ARBA MINCH UNIVERSITY

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Department of Hydrology and Water Resources Management

Development and Regionalization of Intensity- Duration-Frequency (IDF) Relationships for Amhara and Tigray Regions

By
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CERTIFICTION

The undersigned certify that he has read and here by recommend for acceptance by the University of Arba Minch a thesis entitled: **Development and Regionalization of Intensity-Duration-Frequency (IDF) Relationships for Amhara and Tigray Regions** in partial fulfillment of the requirement of the degree of Masters of Science in Hydrology and Water Resources Management.

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Dr. Semu Ayalew Moges

Advisor

Date____________

DECLARATION AND COPYRIGHT

I, Asres Geda, declare that this is my own original work and that it has not been presented and will not be presented to any other University for similar or any other degree award.

Signature________________

DEDICATION

This work is dedicated to my lovely mother, who taught me the best skills to tackle life challenges, and to my lovely wife.

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ABSTRACT

Rainfall of a place can be completely defined if the intensities, durations and frequencies of the various storms occurring at that place are known. Intensity-Duration-Frequency (IDF) relationship is one of the most commonly used tools which provide essential information for planning, designing and operation of water resource projects. Therefore, the main purpose of this research work was to develop operational IDF relationships for Amhara and Tigray regional states based on thirty three first class stations.

Rainfall charts of different years were used to collect annual maximum rainfall depths of varying durations. The best fitted probability distributions are selected for all the principal stations and based on these distributions quantiles are estimated. With the help of the general mathematical forms of IDF, IDF-Curves and IDF-Maps intensities of each station were determined.

Amhara and Tigray regional states have been regionalized and five different regions were established based on pooled quantiles of the 24-hour durations. And the regionalization is used for the determination of intensity of rainfall for areas farthest from the principal stations.

IDF relationship being an important hydrologic tool it helps to fill the gap between the design need and the unavailability of design information. Therefore, the IDF relationship developed in this study can be used to extract vital information's on rainfall intensity, duration and frequency relationships which are highly required by water resource professionals and designers.

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ABBREVATIONS AND ACRONYMS

AM	Annual Maximum
CC	Coefficient of Variation of the coefficient of variation
Ck	Coefficient of Kurtosis
Cs	Coefficient of Skewness
CSA	Central Statistics Authority
Cv	Coefficient of Variation
EVI	Extreme value type I
GEV	Generalized Extreme Value
IDF	Intensity-Duration-Frequency
L-Ck	L-Coefficient of Kurtosis
L-Cs	L-Coefficient of Skewness
L-Cv	L-Coefficient of variation
L-MRD	L-moment ratio diagrams
ML	Maximum Likelihood
MOM	Method of Ordinary Moments
MRD	Moment ratio diagrams
NMSA	National Meteorological Service Agency
PWM	Probability Weighted Moment
SEE	Standard Error of Estimate
SMADA	Storm water Management and Design Aid
WMO	World Meteorological Organization

CHAPTER ONE

INTRODUCTION AND BACKGROUND

1.1. Introduction

Rainfall of a place can be completely defined if the intensities, durations and frequencies of the various storms occurring at that place are known. Whenever, an intense rain occurs, its magnitude and duration is generally known from the meteorological readings. Thus, at a given station, the magnitudes of the isolated rains of various durations, such as 5, 10, 15 minutes, etc., are generally known. This available data can be used to determine the frequencies of the various rains.

One of the first steps in many hydrologic design projects, such as in urban drainage design, is the determination of the rainfall event or events to be used. The most common approach is to use a design storm or event that involves a relationship between rainfall intensity (or depth), duration, and the frequency or return period appropriate for the facility and site location. In many cases, the hydrologist has standard intensity-duration-frequency (IDF) curves available for the site and does not have to perform this analysis. However, it is worthwhile to understand the procedure used to develop the relationships. Usually, the information is presented as a graph, with duration plotted on the horizontal axis, intensity on the vertical axis, and a series of curves, one for each design return period (Chow, 1988).

Rainfall Intensity-Duration-Frequency curves (IDF curves) are graphical representations of the amount of water that falls within a given period of time. The Intensity of rainfall (I) is the rate at which it is falling, Duration(D) is the time for which it is falling with that given intensity and Frequency(F) is the average recurrence time of that magnitude of rainfall.

The development of intensity duration frequency IDF curves for precipitation remains a powerful tool in the risk analysis of natural hazards. Indeed the IDF curves allow for the estimation of the return period of an observed rainfall event or conversely of the rainfall amount corresponding to a given return period for different aggregation times (Gerbi, 2006).

This research work is intended to develop IDF relationships for thirty different first class recording climatological stations in Amhara and Tigray regional states and three neighbouring stations.

To develop IDF curves Annual maximum values of rainfall for different durations will be collected from selected meteorological stations. And from this data intensities can be driven directly. The minimum criteria proposed where each station should have a length of more than 10 years record.

1.2. Back ground

Some research work were done about IDF in SNNPR, Oromia region and Northern Ethiopia.Though the northern part of Ethiopia is very wide, the earlier research work for Northern Ethiopia had only included 11 stations. As it is clearly observed that, former researches about IDF had not covered the whole Ethiopia and there were no chance to get standard IDF relationships.

In addition to the results of the aforementioned researchers for SNNPR, Oromiya region and some parts of Northern Ethiopia, this research work (for Amhara & Tigray regions) will have great contribution for the establishment of comprehensive IDF relationships all over the country.

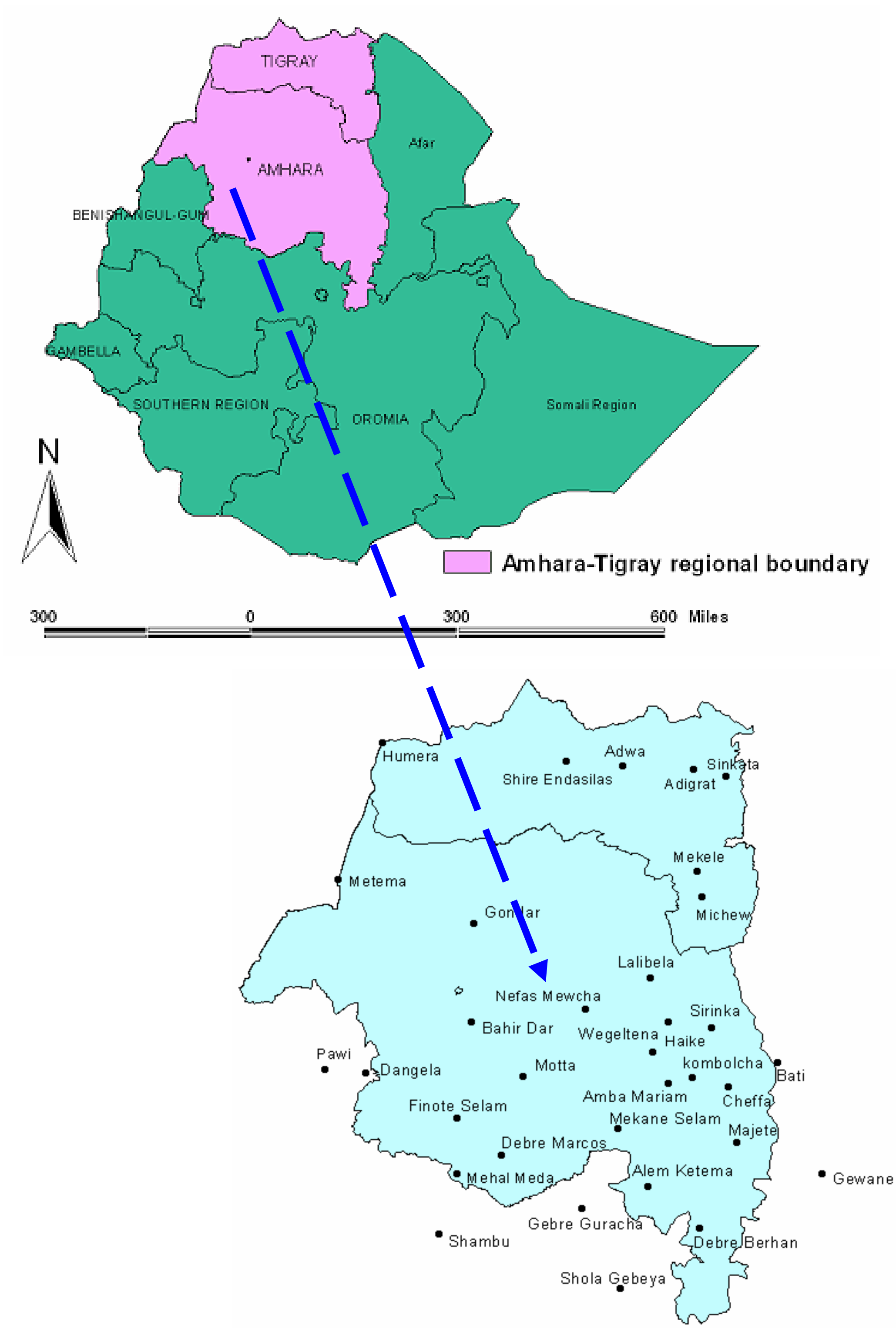
1.3 General Description of the study area

The Amhara region is located in the northern part of Ethiopia with a total area of approximately 170,752 square kilometres (km^2). The region has boundary with Tigray in the north, with Sudan and Benishangul / Gumz in the west, with Oromiya in the south and with Afar region in the east. It is between 8^0 45' to 13^0 30' N latitude and 36^0 20' to 40^0 45' E longitude.

Tigray national regional state is one of the regional states located in the northern part of the country. It has total area of 53,386 km^2 and population of 4.236 million at the end of 2005, of which about 82% accounts for rural population. It is bounded to the north by Eritrea, to the west by the Sudan and to the east and south by the Afar and Amhara regions of Ethiopia.

The region has poor socio-economic development. More than 58% of the total population is living in absolute poverty (earning less than a dollar a day). It is one of the regions vulnerable to recurrent drought and with depleted natural resources. It is approximately between 12^0 15' to 14^0 50' N latitude and 34^0 30' to 38^0 02' E longitude.

Figure 1.1 Location map of the study area



1.4 Problem Statement

Now a day we experience the devastating effects of natural hazards (e.g. flood) in different parts of the country. And the availability of Intensity-Duration-Frequency relationship in standard form, at different regions, is not satisfactory.

Though Intensity- Duration- Frequency (IDF)curves and maps are key tools and principal inputs for planning and design of water resource projects, highways, etc., they are not yet well developed and readily available throughout the country.

For protecting our nation from catastrophic effect of extreme events and to safeguard different infrastructures, the development of standard IDF curve for different regions of the country will be quite important.

1.5. Objectives of the Study

1.5.1 General objective

- The main objective of this study is to show distribution and variability of rainfall and to develop Intensity- Duration- Frequency relationships for Amhara and Tigray Regions.

1.5.2 Specific objectives

1. To develop families of Intensity- Duration- Frequency curves for different stations of the two regions for varying durations and return periods.
2. To construct Intensity- Duration- Frequency maps, that covers the two regions, based on the available first class stations.
3. To generate IDF parameters and to establish mathematical relationship (equation) among Intensity, Duration and Frequency.

4. To group homogeneous regions together and to establish regional IDF relationships.

1.6. Significance of the study

The result of this study will be useful to estimate the intensity and duration of an extreme rainfall event which is ultimately required for planning and design of water resource projects, flood control and flood plain mapping program, urban drainage works, highway and culvert design, etc. Therefore, establishment of IDF-curves (for these two regions) is an important task in a way that institutions and engineers involved in design and evaluation of water resource projects, highways, urban drainage works, etc. in these regions will utilize the result of this study.

1.7. Scope of the study

This research work is limited to the development of IDF relationships, construction of IDF maps covering Amhara & Tigray regions and grouping homogeneous regions together to develop the regional IDF relationship based on the available first class automatically recording rainfall stations in and around the two regions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Rainfall data analysis

Different characteristics of rainfall are important to specialists involved in various fields, and therefore the number of ways of analyzing rainfall data is virtually unlimited. The method chosen depends up on the nature of the available data and the purpose of the investigation. A relatively small number of rainfall-measuring stations are equipped with continuously recording gauges, which yield data on the characteristics of individual storms such as timing and intensity as well as total amount.

Rainfall could be classified according to the amount of rain that is falling in a specified time. And thus it could be classified as Very light (< 0.25 mm/hr), Light (0.25 mm/hr - 1.0 mm/hr), Moderate (1.0 mm/hr - 4.0 mm/hr), Heavy (4.0 mm/hr - 16.0 mm/hr), Very heavy (16.0 mm/hr – 50 mm/hr), and Extreme (> 50.0 mm/hr) (www.najah.edu)

2.1.1 Seasonal variability of rainfall

The seasonal (or intra-annual) variability of precipitation is an important aspect of hydro climatology because it largely determines the seasonality of other hydrologic quantities, such as stream flow and ground water recharge. The seasonal pattern of relative heating of the continents and the migration of large scale circulation features largely control the seasonality of precipitation on a global scale. Monsoon regions in particular have pronounced seasonal variability of precipitation. One way of quantitatively describing seasonality is by means of circular statistics which is useful for quantifying the time of occurrence of events when time is measured on a circle like a clock. The quantification involves calculating average time of occurrence and the degree to which the events tend to be concentrated in time called the seasonality index (Dingman, 2002).

2.1.2 Frequency analysis of point rainfall

For point precipitation frequency analysis, the annual maximum precipitation for a given duration is selected from each year of historical record and for each of series of durations. For each duration frequency analysis is performed on the data to derive the design precipitation depths for various return periods; then the design depths are converted to intensities by dividing by the precipitation duration (Chow, 1988)

Rainfall data can be estimated using either point measured (rain gauge) or measurement over an area (using radar and satellite). Methods of estimating aerial average rainfall (from point measurement) on a basin involve; arithmetic average, Thiessen weighted average and Isohytal methods. According to the World Meteorological Organization (WMO, 1994) cited in Cherkos (2002) for small drainage areas of about 25 sq. km., some sort of relationship needs to be made to relate the rainfall depth to the catchment’s area. When an area is larger than 25 sq. km, the observation from a single station (even if it is at the center of the catchement) is inadequate for the design of drainage works. All the rainfall records within the catchement and its immediate surrounding must be analyzed to take proper account of the spatial and temporal variation over the basin.

2.2 Intensity – Duration – Frequency Relationships

An IDF curve enables the hydrologists to develop hydrologic systems that consider worst-case scenarios of rainfall intensity and duration during a given interval of time. The idea here is that high intensity rainfall in short periods may cause catastrophic consequences. For instance, in urban watersheds, flooding may occur such that large volumes of water may not be handled by the storm water system. Thus, appropriate values of precipitation intensities and frequencies should be considered in the design of the hydrologic systems

The first step in many hydrologic design projects, such as in urban drainage design is the determination of the rainfall event or events to be used. The most common approach is to use a design storm or event that involves a relationship between rainfall intensity (or depth), duration, and the frequency or return period appropriate for the facility and site location. In many cases, the hydrologist has standard intensity duration frequency (IDF) curves available for the site and does not have to perform this analysis. The IDF is usually presented as a graph, with duration plotted on the horizontal axis, intensity on the vertical axis, and a series of curves, one for each design return period (Chow, 1988)

It is usual to provide curves which are graphical representation of the amount of water that falls within a given period of time on a particular area. When a particular rainfall is referred to as a 2-hr, 100-yr storm, it means that the rain will last for two hours (duration) and will only be equaled or exceeded once every one hundred years (frequency) in that particular area. Understanding the significance of each curve, it is then a simple matter to determine the amount of rainfall (intensity) for that particular area during that time period.

2.3 IDF analysis at point

In order to analyze IDF at a given point, maximum amount of annual rainfall for specific duration of first class stations in the study area must be collected. The analysis begins with a review of the history of the weather station to assure that measurement conditions have not changed significantly during the period of record.

Assuming that conditions have been stable, it needs to examine the rainfall records to determine the annual maximum rainfall for each duration of interest for the period of record (this is by far the most time consuming step in the process). In practice one would use the complete record of each rainfall from stations. The next step is to compute the estimated quantile for each value. Interpolation to determine the depths associated with the return periods of interest is usually done on a graph with depth or intensity plotted on a logarithmic or arithmetic scale (which ever gives a smoother and more nearly straight–line pattern) and exceedence probability on a probability scale (Dingman, 2002)

There are different research outputs of IDF relationships in different parts of the world. David Yarnell developed the first "intensity-frequency maps" for the United States in 1935. Yarnell studied 30 years of rainfall intensity-frequency. In 1955, the U.S. Weather Bureau (USWB) and the Soil Conservation Service (SCS) defined the depth-area-duration-frequency regime in the United States.

In 1961 the U.S. Weather Bureau published the Rainfall Frequency Atlas of the United States, commonly known as Hirschfield's Technical Paper No. 40 (TP-40). This document contains rainfall depth maps of the United States for the 1-, 2-, 5-, 10-, 25-, and 100-year recurrence interval storms for durations of 1-, 2-, 3-, 6-, 12-, and 24-hours for areas east of the 105° meridian. For storm durations of less than 1 hour the TP-40 information was superseded by NOAA's technical Memorandum "NEW HYDRO –35."

However, TP-40 wasn't always accurate. One of the problems with TP-40 is that its 100-year, 24-hour values were exceeded too frequently in certain regions of the Midwest. To combat this problem, the National Oceanic and Atmosphere Administration's Midwestern Climate Center has produced a new study that applies to nine states across the Midwest (Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) and it is referred to as

Bulletin 71. Bulletin 71 has a much larger, longer sample of precipitation data that was available for previous U.S. studies. It is a combination of appropriate statistical techniques, guided by available meteorological and climatological knowledge of atmospheric processes.

E.M. West and W. H. Sammons generated the first curves for the Commonwealth of Kentucky in 1955 (Kentucky Department of Highways, Division of Research, Report No. 108, “A Study of Runoff from Small Drainage Areas and the Opening in Attendant Drainage Structures”). They were updated in 1968 by K.D. Clark (Kentucky Department of Highways, Division of Research, Report No. 250, “Application of Stanford Watershed Model Concepts to Predict Flood Peaks for Small Drainage Areas”) and again in 1985 by Jessie Mays. The curves have not been updated since that time.

As a result, the Kentucky Transportation Cabinet (KyTC) approved Research Study KYSPR 98-178, entitled “Revision of Rainfall Intensity-Duration Curves for Kentucky” in 1998. The objective of this research study was to revise and update the rainfall-intensity-duration-frequency curves for Kentucky to include weather data from 1984 through the present (Dupont, B.S and Allen, D.L, 2000).

2.4. Computation Equations for IDF relationships

The intensity of storms decreases with the increase in storm duration. Further, a storm of any given duration will have a larger intensity if its return period is large. In other words, for a storm of given duration, storms of higher intensity in that duration are rather than storms of smaller intensity.

IDF Curves have also been expressed as equations to avoid having to read the design rainfall intensity from a graph. For example, Wenzel (1982) provided coefficients from a number of cities in the United States for an equation of the form

$$i = \frac{C}{T^{e}{}_{d} + f} \text{ --- (2.1)}$$

Where i is the design rainfall intensity, T_d is the duration, and C, e, and f are coefficients varying with location and return period (Chow, 1988).

It is also possible to extend the above equation to include the return period T using the equation

$$i = \frac{CT^{m}}{T_d + f} \quad or \quad i = \frac{CT^{m}}{T_d{}^{e} + f} \text{ ---------------- ------------------ (2.2)}$$

Wenzel, (1982) has also proposed a relationship between intensity–Duration–Frequency which is applicable in most locations by the equation of the form

$$I = \frac{A}{(D + B)^{C}} \quad or \quad I = \frac{A}{D^{C} + B} \text{ ---------------------------------- (2.3)}$$

Where: I is intensity, D is duration, A is a constant for a given return period and B and C are constants that do not depend on return period. These equations have no theoretical basis; they are purely empirical devices that are some times useful for expressing relations such as depth–exceedence probability and return period. The constants in the above equation have a strong geographic variation and must be determined by analysis of data for the location of interest.

Intensity duration frequency (IDF) analysis is used to capture the essential characteristics of point rainfall. IDF analysis provides a convenient tool to summarize regional rainfall information, and is used in municipal storm water management practice.

Thus, in this study the Intensity duration frequency (IDF) analysis starts by gathering time series records of different durations. After time series data is gathered for the selected stations, annual extremes are extracted from the record of each duration. The annual extreme data is then fit to a probability distribution in order to standardize the character of rainfall across stations with widely varying lengths of record.

2.5. Rainfall Frequency Analysis

Frequency analysis is the estimation of how often a specified event will occur. Because there are numerous sources of uncertainty about the physical processes that gives rise to observed events (Hosking and Wallis, 1997), the primary objective of frequency analysis is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions. Data observed over an extended period of time are analyzed in frequency analysis and are assumed to be independent and identically distributed.

Rainfall frequency of various intensities and durations are used extensively in the design and management of many water resources projects involving natural hazards, due to extreme rainfall events. Perhaps the most common frequency analysis consists of developing a relationship between rainfall intensity (depth), duration (minutes), and the frequency (or return period). Such relationships are known as IDF curves or equations and are usually derived using observed annual maximum (AM) series at one site (at-site) or several sites (regional analysis). The IDF relationships are used to calculate design storms used in many practical application. In developing the IDF relationships, the estimates of the rainfall intensity for a given duration (expressed in minutes or hours), and the frequency (or return period expressed in years), can be obtained from frequency analysis employing various probability distributions (such as Gumbel distribution) and parameter estimation methods (such as method of moments).

In practice, the true probability distribution of the data at a site or a region is unknown. The assumption that data in a given system arise from simple parent distribution may be questionable when data from large watersheds are analyzed. In such cases more than one type of rainfall may contribute to extreme events in a region. However, for the analysis to be of practical use, simpler distributions are often used to characterize the relation between magnitudes and their frequencies (Rao, et. al. 2000).

Choice of distribution for AM series has received special attention globally. The choice of distribution is influenced by many factors, such as methods of discrimination between distributions, methods of parameters estimation, the availability of data, etc. Generally, there is no general global agreement as to a preferable technique of model choice and no single one distribution accepted universally. For example,

1. Log Pearson type III distribution was recommended by U.S. Water Resource council (1967) for USA
2. General Extreme Value (GEV) distribution was recommended by the Natural Environmental Research council (NERC,1975) for U.K. and Ireland.
3. Pearson type III was selected by the institute of Engineers in Australia, etc.

In general the chosen distribution should be (Cunnane, 1989) widely accepted, simple and convenient to apply, consistent, flexible, or robust, theoretically well based, or documented in the guide.

There are many distributions that have been suggested for Annual Maximum (AM) series models. The list and mathematical form of this distribution is presented in Appendix H.

2.6. Selection and evaluation of Parent distributions

2.6.1 Conventional moments

Several techniques have been used in the past for evaluating the suitability of different distributions for AM series.

Moment about the origin or about the mean are used to characterize probability distributions. For a distribution with a probability density function *f(x),* the r^{th} moment about the origin is given by

$$\mu_r' = \int_{-\infty}^{\infty} x^r f(x)dx, \qquad \mu_1' = \mu = mean \text{ ------------------------ } (2.4)$$

The Central moments μ_r are computed by

$$\mu_r = \int_{-\infty}^{\infty} (x-\mu_1')^r f(x)dx, \qquad \mu_1 = 0 \text{ ---------------------- } (2.5)$$

Sample moments m'_r and m_r, on the other hand, are calculated as

$$m'_r = \frac{1}{n}\sum_{i}^{n} x^r{}_i, m_1' = \overline{X} = \text{Sample mean -------------------------- } (2.6)$$

$$m_r = \frac{1}{n}\sum_{i=1}^{n} (X_i - \overline{X})^r, m_1 = o$$

These moments are often biased and may be corrected by (Cunnane, 1989)

$$\hat{m}_2 = \frac{1}{N-1}\sum(X_i - \overline{X})^2$$

$$\hat{m}_3 = \frac{N}{(N-1)(N-2)}\sum(X_i - \overline{X})^3 \text{ ---------------------------- } (2.7)$$

$$\hat{m}_4 = \frac{N^2}{(N-1)(N-2)(N-3)}\sum(X_i - \overline{X})^4$$

The conventional moment ratios are defined as;

$$The\ coefficient\ of\ \mathrm{var}iation,\quad C_V = \frac{\hat{m}_2^{1/2}}{\hat{m}_1}$$

$$The\ coefficient\ of\ skewness,\quad C_S = \frac{\hat{m}_3}{\hat{m}_2^{3/2}} \text{ -------------------------- (2.8)}$$

$$The\ coefficient\ of\ kurtosis,\quad C_K = \frac{\hat{m}_4}{\hat{m}_2^2}$$

2.6.2 Probability weighted moments

Probability weighted moments (PWM) are defined by Green wood et al. (1979) as stated in Rao and Hamed (2000)

$$M_{p,r,s} = E\left(x^p F^r (1-F)^s\right) = \int_o^1 (x(F))^p F^r (1-F)^s dF \text{ ---- (2.9)}$$

In particular, the following two moments $M_{1,0,s}$ and $M_{1,r,0}$ are often considered

$$M_{1,0,s} = \alpha_s = \int_o^1 x(F)(1-F)^S dF$$

$$M_{1,r,0} = \beta_r = \int_0^1 x(F)F^r dF \qquad \text{------------------------------------- (2.10)}$$

Where: p, r, and s are real numbers

The plotting position estimates for sample PWM_S are given by

$$a_s = \hat{\alpha}_s = \hat{M}_{1,0,s} = \frac{1}{N}\sum_{i=1}^{N}(1-F)^s x_i$$

$$\text{---------------------------------- (2.11)}$$

$$b_r = \hat{\beta}_r = \hat{M}_{1,r,0} = \frac{1}{N}\sum_{i=1}^{N} F_i^{\,r} x_i$$

L-moments are an alternative system of describing the shapes of probability distributions. Historically they arose as modifications of the probability weighted moments.

On the other hand, L – moments are defined by Hosking in terms of the PWMs α and β as

$$\lambda_{r+1} = (-1)^r \sum_{k=o}^{r} p^*{}_{r,k} \alpha_k = \sum_{k=o}^{r} P^*{}_{r,k} \beta_k$$ ----------------------------- (2.12)

L- Moment ratios, which are analogous to conventional moment ratios, are defined by Hosking (1990) as

$$\tau = \lambda_2 / \lambda,$$
$$\tau_r = \lambda_r / \lambda_2, \quad r \geq 3$$ -- (2.13)

Where: λ_1 is a measure of location, τ is a measure of scale and dispersion (L-Cv), τ_3 is a measure of skewness (L-Cs) and τ_4 is a measure of kurtosis (Lck). Sample L moment rations (t and t_r) are calculated by replacing λ_r by their sample estimates L_r.

The first few L-moments are

$$L_1 = M_{1,0,0}$$
$$L_2 = M_{1,0,0} - 2M_{1,0,1}$$
$$L_3 = M_{1,0,0} - 6M_{1,0,1} + 6M_{1,0,2}$$
$$L_4 = M_{1,0,0} - 12M_{1,0,1} + 30M_{1,0,2} - 20M_{1,0,3}$$ --------------------------- (2.14)

2.7. Parameter and quantile estimation

Numerous parameter estimation procedures have been proposed and studied in order to investigate their performance for various distributions. These include:

1. Method of Moments (MOM)

It is one of the most commonly used methods of estimating parameters of a probability distribution. The estimates of the parameters of a probability distribution function are obtained by equating the moments of the sample with the moments of the probability distribution function. It provides simple calculations, but higher order moment estimates are biased (Wallis, et. al. 1974).

Parameter estimation by MOM is known to be biased and inefficient especially with three parameter distributions.

2. Method of Maximum Likelihood (MLM)

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

3. Method of probability weighted Moments (PWM)

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

2.8. Regional Homogeneity and Regionalization

The availability of data is an important aspect in frequency analysis. In practice, however, data may be limited or in some cases may not be available for a site. In such cases, regional analysis is most useful. Regional analysis is based on the concept of regional homogeneity which assumes that annual maximum flow populations at several sites in a region are similar in statistical characteristics and are not dependent on catchement size (Cunnane, 1989). Regional frequency analysis methods are based on the assumption that the standardized variable at each station has the same distribution at every site in the region under consideration. According to Rao, (2000) a method of assigning homogenous region is geographical similarity in soil types, climate and topography. The integral homogeneity and mutual heterogeneity of these groups are then expressed in terms of a statistics such as Cv. The process is then repeated by altering the Partition points until an acceptable set of regions has been identified.

Different scenarios have used different methods to regionalize hydrologic events. Zrinji et. al. (1994) used the region of influence approach to regionalize an area. Acreman et. al. (1986) proposed a method of identifying homogenous regions by using a clustering algorithm depending on the catchment characteristics and then using a likelihood ratio test to check whether an estimated GEV distribution for a region differs significantly from that of other region.

2.9. Homogeneity tests

Regions can be primarily formed in many ways, but each region should satisfy the homogeneity criteria. Each region is expected to have

a) Dissimilarity from the other regions; and

b) Homogeneity of flood/rainfall characteristics within the region.

Different tests are available to examine regional homogeneity in terms of the hydrologic response of the stations in a region. Hosking and Wallis (1991) gave a statistic which is used to test regional homogeneity. The statistic is a discordance measure, intended to identify those sites that are grossly discordant with the group as a whole. The discordance measure D estimates how far a given site is from the center of the group.

