB for insitu data | | |
|---|---|---|
| Station Code | Latitude | Longitude |
| Assebeteferi | 40.8715 | 9.0725 |
| Awash 7 kilo | 40.15 | 8.983333 |
| Combolcha-1 | 39.717633 | 11.083899 |
| Combolcha-2 | 42.1167 | 9.433333 |
| Dupty | 41.01 | 11.723 |
| Gewane | 40.633 | 10.15 |
| Haik | 39.680205 | 11.305316 |
| Kemisse | 39.833333 | 10.716667 |
| Koka Dam | 39.1542 | 8.46933 |
| Meiso | 40.75 | 9.233333 |
| Metehara | 39.919 | 8.858667 |
| Mojo | 39.108167 | 8.60533 |
| Nazret | 39.283333 | 8.55 |

Table C-2: approximate longitude & latitude for the available stations in LMAWB for GLDAS reanalysis data

| Approximate Location of stations for GLDAS Reanalysis Data | | |
|---|---|---|
| Station Code | Latitude | Longitude |
| Assebeteferi | 40.875 | 9.125 |
| Awash 7 Kilo | 40.125 | 8.875 |
| Combolcha-1 | 39.875 | 10.875 |
| Combolcha-2 | 40.875 | 9.125 |
| Dupty | 40.875 | 10.875 |
| Gewane | 40.875 | 10.125 |
| Haik | 39.875 | 10.875 |
| Kemisse | 39.875 | 10.875 |
| Koka Dam | 39.125 | 8.875 |
| Meiso | 40.875 | 8.875 |
| Metehara | 39.875 | 8.875 |
| Mojo | 39.125 | 8.875 |
| Nazret | 39.125 | 8.875 |

## APPENDIX- D:

Table D-1: Annual Maximum Rainfall of GLDAS for 0.25 by 0.25 grids Size (mm)

| 1 Day Durations, Annual Max | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Gldas 1- Day For 0.25 By 0.25 Grid Size, Year 1986-2010 | | | | | | | | |
| Latitude | 40.875 | 40.125 | 39.875 | 40.875 | 40.875 | 39.125 | 40.875 | 39.875 |
| Longitude | 9.125 | 8.875 | 10.875 | 10.875 | 10.125 | 8.875 | 8.875 | 8.875 |
| 1986 | 66.91 | 48.37 | 2.28 | 17.47 | 46.62 | 20.15 | 18.00 | 53.88 |
| 1987 | 12.36 | 27.14 | 10.48 | 9.94 | 43.53 | 2.82 | 85.58 | 43.53 |
| 1988 | 57.50 | 24.32 | 26.60 | 34.80 | 65.43 | 46.08 | 9.67 | 13.03 |
| 1989 | 15.32 | 5.24 | 5.37 | 26.47 | 2.28 | 9.81 | 49.71 | 29.69 |
| 1990 | 27.95 | 58.85 | 15.59 | 35.20 | 68.79 | 66.24 | 66.10 | 22.17 |
| 1991 | 52.80 | 84.51 | 18.94 | 9.94 | 5.37 | 88.00 | 31.84 | 15.18 |
| 1992 | 36.41 | 10.35 | 9.67 | 6.72 | 4.30 | 81.96 | 31.17 | 18.41 |
| 1993 | 2.15 | 12.63 | 14.24 | 2.42 | 33.19 | 12.50 | 14.24 | 14.24 |
| 1994 | 3.22 | 33.99 | 28.21 | 5.51 | 14.24 | 75.78 | 56.43 | 21.36 |
| 1995 | 24.18 | 9.27 | 9.67 | 14.38 | 47.56 | 22.71 | 67.58 | 16.79 |
| 1996 | 49.85 | 102.51 | 4.70 | 15.45 | 28.75 | 10.00 | 32.38 | 25.26 |
| 1997 | 6.18 | 96.33 | 18.94 | 74.57 | 10.21 | 11.82 | 31.30 | 34.26 |
| 1998 | 5.51 | 9.54 | 31.71 | 88.54 | 21.77 | 36.54 | 58.18 | 22.17 |
| 1999 | 37.62 | 9.67 | 7.52 | 31.44 | 20.42 | 47.43 | 25.39 | 4.97 |
| 2000 | 20.15 | 7.39 | 14.11 | 22.57 | 36.95 | 8.06 | 5.37 | 1.88 |
| 2001 | 17.87 | 28.08 | 31.98 | 24.18 | 59.92 | 5.64 | 10.21 | 10.35 |
| 2002 | 1.75 | 26.47 | 57.37 | 39.90 | 19.75 | 19.48 | 33.99 | 11.69 |
| 2003 | 4.97 | 2.42 | 11.69 | 4.03 | 8.06 | 10.08 | 32.38 | 5.37 |
| 2004 | 56.30 | 25.39 | 19.75 | 4.03 | 8.20 | 4.03 | 16.26 | 18.27 |
| 2005 | 63.42 | 22.44 | 5.60 | 10.35 | 39.50 | 17.60 | 5.24 | 25.12 |
| 2006 | 36.95 | 9.94 | 14.51 | 31.04 | 1.48 | 2.69 | 20.96 | 13.44 |
| 2007 | 34.26 | 5.78 | 14.51 | 48.37 | 63.95 | 4.03 | 4.57 | 21.90 |
| 2008 | 18.00 | 25.39 | 7.39 | 29.42 | 4.97 | 5.60 | 37.35 | 4.03 |
| 2009 | 12.63 | 20.56 | 17.20 | 7.12 | 55.49 | 11.42 | 7.26 | 11.29 |
| 2010 | 15.12 | 36.54 | 45.61 | 26.33 | 57.64 | 32.72 | 26.33 | 35.20 |

