ESTIMATION OF PROBABLE MAXIMUM PRECIPITATION AND ITS UNCERTAINTY FOR AWASH RIVER BASIN, ETHIOPIA

MITIKU TESHOME BEDADA

A THESIS SUBMITTED TO

THE DEPARTMENT OF WATER RESOURCES ENGINEERING

SCHOOL OF CIVIL ENGINEERING AND ARCHITECTURE

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER'S IN WATER RESOURCES ENGINEERING

(SPECIALIZATION IN IRRIGATION ENGINEERING)

OFFICE OF GRADUATE STUDIES

ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

JUNE 2021

ADAMA, ETHIOPIA

Estimation of Probable Maximum Precipitation and Its Uncertainty for Awash River Basin, Ethiopia

By: - Mitiku Teshome

Advisor: - Dereje Birhanu (Ph.D)

A Thesis Submitted to

The department of Water Resources Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Water Resources Engineering

(Specialization in Irrigation Engineering)

Office of Graduate Studies

Adama Science and Technology University

June 2021

Adama, Ethiopia

APPROVAL PAGE

I, the advisor of the thesis entitled "**Estimation of Probable Maximum Precipitation and Its Uncertainty for Awash River Basin, Ethiopia**" and developed by **Mitiku Teshome**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dereje Birhanu (Ph.D)	_______________	July 07, 2021
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Mitiku Teshome Bedada** have read and evaluated the thesis entitled "**Estimation of Probable Maximum Precipitation and Its Uncertainty for Awash River Basin, Ethiopia**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Water Resources Engineering (Specialization in Irrigation Engineering).

_______________________	__________________	__________________
Chairperson	Signature	Date
_______________________	__________________	__________________
Internal Examiner	Signature	Date
_______________________	__________________	__________________
External Examiner	Signature	Date

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

_______________________	__________________	__________________
Department Head	Signature	Date
_______________________	__________________	__________________
School Dean	Signature	Date
_______________________	__________________	__________________
Office of Postgraduate Studies	Signature	Date

DECLARATION

I hereby declare that this Master Thesis entitled "**Estimation of Probable Maximum Precipitation and Its Uncertainty for Awash River Basin, Ethiopia**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Mitiku Teshome Bedada ______________ July 07, 2021

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Estimation of Probable Maximum Precipitation and Its Uncertainty for Awash River Basin, Ethiopia**" prepared under my guidance by **Mitiku Teshome** submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Water Resources Engineering (Specialization in Irrigation Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dereje Birhanu (Ph.D) _______________ July 07, 2021

ACKNOWLEDGMENTS

First, I would like to thank the almighty God, for His mercy and grace upon me and for giving me the chance, strength, and courage to continue my study and for all things done in my entire life during all my works.

I would like to express my sincere gratitude to my advisor Dereje Birhanu (Ph.D) for the continuous support of my study, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis.

Besides my advisor, I would like to thank all the staff of Water Resources Engineering for their encouragement, insightful comments, and hard questions. I would also like to give special thanks to Adama Science and Technology University for sponsoring my studies and for giving chance to upgrade myself academically by supporting me financially and technically.

Lastly, I also like to thank my unique entire family, relatives, and friends for their care and wishes for my success in the course of my study. No words can express my deep feeling of appreciation for their valuable support throughout my academic life and for always being with me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AwRB	Awash River Basin
CDA	Canadian Dam Association
CV	Coefficient of Variation
ECDSWC	Ethiopian Construction Design and Supervision Works Corporation
ETCOLD	Ethiopian Commission for Large Dams
FAFP	Free-Atmospheric Forced Precipitation
FMP	Fractal Maximum Precipitation
GEV	Generalized Extreme Value
GIS	Geographic Information System
GOV	Goodness of Fit
HMR	Hydrometeorological Reports
K	Frequency Factor
NMA	National Meteorology Agency
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWS	National Weather Service
PDF	Probability Density Function
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
RMSE	Root Mean Square Error
S_n	Standard Deviation of Annual Precipitation
SPSS	Statistical Package for the Social Sciences
UAwRB	Upper Awash River Basin
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
WMO	World Meteorological Organization
$\bar{X}_n$	Mean of Annual Maximum Rainfall

ABSTRACT

Probable Maximum Precipitation (PMP) is theoretically defined as the greatest depth of precipitation for a given duration which is physically possible over a given size storm area at a particular geographical location and at a particular time of year. PMP is used to calculate Probable Maximum Flood (PMF), which is used to size the hydraulic structures to minimize the risk of their failure. The purpose of this study was to estimate the value of PMP using the frequency factor obtained from the basin-specific enveloping curve and Hershfield's chart for 1-day, 2-days, and 3-days duration, compare the results and determine the uncertainty analysis associated with it. In this study 51 Awash River basins stations having at least, 30 years of record length and having at least 9-month observations were used and checked for consistency and homogeneity test. The study shows that the maximum frequency factor (K) estimated from the statistical equation was 6.1 and the maximum PMP values estimated from the Basin scale for 1-day, 2-day, and 3-day durations were 329.24mm, 681.98mm, and 796.95mm respectively. Similarly, the 1-day Hershfield chart PMP value was found to be 729.3mm. This result clearly indicated that Hershfield's chart overestimated the PMP value, which leads to uneconomical designs in the Awash River Basin. The frequency distributions analysis were conducted using Easy-Fit statistical computer software to estimate the parameters of the distributions. Three statistical goodness-of-fit test were conducted and Generalized Extreme Value Distribution (GEV) was found to be the best distribution model with a coverage of 50.33%. The maximum estimated extreme rainfall magnitude from observed daily maximum rainfall for 10,000 years return period for 1-day, 2-day, and 3-day durations were 315.35mm, 641.39mm, and 786.02mm respectively. The Salas and Bootstrap methods were used to quantify the uncertainties in PMP caused by K, $\bar{X}_n$ *and* $\mathcal{S}n$ *in the Hershfield method. The maximum PMP values quantified for 24-hour durations were 319.63 mm and 283.89 mm. However, the design risk PMP with conservative estimation approach is considerably high 329.6 mm, which leads to uneconomical investment on irrigation/hydraulic structures. The study reveals that regularly updated and reliable estimates of PMP with uncertainty is crucial to maintain the sustainable development of Awash River basin and others basins.*

Keywords: Hershfield, PMP, Statistical Method, Awash River Basin, Frequency Analysis, Uncertainties.

1. INTRODUCTION

1.1. Background

Probable Maximum Precipitation (PMP) is theoretically defined as the greatest depth of precipitation for a given duration which is physically possible over a given size storm area at a particular geographical location and at a particular time of year (WMO, 2009; Fattahi *et al*., 2010; Vivekanandan, 2015). It is important hydrologic information for the estimation of Probable Maximum Flood (PMF), which is used in the design of hydraulic structures such as large dams spillways, weirs, barrages, culverts, and cross-drainage works (Fernando and Wickramasuriya, 2011). It is also used to size the hydraulic structures such that the risk of their failure is minimized.

Regardless of the method utilized for obtaining the PMP, the practice of designing and evaluating flood-related structures based on PMP has been criticized among others because of the many uncertainties involved in determining them. The lack of a standard approach for estimating the PMP, and the perception that such estimated PMP (and the ensuring PMF) is an upper bound that may not be exceeded and as such a zero risk. However, an upper bound with zero risks is not realistic because there have been documented cases where the recorded floods have exceeded the estimated PMFs (Salas *et al*., 2014). Thus, some hydrologists have advocated a risk-based design approach.

Different procedures are available to compute the PMP based on the location of the project basin, availability of data, and other considerations. Most of them are based on meteorological analysis, whereas some are based on statistical analysis (Casas *et al*., 2010; Vivekanandan, N. 2015; Suribabu, C. R. 2019). Hershfield (statistical) method is a widely used method and the method is particularly useful for those locations where sufficiently long precipitation records are available but other meteorological data (e.g., dew point temperature, wind speed, relative humidity) are lacking, which are essential requirements for other physical methods, such as moisture maximization and storm transposition technique (WMO, 2009; Rouhani, H., and Leconte, R. 2016; Zhang *et al*., 2019). With the availability of a sufficiently long record of precipitation, the PMP estimates by Hershfield method were found to be closely comparable to those by other physical approaches at different parts of the world (Salas *et al*., 2014).

Hershfield’s statistical method is based on an equation similar to that of Chow (Chow, V.T, 1951). Where a quantile of the underlying distribution is expressed as a function of the sample mean, the sample standard deviation, and a frequency factor K (Chow. *et al*., 1988). In the typical procedure for fitting the empirical frequency distribution of the data at hand using a Probability Distribution Function (PDF), the value of K is related to the skewness coefficient and the exceedance probability. But in Hershfield’s method, the value of K was established after analyzing a large number of historical data of storm annual daily maximums so that an upper bound of K was determined, which was bigger than all values of K obtained from the historical sample.

Another problem was that PMP uncertainty needs to be defined during the procedure of estimating PMP. Computed PMP values have uncertainties caused by K, Xn, and Sn, that is, actual true values and computed values are different Zhang *et al*., (2019) and Salas *et al*., (2014) quantify uncertainty in the PMP estimates using the statistical method in two ways. First, uncertainty can be determined due to uncertainties in the frequency factor, and mean and standard deviation of extreme precipitation values. Second, frequency analysis of PMP can be used to quantify uncertainty. There exist uncertainties in the frequency factor (K) which was accounted for by using an enveloping function of the highest frequency factor values.

The practice of design of high dam spillways in Ethiopia is widely employed using the value of Probable Maximum Flood (PMF) obtained from PMP. Apart from being extremely large flood magnitude, the procedure adopted in the country like Tendaho and Kesem Sugar development dam projects, Koga, Ribb, Megech, Gidabo dam projects was based on graphical Hershfield’s estimation procedure (WMO, 1986, No.332) which is not developed for the country. As a result, the cost of dam construction in the country is high due to the extremely high cost of the spillway.

The government of Ethiopia has been engulfed in several large-scale dam construction projects, which are in either several large-scale dam construction projects, which are in either several large-scale dam construction projects, which are for either hydroelectric power generation or irrigation development or both purposes. The proper and timely utilization of water resources by constructing a storage reservoir or dam and its conveyances are vital for the economic development of the country. Construction of storage reservoirs or dams is considered a basic infrastructure investment elsewhere. An economical design discourages the planning and construction of dam facilities in the country for alleviating poverty and food security.

1.2. Statement of the Problem

Due to the lack of a properly established PMF procedure, professionals and practitioners alike tend to use Hershfield's graphical procedure for estimating the PMP and then convert it into PMF (Alemayehu and Semu, 2010). This was due to Hershfield (1961) used 15 as the maximum value of the frequency factor for computing PMP.

In our country, Ethiopia, (Alemayehu and Semu, 2010; Abenezer and Dereje, 2015) have estimated PMP on Upper Blue Nile River Basin and (Birhan and Yilma, 2017) on Upper Awash River Basin 1-day duration using the statistical method and they found that frequency factor of 11 and 6.2 respectively. Therefore, the result of their study shows that these PMP estimates were considerably high and were not economical. Due to this reason, they recommended that like other countries, further researches should be conducted on the rest basins of Ethiopia for fixing the country's reliable maximum frequency factor.

Uncertainties were also occurred in the PMP estimation due to the method used. Uncertainty in the PMP estimates should quantify due to uncertainties in frequency factor, and mean and standard deviation of extreme precipitation values, and frequency analysis of PMP can be used to quantify. There exist uncertainties in the frequency factor, which was accounted for by using an enveloping function of the highest frequency factor values.

Design of dam spillways in Awash River basin like Kessem dam and Irrigation development and Tendaho Dam adopted in the country Hershfield’s graphical estimation procedure for flood magnitude (WMO, 1986, No.332). Now a day, many dams are constructed and proposed on both the main Awash River and tributary of the Awash River (Middle Awash multipurpose dam, Gololcha Irrigation development dam, Logia Multipurpose Dam). Appropriate determinations of PMF are needed in design irrigation schemes such as flow regulation structures and cross drainage structures. Therefore, appropriate and economical design leads to better planning and construction of dam facilities for alleviating poverty and food security.

1.3. Objectives of the Study

1.3.1. General Objective

The objective of the study is to estimate Probable Maximum Precipitation (PMP) values for different durations and locations for the Awash River basin using the statistical method and determine the associated uncertainty.

1.3.2. Specific Objectives

- To construct a basin-specific enveloping curve of the frequency factor and calculate the PMP values by using it, and construct the spatial-temporal characteristics of K and PMP values;
- To determine the best-fit probability distribution for extreme precipitation and probability of exceedance and return period of PMP values;
- To quantify the uncertainties associated which the statistical methods estimates of PMP values.

1.4. Research Questions

Therefore, the research examine the following three questions:

- What are the basin-specific enveloping curves of the frequency factor and PMP estimates of the Awash River basin?
- Which probability distribution is the best-fit and return period of PMP values for the Awash River basin?
- What are the uncertainty associated with the probable maximum precipitation with methods used?

1.5. Significance of the study

The study will provide a valuable information for hydrologists, engineers and policy makers about how to design economical irrigation/hydraulic structures in Awash River basin using reliable PMP and uncertainty analysis. There was a need to update the site-specific PMP for the study area, which can be used for the calculation of PMF. It was also important to see how PMP values vary with the given duration and relation between the PMP values and the mean of extreme values, PMP values, and the highest observed precipitation or the mean and the standard deviation for different stations and durations.

The study calculated PMP for 24, 48, and 72 hour durations and focused on quantify the uncertainties due statistical method used. The design risk calculated the estimate of the PMP values and probability bounds on the design PMP values. Such a design risk estimate gave a more conservative estimate of the PMP.

1.6. Scope of the Study

The scope of the study mainly focused on estimation of probable maximum precipitation using the statistical method and determine the associated uncertainty. Therefore, the task was starting with calculating the basin-specific enveloping curve of the frequency factor and then determining the PMP for each station and duration. Then quantify the uncertainty can be determined due to uncertainties in the frequency factor, and mean and standard deviation of extreme precipitation values and for frequency analysis of PMP.

Comparing the values obtained from the basin and Hershfield’s graphical estimation procedure for frequency factor and probable maximum precipitation was another task in the study. Since some irrigation structures adopted Hershfield’s graphical estimation procedure (WMO, 1986, No.332) across the river, then, compared the magnitude of PMP value found in the design report with the basin-scale PMP values.

The best-fit probability distribution for extreme precipitation and probability of exceedance and return period of PMP for the basin was being determined. Finally, the uncertainty occurred due to the statistical method were quantified by a different method and the result was compared.

2. LITERATURE REVIEW

2.1. Approaches to PMP estimation

PMP is primarily considered as the precipitation resulting from a storm induced by the optimal dynamic factor (usually the precipitation efficiency) and the maximum moisture factor simultaneously. There are two general approaches to estimate PMP: one is based on storm area (area surrounded by isohyets) and the other is based on the specific watershed location (WMO, 2009a; 2009b).

The first approach storm area (the indirect) focuses on the estimation of a group of PMPs with various durations and areas in a wide region (a zone with meteorologically homogeneous conditions) and then provides a set of methods to convert them into the PMP in the design watershed for PMF estimation in high-risk projects(WMO, 2009b).

The second approach based on the watershed area (the direct approach) focuses on the direct estimation of PMP with a given duration according to the requirements of a specific project (usually the design of a reservoir) in the targeted watershed. The reason for introducing the specific project here is that different design scenarios could result in the selection of different design PMPs potentially resulting from different causative factors (WMO, 2009b).

2.2. Application of Probable Maximum Precipitation

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 the 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 in CDA, 1999 as stated for very high dams, the PMF developed because PMP is mandatory, for high dams: the design flood is selected between the PMF and the 1000-years flood, for low dams: the design flood selected between the 1000-year and the 100-year floods and for very low dam: the design flood selected is less than 100-year floods. The PMF represents an estimated upper bound on the maximum runoff potential for a particular watershed. In some approaches, the inherent assumption is that a dam with a spillway designed to pass this flood has zero risks of overtopping.

2.3. Methods of Estimating Probable Maximum Precipitation

Different methods for PMP estimation, which can be categorized, as hydrometeorological and statistical (WMO, 2009). Common hydrometeorological methods include the moisture maximization method, storm transposition method, generalized method, and storm separation method. Statistical methods include Hershfield's method and the multifractal method. Depending upon the watershed topography and data availability, some methods provide better PMP values in certain regions and other methods in other regions.

2.3.1. Moisture Maximization

The basic assumptions in this method are that precipitation is linearly related to perceptible water (Beauchamp, *et al*., 2013). The moisture maximization approach was used because it estimates PMP through physically based principles, although not as explicitly represented as in numerical atmospheric models, but with affordable data and computational sources. While numerical atmospheric models (i.e., inferential method) provide the most detailed representation of storm physics, they still include parameterizations of atmospheric and land processes such as cloud microphysics, radiation, planetary boundary layer, and surface schemes (Ohara *et al*., 2011). The moisture maximization is considered as an approximate solution of the mass conservation equation for an imaginary storm cell (Chen and Bradley, 2003).

As the moisture available to the storm increases the precipitation, the efficiency of the storm does not change and the record of extreme storms is sufficiently large to represent the most efficient storm mechanisms but not the optimum available moisture that would accompany a PMP event. The efficiency with which the storm converts moisture into precipitation and the amount of moisture content are considered important atmospheric conditions in most PMP studies and the moisture maximization procedure is used to approximate the highest moisture potential in the storm. This method is applicable where there are several years of observed data present.

2.3.2. Storm Transposition

Storm transposition is associated with the relocation of storm precipitation within a region that is homogeneous relative to terrain and meteorological features important to the particular storm rainfall. The basic assumption behind the idea is that a meteorologically homogeneous region exists such that a major storm occurring somewhere in the region could occur anywhere else in the region. The storms transported to a location could occur under similar meteorological conditions as the original location. It involves a meteorological analysis of the storm to be transported, the determination of transposition limits, and the application of the appropriate adjustments for the change in storm location. The maximum observed storm precipitation data that is adjusted for moisture maximization is a plot on a map and is analyzed.

2.3.3. Generalized Method

The maximum record rainfall depths of rainstorms over a large area and adjustment source are made in applying the maximum record rain depths to a particular catchment (Kulkarni, 2010). The generalized method has an advantage of using the maximum-recorded rain depths for all combinations of area and duration and allowing for almost free transposition in space (Koutsoyiannis and Papalexiou, 2006). It is used to estimate the PMP values for catchments of four large dam basins in India. It assumes that the PMP values would result from the optimum combination of the available moisture in the atmosphere and the storm mechanism efficiency, which was indirectly measured by observed precipitation.

2.3.4. Storm Separation Method

Storm transposition is widely used by practitioners as a means of incorporating additional information about precipitation events from nearby locations to design areas where high efficiency storms are rare and sometimes lacking (WMO, 2009). In mountainous regions, the transposition areas are usually restricted to those places where the topographic and meteorological characteristics are similar to those at the place where the storm occurred (WMO, 2009). To expand the transposable regions, storm separation method is applied, through which the mountainous storm rainfall can be separated into two components: that caused by the movement of precipitation weather systems, called convergence component or convergence rain; and that caused by orographic effects, called orographic component or orographic rain (WMO, 2009). Then, the convergence component could be transposed in a larger area and may be combined with the local orographic component at the design area to form PMP estimates.

2.3.5. Multifractal Analysis Method

Multifractal, also known as multiscaling, is widely used to describe the scaling behavior of precipitation and streamflow. Douglas and Barros, (2003) used this technique to calculate the physically meaningful estimates of maximum precipitation from observations in the eastern

United States. The multifractal approach has an advantage by providing a formal framework to infer the magnitude of extreme events, called the Fractal Maximum Precipitation (FMP), independently of empirical adjustments, a site-specific application of FMP in orographic regions. The method is constrained by the length of the record, the spatial resolution of the rain gauge network, and the lack of uncertainty estimates.

2.3.6. Statistical method

In this method, the estimates of PMP are derived from frequency analysis of the annual maximum rainfall series for different durations. Hershfield’s (1961, 1965) has developed PMP based on a general frequency equation given by Chow (1951). The use of the statistical method in different countries has shown that the computed PMP estimates are closely comparable to those obtained by the meteorological method. WMO, (2009) has suggested this method for estimating PMP for stations having a long period of daily rainfall data.

Statistical method for estimating PMP useful wherever sufficient precipitation data are available, and are particularly useful for making quick estimates, or where other meteorological data, such as dewpoint and wind records, are lacking. It is used mostly for making quick estimates for basins of no more than around 1,000 km^2, but has been used for much larger areas (WMO, 2009, No.1045). This method is widely used and in this study too.

Hershfield (1961) used 15 as the maximum value of K for computing PMP. Later Hershfield (1965) found that an upper envelope of K tended to decrease with the increasing precipitation amount. In other words, the frequency factor decreases with increasing mean annual maximum precipitation. The value of K varies from 5 to 20, depending upon the precipitation duration and average precipitation (Casas *et al*., 2011).

Hershfield (1965) analyzed over 95,000 station years of annual maxima belonging to 2,645 stations; about 90% of data was from the United States and 10% from other parts of the world, which included some of the heaviest precipitation regions. He then produced an empirical nomograph ranging from 5 minutes to 24 hours that have been standardized by (WMO 1986 and 2009).

The enveloping curves were derived for particular areas and durations and these have been used to calculate the PMP values (Casas *et al*, 2008). The enveloping frequency factor serves the purpose of transposition. Casas *et al*. (2008) used Hershfield's method to estimate the PMP values for one-day duration and their return periods and spatial resolution over the

Catalonia region. The Gumbel distribution with parameters estimated by the L-moments method was used to determine the return periods of calculated PMP values. They showed that 90% of the PMP values had return periods of 10^4 to 10^8 years.

The coefficient of variation (CV), the ratio of standard deviation, and the mean of the annual maximum series is calculate for each station. Sometimes the inclusion of an outlier or an extraordinary extreme precipitation event, with a recurrence period much longer than the series, could cause an anomalous effect in the calculated mean and standard deviation values (Hershfield, 1961). The CV for each station calculates and checks whether it did not differ too much from that of the neighboring stations.

2.4. Previous Studies on PMP Estimation and Its Uncertainty

Using the Hershfield technique and Gumble distribution of extreme values, Boota. M. *et al*. (2015) compute the probable maximum precipitation for a 1-day duration for Gujjar Khan in the Potwar region, Pakistan. Based on the real precipitation data the value of "K" was obtained 8.7.

Lee, K., and Singh, V. P. (2020) determined the PMP values for different durations using the statistical method with data from the Brazos River basin, Texas. It was found that significant uncertainty in the PMP estimates could occur with the use of the enveloping curve of the frequency factor and the number of stations involved in its construction. Hershfield's curve yielded higher frequency factor values by 16% for 1-hour duration, by 17.9% for 6-hour duration, and by 22.1% for a 24-hour duration. In comparison with basin-specific values, the PMP values from the Hershfield enveloping curve were 16.8% higher for 1-hour duration, 18.5% for 6-hour duration, and 23.4% for a 24-hour duration. For most of the Brazos River basin, the return period of the PMP values was in the range of 1000 to 3000 years, which was less than the range of 10^3 to 10^6 years reported in HMR 51. This showing the degree of risk associated with the PMP values and they suggested a basin-specific-enveloping curve.

Quraishi, S. and Berhane, M. (2014) tried to estimate the PMP for the North Shewa region using Hershfield statistical method and Gumbel EVI model. In addition, the highest value of the frequency factor was found to be 5.2, which corresponds to the Debre sina station. They develops a one-day PMP isohyetal map and identifies the best-fit frequency distribution model for each rain gauge station for the zone.

Abenezer E. and Dereje H. (2015) Estimate the probable maximum precipitation using In-situ and Re-analysis global precipitation product on Upper Blue Nile Basin using the new K and the chart values for both in situ and reanalysis products exhibited difference 38% up to 96.4%, this result confirmed the Hershfield's chart overestimated PMP value, which leads to uneconomical designs in the Upper Blue Nile basin. While most of the K values obtained from the chart are about 15, the maximum value obtained using a statistical method for 1-day duration is limited to 11.

Fikre A., *et al*., (2016) developed of one day Probable Maximum Precipitation and Isohyetal Map for Bale Zone, Oromia Region, Ethiopia and they found that the maximum frequency values varied from a maximum 5.09 observed at Robe and Sofumor stations and the minimum 2.24 at Bidre station.

As Birhan and Yilma, (2017) work, a yearly maximum of one day, two days, and three days duration rainfall data of 30 years for 11 stations on the Upper Awash sub river basin were analyzed to estimate PMP based on the statistical method. The study shows that the maximum K founded from the statistical equation is 6.2 and the PMP value obtained using the Hershfield chart maximum frequency factor deviated around 54% from the PMP value obtained from the Hershfield's frequency equation.

Finally, (Abenezer Endale and Dereje Hailu, 2015) & (Birhan and Yilma, 2017) recommended that like another country, further researches should be conducted on the rest of the basins of Ethiopia for fixing the country's reliable maximum frequency factor.

2.5. Uncertainty in PMP Computations

Uncertainties in the PMP estimates using the statistical method or Hershfield method have been limited (Salas *et al*, 2014). There can be two ways to quantify uncertainty in the PMP estimates using the statistical method. First, uncertainty can be determined due to uncertainties in the frequency factor, and mean and standard deviation of extreme precipitation values. Second, frequency analysis of PMP can be used to quantify uncertainty. There exist uncertainties in the frequency factor (K) which is accounted for by using an enveloping function of the highest frequency factor values. The extreme precipitation data used in the Hershfield method suggested a deterministic upper limit of precipitation. He suggested unifying all classes of record length and adding the number of occurrences of all classes after ignoring the effect of record length on K. Considering it as a random variable, the probability of its non-exceedance can be estimated using the Weibull formula, assuming all records of standardized annual maximum precipitation K represented practically the same population.

There are also uncertainties in the sample mean and sample standard deviation, which can affect the PMP estimation. Assuming that the extreme precipitation series followed the Gumbel distribution Salas *et al.,* (2014) considered the uncertainty of PMP estimates arising from the uncertainty of sample mean and sample standard deviation. They calculated the expected value and standard deviation of the PMP values obtained from the Hershfield method and then estimated the design risk values of PMP.

2.6. Frequency Analysis of Extreme Precipitation

On the other hand, the uncertainty of PMP values can be quantified by frequency analysis of the annual maximum precipitation series. The first step is to determine the best-fit probability distribution for the extreme precipitation series and return periods of PMP values. The exceedance probability of PMP values can be used to analyze risk. There is an unknown risk of occurrence of such extreme events. However, by selecting an appropriate distribution for extreme precipitation values and ignoring the concept of the upper limit, the return period can be calculated for the estimated PMP value.

Various probability distributions can be used to calculate the return periods of maximum precipitation of different durations or calculate the return period for extreme precipitation. The traditional fitting method with the conventional moments, such as mean and standard deviation, can result in return periods shorter than the ones corresponding to a longer sample containing a large number of years (Casas *et al.*, 2008). Adjustment of a CV of the annual maximum precipitation series can be done to compensate for the effect of outliers (Boota, M. W.*et al*., 2018).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

The Awash River Basin is one of the 12 river basins of Ethiopia which is found between latitudes of $7^0$52'12" to $12^0$08'24"N and longitudes of $37^0$56'24 to 43^0 17'24"E (Hailu, R. *et al*., 2018). The basin constitutes the central and northern part of the Rift Valley and is bounded to the west, southeast, and south by the Blue Nile, the Rift Valley lakes, and the Wabeshebele basins, respectively (Gedefaw, M. *et al*., 2018). It covers a total area of 110,000 km^2, with a length of 1200 km. The basin is a home of about 15 million inhabitants.

This basin has been the most highly utilized basin in Ethiopia since modern agriculture was introduced, as early as the 1950s (Edossa, D. *et al*., 2010). The basin is divided into upper, middle, and lower valleys. The mean annual rainfall of the basin varies from 1700 mm northeast of Addis Ababa to 110 mm in the northern part of the basin (Figure 3.1) Bekele *et al.*, (2017).The distribution of rainfall is bimodal in the middle and lower parts of the basin and unimodal in the upper part (Hailu, R. *et al*., 2018). The Inter Tropical Convergence Zone (ITCZ) influences the distribution of rainfall in the basin.