Wiltshire (1986a) developed a homogenous test based on the regional variability in the sites coefficient of variations (CV's) (Roa & Hamed, 2000). Such a test would have the advantage of being relatively distribution free. Hosking and Wallis (1991) are also proposed a homogeneity test based on L-moments which proved to be efficient. (Sine, 2004)

The procedures followed to come up with the site-to-site coefficient of variation of the coefficient of variation are described below.

i. For each site in a region calculate mean , standard deviation and coefficient of variation Cv

$$\overline{R}_i = \sum_{j=1}^{n_i} R_{ij} \bigg/ n_i \qquad \text{---} \ (2.15)$$

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{n_i}\left(R_{ij} - \overline{R}_i\right)^2}{n_i - 1}} \qquad \text{---} \ (2.16)$$

$$C_{Vi} = \frac{\sigma_i}{\overline{R}_i}$$

Where: R_{ij} is the rainfall of station j in region i

$\overline{R}_i$ is the mean annual maximum rainfall for station i

σ_i is the standard deviation of R_{ij} for station i

Cv_i is the coefficient of variation of station i

The LCv can be calculated as:

$$LC_{Vi} = L_{2i} / L_{1i} \quad \text{---} \quad (2.17)$$

Where L1 and L2 are as described in section 2.6.2

ii. for each region , the CC value is calculated as

$$C\overline{V} = \sum_{i=1}^{N} CV_i / N \quad \text{---} \quad (2.18)$$

$$\sigma_{CV} = \sqrt{\sum_{i=1}^{N} \left(CV_i - \overline{C}_V\right)^2 / N} \quad \text{--} \quad (2.19)$$

$$CC = \sigma_{CV} / \overline{C}_V \quad \text{--} \quad (2.20)$$

The same procedure is followed for the corresponding L-moment values. The criteria for the region to be homogeneous is CC<0.3 (Gerbi, 2006)

2.10. Previous Study on IDF in the Area

Different researchers have done analysis of IDF relationships at different parts of the country. Some of these research works include: IDF relationships which have been developed for the northern part of the country by Cherkos Tefera, 2002 from Civil Engineering department of Addis Ababa University, for SNNPR and Oromiya regional state by Feleke Gerbi, 2006 and Chali Edessa, 2007 from department of Hydrology and Water Resources Management at Arba Minch Unversity respectively.

Though the northern part of Ethiopia covers large area characterized by rugged topography with strong relief, IDF analysis done by Cherkos Tefera, 2002 did not include as many stations as possible(only 11 stations were considered). And in addition only few durations of 1,2,3,5 and 24 hours are used for the analysis.In the study an extreme value type I distribution is selected as a parent distribution for all the stations and based on this distribution, parameters and quantiles were estimated without considering best parameter selection techniques such as minimum standard error of estimate (SEE).

As it is discussed in the document, the numbers of stations used in the construction of the intensity maps are small and the developed maps are not comprehensive. And therefore, the use of these maps for practical purpose is limited for those indicated stations in the northern part of the country and with some 25-km radius. Due to great variability of rainfall, the direct use of these maps alone for areas farthest from the principal stations is not recommended.

In order to overcome problem of inadequate record length and less coverage of first class meteorological stations, regional IDF analysis is quite important. Based on regional IDF analysis it is possible to obtain IDF-relationships and estimates which can be applied to the respective delineated regions with greater confidence. But the previous study on IDF relationships for northern part of the country doesn't attempt regionalization in the area. All the aforementioned problems were identified and considered in this study to find out better results and to establish comprehensive IDF-relationships for northern part of the country in general and for Amhara and Tigray regional states in particular.

2.11. Methodology and Procedure

Though there are many first class stations in these two regions, it was very difficult to get long years of rainfall data for all automatic recording stations. The first step in this study was setting station selection criteria. The stations selected are all with first class self recording gauges. The locations of these stations are in such a way that they can represent the two regions different geographical coverage. Annual maximum rainfalls of different durations from **33** stations are taken. Out of the 33 stations considered in this study, 3 stations have a length of

30 years record and above, 3 stations have 20-29 years record, 24 stations have 10-20 years record and 3 stations have less than 10 years record. From the length of the data record it could be seen that some of the stations have short length of record due to late establishment.

In order to achieve the objective of this study, as per station selection criteria representative stations were selected, data collection format were prepared and data processing and presenting methodology were developed.

The Intensity duration frequency (IDF) analysis starts by gathering time series records of different durations. After time series data is gathered, annual extremes are extracted from the record of each duration. The annual extreme data is then fit to a probability distribution which is necessary to standardize the character of rainfall across stations with widely varying lengths of record.

Identification of parent distribution was achieved by considering MRD and L-MRD in combination with probability plots and goodness-of-fit tests. A FORTRAN program developed by Sine (2004) is used to estimate parameters, quantiles and SEE. A distribution with the smallest SEE is selected as the best fitted distribution.

Based on the estimated quantiles intensity of rainfall is determined. With the help of IDF-curve fit tool (Miduss software) and calculated intensity values, IDF-parameters were estimated. By making use of the estimated parameters, the IDF-curve is constructed. And these local IDF-curves are used to design municipal water management infrastructure such as sewers, storm water management ponds or detention basins, street curbs and gutters, catch basins, culverts, etc. These curves are also used to design safe and economical flood control measures and to predict when an area will be flooded, or to pinpoint when a certain rainfall rate or a specific volume of flow will recur in the future.

The intensity obtained could also be used to construct intensity maps which provide the magnitude of extreme falls of known duration and frequency at points required. Intensity contour maps of selected durations and frequency were constructed using ARC-view GIS in combination with SURFER-8 and GLOBAL MAPPER-7.

IDF-equations were developed based on the mathematical expression suggested by Wenzel, (1982). Because of its simplicity, applicability for most locations and suitability for Miduss software, equation developed by Wenzel is used for estimation of IDF-parameters for this study.

In order to overcome problem of inadequate record length and less coverage of first class meteorological stations, regional analysis is used in which data for individual stations are lumped together or compounded to yield larger regional data samples. In this regard detailed regions of the study area were defined according to certain criteria.

Regionalization can be done based on geographic proximity, physiographic & climatic characteristics of the catchments (Admassu, 1989). A better approach has come to use statistics of the observed rainfall data other than using geographical location and climatic similarity alone for reliable result of hydrological homogeneous regions. Finally, the delineated regions have to be checked for their homogeneity using different homogeneity tests.

In this study regionalization of homogeneous regions was made based on interpolation of statistical values (LCs, LCk) using Arc-view GIS software. And in addition to statistical values, attention was given for geographical locations.

The results obtained from this study serves to meet the need for rainfall intensity-duration-frequency relationships and estimates in various parts of the two regions for both short and longer recurrence intervals.

The need has been particularly great because many parts of the two regions remain inadequately gauged while some are hardly gauged at all. Therefore, the results of regionalization of this study will provide intensity values that could be used with greater confidence and somewhat calculable risk for each part of the two regions.

CHAPTER THREE

SOURCE AND AVAILABILITY OF DATA

3.1 Availability of data

As per station selection criteria, different first class stations of the two regional states were selected, by considering their length of record. The first step of the IDF relationship development consists in identifying all first class automatic recording stations which has sufficient length of record within the region to retrieve intensities from the available charts. According to NMSA these first class stations consists of both manual and automatic recording rain gages, evaporation pan, screen Thermometer, Wind vane, Sunshine Hours and intensity recording and staffed with well trained personnel(Gerbi, 2006). From the total first class stations available in Amhara and Tigray regional states, some of the stations lack long length of record. And therefore, only 33 stations which have relatively good length of record and which are assumed to represent different climate characteristics of the regions were considered in this study. The stations within the two regions are: Adigrat, Adwa, Alem Ketema, Amba Mariam, Bahir Dar, Bati, Cheffa, Dangla, Debre Berhan, Debre Markos, Finote Selam, Gondar, Haike, Humera, Kombolcha, Lalibela, Majete, Mehal Meda, Mekane Selam, Mekele, Metema, Michew, Motta, Nefas Mewcha, Pawi, Shire Endasilase, Shola Gebeya, Sinkata, Sirinka and Wegel Tena. And Gebre Guracha, Gewane, Shambu are the neighbouring stations of Oromiya and Afar regions considered in the study.

Table 3.1 Basic information of selected rainfall stations

No.	Station Name	Sample Size (Years)	Sample size after extension (Years)	Location			Period of Record	Period for which Data extended with Regression
				Lat. (degrees)	Log. (degrees)	Elevation (masl)		
1	Adigrat	6	13	14.02	39.45	2280	2001-2007	1992-2000
2	Adwa	8	14	14.05	38.80		1992-2005	1994-1999
3	Alem Ketema	10		10.03	39.03	2280	1992-2004	
4	Amba Mariam	13		11.02	39.22	2960	1989-2007	
5	Bahir Dar	31		11.60	37.40	1770	1964-2006	
6	Bati	11		11.22	40.22	1660	1987-2005	
7	Cheffa	8	12	10.98	39.77	1400	1987-2007	1995-2001
8	Dangela	9		11.12	36.42	1290	1988-2006	
9	Debre Berhan	20		9.63	39.50	2750	1985-2007	
10	Debre Marcos	18		10.33	37.67	2515	1966-2002	
11	Finote Selam	7	21	10.68	37.27	1840	1973-1986	1966-2002
12	Gebre Guracha	14		9.82	38.42	2422	1980-1999	
13	Gewane	10		10.15	40.63	561	1980-2002	
14	Gondar	11		12.55	37.42	1967	1976-1995	
15	Haike	8	29	11.32	39.07	1900	1980-1990	1966-2007
16	Humera	9		14.28	36.58	760	1973-1997	
17	kombolcha	29		11.07	39.44	1903	1966-2007	
18	Lalibela	10		12.03	39.05	2500	1989-2007	
19	Majete	14		10.45	39.85	2000	1991-2005	
20	Mehal Meda	12		10.15	37.26	3040	1987-2006	
21	Mekane Selam	10		10.58	38.75	2600	1988-2007	
22	Mekele	11		13.05	39.48	2070	1991-2007	
23	Metema	5	14	12.97	36.17	900	1987-2005	1976-1989
24	Michew	13		12.80	39.53	2400	1992-2007	
25	Motta	8	30	11.08	37.87	2440	1989-2006	1964-1994
26	Nefas Mewcha	6	32	11.73	38.45	3000	1987-1999	1964-2006
27	Pawi	9		11.15	36.05	1050	1987-2001	
28	Shambu	14		9.57	37.10	2556	1987-2006	
29	Shire Endasilase	14		14.10	38.27		1992-2005	
30	Shola Gebeya	17		9.05	38.77	2500	1990-2007	
31	Sinkata	7	13	13.95	39.75		2000-2007	1992-1999
32	Sirinka	18		11.55	39.62	2000	1987-2007	
33	Wegel Tena	9	19	11.60	39.22	3000	1988-2007	1987-2000

3.2 Source of data

Rainfall data, which is used for this study, was collected from daily and hourly recorded rainfall charts available in NMSA. Maximum annual rainfall of 0.5,1,2,3,5,6,12 and 24 hours was collected for the required first class stations.

The charts are traced by a float type gauge in which the rainfall collected by a funnel shaped collector is led in to a float chamber causing a float to rise. As the float rises, a pen attached to the float through a lever system records the elevation of the float on a rotating drum driven by a clock work mechanism. A siphon arrangement empties the float chamber when the float has reached a preset maximum level which in most cases is 10 mm for all of the gauges. The vertical lines in the pen trace correspond to the sudden emptying of the float chamber by siphon action which resets the pen to zero level. (Edessa, 2007)

Figure 3.1 The weekly rainfall chart from Adwa Station

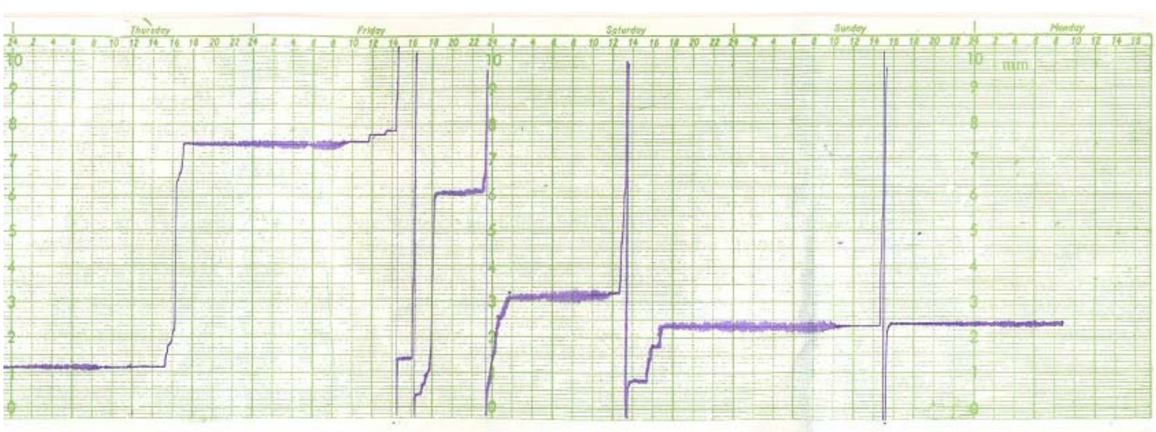
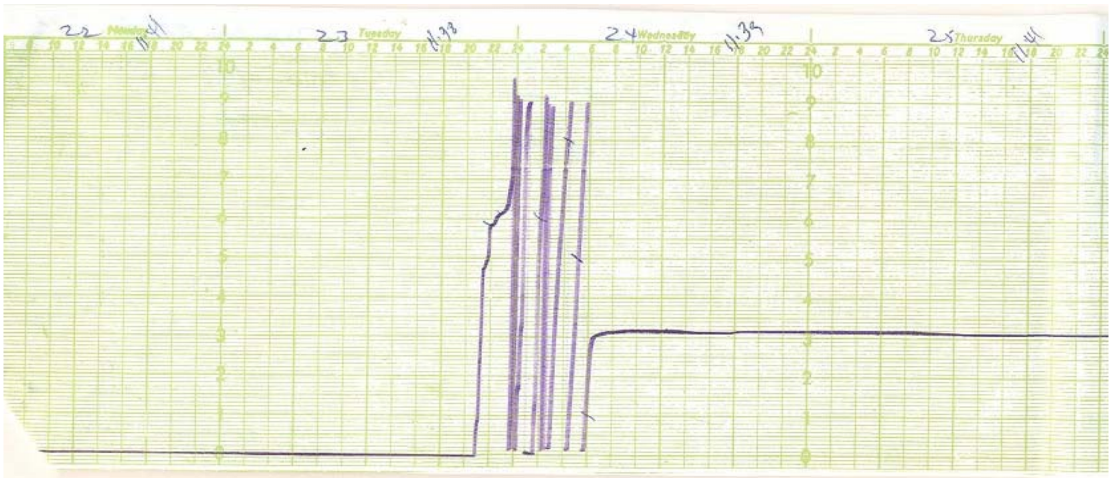


Figure 3.2 The weekly rainfall chart from Bati Station



3.3 Data Collection

From the rainfall charts of NMSA, rainfall data was collected for 0.5,1,2,3,5,6,12 & 24 hours in different years. And the maximum value of each duration in each year was used for the analysis.

Table below shows the maximum depth of rainfall recorded for each durations observed in different months of the year 2005 at Adwa station.

Table 3.2 Samples of data collected from rainfall charts for 2005.

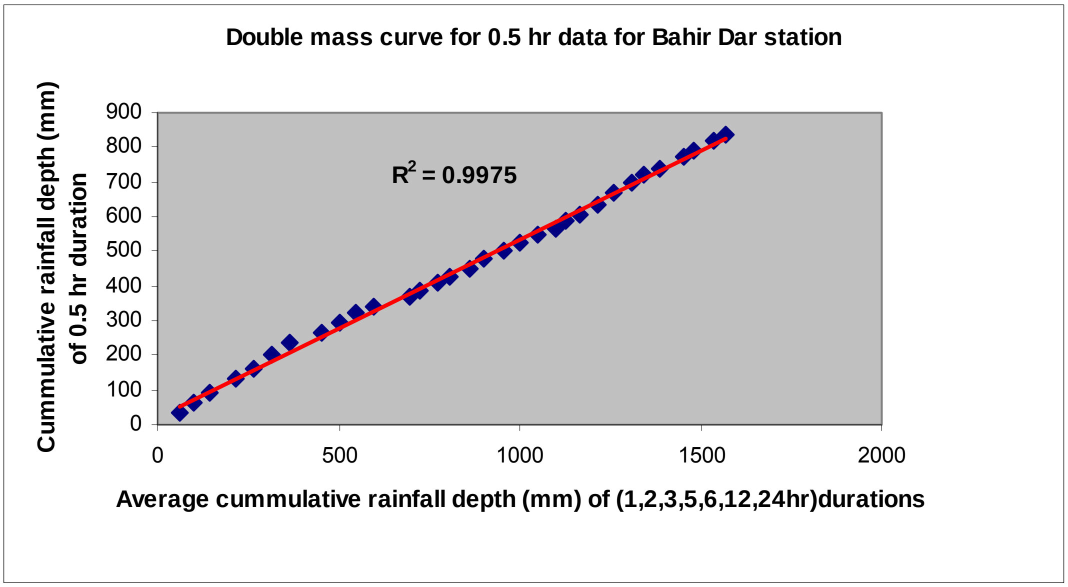
.Year	Date of record	Observed Rainfall (mm) for the indicated duration(hr)							
		0.5	1	2	3	5	6	12	24
2005	22-23/05/2005	20.3	23.1	24.6	24.8	25.8	25.8	25.8	25.8
2005	31/08-01/09/2005	14.5	14.5	14.5	14.5	14.5	14.5	14.5	28.3
2005	26-27/03/2005	15.8	24.6	26.1	26.1	26.1	26.1	26.1	42.1
2005	12-13/09/2005	27.7	30.5	30.8	30.8	30.8	30.8	30.8	31.2
2005	17-18/08/2005	28.2	31.2	33.2	33.2	34.7	36.8	39.7	39.7
2005	**Max**	**28.2**	**31.2**	**33.2**	**33.2**	**34.7**	**36.8**	**39.7**	**42.1**

3.4 Data Quality Control

3.4.1 Testing for consistency

A double mass curve graph was drawn to check the consistency of the collected data. And it is observed that the data of most of the stations are consistent.

Figure 3.3 Double mass curve consistency test of 0.5 hr rainfall at Bahir Dar station



3.4.2 Testing for Outliers

An outlier is an observation that deviates significantly from the bulk of the data, which may be due to errors in data collection, or recording, or due to natural causes. The presence of outliers in the data causes difficulties when fitting a distribution to the data. Low and high outliers are both possible and have different effects on the analysis (Rao and Hamed, 2000)

The retention or deletion of these outliers can significantly affect the magnitude of statistical parameters computed from the data, especially for small samples.

As it is cited in Rao and Hamed (2000) Grubbs and Beck (G-B) (1972) test is used to detect outliers. In this test the quantities X_H and X_L are calculated using the following equations.

$$X_H = \exp(\overline{X} + K_n * S)\text{..........................}(3.1)$$

$$X_L = \exp(\overline{X} - K_n * S)$$

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

$$K_N = -3.62201 + 6.28446N^{1/4} - 2.49835N^{1/2} + 0.49146N^{3/4} - 0.037911N\text{................}3.2$$

Sample values greater than X_H are considered to be high outliers, while those less than X_L are considered to be low outliers.

The result of the outliers test for different duration of rainfall depths for Mekele station is indicated in table 3.3

Table 3.3 Outlier test for Mekele station

Durations (hr)	Mean	Stdev	Limiting Value		Data Range	
			Upper	Lower	Max	Min
0.5	3.07	0.20	32.90	14.11	28.00	15.20
1	3.33	0.29	50.79	15.24	43.30	17.00
2	3.44	0.29	57.91	16.91	44.00	18.20
3	3.47	0.31	62.00	16.81	50.20	18.20
5	3.54	0.22	54.45	21.87	50.20	24.20
6	3.55	0.22	54.72	22.04	50.20	24.20
12	3.60	0.24	60.08	22.33	50.60	24.20
24	3.70	0.27	70.71	23.16	65.70	28.60

3.4.3 Tests for Independence and Stationarity

A hydrologic time series is stationery if it is free of trends , shifts or periodicity (cyclicity) which implies that the statistical parameters of the series , such as the mean, variance, and autocorrelation structure do not change over time (Maidment, 1993)

The statistical analysis for dependence and stationarity is carried out for all the durations of rainfall record with in each station. A FORTRAN program is used for the analysis based on Wald–Wolfowitz (W –W) test and Lag – one serial correlation coefficient test. As a sample the test for Mekele station is shown below.

Table 3.4 Independence and stationarity test result of all durations at Mekele station

Duration (hr)	Statistic	Critical Test Statistic	Remark	L.1-Correlation coefficient	Upper limit	Lower limit	Remark
0.5	1.051	1.96	Independent	0.22788	0.45783	-0.65783	Random
1	-0.188	1.96	Independent	-0.43012	0.45783	-0.65783	Random
2	-0.07	1.96	Independent	-0.44227	0.45783	-0.65783	Random
3	0.019	1.96	Independent	-0.37904	0.45783	-0.65783	Random
5	0.481	1.96	Independent	-0.23358	0.45783	-0.65783	Random
6	0.427	1.96	Independent	-0.25477	0.45783	-0.65783	Random
12	0.398	1.96	Independent	-0.36242	0.45783	-0.65783	Random
24	1.002	1.96	Independent	-0.08968	0.45783	-0.65783	Random

3.5 Data Extension

It is well known that a small sample may define a frequency distribution which differs greatly from the population frequency distribution. Thus it is often emphasized that at least 25-30 years of records are needed to obtain estimates of some practical value for both short and longer durations.

Some of the stations have short length of records and the available records of these stations cannot be used with confidence to obtain IDF estimates for different return periods.

When we estimate quantiles using few years of data record, then the estimated quantiles will either be over estimated or under estimated. Therefore, it is unwise to estimate quantiles with few years of data record. In order to avoid this problem, stations with short record length should be extended by relating them with neighboring or similar behavior stations. And therefore, the stations will be statistically adequate to estimate quantiles.

A Fortran regression program developed by Abebe Sine is used for data extension. Some of the stations which are extended by the regression program include: Adigrat, Adwa, Cheffa, Finote Selam, Haike, Metema, Motta, Nefas Mewcha, Sinkata and Wegel Tena. The following step shows data extension using regression equation for Adigrat station.

Station: Adigrat

Year	Observed annual max. rainfall (mm) for indicated duration (hr)							
	0.5	**1**	**2**	**3**	**5**	**6**	**12**	**24**
2001	11.7	26.6	38.8	38.8	38.8	38.8	48.1	50.5
2002	16.4	17.4	17.5	17.8	22.4	26.6	31.8	40
2003	20.5	24.5	27.4	27.4	29.1	29.1	30.2	45.7
2004	20.4	24	26.6	33.6	33.6	33.6	33.6	52.3
2005	12.9	24.4	39.1	42.1	50.8	51.2	51.2	55.5
2007	19.2	26.2	29.2	29.2	29.2	29.2	29.2	29.2

Station: Michew

Year	Observed annual max. rainfall (mm) for indicated duration (hr)							
	0.5	**1**	**2**	**3**	**5**	**6**	**12**	**24**
1992	18.2	23	24.9	26.9	42.4	42.9	52.5	52.5
1994	22	22.3	22.4	22.4	28	28.4	39.5	39.6
1995	19.5	23.5	25.2	28.9	31.2	34.9	57.7	66.9
1996	24.5	32.5	32.5	34.5	40.8	40.8	40.8	51.1
1997	24.6	24.9	27.9	28	28	28	28	47.9
1999	19	21.8	21.9	23.7	29.8	33.1	33.1	48.9
2000	24	40	45	45	45	45	45	45
2001	14.6	19.6	33.6	33.6	33.6	33.6	33.6	34.1
2002	17	22.3	24.4	31.6	33.9	39.8	39.8	39.8
2003	28.2	35.2	47.5	51.2	52.8	56.2	57	57
2004	27.4	30.9	31.4	31.5	33.5	33.6	51.8	51.8
2005	17.7	25.2	26.7	26.7	28.5	28.6	28.6	39.8
2007	16.7	18.8	20.5	23.5	29.7	34.7	35.2	36.6

First: Correlation between dependent station **(Adigrat)** & independent station **(Michew)**

The fitted regression equation :(For 0.5 hr)

$Z1 = 6.8626 + (0.4928).Z2$

The multiple correlation coefficient: 0.761 (Best)

Second: Correlation between **0.5 hour** and **other durations**

The fitted regression equation :(For 1 hr)

$Z1 = 5.285\, Z2^{0.446}$

The multiple correlation coefficient: 0.850

The fitted regression equation :(For 2 hr)

$Z1 = 52.3962 + (-1.3430).Z2$

The multiple correlation coefficient: 0.630

Where: Z1 is rainfall depth of dependent station/duration and Z2 is rainfall depth of independent station/duration.

Table 3.5 Summarized regression equations between 0.5 hour and other durations for Adigrat station.

S.No.	Duration(hr)	The fitted regression equation	Multiple correlation coefficient
1	1	Z1 = 5.285 Z2^0.446	0.850
2	2	Z1 = 52.3962 +(-1.3430).Z2	0.630
3	3	Z1 = 1.087 Z2^0.991	0.954
4	5	Z1 = 1.853 Z2^0.856	0.905
5	6	Z1 = 7.1935 +(0.9258).Z2	0.829
6	12	Z1 = 8.2285 +(0.9783).Z2	0.826
7	24	Z1 = 19.4016 +(0.6996).Z2	0.702

Table 3.6 Extended data using regression equation for Adigrat station.

Year	Obs. annual max. rainfall (mm) for indicated duration (hr)							
	0.5	**1**	**2**	**3**	**5**	**6**	**12**	**24**
1992	15.8	24.5	31.1	32.8	35.2	36.0	38.7	46.5
1994	17.7	23.6	28.6	30.2	32.7	33.7	36.2	44.7
1995	16.5	24.2	30.3	31.9	34.3	35.2	37.8	45.9
1996	18.9	23.0	27.0	28.5	31.1	32.2	34.6	43.6
1997	19.0	22.9	26.9	28.4	31.0	32.1	34.5	43.6
1999	16.2	24.3	30.6	32.3	34.7	35.5	38.2	46.1
2000	18.7	23.1	27.3	28.8	31.4	32.5	34.9	43.8
2001	11.7	26.6	38.8	38.8	38.8	38.8	48.1	50.5
2002	16.4	17.4	17.5	17.8	22.4	26.6	31.8	40
2003	20.5	24.5	27.4	27.4	29.1	29.1	30.2	45.7
2004	20.4	24	26.6	33.6	33.6	33.6	33.6	52.3
2005	12.9	24.4	39.1	42.1	50.8	51.2	51.2	55.5
2007	19.2	26.2	29.2	29.2	29.2	29.2	29.2	29.2

The derived annual maximum rainfall depths of different durations for Bahir Dar stations are indicated in table 3.7 and for the rest of the stations it is tabulated in Appendix A.

Table 3.7 Annual Maximum Rainfall depths in different durations for Bahir Dar Station

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	**1**	**2**	**3**	**5**	**6**	**12**	**24**
1964	36	43.5	49.6	56.7	58.3	63.9	64.5	78.9
1971	25.1	27.2	37.7	40	40.2	40.9	48.9	64.9
1972	31.8	35.3	37.4	37.6	42.2	45.2	51.6	51.7
1973	38.8	45.7	53.5	62.7	73	77.2	79.2	84
1974	32.1	45.3	47.5	48.8	51.2	51.2	55.4	55.5
1975	38.5	44.7	44.7	48.7	48.7	48.7	53.3	53.3
1976	31.6	44.8	47.9	51	55.8	55.8	56.9	61.9
1978	31.2	37.4	48.9	52.3	52.3	52.3	52.3	52.3
1979	28.9	29.9	29.9	48.2	48.2	48.2	48.2	48.2
1980	16.5	47.7	52.2	52.2	52.2	52.2	52.2	52.2
1981	37.1	41.3	46.1	49.7	60.2	60.5	66.9	67.6
1982	21.5	22.5	29.7	30.4	30.6	30.6	30.6	41.2
1983	18.9	29.8	30.8	32.5	49.6	51.1	64.6	65.7
1984	19	20.9	28.6	33.4	34	34.1	40.1	53.1
1985	23.4	39.2	40.4	40.5	42.4	59.4	79.5	81.7
1986	26.7	28.7	30.3	40.1	40.6	40.6	40.8	41.7
1987	26.8	35.8	42.6	44.9	45	45	72.2	94.4
1988	22.5	31.7	33.5	41.5	53.1	53.8	55.9	56
1989	24.7	39.7	40.2	43.3	56.6	59.1	60.1	67.2
1990	17.6	19.1	35.8	50.7	51.7	51.9	52.1	64.1
1991	18.5	27	28.3	30.3	30.8	31.3	31.3	37.5
1992	20	29.9	37.1	37.1	37.4	38.4	41.5	41.5
1994	30.7	38.1	44.3	46.3	46.3	46.6	46.6	59.4
1996	29.7	40.1	45	45	45	45	45	47.4
1997	30.3	35.5	46.3	49.2	50.1	50.1	63.8	64.4
1998	21.7	26.7	29.7	35.2	36.2	36.7	39.7	40.9
1999	20.4	28.6	36.2	39.7	41.2	41.2	45.7	47.9
2000	31.7	44.1	48.8	60.8	69.1	74.3	98.9	99.9
2001	18.5	21.7	22	24.5	25.2	25.2	25.2	33.6
2005	30	38	48	52.7	52.7	52.7	78.9	78.9
2006	17.8	18	23.2	30	35	36.1	36.1	36.1
Mean	**26.4**	**34.1**	**39.2**	**43.7**	**46.9**	**48.4**	**54.1**	**58.8**
STDEV	**6.7**	**8.7**	**8.9**	**9.4**	**10.8**	**11.9**	**16.3**	**17.0**

CHAPTER FOUR

DATA ANALYSIS, RESULTS AND DISCUSION

4.1 Selection and evaluation of parent distributions for the rainfall data

4.1.1The probability distributions

The distribution models which are recommended by WMO for annual maximum data series (Cunnane, 1989) are;

1. Normal distribution(N)
2. Two parameter Log-Normal distribution(LN2)
3. Three parameter Log Normal distribution(LN3)
4. Exponential distribution(EX)
5. Two parameter Gamma distribution(G2)
6. Pearson three distribution (PIII)
7. Log Pearson three distribution (LP3)
8. Generalized extreme value distribution(GEV)
9. Extreme value type one distribution (EVI)
10. Weibul distribution(W)
11. The five parameter Wakeby distribution(WAK5)
12. The four parameter Wakeby distribution(WAK4)
13. The generalized Pareto distribution(GP)
14. Log Logistic distribution(LLg)
15. Generalized Logistic distribution(GL)

4.1.2 Moment Ratio Diagrams

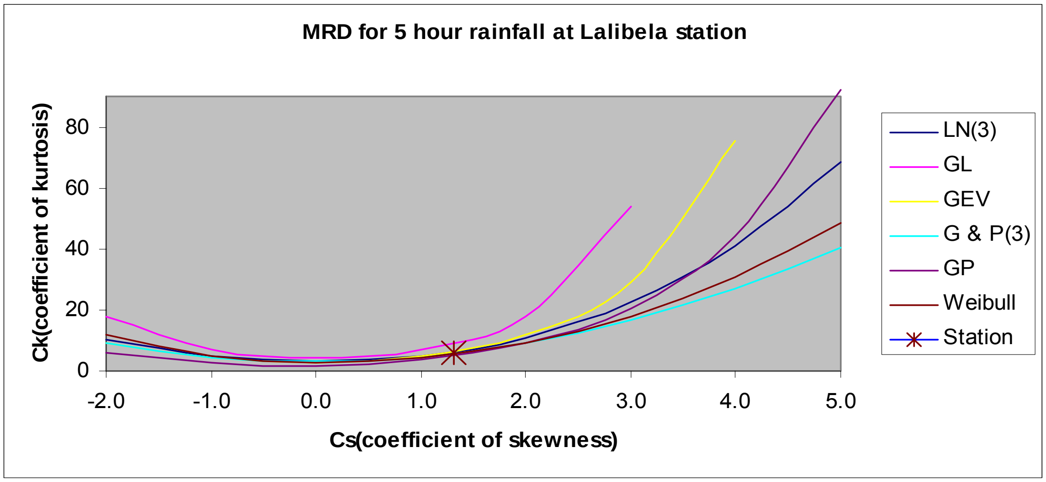
For each station, pairs of coefficient of skew ness (Cs) and coefficient of kurtosis (Ck) have been computed and plotted on the Cs - Ck diagram for each station. The location of the sample estimate with respect to the distributions gives an indication of the suitability of the distribution to the data. However, if the sample size is small, the bias in the values of higher moments may be larger enough to give misleading results. The bias correction depends on the sample size, parent skew ness and the form of the parent distributions (Cunnane, 1989, App.3)

4.1.3 L-Moment Ratio Diagrams

Analogous to the conventional MRDs, the L-moment ratio diagrams are based on the relations between the L-moment ratios. A diagram based on L-Cs (τ_3) versus L-Ck (τ_4) is used to identify appropriate distributions that best fits the rainfall data. For each station the sample L-moment ratios t_3 and t_4 are plotted on the L-moment ratio diagrams. A suitable parent distribution is that which the average value of (t_3, t_4) gets close to it (Rao et. al. 2000).