| 2 Day Durations, Annual Max | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Gldas 2- Day For 0.25 By 0.25 Grid Size, Year 1986-2010 | | | | | | | | |
| Latitude | 40.875 | 40.125 | 39.875 | 40.875 | 40.875 | 39.125 | 40.875 | 39.875 |
| Longitude | 9.125 | 8.875 | 10.875 | 10.875 | 10.125 | 8.875 | 8.875 | 8.875 |
| 1986 | 78.71 | 32.84 | 5.01 | 87.11 | 65.80 | 30.33 | 32.59 | 49.01 |
| 1987 | 10.03 | 11.41 | 15.54 | 6.77 | 50.76 | 8.65 | 125.72 | 38.10 |
| 1988 | 17.55 | 36.98 | 30.46 | 27.32 | 36.35 | 30.71 | 60.41 | 13.16 |
| 1989 | 21.31 | 2.63 | 32.59 | 19.55 | 50.39 | 24.69 | 33.22 | 29.33 |
| 1990 | 8.40 | 49.01 | 18.80 | 32.84 | 106.16 | 26.45 | 83.10 | 50.89 |
| 1991 | 31.08 | 57.16 | 26.57 | 9.28 | 16.29 | 75.45 | 58.91 | 44.37 |
| 1992 | 15.17 | 17.67 | 15.29 | 15.29 | 6.64 | 143.89 | 31.59 | 18.42 |
| 1993 | 42.11 | 4.01 | 41.36 | 6.77 | 22.94 | 7.02 | 10.53 | 15.92 |
| 1994 | 30.58 | 54.52 | 34.97 | 5.14 | 30.96 | 150.53 | 25.95 | 23.56 |
| 1995 | 46.50 | 11.16 | 24.44 | 13.54 | 49.13 | 20.18 | 63.05 | 1.50 |
| 1996 | 53.77 | 96.76 | 60.92 | 9.78 | 17.80 | 12.53 | 60.04 | 6.14 |
| 1997 | 8.90 | 67.93 | 15.79 | 72.32 | 11.78 | 10.15 | 18.17 | 12.28 |
| 1998 | 0.88 | 27.70 | 3.89 | 90.12 | 32.21 | 43.12 | 62.54 | 8.40 |
| 1999 | 31.34 | 4.26 | 10.65 | 31.08 | 17.92 | 62.17 | 14.66 | 7.02 |
| 2000 | 47.88 | 8.27 | 6.89 | 22.81 | 31.21 | 24.82 | 5.77 | 9.53 |
| 2001 | 31.21 | 18.80 | 24.82 | 9.90 | 112.18 | 2.88 | 12.53 | 20.93 |
| 2002 | 30.21 | 25.07 | 36.47 | 38.10 | 60.54 | 16.04 | 37.98 | 20.56 |
| 2003 | 26.57 | 4.64 | 21.31 | 4.51 | 6.77 | 4.39 | 29.58 | 3.38 |
| 2004 | 63.92 | 71.57 | 35.60 | 9.02 | 9.28 | 2.76 | 20.31 | 34.47 |
| 2005 | 80.22 | 26.95 | 3.89 | 5.26 | 10.03 | 21.43 | 16.17 | 45.50 |
| 2006 | 23.81 | 3.76 | 3.13 | 47.38 | 1.38 | 12.16 | 12.91 | 2.63 |
| 2007 | 32.84 | 9.78 | 21.93 | 39.73 | 53.90 | 33.84 | 4.14 | 56.53 |
| 2008 | 28.33 | 20.43 | 12.66 | 0.75 | 6.52 | 4.51 | 32.34 | 42.36 |
| 2009 | 7.02 | 12.41 | 3.01 | 2.51 | 45.50 | 10.03 | 4.26 | 2.01 |
| 2010 | 43.24 | 34.09 | 62.17 | 29.14 | 54.46 | 36.91 | 28.45 | 36.22 |

| 3 Day Durations, Annual Max | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Gldas 3- Day For 0.25 By 0.25 Grid Size, Year 1986-2010 | | | | | | | | |
| Latitude | 40.875 | 40.125 | 39.875 | 40.875 | 40.875 | 39.125 | 40.875 | 39.875 |
| Longitude | 9.125 | 8.875 | 10.875 | 10.875 | 10.125 | 8.875 | 8.875 | 8.875 |
| 1986 | 45.37 | 34.06 | 9.61 | 84.54 | 61.91 | 43.18 | 56.81 | 76.51 |
| 1987 | 21.29 | 36.98 | 29.56 | 51.70 | 35.28 | 7.42 | 165.92 | 36.61 |
| 1988 | 17.03 | 8.39 | 48.53 | 68.12 | 84.05 | 35.52 | 111.06 | 6.69 |
| 1989 | 19.34 | 22.50 | 19.58 | 27.25 | 126.99 | 20.44 | 12.04 | 8.39 |
| 1990 | 48.17 | 52.91 | 5.72 | 43.67 | 9.12 | 68.97 | 34.06 | 30.77 |
| 1991 | 52.79 | 59.24 | 58.27 | 9.00 | 4.50 | 104.00 | 41.36 | 32.72 |
| 1992 | 36.86 | 10.46 | 16.18 | 14.84 | 15.81 | 186.11 | 42.57 | 19.34 |
| 1993 | 52.55 | 37.22 | 21.53 | 12.89 | 34.30 | 5.23 | 12.65 | 7.78 |
| 1994 | 16.42 | 73.71 | 8.88 | 15.08 | 37.95 | 219.93 | 28.83 | 25.18 |
| 1995 | 65.44 | 1.22 | 15.69 | 3.77 | 35.40 | 30.41 | 67.75 | 2.80 |
| 1996 | 71.40 | 93.42 | 49.63 | 9.49 | 16.42 | 12.16 | 67.15 | 14.23 |
| 1997 | 7.78 | 48.29 | 26.52 | 70.19 | 35.52 | 13.99 | 41.84 | 16.54 |
| 1998 | 6.57 | 36.01 | 3.41 | 87.46 | 20.19 | 53.40 | 65.56 | 6.69 |
| 1999 | 20.44 | 6.08 | 8.03 | 44.52 | 16.42 | 56.68 | 17.39 | 4.62 |
| 2000 | 70.79 | 8.15 | 4.62 | 35.52 | 103.52 | 32.60 | 22.50 | 5.84 |
| 2001 | 22.75 | 6.69 | 19.46 | 10.58 | 66.42 | 10.10 | 4.74 | 26.88 |
| 2002 | 61.91 | 9.61 | 34.42 | 73.71 | 14.00 | 33.57 | 36.86 | 32.11 |
| 2003 | 46.47 | 4.87 | 17.76 | 39.29 | 12.78 | 18.61 | 45.37 | 16.42 |
| 2004 | 42.57 | 56.93 | 24.08 | 10.58 | 28.34 | 36.49 | 25.67 | 33.69 |
| 2005 | 80.77 | 28.34 | 6.08 | 4.14 | 2.55 | 64.96 | 16.79 | 45.37 |
| 2006 | 59.60 | 3.89 | 6.57 | 49.63 | 44.64 | 15.57 | 50.36 | 2.55 |
| 2007 | 42.82 | 17.39 | 14.72 | 41.24 | 17.15 | 42.70 | 1.82 | 68.73 |
| 2008 | 17.64 | 44.03 | 25.67 | 2.68 | 79.67 | 2.07 | 68.85 | 51.33 |
| 2009 | 6.69 | 9.12 | 14.72 | 2.43 | 6.33 | 25.06 | 25.18 | 2.80 |
| 2010 | 54.74 | 33.09 | 66.35 | 28.28 | 68.24 | 35.82 | 45.43 | 37.40 |

# APPENDIX- E:

Frequency factor values for both insitu and GLDASreanalysis data

Table E-1: the values of frequency factor (K) for selected stations in the study area

| The Values of Frequency factor for Insitu data In the the Study area by using Hershfield's statistical method | | | |
|---|---|---|---|
| Station Name | 1-Day's | 2-Days' | 3-Days' |
| Assebeteferi | 4.59 | 5.09 | 2.41 |
| Awash 7 Kilo | 4.08 | 3.37 | 3.06 |
| Combolcha-1 | 1.69 | 2.50 | 2.14 |
| Combolcha-2 | 2.17 | 1.58 | 2.37 |
| Dupty | 4.17 | 4.80 | 3.50 |
| Gewane | 1.69 | 2.74 | 3.13 |
| Haik | 3.31 | 2.68 | 2.67 |
| Kemisse | 4.06 | 4.10 | 3.79 |
| Koka Dam | 2.82 | 3.60 | 3.60 |
| Meiso | 2.42 | 3.34 | 4.03 |
| Metehara | 2.13 | 2.74 | 3.38 |
| Mojo | 2.58 | 2.56 | 2.65 |
| Nazret | 3.02 | 5.09 | 3.94 |