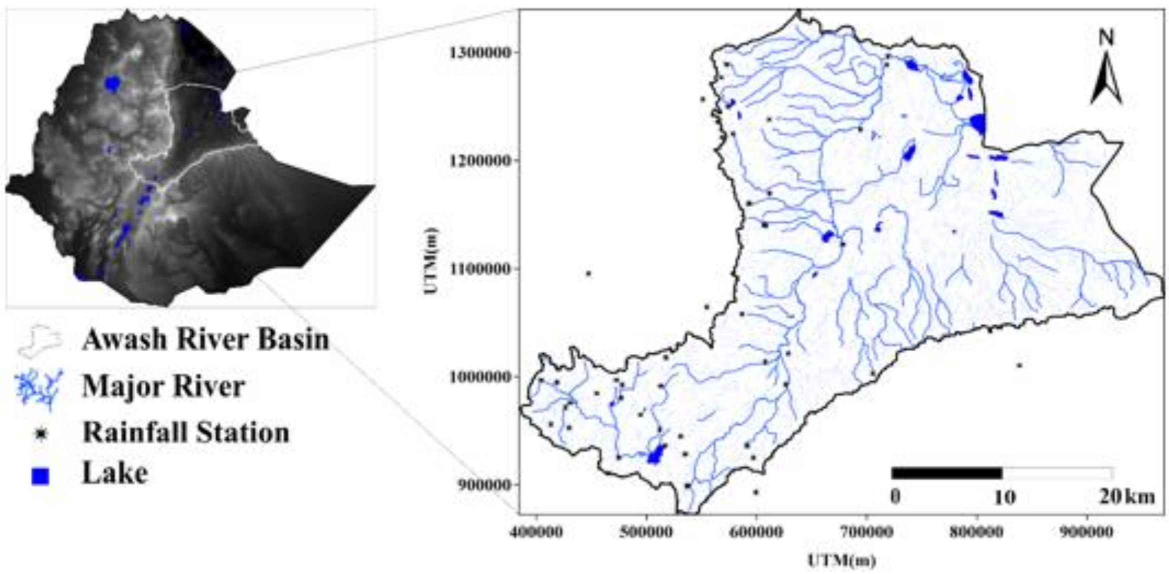


Figure 3.1: Study area of the Awash River basin

The mean surface water resource of the Awash River Basin is approximately 4.9×10^8 m^3 (Mersha, A. *et al*., 2018). Irrigation used 44% from the surface water resources. More than 70% of large-scale irrigated agriculture in Ethiopia is found in this basin. The irrigation potential of the basin is estimated to be 206,000 ha as reported in the ministry of water and energy office. Many rivers are functional only in rainy seasons (July to September) especially in lowland parts of the basin. However, the Mojo, Akaki, Kessem, Kebena, and Mile rivers are functional throughout the year.

3.2. Data Availability and Analysis

3.2.1. Data sources and collection

Precipitation data (daily rainfall)for 1-day duration of the Awash River basin was taken from national meteorology agency (NMA).Then the 2-days and 3-days duration rainfall was generated from1-day rainfall data. The shape files of rain gauging stations were imported into GIS by using the latitude and longitude of stations as shown in figure 3.1.

The stations were selected based on the criteria of having at least 30 years of record length and having at least 9-month observations for each year Singh and Hao, (2013). The time series of stations with different durations was plotted to see if there is any trend in the precipitation records as a function of time. 51 stations of Awash River basin was selected having record length of 30 to 40 years from the meteorological stations of Awash River basin. The basic information for selected stations of river basin are listed on appendix A and the annual maximum for 1-day, 2-days and 3-days of the rainfall data prepared from the daily rainfall data as shown in appendix B.

3.2.2. Data Quality Control

In order to get good results, the qualities of the data were investigated through different methods of checking. Under flood frequency analysis the commonly used test like consistency and homogeneity of data were take taken.

i. Consistency Test for the Data Series

The consistency of a rainfall record was tested with double-mass analysis. The method compares the cumulative annual maximum rainfall values of station X with those of a cumulative annual maximum rainfall of reference station. The reference station is usually the mean of annual maximum rainfall of several neighboring stations. The cumulative pairs (double-mass values) are plotted in XY arithmetic coordinate system. If the plot were essentially linear, the record at station X was consistent. If the plot shows a break in slope, the record at station was inconsistent and should be corrected. The correction was performed by adjusting the records prior to the break to reflect the new state (after the break).

Double mass curve is a simple, visual and practical method, and it is widely used in the study of the consistency and long-term trend test of hydrometeorological data (Mu, *et al.*, 2010 and

Pirnia, A. *et al*., 2019). In this study, the data consistency of a rainfall record at all stations was tested with double-mass analysis. The data consistency of cumulative annual maximum rainfall values of a single station with those of a cumulative annual maximum rainfall of neighbor station was done. The consistency of 51 stations was checked through this method. The double mass curve graph for middle Awash River basin and lower Awash River basin shown in the appendix C and the upper Awash River basin double mass curve of data consistency shown below.

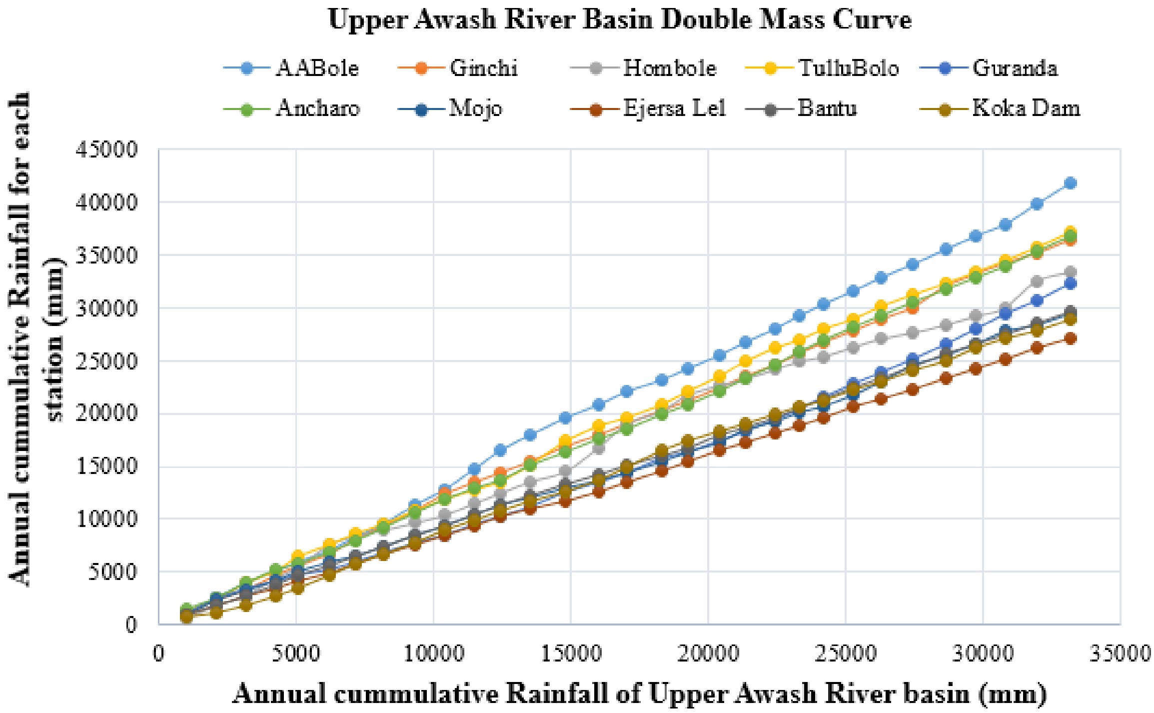


Figure 3.2: Data consistency analysis using double mass curve for UAwRB

ii. Homogeneity Test for the Data Series

In this work, the homogeneity test was done by Mann-Whitney (M-W) test and Rainbow software.

Mann-Whitney (M-W) test of homogeneity, two samples of size p and q with $p \leq q$ were compared. The combined data set of size $N = p + q$ was ranked in increasing order. The Mann-Whitney (M-W) test considered the quantities V and W (Mann & Whitney, 1974 and García-Marín, A. P. *et al*., 2020).

$$V = R - \frac{p(p+1)}{2} \quad (3.1)$$

$$W = Pq - V \quad (3.2)$$

Where:- R is the sum of the ranks of the elements of the first sample (size p) in the combined series (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, is approximately normally distributed with mean and variance.

$$U_{mean} = \frac{p+q}{2} \tag{3.3}$$

$$Var(U) = \left[\frac{pq}{N(N-1)}\right]\left[\frac{N^3-N}{12} - \sum T\right] \tag{3.4}$$

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.

Homogeneity test was done for all stations of 1-day, 2- days and 3-days. 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 & Whitney, (1974) showed that no significant trend in the annual maximum rainfall values exists at all of stations.

Table 3.1: Homogeneity test of Modjo Station

Modjo Station	1-day	2-day	3-day
Sample Size (N)	39	39	39
Sample1 (p)	19	19	19
Sample 2 (q)	20	20	20
R, Sum of the sample p	352	314	317
Number of observation tied (J)	2	2	2
Sum of the tied observation	0	0	0
$Var(U)$	1266.538	1266.538	1266.538
Standard test result for 5% significant level (u)	0.78677<1.96 Homogeneous	1.85453<1.96 Homogeneous	1.77024<1.96 Homogeneous

As shown in the table 3.1 above the standard homogeneity test at Modjo station for 5% significant level was found 0.78677, 1.85453 and 1.77024 for 1-day, 2-day and 3-day respectively which was less than 1.96.

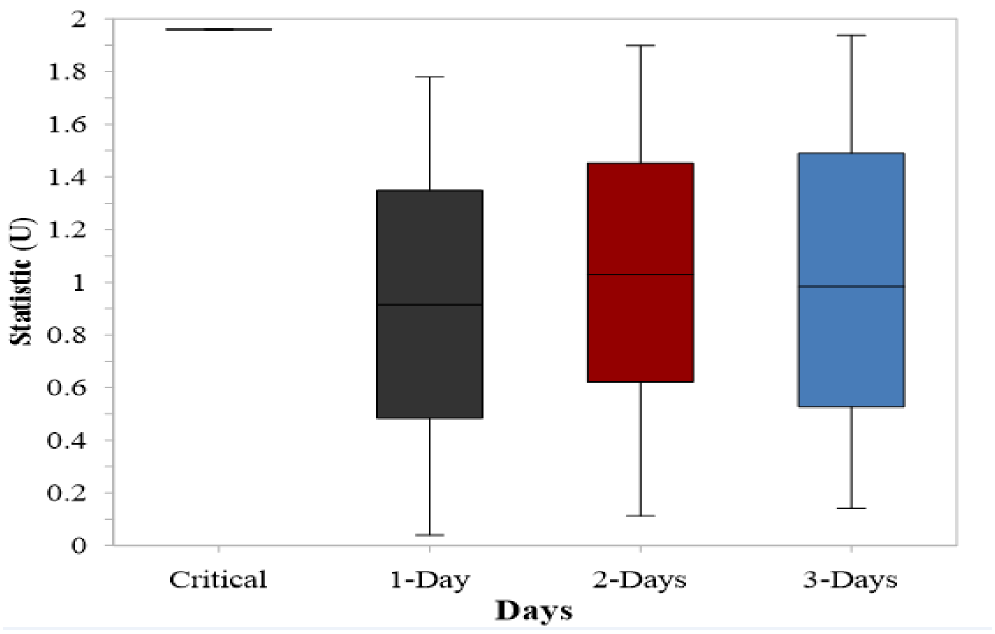


Figure 3.3: Homogeneity test of 1-day, 2-day and 3-days

Therefore, no significant trend in the annual maximum rainfall values exists. Hence, the annual maximum rainfall series for the station was treated as homogeneous for subsequent calculation.

Rainbow software was other way of hydrological data frequency analysis for homogeneity test. All 51 stations of Awash River basin was undertaken through this software.

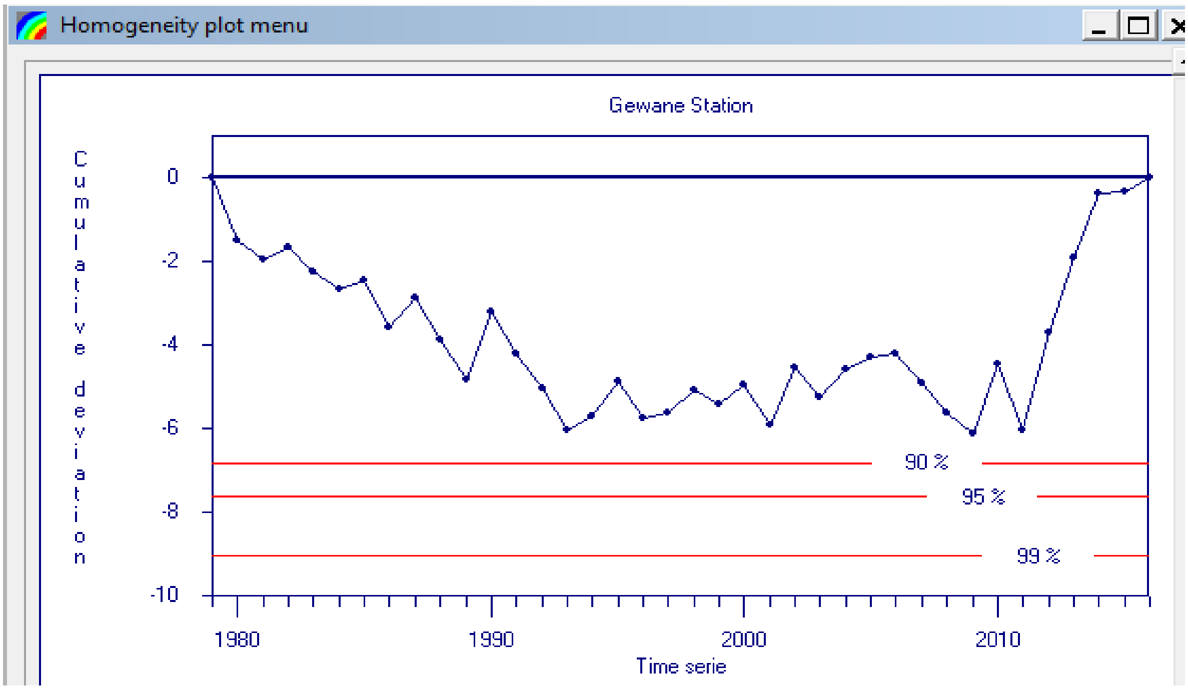


Figure 3.4: Homogeneity test using rainbow for Gewane station for 24-hr duration

The probability of rejecting homogeneity under 90%, 95% and 99% statistic for range of cumulative deviation and maximum of cumulative deviation. At those statistic percentages, no station was rejected.

3.2.3. Software Program Used

RAINBOW software was used for hydrometeorological frequency analysis and testing the homogeneity of historical data sets and Easy-Fit statistical computer software was used for fitting the best probability distributions for the stations and to compute parameters in frequency analysis. SPSS and R programming mosaic and bootstrap package was also used to quantify the uncertainty of the probable maximum precipitation.

3.3. Probable Maximum Precipitation Computation Methods

3.3.1. Hershfield Method

Hershfield (Hershfield, 1961) proposed a frequency factor-based formula to estimate PMP as:

$$PMP = \bar{X}_n + KS_n \qquad (3.5)$$

Where: $\bar{X}_n$ is the mean of extreme annual maximum rainfall values of a given duration, Sn is the standard deviation of extreme annual precipitation series, n is the sample size, and K is the frequency factor(Hershfield, 1965; WMO, 2009).

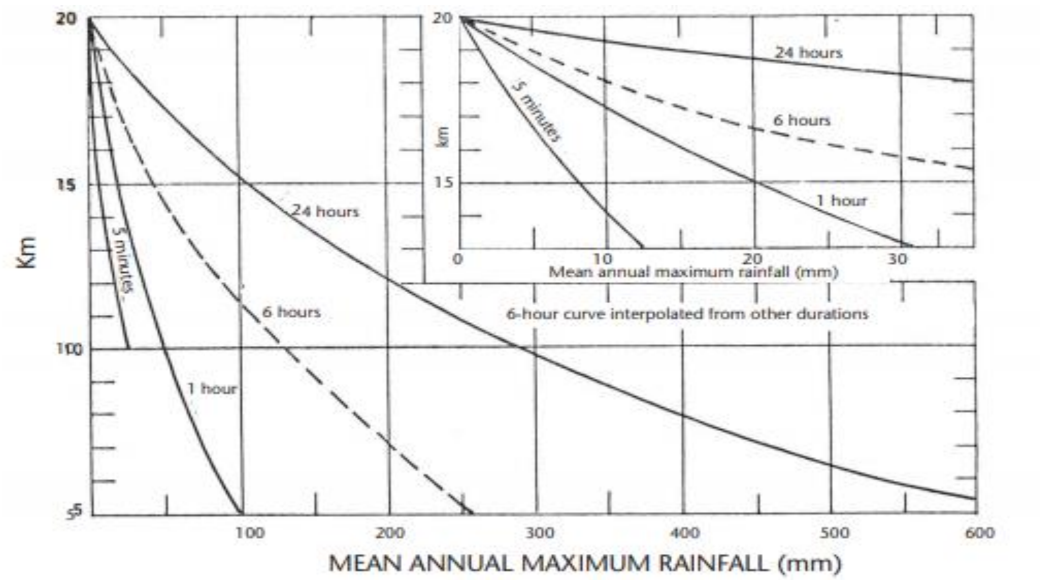


Figure 3.5: K as a function of rainfall duration and MAMR series (Hershfield, 1965)

The frequency factor was constructed by using the mean annual maximum precipitation of each station and duration based on Hershfield's chart as shown in the above figure 3.5.

3.3.2. Basin-scale Method

The values of mean, standard deviation and highest observed precipitation were calculated for the annual maximum series of each station corresponding to each duration. Mean and standard deviation was adjusted for and maximum observed event and sample size. Adjustments were made based on Figures3.6, 3.7 and 3.8 (Hershfield, and 1961b).

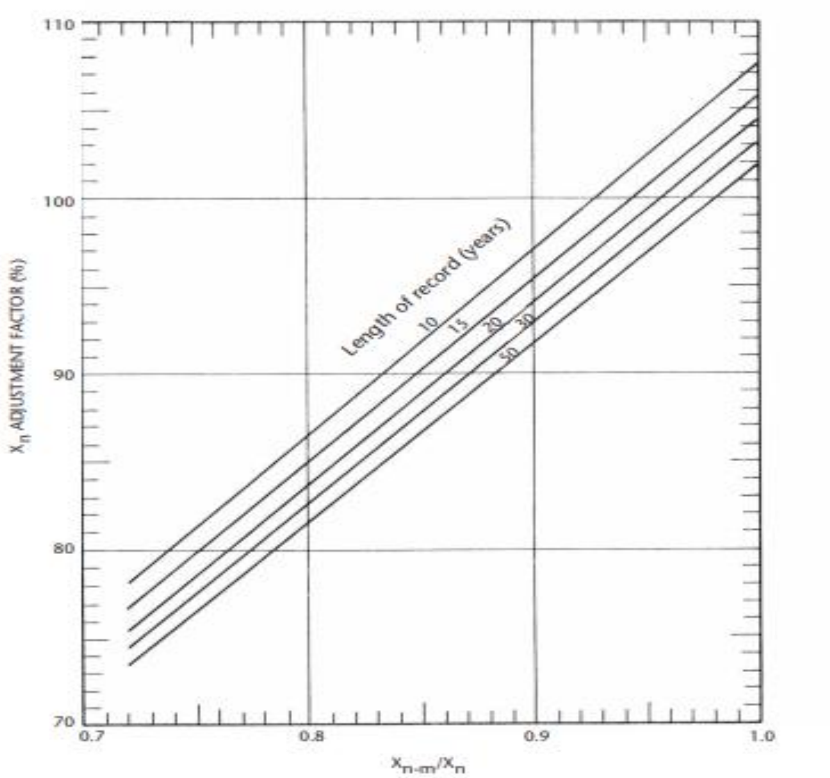


Figure 3.6: Adjustment of mean of annual series for maximum observed rainfall (Hershfield, 1961b)

The mean and standard deviation of the annual maximum series tend to increase with the length of record because the frequency distribution of precipitation extremes is skewed to the right so that there is a greater chance of getting a larger than a small extreme as the length of record increases. Hence, for smaller series of extreme precipitation n, adjustments are made to the mean and standard deviation for the length of record.

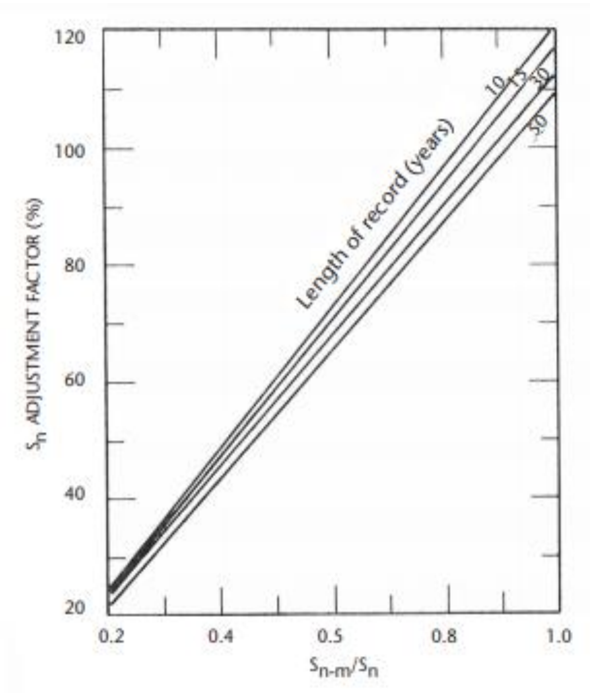


Figure 3.7: Adjustment of standard deviation of annual series for maximum observed rainfall (Hershfield, 1961b)

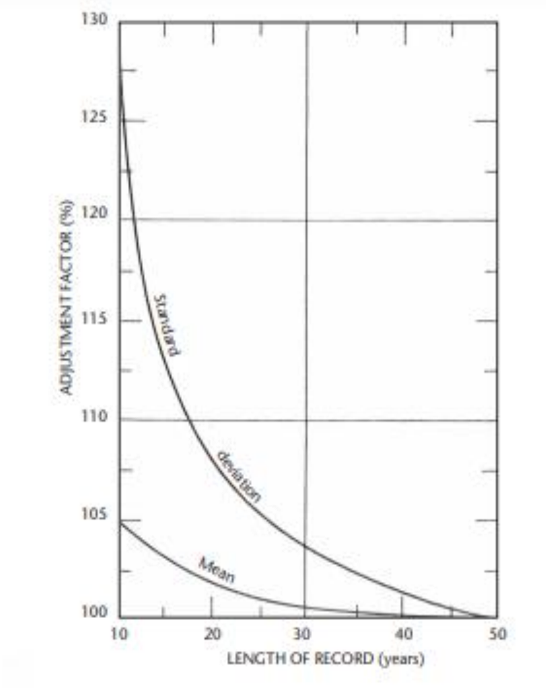


Figure 3.8: Adjustment of mean and standard deviation of annual series for length of record (Hershfield, 1961b)

Then, the PMP of basin scale was construct from Hershfield's chart based on figure 3.5 and K was calculated by observing the biggest maximum annual rainfall as (Hershfield, 1961).

$$K = \frac{X_m - \bar{X}_{n-1}}{S_{n-1}} \tag{3.6}$$

Where:- X_m is the highest of a series of n annual maximum rainfall values of a given duration; $\bar{X}_{n-1}$ and S_{n-1} are the mean and standard deviation of the series excluding the highest value from the series; and K is a frequency factor (WMO, 2009).

The PMP value for different durations (1-day, 2-day and 3-day) was estimated using a statistical approach for the Awash River basin based on the frequency factor obtained. The calculated PMP values adjust for the fixed observational time interval based on the procedure described in WMO, (2009). The adjustments were yield values closely approximating those to be obtained from analysis based on true maxima (Hershfield, 1961a; WMO, 2009). However, less adjustment is required when maximum observe amounts for various durations are determined from two or more fixed time intervals.

3.4. Probable Maximum Precipitation Uncertainty Analysis

3.4.1. Salas Hershfield Methods

To quantify uncertainty due to the sample mean and sample standard deviation the procedure similar to Salas *et al*., (2014) was followed. Chebyshev's inequality was used to obtain the value of PMP with uncertainty. It assumed K as a constant.

$$E(\hat{P}) = E(\bar{X}_n) + KE(S_n) \tag{3.7}$$

Where; E is the expectation operator;

$$E(\bar{X}_n) = E\left[\frac{1}{n}\sum_{i=1}^{n} X_i\right] = \frac{1}{n}\sum_{i=1}^{n} E(X_i) = \mu \tag{3.8}$$

Where; µ represents the mean of population of Xi, and Xi is the individual annual maximum rainfall, and n is the number of annual maximum rainfall values.

$$E(S_n) = \frac{\Gamma\left(\frac{n}{2}\right)\sigma}{\sqrt{\frac{n-1}{2}}\,\Gamma\left(\frac{n-1}{2}\right)} \tag{3.9}$$

Where; σ represents the standard deviation of population of Xi, and Γ is the incomplete gamma function. By substituting equations (3.8) and (3.9) in to equation (3.7) then rewritten as:

$$E(\hat{P}) = \mu + K\frac{\Gamma\left(\frac{n}{2}\right)\sigma}{\sqrt{\frac{n-1}{2}}\,\Gamma\left(\frac{n-1}{2}\right)} \tag{3.10}$$

To quantify uncertainty one of the requirements was the calculation of Variance *Var*(P) of PMP estimate, which can be calculated by (Mood *et al*., 1974).

$$Var(\bar{P}) = Var(\bar{X}_n) + K^2 Var(S_n) + 2\mathrm{cov}(\bar{X}_n, S_n) \tag{3.11}$$

Where:- Var $(\bar{X}_n)$ is the variance of the mean, Var (S_n) is the variance of standard deviation, and Cov$(\bar{X}_n, S_n)$ is the covariance of mean and standard deviation. Each of the elements in equation (12) can be calculated as:

$$\mathrm{Var}(\bar{X}_n) = \frac{\sigma^2}{n},\ Var(Sn) \approx \frac{\sigma^2}{2(n-1)} \text{ and } Cov(\bar{X}_n, Sn) \cong 0 \tag{3.12}$$

Then, the variance of $\bar{P}$ can be expressed as:

$$(\bar{P}) \cong \frac{\sigma^2}{n} + \frac{\sigma^2}{2(n-1)} \tag{3.13}$$

The standard deviation of $\bar{P}$ is

$$\sigma(\bar{P}) \cong \frac{\sigma}{\sqrt{n}}\sqrt{1+\frac{k^2}{2(n-1)}} \quad (3.14)$$

Then, PMP along with uncertainty can be calculated as:

$$PMP = E(\hat{P}) \pm m\sigma(\bar{P}) \quad (3.15)$$

$$P_d = E(\hat{P}) \pm m\sigma(\bar{P}) \quad (3.16)$$

Where:σ(P) is the standard deviation of PMP estimates and m>1 is the parameter, Pd is the value of uncertain PMP value P whose distribution is not known but only the estimates of its mean E(P) and standard deviation σ (P) are known.

Then, the comparison of Hershfield PMP and Design Risk PMP values for the 24-hour duration (mm).

3.4.2. Bootstrap Method

To quantifying uncertainty and explore the distribution of K and PMP at each station, we used the bootstrap method to resample from the original observations. The bootstrap method, introduced by Efron (1979), is a resampling technique and does not require information of the true distribution (Joshi, et al., 2006).

In this study (N=1000) bootstrap samples were generated by resampling from the original sample (annual maximum rainfall series) repeatedly. The bootstrap method based on R-statistics and IBM SPSS statistics.

R is a language and environment for statistical computing and graphics that describe function in the psych package includes the standard error of the mean along with other descriptive statistics. The standard error of a statistic is the estimated standard deviation of the sampling distribution. It is generated by repeatedly (resample) sampling the mean of the population (and sample standard deviation) and examining the variation within the observation data.

IBM SPSS Statistics is a powerful statistical software platform. It delivers a robust set of features that extract actionable insights data. It was used to Analyze and solve research problems through a user friendly interface. IBM SPSS Statistics understand large and complex data sets quickly with advanced statistical procedures that help ensure high accuracy and quality decision making. It use extensions, Python and R programming language code to integrate with open source software.

Run an analysis of the data arranged for the SPSS and select the appropriate variables, and SPSS reads through all your cases, performs the analysis, and presents output as tables or graphs.

After applying the bootstrap method to the study area records, we got the numerical values of the variance of PMP for each station. Then we compared the results with Hershfield methods estimation results.

3.5. Frequency Analysis of Extreme Precipitation and Return Period

3.5.1. Frequency Analysis

In flood frequency analysis an assumed probability distribution fit to the available data to estimate the flood magnitude for a specified return period. The choice of an appropriate probability distribution is quite arbitrary, as no physical basis is available to rationalize the use of any particular distribution. The first error, which is associated with the wrong assumption of a particular distribution for the given data, can be check to a certain extent by using goodness-of-fit tests. These statistical tests provide a probabilistic framework to evaluate the adequacy of a distribution. Even if an acceptable distribution is selected, a proper estimation of parameters is important. Some of the parameter estimation methods may not yield good estimates, or even converge.

The parameter estimation was done by using the Easy-Fit statistical computer software with proper parameter estimation method suitable for each distribution within the interface. Easy-Fit software uses the least computationally intensive methods. Thus, it employs the method of moments for those distributions whose moment estimates are available for all possible parameter values, and do not involve the use of iterative numerical methods. In this study Easy-Fit statistical computer software were used for parameter estimation of selected distributions.

3.5.2. Frequency Analysis of Extreme Precipitation

Frequency analysis of extreme precipitation was performed for different durations. The best-fit probability distribution was determined for the study area. To find the best-fit probability distribution for each station and different durations, a three-step process similar to Olofintoye *et al*., (2009) was used. The three-step process: In the initial processing all common statistical distributions were used and for each station and duration the test statistic values of

Kolmogorov-Smirnov, Anderson Darling, and Chi-square are calculated for every distribution.