The L-moment ratio diagrams are based on unbiased sample quantities in contrast to Cs and Ck which have to be corrected for bias. It was shown by Hosking (1990) that Cs and Ck values from several samples drawn from three different distributions lay close to a single line on the graph and overlaps each other offering little hope of identifying the population distribution. In contrast, the sample L-moment ratios plot as fairly well separated groups and permit better discrimination between the distributions. Thus, the identification of a parent distribution can be achieved much more easily by using L-moment ratio diagrams than conventional moment ratio diagrams especially for skewed distributions.

Figure 4.1 MRD and L-MRD of 5 hour rainfall depth at Lalibela station.



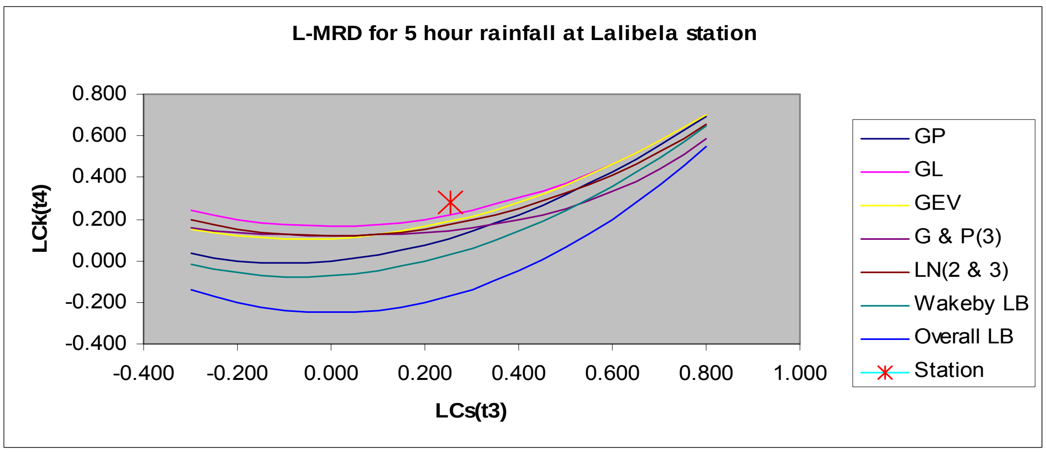


Table 4.1 Candidate distributions based on the MRD and L-MRD for 5-hour rainfall depth at Lalibela station.

L-MRD					MRD				
Duration (hr)	Average L-Moments			Candidate distributions	Duration (hr)	Conventional Moments			Candidate distributions
	t	t_3	t_4			Cv	Cs	Ck	
0.5	0.21	0.22	0.25	GL/GEV/LN(2 & 3)	0.5	0.36	1.31	6.12	GEV/G & P(3)/Weibull
1	0.24	0.31	0.30	GL/GEV/LN(2 & 3)	1	0.44	1.69	7.13	Weibull/GP/GEV
2	0.26	0.31	0.31	GL/GEV/LN(2 & 3)	2	0.47	1.75	7.62	Weibull/GP/GEV
3	0.23	0.21	0.28	GL/GEV/LN(2 & 3)	3	0.41	1.28	6.52	GEV/G & P(3)/Weibull
5	0.21	0.26	0.28	GL/GEV/LN(2 & 3)	5	0.36	1.31	5.92	GEV/G & P(3)/Weibull
6	0.21	0.22	0.25	GL/GEV/LN(2 & 3)	6	0.35	1.00	4.97	GEV/G & P(3)/Weibull
12	0.21	0.14	0.20	GL/GEV/LN(2 & 3)	12	0.33	0.41	3.76	G & P(3)/Weibull/GP
24	0.20	0.08	0.22	GL/LN(2 & 3)/G & P(3)	24	0.31	0.10	3.93	GL/G & P(3)/Weibull

4.2 Probability Plots and Goodness-of-fit tests

Probability plots are used to visually evaluate the agreement between distribution and observed data and also extremely useful for visually revealing the character of a data set. If the fitted distribution is the exact parent distribution, this relationship should appear as a straight line through the origin with a 45^0 slope. Plots are an effective way to see what the data looks like and to determine if fitted distributions appear consistent with the data. Analytical goodness of fit criteria are useful for gaining an appreciation for whether the lack of fit is likely to be due to sample to sample variability, or whether a particular departure of the data from a model is statistically significant. In most cases several distributions will provide statistically acceptable fits to the available data so that goodness of fit tests is unable to identify the “true” or “best” distribution to use. Such tests are valuable when they can demonstrate that some distributions appear inconsistent with the data (Rao et. al., 2000).

The graphical evaluation of the adequacy of the fitted distribution is generally performed by plotting the observations so that they would fall approximately on a straight line if a postulated distribution were the true distribution from which the observations were drawn. This can be done with the use of special commercially available probability papers for some distributions. The following two distributions are compared for their fitness for 3 hour and 24 hour annual maximum rainfall of Mekele station graphically.

Extreme Value Type I distribution

An ordered observations X_i is plotted vs. the reduced variate Yi of the distribution

$$Yi = -LN\left(-LN\left(\frac{T}{T-1}\right)\right). \text{ -- } (4.1)$$

The Grin Gorton Plotting position is applied with the relation.

$$T = \frac{N + 0.12}{m - 0.44} \quad \text{-- (4.2)}$$

Where; i: is the rank in ascending order=N-m+1

m: is the rank in descending order =N-i+1

N: is the number of observations

Pearson Type III Distribution

An ordered observations X_i is plotted versus the Standard Normal Variate, u of the distribution

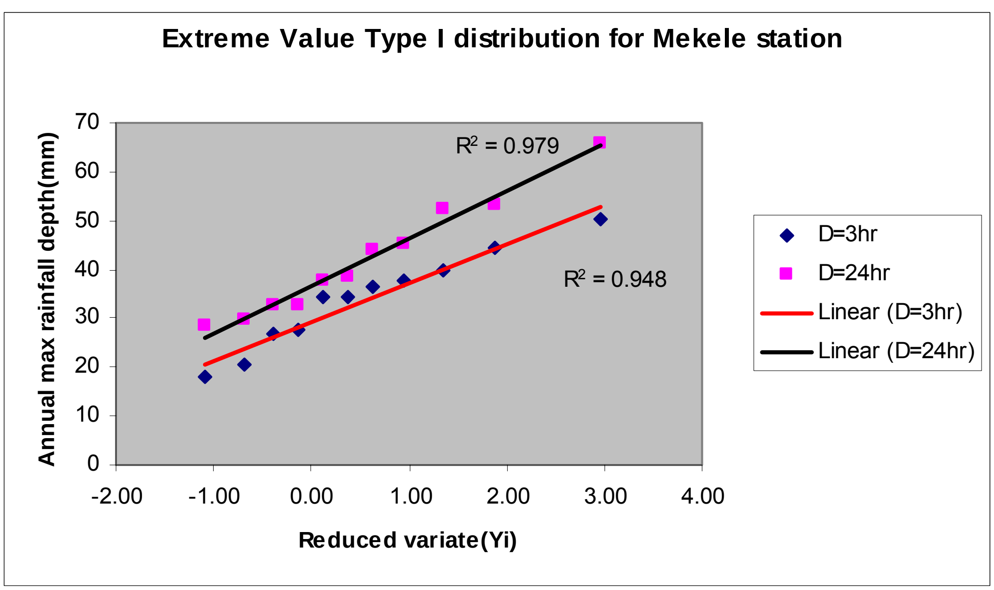
$$u = W - \frac{C_o + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} + \varepsilon(p) \quad \text{------------------------ (4.3)}$$

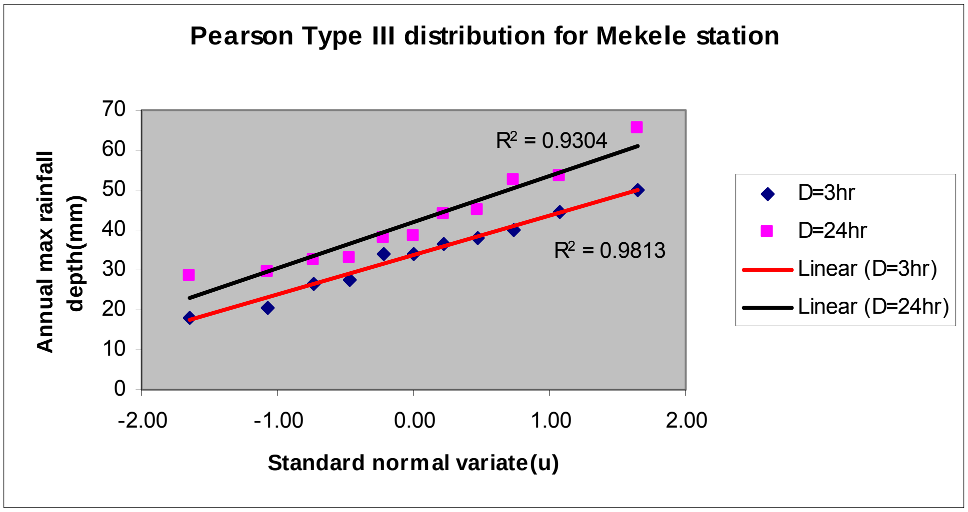
Where:

$$W = \sqrt{-2\ln(p)} \;\; for \;\; p < 0.5$$
$$p = 1 - F$$
$$p = 1 - p \;\; for \;\; p > 0.5$$

Co, C1, C2, d1, d2, d3 are constants and $\varepsilon(p)$ is the error term

Figure 4.2 Fitting EVI and Pearson Type III distributions for 3-hour and 24-hour rainfall at Mekele station.





From the above figures it is observed that EVI best fitted the annual maximum rainfall of 24 –hour duration while Pearson type III best fitted 3-hour duration.

4.3 Parameters and Quantile Estimation

Parameters of the best fitted distributions are estimated based on the methods described in section 2.7 after which, quantile estimates (X_T) corresponding to different return periods may be computed. The relation between return period and the probability of non-expedience (F) is given by

$$F = 1 - \frac{1}{T} \qquad \text{--} \ (4.4)$$

Where; F=F (X_T) is the probability of having a flood of magnitude X_T or smaller. The problem thus reduces to evaluating X_T for a given value of F. Chow (1964) proposed a general for calculating X_T as follows.

$$X_T = u_1' K_T \sqrt{\mu_2} \qquad \text{--} \ (4.5)$$

Where; K_T is the frequency factor which is a function of the return period and of the parameters of the distribution

u_1' *and* μ_2 are the moments of the distribution

It is clear that a point estimate of a certain quantile corresponding to a return period may be of no real significance unless there is an indication of the accuracy of the estimate. A measure of the variability of the estimated value is the standard error of estimate S_T which is defined as (Cunnane, 1989)

$$S_T = \sqrt{E\left\{\hat{X}_T - E\left(\hat{X}_T\right)\right\}^2} \quad \text{-------------------------------------- (4.6)}$$

The standard error of estimate accounts for the error due to small samples, but not the error due to the choice of inappropriate distribution. The standard error of estimate depends in general on the method of parameter estimation. The most efficient method is that which gives the smallest standard error of estimate (Rao, 2000). The standard error of estimate (SEE) for annual maximum rainfall of 1-hour and 24-hour durations in the different return periods for Bahir Dar station are shown in tables (4.2) & (4.3) respectively.

Table 4.2 Standard Error of Estimate of the Candidate distributions for 1-hour rainfall at Bahir Dar station

Distributions	SEE for the indicated return periods in years						REMARK
	T=2	T=5	T=10	T=25	T=50	T=100	
EVI/MOM	1.48	1.45	1.58	1.88	2.16	2.48	
EVI/ML	1.54	1.91	2.31	2.89	3.36	3.84	
EVI/PWM	1.49	1.44	1.58	1.91	2.21	2.55	
LN/MOM	1.52	1.65	1.98	2.58	3.11	3.71	
P3/MOM	1.73	1.51	1.39	1.4	1.55	1.79	
P3/PWM	0.99	0.91	0.91	1.06	1.27	1.56	MINIMUM SEE
LP3/MOM	1.81	1.66	1.6	1.84	2.27	2.86	
G2/MOM	1.51	1.47	1.58	1.85	2.1	2.37	
G2/ML	1.5	1.46	1.59	1.87	2.13	2.42	
G2/PWM	1.52	1.46	1.58	1.87	2.13	2.44	
GEV/PWM	1.92	1.62	1.35	1.41	1.82	2.38	
GEV/MOM	1.79	1.56	1.39	1.39	1.58	1.86	
LLG/PWM	1.89	1.6	1.37	1.41	1.87	2.63	
EXP/MOM	1.51	1.44	1.58	1.96	2.34	2.76	

Table 4.3 Standard Error of Estimate of the Candidate distributions for 24-hour rainfall at Bahir Dar station

Distributions	SEE for the indicated return periods in years						REMARK
	T=2	T=5	T=10	T=25	T=50	T=100	
EVI/MOM	2.7	3.74	4.73	6.14	7.23	8.34	
EVI/ML	2.73	3.88	4.84	6.16	7.17	8.2	
EVI/PWM	2.68	3.84	4.91	6.4	7.55	8.71	
LN/MOM	2.72	3.84	4.95	6.58	7.88	9.28	
P3/MOM	3.07	3.97	4.78	6.04	7.09	8.27	
P3/PWM	3.03	3.82	4.7	6.28	7.69	9.29	
LP3/MOM	2.98	3.91	4.94	6.85	8.69	10.94	
G2/MOM	2.76	3.82	4.8	6.12	7.1	8.1	
G2/ML	2.75	3.82	4.8	6.1	7.06	8.04	MINIMUM SEE
G2/PWM	2.74	3.9	4.94	6.33	7.35	8.4	
GEV/PWM	3.02	3.99	4.95	6.92	9.08	11.85	
GEV/MOM	2.98	4.02	4.83	6.08	7.21	8.53	
LLG/PWM	3.01	3.86	4.78	6.74	8.96	12	
EXP/MOM	2.63	3.57	4.73	6.48	7.87	9.3	

Based on the smallest standard error of estimate, the best fitted candidate distributions of different rainfall duration’s for all stations are shown in table 4.4

Table 4.4 Best Fitted Distributions for the indicated durations depending on the smallest Standard Error of Estimate

No	Station Name	0.5hr	1hr	2hr	3hr	5hr	6hr	12hr	24hr
1	Adigrat	GEV/MOM	P3/PWM	P3/PWM	P3/PWM	G2/PWM	EV1/ML	G2/ML	P3/PWM
2	Adwa	G2/PWM	P3/MOM	G2/ML	P3/PWM	P3/PWM	G2/PWM	G2/ML	EV1/ML
3	Alem ketema	P3/MOM	P3/PWM	P3/MOM	P3/MOM	G2/ML	G2/ML	G2/ML	P3/PWM
4	Amba Mariam	G2/MOM	EV1/ML	G2/ML	P3/MOM	P3/MOM	P3/MOM	P3/MOM	G2/MOM
5	Bahir Dar	G2/MOM	P3/PWM	P3/MOM	G2/MOM	G2/ML	G2/ML	G2/ML	G2/ML
6	Bati	P3/PWM	G2/ML	P3/MOM	G2/ML	P3/MOM	P3/MOM	P3/MOM	G2/ML
7	Cheffa	G2/ML	EV1/ML	EV1/ML	EV1/ML	EV1/ML	EV1/MOM	GEV/MOM	P3/MOM
8	Dangla	P3/MOM	G2/ML	G2/MOM	G2/PWM	G2/PWM	G2/PWM	P3/MOM	G2/MOM
9	Debre Birhan	G2/PWM	EV1/ML	EV1/ML	EV1/ML	EV1/ML	EV1/ML	GEV/MOM	GEV/MOM
10	Debre Markos	G2/MOM	EV1/ML	EV1/ML	EV1/ML	EV1/ML	EV1/ML	EV1/ML	EV1/ML
11	Finote Selam	P3/PWM	P3/PWM	P3/PWM	P3/PWM	P3/PWM	G2/PWM	P3/PWM	GEV/MOM
12	Gebre Guracha	GEV/MOM	GEV/MOM	GEV/MOM	P3/MOM	GEV/PWM	GEV/PWM	GEV/MOM	GEV/MOM
13	Gewane	EV1/ML	P3/PWM	P3/MOM	P3/MOM	P3/MOM	P3/PWM	P3/PWM	EV1/PWM
14	Gondar	P3/MOM	GEV/MOM	G2/ML	P3/MOM	P3/MOM	P3/PWM	GEV/MOM	GEV/MOM
15	Haike	G2/PWM	G2/PWM	G2/ML	G2/ML	G2/ML	P3/PWM	G2/PWM	G2/PWM
16	Humera	G2/ML	P3/MOM	G2/MOM	P3/MOM	P3/MOM	GEV/MOM	GEV/MOM	P3/MOM
17	Kombolcha	P3/PWM	EV1/ML	EV1/ML	EV1/ML	P3/MOM	P3/MOM	P3/MOM	P3/MOM
18	Lalibela	EV1/ML	EV1/ML	EV1/ML	EV1/ML	EV1/ML	G2/ML	P3/MOM	P3/PWM
19	Majete	EV1/ML	P3/PWM	G2/ML	P3/MOM	P3/MOM	P3/MOM	P3/MOM	P3/MOM
20	Mehal meda	G2/ML	G2/ML	EV1/ML	EV1/MOM	P3/PWM	P3/PWM	P3/PWM	P3/MOM
21	Mekane Selam	G2/ML	P3/MOM	P3/MOM	P3/MOM	P3/MOM	P3/MOM	P3/MOM	G2/ML
22	Mekele	P3/MOM	G2/ML	P3/MOM	P3/MOM	G2/ML	G2/ML	P3/MOM	EV1/ML
23	Metema	GEV/MOM	G2/PWM	G2/ML	G2/ML	G2/ML	G2/ML	G2/ML	G2/PWM
24	Michew	P3/MOM	P3/MOM	G2/ML	G2/ML	G2/ML	EV1/ML	P3/MOM	G2/ML

No	Station Name	0.5hr	1hr	2hr	3hr	5hr	6hr	12hr	24hr
25	Motta	G2/PWM	G2/PWM	G2/PWM	G2/ML	EV1/ML	EV1/ML	EV1/ML	G2/PWM
26	Nefas Mewcha	G2/PWM	G2/PWM	G2/ML	G2/ML	G2/ML	G2/ML	G2/PWM	G2/PWM
27	Pawi	P3/MOM	P3/MOM	G2/MOM	G2/ML	P3/MOM	P3/MOM	P3/MOM	P3/MOM
28	Shambu	P3/PWM	G2/ML	EV1/ML	G2/PWM	G2/ML	P3/MOM	P3/PWM	EV1/PWM
29	Shire Endasillse	G2/ML	GEV/MOM	P3/MOM	P3/MOM	P3/PWM	P3/PWM	P3/PWM	P3/MOM
30	Shola Gebeya	GEV/MOM	EV1/ML	EV1/ML	EV1/ML	P3/MOM	P3/MOM	P3/MOM	P3/MOM
31	Sinkata	G2/ML	P3/PWM	P3/MOM	P3/MOM	P3/MOM	P3/MOM	P3/PWM	G2/ML
32	Sirinka	P3/MOM	P3/MOM	G2/MOM	G2/ML	G2/ML	EV1/ML	G2/ML	P3/MOM
33	Wegel Tena	G2/ML	G2/ML	G2/MOM	EV1/MOM	P3/PWM	P3/PWM	P3/PWM	P3/MOM

Even though different types of best fitted distributions were selected for each station, it is observed that most of the stations in Amhara and Tigray regional states are represented by Gamma family (Two parameter gamma distributions and Pearson III distributions).

Based on the selected distributions the estimated quantiles for different rainfall durations at Bahir Dar station is shown in table 4.5. The estimated quantiles for the rest of stations are tabulated in appendix D.

Table 4.5 Estimated Quantiles for Bahir Dar station

Return Period (years)	Estimated Quantiles for the indicated durations of rainfall, mm at Bahir Dar station							
	0.5hr	1hr	2hr	3hr	5hr	6hr	12hr	24hr
2	25.82	34.47	39.60	43.07	46.10	47.41	52.54	57.26
5	31.79	41.52	46.77	51.38	55.71	57.96	67.17	72.41
10	35.25	45.04	50.33	56.14	61.24	64.06	75.81	81.29
25	39.21	48.64	53.97	61.52	67.51	71.00	85.76	91.47
50	41.87	50.86	56.21	65.11	71.72	75.68	92.53	98.38
100	44.44	52.86	58.23	68.56	75.76	80.18	99.08	105.05

4.4. Intensity of Rainfall

The intensity is the time rate of precipitation, that is, depth per unit time (mm/hr or in/hr).Intensity of rainfall, i can be determined by using the following relation.

$$i = \frac{Rain\ fall\ depth(mm)}{Duration\ of\ rain\ fall(minutes)} = \frac{X_T}{D_i} \quad \text{------------------------------} \ (4.7)$$

Table 4.6 shows the intensity for different durations and frequencies for Bahir Dar station. The intensity for the rest of stations is tabulated in appendix E.

Table 4.6 intensity of rainfall for Bahir Dar station

Return Period (years)	Intensity of rainfall for the indicated durations, mm/hr at Bahir Dar station							
	0.5hr	1hr	2hr	3hr	5hr	6hr	12hr	24hr
2	51.64	34.47	19.80	14.36	9.22	7.90	4.38	2.39
5	63.58	41.52	23.39	17.13	11.14	9.66	5.60	3.02
10	70.50	45.04	25.17	18.71	12.25	10.68	6.32	3.39
25	78.42	48.64	26.99	20.51	13.50	11.83	7.15	3.81
50	83.74	50.86	28.11	21.70	14.34	12.61	7.71	4.10
100	88.88	52.86	29.12	22.85	15.15	13.36	8.26	4.38

4.5 Estimation of the IDF Parameters

The IDF-Curve Fit Tool (version 2.07) is used for this analysis which is a window version of the DOS program that estimate the parameter values from observed records of either depth or intensity within a range of time intervals and for a specified return interval based on the equation

$$I = \frac{A}{(D+B)^C} \qquad \text{---------------------------------} \ (4.8)$$

Where; I= rainfall intensity (mm/hr)

D= duration of rainfall (minutes)

A= coefficient with units of mm/hr

B= time constant in minutes

C= an exponent usually less than one

The IDF Curve Fit tool manipulates data describing an Intensity-Duration-Frequency relates for a particular geographical locality and can be used in two modes:

(1) To compute the ‘A’, ‘B’ and ‘C’ parameters that most closely approximates a set of observed rainfall data.

(2) To compute the IDF curve for user-supplied values of the three coefficients and compare this with observed data.

For any time interval the rainfall can be defined either as a total depth of rainfall or as an average intensity over the time interval (Gerbi, 2006).

4.5.1 The 'A' coefficient

The value of the 'A' coefficient depends on (i) the return interval in years of the storm and (ii) the system of units being used.

4.5.2 The B-constant

This constant in minutes is used to make the log-log correlation as linear as possible. Typical values range from 2 to 12 minutes. A value of zero for this parameter represents a special case of the IDF equation where

$$i = \frac{A}{D^C} \qquad \text{---} \; (4.9)$$

In general, this results in poor agreement between observed values of intensity and duration and those represented by the IDF equation.

4.5.3 The C-exponent

This parameter is usually less than 1.0 and is obtained in the process of fitting the data to the power expression. Values are usually in the range of 0.75 to 1.0
Table 4.7 shows the computed parameters A, B, C of the IDF of various frequencies for all the stations.

Table 4.7 Summaries of the Estimated IDF Parameters

Station Name	T=2 Years			T=5 Years			T= 10 Years			T=25 Years			T=50 years			T=100 Years		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Adigrat	894.3	12.74	0.852	1243	19.94	0.881	1744	30.01	0.922	2654.3	44	0.972	4060.9	59.69	1.027	6304.2	77.03	1.083
Adwa	819.5	2.8	0.819	702.5	0.01	0.77	680.9	0.01	0.753	655	0.01	0.733	637.1	0.01	0.72	620.7	0.01	0.708
Alem ketema	1200.9	10.95	0.88	1278	11.36	0.854	1368	12.72	0.847	1448	13.76	0.838	1489.7	14.25	0.831	1609.7	16.33	0.832
Amba Mariam	506.4	13.42	0.782	459.1	4.47	0.741	444.9	0.53	0.723	493.3	0.15	0.726	530.9	0.03	0.729	569	0.01	0.732
Bahir Dar	1643.2	16.33	0.898	1526	10.67	0.854	1433	7.47	0.829	1333	4.16	0.801	1268.6	2.09	0.784	1214.4	0.3	0.768
Bati	862.1	19.94	0.79	1217	27.47	0.806	1465	31.4	0.816	2042.8	40.88	0.847	2343.8	43.97	0.856	2835.3	49.5	0.873
Cheffa	333.01	0.014	0.7094	910.6	13.47	0.821	1835	25.8	0.907	4139	40.98	1.01	6823.9	52.21	1.068	7475.7	52.25	1.066
Dangla	782.8	2.09	0.85	954.6	4.47	0.853	1024	4.62	0.852	1139.7	5.62	0.855	1209.2	6.01	0.856	1290.1	6.62	0.859
Debre Birhan	543.8	0.01	0.798	762.5	1.98	0.811	1084	6.62	0.847	1007.7	0.91	0.824	1007.7	0.91	0.824	3926.2	29.03	1.002
Debre Markos	1204.3	7.47	0.9	2083	15.09	0.936	2696	18.8	0.95	3871.7	25.8	0.977	4716.8	30.01	0.988	5695.6	34.03	1
Finote Selam	716.3	15.05	0.855	1104	25.8	0.9	1318	30.03	0.919	1592	34.27	0.942	1739.8	35.89	0.952	2064.3	40.97	0.974
Gebre Guracha	849.69	2.584	0.84	1306	5.597	0.88	1596	7.472	0.9	2040.8	10.91	0.93	2324.8	12.76	0.95	2654.4	15.04	0.96
Gewane	1554.5	4.47	0.937	2374	10.09	0.947	2951	12.76	0.951	3824.1	16.33	0.958	4478.7	18.8	0.962	4973.6	19.94	0.96
Gondar	541.4	7.47	0.822	779.9	13.39	0.85	939.4	16.33	0.868	1283.9	22.96	0.905	1595.5	29.03	0.932	2071.5	37.26	0.966
Haike	634.2	4.47	0.78	797.9	7.53	0.796	926.2	10.09	0.809	1053.7	12.01	0.818	1147.2	13.39	0.825	1228.1	14.35	0.829
Humera	947.6	10.09	0.875	1578	17.18	0.921	2031	19.94	0.947	2783.1	23.87	0.983	3356.7	25.79	1.004	3793.1	25.89	1.018
Kombolc ha	950.4	10.91	0.847	1795	18.8	0.914	2775	25.79	0.965	4559.9	34.03	1.024	6581.5	40.98	1.069	8645.9	45.8	1.101
Lalibela	912.7	18.32	0.891	1462	23.18	0.92	1930	25.8	0.941	2680	29.03	0.969	3229.8	30.02	0.985	3999.8	32.33	1.005
Majete	1196.4	12.71	0.846	1726	14.45	0.868	2119	15.23	0.883	2691.6	16.33	0.904	3078.6	16.33	0.915	3435.7	15.95	0.924

Station Name	T=2 Years			T=5 Years			T= 10 Years			T=25 Years			T=50 years			T=100 Years		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Mehal meda	326.7	0.04	0.715	365.2	0.04	0.693	389.6	0.04	0.683	419.1	0.01	0.674	441.1	0.04	0.67	462.1	0.04	0.666
Mekane Selam	1039	7.47	0.922	1347	11.83	0.942	1499	13.47	0.949	1616.8	14.25	0.952	1716.3	15.09	0.956	1713.2	14.47	0.951
Mekele	1749.6	16.33	0.957	2098	17.18	0.953	2257	17.47	0.95	2466.3	18.32	0.948	2594.2	18.8	0.947	2667.8	18.8	0.943
Metema	1723.2	23.28	0.923	1984	28.02	0.91	2366	35.49	0.919	3117.4	48.36	0.942	4026.4	60.94	0.967	5899	80.16	1.011
Michew	707.2	2.58	0.811	1072	7.47	0.846	1372	10.95	0.869	1742.8	14.13	0.891	2037.9	16.33	0.905	2314.1	17.89	0.916
Motta	1698.3	17	0.966	2209	23.27	0.984	2581	27.56	0.996	2938.2	31.42	1.002	3371.8	35.89	1.014	3863.3	40.97	1.025
Nefas Mewcha	655.7	12.7	0.795	1177	27.09	0.865	1650	36.27	0.906	2483.8	48.34	0.957	3123.2	55.06	0.984	4047.2	63.3	1.017
Pawi	2032.9	25.79	0.956	3324	30.01	1	4166	31.43	1.02	5643.4	35.89	1.049	6514.7	37.63	1.059	7948.4	41.21	1.079
Shambu	993	3.2	0.836	1259	4.43	0.833	1374	4.47	0.826	1466.7	3.98	0.815	1496.4	3.2	0.804	1565	3.2	0.798
Shire Endasila se	1153.9	13.47	0.883	1384	16.85	0.878	1585	19.94	0.884	1823.7	23.27	0.891	1896.8	23.8	0.889	2025.2	25.8	0.891
Shola Gebeya	408.1	0.94	0.751	638.1	7.47	0.772	900.9	15.09	0.801	1444.5	27.8	0.848	2000.9	37.51	0.881	2918.1	50.36	0.924
Sinkata	1156.6	0.15	0.911	1265	0.14	0.903	1317	0.04	0.898	1376.4	0.03	0.894	1413.3	0.01	0.891	1448.9	0.01	0.889
Sirinka	714.6	8.76	0.79	653	3.2	0.745	620.2	0.53	0.721	633.8	0.03	0.707	647.3	0.01	0.7	659.6	0.01	0.693
Wegel Tena	754.1	18.8	0.882	969.6	19.94	0.89	1113	20.56	0.896	1378	23.27	0.913	1621.1	25.8	0.928	1934.4	29.03	0.946

From the above table a general trend of the following was observed. Except station Adwa and Bahir Dar, the “A” coefficient increases with an increase in return period for most of the stations. But at Adwa and Bahir Dar a decreasing trend of “A” coefficient is seen for an increase in return period. The “B” constant and the “C” exponent generally increase or decrease with an increase or decrease of the “A” coefficient. For some exceptional stations a decrease of “B” and “C” for an increase in A was observed.