Table E-2: the values of frequency factor (K) for GLDAS data for selected stations in the study area

| The Values of Frequency factor for GLDAS data in the the Study area By using Hershfield's statistical method | | | |
|---|---|---|---|
| Station Name | 1-Day's | 2-Days' | 3-Days' |
| Assebeteferi | 2.13 | 2.63 | 2.03 |
| Awash 7 Kilo | 3.14 | 3.38 | 3.16 |
| Combolcha-1 | 3.96 | 2.82 | 3.09 |
| Combolcha-2 | 2.13 | 2.63 | 2.03 |
| Dupty | 3.89 | 3.06 | 2.22 |
| Gewane | 1.82 | 3.14 | 3.27 |
| Haik | 3.96 | 2.82 | 3.09 |
| Kemisse | 3.96 | 2.82 | 3.09 |
| Koka Dam | 2.73 | 3.99 | 4.60 |
| Meiso | 2.95 | 4.17 | 5.01 |
| Metehara | 3.41 | 2.23 | 3.09 |
| Mojo | 2.73 | 3.99 | 4.60 |
| Nazret | 2.73 | 3.99 | 4.60 |

# APPENDIX- F:

PMP values obtained by Statistical method for both insitu and GLDAS reanalysis data for 1day, 2 day and 3-day durations

Table F-1: Probable maximum precipitation (PMP) for insitu 1-day, 2-day and 3-day durations

| Probable maximum precipitation for insitu data | | | |
|---|---|---|---|
| Station Name | 1-day PMP | 2-day PMP | 3-day PMP |
| Assebeteferi | 156.43 | 181.00 | 168.55 |
| Awash 7 Kilo | 146.70 | 149.15 | 162.26 |
| Combolcha-1 | 82.43 | 129.04 | 139.95 |
| Combolcha-2 | 93.98 | 113.29 | 148.11 |
| Dupty | 108.46 | 148.09 | 147.73 |
| Gewane | 103.66 | 151.07 | 181.82 |
| Haik | 121.64 | 146.60 | 146.60 |
| Kemisse | 134.21 | 170.74 | 195.17 |
| Koka Dam | 120.20 | 193.58 | 270.78 |
| Meiso | 115.48 | 159.71 | 214.23 |
| Metehara | 78.11 | 104.75 | 118.08 |
| Mojo | 111.66 | 123.43 | 146.71 |
| Nazret | 123.19 | 181.00 | 178.96 |

Table F-2: Probable maximum precipitation (PMP) for GLDAS reanalysis data for 1-day, 2-day and 3-day durations

| Probable maximum precipitation for GLDAS reanalysis data | | | |
|---|---|---|---|
| Station Name | 1-day PMP | 2-day PMP | 3-day PMP |
| Assebeteferi | 71.35 | 87.76 | 85.04 |
| Awash 7 Kilo | 117.91 | 113.16 | 107.03 |
| Combolcha-1 | 69.73 | 69.13 | 75.42 |
| Combolcha-2 | 71.35 | 87.76 | 85.04 |
| Dupty | 107.84 | 103.20 | 93.92 |
| Gewane | 72.13 | 128.22 | 146.86 |
| Haik | 70.49 | 69.13 | 75.42 |
| Kemisse | 70.49 | 69.13 | 75.42 |
| Koka Dam | 98.37 | 187.74 | 288.88 |
| Meiso | 95.95 | 180.22 | 221.82 |
| Metehara | 62.15 | 64.27 | 78.11 |
| Mojo | 98.37 | 187.74 | 288.88 |
| Nazret | 98.37 | 187.74 | 288.88 |

# APPENDIX- G:

Estimated rainfall quantiles for both insitu and GLDAS reanalysis data for different return periods.

Table G-1: Estimated Rainfall Depths for insitu data for Different Return Periods

| Estimated Rainfall Depths of in-situ 1-Day duration for the indicated frequency(years) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Station Name | Return Periods | | | | | | | |
| | 2 | 10 | 50 | 100 | 200 | 500 | 1000 | 10000 |
| Assebeteferi | 56.87 | 88.40 | 116.05 | 127.74 | 139.38 | 154.75 | 166.36 | 351.97 |
| Awash 7 Kilo | 49.85 | 82.57 | 111.26 | 123.38 | 135.47 | 151.41 | 163.46 | 277.27 |
| Combolcha-1 | 54.70 | 70.38 | 84.12 | 89.93 | 95.71 | 103.35 | 109.12 | 217.62 |
| Combolcha-2 | 52.75 | 72.83 | 90.44 | 97.88 | 105.30 | 115.08 | 122.48 | 224.61 |
| Dupty | 39.70 | 62.57 | 82.63 | 91.10 | 99.55 | 110.70 | 119.12 | 180.04 |
| Gewane | 55.54 | 84.33 | 109.57 | 120.24 | 130.87 | 144.90 | 155.50 | 203.17 |
| Haik | 59.27 | 82.36 | 102.61 | 111.17 | 119.69 | 130.94 | 139.45 | 296.80 |
| Kemisse | 58.27 | 83.57 | 105.75 | 115.12 | 124.47 | 136.79 | 146.10 | 289.90 |
| Koka Dam | 48.06 | 78.23 | 104.69 | 115.87 | 127.01 | 141.71 | 152.82 | 266.85 |
| Meiso | 52.82 | 81.77 | 107.15 | 117.88 | 128.58 | 142.68 | 153.34 | 204.40 |
| Metehara | 38.30 | 54.36 | 68.44 | 74.39 | 80.32 | 88.15 | 94.06 | 110.91 |
| Mojo | 51.63 | 78.05 | 101.21 | 111.00 | 120.76 | 133.63 | 143.36 | 236.73 |
| Nazret | 56.73 | 82.96 | 105.96 | 115.68 | 125.37 | 138.15 | 147.81 | 347.41 |

| Estimated Rainfall Depths of in-situ 2-Day duration for the indicated frequency(years) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Station Name | Return Periods | | | | | | | |
| | 2 | 10 | 50 | 100 | 200 | 500 | 1000 | 10000 |
| Assebeteferi | 73.49 | 107.31 | 136.97 | 149.50 | 161.99 | 178.47 | 190.93 | 381.91 |
| Awash 7 Kilo | 57.66 | 91.89 | 121.90 | 134.59 | 147.23 | 163.91 | 176.52 | 246.10 |
| Combolcha-1 | 75.25 | 98.67 | 119.20 | 127.89 | 136.53 | 147.94 | 156.57 | 171.63 |
| Combolcha-2 | 68.33 | 96.09 | 120.42 | 130.71 | 140.96 | 154.48 | 164.71 | 217.52 |
| Dupty | 45.04 | 77.27 | 105.52 | 117.46 | 129.36 | 145.06 | 156.92 | 342.10 |
| Gewane | 66.45 | 102.35 | 133.82 | 147.13 | 160.39 | 177.87 | 191.09 | 380.70 |
| Haik | 82.87 | 109.41 | 132.68 | 142.51 | 152.31 | 165.24 | 175.01 | 384.09 |
| Kemisse | 80.00 | 109.87 | 136.04 | 147.11 | 158.14 | 172.69 | 183.68 | 302.21 |
| Koka Dam | 67.07 | 112.89 | 153.06 | 170.05 | 186.97 | 209.29 | 226.16 | 408.45 |
| Meiso | 62.67 | 99.15 | 131.14 | 144.66 | 158.13 | 175.90 | 189.33 | 327.40 |
| Metehara | 53.37 | 74.78 | 93.55 | 101.49 | 109.39 | 119.82 | 127.71 | 163.40 |
| Mojo | 68.60 | 92.23 | 112.94 | 121.70 | 130.42 | 141.93 | 150.63 | 212.30 |
| Nazret | 71.69 | 104.51 | 133.28 | 145.45 | 157.56 | 173.55 | 185.64 | 338.47 |