For each of the three tests the distributions were ranked according to the lowest test statistic value. The distribution having the 1st rank was assigned a score highest, 2nd rank distribution a score of 2nd highest and so on. The total scores from the three tests of each distribution were added to see which distribution had the highest score, the second highest, and so on. Then, the distributions having the 1st rank by each goodness of fit test were chosen.

3.5.3. Return Period of Estimated PMP Values

The return periods of the PMP values was determined for each duration. The PMP values derived from the basin-specific enveloping curve of k using the data for the Awash River basin determined and the amount of risk associated with the PMP values also calculated.

4. RESULTS AND DISCUSIONS

4.1. Probable Maximum Precipitation (PMP)

Different studies show that the frequency factor found from Hershfield's graphical procedure was overestimated the actual value.

In this study, the K value of the Awash River basin was calculated by both statistical procedure and Hershfield's chart, and then the study put how much Hershfield's chart overestimate the actual value in the basin.

4.1.1. Determination of frequency factors

Using the similar technique described in the methodology part and using the statistical values of the stations in the basin the frequency factor for every rainfall station was calculated by using equation 3.5 and the detail values are shown in appendix D.

The results of this study show that the maximum frequency factor of the basin found for 24-hr and 48-hr were 5.63 and 6.1 at Nuraera station and for the 72-hr duration, the magnitude of k value were 5.80 at Aliyu Amba station at the lower Awash River basin. As shown in the figure below around 7.84% of the stations have a frequency factor of 2 and below. About 90.2% of the stations have the value of frequency factor between 2 and 5. Only 1.96% of the stations have a frequency factor above 5. This indicates that in the Awash River basin the value of the maximum frequency factor is closely the same in different stations.

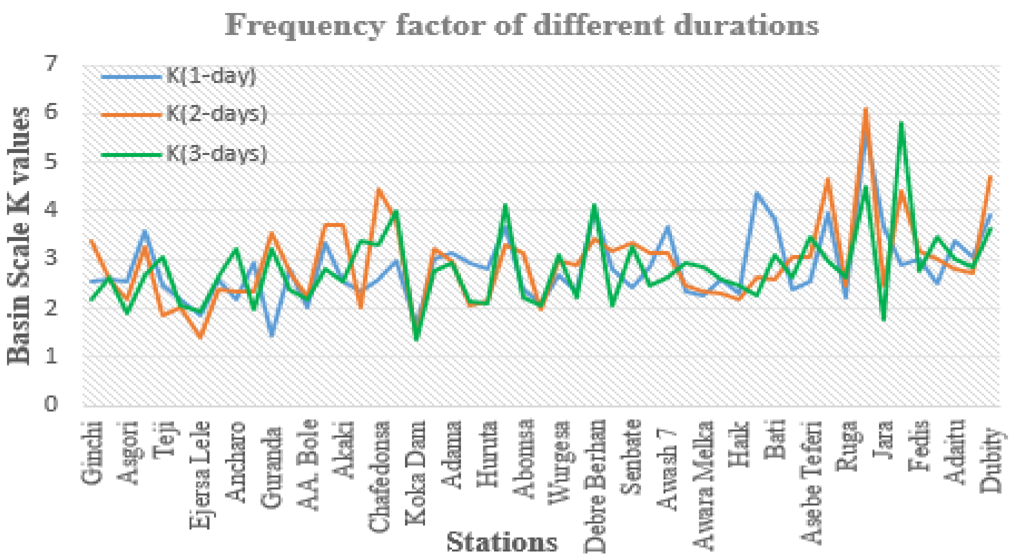


Figure 4.1: Plots of frequency factor values of 1-day, 2 and 3 days durations

Our country often used the maximum value of the frequency factor from Hershfield's chart (K=15) for design of large hydraulic structures. The previous dam design of Ribb, Megech, and Gumara have overestimated the PMP value by 45, 42, and 29 percentages respectively (Abenezer and Dereje, 2015). The same procedure was adopted for the dams constructed on the Awash River basin such as Tendaho and Kessem dam and irrigation development (from design report). However, figure 4.1 shows that almost all stations have a frequency factor below six. This shows that the country constructed uneconomical hydraulic structures across the river basins.

However, Ethiopia uses Hershfield's frequency factor fifteen for estimating the PMP for all river basins. This paper indicates that using the frequency factor of 15 without a detailed study of estimating the PMP leads the country to construct uneconomical hydraulic structures. Hence, a suitable K value based on in-situ data of a particular study area would give good estimates of PMP than Hershfield's chart

The estimation of frequency factor using Hershfield's chart was constructed and the results show that all the stations have a value of the frequency factor around 15 and the maximum frequency factor obtained 16.75 at Ejersa Lele station of upper Awash River basin.

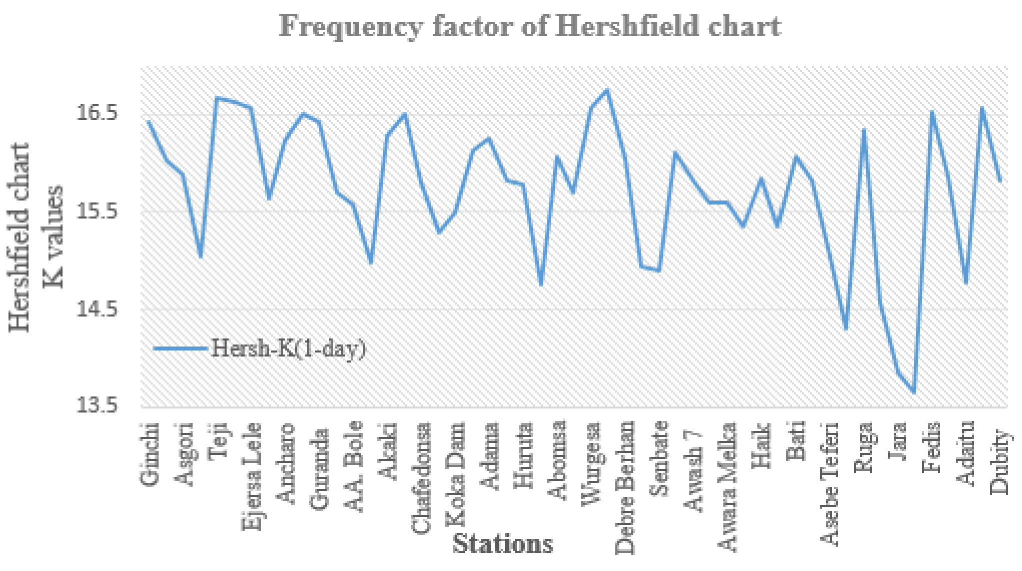


Figure 4.2: 1-day frequency factor from Hershfield's chart

The ratio value of the 1-day duration maximum frequency factor founded from Hershfield's chart to the basin-scale statistical method was more than double. It means that the frequency factor of the Hershfield chart increased by 63.6% over the basin scale. Therefore, in this basin, the frequency factor found from Hershfield's graphical procedure overestimates the actual value by 2.75 times.

Awash River basin has a smaller number of stations than the 2,645 stations that Hershfield (1965) used; hence, the frequency factor markedly depends on the number of stations. The enveloping curve specific for the Awash River basin is lower than the Hershfield curve, which was constructed using some of the highest precipitation producing regions with long-term records. The Hershfield enveloping curve seems to give higher values of frequency factor as the mean increases.

4.2. Computation of Probable Maximum Precipitation

Hershfield's (statistical) method of estimating PMP is a very valuable, common and reliable method for hydrologic design. The estimation of the PMP rainfall at a given area or location which is calculated from the distribution of the frequency fitted to the maximum rainfall records annually. The annual maximum rainfall data are usually used as a key variable in problems related to hydraulic structures design (Sammen *et al*., 2018).

In this study, daily rainfall data of 51 stations of the Awash River basin were taken with the adjusted values of the mean ($\bar{X}n$) and standard deviations Sn of the stations to estimate point PMP. The maximum frequency factor was also taken to estimate the probable maximum precipitation of the stations.

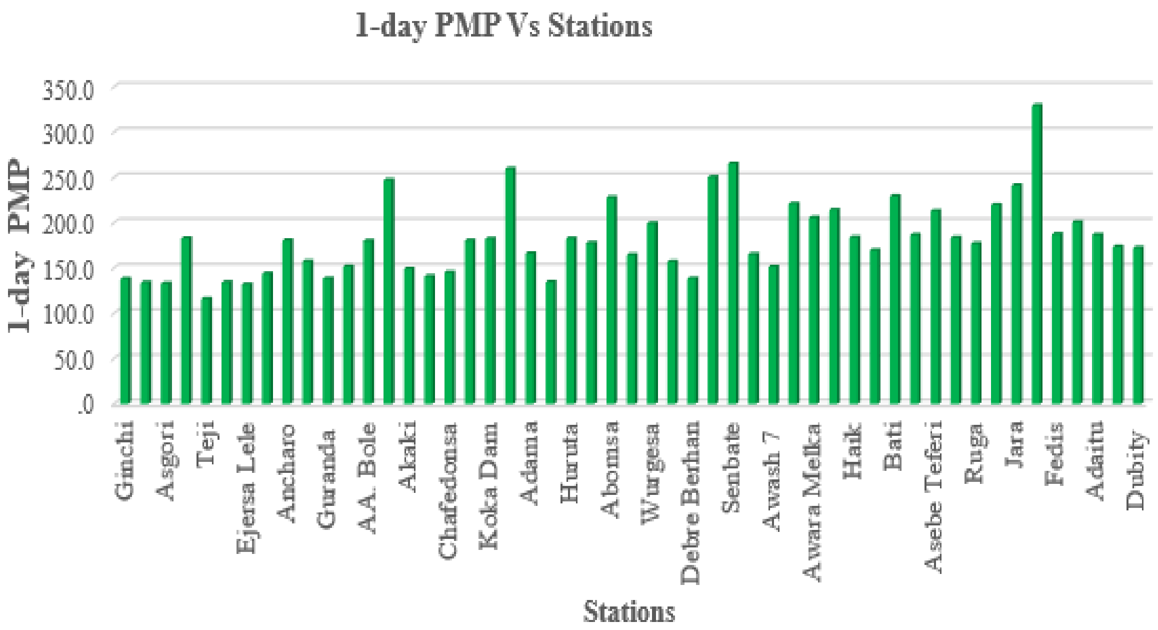
Table 4.2: Procedure to estimate the PMP at Awash 7 station

No	Descriptions	Symbol	Values
1	Station Name		Awash 7
2	Sample Size	N	38
3	Mean(mm)	$\bar{X}_n$	47.08
4	Standard Deviation(mm)	δ_n	14.14
5	Mean after excluding the maximum rainfall depth from the series(mm)	$\bar{X}_{n-1}$	45.90
6	Standard deviation after excluding the maximum rainfall depth from the series(mm)	δ_{n-1}	12.26
7	The ratio of 5 and 3	$\frac{\bar{x}_{n-1}}{\bar{x}}$	0.975
8	The ratio of 6 and 4	$\frac{\delta_{n-1}}{\delta}$	0.867
9	Adjustment of mean for the max. observed	From figure (3.2)	1.0272

10	Adjustment of mean for length of record	From figure (3.4)	1.007
11	Adjustment of St. dev. for the max. observed	From figure (3.3)	0.969
12	Adjustment of St. dev. for length of record	From figure (3.4)	1.0353
13	Adjusted mean(mm)	Mean adj.	48.70
14	Adjusted standard deviation(mm)	Std. dev. adj.	14.18
15	Frequency factor	Km	6
16	1-day probable maximum precipitation(mm)	1-day PMP	133.80
17	24 hrs probable maximum precipitation(mm)	1.13*daily PMP	151.19

The highest value of probable maximum precipitation for a 1-day duration was found at Awash 7 station with a value of 151.19mm. The PMP values for all stations of the Awash River basin using the basin-specific enveloping curve are shown below.

The PMP value increased at the Middle part of the Awash River basin. From the result, the maximum PMP value for 24-hr and 48-hr were 329.24 mm and 681.98 mm at Aliyu Amba and Nuraera station respectively. The 3 days rainfall duration maximum PMP value obtained at the upper portion of the river basin and the value was 796.98mm at Addis Ababa station.



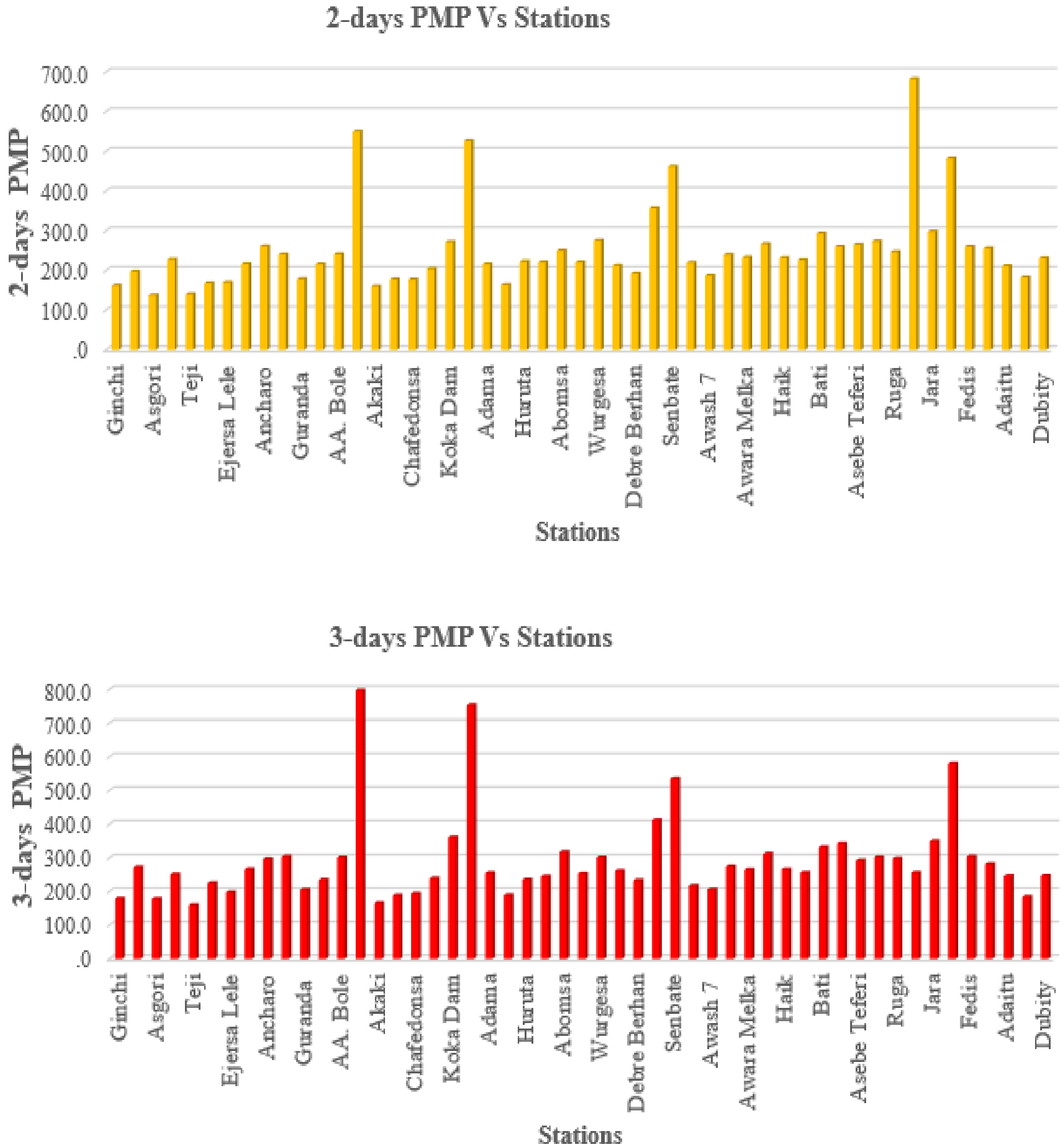


Figure 4.3: PMP of the 51 stations for 1-day, 2 and 3 days durations

To evaluate the frequency factor of Hershfield (1961) initially analyzed a total of 95, 000 station-years of annual maximum rainfall belonging to 2,645 stations of which about 90% were in the USA, and found that the maximum observed value was 15. Then, they decided that an estimate of the PMP values could be calculated by using K 15. However, in 1995, they proposed that the K value equal to 15 is not compatible for all areas in the USA. Therefore, they constructed a chart indicating that the K value varies between 5 and 20 depending on the rainfall duration and the mean (WMO, 2009).

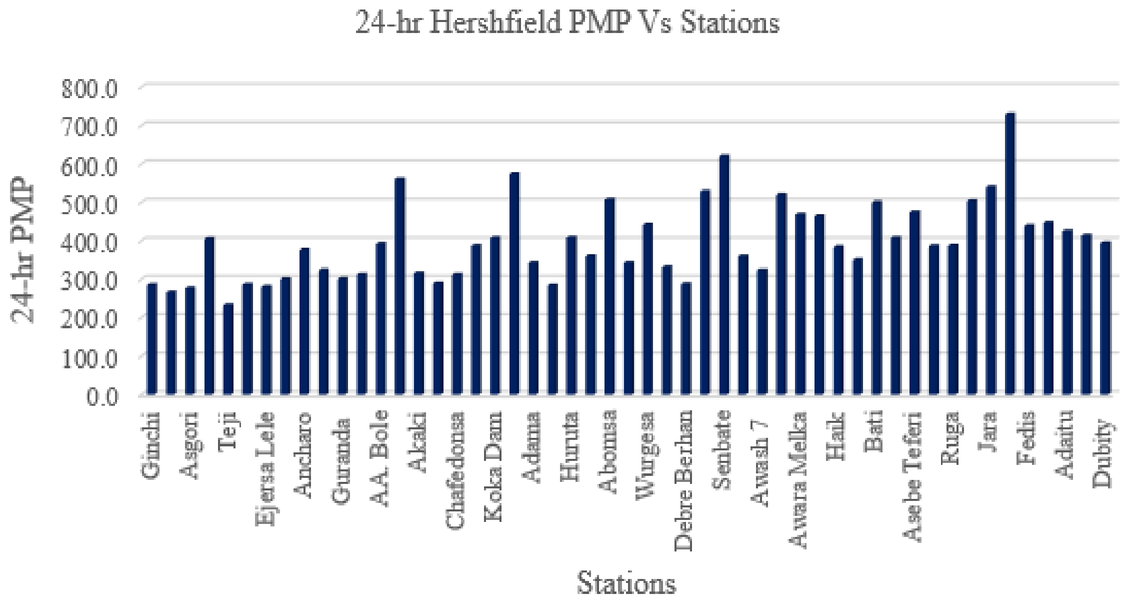


Figure 4.4:1-day duration PMP value obtained from Hershfield's chart

Different studies show that experts in Ethiopia have been using Hershfield's chart for estimation of PMP and their results indicate that Hershfield's graphical procedure is not well tested (Alemayehu and Semu, 2010). Estimation of PMP was made by both Hershfield's chart and Hershfield's frequency equation for 1-day duration and tried to give reasonable justification. For all stations of 1-day duration, probable maximum precipitation values obtained from Hershfield's chart are listed in appendix F and the Maximum 24 hr. Hershfield's chart of PMP was found 729.3mm

The maximum PMP value obtained using Hershfield's chart maximum frequency factor deviated around 138.4% from the PMP value obtained from the basin scale at Logia station. The deviation was between the ranges of 99.3% to 138.4%. The results indicated that the estimated value of probable maximum precipitation using the maximum frequency factor was around three times the PMP values obtained from Hershfield's frequency equations.

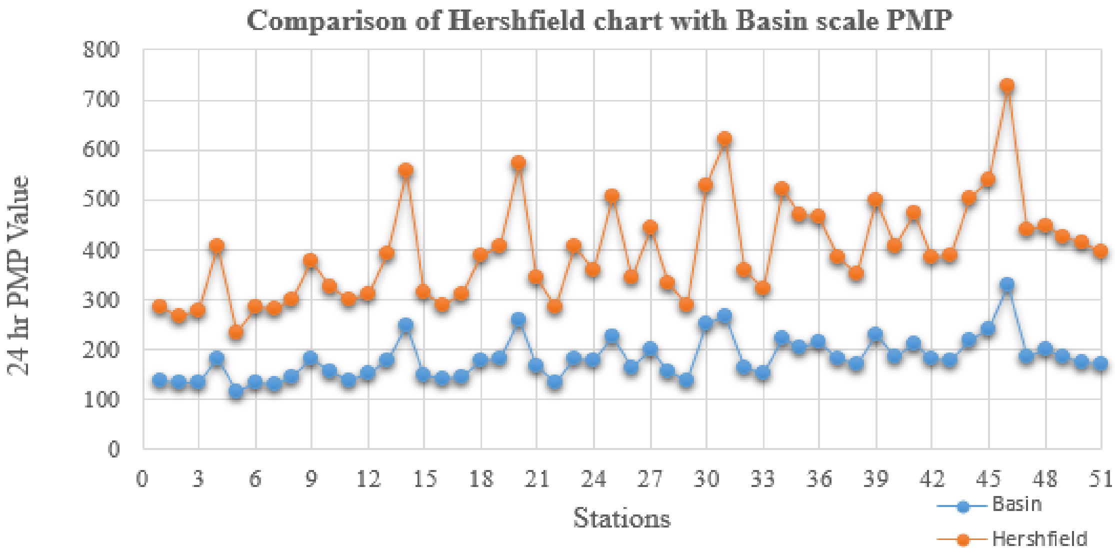


Figure 4.5: Comparison between Basin scales with Hershfield chart PMP

This large difference of PMP value obtained because of the difference in frequency factor from Hershfield's statistical procedure and Hershfield's chart and has a significant consequence in the total cost of dam projects when dam design is considered based on PMF. Therefore, high attention should be provided to the estimation of K values. Because of the frequency factor, a constant is very sensitive in estimating PMP.

4.3. Frequency Analysis

Hershfield method is the most frequently used (WMO, 1986 and 2009; Lan *et al*., 2017; Singh *et al*., 2018). Basically, this approach is a frequency analysis method; it is different from traditional frequency analysis methods in two important aspects. First, frequency analysis methods are used to determine the statistics of extremes, and this method involves the application of the process of enveloping. Second, it focuses on a wide region, rather than a single station or single watershed, in order to capture a storm that approximates the physical upper limit of precipitation (WMO, 2009).

In this study, comparing the result of 1-day, 2-day and 3-day point PMP with the rainfall events of 10,000 years return period is very important because the dimensions of the emergency spillways and the dam crest level designs depend on the criterion of 10,000 years return period flood.

Under frequency analysis :data preparation, selection of the best fit frequency distribution, estimation of parameters and calculating the magnitude of rainfall for 10,000 years return period were executed.

4.3.1. Probability Distribution

A three-step process similar to Olofintoye *et al*. (2009) was used to find the best-fit probability distribution for each station and different durations. It may be noted that our focus was on the right tail of the distribution where extreme precipitation occurs.

For each station and duration, the test statistic values of Kolmogorov Smirnov, Anderson Darling, and chi-squared were calculated for every distribution. For each of the three tests, the distributions were ranked according to the lowest test statistic value.

The distribution models which are suggested by WMO for annual maximum data series (Nguyen, T. H, *at al*., 2017) were: Normal distribution, Two parameters Log-Normal distribution, Three Parameter Log-Normal distribution, Exponential distribution, Two parameter Gamma distribution, Pearson three distribution, Log Pearson three distribution, Generalized extreme value distribution, Extreme value type one distribution, Weibull distribution, Four parameters Wakeby distribution and Five parameters Wakeby distribution.

In this study, Easy-Fit statistical computer software was used to select the best-fit distribution model of the stations. Table 4.3 shows that the best fit distribution for 1-day, 2-day, and 3-day maximum rainfall duration from easy–fit statistical computer software.

Table 4.3: Best fit distribution for 1-day, 2-days and 3-days maximum rainfall duration

S.No	Station	Duration		
		24-hr	48-hr	72-hr
1	Ginchi	Weibull (3P)	Weibull (3P)	Lognormal
2	Hombole	Lognormal (3P)	GEV	Lognormal
3	Asgori	GEV	Lognormal	GEV
4	Aleltu	GEV	GEV	GEV
5	Teji	Lognormal (3P)	GEV	Lognormal (3P)
6	Tulu Bolo	GEV	GEV	GEV
7	Ejersa Lele	Lognormal (3P)	Lognormal (3P)	Lognormal (3P)
8	Batu liben	GEV	GEV	Lognormal (3P)
9	Ancharo	GEV	GEV	Normal
10	Gunna	GEV	GEV	Normal
11	Guranda	GEV	Lognormal (3P)	GEV

12	Dengego	GEV	GEV	Lognormal (3P)
13	AA. Bole	Lognormal	Weibull (3P)	GEV
14	AA.Obs	Weibull (3P)	Lognormal (3P)	Lognormal (3P)
15	Akaki	Weibull	Lognormal (3P)	Lognormal (3P)
16	Debre Zeit	Lognormal (3P)	Lognormal (3P)	Lognormal (3P)
17	Chafedonsa	Weibull (3P)	GEV	GEV
18	Modjo	Lognormal (3P)	GEV	GEV
19	Koka Dam	Lognormal (3P)	GEV	GEV
20	Melkasa	Log-Pearson 3	Weibull	Exponential (2P)
21	Adama	GEV	Normal	Lognormal (3P)
22	Etheya	Lognormal (3P)	GEV	Weibull (3P)
23	Huruta	Lognormal (3P)	GEV	GEV
24	Welenchiti	GEV	GEV	GEV
25	Abomsa	Lognormal (3P)	Weibull (3P)	Lognormal
26	Makassar	GEV	Log-Pearson 3	Lognormal (3P)
27	Wurgesa	GEV	Log-Pearson 3	GEV
28	Ejere	GEV	Normal	Lognormal (3P)
29	Debre Berhan	GEV	GEV	Lognormal (3P)
30	Debre Sina	Lognormal	GEV	GEV
31	Senbate	Lognormal (3P)	GEV	GEV
32	Boru Meda	GEV	GEV	GEV
33	Awash 7	Normal	GEV	GEV
34	Melka Sedi	Lognormal (3P)	Lognormal (3P)	GEV
35	Awara Melka	Lognormal (3P)	Weibull (3P)	GEV
36	Majete	GEV	Lognormal	Lognormal (3P)
37	Haik	GEV	GEV	GEV
38	Combolcha	Lognormal (3P)	Lognormal (3P)	Lognormal
39	Bati	Lognormal	Lognormal	GEV
40	Artuma	GEV	GEV	GEV
41	Asebe Teferi	GEV	Lognormal (3P)	GEV
42	Merssa	Lognormal	GEV	GEV
43	Ruga	GEV	GEV	Log-Pearson 3
44	Nuraera	GEV	GEV	GEV
45	Jara	GEV	GEV	Log-Pearson 3
46	Aliyu Amba	Weibull	Lognormal	Lognormal
47	Fedis	GEV	Normal	GEV
48	Gewane	Weibull (3P)	GEV	Weibull (3P)
49	Adaitu	Weibull	GEV	Lognormal
50	Logya	GEV	GEV	Normal
51	Dubity	GEV	Lognormal (3P)	Lognormal (3P)

In many European countries, such as Austria, Germany, Italy, and Spain, the GEV distribution was recommended to provide the best fit to flood data analysis (Salinas, J. L *at al*., 2014). As the result indicates that majority of the station in the basin was fitted with generalized extreme value distribution. The average GEV distribution model coverage on the Awash River basin was about 50.33%.