In general the following range of IDF parameter values were observed in the study area and it is tabulated as below.

Table 4.8 Range of IDF parameter values in the study area

Return Period (years)	Parameters	Minimum Value	Maximum Value
2	A	326.7	2032.9
	B	0.01	25.79
	C	0.7094	0.966
5	A	365.2	3323.6
	B	0.01	30.01
	C	0.693	1
10	A	389.6	4166
	B	0.01	36.27
	C	0.683	1.02
25	A	419.1	5643.4
	B	0.01	48.36
	C	0.674	1.049
50	A	441.1	6823.9
	B	0.01	60.94
	C	0.67	1.069
100	A	462.1	8645.9
	B	0.01	80.16
	C	0.666	1.101

Rainfall intensity of each station for all durations can easily be calculated based on the estimated IDF parameters with the general equation of the form

$$i = \exp\left[(\ln(A) - C\ln(B + D))\right] \qquad \text{-----------} \ (4.10)$$

Each station has different equation for different return period. The resulting six equations for each station can be used for intensity calculations in the area represented by that station. Listed below are the six equations for the IDF relationships at Bahir Dar station.

2 Year return period, i = exp [7.40 - 0.898*ln (16.33+D)]

5 Year return period, i = exp [7.33 - 0.854*ln (10.67+D)]

10 Year return period, i = exp [7.27 - 0.829*ln (7.47+D)]

25 Year return period, i = exp [7.20 - 0.801*ln (4.16+D)]

50 Year return period, i = exp [7.15 - 0.784*ln (2.09+D)]

100 Year return period, i = exp [7.10 - 0.768*ln (0.3+D)]

Intensity Values generated from the above equations at Bahir Dar station for different return periods are listed in table 4.9 below

Table 4.9 Calculated Intensity values for Bahir Dar station

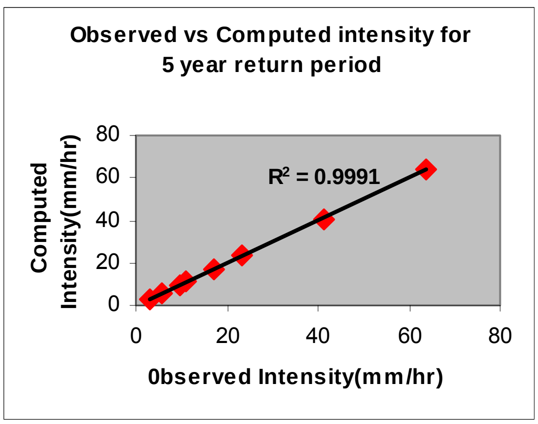
Return Period (years)	Computed Intensity of rainfall(mm/hr) for the indicated durations – at Bahir Dar Station							
	0.5hr	1hr	2hr	3hr	5hr	6hr	12hr	24hr
2	52.45	33.50	19.90	14.34	9.34	8.00	4.38	2.37
5	64.45	40.20	23.79	17.23	11.35	9.76	5.47	3.04
10	71.07	43.64	25.76	18.71	12.41	10.71	6.08	3.44
25	78.79	47.56	28.03	20.44	13.67	11.84	6.83	3.93
50	83.62	49.84	29.33	21.44	14.42	12.51	7.28	4.23
100	88.43	52.13	30.67	22.48	15.19	13.21	7.76	4.56

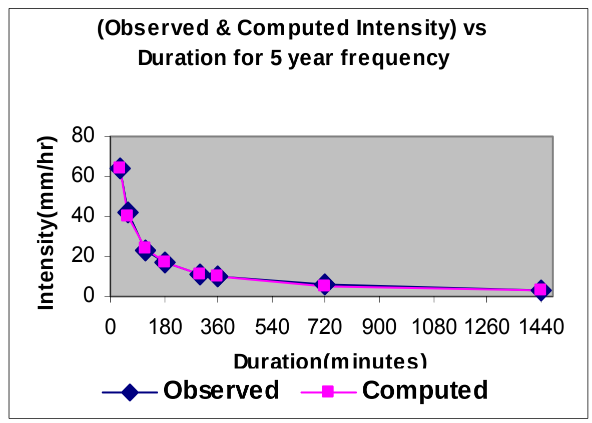
4.6 Evaluation of the method of parameter estimation

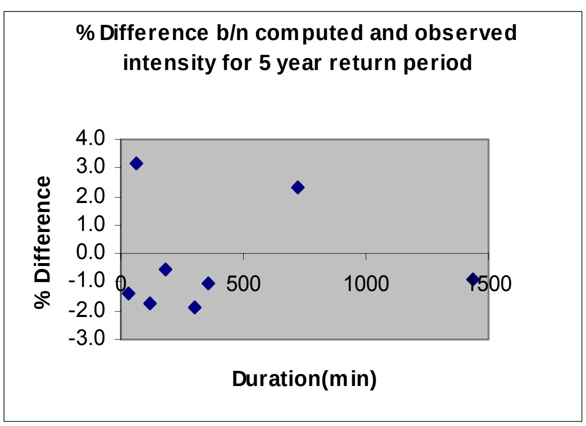
Graphical/Visual verification

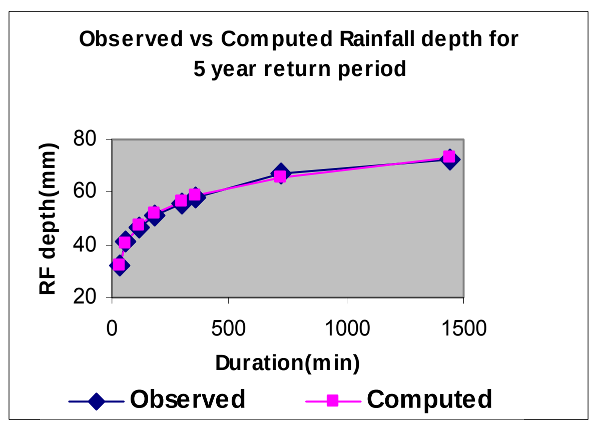
Observed and computed intensities are plotted on the same graph and goodness of fit is evaluated. The result of the graph indicated that, the plot fall approximately on a straight line and the efficiency (R^2) is approaching to 100% for all frequency. The percentage difference between computed and observed intensities is plotted versus duration of rainfall for different return periods. Figure 4.3 shows the graphical comparisons of the computed and observed intensities with the percentage difference of estimate from the observed value and in addition observed and computed rainfall depths are compared graphically.

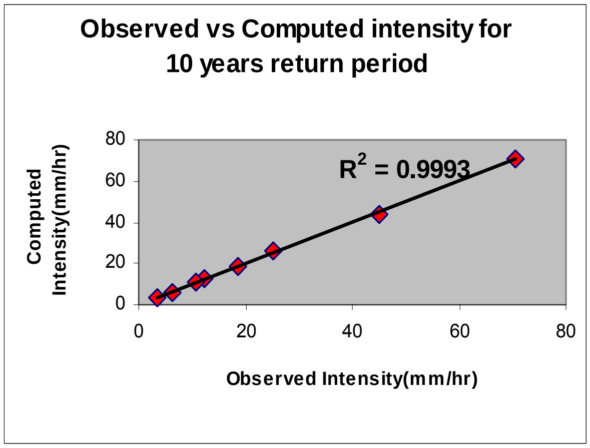
Figure 4.3 Comparison of observed versus computed IDF values at Bahir Dar station

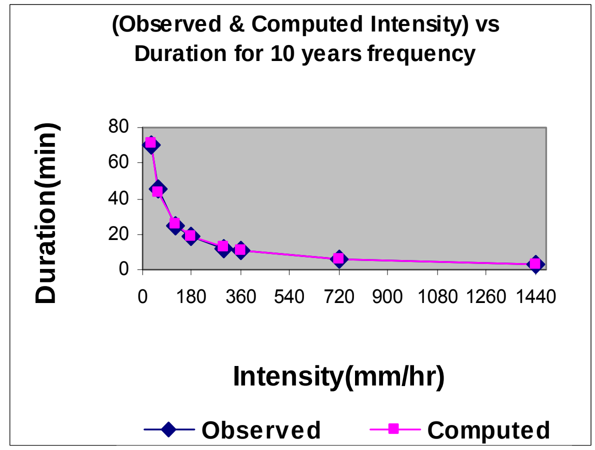


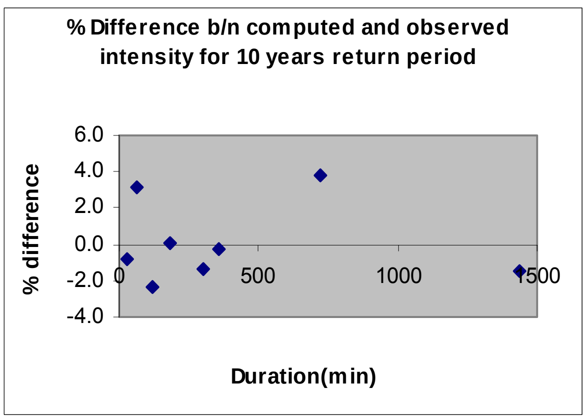


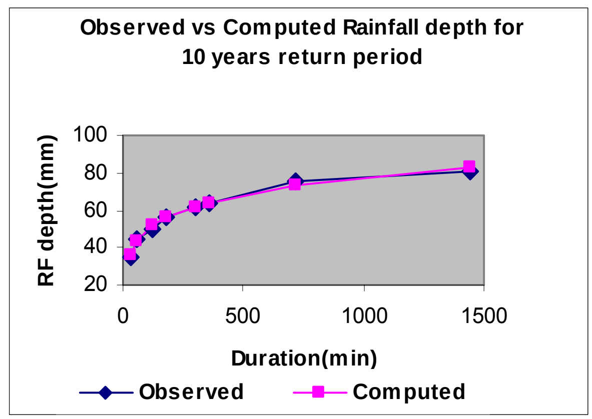










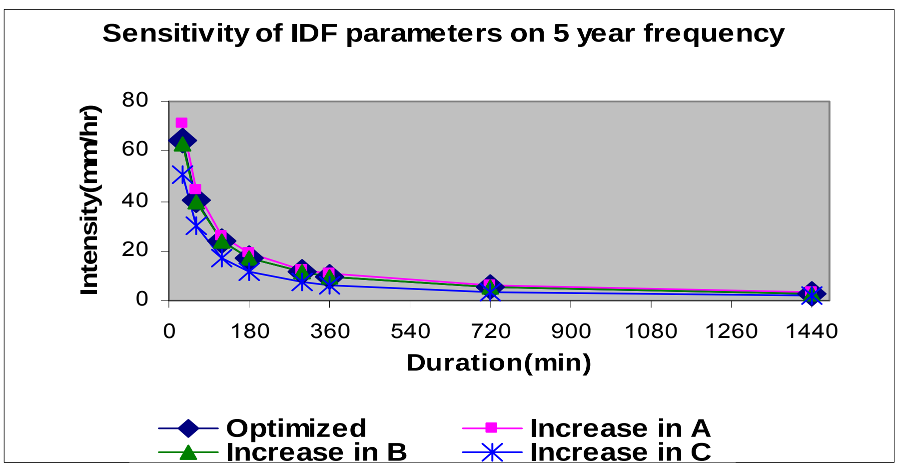


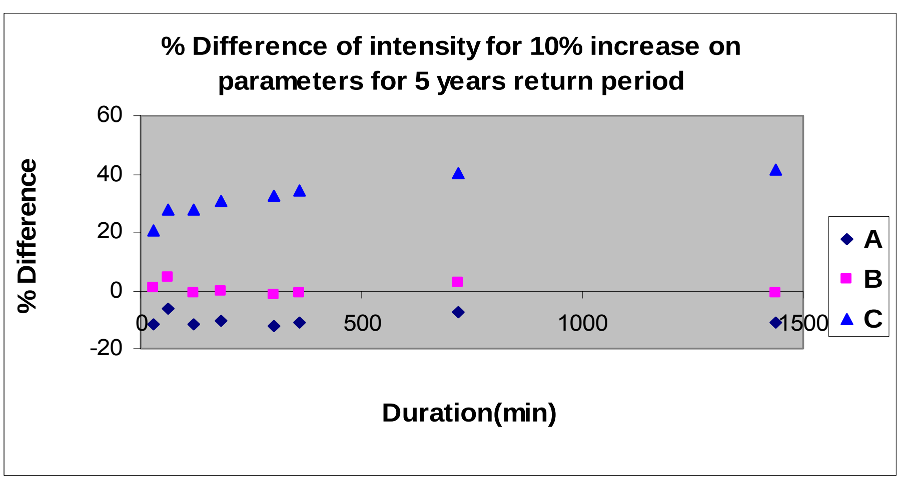
For lower durations a relatively higher difference between computed and observed intensity was seen from the graph of percentage difference. Generally percentage difference is minimum(less than 10%) for all return period and from the graphs of observed versus estimated values of intensities and rainfall depths with their percentage difference, it can be concluded that the estimated values using parameters describe the observed values.

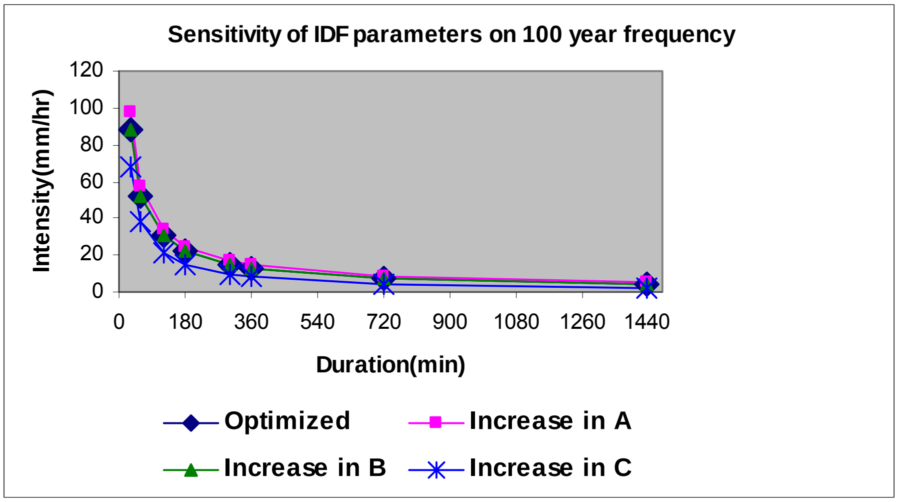
4.7 Sensitivity of the IDF parameters

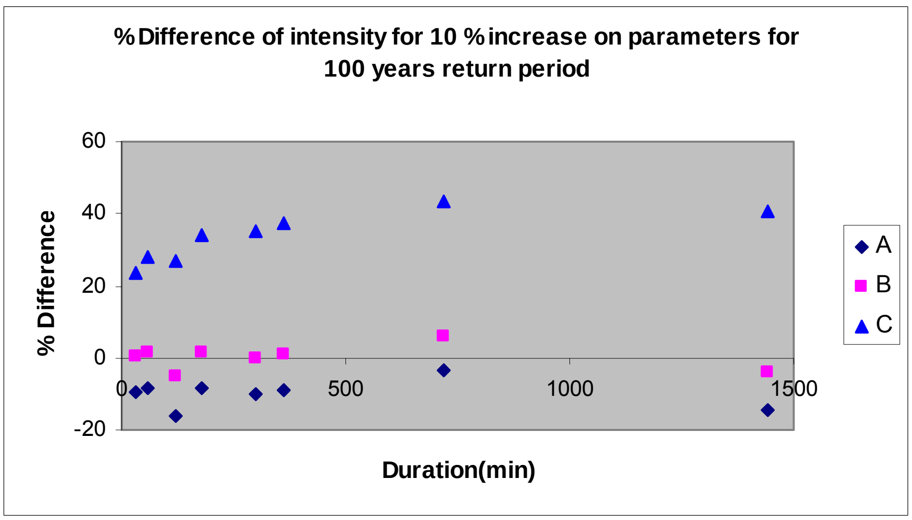
With an increase of the three IDF parameters by 10% and computation of rainfall intensities using increased parameters, the sensitivity of IDF parameters were evaluated. Intensity obtained from the optimized IDF parameters and increased IDF parameters was compared. From the comparison it is observed that the “C” exponent is the most sensitive parameter. An increase in “C” exponent by 10% resulted in a difference of more than 40% between the two values of rainfall intensity mostly for larger return periods. This is a good indication that care has to be taken in determining the “C” exponent. Increasing the “A” coefficient by 10% resulted in a slight increase on the intensity by approximately 5 to 6% which indicate that the rate of increase or decrease in “A” coefficient causes a slight increase or decrease of the intensity of rainfall. An increase in the “B” constant has no significant change on the intensity of rainfall. Figure 4.4 shows graphical comparison of the intensity of rainfall obtained from the optimized parameters and the increased parameters.

Figure 4.4 Results of the sensitivity test on the IDF parameters at Bahir Dar station









4.8 Construction of the IDF curve

The IDF curves were plotted on a double logarithmic scale, the duration D as abscissa and the intensity I as ordinate with the help of IDF curve fit tool. Figure 4.5 and 4.6 shows the IDF curves plotted on double logarithmic scale and normal scale respectively for Bahir Dar station. The rest of the IDF curves for all the stations are compiled in appendix B.

Figure 4.5 IDF curves plotted on double logarithmic scale for Bahir Dar Station

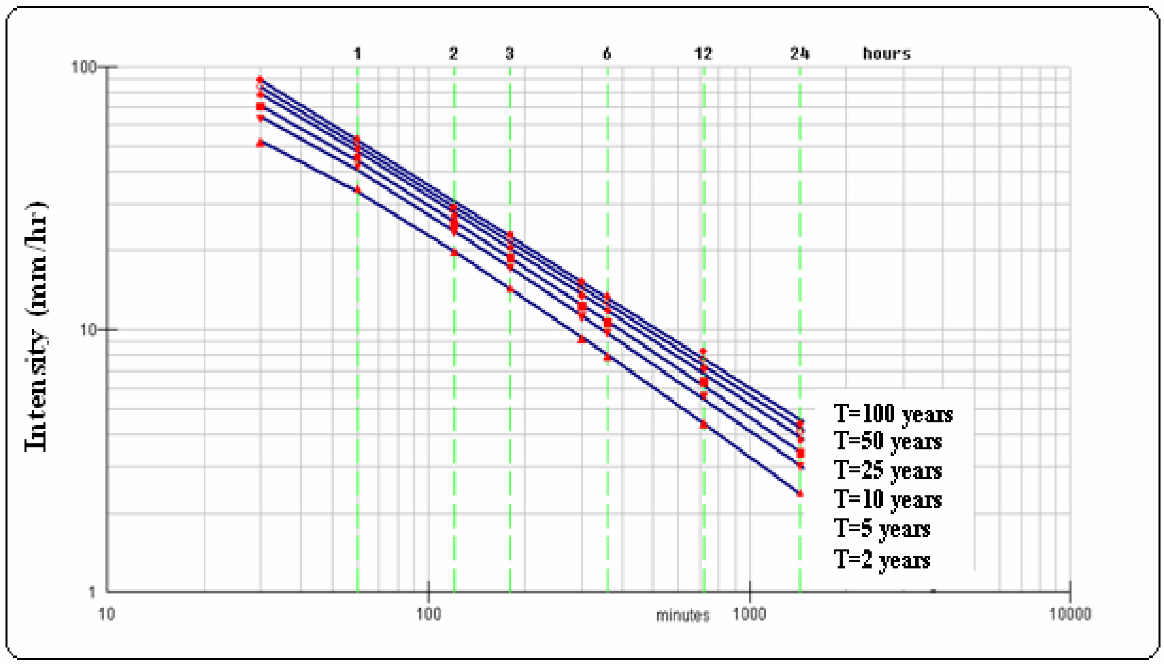
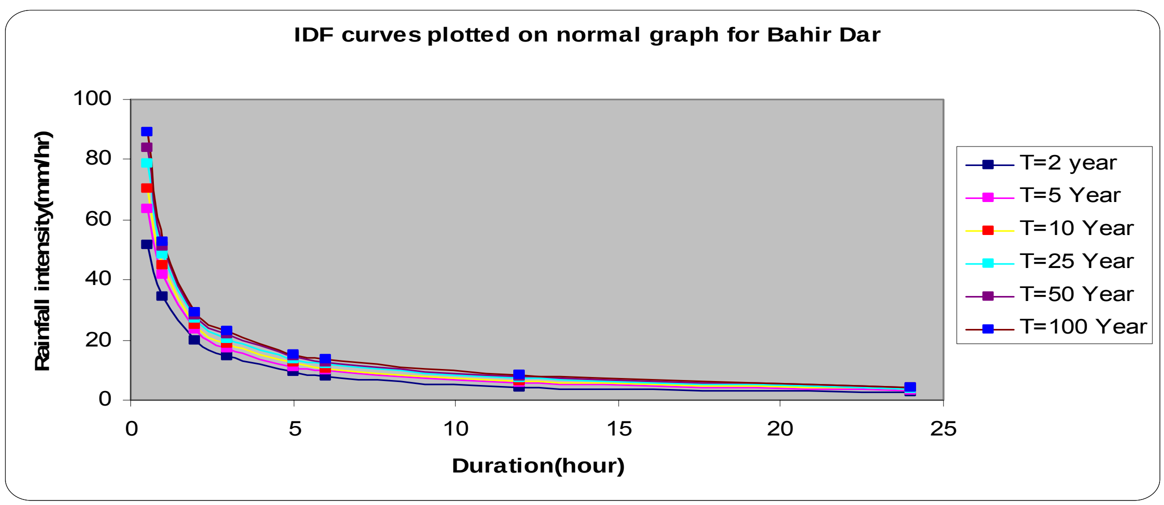


Figure 4.6 IDF curves plotted on a normal scale for Bahir Dar Station



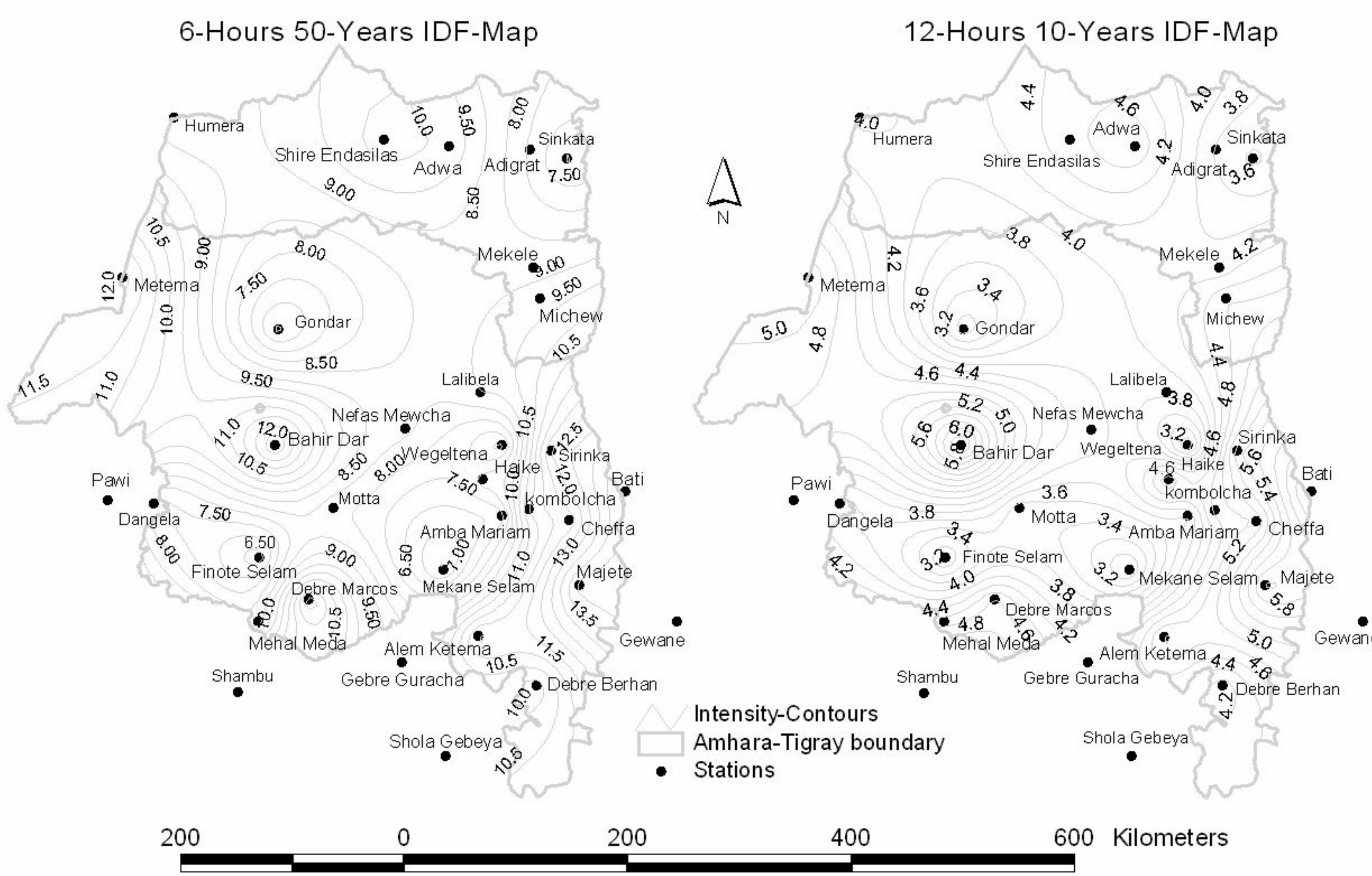
4.9 Construction of the IDF maps

By using SURFER-8, GLOBAL MAPPER-7 and ARC-VIEW 3.3 softwares intensity contours of IDF maps are drawn for each station of selected frequency and duration to show the spatial distribution of the intensity of rainfall with in the two regions.

Figure 4.7 shows the constructed IDF maps for 6-hours 50-years and 12-hours10-years rainfall intensity maps covering the study area. The rest of the IDF maps for different recurrence intervals and durations are compiled in Appendix C.

IDF maps help to interpolate intensities for areas where there has no intensity data. It is also possible to interpolate rainfall intensities for various rainfall durations and frequencies by making use of these maps. (Gerbi, 2006)

Figure 4.7 IDF map for 6-hours 50-years and 12-hours 10-years rainfall intensities



4.10 Different comparison between previous work by Tefera (2002) and this study

4.10.1 Comparison of collected annual maximum rainfall data

As it is stated in section 2.3 data collection was the most time consuming step in the process. And in order to properly estimate the quantiles at different return periods, the annual maximum rainfall depth must be collected curiously and with greater accuracy. Difference in data collection was observed between the previous work and this study for some stations and it is tabulated as below.