| Estimated Rainfall Depths of in-situ 3-Day duration for the indicated frequency(years) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| RETURN PERIODS | | | | | | | | |
| Station Name | 2 | 10 | 50 | 100 | 200 | 500 | 1000 | 10000 |
| Assebeteferi | 88.40 | 124.84 | 156.79 | 170.29 | 183.75 | 201.51 | 214.92 | 298.33 |
| Awash 7 Kilo | 66.48 | 104.38 | 137.61 | 151.66 | 165.65 | 184.12 | 198.07 | 267.73 |
| Combolcha-1 | 88.85 | 113.19 | 134.54 | 143.56 | 152.55 | 164.41 | 173.37 | 275.71 |
| Combolcha-2 | 78.29 | 110.38 | 138.52 | 150.42 | 162.27 | 177.91 | 189.73 | 229.57 |
| Dupty | 49.56 | 85.74 | 117.46 | 130.87 | 144.23 | 161.86 | 175.19 | 317.63 |
| Gewane | 75.52 | 117.14 | 153.62 | 169.05 | 184.42 | 204.69 | 220.02 | 463.65 |
| Haik | 82.88 | 109.43 | 132.70 | 142.54 | 152.35 | 165.28 | 175.05 | 212.57 |
| Kemisse | 96.51 | 130.18 | 159.71 | 172.19 | 184.63 | 201.03 | 213.43 | 511.34 |
| Koka Dam | 81.82 | 150.67 | 211.04 | 236.56 | 261.98 | 295.53 | 320.88 | 628.21 |
| Meiso | 76.72 | 123.39 | 164.31 | 181.61 | 198.84 | 221.58 | 238.77 | 411.32 |
| Metehara | 58.69 | 80.33 | 99.30 | 107.32 | 115.32 | 125.86 | 133.83 | 181.85 |
| Mojo | 83.00 | 109.67 | 133.05 | 142.94 | 152.79 | 165.78 | 175.60 | 214.19 |
| Nazret | 85.52 | 116.88 | 144.38 | 156.00 | 167.58 | 182.86 | 194.41 | 332.86 |

Table G-2: Estimated Rainfall Depths for GLDAS reanalysis data for Different Return Periods

| GLADS 1 DAY DURATIONS, QUANTILES | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| GLADS 1- DAY FOR 0.25 BY 0.25 GRID SIZE | | | | | | | | | | |
| RETURN PERIODS | | | | | | | | | | |
| Station Name | Lat. | Lon. | 2 | 10 | 50 | 100 | 200 | 500 | 1000 | 10000 |
| Assebeteferi | 40.875 | 9.125 | 23.77 | 54.24 | 80.95 | 92.25 | 103.50 | 118.34 | 129.56 | 166.81 |
| Awash 7 kilo | 40.125 | 8.875 | 25.14 | 66.31 | 102.41 | 117.67 | 132.87 | 152.93 | 168.09 | 218.43 |
| Combolcha-1 | 39.875 | 10.875 | 15.60 | 34.84 | 51.70 | 58.83 | 65.94 | 75.31 | 82.39 | 105.91 |
| Combolcha-2 | 40.875 | 9.125 | 23.77 | 54.24 | 80.95 | 92.25 | 103.50 | 118.34 | 129.56 | 166.81 |
| Dupty | 40.875 | 10.875 | 21.32 | 52.60 | 80.02 | 91.61 | 103.16 | 118.39 | 129.91 | 168.15 |
| Gewane | 40.875 | 10.125 | 27.01 | 60.43 | 89.72 | 102.11 | 114.45 | 130.73 | 143.03 | 183.89 |
| Haik | 39.875 | 10.875 | 15.60 | 34.84 | 51.70 | 58.83 | 65.94 | 75.31 | 82.39 | 105.91 |
| Kemisse | 39.875 | 10.875 | 15.60 | 34.84 | 51.70 | 58.83 | 65.94 | 75.31 | 82.39 | 105.91 |
| Koka Dam | 39.125 | 8.875 | 22.96 | 54.39 | 81.93 | 93.58 | 105.18 | 120.49 | 132.06 | 170.48 |
| Mojo | 40.875 | 8.875 | 27.50 | 59.77 | 88.07 | 100.03 | 111.95 | 127.67 | 139.55 | 179.01 |
| Metehara | 39.875 | 8.875 | 17.70 | 35.96 | 51.96 | 58.73 | 65.47 | 74.36 | 81.09 | 103.40 |
| Mojo | 39.875 | 8.875 | 22.96 | 54.39 | 81.93 | 93.58 | 105.18 | 120.49 | 132.06 | 170.48 |
| Nazret | 39.875 | 8.875 | 22.96 | 54.39 | 81.93 | 93.58 | 105.18 | 120.49 | 132.06 | 170.48 |

GLADS 2 DAY DURATIONS, QUANTILES

GLADS 2- DAY FOR 0.25 BY 0.25 GRID SIZE

RETURN PERIODS

| Station Name | Lat. | Lon. | 2 | 10 | 50 | 100 | 200 | 500 | 1000 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|
| Assebeteferi | 40.875 | 9.125 | 29.03 | 59.80 | 86.79 | 98.19 | 109.56 | 124.55 | 135.89 | 173.51 |
| Awash 7 kilo | 40.125 | 8.875 | 24.29 | 61.01 | 93.20 | 106.81 | 120.36 | 138.25 | 151.77 | 196.66 |
| Combolcha-1 | 39.875 | 10.875 | 20.04 | 44.19 | 65.36 | 74.31 | 83.23 | 94.99 | 103.88 | 133.41 |
| Combolcha-2 | 40.875 | 9.125 | 29.03 | 59.80 | 86.79 | 98.19 | 109.56 | 124.55 | 135.89 | 173.51 |
| Dupty | 40.875 | 10.875 | 21.24 | 58.49 | 91.14 | 104.94 | 118.70 | 136.84 | 150.56 | 196.09 |
| Gewane | 40.875 | 10.125 | 31.49 | 74.45 | 112.11 | 128.04 | 143.90 | 164.83 | 180.65 | 233.17 |
| Haik | 39.875 | 10.875 | 20.04 | 44.19 | 65.36 | 74.31 | 83.23 | 94.99 | 103.88 | 133.41 |
| Kemisse | 39.875 | 10.875 | 20.04 | 44.19 | 65.36 | 74.31 | 83.23 | 94.99 | 103.88 | 133.41 |
| Koka Dam | 39.125 | 8.875 | 26.27 | 83.28 | 133.26 | 154.39 | 175.44 | 203.22 | 224.21 | 293.90 |
| Mojo | 40.875 | 8.875 | 30.71 | 72.75 | 109.60 | 125.18 | 140.71 | 161.19 | 176.67 | 228.06 |
| Metehara | 39.875 | 8.875 | 20.82 | 46.58 | 69.16 | 78.71 | 88.23 | 100.78 | 110.26 | 141.76 |
| Mojo | 39.875 | 8.875 | 26.27 | 83.28 | 133.26 | 154.39 | 175.44 | 203.22 | 224.21 | 293.90 |
| Nazret | 39.875 | 8.875 | 26.27 | 83.28 | 133.26 | 154.39 | 175.44 | 203.22 | 224.21 | 293.90 |