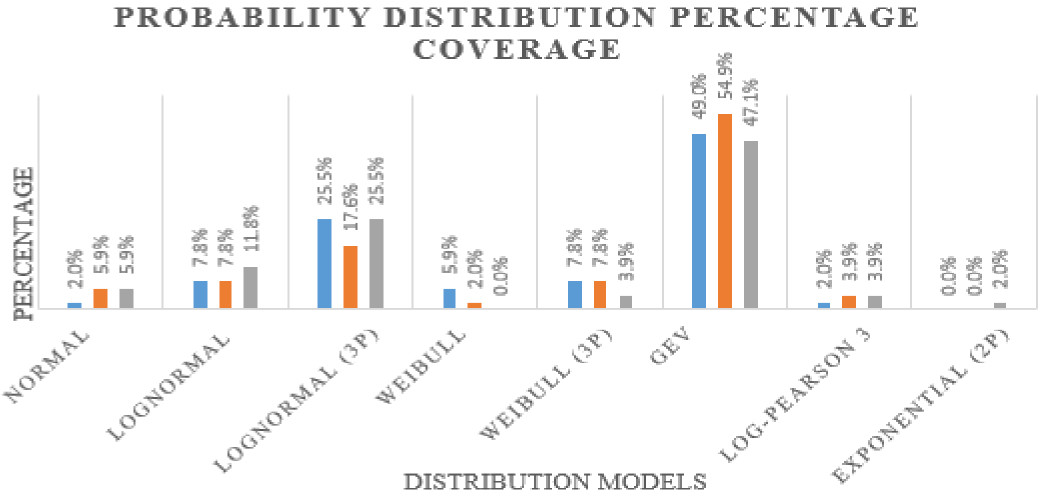


Figure 4.6: Probability distribution percentage coverage of the river basin

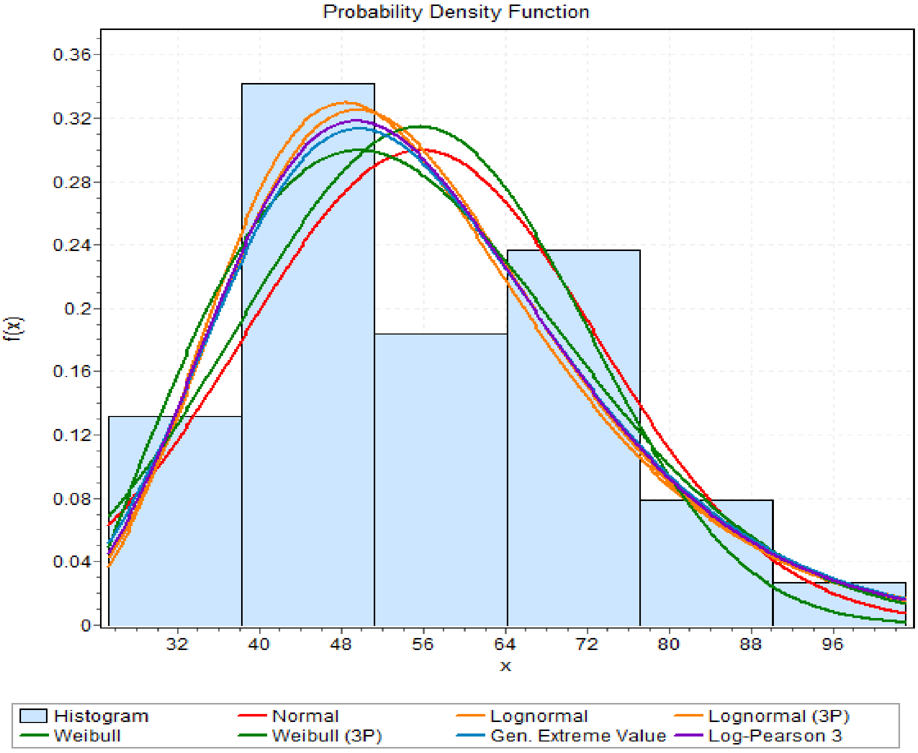
4.3.2. Parameter Estimation

Numerous methods can be used for parameter estimation in easy-fit statistical software; the most common methods are the method of moments (MOM), the method of maximum likelihood (MML), and the L-moment method (LMM). In the study, the parameter estimations were estimated by excel helper software (easy-fit) and the results are shown in Appendix G.

Table 4.4: Estimated parameters of GEV distributions for Asgori station

Name of Stations	Selected Distributions	Parameters	Value
1-day duration			
Asgori	Generalized Extreme Value	K	0.18601
		σ	7.321
		μ	39.551
2-day duration			
Asgori	Generalized Extreme Value	K	-0.05658
		σ	9.524
		μ	54.723
3-day duration			
Asgori	Generalized Extreme Value	K	-0.10928
		σ	13.796
		μ	64.873

The probability density function (PDF) or density of a continuous random variable is a function whose value at any given sample (or point) in the sample space. The result of PDF at Awash 7 station with the most selected distribution model and Goodness of fit summary was shown as below.



Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.07408	2	0.16588	2	1.0171	1
3	Lognormal	0.08512	6	0.186	5	1.3837	2
4	Lognormal (3P)	0.08184	4	0.182	4	2.4708	3
2	Log-Pearson 3	0.07698	3	0.16684	3	2.6477	4
6	Weibull	0.08246	5	0.47245	7	3.022	5
7	Weibull (3P)	0.06781	1	0.15995	1	3.1276	6
5	Normal	0.09748	7	0.35692	6	3.1558	7

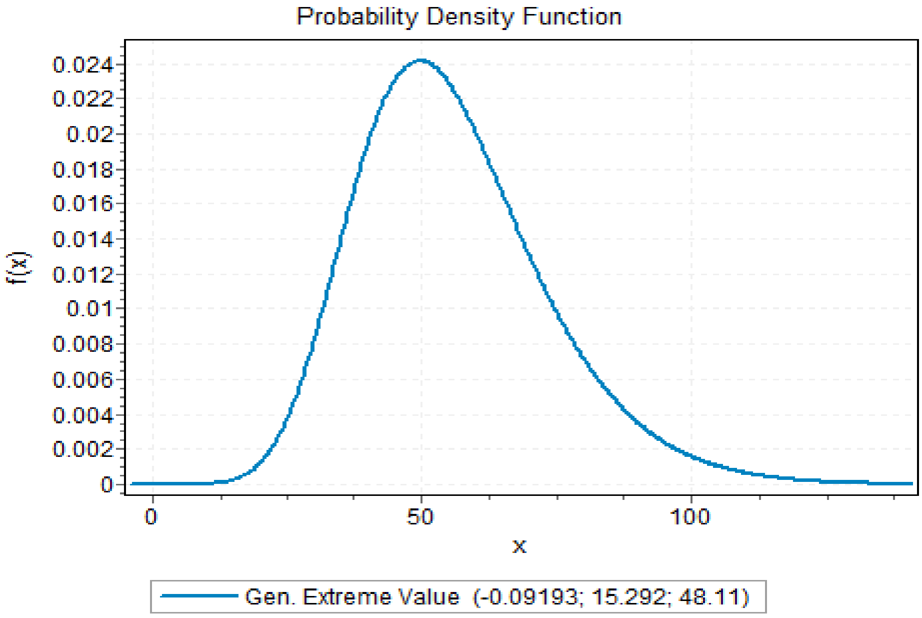


Figure 4.7: PDF and Goodness of fit for Awash 7 station

Goodness-of-fit test statistics are used for checking the validity of a specified or assumed probability distribution model. A well-known three-parameter distribution for maxima in the GEV are a shape k, a scale σ and a location μ parameters.

4.3.3. Estimation of Return Period and comparison with PMP Values

The frequency of extreme events such as precipitation and floods can be expressed in terms of the "return period," also known as the "recurrence interval." In extreme value analysis, the return period is defined as the average length of time between events of the same magnitude or greater. It is derived from quantiles of a parametric probability distribution fitted to the extreme values of the recorded data (Alam *et al*., 2018).

From the study result, GEV was the best-fit distribution for the station used in the river basin and then estimate the magnitude of 1-day, 2-days and 3-days rainfall durations for 10,000 years return period for the design of the dam crest level and the emergency spillway dimension.

The results of estimated extreme rainfall magnitude from observed daily maximum rainfall for all the stations of 1-day, 2-days, and 3-days rainfall durations in the river basin are shown in appendix H for different year return periods.

Table 4.5: Estimated rainfall depth for Aliyu Amba station

Return Period	Estimated rainfall depth for Aliyu Amba station		
	1-Day	2-Days	3-Days
2	88.35	118.20	136.81
5	117.45	160.98	191.57
10	136.71	189.31	227.84
25	161.05	225.11	273.65
50	179.10	251.66	307.64
100	197.02	278.02	341.38
200	214.88	304.28	374.99
500	238.44	338.93	419.34
1000	256.24	365.11	452.86
2000	274.04	391.29	486.36
5000	297.56	425.88	530.64
10000	315.35	452.05	564.14

For any hydraulic structure, the critical flood peaks to be designed mostly based on the extreme rainfall events with the return period of 10,000 years (Haktanier, Cobaner, and Kisi, 2010). As shown in the above table at Aliyu Amba station 10,000years, return period of 1, 2 and 3 days was 315.35, 452.05 and 564.14mm respectively.

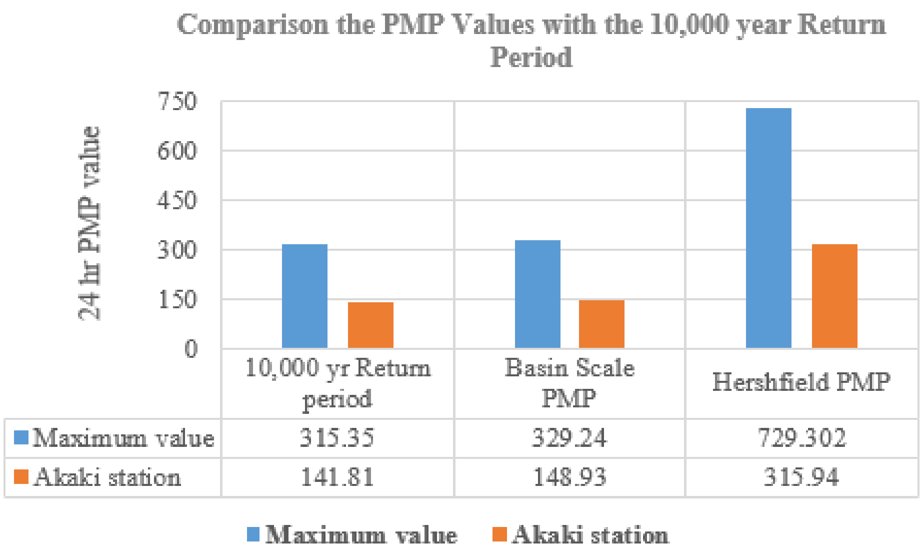


Figure 4.8: Comparison the PMP values with the 10,000-year return period

The maximum value of 10,000 years return period rainfall depth for 1-day at Aliyu Amba station was 315.35mm. It means that the value was relatively the same with a basin-scale of

329.24mm. The PMP value founded from Hershfield's statistical procedure was around 2.22 and 2.31 times that of basin-scale and 10,000 years return period rainfall depth for 1-day respectively.

4.3.4. Spatial Distribution of K and PMP

Spatial distribution describes how spread out a population is (what area it occurs in), while population density describes how many individuals are found in a given area. The inverse distance weighting (IDW) is one of the Interpolation Method to estimate an unknown value at a location using some known values with corresponding weighted values. 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.

With Frequency factor point estimation of basin-scale for 24-hr, 48-hr, 48-hr, and 24-hr Hershfield were interpolated using the inverse distance weighting method in Arc-GIS map, and the spatial distribution of Hershfield and basin-scale results were highly consistent, because the main cause of the difference in PMP values was K, while the pattern of enveloping curves of K was consistent, even though the magnitudes were different.

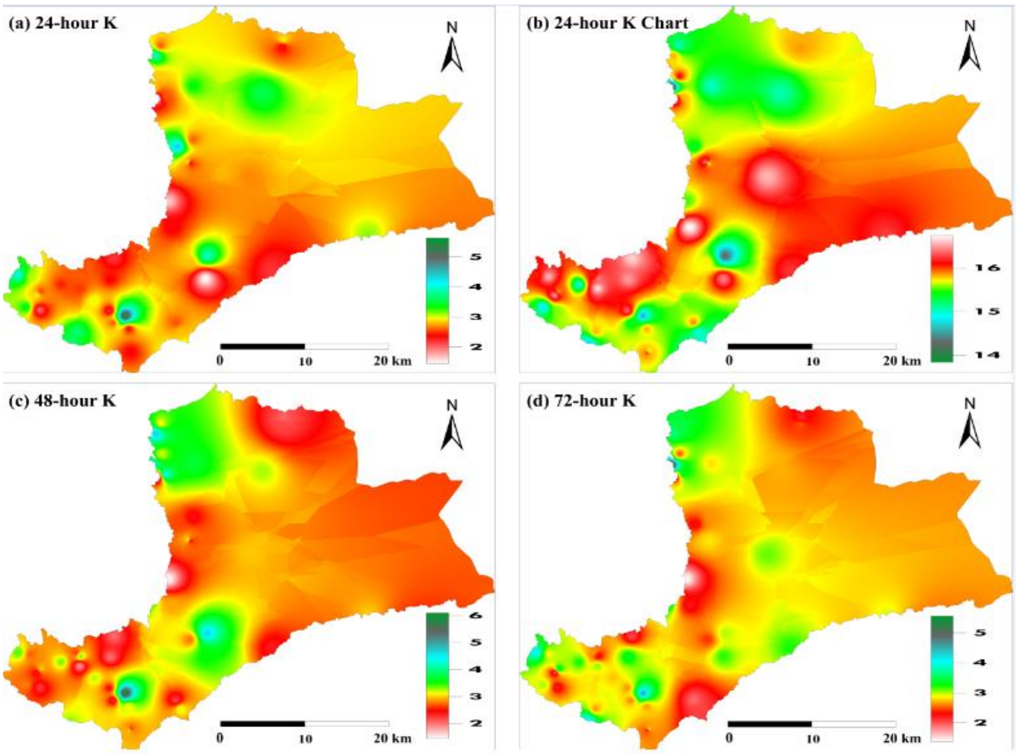


Figure 4.9: Spatial distribution of K maps values in Awash River basin

The Probable Maximum Precipitation values of basin scale of 1- day, 2, 3-days and 1-day of Hershfield chart also showed similar trends. As shown in figures 4.9 and Figure 4.10 spatial distribution of K and PMP maps values in Awash River basin for the Hershfield 1-day duration and basin-scale for different durations.

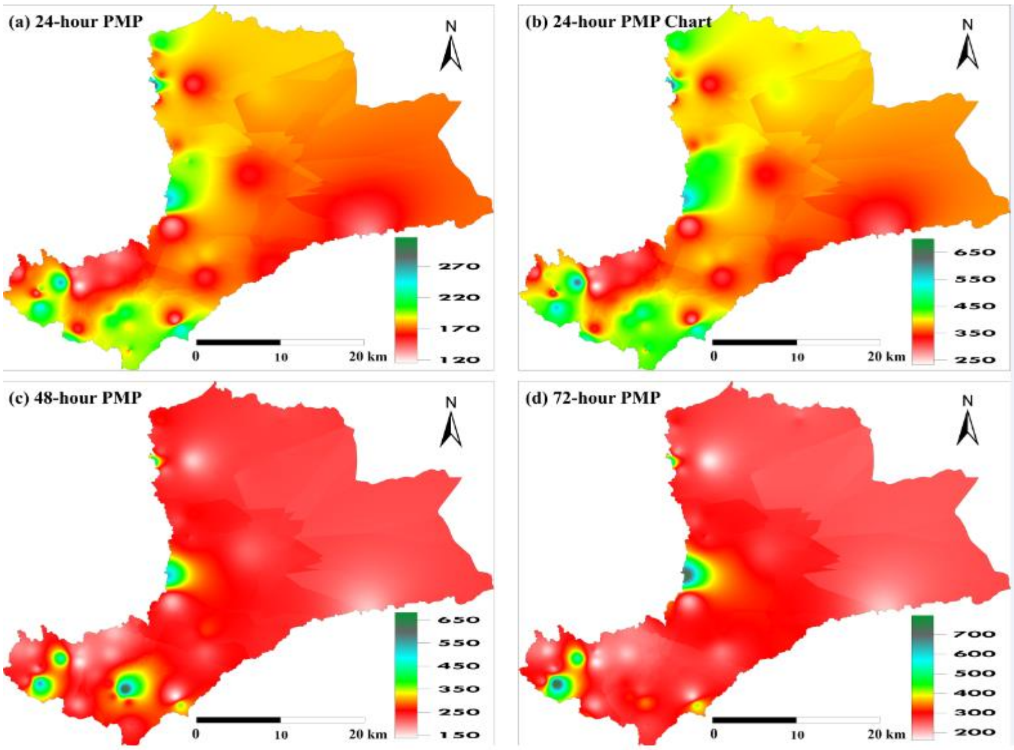


Figure 4.10: Spatial distribution of K and PMP values in Awash River basin

4.4. Uncertainty Analysis of PMP

Basin-scale probable maximum precipitation quantified uncertainties caused by K, $\bar{X}_n$, and Sn of the annual maximum rainfall series, and K values were calculated from the basin enveloping curve. Two methods used to quantified uncertainties in PMP are Salas method and Bootstrap Method.

4.4.1. PMP Uncertainty Estimated Using Salas Method

Basin-scale method quantified uncertainties caused by K, $\bar{X}_n$ and Sn without making any assumptions about distributions of the annual maximum rainfall series, and K values were calculated from the basin enveloping curve. Salas method used Hershfield K enveloping curve and assumed normally distributed rainfall series. Determine the variance of PMP and then used Chebyshev's inequality to probabilistically state to obtain the value of PMP with uncertainty. Salas *et al*. (2014) was quantified the uncertainty in the Hershfield method, which provided a way to consider the PMP uncertainty in the statistical method. They assumed K as a constant, which caused no uncertainty (in actuality K is not constant and was cause uncertainty).

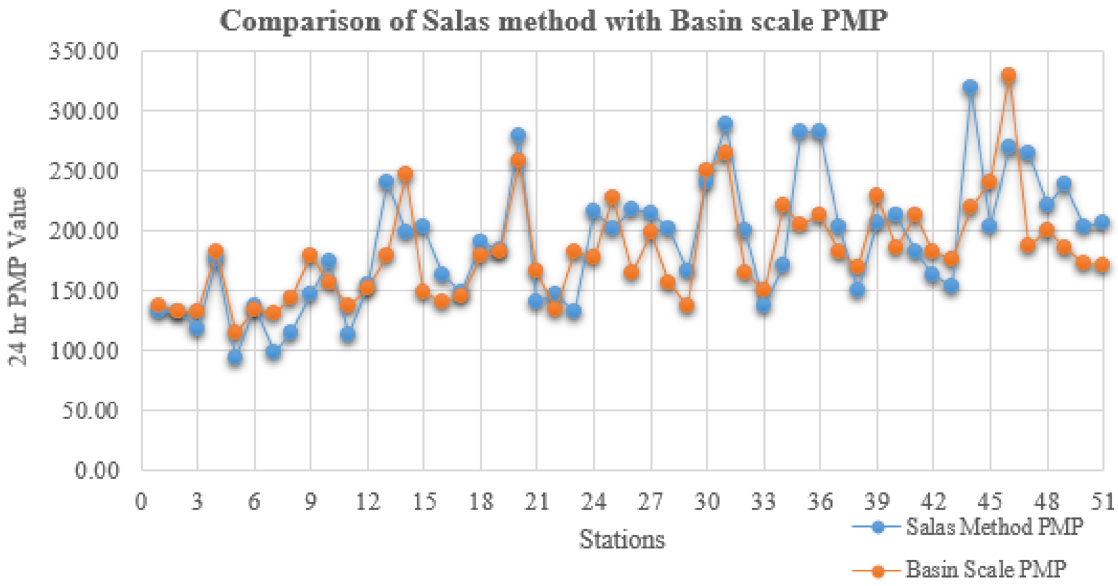


Figure 4.11: Comparison of Salas Method and Basin scale PMP

Where the maximum PMP uncertainty obtain value compared Basin scale method with Salas method was 329.24mm and 269.55mm and it deviated by 18.13%.

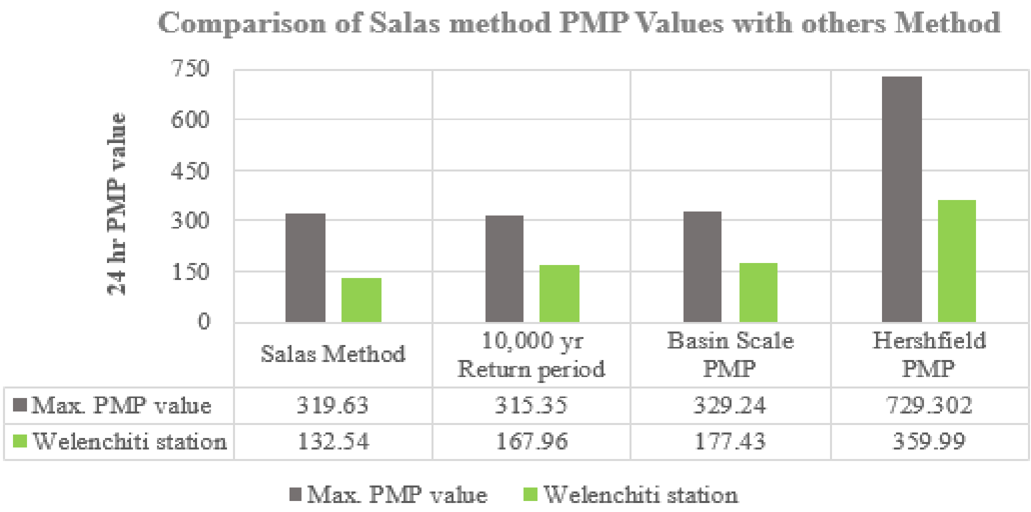


Figure 4.12: Comparison of Salas Method PMP with other methods

For different values of m the design risk PMP P_d were calculated. With m =1 and +sign $P_d = E(\hat{P}) \pm m\sigma(\bar{P})$ it gave P_d = 319.63 mm. The value of m = 3 which was a more conservative estimate than using m =1and gave the value of P_d = 329.6 mm. The Hershfield's chart and basin-specific enveloping curve method the PMP estimate was 729.3mm and 329.24mm.

Table 4.6: Comparison of Hershfield, Basin scale and Design Risk PMP value for 24-hr duration (mm)

Hershfield's PMP	Basin scale PMP	Design Risk PMP using $P_d = E(\hat{P}) \pm m\sigma(\bar{P})$		
		m= 1	m= 2	m= 3
729.3	329.24	319.63	324.01	329.6

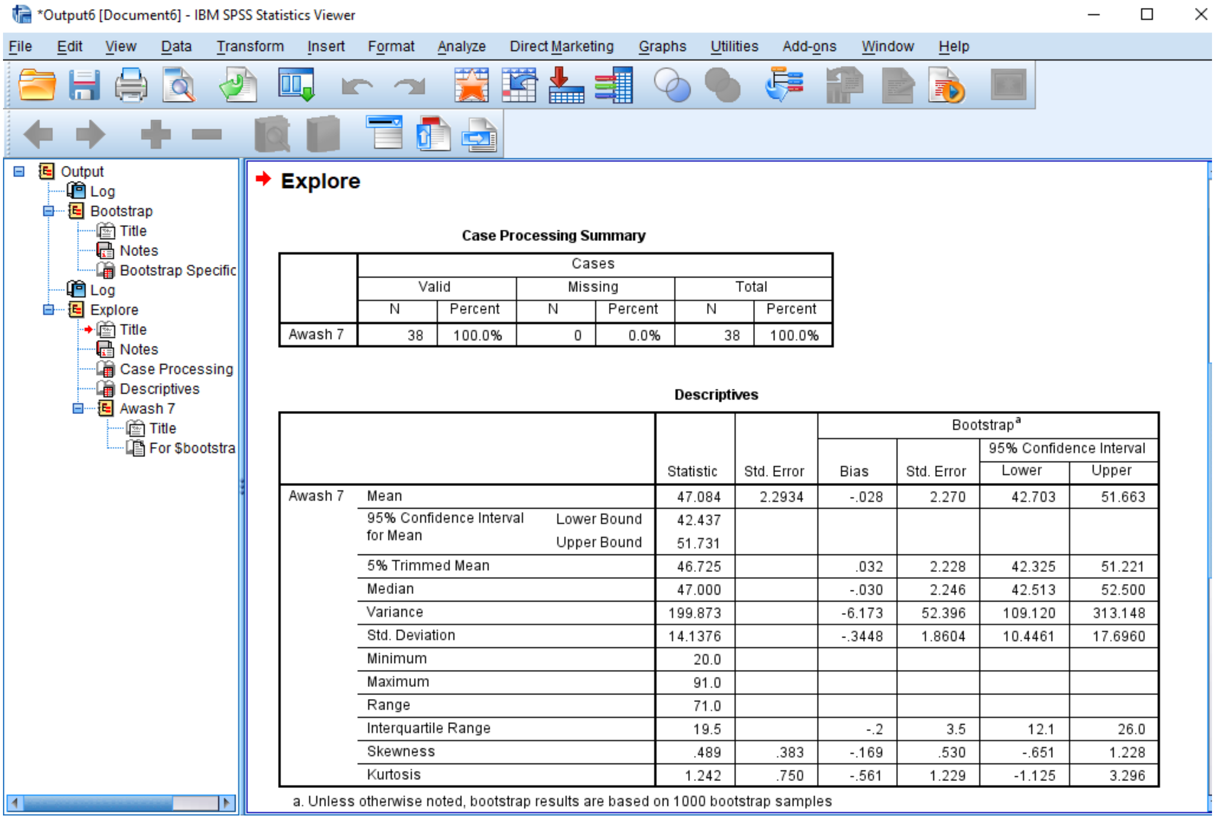
As a results showed the design risk PMP more conservative estimate with m =3 and basin specific PMP value which was P_d = 329.6 mm and 329.24mm have almost all the same values. It can be concluded that a bigger value of PMP must be selected, considering the associated exceedance probabilities (risk) of PMP, which was very far from Hershfield's chart of PMP 729.3mm.

4.4.2. PMP Uncertainty Estimated Using Bootstrap Method

Bootstrap method the method that explore the distribution of K and PMP at each station, by resample the data from original observations. 1,000 resamples were generated for each station's data, which led to 1,000 PMP values for each station. Thus, PMP frequency analysis was done through 51 stations for each duration.

The results of the standard error of PMP was calculated by open sources IBM SPSS and R-statistics method. As duration became longer, the standard error tended to be bigger, because the PMP values also followed the same pattern.

The average differences between the Salas values and bootstrap values and between the Basin scale values and bootstrap values for 24hr duration were 18.4% and 15.2%, respectively. The average percentage of standard error of the PMP estimate for the basin-scale method for 24-hr durations was 13.77%.



Explore

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Awash 7	38	100.0%	0	0.0%	38	100.0%

Descriptives

					Bootstrap[a]			
							95% Confidence Interval	
			Statistic	Std. Error	Bias	Std. Error	Lower	Upper
Awash 7	Mean		47.084	2.2934	-.028	2.270	42.703	51.663
	95% Confidence Interval for Mean	Lower Bound	42.437					
		Upper Bound	51.731					
	5% Trimmed Mean		46.725		.032	2.228	42.325	51.221
	Median		47.000		-.030	2.246	42.513	52.500
	Variance		199.873		-6.173	52.396	109.120	313.148
	Std. Deviation		14.1376		-.3448	1.8604	10.4461	17.6960
	Minimum		20.0					
	Maximum		91.0					
	Range		71.0					
	Interquartile Range		19.5		-.2	3.5	12.1	26.0
	Skewness		.489	.383	-.169	.530	-.651	1.228
	Kurtosis		1.242	.750	-.561	1.229	-1.125	3.296

a. Unless otherwise noted, bootstrap results are based on 1000 bootstrap samples

Figure 4.13: Bootstrap method for explore the distribution

As shown in the above figure 4.13 the standard error of mean obtained at Awash 7 station 2.2934mm and the upper limit 95% confidential interval mean become 51.663mm were the statistic one was 47.084mm. The bootstrap mean can increase the basin scale for the Awash 7 station by 8.9%.

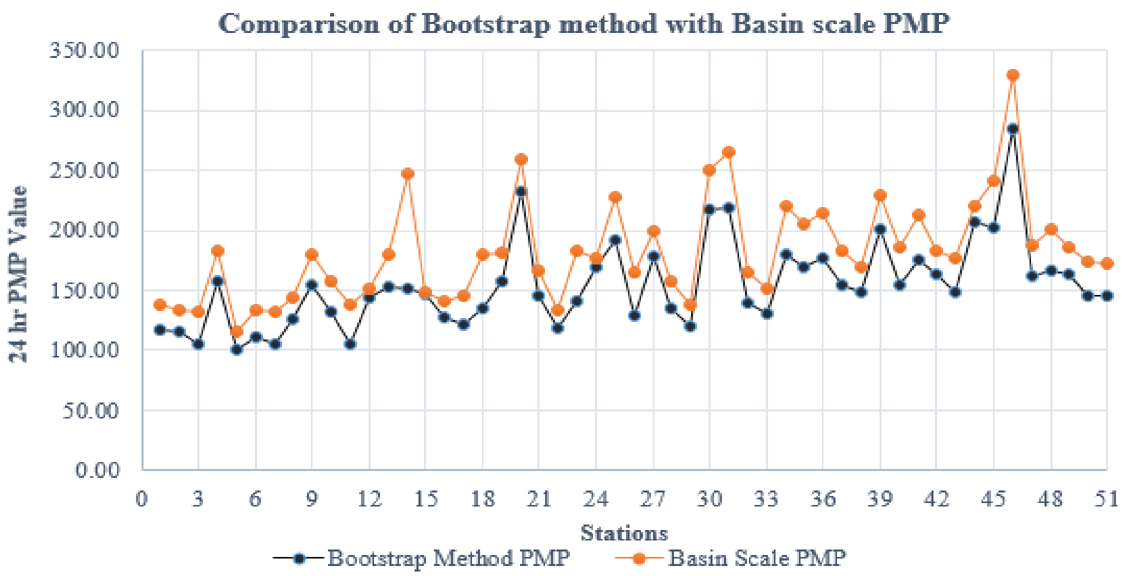


Figure 4.14: Comparison of Bootstrap Method and Basin scale PMP

The differences in PMP values with respect to the bootstrap PMP values, the Salas PMP values, Basin scale PMP value, 10,000 yr. return period and Hershfield PMP values for 24 hr. duration were 11.18%, 9.98%, 13.77% and 61.07% respectively. The difference between design risk PMP value and bootstrap PMP were also around 13.87%, which was the same with basin scale PMP values.