Table 4.10 Comparison of collected annual maximum rainfall data between previous work and this study at Bahir Dar station

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)									
	1		2		3		5		24	
	previous	Now	previous	Now	previous	Now	previous	Now	previous	Now
1964	43.5	43.5	43.9	49.6	43.9	56.7	43.9	58.3	68.3	78.9
1971	18.2	27.2	18.2	37.7	18.2	40.0	18.2	40.2	19.6	64.9
1972	30.4	35.3	30.4	37.4	30.4	37.6	30.4	42.2	46.7	51.7
1973	46.8	45.7	56.3	53.5	72.1	62.7	81.4	73.0	86.2	84.0
1974	54.0	45.3	56.4	47.5	57.7	48.8	60.9	51.2	66.2	55.5
1975	51.1	44.7	51.1	44.7	60.9	48.7	60.9	48.7	95.1	53.3
1976	37.8	44.8	47.8	47.9	51.6	51.0	57.3	55.8	62.4	61.9
1977	56.6	42.6	57.9	61.4	57.9	93.2	78.7	93.2	117.2	118.6
1978	44.5	37.4	62.3	48.9	62.3	52.3	63.3	52.3	62.3	52.3
1979	31.2	29.9	35.0	29.9	35.0	48.2	35.0	48.2	69.6	48.2
1980	42.3	47.7	43.4	52.2	43.4	52.2	43.4	52.2	76.1	52.2
1981	88.4	41.2	109.2	101.4	109.2	101.4	109.2	101.4	115.4	110.8
1982	27.6	22.5	31.9	29.7	32.3	30.4	33.0	30.6	46.1	41.2
1983	30.0	29.8	32.5	30.8	44.0	32.5	56.5	49.6	61.5	65.7
1984	22.1	20.9	32.0	28.6	37.5	33.4	37.6	34.0	61.4	53.1
1985	21.5	39.2	40.0	40.4	50.0	40.5	50.0	42.4	67.0	81.7
1986	18.1	28.7	18.1	30.3	24.0	40.1	48.0	40.6	55.4	41.7
1987	23.2	35.8	25.7	42.6	32.4	44.9	32.4	45.0	43.1	94.4
1988	21.7	31.7	45.1	33.5	58.9	41.5	65.1	53.1	66.7	56.0
1989	25.5	39.7	37.9	40.2	40.6	43.3	44.0	56.6	70.4	67.2
1990	31.5	19.1	69.0	35.8	71.0	50.7	71.3	51.7	80.1	64.1
1991	26.3	27.0	45.9	28.3	48.9	30.3	50.2	30.8	76.9	37.5
1992	27.1	29.9	36.5	37.1	37.2	37.1	37.2	37.4	41.3	41.5
1994	23.5	38.1	33.7	44.3	38.4	46.3	38.4	46.3	40.1	59.4
1996	14.7	40.1	14.7	45.0	27.2	45.0	38.2	45.0	65.2	47.4
Mean	**34.3**	**35.5**	**43.0**	**43.1**	**47.4**	**48.4**	**51.4**	**51.2**	**66.4**	**63.3**
STDEV	**16.4**	**8.4**	**19.6**	**15.0**	**19.2**	**16.8**	**19.8**	**16.7**	**22.1**	**21.0**

Table 4.11 Comparison of collected annual maximum rainfall data between previous work and this study at Kombolcha station

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)									
	1		2		3		5		24	
	previous	Now	previous	Now	previous	Now	previous	Now	previous	Now
1966	22.1	21.7	27.1	22.2	27.1	23	40.7	31.4	42.1	41.7
1967	59.2	53.7	68.2	62.9	68.7	62.9	68.7	62.9	68.7	62.9
1968	38.5	21	38.6	21	38.6	21	38.6	55	38.6	55
1969	35.0	32.1	43.7	36.5	44.4	39.5	50.1	47	61.1	47
1970	22.9	23.3	34.5	27.2	40.0	36	53.2	53.9	61.1	60.5
1971	23.9	23.9	37.0	34.4	43.2	42	43.2	44	43.2	44
1972	37.2	36.2	37.2	36.2	37.2	36.2	37.2	36.2	42.9	46.9
1973	13.0	15.4	18.7	20.2	20.2	21.6	22.2	23.5	42.4	46.9
1975	21.1	21.3	22.6	23.1	23.5	23.1	23.5	23.1	33.6	58.4
1976	29.0	30.5	29.0	30.5	29.0	30.5	29.0	30.5	43.7	45.1
1977	33.2	33.5	35.5	37.6	36.6	39.9	37.1	40.7	50.0	57.8
1978	23.7	23.9	24.2	38	24.2	39.7	26.9	41.9	54.9	46.4
1979	30.8	30.7	36.0	37.4	36.2	38.4	36.2	38.4	37.9	47.4
1980	19.3	18.7	21.0	21.5	22.4	21.5	23.7	30.4	38.3	32.2
1981	45.5	45.7	46.5	46.5	46.5	46.5	46.7	46.7	46.7	46.7
1982	20.0	49.4	26.0	52.6	33.0	52.6	37.2	52.6	41.0	52.6
1983	30.5	28.1	31.4	28.8	31.5	28.9	37.4	29.8	46.0	42.7
1984	34.5	32.5	34.5	33.4	34.5	33.4	34.5	33.4	34.5	33.4
1985	26.4	24.9	34.9	31.7	35.5	38.4	36.7	39.9	41.5	47.8
1986	22.0	22.2	28.8	22.2	29.3	34.2	29.6	35.5	37.3	36
1987	33.2	29.1	36.7	49.1	37.2	59.5	37.6	59.5	46.9	59.5
1988	18.6	18.7	18.6	18.7	19.1	19.2	28.6	27.7	28.6	27.7
1990	11.0	14.8	25.6	24.4	25.6	24.4	36.0	32.1	54.0	51.8
Mean	**28.3**	**28.3**	**32.9**	**32.9**	**34.1**	**35.3**	**37.2**	**39.8**	**45.0**	**47.4**
STDEV	**10.8**	**10.3**	**10.8**	**11.5**	**10.8**	**12.1**	**10.6**	**11.3**	**9.7**	**9.3**

4.10.2 Comparison of estimated quantiles

It is clear that estimation of quantiles greatly depend on the parent distribution and the type of the parameter selected for that specific distribution. Whenever different distributions and parameters are used to estimate quantiles of same station then there will be a possibility to obtain different values of quantiles for that station. This is clearly observed from the following tables and bar charts.

Table 4.12 Comparison of estimated quantiles between previous work and this study at Bahir Dar station

Estimated Quantiles(mm) at Bahir Dar							
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)						
		2	5	10	25	50	100
60	Previous	31.41	45.62	55.03	66.92	75.74	84.49
	Now	34.47	41.52	45.04	48.64	50.86	52.86
120	Previous	39.72	56.47	67.57	81.58	91.98	102.30
	Now	39.60	46.77	50.33	53.97	56.21	58.23
180	Previous	44.21	60.84	71.84	85.75	96.06	106.30
	Now	43.07	51.38	56.14	61.52	65.11	68.56
300	Previous	47.94	65.10	76.47	90.82	101.48	112.05
	Now	46.10	55.71	61.24	67.51	71.72	75.76
1440	Previous	61.97	81.43	94.31	110.59	122.67	134.65
	Now	57.26	72.41	81.29	91.47	98.38	105.05

Table 4.13 Comparison of estimated quantiles between previous work and this study at Kombolcha station

Estimated Quantiles(mm) at Kombolcha							
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)						
		2	5	10	25	50	100
60	Previous	26.14	35.61	41.89	49.81	55.69	61.53
	Now	25.64	33.10	38.04	44.28	48.90	53.50
120	Previous	30.73	40.20	46.46	54.38	60.26	66.09
	Now	30.03	38.46	44.05	51.11	56.34	61.54
180	Previous	32.33	41.67	47.85	55.67	61.46	67.22
	Now	32.38	42.07	48.49	56.59	62.60	68.30
300	Previous	35.42	44.78	50.98	58.81	64.61	70.38
	Now	37.67	47.25	52.93	59.50	63.88	68.32
1440	Previous	43.48	51.82	57.35	64.33	69.50	74.64
	Now	46.70	54.28	58.14	62.14	65.07	68.41

Figure 4.8 Graphical comparison of estimated quantiles between previous work and this study at Bahir Dar for 2, 5 and 10 years return periods

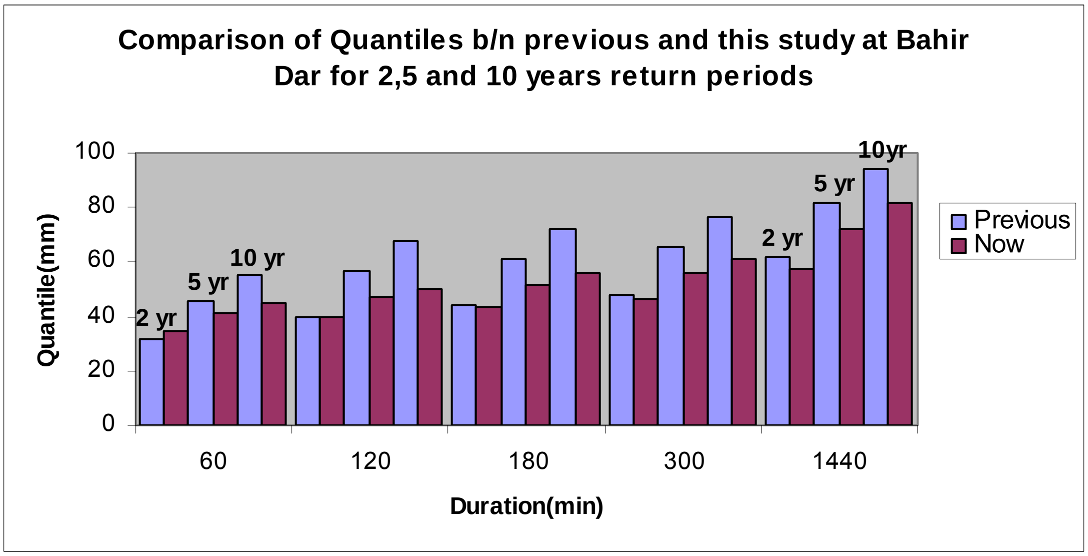


Figure 4.9 Graphical comparison of estimated quantiles between previous work and this study at Bahir Dar for 25, 50 and 100 years return periods

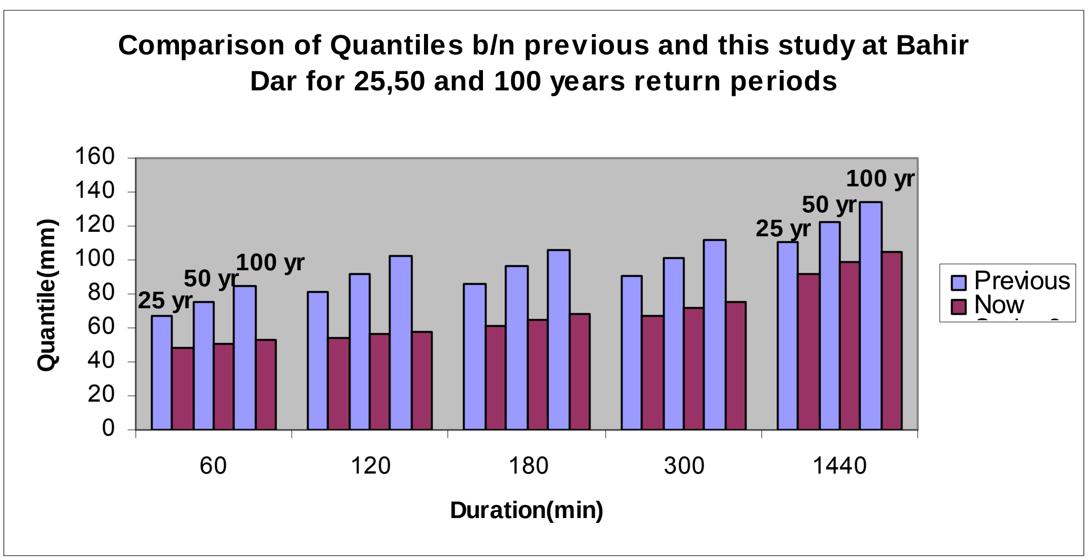


Figure 4.10 Graphical comparison of estimated quantiles between previous work and this study at Kombolcha for 2, 5 and 10 years return periods

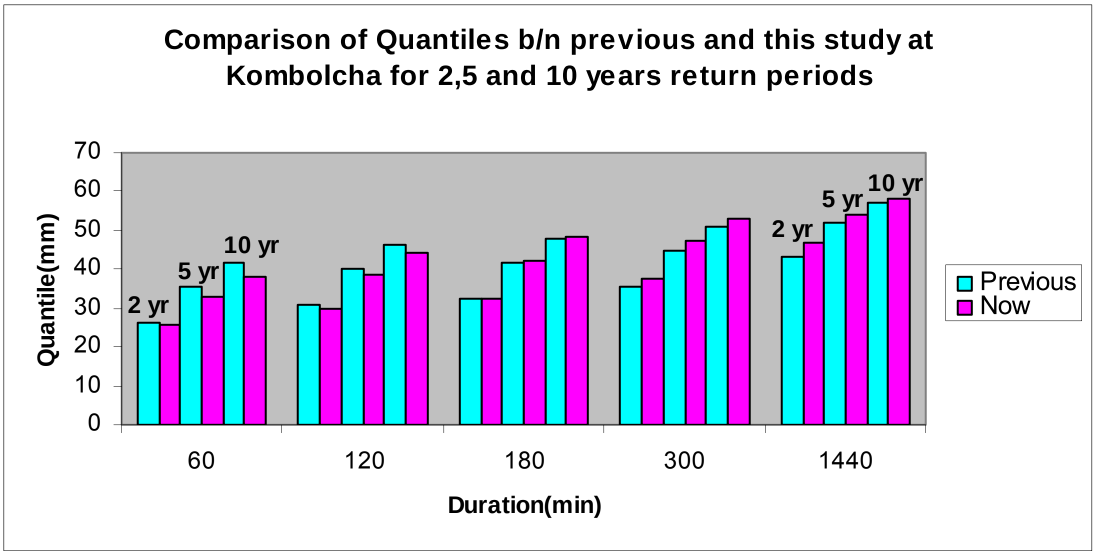
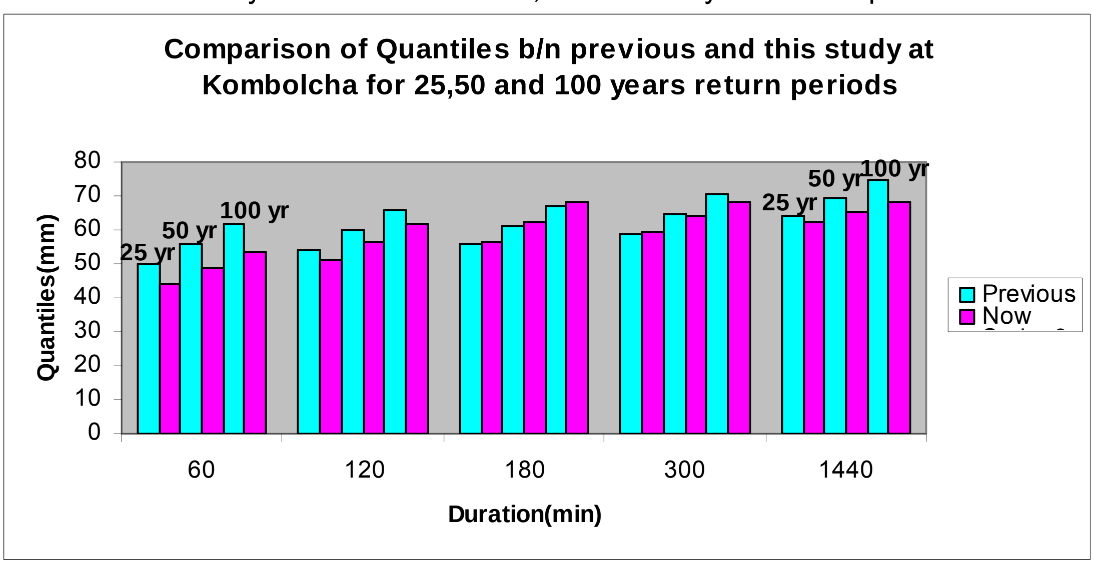


Figure 4.11Graphical comparison of estimated quantiles between previous work and this study at Kombolcha for 25, 50 and 100 years return periods



4.10.3 Comparison of estimated IDF-parameters (using Miduss software)

In both the studies IDF-parameters were determined using Wenzel mathematical equation in combination with Miduss software. Because different values of quantiles are observed in both the studies, the estimated IDF-parameters in the previous study generally differ from the results of this study.

Table 4.14 Comparison of estimated IDF-parameters for common stations of the two studies

Stations	Parameters		Estimated Parameters for the indicated frequency					
			T=2yrs	T=5yrs	T=10yrs	T=25yrs	T=50yrs	T=100yrs
Bahir Dar	A	Previous	1619	2367	2948	3635	4233	4648
		Now	1643.2	1525.9	1433	1333	1268.6	1214.4
	B	Previous	26.2	20.2	19.1	17.6	17.6	16.0
		Now	16.33	10.67	7.47	4.16	2.09	0.3
	C	Previous	0.844	0.899	0.909	0.916	0.923	0.923
		Now	0.898	0.854	0.829	0.801	0.784	0.768
Debre Berhan	A	Previous	1422	731	728	831	929	1004
		Now	543.8	762.5	1084.2	1007.7	1007.7	3926.2
	B	Previous	44.9	5.0	0.0	0.0	0.0	0.0
		Now	0.01	1.98	6.62	0.91	0.91	29.03
	C	Previous	0.932	0.816	0.802	0.806	0.811	0.813
		Now	0.798	0.811	0.847	0.824	0.824	1.002
Gondar	A	Previous	505	615	707	786	876	948
		Now	541.4	779.9	939.4	1283.9	1595.5	2071.5
	B	Previous	0.0	0.0	0.0	0.1	0.0	0.0
		Now	7.47	13.39	16.33	22.96	29.03	37.26
	C	Previous	0.802	0.789	0.787	0.778	0.778	0.776
		Now	0.822	0.85	0.868	0.905	0.932	0.966
Kombolcha	A	Previous	1442	1709	2112	2643	3080	3541
		Now	950.4	1794.9	2775.3	4559.9	6581.5	8645.9
	B	Previous	11.1	8.1	7.0	6.1	6.0	6.1
		Now	10.91	18.8	25.79	34.03	40.98	45.8
	C	Previous	0.886	0.917	0.932	0.947	0.958	0.967
		Now	0.847	0.914	0.965	1.024	1.069	1.101
Mekele	A	Previous	804	863	691	1130	1203	1306
		Now	1749.6	2098.3	2257.2	2466.3	2594.2	2667.8
	B	Previous	4.1	0.0	0.0	0.0	0.0	0.0
		Now	16.33	17.18	17.47	18.32	18.8	18.8
	C	Previous	0.895	0.851	0.841	0.835	0.826	0.822
		Now	0.957	0.953	0.95	0.948	0.947	0.943
Shire Endasi.	A	Previous	1237	1778	2173	2550	2975	3266
		Now	1153.9	1383.9	1585	1823.7	1896.8	2025.2
	B	Previous	20.2	25.4	28.4	29.0	31.7	31.9
		Now	13.47	16.85	19.94	23.27	23.8	25.8
	C	Previous	0.906	0.915	0.922	0.92	0.927	0.926
		Now	0.883	0.878	0.884	0.891	0.889	0.891

From the above comparison the following points are concluded:

1. In the data collection part it is seen that different values of annual maximum rainfall depths were recorded for the same station in similar years between the two studies. This discrepancy may occur due to personal judgments in interpreting rainfall chart value in to numerical value. That is, if the charts are not interpreted curiously then there will be a chance to record underestimated or overestimated rainfall depths. And this is clearly observed at Bahir Dar station. But for station Kombolcha both the studies have almost similar record of rainfall depth.
2. For estimation of quantiles the type of the raw data, parent distribution, the type of the parameter used, etc. are some of the factors that need special attention. As it is observed from the bar charts of previous work and this study, different values of quantiles are estimated at station Bahir Dar.

Basically the following factors are assumed to be the cause for the difference.

- The rainfall depths recorded by the two studies in similar years are not equivalent and apart from this, additional years of record are included in this study. And therefore, this is one of the causes for dissimilarity of the estimated quantiles.
- In the previous study quantiles are estimated based on EVI-distribution and no parameter selection was made for estimation. But in this study distributions and parameters are properly selected based on SEE. And unlike the previous study G2 and PIII distributions with appropriate parameters were used for quantile estimation of different durations at Bahir Dar station.

In the case of station Kombolcha, good match between the two studies was observed in quantile estimation.

The following factors played significant role for obtaining similar results in station Kombolcha. These are:

- The rainfall depth recorded by the two studies is similar. Since the primary input for quantile estimation is the raw data, the similar rainfall record contributed a lot for obtaining equivalent quantiles between the two studies.
- Similar to the previous study, EVI-distribution was used for quantile estimation of most of the durations of this study at station Kombolcha. And therefore, the similarity of selected distributions resulted in giving equivalent quatiles between the two studies for Kombolcha.

Generally estimated quantiles are the primary inputs for estimation of IDF-parameters. Six stations are common for both the studies. And for most of these stations different values of quantiles are estimated by the previous study and this study. Therefore, this is the cause for different values of IDF-parameters between the two studies for the common stations.

From the preceding results of this study it could be concluded that proper data collection, data testing, inclusion of additional years of record and procedural selection of distributions and parameters end up with preferable and reliable results of IDF-relationships.

CHAPTER FIVE

REGIONALIZATION

5.1 Introduction

Of all the stages in a regional frequency analysis involving many sites, the identification of homogeneous regions is usually the most difficult and requires the greatest amount of subjective judgment. The aim is to form groups of sites that approximately satisfy the homogeneity condition, that the sites frequency distributions are identical apart from a site-specific scale factor. This is usually achieved by partitioning the sites in to disjoint groups. An alternative approach is to define for each site of interest a region containing those sites whose data can advantageously be used in the estimation of the frequency distribution at the site of interest (Hosking and Wallis, 1997).

A homogeneous region is the one which contains stations having similar climatic characteristics, geographic proximity, etc. In a practical world, there may be limited or no data for a given site. And therefore, regional analysis is become most useful.

The concept of “regionalization” in the context of a precipitation frequency analysis is the process by which the precipitation characteristics surrounding a particular station are combined or “pooled together” to develop more accurate statistical summaries of precipitation characteristics than can be derived from a single station. Additionally, once regionalization is completed, precipitation frequency can be estimated for locations other than precipitation stations.

Regionalization serves two purposes. For sites where data are not available, the analysis is based on regional data. For sites with available data, the joint use of data measured at a site, called at-site data, and regional data from a number of stations in a region provides sufficient information to enable a probability distribution to be used with greater reliability (Cunnane, 1989).

5.2 Delineation of Homogenous Regions

In the delineation of homogenous regions Arc-View 3.3 software is used. Delineation of homogenous regions was made based on the annual maximum rainfall depth of **24 hour** durations data. The primary identification of homogenous regions was done by using L-MRD. The sample L-moment ratios LCs and LCk for each station based on specific duration data as well as their regional averages are plotted on L-moment ratio diagrams. It is assumed that (LCs, LCk) values of one station varies linearly with (LCs, LCk) values of the neighboring station. A suitable parent distribution is that which averages the scattered data and around which the data spread consistently and considered as the same region. On the digitized map of the region, (on Arc View GIS software) the distance between one station and its neighboring station was determined and (LCs, LCk) values were interpolated to fix the boundary between two stations of different regions. Two boundaries are fixed, one from the LCs and the other from the LCk values. The final boundary between regions is fixed between the mid ways of the two boundaries (Edessa, 2007).

5.3 Goodness of fit tests

Hosking and Wallis (1991) give a goodness of fit measure based on $\bar{t}_r$, the regional average of the sample L-kurtosis, mainly for three parameter distributions. Since all three parameter distributions fitted to the data will have the same t_3 on the LCs, Vs. LCk diagram, the quality of fit can be judged by the difference between regional average $\bar{t}_4$ and the value of τ_4^{Dist} for the fitted distribution. The statistic

$$Z^{Dist} = \left(\bar{t}_4 - \tau_4^{Dist}\right) / \sigma_4 \qquad (5.1)$$

is a goodness-of-fit measure.

Where: σ_4 is the standard deviation of $\bar{t}_4$

τ^{Dist} is L-kurtosis value of the distribution

The value of σ_4 can be obtained by simulation after fitting Kappa distributions to the observations. A fit is adequate if Z^{Dist} is sufficiently close to zero, a reasonable criterion being $/Z^{Dist}/ \leq 1.64$ (Rao and Hamed, 2000).

5.4. Regional Homogeneity Test

Cv- based homogeneity test and discordance measure are some of the techniques used to identify homogeneous regions. Cv- based homogeneity test can be done as it is discussed in section 2.9.

Discordance measure is intended to identify those sites that are grossly discordant with the group as a whole. The discordance measure, D estimates how far a given site is from the center of a group. If $U_i = \left[t^{(i)}, t_3^{(i)}, t_4^{(i)}\right]^T$ is the vector containing the t, t_3, t_4 values for site (i), then the group average for NS sites is given by

$$\overline{U} = \frac{1}{NS}\sum_{i=1}^{NS} U_i \quad \text{...} \quad (5.2)$$

The sample covariance matrix is given by

$$S = (NS-1)^{-1}\sum_{i=1}^{NS}\left(U_i - \overline{U}\right)\left(U_i - \overline{U}\right)^T \quad \text{..................................} \quad (5.3)$$

The discordance measure is defined by

$$D_i = \frac{1}{3}\left(U_i - \overline{U}\right)^T S^{-1}\left(U_i - \overline{U}\right) \text{...} \quad (5.4)$$

A site (i) is declared to be unusual if D_i is large. A suitable criterion to classify a station as a discordant is that D_i should be greater than or equal to 3.

5.5 Results of Regionalization

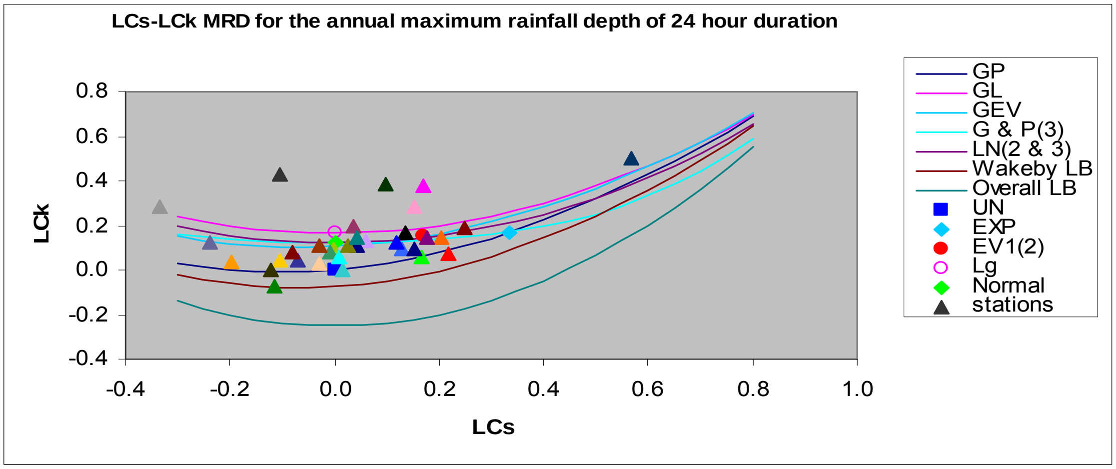
5.5.1 Identification of homogeneous Regions

In addition to at –site statistics, it is important to consider site characteristics such as geographic location, elevation and other physical properties for identifying homogeneous regions. Several researchers have proposed different methods for grouping similar sites.

In this study regionalization was made based on the statistical values (LCs & LCk) of maximum rainfall of the 24 hour duration for each station. Generally stations from the same region will have a data series which comes from the same parent distribution.

The LCs-LCk and Cs-Ck moment ratio diagrams for durations of 24 hour data are shown in figure 5.1 with various distributions. The primary selection of the regions is made on the bases of the closeness of the stations (Cs, Ck) and (LCs-LCk) value to the theoretical probability distributions. Best fitted theoretical probability distributions according to their priority of closeness are shown in table 5.1. And those distributions based on which the primary classification of the regions are made and common for both (Cs, Ck) and (LCs, LCk) are determined. As per the aforementioned procedures, 5 regions were identified in the Amhara and Tigray regional states.