GLADS 3 DAY DURATIONS, QUANTILES

GLADS 3- DAY FOR 0.25 BY 0.25 GRID SIZE

RETURN PERIODS

| Station Name | Lat | Lon | 2 | 10 | 50 | 100 | 200 | 500 | 1000 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|
| Assebeteferi | 40.875 | 9.125 | 35.86 | 68.79 | 97.66 | 109.87 | 122.03 | 138.07 | 150.20 | 190.46 |
| Awash 7 kilo | 40.125 | 8.875 | 25.69 | 61.59 | 93.06 | 106.36 | 119.62 | 137.11 | 150.32 | 194.20 |
| Combolcha-1 | 39.875 | 10.875 | 19.40 | 44.68 | 66.84 | 76.21 | 85.54 | 97.86 | 107.17 | 138.07 |
| Combolcha-2 | 40.875 | 9.125 | 35.86 | 68.79 | 97.66 | 109.87 | 122.03 | 138.07 | 150.20 | 190.46 |
| Dupty | 40.875 | 10.875 | 29.18 | 68.95 | 103.81 | 118.55 | 133.23 | 152.61 | 167.25 | 215.86 |
| Gewane | 40.875 | 10.125 | 33.70 | 82.06 | 124.46 | 142.38 | 160.24 | 183.80 | 201.60 | 260.72 |
| Haik | 39.875 | 10.875 | 19.40 | 44.68 | 66.84 | 76.21 | 85.54 | 97.86 | 107.17 | 138.07 |
| Kemisse | 39.875 | 10.875 | 19.40 | 44.68 | 66.84 | 76.21 | 85.54 | 97.86 | 107.17 | 138.07 |
| Koka Dam | 39.125 | 8.875 | 38.39 | 115.56 | 183.22 | 211.82 | 240.32 | 277.91 | 306.33 | 400.67 |
| Meiso | 40.875 | 8.875 | 39.55 | 91.44 | 136.94 | 156.17 | 175.33 | 200.61 | 219.72 | 283.16 |
| Metehara | 39.875 | 8.875 | 21.14 | 51.05 | 77.28 | 88.37 | 99.41 | 113.98 | 125.00 | 161.57 |
| Mojo | 39.875 | 8.875 | 38.39 | 115.56 | 183.22 | 211.82 | 240.32 | 277.91 | 306.33 | 400.67 |
| Nazret | 39.875 | 8.875 | 38.39 | 115.56 | 183.22 | 211.82 | 240.32 | 277.91 | 306.33 | 400.67 |

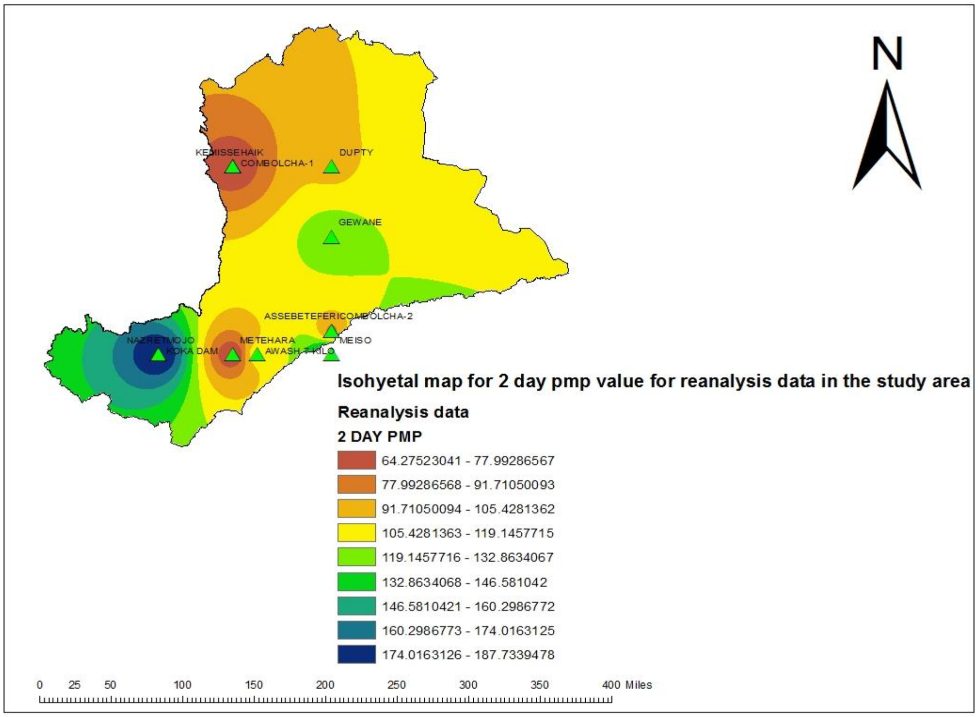
# APPENDIX- H:

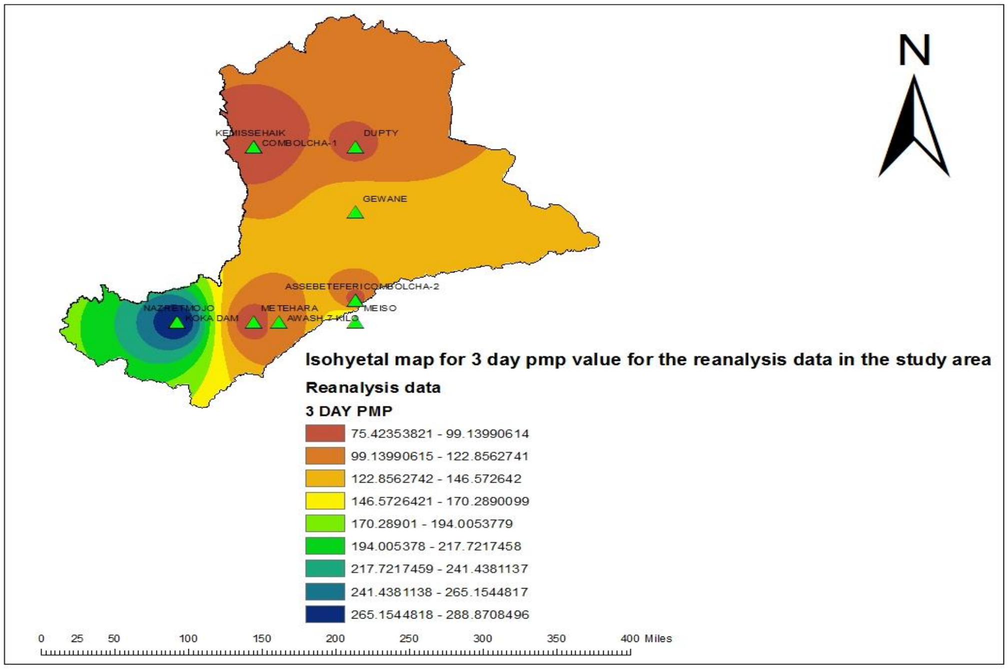
Probable Maximum Precipitations (PMP) of Different Stations in the LAWB and the Ratios of PMP to 10,000 Years Return Period Quantiles for in situ and Reanalysis data.