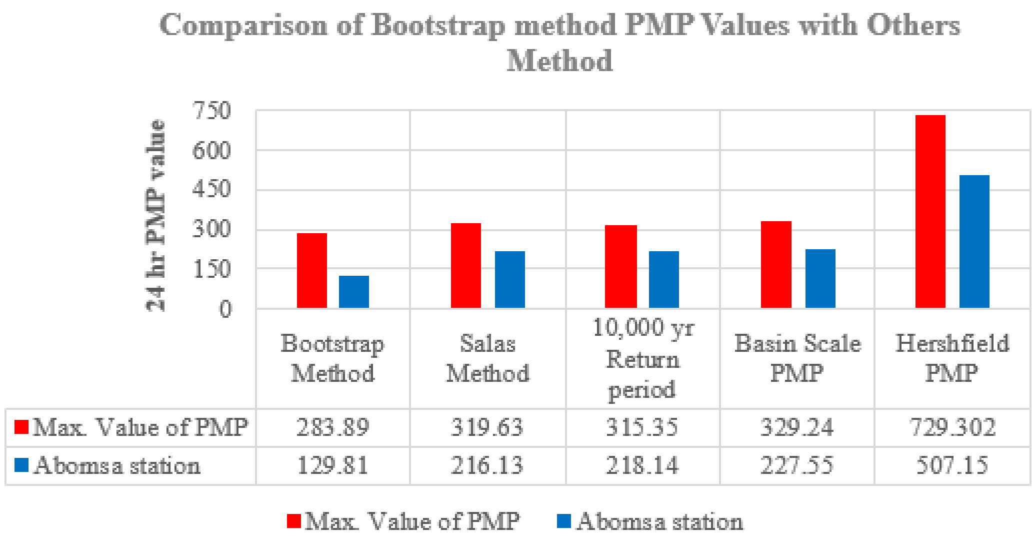


Figure 4.15: Comparison of Bootstrap Method PMP with other methods

4.4.3. Comparing the PMP values of Some Dam Design Trend with Study Results

The design of Ribb dam and irrigation development was one of the case that PMF was determined by convoluting the PMP. The Debre Tabor station with 24, 48 and 72 hours maximum annual rainfall depth values in the period 1951–2004 were the basis for the evaluation of the 24, 48 and 72 hours PMP values. These values were determined using the Hershfield method (WMO, 1986, No.332). As per design report, the design hydrograph to determine the emergency spillway width was adopt 1-day ½ PMF of 1060 m3/s.

According to the ECDSWC Water and Energy Design and Supervision Works Sector, design report on December 2016 of Upper Guder Multipurpose Project that has 4,947 ha sprinkler irrigation system from Fato dam, and 18MW hydropower scheme supplied by Belo dam. Fato dam was designed with spillways capable for pass extreme floods that determined from the PMP which was estimated based on Hershfield’s procedure and derived PMP was converted to runoff based on the UH developed by Snyder’s method convolution procedures. PMF peak of 353.49m3/s was found at 17 hours duration and 1/2PMF was adopted to spillway design flood.

As per the Oromia Water Works Design and Supervision Enterprise design report of August 2018, the hydrological analysis for the Gololcha dam was undertaken to be primarily used for the design of the proposed dam. The probable maximum flood (PMF) was also determined from the probable Maximum Precipitation (PMP), which was estimated based on Hershfield's procedure (k = 15). The derived PMP was converted to runoff using the unit hydrograph convolution procedures.

Different approaches were consulted for the selection of the design flood. The USACE, USDA and Ethiopian Draft Dam Safety Guideline prepared ETCOLD. For Gololcha dam, the draft guideline proposed by ETCOLD was adapted. Accordingly, the inflow design flood (IDF) adapted was a 1,000years return period with a peak discharge of 547.4m3/s and safety checked flood (SCF) of 10,000years return period or 1/2PMF.

The other dam proposed on Awash River basin was Middle Awash Multi-Purpose Dam, which located in Afar and Oromia National Regional State, around Awash town, mainly used for flood control and to supply water for middle Awash irrigation development schemes water for the existing command area in Amibara irrigation project and for potential land of around 40,000 ha (ECDSWC, January 2016).

Peak flood flow to the dam site was determined using the statistical analysis software and the daily maximum annual series was abstracted from the daily flows obtained. The flood frequency analysis based upon the 35 annual daily maximum flow series and fitting the best probability distribution with General extreme value distribution function was analysed. Standardized flood quantiles of different return period has been derived.

The Probable Maximum Flood was also determined from the Probable Maximum Precipitation, which was estimated based on Hershfield's procedure. The derived PMP was converted to runoff using the HEC-HMS to determine the PMF. The 10,000 year return period flood peak estimated by the flood frequency analysis using GEV was 4,483.6m3/s. Accordingly, as per design report, the design hydrograph to determine the emergency spillway width adopt PMF of 12,844.5 m^3/s and they adopt the exercise of the worst scenario i.e. PMF when Koka dam is breached.

Finally, the PMF value exceed the 10,000yr return period by 65.1%. This huge number of difference occur due to the difference obtained in frequency factor. Therefore, the embedded K value should be update with site-specific data to design the reliable PMP value in River basin.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

One of the most problems in the estimation of reliable probable maximum precipitation (PMP) for different durations that are expected to occur over a point or an area. These estimates are of considerable importance to hydrologists for calculating the probable maximum flood (PMF) for planning, design, and risk assessment of hydrological structures such as flood control dams upstream of populated areas, and spillways on large dams.

The purpose of this study was to evaluate the basin-specific enveloping curve of the frequency factor for the Awash River basin, calculate the Probable Maximum Precipitation values, and determine the associated uncertainty for different durations and locations. In this study, 51 stations were used to estimate new PMP based on the statistical procedure. The methodology chosen for the study area was the statistical method developed by Hershfield (1961, 1965) to estimate PMP based on a general frequency equation given by Chow (1951) for estimating PMP but the statistical value results of the basin were used instead of the Hershfield's chart to determine the values of frequency factor embedded with the equation. The comparison of the K value obtained from basin-specific enveloping curve and the Hershfield's chart was far from each other. While most of the K values obtained from the chart varies from 13.65 to 16.75 the maximum K value obtained using the statistical method for 1-day, 2 and 3 days' durations varies from 1.4 to 6.1.

A similar procedure applied in the world like the USA (Lee, K., and Singh, V. P. 2020) on Brazos River basin, Texas, China (Desa *et al*., 2001 and M.N. Desa *et al*., 2003) and Boota, M. *et al*. (2015) on Potwar region, Pakistan to validate the K value obtained from the chart proved similar trend of lower value. The maximum PMP values estimated from the statistical method for 1-day, 2-day, and 3-day durations were 329.24mm, 681.98mm, and 796.95mm observed at Aliyu Amba, Nuraera, and Addis Ababa Obs. stations respectively and were the 1-day Hershfield chart PMP value 729.3mm. The maximum PMP value obtained using Hershfield's chart maximum frequency factor deviated around 138.4% from the PMP value obtained from the basin scale at Logia station. The deviation was between the ranges of 99.3% to 138.4%.

Frequency analysis was done by commonly used probability distributions, 3 GOF tests, and using the PDFs of the distributions. The generalized extreme value distribution (GEV) performed a better distribution model with coverage of 50.33%. The maximum estimated extreme rainfall magnitude from observed daily maximum rainfall for 10,000 years return period for 1-day, 2-day, and 3-day durations were 315.35mm, 641.39mm, and 786.02mm respectively.

Uncertainty was also quantified in PMP estimate which caused by K, Xn, and Sn, in the Hershfield method. The Salas method and Bootstrap method were used to quantify the uncertainties. The maximum PMP values by salas and bootstrap method of 24-hour durations were 319.63 mm and 283.89 mm. The maximum design risk PMP with conservative estimation 329.6 mm, which was all almost, have the same values with basin-scale PMP of 329.24mm and very far from Hershfield's chart of PMP 729.3mm.

Inaccuracy in PMP estimates results in similar inaccuracy in PMF determination, a risk-based approach to hydraulic design criteria, overestimation of which also results in unwanted economic loss. So far in Ethiopia, the frequency factor used for the PMP estimate was made using Hershfield's chart, but the result of this study shows that these PMP estimates were considerably high and were not, therefore, economical. Fresh and reliable estimates are made through this study for the Awash River basin.

5.2. Recommendations

According to the results of this study, the following points are recommended:

- Further researches like other country, should be conducted on the rest of basins of Ethiopia for fixing the country's reliable frequency factor (k).
- Rather than fix the embedded value of frequency factor it is good to make a range, its better use depend on the basin envelop curve.
- Different country in the world uses physical (storm maximization) model to get reliable PMP values because it needs more site specific data. Therefore, like other country, further research should be conducted on river basins of Ethiopia on the application of this model and compare the result with the values founded from statistical based model.
- The probable maximum flood is a powerful tool for practical purposes of water resource developments like in design of spillways to avoid the overtopping 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.

REFERENCES

Abenezer, E., & Dereje, H. (2015). Estimation of Probable Maximum Precipitation (PMP) using In-situ and Reanalysis global precipitation product (A case study on upper Blue Nile Basin. Thesis submitted to the school of graduate studies of Addis Ababa University.

Alam, M. A., Emura, K., Farnham, C., & Yuan, J. (2018). Best-fit probability distributions and return periods for maximum monthly rainfall in Bangladesh. Climate, 6(1), 9.

Alaya, M. B., Zwiers, F., & Zhang, X. (2018). Probable maximum precipitation: Its estimation and uncertainty quantification using bivariate extreme value analysis. Journal of Hydrometeorology, 19(4), 679-694.

Anderson, I. and Raska, C., 1999. Dam safety guidelines by the Canadian Dam Association.

Bekele, D., Alamirew, T., Kebede, A., Zeleke, G., & Melese, A. M. (2017). Analysis of rainfall trend and variability for agricultural water management in Awash River Basin, Ethiopia. Journal of Water and Climate Change, 8(1), 127-141.

Beauchamp, J., Leconte, R., Trudel, M., & Brissette, F. (2013). Estimation of the summer-fall PMP and PMF of a northern watershed under a changed climate. Water Resources Research, 49(6), 3852-3862.

Birhan, T & Yilma, S. (2017). Estimation of Probable Maximum Precipitation (PMP) (Case Study on Upper Awash Sub River Basin) Thesis submitted to the school of graduate studies of Addis Ababa University.

Boota, M. W., Nabi, G., Abbas, T., Jin, H., Yousaf, A., & Boota, M. A. (2018). Comparative study of probable maximum precipitation and isohyetal maps for mountainous regions, Pakistan. Sciences in Cold and Arid Regions, 10(1), 55-68.

Boota, M. W., Nabi, G., Ahsan, H., & Abbas, T. (2015). Estimation of probable maximum precipitation for one-day duration: A case study of Gujjar Khan in Potwar region, Pakistan. Journal of Himalayan Earth Sciences, 48(2), 148.

Casas Castillo, M., Rodríguez Solá, R., Gázquez, A., & Redaño Xipell, Á. (2010). Estimation of the probable maximum precipitation in Barcelona (Spain). International journal of climatology.

Casas. MC, Rodriguez R, Nieto R, et al. The Estimation of Probable Maximum Precipitation: The Case of Catolonia. Annals of the New York Academy of Sciences. 2008; 1146:291–302.

Casas. M.C., Rodriguez, R., Redano, A., Prohom, M., and Gazquez, A. (2011). “Estimation of the Probable Maximum Precipitation in Barcelona (Spain)”. International Journal of Climatology, 10.1002.

Cejka, J., Mood, D. W., & Su Kim, C. (1974). Immunoglobulin concentrations in sera of normal children: quantitation against an international reference preparation. Clinical chemistry, 20(6), 656-659.

Chow, V.T., Maidment, D.R., and Mays, L.W. 1988. Applied Hydrology, McGraw Hill Book, Co., New York

Chow, V.T. (1951). “A General Formula for Hydrologic Frequency Analysis.” Transactions-American Geophysical Union, 32, 231-237

Desa, M. N., Sharifuddin, S., & Rakhecha, P. R. (2003). Estimating probable maximum precipitation in the Malaysia State of Kelantan-Int. J. Water Power and Dam Construction, November Issue, 36-39.

Douglas, E. M., & Barros, A. P. (2003). Probable maximum precipitation estimation using multifractals: application in the eastern United States. Journal of Hydrometeorology, 4(6), 1012-1024.

Edossa, D. C., Babel, M. S., & Gupta, A. D. (2010). Drought analysis in the Awash river basin, Ethiopia. Water resources management, 24(7), 1441-1460.

Ethiopian Construction Design and Supervision Works Corporation (January 2016) Middle Awash Feasibility Study and Detail Design of Multipurpose Dam Project, Detail Design Reports.

Ethiopian Construction Design and Supervision Works Corporation (December, 2016) Upper Guder Multipurpose Project, Detail Design Reports.

Fattahi, E., Noorian, A. M., & Noohi, K. (2010). Comparison of physical and statistical methods for estimating probable maximum precipitation in southwestern basins of Iran.

Fernando W.C.D.K., Wickramasuriya S.S. The hydro-meteorological estimation of probable maximum precipitation under varying scenarios in Sri Lanka. Int. J. Climatol. 2011; 31:668–676. doi: 10.1002/joc.2096.

Fikre, A., Quraishi, S., & Bezabih, B. (2016). Development of One-Day Probable Maximum Precipitation (PMP) and Isohyetal Map for Bale Zone, Oromiya Region, Ethiopia. Development, 8(12).

García-Marín, A. P., Estévez, J., Morbidelli, R., Saltalippi, C., Ayuso-Muñoz, J. L., & Flammini, A. (2020). Assessing inhomogeneities in extreme annual rainfall data series by multifractal approach. Water, 12(4), 1030.

Gedefaw, M., Wang, H., Yan, D., Song, X., Yan, D., Dong, G., & Qin, T. (2018). Trend analysis of climatic and hydrological variables in the Awash river basin, Ethiopia. Water, 10(11), 1554.

Hailu, R., Tolossa, D., & Alemu, G. (2018). Water institutions in the Awash basin of Ethiopia: the discrepancies between rhetoric and realities. International journal of river basin management, 16(1), 107-121.

Hanssen-Bauer, I., & Førland, E. J. (1994). Homogenizing long Norwegian precipitation series. Journal of Climate, 7(6), 1001-1013.

Hao Z, Singh VP. Entropy–based Method for Extreme Precipitation Analysis in Texas. Journal of Geophysical research: Atmospheres. 2013; 10:1–11.

Hershfield, D. M. (1961a) Estimating the probable maximum precipitation. J. Hydraul. Div. ASCE 87 (HY5), 99-116.

Hershfield, D. M. (1961b) Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods, 1 to 100 years. US Weather Bureau Tech. Pap. No. 40, Washington DC.

Hershfield, D. M. (1965) Method for estimating probable maximum rainfall. J. Am. Wat. Wks Ass. 57, 965-972.

Koutsoyiannis, D., and Papalexiou, S.S. (2006) "A probabilistic approach to the concept of Probable Maximum Precipitation." Advances in Geosciences, 7, 51-54.

Kulkarni BD. Generalized Physical Approach of Estimating Areal Probable Maximum Precipitation for Plain Region of the Godavari River Basin (India). Journal of Spatial Hydrology. 2010; 2(2).

Lan, P., Lin, B., Zhang, Y., & Chen, H. (2017). Probable maximum precipitation estimation using the revised K m-value method in Hong Kong. Journal of Hydrologic Engineering, 22(8), 05017008.

Lee, K., & Singh, V. P. (2020). Analysis of uncertainty and non-stationarity in probable maximum precipitation in Brazos River basin. Journal of Hydrology, 590, 125526

Lorenzen, P., Prastawa, M., Davis, B., Gerig, G., Bullitt, E., & Joshi, S. (2006). Multi-modal image set registration and atlas formation. Medical image analysis, 10(3), 440-451.

Mersha, A. N., Masih, I., De Fraiture, C., Wenninger, J., & Alamirew, T. (2018). Evaluating the impacts of IWRM policy actions on demand satisfaction and downstream water availability in the upper Awash Basin, Ethiopia. Water, 10(7), 892.

Ministry of water Resources, Lake Tana Sub-basin four dams project Ribb (February 2010) and Megech (February 2010) Final Detail Design Reports.

Miyashiro, C. M., & Russell, D. L. (1974). Experimental participation as a source of stimulation in sensory and perceptual deprivation studies of stimulus-seeking behavior by introverts and extraverts. Perceptual and motor skills, 38(1), 235-238.

Nguyen, T. H., El Outayek, S., & Lim, S. H. (2017). A systematic approach to selecting the best probability models for annual maximum rainfalls–A case study using data in Ontario (Canada). Journal of hydrology, 553, 49-58.

Noriah, A. B., & Rakhecha, P. R. (2001). Probable maximum precipitation for 24 h duration over Southeast Asian monsoon region—Selangor, Malaysia. Atmospheric research, 58(1), 41-54.

Noriah, A. B., & Rakhecha, P. R. (2001). Probable maximum precipitation for 24 h duration over Southeast Asian monsoon region—Selangor, Malaysia. Atmospheric research, 58(1), 41-54.

Olofintoye, O. O., Sule, B. F., & Salami, A. W. (2009). Best–fit Probability distribution model for peak daily rainfall of selected Cities in Nigeria. New York Science Journal, 2(3).

Oromia Water Works Design and Supervision Enterprise (August, 2018) Detail Design Reports

Pirnia, A., Golshan, M., Darabi, H., Adamowski, J., & Rozbeh, S. (2019). Using the Mann–Kendall test and double mass curve method to explore stream flow changes in response to climate and human activities. Journal of Water and Climate Change, 10(4), 725-742.

Quraishi, S., & Berhane, M. (2014). Development of One Day Probable Maximum Precipitation and Isohyetal Map for North Shewa Zone of Amhara Region, Ethiopia (Doctoral dissertation, Haramaya University).

Rouhani, H., & Leconte, R. (2016). A novel method to estimate the maximization ratio of the P robable M aximum P recipitation (P MP) using regional climate model output. Water Resources Research, 52(9), 7347-7365.

Salas, J. D., Gavilán, G., Salas, F. R., Julien, P. Y., & Abdullah, J. (2014). Uncertainty of the PMP and PMF. Handbook of engineering hydrology, 2, 575-603.

Sammen, S., Mohamed, T., Ghazali, A. A., Sideq, L., & Aziz, A. A. (2018). Estimation of probable maximum precipitation for tropical catchment.

Salinas, J. L., Castellarin, A., Kohnova, S., & Kjeldsen, T. R. (2014). Regional parent flood frequency distributions in Europe–Part 2: Climate and scale controls. Hydrology and Earth System Sciences, 18(11), 4391-4401.

Singh, A., Singh, B. P., & Ar, B. (2018). Risk analysis of probable maximum precipitation estimates. Int. J. Hydrol, 2(4), 411-422.

Suribabu, C. R. (2019). An alternate method for finding Probable Maximum Precipitation (PMP) for Indian monsoon precipitation. ISH Journal of Hydraulic Engineering, 1-5.

Vivekanandan, N. (2015). Estimation of probable maximum precipitation using statistical methods. World Journal of Research and Review, 1(2), 262991.

Vivekanandan, N. (2015). Flood frequency analysis using method of moments and L-moments of probability distributions. Cogent engineering, 2(1), 1018704.

World Meteorological Organization. Manual for Estimation of Probable Maximum Precipitation. Operational Hydrology Report 1, Publication 332, World Meteorological Organization, Geneva. 1986.

World Meteorological Organization. Manuel on Estimation of Probable Maximum Precipitation. WMO–No 1045, Geneva, Switzerland. 2009.

Yung, Y. F., & Bentler, P. M. (1996). Bootstrapping techniques in analysis of mean and covariance structures. Advanced structural equation modeling: Issues and techniques, 195-226.

Zhang, Y., Singh, V. P., & Byrd, A. R. (2019). Basin-scale statistical method for probable maximum precipitation with uncertainty analysis. Journal of Hydrologic Engineering, 24(2), 04018067.

APPENDIXES

A: Available Meteorological Stations used for AwRB

Sta. No	Stations Name	Latitude	Longitude	Elevation	Record length		
					From	To	Total yr
1	Ginchi	9.02	38.13	2132	1980	2010	31
2	Hombole	8.37	38.77	1743	1980	2010	31
3	Asgori	8.79	38.33	2072	1980	2017	38
4	Aleltu	9.21	39.16	2663	1980	2018	38
5	Teji	8.83	38.37	2091	1980	2017	38
6	Tulu Bolo	8.65	38.21	2190	1980	2017	38
7	Ejersa Lele	8.24	38.69	1797	1980	2018	39
8	Bantu Liben	8.62	38.36	2167	1980	2013	34
9	Ancharo	11.05	39.63	2000	1980	2018	39
10	Gunna	8.37	39.88	2531	1980	2019	34
11	A.A Bole	8.98	38.80	2354	1980	2018	39
12	A.A Obs	9.02	38.75	2386	1980	2019	40
13	Akaki	8.87	38.79	2057	1980	2018	39
14	Debre Zeit	8.73	38.95	1900	1980	2010	31
15	Chefedonsa	8.97	39.12	2392	1980	2018	39
16	Modjo	8.61	39.11	1763	1980	2018	39
17	Koka Dam	8.47	39.15	1618	1981	2016	36
18	Melkasa	8.40	39.32	1540	1980	2014	35
19	Adama	8.55	39.28	1622	1980	2010	31
20	Etheya	8.13	39.33	2129	1980	2018	39
21	Huruta	8.14	39.34	2044	1980	2018	39
22	Guranda	8.91	38.59	2187	1980	2010	31
23	Nuraera	8.08	39.90	1140	1983	2017	34
24	Welenchiti	9.00	38.26	2165	1980	2017	34
25	Abomsa	8.47	39.83	1630	1988	2017	30
26	Makassar	8.40	39.32	1540	1980	2010	31
27	Wurgesa	11.55	39.62	2000	1980	2014	35
28	Ejere	9.91	38.52	2362	1980	2017	38
29	D/Berhan	9.63	39.50	2750	1980	2019	40
30	Debre Sina	9.87	39.75	2800	1980	2018	39
31	Senbate	10.32	39.97	1500	1980	2010	31
32	Boru Meda	11.37	39.47	2720	1980	2010	31
33	Awash 7	8.98	40.15	923	1980	2017	38
34	Melka Sedi	9.24	40.17	749	1980	2010	31
35	Awara Melka	9.17	39.98	960	1980	2012	33
36	Majete	10.50	39.85	2000	1988	2018	31

37	Haik	11.31	39.68	1985	1980	2010	31
38	Combolcha	11.08	39.72	1857	1980	2018	39
39	Bati	11.20	40.02	1660	1988	2019	32
40	Artuma	10.58	40.02	1880	1980	2010	31
41	Asebe Teferi	9.07	40.87	1792	1980	2018	39
42	Merssa	11.66	39.67	1578	1980	2013	34
43	Ruga	11.18	39.59	1740	1980	2018	39
44	Jara	10.31	39.99	1960	1980	2019	40
45	Aliyu Amba	9.57	39.79	1813	1980	2018	34
46	Dengego	9.45	41.92	2078	1980	2010	31
47	Fedis	9.13	42.08	1690	1980	2010	31
48	Gewane	10.15	40.63	568	1980	2016	37
49	Adaiytu	11.11	40.78	507	1980	2015	32
50	Logya	11.65	41.00	393	1981	2011	31
51	Dubity	11.72	41.01	376	1982	2012	31

B: Annual Maximum Rainfall for different stations in the AwRB

Addis Ababa Bole

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	54	58	87
1981	65	82	105
1982	90	115	145
1983	49	88	130
1984	56	77	90
1985	52	85	86
1986	38	51	78
1987	55	68	102
1988	37	64	85
1989	30	53	61
1990	49	55	76
1991	48	60	68
1992	51	62	86
1993	82	87	100
1994	53	97	148
1995	43	64	79
1996	33	55	76
1997	58	87	92
1998	63	96	121
1999	49	78	94

Addis Ababa Obs

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	36	72	88
1981	58	84	84
1982	41	49	74
1983	50	68	106
1984	55	78	80
1985	43	57	80
1986	84	118	119
1987	57	86	101
1988	36	41	65
1989	49	67	101
1990	40	49	70
1991	47	59	59
1992	51	57	61
1993	54	67	82
1994	57	73	78
1995	85	87	105
1996	67	102	107
1997	46	48	55
1998	78	87	97
1999	37	52	80

2000	57	85	99
2001	94	101	134
2002	51	78	98
2003	60	70	86
2004	59	62	84
2005	34	49	58
2006	82	103	125
2007	51	59	77
2008	40	56	72
2009	48	59	76
2010	51	71	108
2011	36.9	45.7	55.9
2012	64.7	88.6	90.9
2013	42.6	46.6	51.9
2014	27.2	44.5	55
2015	60.5	121	142.5
2016	33	46.2	47.9
2017	49.1	64.1	86.1
2018	60	75.1	86.6

2000	37	57	78
2001	43	85	99
2002	30	43	53
2003	55	60	76
2004	44	45	61
2005	59	107	112
2006	71	82	98
2007	64	69	85
2008	53	76	81
2009	55	57	81
2010	45	60	75
2011	97	189	278
2012	92	179	262
2013	96	181	267
2014	98	196	294
2015	98	196	293
2016	96	189	280
2017	94	180	260
2018	86	164	242
2019	97	192	287

Asgori

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	32.6	45.7	55.8
1981	63.5	65.8	81.8
1982	41.3	54.6	61.5
1983	55.1	64.1	68.3
1984	38.4	52.6	70.3
1985	47.2	59.3	95.6
1986	66.9	69.8	76.8
1987	38.2	59	68.2
1988	36.4	55	68.2
1989	38.5	58.9	64.7
1990	43.4	67	87.8
1991	48.5	62.8	76.3
1992	45.2	71.4	89.9
1993	47.3	65.8	93.2
1994	53.5	78.6	102

Chafedonsa

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	37.4	72	72
1981	44.5	56.5	57.3
1982	45.6	57.3	70.8
1983	70	85	116.7
1984	50.9	55.9	65.9
1985	62.5	80.3	92.1
1986	56.2	79.3	85.3
1987	47.2	55	74.8
1988	38.9	47.7	68.2
1989	41.8	73.1	88.5
1990	56	56	76.5
1991	51	67.9	78.1
1992	35.5	51	57.5
1993	40	57.1	67.4
1994	23.3	43	55.2

1995	31.4	50.6	66.1
1996	67.2	67.2	75.7
1997	46.3	59.9	59.9
1998	49.3	72.4	90.5
1999	55.8	58.3	59.4
2000	40	60.9	68.9
2001	37.1	50.3	56.7
2002	37.5	71.8	80.5
2003	39	57.9	78.1
2004	54	62.7	63.6
2005	40.2	50.7	57.9
2006	35.9	53.7	65.2
2007	41.4	55.4	93.0
2008	42.4	54.7	55.5
2009	27.1	44.2	53.9
2010	39.5	57.8	73.1
2011	37.8	43.7	54.0
2012	42.6	47.0	47.2
2013	42.3	43.0	52.2
2014	60.1	74.0	76.2
2015	38.4	42.7	46.8
2016	71	75.0	78.0
2017	35.1	57.2	78.1

1995	27.7	48.6	65
1996	53	78	91.7
1997	31	31.7	41.1
1998	45.3	59.2	69.5
1999	43.6	61.5	83.6
2000	31.1	40.5	52.1
2001	26.7	45.6	56.7
2002	27.5	44.2	58
2003	55.6	62.1	73.3
2004	30.2	43.7	53.7
2005	68.8	86.8	88.8
2006	48.2	72.7	93.2
2007	57.3	84	85.7
2008	40.2	42.9	59.3
2009	36.5	62.6	83.6
2010	50.2	60.6	76.1
2011	53.6	65.9	74.2
2012	34.5	67.7	74.1
2013	40	60.5	77.8
2014	36.6	49.1	71.3
2015	22.5	41.2	54.2
2016	42.5	58.7	62.3
2017	72	80.2	94.6
2018	55	60.8	72.7

Dubity

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1982	55	60	60
1983	23.6	33.5	33.5
1984	64	98	123
1985	51	51	51
1986	58.4	58.4	65.5
1987	52.2	52.2	61.9
1988	26	26	26
1989	33.4	33.4	33.4
1990	38.4	45.6	45.6
1991	40.2	40.2	56.2
1992	46.8	46.9	46.9

Logya

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1981	19	23	53
1982	70	70	70
1983	92	102	125
1984	27	45	69
1985	36.2	36.2	36.2
1986	16.8	23.4	23.4
1987	28.9	36.1	36.1
1988	57.6	58.7	58.7
1989	27.5	46.7	71
1990	15.3	19.7	22.1
1991	23	23	38.3

1993	35.3	39.1	39.1
1994	90.8	56.0	72.0
1995	39.4	39.4	39.4
1996	20	20	24.9
1997	48.3	49.7	61.5
1998	31.5	31.5	32.3
1999	17	23.6	23.6
2000	46.2	54	84.2
2001	25.4	25.4	25.4
2002	43.2	43.2	43.2
2003	40	45	51.5
2004	38	41	41
2005	31.8	45.1	46.7
2006	44.5	44.5	44.5
2007	39.2	46.5	46.5
2008	16.2	16.2	16.2
2009	31.6	34.4	37.9
2010	48.8	53	53
2011	37.5	38.3	38.3
2012	23.2	23.2	23.2