Figure 5.1 L-MRD and conventional MRD of 24-hour rainfall data



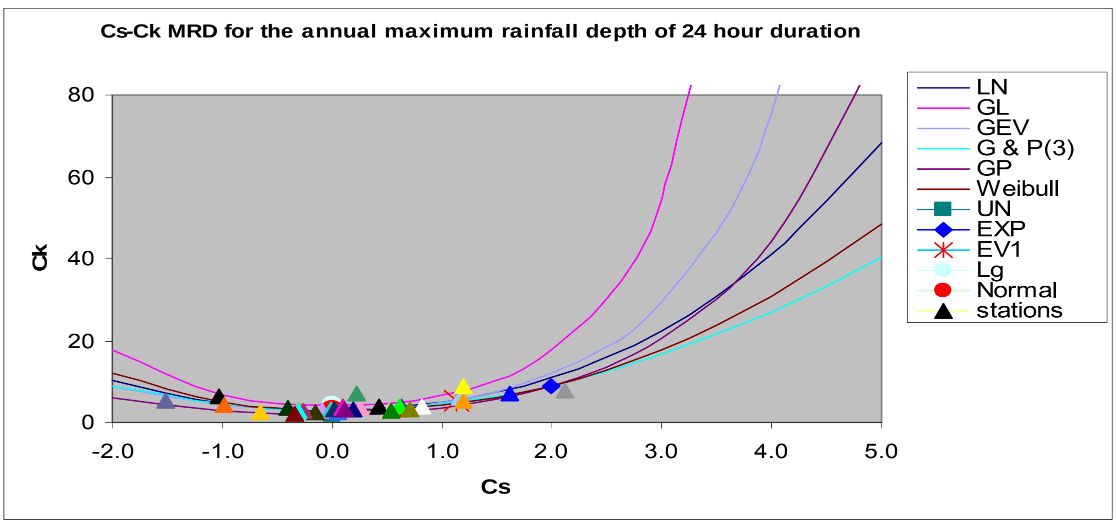


Table 5.1 Prioritized distributions based on closeness to stations on L-MRD and conventional MRD

S.No.	Station	Distribution on L-MRD			Distribution on conv. MRD			Selected Distn.
1	Adigrat	GL	LN(2 & 3)	G & P(3)	GL	Weibull	LN	LN
2	Adwa	GL	GEV	LN(2 & 3)	GEV	LN	EV1	LN
3	Alem Ketema	G & P(3)	GEV	LN(2 & 3)	LN	G & P(3)	GEV	LN
4	Amba Mariam	GP	UN	GEV	G & P(3)	Weibull	GEV	GEV
5	Bahir Dar	G & P(3)	GEV	LN(2 & 3)	GP	Weibull	GEV	GEV
6	Bati	GP	UN	Wakeby LB	Weibull	GEV	GP	GP
7	Cheffa	GEV	LN(2 & 3)	G & P(3)	G & P(3)	Normal	LN	LN
8	Dangela	GP	GEV	G & P(3)	Weibull	GEV	LN	GEV
9	Debre Berhan	GP	Wakeby LB	GEV	GP	GEV	Weibull	GEV
10	Debre Markos	G & P(3)	LN(2 & 3)	GEV	G & P(3)	Weibull	EV1	G & P(3)
11	Finote Selam	GEV	G & P(3)	LN(2 & 3)	GEV	G & P(3)	Weibull	GEV
12	Gebre Guracha	GL	LN(2 & 3)	G & P(3)	GP	GEV	G & P(3)	G & P(3)
13	Gewane	GL	GEV	GP	G & P(3)	Weibull	GP	GP
14	Gondar	GEV	G & P(3)	LN(2 & 3)	G & P(3)	Weibull	GEV	GEV
15	Haike	GL	GEV	LN(2 & 3)	GL	G & P(3)	GEV	GEV
16	Humera	GP	Wakeby LB	GEV	G & P(3)	Weibull	GEV	GEV
17	Kombolcha	GEV	G & P(3)	LN(2 & 3)	GEV	Weibull	LN	GEV
18	Lalibela	GL	LN(2 & 3)	G & P(3)	GL	G & P(3)	GEV	G & P(3)
19	Majete	GP	GEV	G & P(3)	GEV	Weibull	G & P(3)	GEV
20	Mehal Meda	GL	GEV	LN(2 & 3)	GEV	G & P(3)	LN	GEV
21	Mekane Selam	GEV	G & P(3)	LN(2 & 3)	GL	LN	G & P(3)	LN
22	Mekele	GP	G & P(3)	Wakeby LB	Weibull	G & P(3)	GEV	G & P(3)
23	Metema	GP	Wakeby LB	G & P(3)	Weibull	GEV	G & P(3)	GEV
24	Michew	G & P(3)	GEV	LN(2 & 3)	LN	G & P(3)	GEV	LN
25	Motta	GEV	LN(2 & 3)	GL	G & P(3)	Weibull	GEV	GEV
26	Nefas Mewcha	GL	GEV	LN(2 & 3)	GL	GEV	LN	GEV
27	Pawi	GEV	GP	UN	G & P(3)	LN	GEV	GEV
28	Shambu	GEV	G & P(3)	LN(2 & 3)	GEV	Weibull	G & P(3)	GEV
29	Shire Endasilase	Wakeby LB	GP	GEV	GP	GEV	Weibull	GEV
30	Shola Gebeya	G & P(3)	LN(2 & 3)	GP	Weibull	LN(2 & 3)	G & P(3)	LN
31	Sinkata	GEV	G & P(3)	LN(2 & 3)	G & P(3)	LN(2 & 3)	GEV	LN
32	Sirinka	LN(2 & 3)	GEV	EV1(2)	Weibull	GEV	G & P(3)	GEV
33	Wegel Tena	GL	LN(2 & 3)	G & P(3)	G & P(3)	LN(2 & 3)	Weibull	LN

Table 5.2 Regions based on closeness to distributions common to L-MRD and MRD

Region 1		Region 2		Region 3	
Station	Distribution	Station	Distribution	Station	Distribution
Adigrat	LN(2 & 3)	Gondar	GEV	Bahir Dar	GEV
Adwa		Lalibela		Dangela	
Humera		Metema		Finote Selam	
Mekele				Mehal Meda	
Michew				Motta	
Shire Endasilase				Nefas Mewcha	
Sinkata				Pawi	
				Shambu	

Region 4		Region 5	
Station	Distribution	Station	Distribution
Alem Ketema	LN(2 & 3)	Bati	GEV
Cheffa		Debre Berhan	
Debre Markos		Gewane	
Gebre Guracha		Haike	
Mekane Selam		Kombolcha	
Shola Gebeya		Majete	
Wegel Tena		Sirinka	
Amba Mariam			

5.5.2. Discordance Test

The discordance test of the classified five regions is done based on the method described in section 5.4 and the result of the test is shown in table 5.3.

Table 5.3 Discordance test results

Station Name	Discordant Measure	Remark
Region-1		
Adigrat	0.71	Homogeneous
Adwa	0.26	Homogeneous
Humera	0.26	Homogeneous
Mekele	0.28	Homogeneous
Michew	0.06	Homogeneous
Shire Endasilase	0.42	Homogeneous
Sinkata	0.005	Homogeneous
Region -2		
Gondar	0.14	Homogeneous
Lalibela	0.20	Homogeneous
Metema	0.33	Homogeneous
Region -3		
Bahir Dar	0.11	Homogeneous
Dangela	0.24	Homogeneous
Finote Selam	0.65	Homogeneous
Mehal Meda	0.15	Homogeneous
Motta	0.45	Homogeneous
Nefas Mewcha	0.74	Homogeneous
Pawi	0.04	Homogeneous
Shambu	0.001	Homogeneous
Region- 4		
Alem Ketema	0.02	Homogeneous
Amba Mariam	0.12	Homogeneous
Cheffa	0.03	Homogeneous
Debre Markos	0.38	Homogeneous
Gebre Guracha	1.51	Homogeneous
Mekane Selam	0.05	Homogeneous
Shola Gebeya	0.23	Homogeneous
Wegel Tena	0.006	Homogeneous
Region- 5		
Bati	0.117	Homogeneous
Debre Berhan	0.32	Homogeneous
Gewane	1.17	Homogeneous
Haike	0.06	Homogeneous
Kombolcha	0.13	Homogeneous
Majete	0.03	Homogeneous
Sirinka	0.18	Homogeneous

5.5.3 Cv and LCv Homogeneity Tests

This test was done using a FORTRAN program developed by Sine (2004).The program is developed based on the method described in sections 2.9. From the test result, it is observed that all stations with in a particular region satisfy homogeneity criteria for both conventional and L-moment Cv based homogeneity tests. Table 5.4 shows the summarized result of this test.

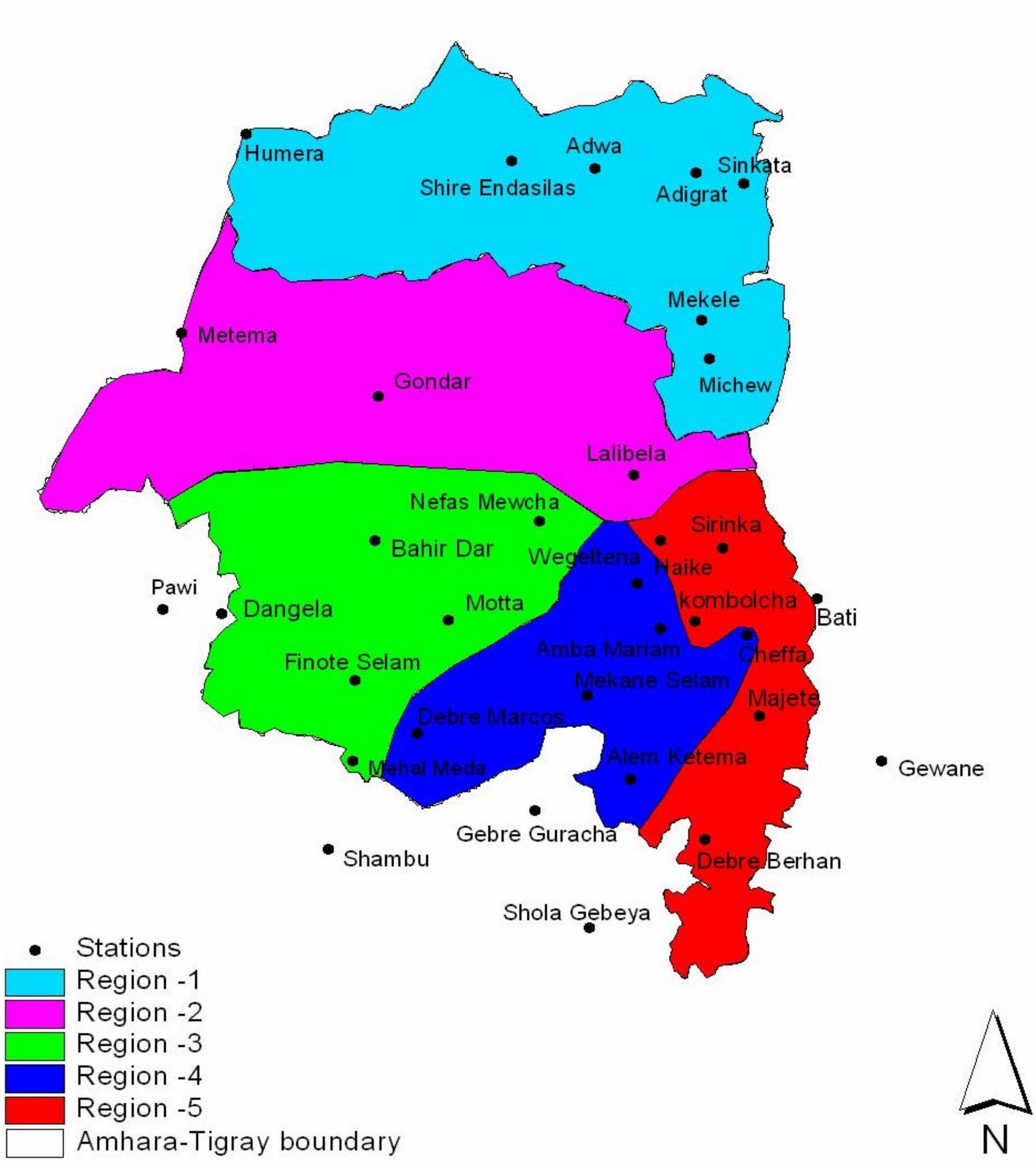
Table 5.4The CC values for the delineated regions

Region	CC value		Conclusion
	Conv. CV-based method	L-Moment CV-based method	
One	0.223	0.239	Homogenous
Two	0.249	0.254	Homogenous
Three	0.270	0.298	Homogenous
Four	0.273	0.258	Homogenous
Five	0.275	0.269	Homogenous

Table 5.5 summarized results of conventional and L-moment homogeneity tests

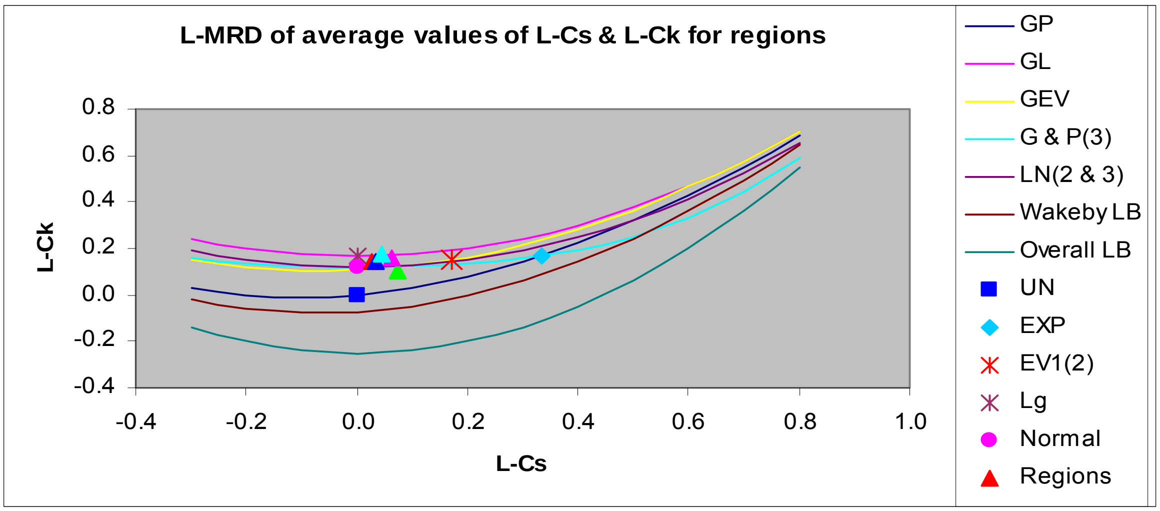
Region Name	Average Rainfall(mm)	Cv	Cs	Ck	t	t_3(LCs)	t_4(LCk)	Remark
Region 1	43.70	0.232	0.160	4.229	0.133	0.026	0.143	homogeneous
Region 2	41.17	0.253	0.284	3.388	0.150	0.074	0.103	homogeneous
Region 3	45.46	0.193	0.481	4.993	0.109	0.065	0.162	homogeneous
Region 4	40.10	0.264	0.182	3.955	0.151	0.033	0.146	homogeneous
Region 5	51.90	0.250	0.155	4.129	0.138	0.046	0.178	homogeneous

Figure 5.2 Delineated homogeneous regions



5.6. Selection of best fitted distributions for the delineated regions based on average values

Figure 5.3 L-MRD of mean value of L-Cs and L-Ck for the delineated regions



Using L-MRD of average L-moments shown above, the candidate distributions for the delineated regions were determined. And from these candidate distributions the final and best fitted distribution of each region is selected based on goodness of fit measure, Z^{Dist} as it is discussed in section 5.3. Table 5.7 shows the best fit distributions for the delineated regions.

Table 5.6 Candidate distributions based on L-MRD of average L-Cs & L-Cv

Region	Candidate distribution	Goodness of fit measure, Z^{Dist}	Remark
1	LN(2 & 3)	0.074	desirable
	G & P(3)	0.134	desirable
	GEV	0.193	desirable
2	GEV	0.228	desirable
	G & P(3)	0.295	desirable
	LN(2 & 3)	0.363	desirable
3	GL	0.073	desirable
	LN(2 & 3)	0.301	desirable
	G & P(3)	0.395	desirable
4	LN(2 & 3)	0.246	desirable
	G & P(3)	0.395	desirable
	GEV	0.545	desirable
5	GL	0.044	desirable
	LN(2 & 3)	0.250	desirable
	G & P(3)	0.302	desirable

Table 5.7 The best fit distributions based on L-MRD of Average L-moments

Duration	Region	Distribution
24-hour	1	LN(2 & 3)
	2	GEV
	3	GL
	4	LN(2 & 3)
	5	GL

5.7 Regional quantiles

The best fit distributions found in section 5.6 are used to estimate regional quantiles. The quantiles for each station grouped in a region are estimated using the regional best fitted distribution. Finally estimated quantiles of each station within a specific region are pooled together and the mean value for each return period and duration is determined. And these mean quantiles are used for the estimation of regional IDF parameters.

5.8 Regional IDF Parameters

Regional IDF parameters for each classified regions with in the study area are estimated based on the methods described in section 4.5 using mean quantiles obtained in section 5.7.

Table 5.8 Estimated regional IDF parameters with SEE

Region	Parameters	Estimated Parameters for the indicated frequency					
		T=2yrs	T=5yrs	T=10yrs	T=25yrs	T=50yrs	T=100yrs
Region1	A	999.47	1196.14	1361.24	1464.56	1600.78	1709.75
	B	7.472	9.236	11.146	11.359	12.692	13.477
	C	0.8718	0.8693	0.8731	0.8673	0.87	0.8699
	SEE	0.56	0.64	0.73	0.84	0.93	1.01
Region2	A	936.38	1403.67	1979.39	3156.47	4678.93	5653.67
	B	15.09	21.33	29.034	40.978	52.215	57.446
	C	0.8763	0.9	0.9318	0.98	1.0241	1.0384
	SEE	0.49	1.34	2.11	2.84	3.24	3.51
Region3	A	924.32	1092.49	1190.79	1306.19	1395.46	1487.99
	B	13.467	13.764	13.477	12.666	11.947	11.125
	C	0.8587	0.8567	0.8545	0.8505	0.8476	0.8447
	SEE	0.18	0.18	0.23	0.26	0.28	0.32
Region4	A	840.44	1233.61	1575.16	2058.38	2363.64	2853.78
	B	6.0	10.639	14.25	18.32	19.94	23.27
	C	0.8621	0.8824	0.899	0.917	0.92	0.939
	SEE	0.43	0.32	0.31	0.36	0.40	0.47
Region5	A	847.94	1124.56	1456.54	1987.53	2769.78	3654.65
	B	7.472	9.236	12.743	16.851	23.18	28.035
	C	0.8231	0.8327	0.8518	0.8739	0.9048	0.9269
	SEE	0.63	0.64	0.56	0.47	0.56	0.84

As it is explained in the mathematical expression of IDF, the A coefficient is dependent on return period (T). Therefore, an equation which relates A coefficient and return period is tabulated below and this will help to determine the A coefficient for any return period. The two parameters B and C do not depend with return period. And therefore their arithmetic average is considered for each region.

S.No.	Region	The fitted equation between A and T	R^2	Avg. B	Avg. C
1	Region 1	$A = 951.36*T^{0.1331}$	0.9721	10.897	0.870
2	Region 2	$A = 667.35*T^{0.4778}$	0.9954	36.016	0.958
3	Region 3	$A = 883.82*T^{0.1177}$	0.9790	12.741	0.852
4	Region 4	$A = 732.10*T^{0.3055}$	0.9848	15.403	0.903
5	Region 5	$A = 626.02*T^{0.3758}$	0.9954	16.253	0.869

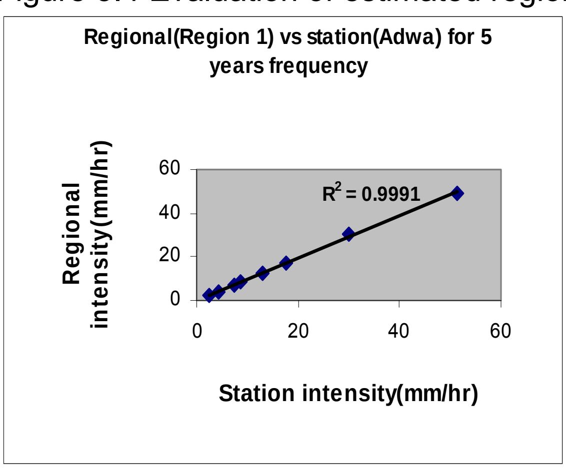
5.9 Graphical evaluation of estimated regional parameters

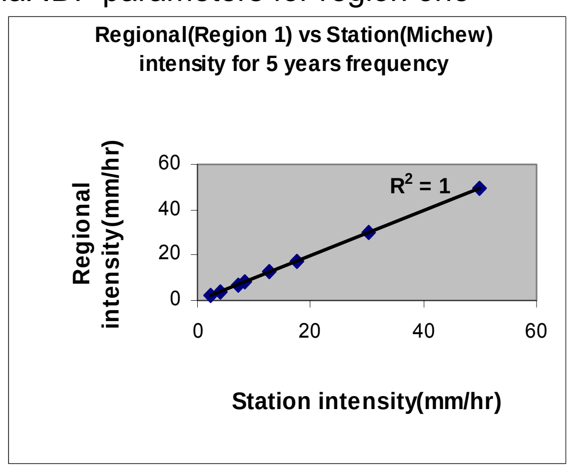
Comparison is made between intensity obtained from the estimated parameters of the stations with in a region and intensity values obtained from the estimated regional parameters. By plotting their graph and looking the value of R^2 it is concluded that regional parameters sufficiently represent the station parameters. And in addition goodness of fit between the two intensities was observed.

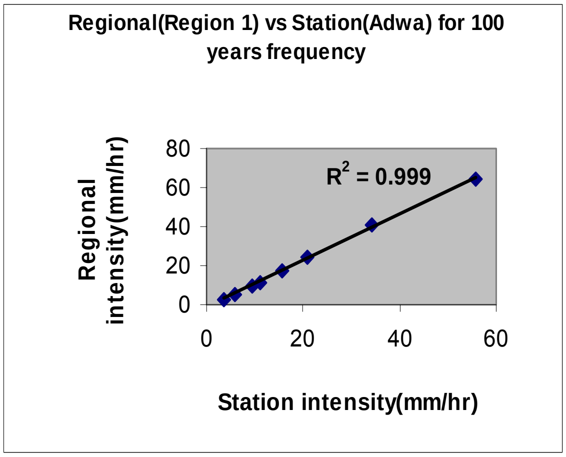
5.9.1 Region one graphical evaluation

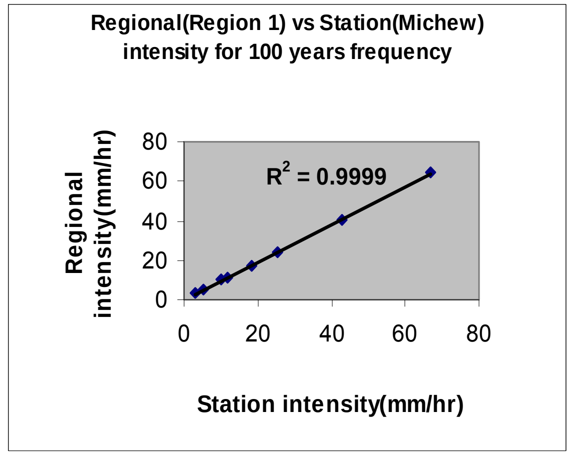
This region contains seven stations. From the comparison of regional and stations intensities good R^2 value is obtained. In addition it is observed that station intensity curves have good fit with the regional (pooled) intensity curve. Therefore, from the above comparisons it is concluded that the regional parameters are adequate and representative for this region. The intensity of all the stations in this region has a perfect match with the regional intensity. And therefore, the intensity for any ungauged station which is located around the seven stations of region one can be estimated confidentially using IDF-parameters developed for region one.

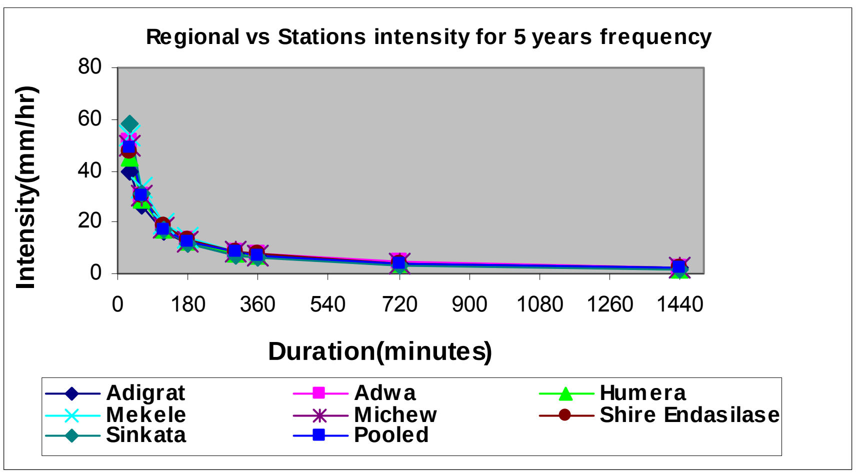
Figure 5.4 Evaluation of estimated regional IDF parameters for region one

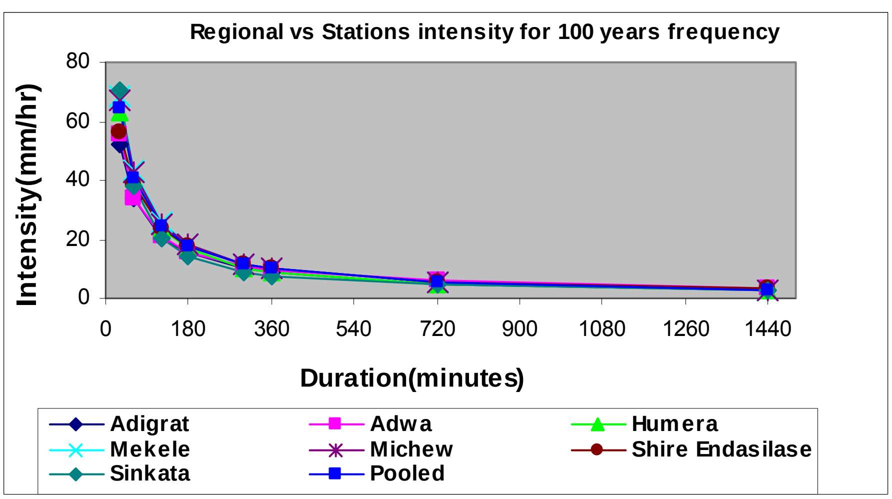





Regional(Region 1) vs Station(Adwa) for 100 years frequency
R² = 0.999
Regional intensity(mm/hr)
Station intensity(mm/hr)


Regional(Region 1) vs Station(Michew) intensity for 100 years frequency
R² = 0.9999
Regional intensity(mm/hr)
Station intensity(mm/hr)

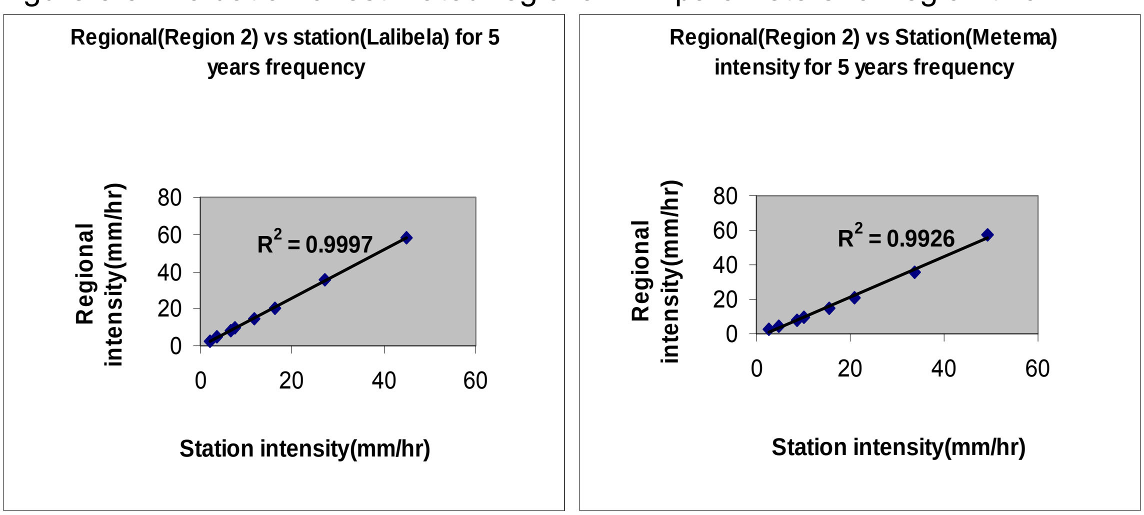

Regional vs Stations intensity for 5 years frequency
Intensity(mm/hr)
Duration(minutes)
Adigrat
Adwa
Humera
Mekele
Michew
Shire Endasilase
Sinkata
Pooled

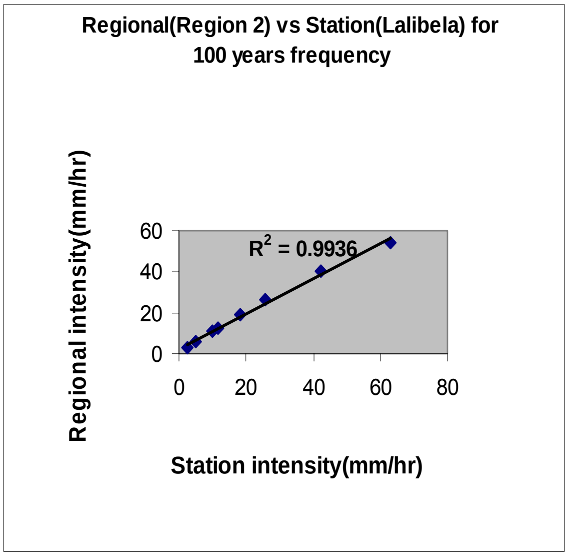

Regional vs Stations intensity for 100 years frequency
Intensity(mm/hr)
Duration(minutes)
Adigrat
Adwa
Humera
Mekele
Michew
Shire Endasilase
Sinkata
Pooled

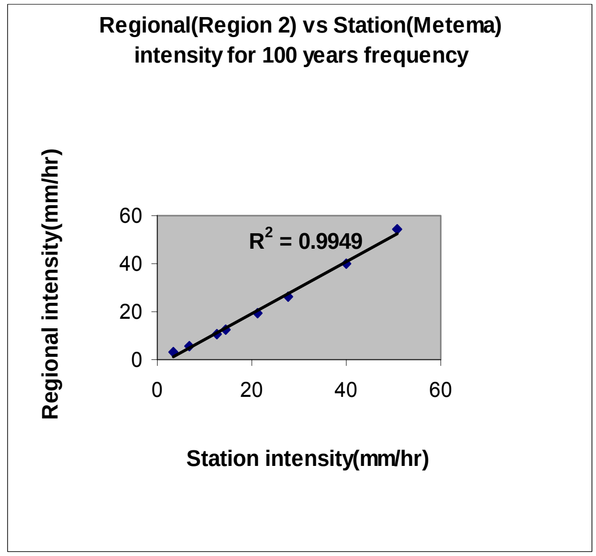
5.9.2 Region two graphical evaluation

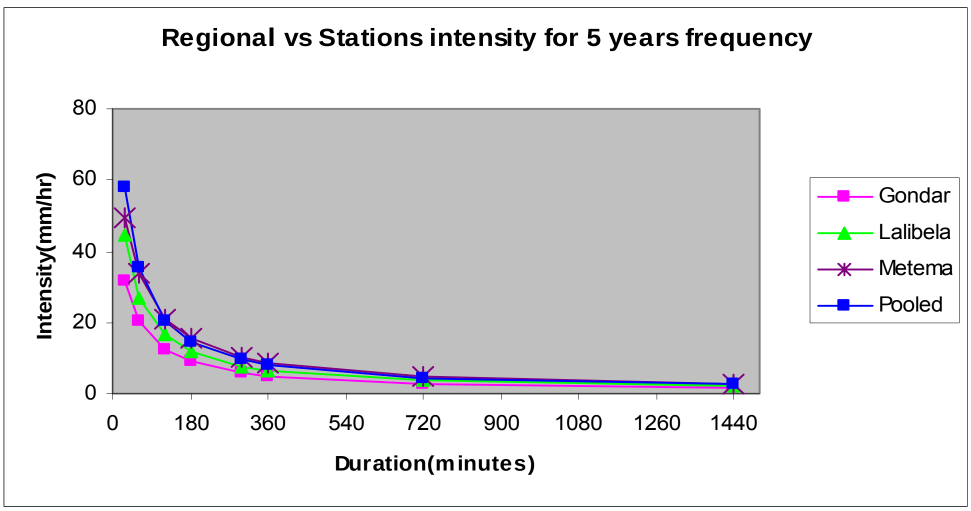
Unlike other regions, this region includes only three stations. From the intensity-curves of both lower and higher return periods station Gondar shows greater divergence from the regional (pooled) intensity curve at lower durations. This is a good indication that care must be taken in using the regional parameters in this region. That is, for estimation of intensity of lower durations at ungauged stations around Gondar the regional parameters may not give good result. Therefore, shorter durations intensity of Gondar and its surrounding ungauged stations can be determined preferably using the methods developed for principal stations in combination with IDF-maps than regional parameters. But in the case of longer durations the regional parameters can be used for intensity determination without any hesitation.