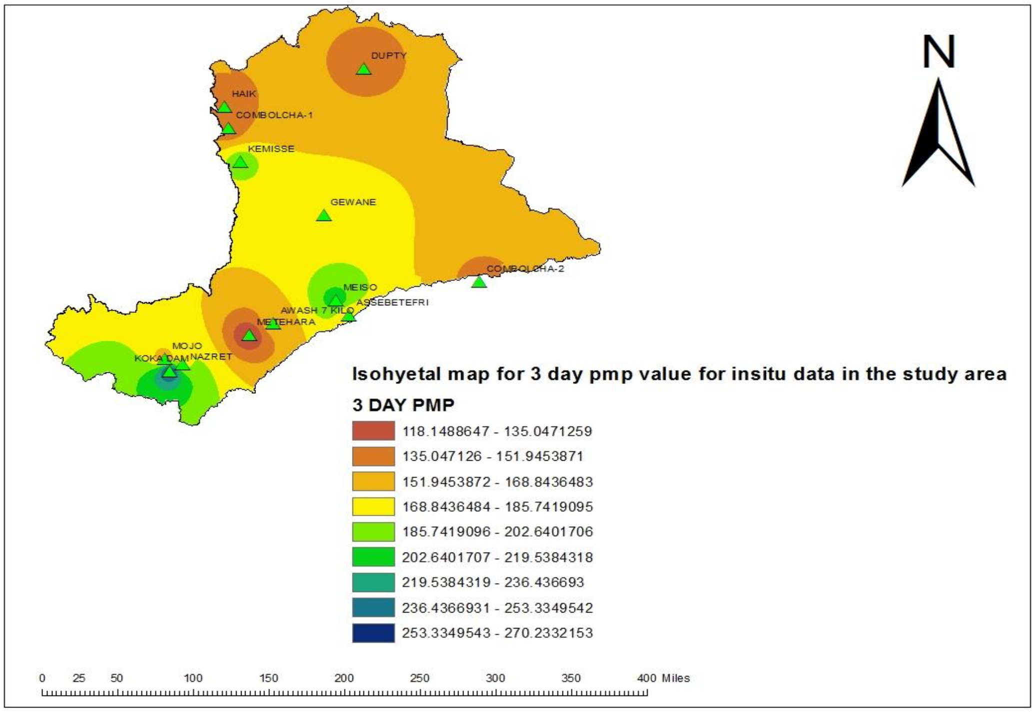
| Ratio of PMP Values with the 10,000 years Return Period Quantiles for GLDAS data in the Study Area | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Station Name | 1-day PMP | 2-day pmp | 3-day pmp | 1 Day 10000 Year Quantile | 2 Day 10000 Year Quantile | 3 Day 10000 Year Quantile | Ratio of 1Day | 2 Day ratios | 3 Day ratios |
| Assebeteferi | 71.35 | 87.76 | 85.04 | 166.81 | 173.51 | 190.46 | 2.34 | 1.98 | 2.24 |
| Awash 7 Kilo | 117.91 | 113.16 | 107.03 | 218.43 | 196.66 | 194.20 | 1.85 | 1.74 | 1.81 |
| Combolcha-1 | 69.73 | 69.13 | 75.42 | 105.91 | 133.41 | 138.07 | 1.52 | 1.93 | 1.83 |
| Combolcha-2 | 71.35 | 87.76 | 85.04 | 166.81 | 173.51 | 190.46 | 2.34 | 1.98 | 2.24 |
| Dupty | 107.84 | 103.20 | 93.92 | 168.15 | 196.09 | 215.86 | 1.56 | 1.90 | 2.30 |
| Gewane | 72.13 | 128.22 | 146.86 | 183.89 | 233.17 | 260.72 | 2.55 | 1.82 | 1.78 |
| Haik | 70.49 | 69.13 | 75.42 | 105.91 | 133.41 | 138.07 | 1.50 | 1.93 | 1.83 |
| Kemisse | 70.49 | 69.13 | 75.42 | 105.91 | 133.41 | 138.07 | 1.50 | 1.93 | 1.83 |
| Koka Dam | 98.37 | 187.74 | 288.88 | 170.48 | 293.90 | 400.67 | 1.73 | 1.57 | 1.39 |
| Meiso | 95.95 | 180.22 | 221.82 | 179.01 | 228.06 | 283.16 | 1.87 | 1.27 | 1.28 |
| Metehara | 62.15 | 64.27 | 78.11 | 103.40 | 141.76 | 161.57 | 1.66 | 2.21 | 2.07 |
| Mojo | 98.37 | 187.74 | 288.88 | 170.48 | 293.90 | 400.67 | 1.73 | 1.57 | 1.39 |
| Nazret | 98.37 | 187.74 | 288.88 | 170.48 | 293.90 | 400.67 | 1.73 | 1.57 | 1.39 |