1992	27.3	33.9	42.2
1993	69.9	69.9	69.9
1994	34.3	34.3	34.3
1995	30.4	39.9	48.6
1996	38.5	46.1	55.4
1997	38.7	57.1	57.1
1998	32.5	33	51.1
1999	37	37	47.4
2000	47.6	47.6	47.6
2001	40.1	40.1	40.1
2002	68.4	76	76
2003	32.6	34	34
2004	34	34	34
2005	43.8	43.8	43.8
2006	26.5	31.1	34.3
2007	18.0	18.0	30.8
2008	44.5	44.5	44.5
2009	34.4	34.8	37.4
2010	13.8	22.3	22.3
2011	9.8	9.8	9.8

Huruta

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	60	63	66
1981	34	53	70
1982	40	55	62
1983	56	60	66
1984	42	72	90
1985	38	60	74
1986	38	75	75
1987	40	56	66
1988	48	63	68
1989	59	66	85
1990	49	68	72
1991	64	68	68
1992	42	76	100
1993	59	96	106
1994	91	92	92
1995	67	70	75

Jara

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	40.3	58.7	63
1981	60.8	103.4	118.4
1982	62	99.1	143.6
1983	69.7	111.3	145.6
1984	146.5	162	217
1985	90.8	121.2	153.5
1986	100	140	160
1987	100.5	150.7	165.7
1988	100.7	110.2	147
1989	100.6	110	152.2
1990	66	66	79.2
1991	58.2	94.7	119.2
1992	99.9	118.8	149.9
1993	45.2	75.9	93.6
1994	83	125.5	158.2
1995	38.3	50.5	70.5

1996	53	67	68
1997	75	87	112
1998	31	57	63
1999	63	64	69
2000	50	67	87
2001	59	59	68
2002	80	84	86
2003	44	47	49
2004	45	55	59
2005	48	89	92
2006	41	46	64
2007	17	33	49
2008	54	70	86
2009	17	17	24
2010	57	76	92
2011	40.1	59	66
2012	52	62.1	71.8
2013	41	51.2	70.3
2014	39.5	63	63.6
2015	37.7	70.5	82
2016	52	59.7	59.7
2017	54	99	99
2018	7.4	7.4	9.2

1996	60	115.3	115.3
1997	34.3	55.3	70.3
1998	54.3	60.1	64
1999	48	62.6	87.4
2000	30.5	41.4	41.4
2001	24.9	36.8	55.1
2002	48.8	55	57.4
2003	28.9	46.5	53.3
2004	38.4	54.9	69.1
2005	57.2	79.4	92.9
2006	99.8	102.5	137.6
2007	52.9	55.1	73.3
2008	66	74.6	88
2009	48.5	74.6	88
2010	81.5	99.2	147
2011	73.8	73.8	73.8
2012	79	109	127
2013	78	83.2	91.9
2014	78	78	79.5
2015	60.3	90.4	102.6
2016	30.8	52	67.3
2017	75.2	92.4	119.7
2018	49.3	80.1	92.9
2019	66.2	90.3	98.5

Debre Berhan

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	46	63.8	68.3
1981	46	50.3	63.4
1982	44	79.1	102
1983	50	94.5	109.7
1984	33	53.6	69.5
1985	38.8	58.5	77.2
1986	46.5	58.8	69.4
1987	34.1	41.3	61.9
1988	46.6	67.1	78.3
1989	30	49	67
1990	53.3	56.3	66.2

Modjo

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	52	57	66
1981	50	71	87
1982	71	76	80
1983	57	66	78
1984	48	85	89
1985	65	76	76
1986	34	55	63
1987	48	59	92
1988	45	65	87
1989	61	80	89
1990	62	62	91

1991	45.6	66.9	87.5
1992	58.0	87	97.0
1993	41.2	69.3	105.7
1994	60.2	75	93.8
1995	40.0	60.3	63
1996	42	57	74.7
1997	31.6	50.3	63.5
1998	40	53.2	77.7
1999	45.7	57.6	71
2000	43.8	74.8	104.9
2001	38.2	62.3	70.3
2002	40.6	54.4	69.8
2003	47.8	63.1	82.8
2004	45.6	64.5	67.9
2005	46.2	61.8	63.3
2006	43.5	70.7	96.3
2007	57.2	69.2	78
2008	57	69.7	83.6
2009	59.5	84.9	92.7
2010	60	87.3	93.8
2011	84.3	109.9	145.2
2012	41	58	85
2013	34.5	43.5	53.3
2014	38.4	60.6	69.2
2015	63.2	73.5	74.6
2016	60.4	67.2	110.4
2017	68.6	99	100.1
2018	38.3	57.3	80.4
2019	43.5	69	107.1

1991	69	89	112
1992	35	69	69
1993	48	73	89
1994	39	46	65
1995	36	56	71
1996	45	54	75
1997	54	61	72
1998	83	91	105
1999	49	77	110
2000	45	74	74
2001	43	61	65
2002	47	65	72
2003	78	89	121
2004	47	77	79
2005	56	85	102
2006	35	60	74
2007	39	60	77
2008	78	93	97
2009	48	80	80
2010	56	87	105
2011	44.3	50.5	75.8
2012	81.4	82.9	120.7
2013	62.8	84	110.3
2014	61.8	78	90
2015	44.8	55.7	73.1
2016	91.6	69.8	115.7
2017	64.4	64.4	83.7
2018	88.2	127	141.1

Gewane

Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	25.6	28	49.6
1981	45	49.2	73.9
1982	60	95.5	115.7
1983	42.9	42.9	76.7
1984	46.2	46.2	46.2
1985	58	66.7	67.5

Nuraera

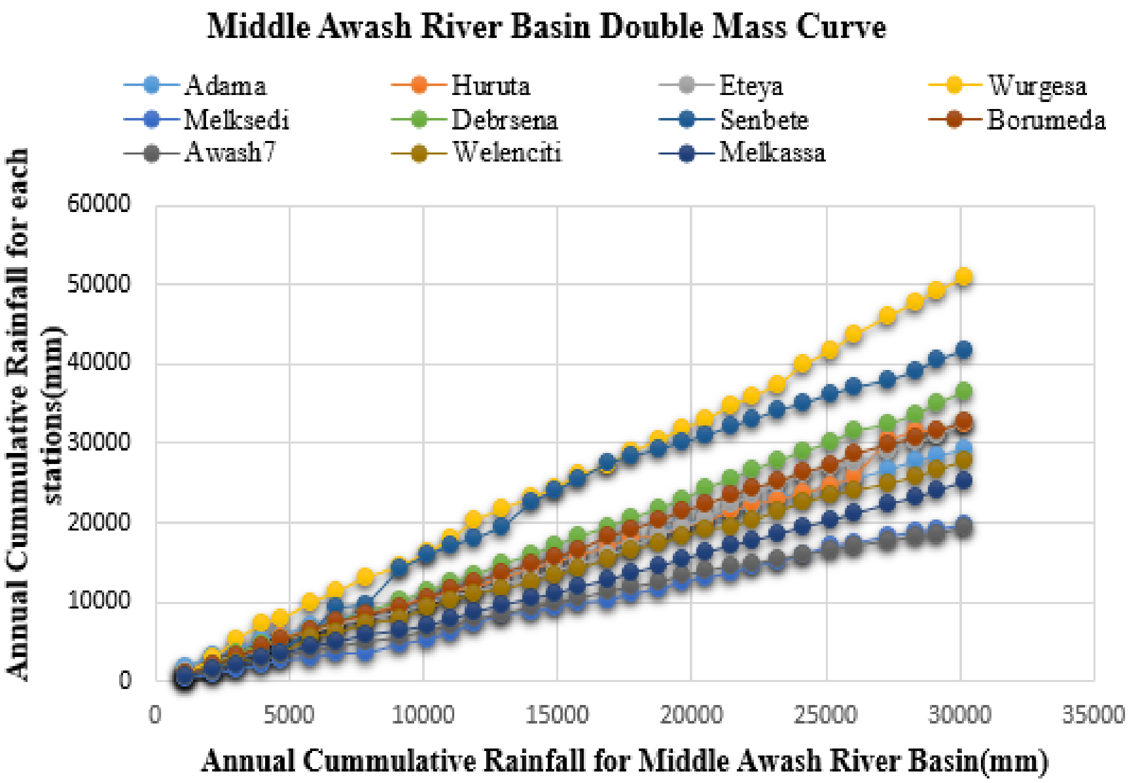
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1983	31.2	60.8	66.1
1984	20.4	32.2	32.2
1986	50.5	52.6	52.6
1987	82.4	82.4	91.6
1988	40.2	53.6	57.8
1989	58.1	84	85.4

1986	33	43	52
1987	67.7	95.5	105.9
1988	35.3	55	55
1989	35.5	58.5	58.9
1990	85.7	124.2	153.1
1991	34.5	39.5	48.7
1992	38.5	52.5	56.2
1993	35.3	47.2	52.5
1994	60	65.5	65.5
1995	70.6	90.2	93.7
1996	36.9	51	62.5
1997	56.6	65.2	91.6
1998	64.2	74.6	78.1
1999	48	48.9	48.9
2000	63.2	63.2	65.5
2001	35.7	38.3	52
2002	80.3	127.8	137.1
2003	41	43.8	46.8
2004	66.2	74.1	82.5
2005	60.1	81.5	81.5
2006	56	56	64
2007	40.3	55.7	66.2
2008	40.8	45.4	66
2009	44.5	50.6	51.9
2010	85.8	86.9	117.4
2011	24.4	35.8	42.8
2012	89.5	89.5	104.8
2013	88.4	88.4	102.7
2014	84	84	84
2015	54.4	54.4	55.8
2016	60.8	60.8	60.8

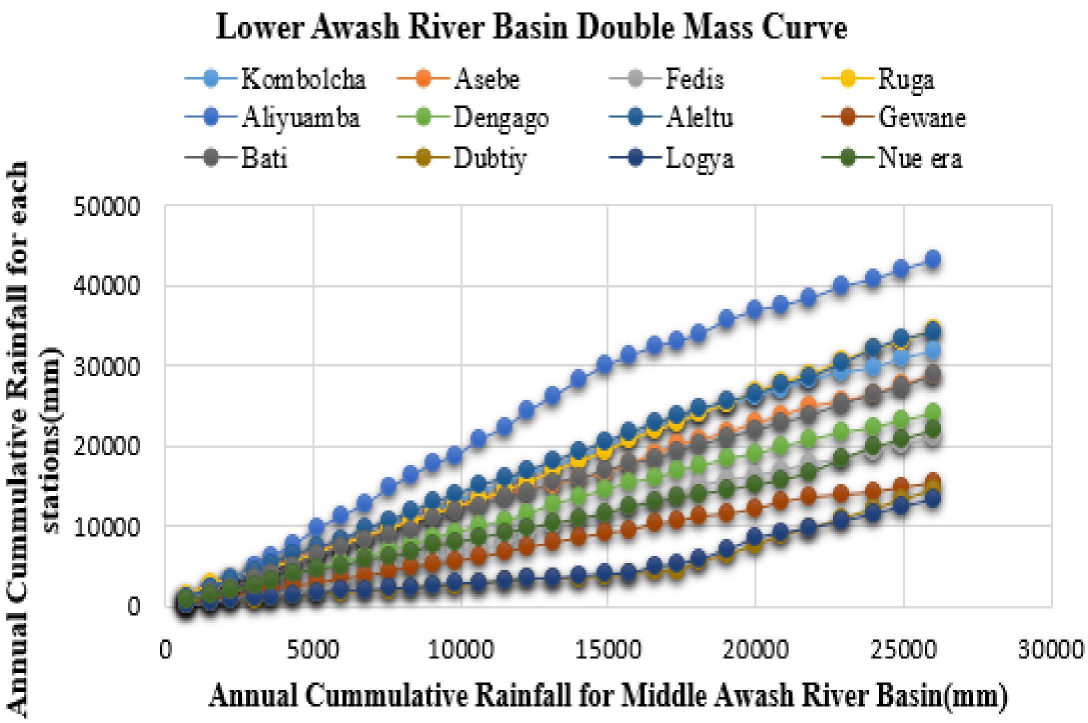
1990	53.2	71.7	89.7
1991	54.5	62.2	65.6
1992	48.1	63.8	65.1
1993	49	54	65
1994	52.7	52.7	52.9
1995	48.6	48.6	48.6
1996	126	141	162.5
1997	36.2	46	55
1998	33	49.6	59.3
1999	53.7	74.9	98.1
2000	35	35	43.5
2001	35	39	57.8
2002	56.4	61.4	66.9
2003	38.5	58.5	66.5
2004	32.2	49.1	55.4
2005	48.2	51	62.1
2006	42	57	72.0
2007	46.5	70	74
2008	46.5	55	55.0
2009	40.2	44	48.4
2010	75.8	82.3	86.3
2011	82.6	92.1	94.4
2012	70	70	110.8
2013	35.5	42.5	48.3
2014	58.8	58.8	58.8
2015	52	62	68
2016	44.4	57.2	65.7
2017	53.7	57.1	57.7

C: Data Consistency Test Results

C1: Middle Awash River basin Double mass curve for data consistency



C2: Lower Awash River basin Double mass curve for data consistency



D: Homogeneity Test Results for Different Durations

Station No	Stations Name	Homogeneity Test for d/t duration			
		Critical Statistic (U critical)	1-Day Statistic (U)	2-Days Statistic (U)	3-Days Statistic (U)
1	Addis Ababa Bole	1.96	1.153	0.590	0.927
2	Addis Ababa Obs	1.96	0.528	1.856	0.691
3	Abomsa	1.96	0.915	1.455	1.330
4	Adaiytu	1.96	1.114	1.378	0.736
5	Akaki	1.96	1.208	1.377	0.983
6	Aleltu	1.96	0.672	0.468	0.556
7	Aliyu Amba	1.96	1.381	0.621	1.829
8	Ancharo	1.96	1.096	0.872	1.124
9	Artuma	1.96	0.356	1.146	1.621
10	Asebe Teferi	1.96	1.349	0.731	0.309
11	Asgori	1.96	1.023	1.637	1.696
12	Awash 7 Kilo	1.96	1.725	1.082	1.169
13	Awara Melka	1.96	1.117	1.369	1.225
14	Batu Liben	1.96	0.518	1.035	0.587
15	Bati	1.96	0.321	0.623	0.812
16	Boru Meda	1.96	0.474	1.305	1.581
17	Chefedonsa	1.96	0.534	0.365	0.590
18	Combolcha	1.96	1.630	1.826	1.602
19	Debre Berhan	1.96	1.503	1.693	1.259
20	Debre Sina	1.96	0.983	1.742	1.489
21	Debre Zeit	1.96	1.739	1.226	0.316
22	Dengego	1.96	1.621	1.463	1.937
23	Dubity	1.96	1.146	0.830	1.067
24	Ejere	1.96	0.322	0.702	0.819
25	Ejersa Lele	1.96	0.197	0.253	0.759
26	Etheya	1.96	0.843	0.112	0.140
27	Fedis	1.96	1.107	1.898	1.660
28	Gewane	1.96	1.155	0.213	0.517
29	Ginchi	1.96	0.751	0.988	0.277
30	Gunna	1.96	1.380	1.587	1.656
31	Guranda	1.96	0.395	1.146	1.384
32	Haik	1.96	0.237	1.028	0.435
33	Hombole	1.96	1.028	0.751	1.028
34	Huruta	1.96	0.253	0.927	0.590
35	Jara	1.96	1.557	1.801	1.097
36	Koka Dam	1.96	1.093	0.618	0.871

37	Logya	1.96	1.423	0.593	0.395
38	Majete	1.96	0.435	1.423	1.858
39	Makassar	1.96	1.779	1.779	1.344
40	Melkasa	1.96	0.495	0.462	0.660
41	Merssa	1.96	0.725	0.483	0.242
42	Melka Sedi	1.96	0.277	0.593	1.186
43	Mojo	1.96	0.787	1.855	1.770
44	Nazeret	1.96	0.040	0.791	0.791
45	Nuraera	1.96	0.483	1.001	0.345
46	Ruga	1.96	0.309	0.646	0.421
47	Senbete	1.96	1.581	1.028	1.621
48	Teji	1.96	0.731	1.374	1.140
49	Tulu Bolo	1.96	1.520	0.994	0.526
50	Welenchiti	1.96	0.656	0.242	0.449
51	Wurgesa	1.96	0.726	0.165	0.363

E: Frequency Factor (K) Values

E1: Frequency factor (K) founded from basin

S.No	Station Name	frequency factor K for (1-day, 2- days and 3-days) duration		
		K (1-day) duration	K (2-days) duration	K (3-days) duration
1	Ginchi	2.580	3.384	2.203
2	Hombole	2.590	2.606	2.638
3	Asgori	2.565	2.185	1.898
4	Aleltu	3.573	3.248	2.700
5	Teji	2.494	1.850	3.053
6	Tulu Bolo	2.184	2.032	2.054
7	Batu liben	1.878	1.395	1.928
8	Ancharo	2.598	2.385	2.637
9	Gunna	2.187	2.362	3.222
10	Guranda	2.929	2.346	1.997
11	Dengego	1.451	3.553	3.202
12	AA. Bole	2.820	2.757	2.411
13	AA.Obs	2.024	2.221	2.188
14	Akaki	3.346	3.717	2.815
15	Debre Zeit	2.541	3.730	2.553
16	Chafedonsa	2.359	2.024	3.377
17	Modjo	2.582	4.467	3.310
18	Koka Dam	2.964	3.811	4.019
19	Melkasa	1.636	1.430	1.370

20	Adama	2.999	3.239	2.747
21	Etheya	3.139	2.975	2.917
22	Huruta	2.946	2.049	2.146
23	Welenchiti	2.819	2.148	2.101
24	Abomsa	3.683	3.291	4.137
25	Makassar	2.381	3.140	2.240
26	Wurgesa	2.104	1.983	2.053
27	Ejere	2.685	2.982	3.099
28	Ejersa Lele	2.337	2.885	2.222
29	Debre Berhan	4.044	3.420	4.103
30	Debre Sina	2.814	3.160	2.052
31	Senbate	2.437	3.354	3.249
32	Boru Meda	2.849	3.149	2.490
33	Awash 7	3.678	3.126	2.657
34	Melka Sedi	2.354	2.490	2.921
35	Awara Melka	2.277	2.375	2.850
36	Majete	2.589	2.303	2.606
37	Haik	2.295	2.194	2.494
38	Combolcha	4.389	2.633	2.255
39	Bati	3.850	2.608	3.077
40	Artuma	2.394	3.074	2.662
41	Asebe Teferi	2.577	3.072	3.451
42	Merssa	3.956	4.645	2.986
43	Ruga	2.214	2.465	2.642
44	Nuraera	5.633	6.100	4.504
45	Jara	3.656	2.490	1.766
46	Aliyu Amba	2.905	4.396	5.805
47	Fedis	3.002	3.193	2.782
48	Gewane	2.534	3.017	3.460
49	Adaitu	3.387	2.788	3.012
50	Logya	3.048	2.710	2.866
51	Dubity	3.935	4.702	3.646

E2: Frequency factor (K) founded from Hershfield's chart

S.No	Station Name	Km for (1-day)	S.No	Station Name	Km for (1-day)	S.No	Station Name	Km for (1-day)
1	Ginchi	16.42	18	Koka Dam	15.29	35	Awara Melka	15.61
2	Hombole	16.04	19	Melkasa	15.50	36	Majete	15.36
3	Asgori	15.89	20	Adama	16.14	37	Haik	15.86
4	Aleltu	15.06	21	Etheya	16.26	38	Combolcha	15.36
5	Teji	16.67	22	Huruta	15.82	39	Bati	16.07
6	Tulu Bolo	16.64	23	Welenchiti	15.79	40	Artuma	15.82

7	Batu liben	16.57	24	Abomsa	14.76	41	Asebe Teferi	15.04
8	Ancharo	15.64	25	Makassar	16.07	42	Merssa	14.30
9	Gunna	16.23	26	Wurgesa	15.70	43	Ruga	16.34
10	Guranda	16.50	27	Ejere	16.57	44	Nuraera	14.58
11	Dengego	16.43	28	Ejersa Lele	16.75	45	Jara	13.85
12	AA. Bole	15.72	29	D/Berhan	16.06	46	Aliyu Amba	13.65
13	AA.Obs	15.57	30	Debre Sina	14.95	47	Fedis	16.53
14	Akaki	14.99	31	Senbate	14.90	48	Gewane	15.88
15	Debre Zeit	16.28	32	Boru Meda	16.11	49	Adaitu	14.79
16	Chafedonsa	16.50	33	Awash 7	15.82	50	Logya	16.57
17	Modjo	15.80	34	Melka Sedi	15.61	51	Dubity	15.83

F: Probable maximum precipitation for different duration

F1: Probable maximum precipitation for 1-day duration

S.No	Station Name	Adj. mean (Xn) (mm)	Adj. Stdev (σn) (mm)	1-day km	24-hr PMP
1	Ginchi	48.98	12.16	2.58	137.82
2	Hombole	52.70	10.92	2.59	133.61
3	Asgori	46.48	11.83	2.56	132.75
4	Aleltu	51.68	18.33	3.57	182.65
5	Teji	44.73	9.61	2.49	115.71
6	Tulu Bolo	43.57	12.51	2.18	134.08
7	Batu liben	49.68	12.92	1.88	143.70
8	Ancharo	62.66	16.14	2.60	180.24
9	Gunna	56.68	13.73	2.19	157.13
10	Guranda	41.76	13.43	2.93	138.26
11	Dengego	54.93	13.21	1.45	151.64
12	AA. Bole	54.07	17.49	2.82	179.66
13	AA.Obs	64.05	25.76	2.02	247.00
14	Akaki	49.30	13.75	3.35	148.93
15	Debre Zeit	50.97	12.25	2.54	140.66
16	Chafedonsa	45.88	13.75	2.36	145.03
17	Modjo	56.93	17.05	2.58	179.94
18	Koka Dam	49.66	18.58	2.96	182.09
19	Melkasa	73.82	25.94	1.64	259.29
20	Adama	59.21	14.60	3.00	165.91
21	Etheya	44.81	12.33	3.14	134.20
22	Huruta	49.96	18.59	2.95	182.51
23	Welenchiti	66.85	15.03	2.82	177.43
24	Abomsa	63.27	23.02	3.68	227.55

25	Makassar	57.07	14.73	2.38	164.36
26	Wurgesa	56.04	20.03	2.10	199.12
27	Ejere	52.21	14.42	2.69	156.80
28	Ejersa Lele	42.82	12.28	2.34	131.64
29	Debre Berhan	48.72	12.29	4.04	138.39
30	Debre Sina	83.97	22.90	2.81	250.15
31	Senbate	59.43	29.21	2.44	265.17
32	Boru Meda	49.83	16.03	2.85	165.00
33	Awash 7	48.70	14.18	3.68	151.19
34	Melka Sedi	47.72	24.61	2.35	220.81
35	Awara Melka	51.73	21.67	2.28	205.36
36	Majete	65.82	20.61	2.59	214.10
37	Haik	63.38	16.51	2.30	183.57
38	Combolcha	60.54	14.90	4.39	169.42
39	Bati	68.78	22.32	3.85	229.03
40	Artuma	55.66	18.22	2.39	186.41
41	Asebe Teferi	58.99	21.57	2.58	212.88
42	Merssa	61.91	16.72	3.96	183.33
43	Ruga	52.18	17.35	2.21	176.61
44	Nuraera	53.92	23.40	5.63	219.55
45	Jara	65.25	24.64	3.66	240.81
46	Aliyu Amba	93.76	32.93	2.90	329.24
47	Fedis	41.30	20.73	3.00	187.20
48	Gewane	55.67	20.29	2.53	200.48
49	Adaitu	47.47	19.60	3.39	186.50
50	Logya	34.93	19.76	3.05	173.45
51	Dubity	42.53	18.31	3.93	172.20

F2: Probable maximum precipitation for 2-day duration

S.No	Station Name	Adj. mean (Xn) (mm)	Adj. Stdev (σn) (mm)	2-day km	48-hr PMP
1	Ginchi	63.59	12.75	3.38	161.20
2	Hombole	72.26	16.37	2.61	196.34
3	Asgori	61.20	9.67	2.19	136.93
4	Aleltu	70.49	21.05	3.25	227.14
5	Teji	57.12	10.72	1.85	139.63
6	Tulu Bolo	62.89	13.74	2.03	167.32
7	Batu liben	69.77	19.56	1.39	215.87
8	Ancharo	89.83	22.66	2.39	260.28
9	Gunna	77.47	21.82	2.36	240.43
10	Guranda	58.42	15.95	2.35	177.73

11	Dengego	69.28	19.57	3.55	215.37
12	AA. Bole	73.92	22.48	2.76	241.00
13	AA.Obs	98.07	62.58	2.22	549.23
14	Akaki	60.38	13.00	3.72	159.32
15	Debre Zeit	62.56	15.19	3.73	177.09
16	Chafedonsa	62.20	15.20	2.02	176.74
17	Modjo	74.02	17.05	4.47	203.10
18	Koka Dam	68.38	27.68	3.81	271.17
19	Melkasa	132.15	53.73	1.43	525.79
20	Adama	74.38	18.72	3.24	215.22
21	Etheya	58.99	13.82	2.98	163.46
22	Huruta	65.82	21.05	2.05	221.86
23	Welenchiti	83.37	17.97	2.15	220.10
24	Abomsa	76.94	23.20	3.29	249.49
25	Makassar	68.75	20.37	3.14	220.37
26	Wurgesa	80.56	26.26	1.98	275.00
27	Ejere	66.45	19.50	2.98	211.72
28	Ejersa Lele	56.01	15.15	2.89	169.45
29	Debre Berhan	68.53	16.32	3.42	191.79
30	Debre Sina	118.87	31.70	3.16	356.39
31	Senbate	83.64	52.38	3.35	461.49
32	Boru Meda	65.11	20.80	3.15	219.27
33	Awash 7	57.57	17.30	3.13	186.27
34	Melka Sedi	58.27	24.74	2.49	239.16
35	Awara Melka	59.50	23.55	2.38	232.22
36	Majete	86.02	24.14	2.30	266.32
37	Haik	86.83	19.01	2.19	231.28
38	Combolcha	78.65	19.54	2.63	225.78
39	Bati	89.41	27.39	2.61	292.94
40	Artuma	78.68	24.31	3.07	259.23
41	Asebe Teferi	74.27	25.79	3.07	264.63
42	Merssa	82.61	25.65	4.64	273.03
43	Ruga	70.94	23.73	2.46	246.43
44	Nuraera	159.32	71.65	6.10	681.98
45	Jara	85.77	28.57	2.49	297.07
46	Aliyu Amba	126.15	48.44	4.40	481.89
47	Fedis	52.60	28.52	3.19	259.25
48	Gewane	66.24	25.75	3.02	255.27
49	Adaitu	53.98	21.33	2.79	210.44
50	Logya	39.20	19.67	2.71	182.10
51	Dubity	47.74	25.17	4.70	230.29

F3: Probable maximum precipitation for 3-day duration

S.No	Station Name	Adj. mean (Xn) (mm)	Adj. Stdev (σn) (mm)	3-day km	72-hr PMP
1	Ginchi	76.17	13.89	2.20	178.68
2	Hombole	87.58	25.87	2.64	271.45
3	Asgori	73.59	14.14	1.90	177.44
4	Aleltu	85.90	23.01	2.70	250.45
5	Teji	69.77	12.00	3.05	158.83
6	Tulu Bolo	82.89	19.76	2.05	225.42
7	Batu liben	86.66	25.14	1.93	265.55
8	Ancharo	107.03	26.33	2.64	296.47
9	Gunna	95.31	29.48	3.22	304.23
10	Guranda	72.51	18.49	2.00	205.20
11	Dengego	80.08	21.58	3.20	234.34
12	AA. Bole	93.30	29.37	2.41	301.24
13	AA.Obs	130.16	97.48	2.19	796.95
14	Akaki	71.62	12.62	2.81	165.04
15	Debre Zeit	74.58	15.56	2.55	188.04
16	Chafedonsa	75.27	16.26	3.38	193.43
17	Modjo	90.11	20.54	3.31	238.79
18	Koka Dam	83.51	40.04	4.02	361.28
19	Melkasa	190.26	80.84	1.37	753.98
20	Adama	91.00	22.71	2.75	254.27
21	Etheya	72.53	16.05	2.92	188.96
22	Huruta	74.87	22.61	2.15	235.33
23	Welenchiti	95.63	20.41	2.10	244.13
24	Abomsa	87.64	32.67	4.14	316.84
25	Makassar	80.75	24.21	2.24	252.68
26	Wurgesa	96.49	28.87	2.05	301.51
27	Ejere	82.59	25.12	3.10	260.78
28	Ejersa Lele	65.63	18.48	2.22	197.38
29	Debre Berhan	85.25	20.53	4.10	233.21
30	Debre Sina	142.61	37.55	2.05	411.51
31	Senbate	102.41	62.92	3.25	535.21
32	Boru Meda	77.55	19.43	2.49	217.17
33	Awash 7	65.76	19.79	2.66	206.25
34	Melka Sedi	68.42	29.57	2.92	274.43
35	Awara Melka	68.01	28.10	2.85	264.22
36	Majete	103.60	29.18	2.61	311.62
37	Haik	102.98	22.27	2.49	264.82
38	Combolcha	93.23	22.50	2.25	255.34