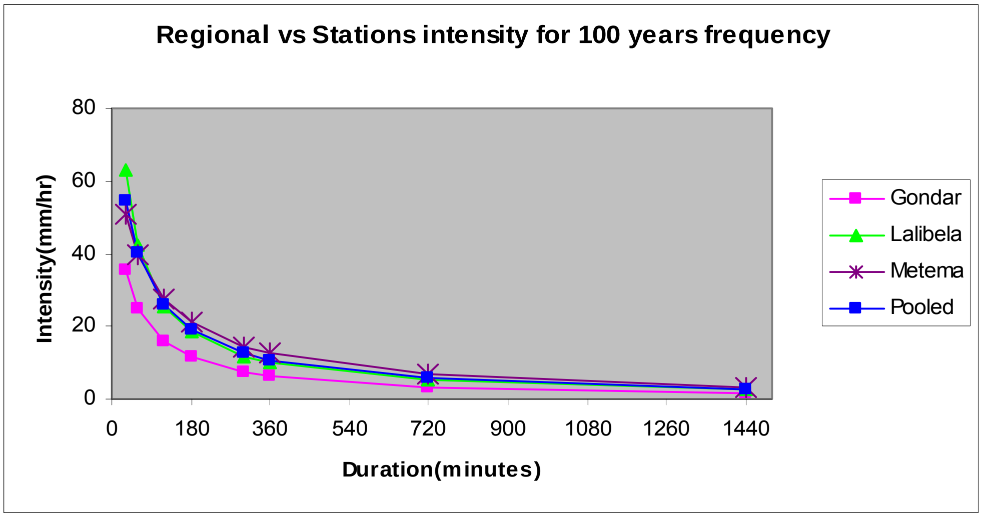
Figure 5.5 Evaluation of estimated regional IDF parameters for region two




Regional(Region 2) vs Station(Lalibela) for 100 years frequency
R^2 = 0.9936
Regional intensity(mm/hr)
Station intensity(mm/hr)
0
20
40
60
80


Regional(Region 2) vs Station(Metema) intensity for 100 years frequency
R^2 = 0.9949
Regional intensity(mm/hr)
Station intensity(mm/hr)
0
20
40
60

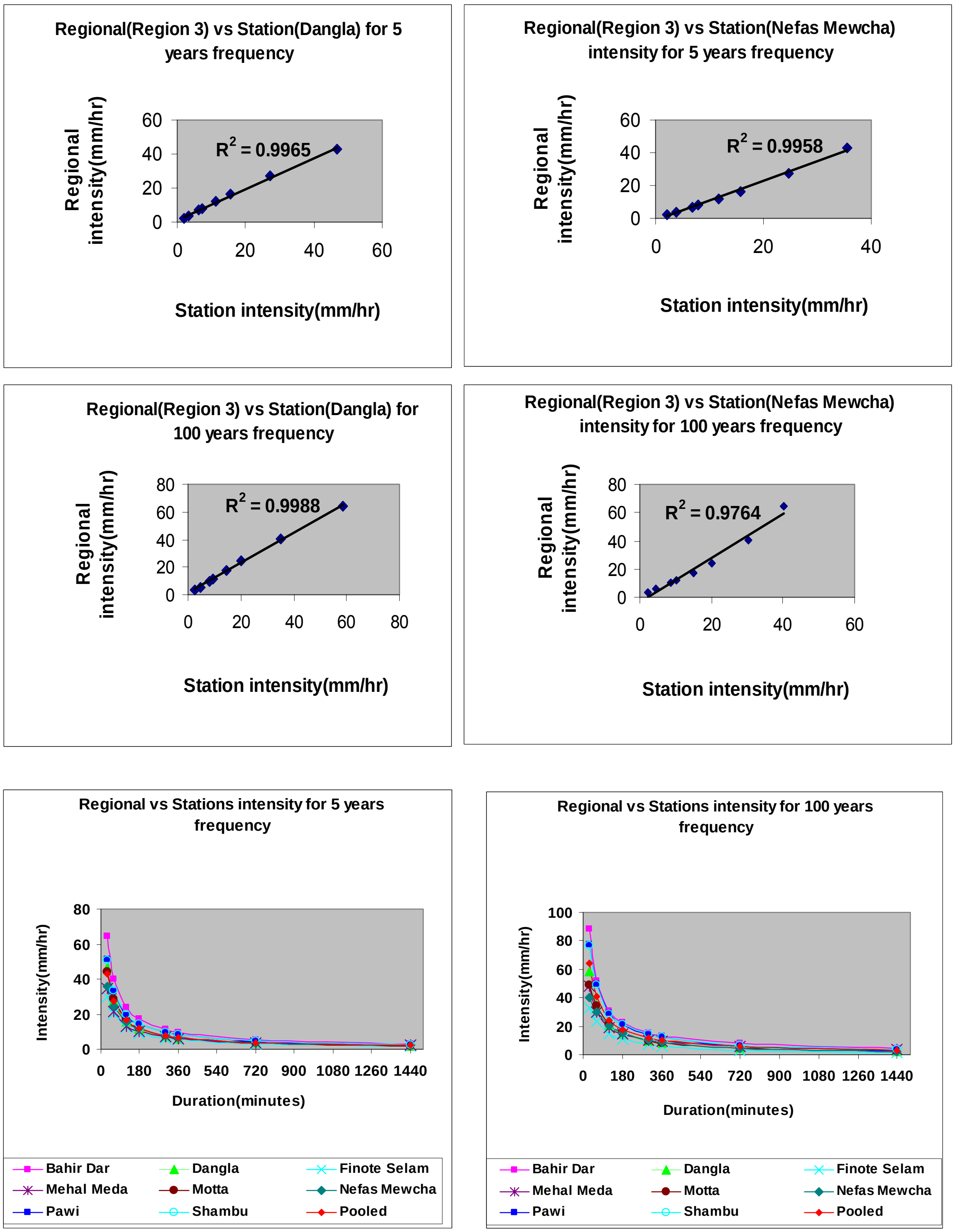

Regional vs Stations intensity for 5 years frequency
Intensity(mm/hr)
Duration(minutes)
0
20
40
60
80
180
360
540
720
900
1080
1260
1440
Gondar
Lalibela
Metema
Pooled



5.9.3 Region three graphical evaluation

This is a region with eight stations. In this region except Bahir Dar the intensity curves of all the stations properly fit with the regional intensity curve. Bahir Dar shows some deviation from the regional (pooled) intensity curve at lower durations. Because station Bahir Dar doesn't show perfect match with the regional parameters, estimation of intensity of lower durations at ungauged stations around Bahir Dar with regional parameters may not give good result. Therefore, shorter durations intensity of Bahir Dar and its surrounding ungauged stations can be determined preferably using the methods developed for principal stations in combination with IDF-maps than regional parameters. But in the case of longer durations the regional parameters can be used for intensity determination without any hesitation.

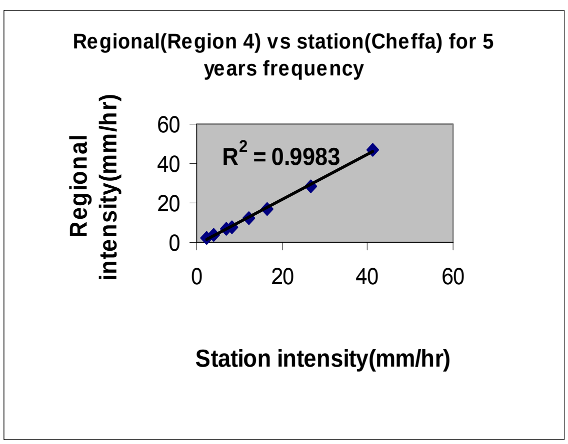
Figure 5.6 Evaluation of estimated regional IDF parameters for region three

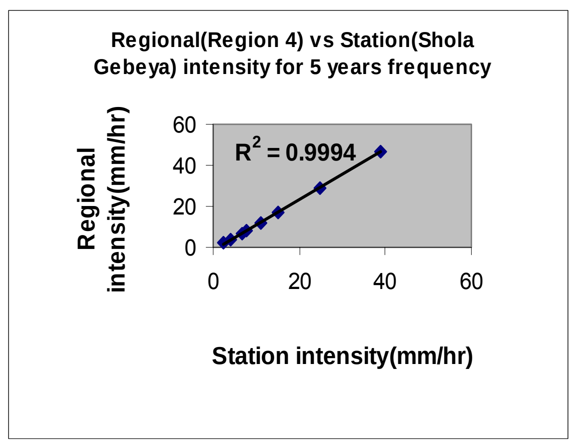


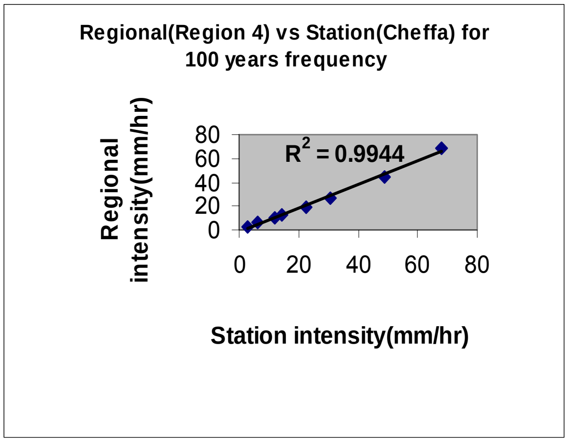
5.9.4 Region four graphical evaluation

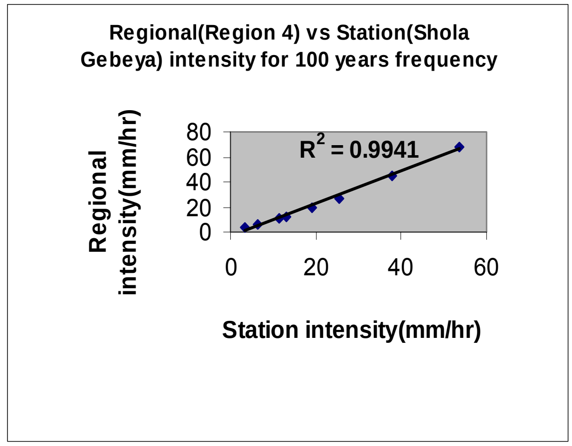
Similar to region three this region contains eight stations. In this region except Mekane Selam and Wegel Tena the intensity curves of all the stations fit with the regional intensity curve in a better way. Mekane Selam and Wegel Tena show some divergence at lower durations of higher return periods. Therefore, the use of IDF-parameters developed for these stations jointly with the IDF-maps developed for the study area will give better result for annual maximum rainfall of lower durations of higher return periods. Excluding these two stations and their surrounding ungauged stations, the regional IDF parameters which are developed for this region can be used for the rest of the stations at lower durations of higher return periods. And the regional IDF parameters can be used for all the stations of this region at higher durations of all frequencies and at shorter durations of lower return periods.

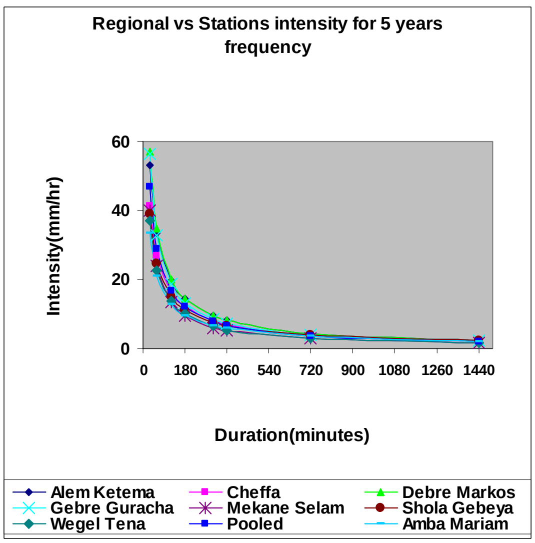
Figure 5.7 Evaluation of estimated regional IDF parameters for region four

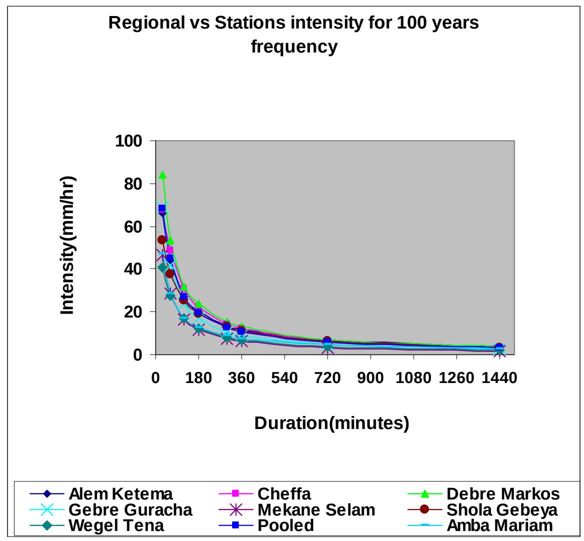








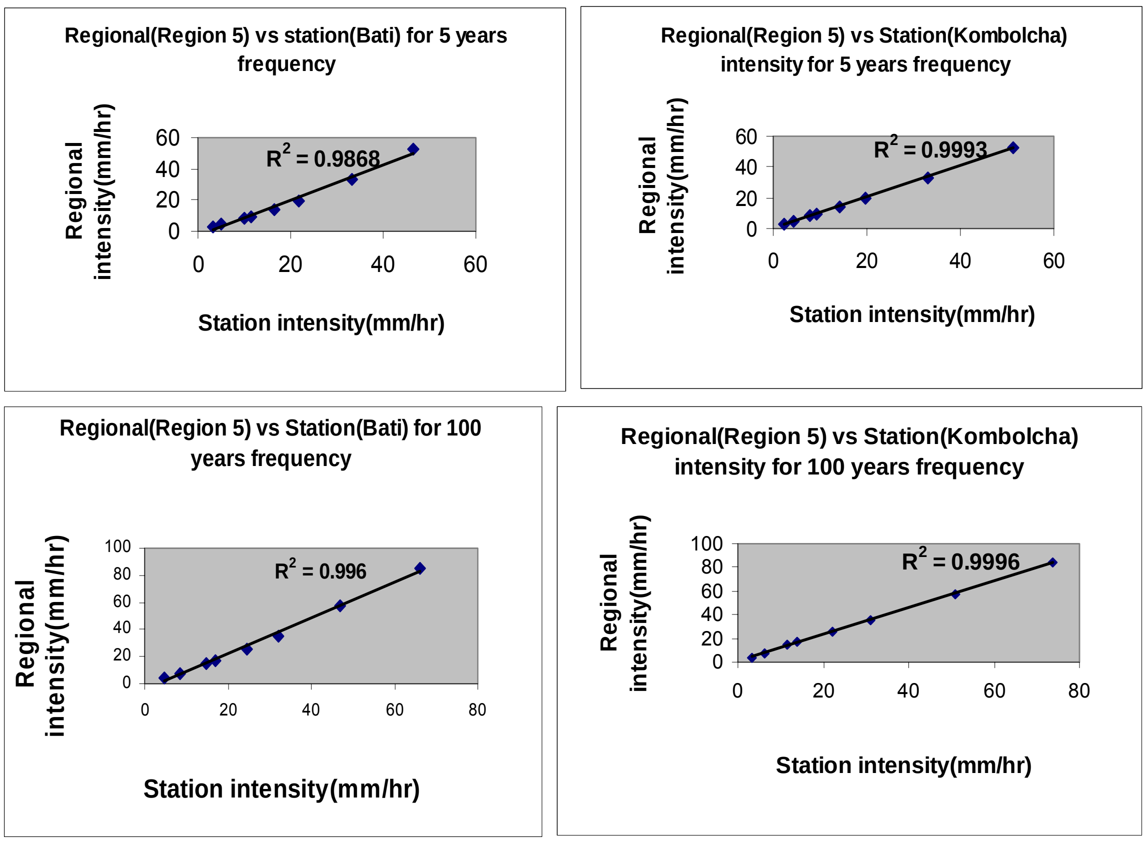


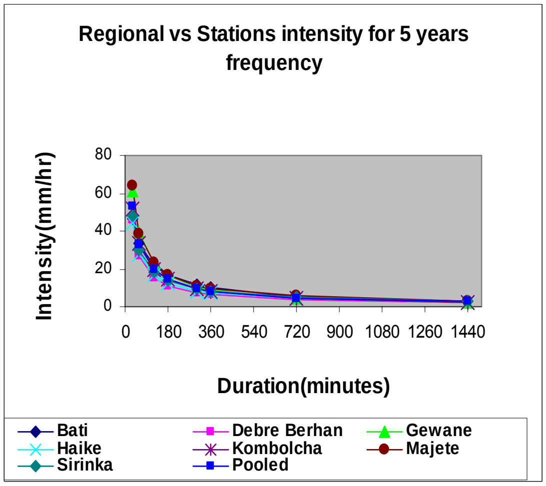


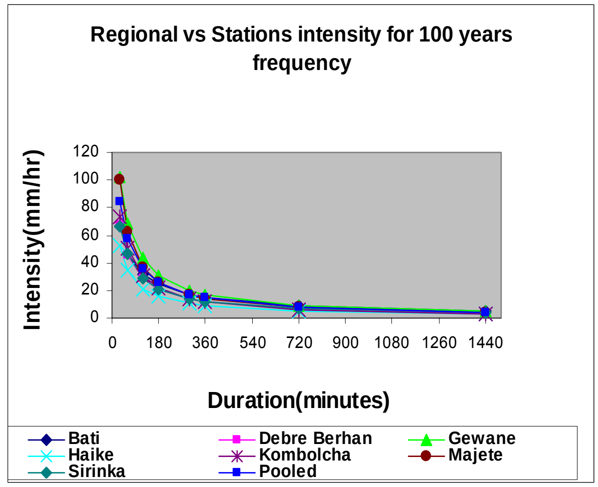
5.9.5 Region five graphical evaluation

Similar to region one and four this region contains seven stations. In this region except station Haike the intensity curves of all the stations properly fit with the regional intensity curve. Haike shows some deviation from the regional (pooled) intensity curve at lower durations of higher return period. Because station Haike doesn't show perfect match with the regional parameters, estimation of intensity of lower durations of higher return period at ungauged stations around Haike with regional parameters may not give good result. Therefore, shorter durations intensity of Haike and its surrounding ungauged stations can be determined preferably using the methods developed for principal stations in combination with IDF-maps than regional parameters. But in the case of longer durations the regional parameters can be used for intensity determination without any hesitation.

Figure 5.8 Evaluation of estimated regional IDF parameters for region five







5.10. Regional IDF Curves

These are IDF curves which are developed for the classified regions on the bases of regional intensity. Considering the limitations explained in section 5.9, these curves can be used for intensity determination in ungauged areas within the delineated regions.

Figure 5.9 IDF curves for region one

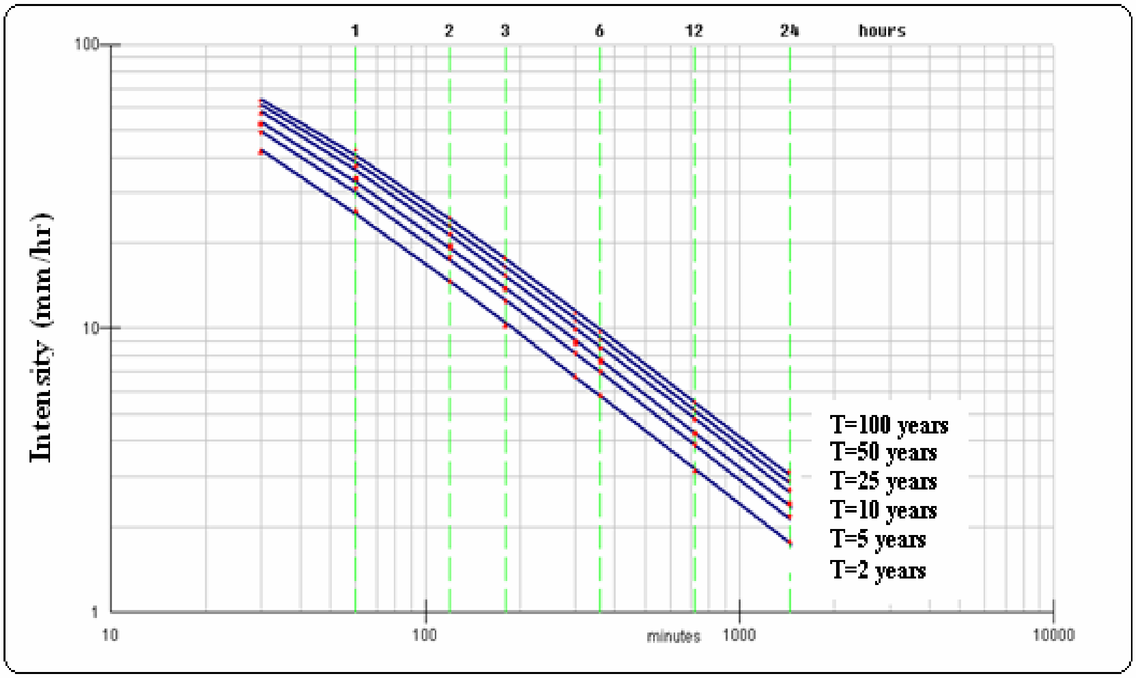


Figure 5.10 IDF curves for region two

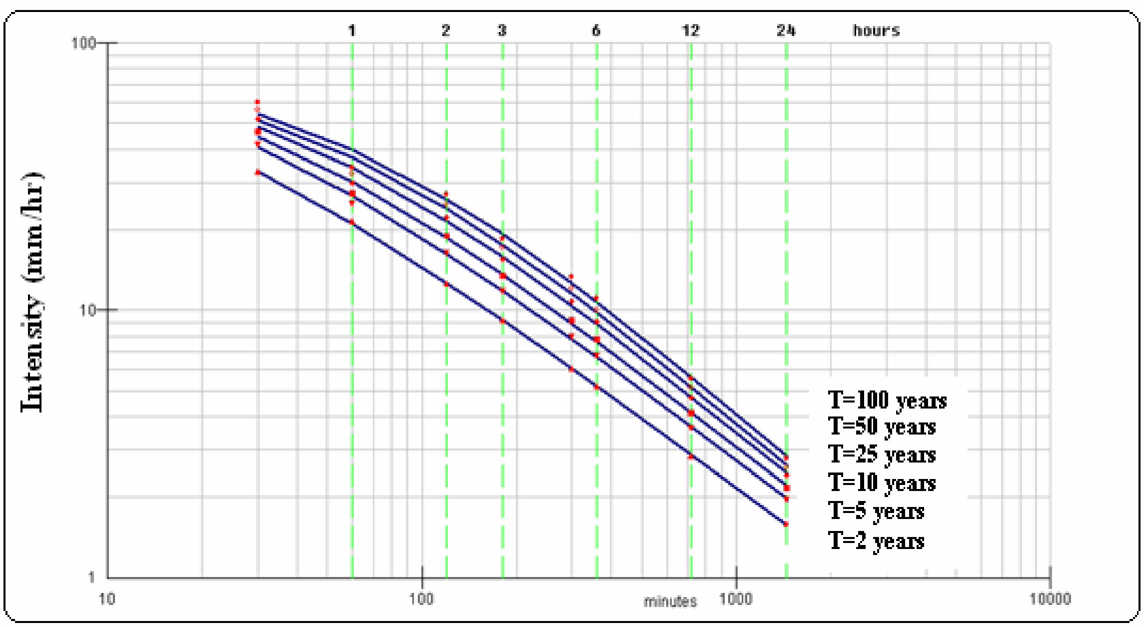


Figure 5.11 IDF curves for region three

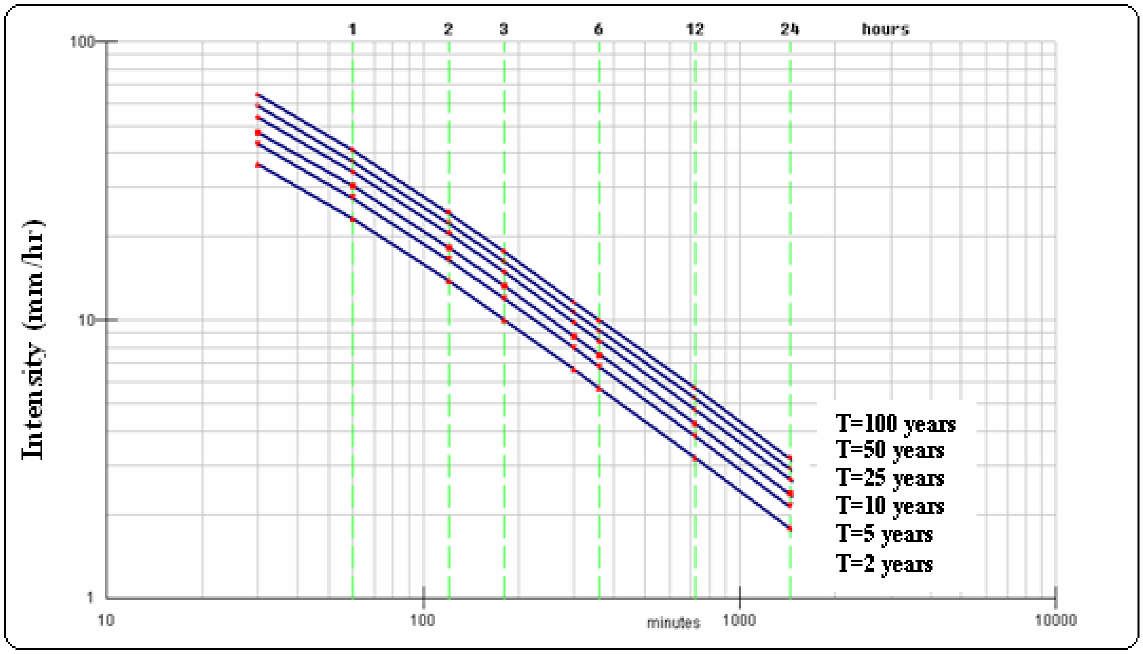


Figure 5.12 IDF curves for region four

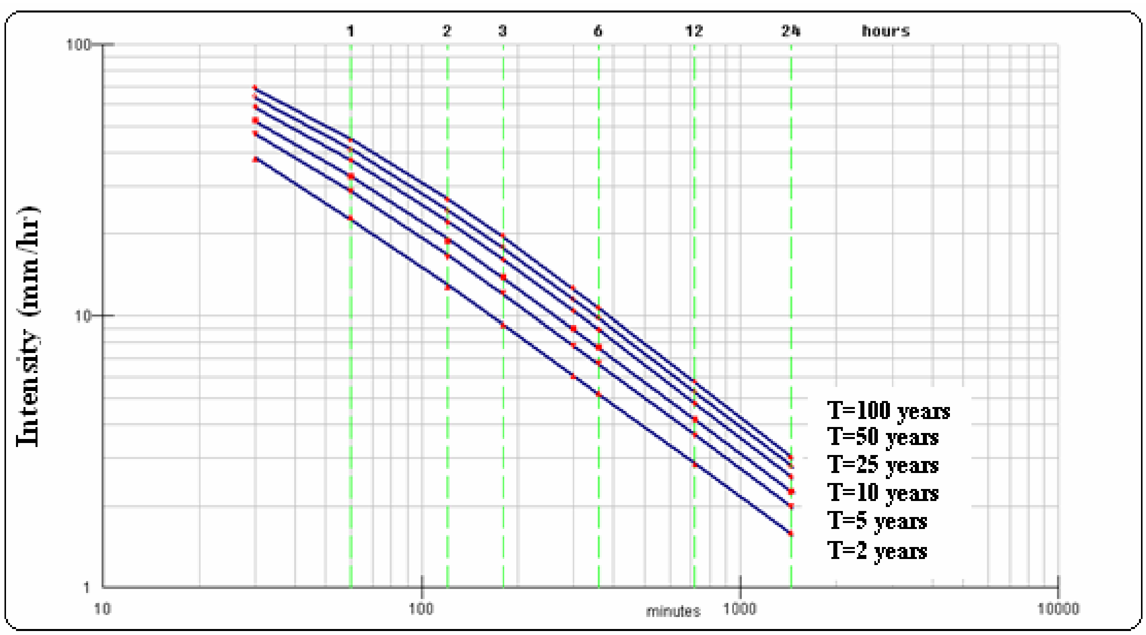
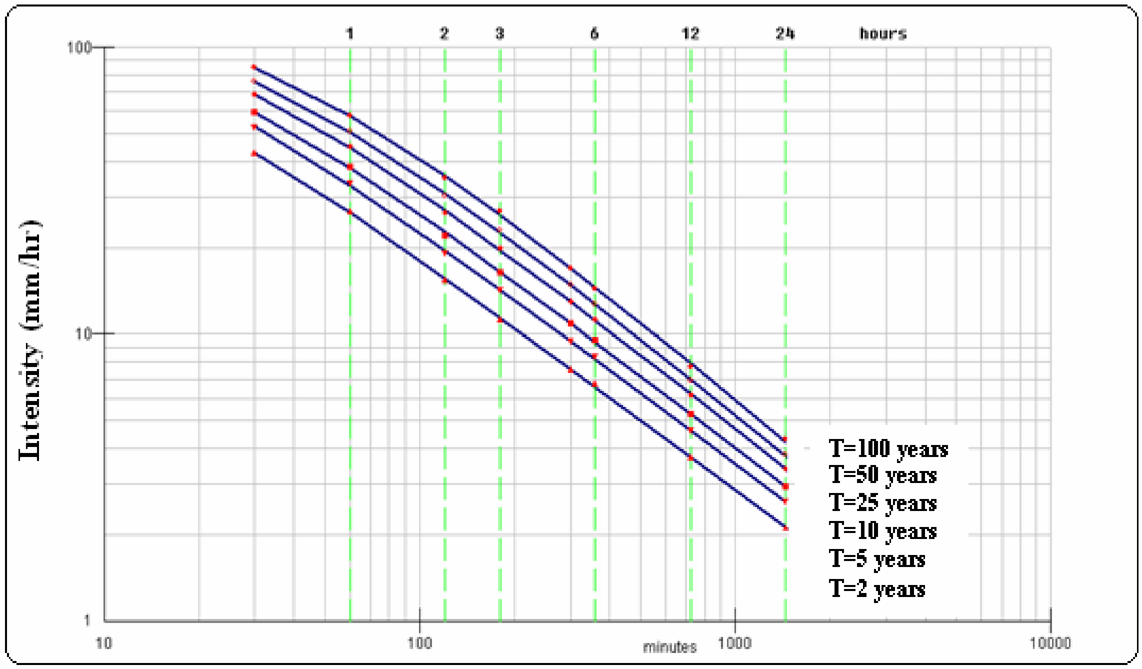


Figure 5.13 IDF curves for region five



CHAPTER SIX

SUMMARY CONCLUSION AND RECOMMENDATION

6.1 Summary

This paper presents operational IDF relationships which are developed for Amhara and Tigray regional states. For the analysis work, maximum annual rainfall depths of 0.5,1,2,3,5,6,12 and 24 hour were collected for thirty three selected stations in the study area from available charts of NAMSA. The quality of all the collected data was checked in order to make it ready for analysis work.