# APPENDIX- I:

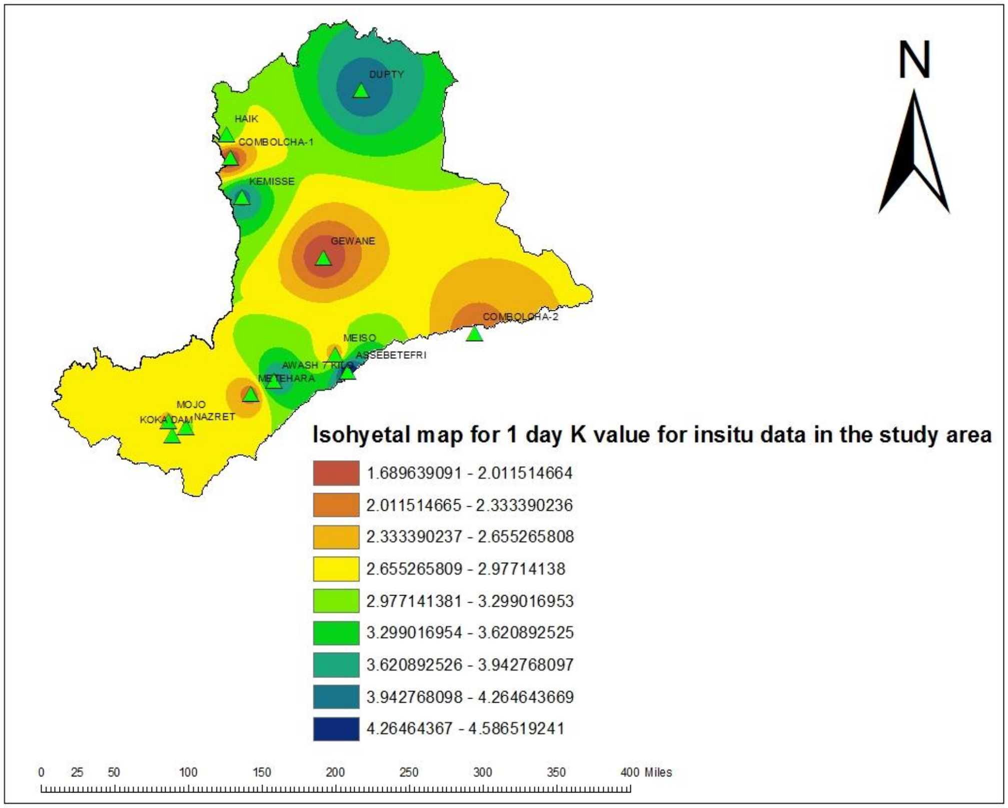
## GLDAS PMP contour Maps of MLAWB

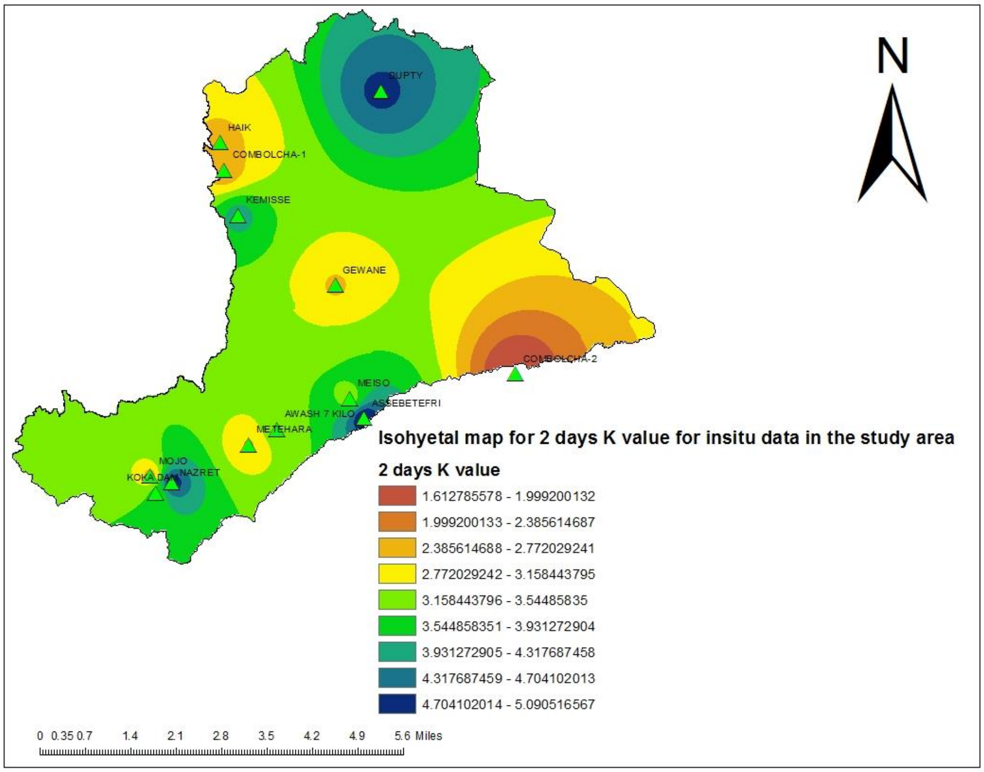


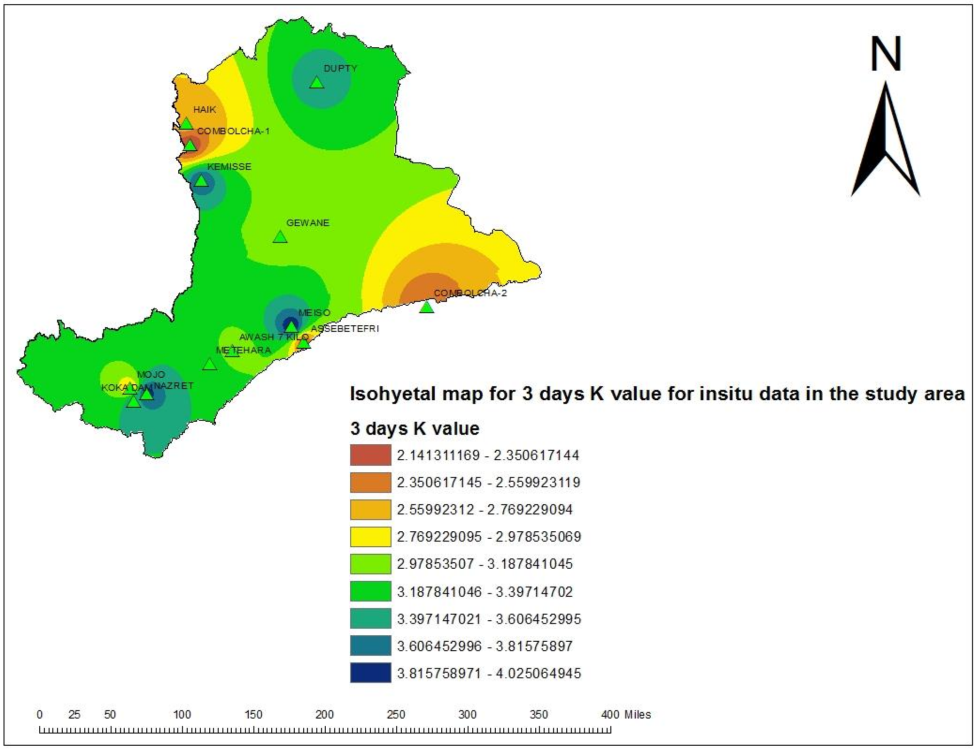




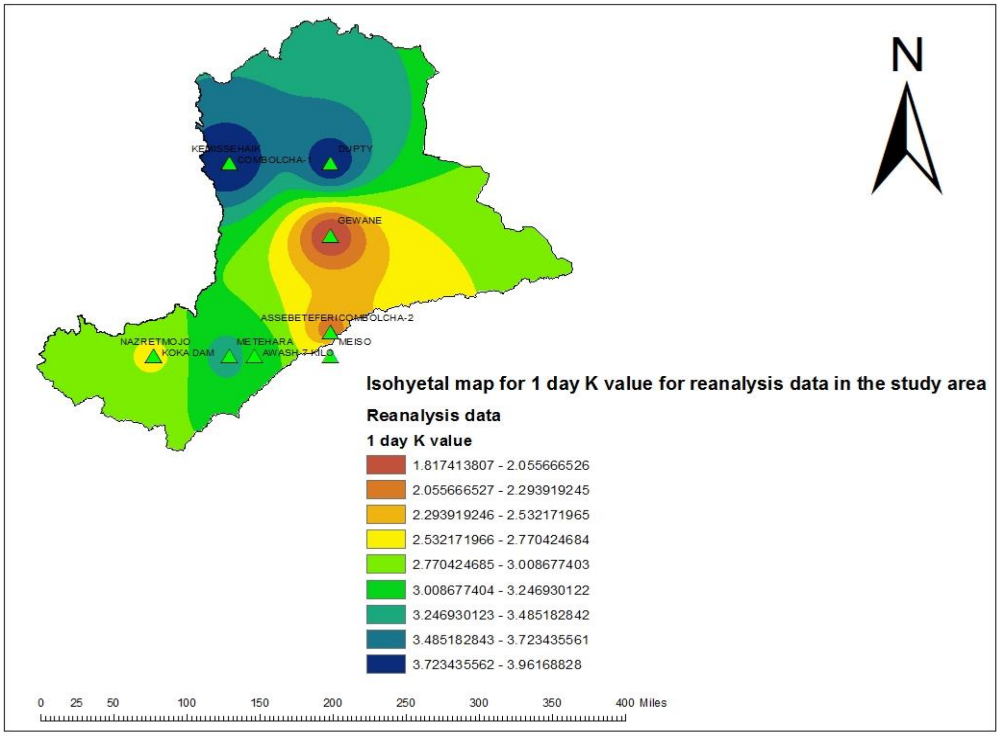
## Contour Maps of Frequency factors of insitu data for MLAWB