39	Bati	104.61	32.01	3.08	331.59
40	Artuma	98.61	34.57	2.66	341.89
41	Asebe Teferi	86.32	29.21	3.45	292.26
42	Merssa	97.09	28.90	2.99	302.41
43	Ruga	87.59	29.85	2.64	297.99
44	Nuraera	71.84	26.09	4.50	255.11
45	Jara	103.51	34.83	1.77	349.19
46	Aliyu Amba	146.99	62.00	5.80	579.43
47	Fedis	61.27	35.28	2.78	304.47
48	Gewane	75.97	29.31	3.46	281.24
49	Adaitu	62.16	26.32	3.01	245.72
50	Logya	43.44	20.26	2.87	184.13
51	Dubity	51.72	28.15	3.65	246.14

G: 1-day PMP obtained from Hershfield's chart

S.No	Station Name	Adj. mean (Xn) (mm)	Adj. Stdev (σn) (mm)	1-day km (chart)	Hershfield 24-hr PMP
1	Ginchi	48.98	12.16	16.42	285.58
2	Hombole	52.70	10.92	16.04	266.30
3	Asgori	46.48	11.83	15.89	276.50
4	Aleltu	51.68	18.33	15.06	405.28
5	Teji	44.73	9.61	16.67	232.47
6	Tulu Bolo	43.57	12.51	16.64	286.10
7	Batu liben	49.68	12.92	16.57	300.60
8	Ancharo	62.66	16.14	15.64	376.32
9	Gunna	56.68	13.73	16.23	323.91
10	Guranda	41.76	13.43	16.50	301.44
11	Dengego	54.93	13.21	16.43	312.12
12	AA. Bole	54.07	17.49	15.72	392.09
13	AA.Obs	64.05	25.76	15.57	559.88
14	Akaki	49.30	13.75	14.99	315.94
15	Debre Zeit	50.97	12.25	16.28	289.48
16	Chafedonsa	45.88	13.75	16.50	312.00
17	Modjo	56.93	17.05	15.80	387.07
18	Koka Dam	49.66	18.58	15.29	407.79
19	Melkasa	73.82	25.94	15.50	574.41
20	Adama	59.21	14.60	16.14	343.30
21	Etheya	44.81	12.33	16.26	283.94
22	Huruta	49.96	18.59	15.82	408.37
23	Welenchiti	66.85	15.03	15.79	359.99

24	Abomsa	63.27	23.02	14.76	507.15
25	Makassar	57.07	14.73	16.07	343.29
26	Wurgesa	56.04	20.03	15.70	442.41
27	Ejere	52.21	14.42	16.57	332.02
28	Ejersa Lele	42.82	12.28	16.75	280.81
29	Debre Berhan	48.72	12.29	16.06	287.71
30	Debre Sina	83.97	22.90	14.95	528.34
31	Senbate	59.43	29.21	14.90	619.97
32	Boru Meda	49.83	16.03	16.11	359.76
33	Awash 7	48.70	14.18	15.82	323.47
34	Melka Sedi	47.72	24.61	15.61	519.80
35	Awara Melka	51.73	21.67	15.61	468.56
36	Majete	65.82	20.61	15.36	464.44
37	Haik	63.38	16.51	15.86	384.15
38	Combolcha	60.54	14.90	15.36	350.42
39	Bati	68.78	22.32	16.07	500.12
40	Artuma	55.66	18.22	15.82	407.70
41	Asebe Teferi	58.99	21.57	15.04	474.86
42	Merssa	61.91	16.72	14.30	386.46
43	Ruga	52.18	17.35	16.34	387.39
44	Nuraera	53.92	23.40	14.58	503.75
45	Jara	65.25	24.64	13.85	540.17
46	Aliyu Amba	93.76	32.93	13.65	729.30
47	Fedis	41.30	20.73	16.53	438.99
48	Gewane	55.67	20.29	15.88	446.96
49	Adaitu	47.47	19.60	14.79	424.54
50	Logya	34.93	19.76	16.57	413.50
51	Dubity	42.53	18.31	15.83	394.61

H: Estimated parameters of GEV distributions

H1: Estimated parameters of GEV distributions for 1-day duration

Name of Station	Estimated Parameter for GEV Distribution for 1-Day		
	K value	σ value	µ value
Ginchi	0.02179	9.269	42.204
Hombole	-0.12270	9.669	47.411
Asgori	0.18601	7.321	39.551
Aleltu	0.01070	16.110	40.624
Teji	-0.13712	9.439	39.413
Tulu Bolo	-0.14105	11.707	37.193
Ejersa Lele	-0.34324	11.105	38.068

Batu Liben	0.35622	10.929	44.789
Ancharo	-0.05818	12.798	54.322
Gunna	-0.36593	12.852	50.892
Guranda	0.14442	7.998	34.804
Dengego	-0.37439	15.914	48.764
Addis Ababa Bole	-0.05890	12.268	46.068
Addis Ababa Obs	-0.02336	18.117	51.977
Akaki	0.26124	9.545	42.686
Debre Zeit	0.08437	9.337	43.072
Chefedonsa	-0.17938	12.127	39.225
Mojo	0.03330	12.075	48.063
Koka Dam	-0.04964	16.567	39.630
Melkasa	-0.54564	29.755	65.634
Adama	-0.20450	12.418	52.217
Etheya	-0.13210	9.791	38.800
Huruta	-0.14573	13.808	43.824
Welenchiti	-0.12937	14.194	57.814
Abomsa	0.13013	13.718	51.488
Makassar	-0.13045	12.323	49.826
Wurgesa	-0.14479	19.893	47.137
Ejere	-0.48503	13.437	47.032
Debre Berhan	0.04026	8.347	41.929
Debre Sina	-0.20223	19.634	73.119
Senbete	0.09272	19.819	44.055
Boru Meda	0.04671	10.792	41.391
Awash 7	-0.23334	13.576	41.847
Melka Sedi	0.20057	14.739	34.433
Awara Melka	0.15318	15.019	39.433
Majete	-0.05392	15.140	55.931
Haik	-0.12172	13.436	55.090
Combolcha	-0.17221	12.106	53.323
Bati	0.05059	14.844	57.118
Artuma	-0.17315	12.885	56.184
Asebe Teferi	-0.00183	18.859	47.866
Merssa	0.12510	12.014	54.173
Ruga	-0.42344	17.215	45.898
Nuraera	0.14334	13.041	42.440
Jara	-0.09447	22.740	54.510
Aliyu Amba	-0.08637	25.392	78.014
Fedis	-0.35819	19.668	33.331
Gewane	-0.07419	16.327	45.614
Adaiytu	0.09835	13.722	37.454
Logya	-0.08636	14.981	25.591
Dubity	-0.12098	14.182	34.509

H2: Estimated parameters of GEV distributions for 2-day duration

Name of Station	Estimated Parameter for GEV Distribution for 2- Days		
	K value	σ value	μ value
Ginchi	-0.08366	10.548	56.720
Hombole	0.15092	12.763	62.898
Asgori	-0.05658	9.524	54.723
Aleltu	0.08247	16.578	57.296
Teji	-0.17401	11.077	51.089
Tulu Bolo	-0.22132	13.478	56.039
Ejersa Lele	-0.27788	12.866	49.790
Batu Liben	0.07307	20.073	64.546
Ancharo	-0.23326	20.593	79.520
Gunna	-0.11315	17.737	66.410
Guranda	0.00138	11.896	50.117
Dengego	-0.04539	18.485	57.579
Addis Ababa Bole	-0.03452	16.709	62.878
Addis Ababa Obs	0.21895	30.991	68.843
Akaki	0.08310	12.131	54.471
Debre Zeit	0.18291	10.015	52.552
Chefedonsa	-0.18962	13.531	54.513
Mojo	0.13386	13.304	64.956
Koka Dam	-0.01792	22.303	54.188
Melkasa	-0.25640	54.686	108.730
Adama	-0.21908	15.609	66.180
Etheya	-0.10956	11.002	51.755
Huruta	-0.27545	15.299	59.902
Welenchiti	-0.18863	18.290	72.319
Abomsa	0.04813	17.703	63.589
Makassar	-0.13064	16.725	59.152
Wurgesa	-0.13873	23.934	67.222
Ejere	-0.29679	15.541	58.939
Debre Berhan	0.03211	11.290	59.349
Debre Sina	-0.17349	26.659	104.140
Senbete	0.39125	20.323	56.518
Boru Meda	0.07557	13.370	54.118
Awash 7 Kilo	-0.09193	15.292	48.110
Melka Sedi	0.14657	16.266	44.716
Awara Melka	0.04525	18.818	46.650
Majete	-0.04693	17.450	74.211
Haik	-0.28308	17.328	77.987
Combolcha	0.00970	14.128	67.742

Bati	0.03113	18.886	74.894
Artuma	-0.06895	15.817	79.111
Asebe Teferi	-0.11174	24.796	62.106
Merssa	0.12434	15.987	71.486
Ruga	-0.21046	21.336	60.271
Nuraera	0.13538	13.578	52.436
Jara	-0.12751	27.665	73.499
Aliyu Amba	0.00092	32.814	103.800
Fedis	-0.21078	24.651	41.033
Gewane	0.07545	17.369	52.783
Adaiytu	0.12294	13.973	43.080
Logya	-0.10408	15.190	29.455
Dubity	0.10195	14.675	36.104

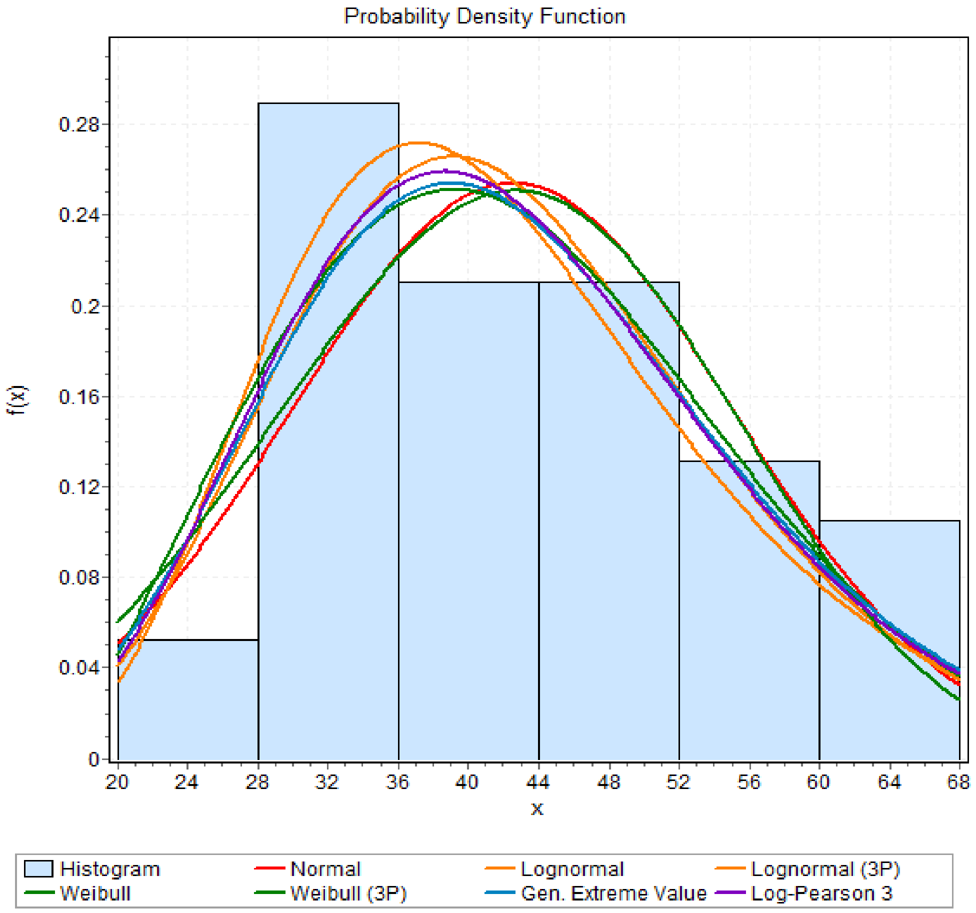
H3: Estimated parameters of GEV distributions for 3-day duration

Name of Station	Estimated Parameter for GEV Distribution for 3- Days		
	K value	σ value	μ value
Ginchi	-0.16344	12.478	68.819
Hombole	0.05602	21.763	74.038
Asgori	-0.10928	13.796	64.873
Aleltu	-0.00712	20.874	71.358
Teji	-0.23691	12.588	63.373
Tulu Bolo	-0.26907	19.958	73.644
Ejersa Lele	-0.27487	16.245	57.896
Batu Liben	-0.03562	27.563	79.286
Ancharo	-0.27080	24.148	95.503
Gunna	-0.13821	23.225	81.504
Guranda	-0.20839	16.588	64.054
Dengego	-0.03508	19.904	67.148
Addis Ababa Bole	-0.05504	21.846	79.364
Addis Ababa Obs	0.34813	37.348	85.448
Akaki	-0.17797	15.442	67.629
Debre Zeit	0.15945	10.729	63.965
Chefedonsa	-0.18387	14.105	66.856
Mojo	0.27689	13.289	77.700
Koka Dam	0.16645	25.739	61.544
Melkasa	-0.21518	80.760	153.750
Adama	-0.31600	20.196	81.496
Etheya	-0.26695	14.397	64.875
Huruta	-0.20008	15.827	68.074
Welenchiti	-0.14055	20.291	81.375

Abomsa	0.10228	19.244	71.820
Makassar	0.00786	17.673	68.209
Wurgesa	-0.12212	27.249	79.658
Ejere	0.00604	16.568	70.235
Debre Berhan	0.05765	13.843	73.573
Debre Sina	-0.19940	32.364	125.390
Senbete	0.36195	25.724	70.068
Boru Meda	-0.04262	14.571	67.110
Awash 7 Kilo	-0.05107	16.851	54.663
Melka Sedi	0.23374	16.751	52.095
Awara Melka	0.12152	20.206	52.342
Majete	-0.03258	20.988	89.110
Haik	-0.16853	18.827	91.603
Combolcha	-0.12983	18.662	81.500
Bati	-0.07794	24.454	88.730
Artuma	-0.14919	24.046	98.574
Asebe Teferi	-0.18144	29.372	73.509
Merssa	0.05089	19.279	84.812
Ruga	-0.14122	25.485	73.765
Nuraera	0.13601	14.974	58.442
Jara	-0.18026	35.204	89.287
Aliyu Amba	0.05237	37.608	119.290
Fedis	-0.17039	29.379	46.667
Gewane	0.18768	16.960	60.276
Adaiytu	0.44088	12.715	47.231
Logya	-0.19415	16.940	33.659
Dubity	0.11455	17.044	38.061

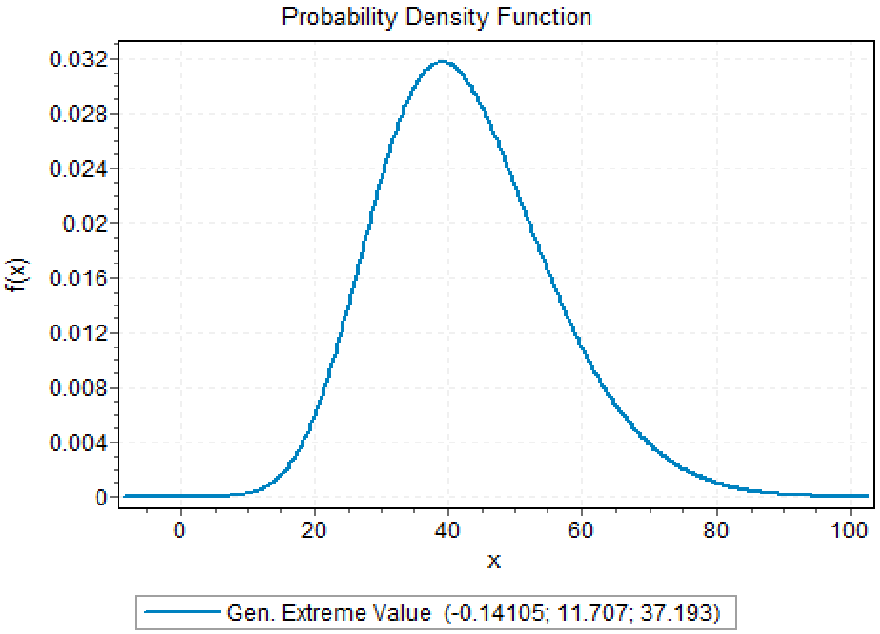
I: Probability density function and Goodness of fit summary

I1: Tulu bolo station probability density function and Goodness of fit summary

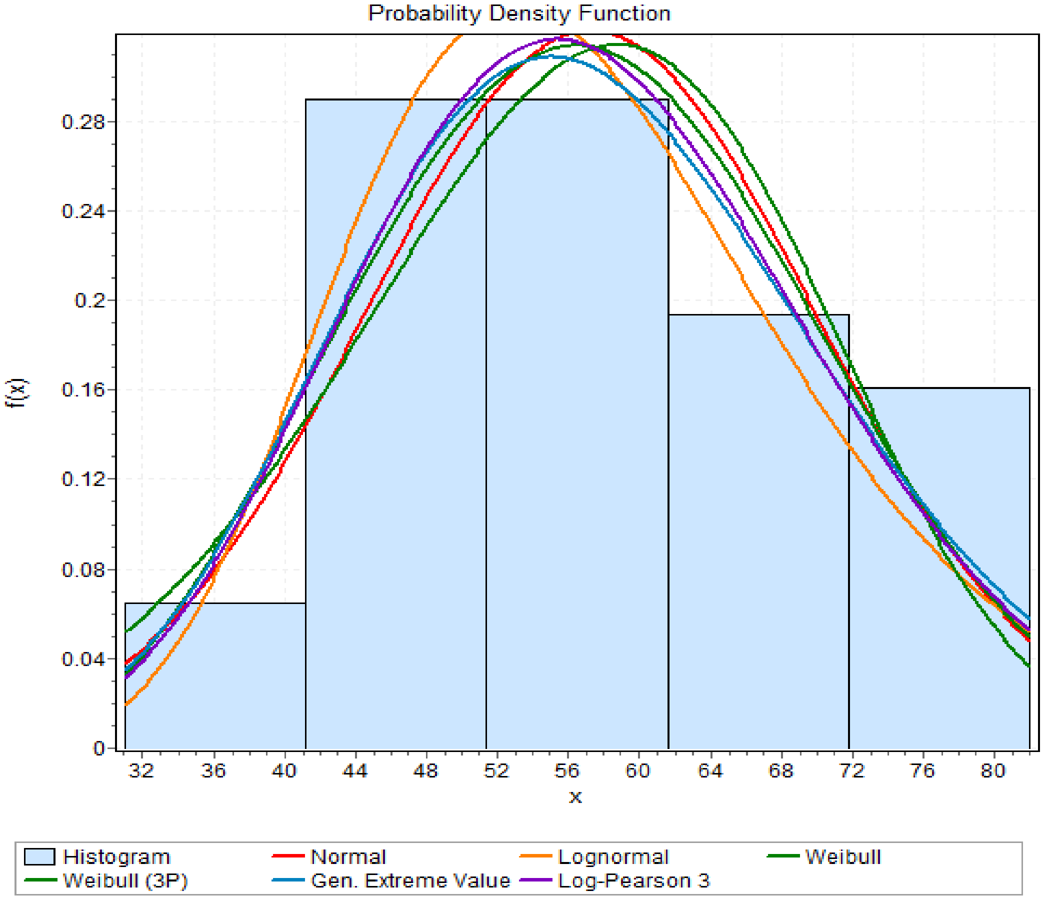


Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.11046	3	0.3217	1	0.71533	3
2	Log-Pearson 3	0.11518	5	0.33185	2	0.73129	4
7	Weibull (3P)	0.10933	2	0.3368	3	1.5574	7
3	Lognormal	0.12946	7	0.36756	4	0.56882	2
4	Lognormal (3P)	0.11894	6	0.37244	5	0.78423	5
5	Normal	0.11355	4	0.48113	6	1.2259	6
6	Weibull	0.10458	1	0.51856	7	0.56384	1

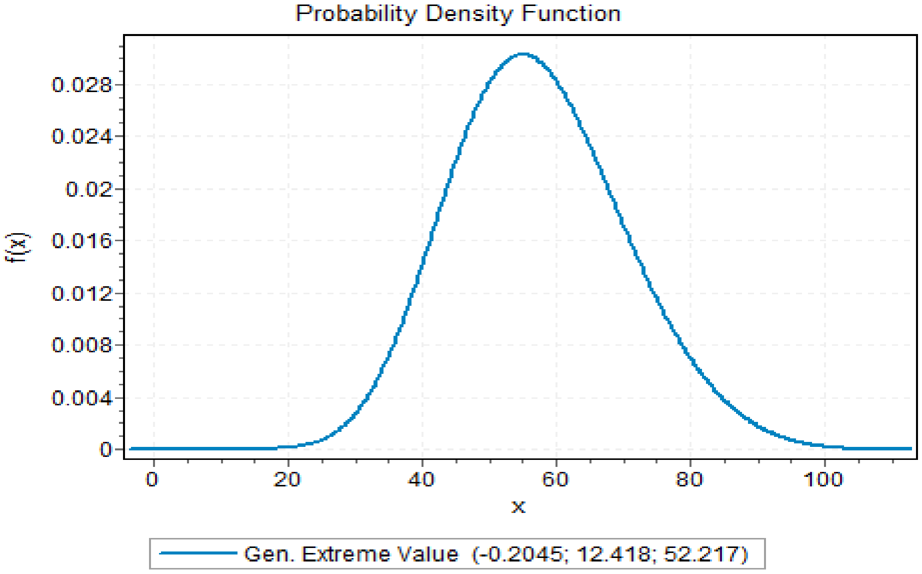


I2: Adama station probability density function and Goodness of fit summary

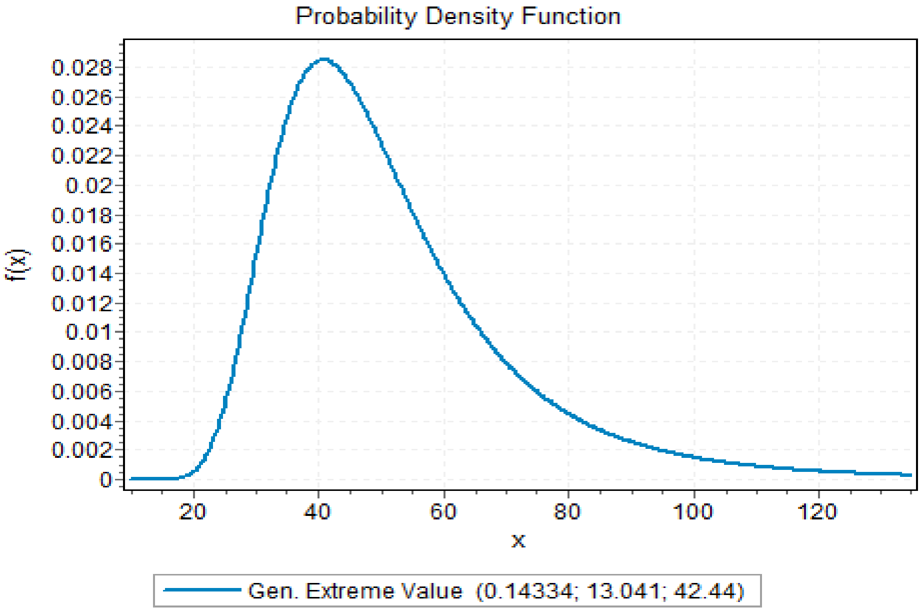


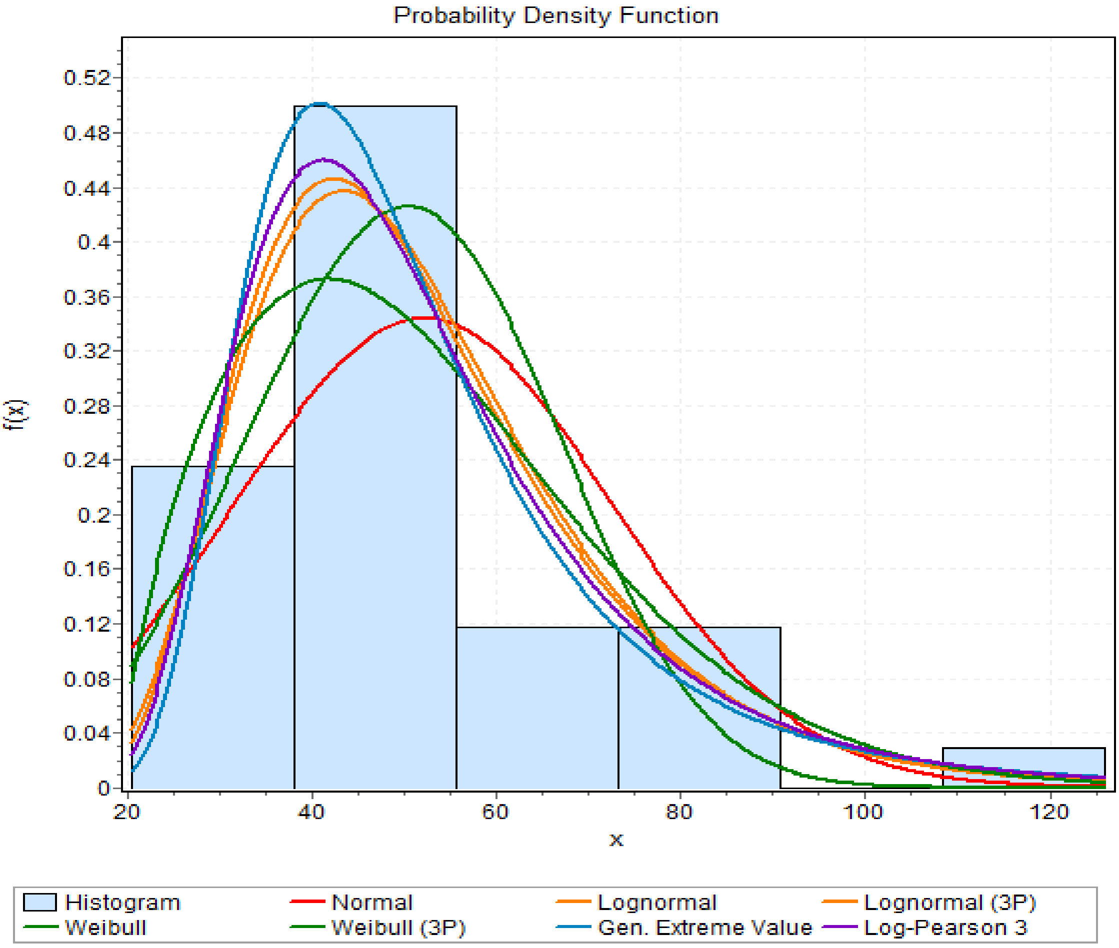
Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.07014	1	0.16603	1	0.48715	3
2	Log-Pearson 3	0.07691	3	0.17886	2	0.5294	5
3	Lognormal	0.08069	5	0.22317	5	0.50046	4
4	Normal	0.07782	4	0.22108	4	0.06973	2
5	Weibull	0.09095	6	0.31376	6	0.00892	1
6	Weibull (3P)	0.07665	2	0.19572	3	0.63145	6



I3: Nuraera station probability density function and Goodness of fit summary





Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Gen. Extreme Value	0.096	1	0.336	1	1.3544	2
2	Log-Pearson 3	0.11139	2	0.37076	2	1.2351	1
3	Lognormal	0.12219	4	0.42286	4	2.0576	4
4	Lognormal (3P)	0.11745	3	0.39163	3	3.0833	5
5	Normal	0.19495	7	1.3847	6	4.76	7
6	Weibull	0.12557	5	1.3887	7	1.7175	3
7	Weibull (3P)	0.14837	6	0.73038	5	4.0133	6