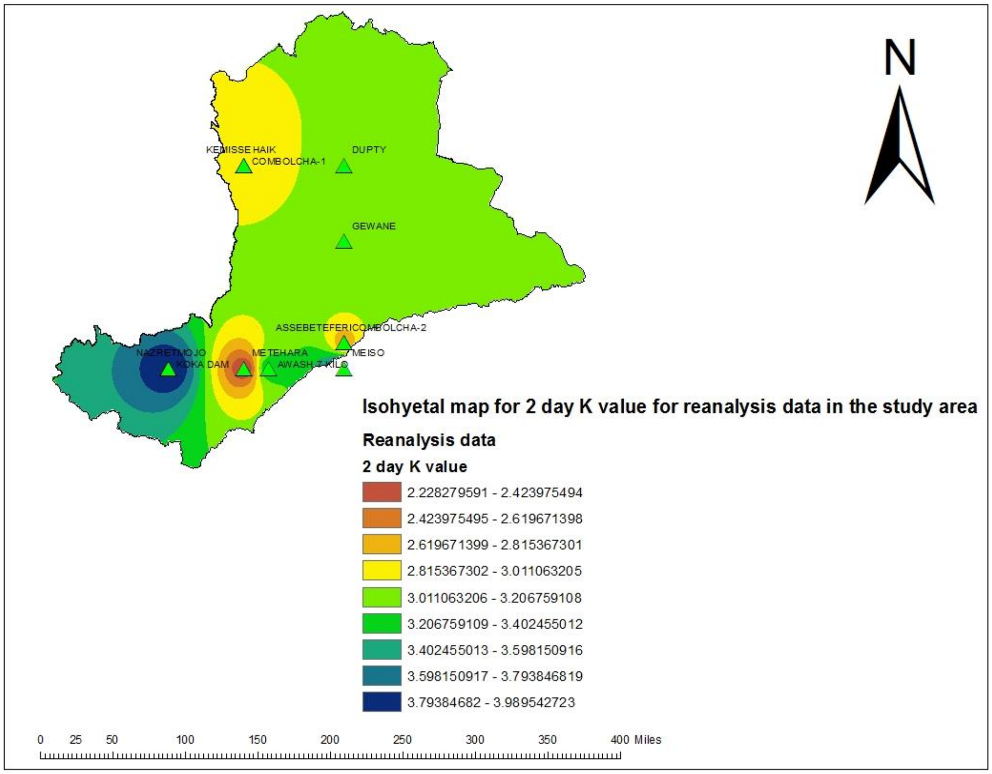


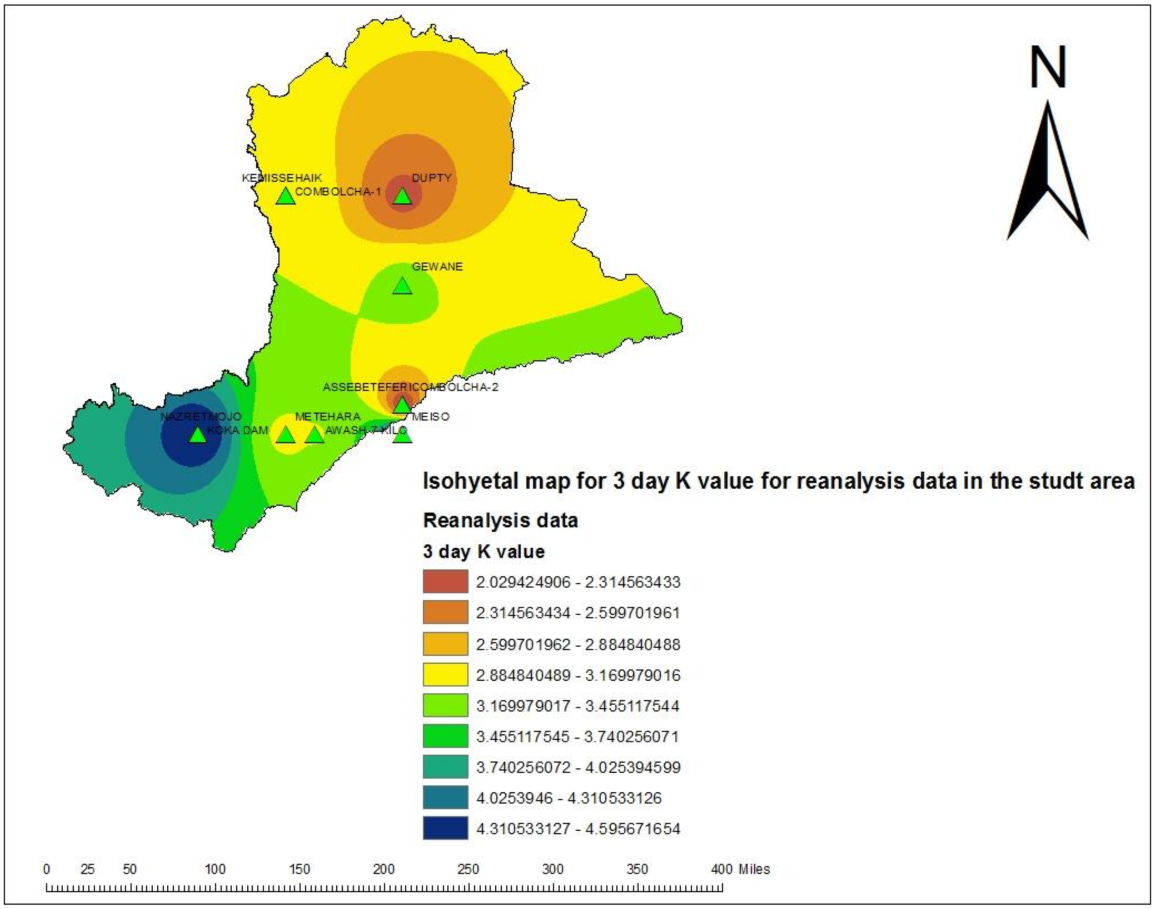

N
DUPTY
HAIK
COMBOLCHA-1
KEMISSE
GEWANE
COMBOLCHA-2
MEISO
ASSEBETEFRI
AWASH 7 KILO
METEHARA
MOJO
KOKA DAM
NAZRET
Isohyetal map for 2 days K value for insitu data in the study area
2 days K value
1.612785578 - 1.999200132
1.999200133 - 2.385614687
2.385614688 - 2.772029241
2.772029242 - 3.158443795
3.158443796 - 3.54485835
3.544858351 - 3.931272904
3.931272905 - 4.317687458
4.317687459 - 4.704102013
4.704102014 - 5.090516567
0 0.35 0.7 1.4 2.1 2.8 3.5 4.2 4.9 5.6 Miles


N
DUPTY
HAIK
COMBOLCHA-1
KEMISSE
GEWANE
COMBOLCHA-2
MEISO
AWASH 7 KILO
ASSEBETEFRI
METEHARA
MOJO
KOKA DAM
NAZRET
Isohyetal map for 3 days K value for insitu data in the study area
3 days K value
2.141311169 - 2.350617144
2.350617145 - 2.559923119
2.55992312 - 2.769229094
2.769229095 - 2.978535069
2.97853507 - 3.187841045
3.187841046 - 3.39714702
3.397147021 - 3.606452995
3.606452996 - 3.81575897
3.815758971 - 4.025064945
0 25 50 100 150 200 250 300 350 400 Miles

## Contour Maps of Frequency factors of reanalysis data for MLAWB






N
KEMISSEHAIK
COMBOLCHA-1
DUPTY
GEWANE
ASSEBETEFERI
COMBOLCHA-2
NAZRETMOJO
KOKA DAM
METEHARA
AWASH 7 KILO
MEISO
Isohyetal map for 3 day K value for reanalysis data in the studt area
Reanalysis data
3 day K value
2.029424906 - 2.314563433
2.314563434 - 2.599701961
2.599701962 - 2.884840488
2.884840489 - 3.169979016
3.169979017 - 3.455117544
3.455117545 - 3.740256071
3.740256072 - 4.025394599
4.0253946 - 4.310533126
4.310533127 - 4.595671654
0 25 50 100 150 200 250 300 350 400 Miles