J: Estimated Rainfall depth for different Return Periods

J1: Estimated Rainfall depth for different Return Periods for 1-day duration

Station	Estimated Rainfall Depths of 1-day duration for the indicated frequency (Years) in mm											
	2	5	10	25	50	100	200	500	1000	2000	5000	10000
Ginchi	46.99	57.73	64.84	73.83	80.50	87.12	93.72	102.42	108.99	115.57	124.25	130.83
Hombole	50.90	60.55	66.94	75.01	81.00	86.95	92.87	100.68	106.59	112.49	120.29	126.19
Asgori	44.54	54.99	61.91	70.66	77.14	83.58	90.00	98.46	104.86	111.26	119.71	126.10
Aleltu	48.67	64.86	75.58	89.12	99.17	109.14	119.08	132.19	142.10	152.00	165.09	174.99
Teji	43.15	51.64	57.26	64.37	69.64	74.87	80.08	86.95	92.15	97.34	104.21	109.40
Tulu Bolo	41.51	52.57	59.88	69.13	75.99	82.80	89.59	98.54	105.31	112.07	121.01	127.77
Batu liben	47.55	58.96	66.52	76.06	83.14	90.17	97.18	106.41	113.40	120.38	129.60	136.58
Ejersa Lele	40.80	51.65	58.83	67.90	74.64	81.32	87.98	96.76	103.40	110.04	118.81	125.44
Ancharo	60.01	74.27	83.71	95.64	104.49	113.27	122.02	133.57	142.29	151.02	162.55	171.27
Gunna	54.43	66.56	74.59	84.73	92.26	99.73	107.17	116.99	124.42	131.83	141.64	149.06
Guranda	39.55	51.42	59.28	69.20	76.57	83.88	91.16	100.77	108.03	115.29	124.89	132.14
Dengego	52.76	64.43	72.16	81.92	89.16	96.35	103.51	112.96	120.11	127.25	136.68	143.82
AA. Bole	51.19	66.64	76.87	89.79	99.38	108.90	118.38	130.89	140.34	149.79	162.28	171.73
AA.Obs	59.82	82.57	97.64	116.67	130.79	144.81	158.77	177.20	191.12	205.04	223.44	237.35
Akaki	47.04	59.19	67.23	77.39	84.93	92.41	99.86	109.70	117.13	124.56	134.38	141.81
Debre Zeit	48.96	59.78	66.94	76.00	82.71	89.38	96.02	104.79	111.41	118.03	126.78	133.40
Chafedonsa	43.62	55.76	63.80	73.96	81.49	88.97	96.43	106.26	113.69	121.12	130.93	138.36
Modjo	54.13	69.19	79.17	91.77	101.12	110.39	119.64	131.84	141.05	150.27	162.45	171.66
Koka Dam	46.60	63.02	73.89	87.62	97.80	107.91	117.99	131.28	141.32	151.36	164.64	174.67
Melkasa	69.56	92.47	107.64	126.81	141.03	155.15	169.22	187.77	201.80	215.82	234.34	248.36
Adama	56.81	69.71	78.25	89.05	97.05	105.00	112.91	123.36	131.25	139.15	149.58	157.46

Etheya	42.78	53.67	60.88	69.99	76.75	83.45	90.14	98.96	105.62	112.28	121.08	127.74
Huruta	46.91	63.33	74.20	87.94	98.14	108.26	118.34	131.64	141.69	151.74	165.02	175.06
Welenchiti	64.38	77.65	86.44	97.55	105.79	113.97	122.11	132.86	140.99	149.11	159.84	167.96
Abomsa	59.49	79.82	93.28	110.29	122.91	135.44	147.92	164.38	176.82	189.26	205.70	218.14
Makassar	54.65	67.67	76.28	87.17	95.24	103.26	111.24	121.78	129.74	137.70	148.23	156.18
Wurgesa	52.76	70.45	82.16	96.96	107.94	118.84	129.70	144.03	154.85	165.68	179.98	190.80
Ejere	49.84	62.59	71.02	81.68	89.59	97.44	105.26	115.58	123.38	131.17	141.48	149.27
Debre Berhan	46.70	57.56	64.75	73.83	80.57	87.26	93.93	102.72	109.36	116.01	124.79	131.43
Debre Sina	80.21	100.44	113.83	130.76	143.31	155.77	168.19	184.57	196.95	209.33	225.69	238.06
Senbate	54.63	80.43	97.51	119.10	135.11	151.00	166.84	187.73	203.52	219.30	240.16	255.94
Boru Meda	47.19	61.36	70.73	82.58	91.37	100.09	108.79	120.26	128.92	137.59	149.04	157.70
Awash 7	46.37	58.90	67.20	77.68	85.45	93.17	100.86	111.01	118.67	126.34	136.47	144.13
Melka Sedi	43.68	65.42	79.82	98.01	111.50	124.89	138.24	155.85	169.15	182.45	200.04	213.33
Awara Melka	48.17	67.31	79.98	95.99	107.87	119.66	131.41	146.91	158.62	170.33	185.81	197.52
Majete	62.44	80.64	92.70	107.93	119.22	130.44	141.61	156.35	167.49	178.63	193.35	204.48
Haik	60.67	75.26	84.91	97.12	106.17	115.15	124.11	135.92	144.84	153.77	165.56	174.48
Combolcha	58.09	71.25	79.97	90.98	99.14	107.25	115.33	125.99	134.04	142.10	152.74	160.79
Bati	65.12	84.83	97.89	114.38	126.61	138.76	150.85	166.82	178.88	190.94	206.88	218.94
Artuma	52.67	68.76	79.42	92.88	102.87	112.78	122.66	135.69	145.54	155.38	168.39	178.23
Asebe Teferi	55.45	74.50	87.11	103.05	114.87	126.61	138.30	153.73	165.39	177.04	192.45	204.10
Merssa	59.16	73.93	83.71	96.07	105.24	114.34	123.40	135.36	144.40	153.44	165.39	174.42
Ruga	49.33	64.66	74.81	87.63	97.14	106.58	115.99	128.40	137.79	147.16	159.56	168.93
Nuraera	50.08	70.74	84.43	101.72	114.54	127.27	139.96	156.69	169.34	181.99	198.70	211.34
Jara	61.20	82.97	97.38	115.59	129.10	142.51	155.88	173.50	186.83	200.14	217.75	231.06
Aliyu Amba	88.35	117.45	136.71	161.05	179.10	197.02	214.88	238.44	256.24	274.04	297.56	315.35
Fedis	37.90	56.21	68.33	83.65	95.01	106.29	117.53	132.36	143.56	154.76	169.57	180.77
Gewane	52.34	70.26	82.13	97.12	108.25	119.29	130.29	144.80	155.77	166.74	181.23	192.19
Adaitu	44.25	61.56	73.02	87.50	98.24	108.91	119.53	133.55	144.14	154.73	168.73	179.32
Logya	31.68	49.14	60.70	75.30	86.13	96.89	107.60	121.74	132.42	143.10	157.21	167.89
Dubity	39.52	55.70	66.41	79.94	89.97	99.94	109.86	122.96	132.86	142.75	155.83	165.72

J2: Estimated Rainfall depth for different Return Periods for 2-day duration

Station	Estimated Rainfall Depths of 2-days duration for the indicated frequency (years) in mm											
	2	5	10	25	50	100	200	500	1000	2000	5000	10000
Ginchi	61.49	72.76	80.22	89.64	96.63	103.57	110.49	119.61	126.51	133.40	142.51	149.40
Hombole	69.57	84.03	93.61	105.70	114.68	123.58	132.46	144.17	153.02	161.86	173.56	182.40
Asgori	59.61	68.16	73.82	80.97	86.27	91.53	96.78	103.70	108.93	114.16	121.06	126.29
Aleltu	67.04	85.63	97.94	113.50	125.04	136.50	147.91	162.97	174.35	185.72	200.76	212.13
Teji	55.36	64.83	71.09	79.01	84.89	90.72	96.53	104.20	109.99	115.78	123.44	129.23
Tulu Bolo	60.63	72.77	80.80	90.96	98.49	105.97	113.41	123.24	130.67	138.09	147.91	155.33
Batu liben	66.56	83.84	95.28	109.73	120.45	131.10	141.70	155.69	166.27	176.84	190.81	201.37
Ejersa Lele	53.52	66.90	75.77	86.97	95.27	103.52	111.74	122.57	130.77	138.96	149.78	157.97
Ancharo	86.11	106.13	119.38	136.13	148.56	160.89	173.18	189.39	201.64	213.89	230.07	242.32
Gunna	73.88	93.16	105.92	122.05	134.02	145.89	157.72	173.33	185.13	196.92	212.51	224.30
Guranda	55.80	69.89	79.22	91.00	99.74	108.42	117.06	128.47	137.09	145.71	157.09	165.71
Dengego	66.06	83.35	94.79	109.25	119.98	130.63	141.24	155.23	165.81	176.39	190.36	200.93
AA. Bole	70.23	90.08	103.23	119.84	132.16	144.39	156.58	172.66	184.81	196.96	213.01	225.16
AA.Obs	87.79	143.07	179.67	225.92	260.22	294.27	328.20	372.96	406.79	440.61	485.31	519.12
Akaki	58.25	69.73	77.34	86.95	94.07	101.15	108.20	117.50	124.53	131.55	140.84	147.86
Debre Zeit	60.07	73.48	82.36	93.59	101.91	110.17	118.41	129.27	137.48	145.69	156.53	164.74
Chafedonsa	59.70	73.12	82.01	93.24	101.57	109.84	118.08	128.95	137.16	145.38	156.23	164.44
Modjo	71.22	86.28	96.26	108.86	118.20	127.48	136.73	148.92	158.14	167.36	179.54	188.75
Koka Dam	63.84	88.29	104.47	124.92	140.10	155.16	170.16	189.96	204.92	219.88	239.65	254.60
Melkasa	123.32	170.79	202.22	241.93	271.38	300.62	329.76	368.20	397.24	426.28	464.66	493.69
Adama	71.31	87.85	98.80	112.63	122.90	133.09	143.24	156.63	166.75	176.87	190.24	200.35
Etheya	56.72	68.93	77.01	87.22	94.79	102.31	109.80	119.69	127.15	134.62	144.49	151.95
Huruta	62.36	80.95	93.27	108.82	120.37	131.82	143.23	158.29	169.67	181.05	196.09	207.46

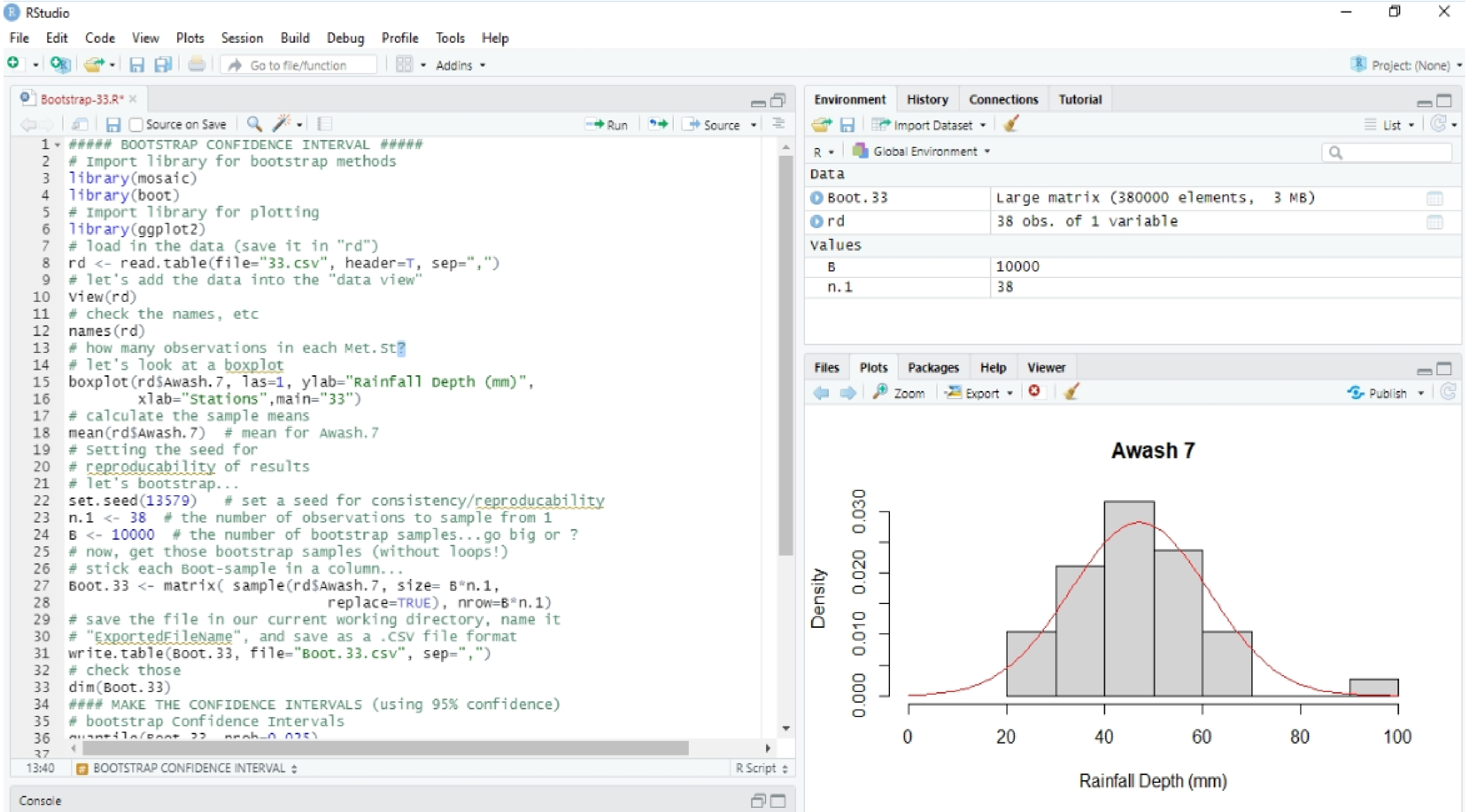
Welenchiti	80.42	96.29	106.80	120.08	129.93	139.71	149.45	162.31	172.02	181.73	194.57	204.27
Abomsa	73.13	93.62	107.19	124.34	137.06	149.68	162.26	178.86	191.40	203.94	220.51	233.04
Makassar	65.40	83.39	95.31	110.36	121.52	132.60	143.65	158.21	169.22	180.23	194.78	205.78
Wurgesa	76.25	99.45	114.80	134.21	148.60	162.89	177.13	195.91	210.10	224.29	243.05	257.24
Ejere	63.24	80.47	91.88	106.29	116.98	127.59	138.17	152.12	162.66	173.20	187.13	197.67
Debre Berhan	65.85	80.26	89.81	101.87	110.82	119.70	128.55	140.23	149.05	157.87	169.53	178.35
Debre Sina	113.67	141.66	160.20	183.63	201.00	218.25	235.44	258.11	275.24	292.37	315.01	332.14
Senbate	75.04	121.31	151.94	190.65	219.37	247.87	276.27	313.74	342.06	370.37	407.78	436.08
Boru Meda	61.70	80.07	92.23	107.60	119.00	130.31	141.59	156.46	167.70	178.94	193.80	205.03
Awash 7	54.73	70.01	80.13	92.91	102.40	111.81	121.20	133.57	142.93	152.28	164.63	173.98
Melka Sedi	54.21	76.06	90.53	108.81	122.37	135.83	149.25	166.94	180.32	193.69	211.36	224.72
Awara Melka	55.63	76.44	90.21	107.61	120.52	133.34	146.11	162.95	175.68	188.41	205.23	217.95
Majete	82.06	103.38	117.50	135.34	148.57	161.71	174.79	192.06	205.11	218.16	235.40	248.44
Haik	83.71	100.50	111.61	125.66	136.08	146.42	156.73	170.33	180.60	190.87	204.45	214.72
Combolcha	75.44	92.70	104.13	118.57	129.28	139.92	150.51	164.49	175.05	185.62	199.57	210.13
Bati	84.91	109.11	125.13	145.37	160.39	175.29	190.14	209.74	224.55	239.35	258.91	273.71
Artuma	74.68	96.16	110.38	128.35	141.67	154.90	168.09	185.48	198.62	211.76	229.12	242.26
Asebe Teferi	70.03	92.82	107.90	126.96	141.10	155.14	169.12	187.57	201.52	215.46	233.88	247.81
Merssa	78.40	101.06	116.06	135.01	149.07	163.02	176.93	195.27	209.14	223.00	241.32	255.17
Ruga	67.04	88.01	101.89	119.42	132.43	145.35	158.21	175.19	188.02	200.85	217.80	230.62
Nuraera	147.55	210.84	252.75	305.69	344.97	383.96	422.80	474.05	512.79	551.50	602.68	641.39
Jara	81.08	106.32	123.03	144.14	159.80	175.35	190.83	211.27	226.71	242.15	262.56	277.99
Aliyu Amba	118.20	160.98	189.31	225.11	251.66	278.02	304.28	338.93	365.11	391.29	425.88	452.05
Fedis	47.92	73.11	89.79	110.87	126.50	142.02	157.49	177.89	193.31	208.72	229.09	244.50
Gewane	62.01	84.76	99.82	118.85	132.97	146.98	160.95	179.37	193.29	207.21	225.60	239.51
Adaitu	50.48	69.32	81.80	97.56	109.25	120.86	132.43	147.68	159.22	170.74	185.98	197.50
Logya	35.97	53.35	64.85	79.39	90.17	100.87	111.54	125.61	136.24	146.87	160.92	171.55
Dubity	43.61	65.84	80.56	99.16	112.96	126.66	140.31	158.31	171.92	185.52	203.50	217.10

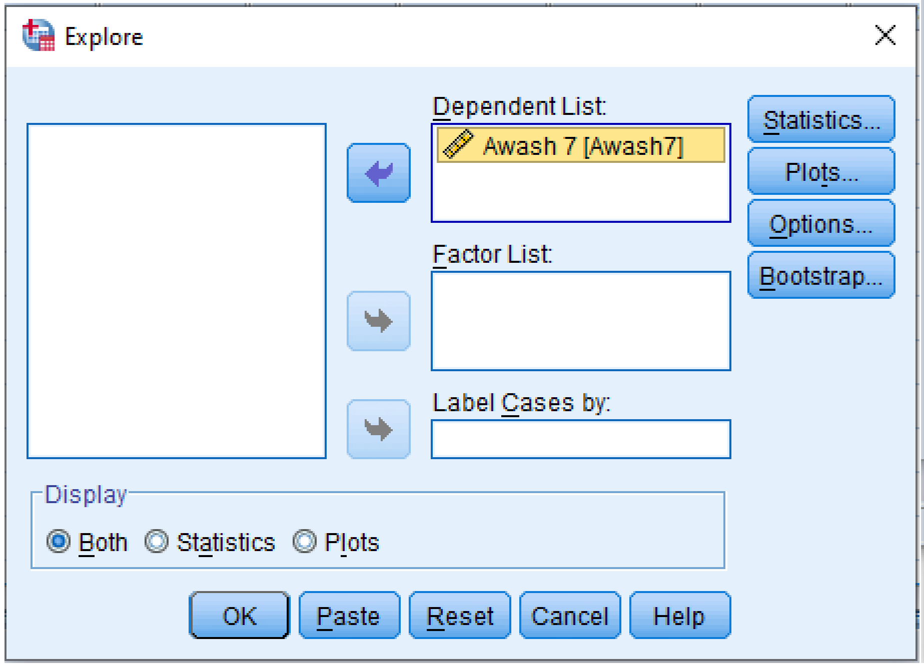
J3: Estimated Rainfall depth for different Return Periods for 3-day duration

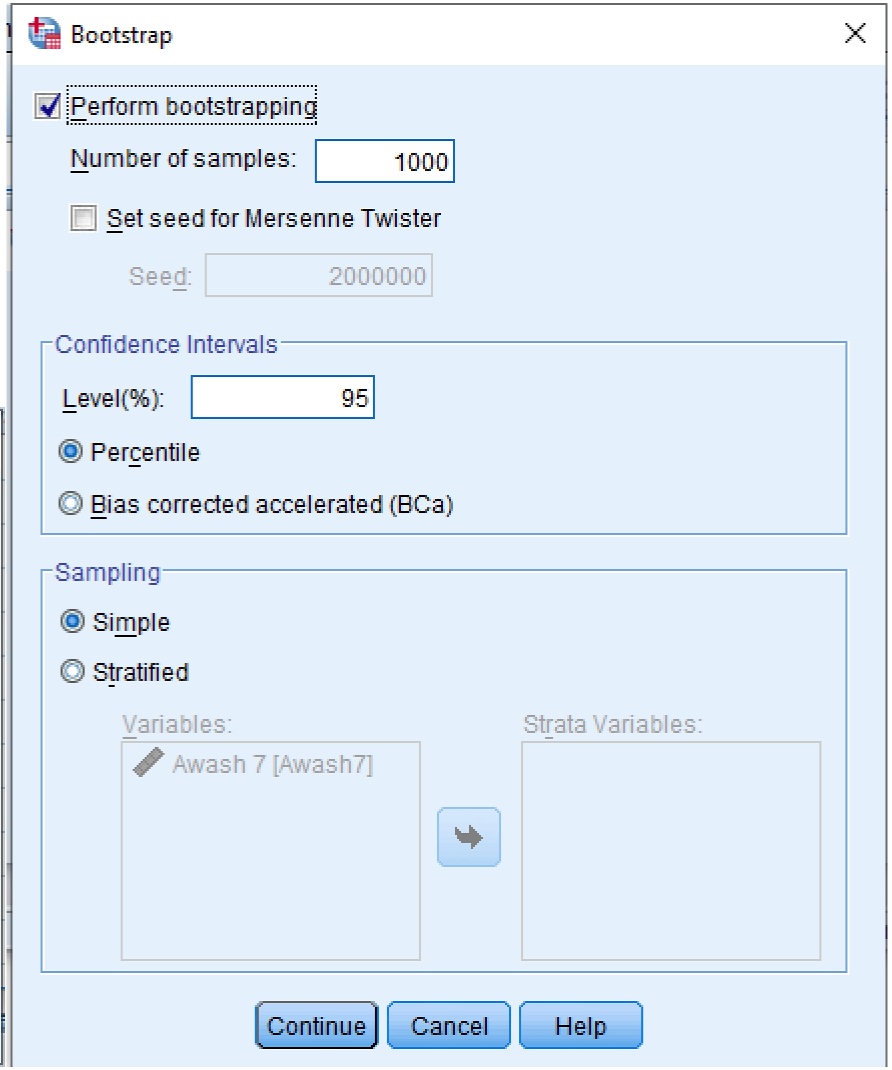
Station	Estimated Rainfall Depths of 3-days duration for the indicated frequency (years) in mm											
	2	5	10	25	50	100	200	500	1000	2000	5000	10000
Ginchi	73.88	86.16	94.28	104.54	112.16	119.72	127.25	137.19	144.70	152.20	162.12	169.63
Hombole	83.33	106.18	121.31	140.43	154.62	168.69	182.72	201.23	215.21	229.20	247.68	261.65
Asgori	71.27	83.76	92.03	102.48	110.23	117.93	125.60	135.71	143.36	151.00	161.10	168.74
Aleltu	82.12	102.44	115.90	132.90	145.51	158.03	170.51	186.96	199.40	211.83	228.27	240.70
Teji	67.80	78.40	85.42	94.28	100.86	107.39	113.90	122.48	128.96	135.45	144.02	150.50
Tulu Bolo	79.64	97.10	108.66	123.26	134.10	144.85	155.57	169.70	180.39	191.07	205.18	215.86
Batu liben	82.53	104.74	119.45	138.03	151.81	165.49	179.12	197.11	210.70	224.29	242.25	255.83
Ejersa Lele	62.59	78.92	89.73	103.39	113.52	123.58	133.60	146.82	156.81	166.80	180.00	189.98
Ancharo	102.71	125.96	141.36	160.82	175.25	189.58	203.85	222.68	236.92	251.14	269.95	284.17
Gunna	90.47	116.51	133.75	155.53	171.69	187.73	203.72	224.80	240.74	256.67	277.73	293.65
Guranda	69.47	85.80	96.62	110.28	120.42	130.48	140.51	153.73	163.73	173.72	186.93	196.92
Dengego	76.54	95.60	108.21	124.16	135.99	147.73	159.43	174.86	186.52	198.18	213.60	225.25
AA. Bole	88.48	114.42	131.60	153.30	169.40	185.39	201.31	222.32	238.20	254.07	275.05	290.91
AA.Obs	114.15	200.26	257.27	329.30	382.74	435.79	488.64	558.36	611.06	663.74	733.36	786.02
Akaki	69.55	80.69	88.07	97.40	104.31	111.18	118.02	127.04	133.86	140.68	149.69	156.51
Debre Zeit	72.02	85.77	94.87	106.37	114.91	123.38	131.81	142.95	151.36	159.77	170.89	179.30
Chafedonsa	72.60	86.96	96.47	108.48	117.39	126.24	135.05	146.68	155.47	164.25	175.86	184.65
Modjo	86.74	104.88	116.90	132.08	143.34	154.52	165.66	180.36	191.46	202.56	217.24	228.34
Koka Dam	76.94	112.31	135.72	165.31	187.25	209.04	230.75	259.38	281.03	302.66	331.26	352.89
Melkasa	176.98	248.40	295.68	355.42	399.74	443.74	487.57	545.40	589.10	632.79	690.54	734.21
Adama	87.27	107.34	120.62	137.41	149.86	162.22	174.54	190.78	203.06	215.34	231.56	243.84
Etheya	69.89	84.07	93.46	105.32	114.12	122.85	131.55	143.03	151.71	160.38	171.85	180.52
Huruta	71.16	91.13	104.35	121.06	133.45	145.75	158.01	174.18	186.40	198.62	214.77	226.98
Welenchiti	92.28	110.31	122.24	137.33	148.51	159.62	170.68	185.28	196.32	207.35	221.92	232.95
Abomsa	82.27	111.13	130.24	154.38	172.29	190.07	207.78	231.15	248.81	266.47	289.80	307.45

Makassar	76.78	98.16	112.33	130.22	143.49	156.67	169.80	187.12	200.21	213.29	230.58	243.67
Wurgesa	91.75	117.25	134.14	155.47	171.30	187.01	202.66	223.31	238.92	254.52	275.14	290.74
Ejere	78.46	100.65	115.34	133.90	147.67	161.34	174.96	192.93	206.51	220.08	238.02	251.59
Debre Berhan	81.88	100.01	112.02	127.19	138.45	149.62	160.75	175.44	186.54	197.63	212.29	223.39
Debre Sina	136.45	169.62	191.58	219.33	239.92	260.35	280.71	307.58	327.88	348.17	374.99	395.28
Senbate	92.08	147.66	184.46	230.96	265.45	299.69	333.81	378.81	412.83	446.83	491.77	525.77
Boru Meda	74.36	91.52	102.89	117.24	127.90	138.47	149.00	162.90	173.41	183.91	197.78	208.28
Awash 7	62.51	79.99	91.57	106.19	117.04	127.81	138.54	152.69	163.39	174.09	188.22	198.91
Melka Sedi	63.57	89.68	106.98	128.82	145.03	161.12	177.15	198.30	214.28	230.26	251.38	267.35
Awara Melka	63.40	88.23	104.66	125.43	140.84	156.13	171.37	191.47	206.66	221.85	241.92	257.11
Majete	98.80	124.58	141.65	163.21	179.21	195.09	210.92	231.79	247.57	263.34	284.18	299.95
Haik	99.32	118.99	132.02	148.47	160.68	172.80	184.87	200.80	212.84	224.87	240.77	252.80
Combolcha	89.53	109.41	122.56	139.19	151.53	163.77	175.97	192.06	204.22	216.38	232.45	244.61
Bati	99.36	127.63	146.35	170.00	187.55	204.96	222.32	245.21	262.51	279.81	302.67	319.96
Artuma	92.93	123.47	143.69	169.23	188.18	206.99	225.73	250.46	269.15	287.83	312.52	331.20
Asebe Teferi	81.52	107.32	124.40	145.99	162.00	177.89	193.73	214.62	230.41	246.19	267.06	282.83
Merssa	92.34	117.88	134.78	156.14	171.98	187.71	203.38	224.06	239.68	255.30	275.95	291.56
Ruga	82.69	109.06	126.51	148.57	164.94	181.18	197.37	218.72	234.86	250.99	272.31	288.44
Nuraera	67.55	90.60	105.86	125.14	139.44	153.64	167.78	186.45	200.55	214.65	233.28	247.38
Jara	97.79	128.56	148.94	174.68	193.77	212.73	231.61	256.53	275.36	294.18	319.06	337.88
Aliyu Amba	136.81	191.57	227.84	273.65	307.64	341.38	374.99	419.34	452.86	486.36	530.64	564.14
Fedis	55.47	86.64	107.28	133.36	152.70	171.90	191.03	216.27	235.35	254.41	279.62	298.68
Gewane	71.15	97.04	114.19	135.85	151.91	167.86	183.75	204.72	220.56	236.40	257.34	273.17
Adaitu	57.83	81.09	96.48	115.93	130.36	144.69	158.96	177.79	192.02	206.24	225.04	239.26
Logya	40.11	58.01	69.85	84.82	95.93	106.95	117.93	132.42	143.37	154.32	168.79	179.73
Dubity	47.10	71.97	88.43	109.24	124.67	139.99	155.25	175.39	190.61	205.83	225.94	241.15

K: R-Statistics coding and IBM SPSS statistics results




Explore
Dependent List:
Awash 7 [Awash7]
Factor List:
Label Cases by:
Statistics...
Plots...
Options...
Bootstrap...
Display
Both
Statistics
Plots
OK
Paste
Reset
Cancel
Help


Bootstrap
Perform bootstrapping
Number of samples: 1000
Set seed for Mersenne Twister
Seed: 2000000
Confidence Intervals
Level(%): 95
Percentile
Bias corrected accelerated (BCa)
Sampling
Simple
Stratified
Variables:
Awash 7 [Awash7]
Strata Variables:
Continue
Cancel
Help