Different methods like conventional moment ratio diagrams, L-moment ratio diagrams, and minimum standard error of estimate were used in combination with a FORTRAN program which is developed by Abebe Sine in order to select parent distribution and to estimate quantiles.

Using IDF-Curve fit tool, estimation of IDF parameters was done and based on the estimated parameters IDF-Curves were drawn for the selected thirty three principal stations. Graphical evaluation between observed and computed intensities was done and satisfactory result was obtained.

With the help of SURFER-8, GLOBAL MAPPER-7 and ARC-VIEW GIS soft wares, IDF maps were developed for some frequencies and durations to show the spatial distribution of the rainfall intensity within the study area.

For the establishment of IDF relationship in ungauged stations within the study area, regionalization has been done on the bases of 24-hour annual maximum rainfall depth.

Based on different homogeneity tests, five distinct regions were identified in the study area. Regional IDF parameters and quantiles were estimated and adequacy of the regional parameters was checked.

Finally, using SMADA software, regional regression equations have been developed by relating the 24-hour intensity with other duration intensities.

6.2 Conclusion

Even though different types of best fitted distributions were selected for each station, it is observed that most of the stations in Amhara and Tigray regional states are represented by Gamma family (Two parameter gamma distributions and Pearson III distributions).

IDF relationships are perfectly established for stations with long record length. For those stations with short record length, the data is extended using regression equation obtained from FORTRAN-program. And therefore, data extension is used to improve the biasness of the results that could be obtained using short length data. That is, data extension is used to avoid overestimation and underestimation of quantiles for short record length stations.

As compared to the shape of the IDF-Curve of long record length stations, the shape of the IDF-Curve of some short record length stations is not perfect. In order to obtain the required shape of the IDF-curves, sufficient years of data must be used at each station.

Concerning regionalization, first it was tried to classify the principal stations in to homogeneous regions using L-MRD alone. But classifying stations using L-MRD resulted in good statistical homogeneity and poor geographical homogeneity. That is, it resulted in classifying stations mixed up from different geographical locations. Therefore, combination of conventional-MRD and L-MRD was used to categorize the principal stations in to homogenous regions. The results of the combined-MRDs have shown that the stations within the classified regions are both statistically and geographically homogeneous.

The homogeneity test has some limitations. That is, it mostly gives good results while stations are mixed from different localities. And this is somehow misleading and cannot be avoided.

In the general mathematical form of IDF [$I = A/(B+D)^C$], except station Adwa and Bahir Dar, the “A” coefficient increases with an increase in return period for most of the stations. But at Adwa and Bahir Dar a decreasing trend of “A” coefficient is seen for an increase in return period. The “B” constant and the “C” exponent generally increase or decrease with an increase or decrease of the “A” coefficient. For some exceptional stations a decrease of “B” and “C” for an increase in A was observed.

In order to obtain intensity of rainfall at areas farthest from the principal stations, the Amhara and Tigray regional states have been regionalized and the regional IDF parameters, IDF curves and regression equations have been developed for the classified regions. For some of the established regions which show some divergence of regional intensity from station intensity within the specified region, the use of IDF relationships which is developed for the region jointly with the IDF-Maps gives better results.

Regional regression equations have been developed by relating the commonly available 24-hour rainfall depth with other durations. From the results of the developed regional regression equations it is observed that the coefficient of determination for region 2 is greater than 90%, for region 4 except shorter durations it is more than 70% and as compared to region 2 and 4 the coefficient of determination for region 1, 3 and 5 is less satisfactory. The cause for obtaining lesser coefficient of determination in the regression equation may be due to shorter length of record in the stations. Thus, it is advisable to use only a regression equation with good coefficient of determination for different return periods.

Water resource professionals, designers and concerned institutions in Amhara and Tigray regional states can effectively utilize one or all of the procedures of this study to derive the IDF value in any part of the two regions. And in addition the network of automatic recording stations of these two regional states must be improved in number as well as in type so that the IDF-relationships of the study area can be revised and updated time to time for further improvement.

6.3 Recommendations

On the bases of the results of this study the following are recommended

1. There are only limited number of first class recording stations in Amhara and Tigray regional states. In addition, most of those available stations have short record length and concentrated to the southern part of the study area. The northern part of the study area has very few stations as compared to other parts. Therefore, establishment of additional first class stations within the study area is very essential to extract basic information for water resource projects within the two regional states in particular and to develop comprehensive IDF relationships for the country in general.
2. Any of the IDF relationships developed for the two regional states can be used to obtain intensity or depth of rainfall of specific duration and frequency for water resource projects within the study area.
3. For those areas closer to the principal stations, the IDF relationships developed for the principal stations can be used. And for areas farthest from

those principal stations(more than about 25 km radius according to the WMO guide line), the regional IDF relationships developed for the two regional states can give better results for intensity determination.

4. In addition to the research work on IDF relationships for individual regional states so far, it is recommended to combine all the studies and establish a general and comprehensive IDF relationships for the country as a whole.

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APPENDIX

Appendix A: Annual maximum rainfall of the principal stations

Station: Adigrat

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1992	15.83	24.49	31.13	32.81	35.16	36.02	38.69	46.47
1994	17.70	23.59	28.62	30.18	32.72	33.69	36.23	44.75
1995	16.47	24.19	30.27	31.91	34.33	35.22	37.85	45.88
1996	18.94	22.97	26.96	28.45	31.09	32.16	34.61	43.61
1997	18.99	22.95	26.90	28.39	31.03	32.10	34.54	43.57
1999	16.23	24.31	30.60	32.26	34.65	35.53	38.17	46.10
2000	18.69	23.10	27.30	28.80	31.42	32.46	34.93	43.84
2001	11.70	26.60	38.80	38.80	38.80	38.80	48.10	50.50
2002	16.40	17.40	17.50	17.80	22.40	26.60	31.80	40.00
2003	20.50	24.50	27.40	27.40	29.10	29.10	30.20	45.70
2004	20.40	24.00	26.60	33.60	33.60	33.60	33.60	52.30
2005	12.90	24.40	39.10	42.10	50.80	51.20	51.20	55.50
2007	19.20	26.20	29.20	29.20	29.20	29.20	29.20	29.20
Mean	**17.23**	**23.75**	**29.26**	**30.90**	**33.41**	**34.28**	**36.85**	**45.19**
STDEV	**2.69**	**2.20**	**5.46**	**5.81**	**6.52**	**6.04**	**6.40**	**6.31**

N.B: The shaded part of the table represents extended data.

Station: Adwa

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1992	20.80	24.40	26.50	28.00	41.20	42.10	47.70	58.70
1993	22.50	32.20	35.70	36.10	36.60	36.90	40.20	40.40
1994	22.04	32.53	36.46	37.85	45.46	48.50	54.74	64.15
1995	23.55	28.51	31.16	33.34	39.79	41.87	46.21	52.00
1996	23.02	29.91	33.02	34.93	41.79	44.21	49.22	56.18
1997	23.57	28.47	31.11	33.30	39.74	41.80	46.13	51.88
1998	22.58	31.07	34.53	36.23	43.42	46.11	51.67	59.66
1999	23.90	27.60	29.96	32.30	38.48	40.33	44.23	49.32
2000	23.90	26.40	28.40	30.10	32.10	32.70	34.60	35.10
2001	20.00	24.40	30.00	37.90	51.90	56.40	66.70	88.00
2002	26.70	26.70	26.70	26.70	27.20	27.90	29.80	32.50
2003	24.70	25.30	27.70	31.80	39.80	43.70	45.40	47.50
2004	25.40	27.30	27.70	31.70	40.70	41.90	44.30	50.80
2005	28.20	31.20	33.20	33.20	34.70	36.80	39.70	42.10
Mean	**23.63**	**28.28**	**30.87**	**33.10**	**39.49**	**41.52**	**45.76**	**52.02**
STDEV	**2.17**	**2.76**	**3.31**	**3.38**	**5.90**	**6.86**	**8.87**	**13.85**

Station: Alem Ketema

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1992	29	40	43.5	48.7	58.4	68	69.5	69.5
1993	18.4	31.5	36	38	39.1	39.1	41	41
1994	17	20	22	26.5	31.5	34.1	34.1	35.6
1995	20.5	24	29	31.4	31.4	37.5	37.5	45
1996	25.4	28.1	28.4	35.2	44.2	49	56.1	64.9
1997	24.8	28	29.8	39.7	44.7	44.7	44.7	51.6
1998	26.9	30	31.1	31.1	31.1	31.1	31.1	39.5
2002	21.6	31.4	42.4	49.9	50.6	51.3	51.3	53.3
2003	17.6	28.6	31.5	31.5	40.5	47.5	49	52.1
2004	27.8	27.9	27.9	27.9	27.9	27.9	27.9	27.9
Mean	**22.90**	**28.95**	**32.16**	**35.99**	**39.94**	**43.02**	**44.22**	**48.04**
STDEV	**4.44**	**5.20**	**6.67**	**8.12**	**9.80**	**11.77**	**12.69**	**12.88**

Station: Amba Mariam

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1989	15	18.4	22.8	23.1	23.3	23.3	24.8	26
1994	10.1	16.5	22.2	26.2	29.2	29.2	30.1	43
1995	13.7	18.5	20	29	30.4	30.5	39.8	54.1
1996	9.2	13.5	16.5	17.5	19.6	24.3	24.3	27.4
1999	8.5	11	20.1	23.2	27	29.2	40.3	50.4
2000	12.3	16	24.8	25.5	25.5	25.5	31.3	41
2001	17.4	20.5	26.5	31.5	34.8	37.8	49	60.5
2002	11.4	15	16.4	20.3	27.2	27.2	27.2	38.3
2003	13	16.4	19.8	22.8	31.5	39.3	40.5	44
2004	14.7	17	20	21.5	26.5	26.5	26.7	27.6
2005	16.5	18	20	22.5	32.7	33	33	49.6
2006	16.5	20.5	26.5	30.5	33.3	33.4	34.9	34.9
2007	20.9	31.2	31.2	33.8	37	38	45.9	50.4
Mean	**13.78**	**17.88**	**22.06**	**25.18**	**29.08**	**30.55**	**34.45**	**42.09**
STDEV	**3.56**	**4.79**	**4.24**	**4.79**	**4.87**	**5.38**	**8.07**	**10.93**

Station: Bati

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1987	21	21.2	30	31.5	41.2	42.2	42.2	52.2
1988	28.9	38.5	48.1	69.3	77.1	78.6	84.3	88.7
1989	19.6	34.4	49.9	63.8	67	67.8	71.5	73.7
1990	18.9	23.9	25.9	41.7	53.1	57.5	68.6	92.5
1991	25.4	28.5	34.4	35.7	36.9	43.1	58.2	75
2000	20.5	27.1	31.5	33.4	42.7	48.8	66.1	71.7
2001	19.5	21.5	31.7	43.7	58.8	61.5	74.6	76.6
2002	16.4	24.4	26.3	33.7	36	36.3	38.5	52.7
2003	13	29.6	32.5	35.9	40.1	40.3	40.7	45.1
2004	20.6	30.4	38.4	38.9	43.3	43.6	43.6	53.6
2005	18.8	24.8	25.7	28.2	35.1	35.1	37.6	39.6
Mean	**20.24**	**27.66**	**34.04**	**41.44**	**48.30**	**50.44**	**56.90**	**65.58**
STDEV	**4.18**	**5.37**	**8.33**	**13.23**	**13.94**	**14.06**	**16.93**	**17.76**

Station: Cheffa

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1987	9.4	16.7	18.9	24.1	24.5	24.6	50.6	54.8
1995	11.4	14.5	15.1	17.9	21.4	23.8	33.8	39.2
1996	14.3	19.5	21.4	24.4	27.6	29.6	38.5	42.7
1999	16.9	24.0	27.2	30.2	33.3	34.9	42.7	45.9
2000	9	11.6	11.6	11.6	11.6	11.6	13.6	27.4
2001	22.6	33.9	39.9	43.0	45.7	46.5	51.9	52.9
2002	8.8	8.8	8.8	12.3	13.5	21.8	28.7	33.4
2003	12.7	12.9	13	14.1	20	21.3	22	27.8
2004	13	18	18	19.8	33.2	35.5	47.5	47.5
2005	29	47.6	59.7	61.2	61.4	61.4	61.4	61.4
2006	18.2	18.8	23.1	26.6	29	30.4	42.8	42.8
2007	20.4	31.9	31.9	38.8	41.1	42.6	51.1	53.8
Mean	**15.48**	**21.51**	**24.05**	**27.00**	**30.19**	**31.99**	**40.38**	**44.12**
STDEV	**6.20**	**11.19**	**14.31**	**14.61**	**14.13**	**13.39**	**13.80**	**10.81**

Station: Dangla

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1988	25.1	26.4	32.8	33.8	33.8	33.8	42.1	44.7
1989	22.8	29.3	30.3	30.3	30.3	30.3	33.7	37.9
1990	18	22	22	22	22	22	30.8	31.4
1993	17.1	19.8	25.4	29.4	30.4	30.4	34.3	45.2
1995	19.6	20.8	24.4	24.4	24.4	24.4	27.4	33.3
1996	17.9	22.4	22.7	23.3	23.3	23.3	23.6	26.4
1997	24.1	34.2	35.1	35.1	35.1	35.1	37.1	53
2005	21	22	31.3	31.5	32.1	32.1	43.4	49.5
2006	18.6	18.6	31.7	31.9	32.7	32.7	44.5	44.9
Mean	**20.47**	**23.94**	**28.41**	**29.08**	**29.34**	**29.34**	**35.21**	**40.70**
STDEV	**2.93**	**5.07**	**4.82**	**4.73**	**4.86**	**4.86**	**7.27**	**8.92**

Station: Debre Berhan

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1985	31	41	41	41	44.3	44.3	49.9	53.4
1986	22	26.5	26.5	26.5	36.5	36.5	47	54
1987	12.4	19	21.6	24.9	29.8	29.8	33.5	36.2
1988	19.4	37.4	47.1	56.8	56.8	56.8	56.8	56.8
1989	21.1	22.2	22.2	22.2	23	24.3	26.8	35.5
1990	18.9	23.5	23.5	28.4	31.1	31.1	35.75	50.7
1991	14.5	14.6	15	15.7	23.2	23.2	24.1	48.3
1992	19.2	25.4	25.6	25.6	36.8	46.5	46.5	46.5
1993	24	29.3	29.3	29.3	29.3	29.3	29.3	29.3
1994	17.6	21.3	24.3	26.2	28.5	37.1	42.9	45.3
1995	7.4	10.7	13	14.5	14.5	14.5	14.5	14.5
1996	12.9	14.9	18.4	18.6	18.6	19.1	19.4	19.5
2000	19	23	28.8	29.7	30.5	30.5	35.6	45.5
2001	16.7	24.2	24.9	30.2	32.3	34.3	36.4	46.3
2002	14.5	16	17.8	25.4	27	27	39.4	48.9
2003	23	29.5	29.9	29.9	29.9	29.9	29.9	29.9
2004	19.6	24.1	25.8	32.1	32.1	32.1	34.9	52.8
2005	18.8	21.3	21.3	21.3	22.9	22.9	22.9	22.9
2006	16.7	16.8	17.5	17.8	17.8	17.8	17.8	25.4
2007	18.3	21.7	22.3	24.2	29.1	29.2	29.6	43.3
Mean	**18.35**	**23.12**	**24.79**	**27.02**	**29.70**	**30.81**	**33.65**	**40.25**
STDEV	**4.92**	**7.37**	**8.09**	**9.33**	**9.45**	**10.12**	**11.25**	**12.69**

Station: Debre Markos

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1966	23.5	24.1	27.9	28.7	29.3	32.8	34.5	34.6
1967	27.2	37.5	47.5	57.5	59.7	59.7	59.7	66.8
1968	32.6	41	42.9	43.5	43.5	43.5	43.5	43.5
1969	30.2	31.1	31.1	31.1	31.1	31.1	31.1	31.1
1970	10.5	12.2	12.2	12.2	15.7	21	27.8	57.6
1971	25.1	34.5	36.5	36.5	38.5	38.5	39.6	49.1
1972	20.4	30.8	33.2	35.4	37	37.3	37.3	42.2
1973	20.4	27	30.1	32.8	34	34	34	48.4
1974	29.3	30.9	31.8	37.7	37.7	37.7	39.7	59.7
1975	24.8	36.9	36.9	36.9	41.7	41.7	44.1	65.4
1976	20.4	26.5	26.5	26.5	26.5	26.5	30.9	37.4
1985	23.4	32.8	38.6	38.6	38.6	38.6	38.6	44.8
1990	20.5	32.7	39.7	39.7	43.5	43.5	43.5	55.3
1994	21	22	23	24	25	26	27	28
1999	15.5	19.9	21.4	22.3	22.8	22.8	29	30.2
2000	12.9	16.3	16.9	16.9	16.9	16.9	16.9	24.2
2001	38.5	59.5	72	75.8	78.2	80	80.3	98.2
2002	19.4	24.3	25.6	25.6	25.6	25.6	25.6	25.6
Mean	**23.09**	**30.00**	**32.99**	**34.54**	**35.85**	**36.51**	**37.95**	**46.78**
STDEV	**6.89**	**10.55**	**13.28**	**14.63**	**15.04**	**14.86**	**14.13**	**18.57**

Station: Gewane

Year	Observed annual max Rainfall depth(mm) for indicated durations(hr)							
	0.5	1	2	3	5	6	12	24
1980	20.1	20.1	23.4	27	27.2	27.2	27.2	27.2
1981	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2
1989	27.2	32.4	33.4	33.4	34.9	36.3	37.9	37.9
1990	51.3	61.2	68.7	69.5	69.8	69.8	69.8	69.8
1996	25.1	26.3	34	34	34	34	34	45.1
1997	22.2	28.5	32.8	36.9	36.9	36.9	36.9	36.9
1998	32.6	33.3	33.3	37.9	37.9	37.9	37.9	37.9
1999	20.6	27.6	32.6	32.6	32.6	34.8	36.5	36.5
2001	30.9	35.9	35.9	35.9	35.9	36.7	36.7	37.9
2002	34.8	60.9	60.9	64.4	65.9	66.8	72.2	106.1
Mean	**29.50**	**35.64**	**38.52**	**40.18**	**40.53**	**41.06**	**41.93**	**46.55**
STDEV	**9.19**	**14.07**	**14.37**	**14.51**	**14.77**	**14.74**	**15.72**	**23.92**

Station: Finote Selam

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1966	13.3	16.9	19.5	20.3	23.0	24.6	28.5	30.4
1967	14.4	19.3	25.2	26.7	32.9	32.9	34.4	36.6
1968	14.2	19.0	24.6	25.9	31.7	31.9	33.7	35.9
1969	13.5	17.3	20.5	21.3	24.6	25.9	29.4	31.4
1970	13.6	17.6	21.2	22.1	25.8	26.9	30.2	32.2
1971	14.2	18.9	24.2	25.6	31.1	31.4	33.4	35.6
1972	14.0	18.6	23.5	24.7	29.8	30.3	32.6	34.7
1973	9.4	19.3	29.2	29.2	29.2	29.2	29.2	29.2
1974	17.9	17.9	22.8	22.8	30	30.7	34.5	35.5
1975	13.9	18.2	22.5	22.9	33	33	33	34.5
1976	15.6	15.6	15.6	15.6	20	20	20	25.5
1980	11.9	18.5	21	26.5	26.5	29.5	34.9	40
1984	10	12.4	12.5	12.5	12.5	17.5	19.5	19.5
1985	14.2	18.9	24.3	25.6	31.2	31.5	33.4	35.6
1986	16.5	17.3	17.5	17.5	17.5	18.5	32.9	33
1990	14.1	18.8	24.1	25.4	30.8	31.1	33.2	35.4
1994	12.7	15.8	17.2	17.7	19.3	21.5	26.3	27.7
1999	12.5	15.2	16.0	16.4	17.5	19.9	25.2	26.3
2000	14.3	19.2	24.9	26.3	32.3	32.4	34.1	36.3
2001	14.4	19.4	25.4	26.9	33.2	33.2	34.6	36.8
2002	12.8	15.9	17.6	18.1	19.8	21.9	26.6	28.1
Mean	**13.68**	**17.61**	**21.40**	**22.38**	**26.27**	**27.32**	**30.45**	**32.39**
STDEV	**1.88**	**1.79**	**4.11**	**4.55**	**6.30**	**5.38**	**4.64**	**4.89**

Station: Gebre Guracha

Year	Observed annual max Rainfall depth(mm) for indicated durations(hr)							
	0.5	1	2	3	5	6	12	24
1980	31.0	33.1	35.1	35.1	35.1	35.1	36.5	37.4
1981	32.4	33.9	35.4	36.7	36.7	36.7	37.0	37.1
1986	27.6	31.4	32.4	33.3	33.6	33.6	36.1	36.9
1987	30.2	31.6	32.4	32.4	33.3	34.8	34.8	37.4
1988	31.4	32.1	32.3	34.1	37.0	37.8	40.6	40.6
1989	32.2	34.0	35.3	35.5	35.5	35.5	37.4	39.4
1990	33.2	37.1	37.9	38.1	38.1	38.1	39.0	39.4
1991	32.1	33.9	36.9	37.3	37.3	37.3	37.3	39.3
1992	33.4	35.0	35.0	35.1	35.1	35.1	37.1	40.1
1993	34.3	36.3	36.3	36.3	36.3	36.3	36.3	37.3
1994	21.6	24.2	24.6	25.4	26.3	26.3	26.3	29.0
1995	25.6	25.6	28.8	31.7	32.1	32.1	34.9	35.4
1996	26.8	29.1	30.3	31.8	33.7	34.9	35.6	37.2
1999	20.8	22.2	22.5	22.5	22.5	22.5	22.5	29.8
Mean	**29.47**	**31.39**	**32.51**	**33.24**	**33.76**	**34.01**	**35.10**	**36.88**
STDEV	**4.34**	**4.54**	**4.58**	**4.44**	**4.38**	**4.44**	**4.84**	**3.49**

Station: Gondar

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1976	14.5	17	17	17	22	29	29	29
1977	12.5	33.9	33.9	33.9	33.9	33.9	33.9	33.9
1978	19.9	22.5	30.8	30.8	30.8	30.8	39.4	39.5
1979	22.9	23.8	23.8	23.8	25.5	25.5	26.5	26.5
1980	10.4	17.9	19	19	19	21.3	31.3	43.4
1982	15	15	15	15	15	16	18.3	23.4
1985	32.8	40.6	45.3	45.6	46.5	46.5	46.5	46.5
1986	18.5	30.2	31	31	31	33.8	34.8	34.8
1987	18.4	28.6	29.3	29.3	29.3	29.3	29.3	38.1
1988	20.4	30.7	34.3	34.3	34.3	34.3	34.3	44.1
1989	20.9	23.5	24.1	24.1	24.1	24.1	46.5	53.8
Mean	**18.75**	**25.79**	**27.59**	**27.62**	**28.31**	**29.50**	**33.62**	**37.55**
STDEV	**6.04**	**7.83**	**8.91**	**8.97**	**8.61**	**8.04**	**8.35**	**9.17**

Station: Humera

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1973	16.2	20.2	24.5	25.2	29	32.1	34.6	35.4
1974	17.6	17.8	30.2	30.2	30.2	31.2	32.8	33
1975	15.4	17.7	17.7	18.2	18.9	19.1	21.4	22
1976	16.3	18.7	21.4	21.4	21.4	25.7	36.3	39.6
1980	27.6	34.5	35.5	37.6	39.2	41.7	45.1	46.9
1981	21.5	24.1	33.1	33.7	34	35.1	37.2	39.8
1982	18.2	18.2	18.2	18.2	18.2	20.9	22.4	29.9
1983	15.5	28.5	32.6	33.3	35.6	44.5	46.9	48.7
1997	22.7	36	36	40.8	44.4	44.4	45.3	46.6
Mean	**19.00**	**23.97**	**27.69**	**28.73**	**30.10**	**32.74**	**35.78**	**37.99**
STDEV	**4.14**	**7.32**	**7.33**	**8.37**	**9.20**	**9.61**	**9.35**	**8.85**

Station: Haike

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1966	19.2	23.3	27.5	31.8	33.4	35.1	46.2	49.7
1967	23.8	34.0	39.8	42.1	45.6	45.6	58.6	59.8
1968	19.0	23.0	27.1	31.5	33.0	34.8	45.9	49.4
1969	21.1	27.5	32.3	35.9	38.1	39.1	51.0	53.6
1970	19.5	24.1	28.3	32.5	34.2	35.8	47.0	50.4
1971	19.6	24.3	28.6	32.8	34.5	36.0	47.3	50.6
1972	21.7	28.9	33.9	37.3	39.7	40.5	52.6	55.0
1973	17.7	20.2	23.9	28.6	29.8	32.1	42.6	46.7
1974	18.6	22.2	26.1	30.6	32.0	34.0	44.9	48.6
1975	19.1	23.2	27.3	31.6	33.2	34.9	46.0	49.5
1976	20.8	26.9	31.6	35.3	37.4	38.5	50.3	53.1
1977	21.3	28.0	32.8	36.4	38.6	39.6	51.5	54.1
1978	19.6	24.3	28.6	32.8	34.5	36.0	47.3	50.6
1979	20.8	27.0	31.7	35.4	37.5	38.6	50.4	53.2
1980	24.6	26.2	27	28	28	31.2	39.1	42.5
1981	21.8	35.7	42.3	43.7	47.5	47.2	47.4	48.6
1982	18.6	28.1	32.4	32.9	33.5	36.3	46.2	48.9
1983	20.4	26.0	30.6	34.5	36.4	37.7	49.3	52.2
1984	21.1	27.6	32.4	36.0	38.2	39.2	51.1	53.8
1985	19.7	26	38.4	43.8	43.9	44.1	68.7	71.3
1986	17.6	20.3	24.6	24.6	24.6	24.6	27.3	32
1988	24.9	27.3	31.6	44.3	48.5	48.5	58.5	59.6
1989	18.2	21.2	21.7	27.1	27.3	27.3	40.9	47.5
1990	14.1	15.4	19.1	26.1	28.9	34.5	62.4	63.5
2003	18.7	22.4	26.4	30.8	32.3	34.1	45.1	48.8
2004	18.8	22.6	26.6	31.0	32.5	34.3	45.3	49.0
2005	20.2	25.6	30.1	34.1	35.9	37.3	48.8	51.9
2006	20.0	25.1	29.6	33.6	35.4	36.8	48.3	51.4
2007	20.4	25.9	30.4	34.3	36.3	37.5	49.1	52.1
Mean	**20.04**	**25.25**	**29.74**	**33.78**	**35.53**	**36.94**	**48.60**	**51.63**
STDEV	**2.16**	**3.97**	**4.99**	**5.02**	**5.70**	**5.17**	**7.43**	**6.70**

Station: Kombolcha

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1966	21.7	21.7	22.2	23	31.4	40.7	41.7	41.7
1967	31.1	53.7	62.9	62.9	62.9	62.9	62.9	62.9
1968	21	21	21	21	55	55	55	55
1969	22.5	32.1	36.5	39.5	47	47	47	47
1970	23.3	23.3	27.2	36	53.9	57.9	60.5	60.5
1971	17	23.9	34.4	42	44	44	44	44
1972	29.4	36.2	36.2	36.2	36.2	38	46	46.9
1973	11.6	15.4	20.2	21.6	23.5	23.8	44	46.9
1974	19.2	19.2	25.6	25.6	38.7	38.7	38.7	38.7
1975	21.3	21.3	23.1	23.1	23.1	23.1	33.2	58.4
1976	24.5	30.5	30.5	30.5	30.5	35.2	35.2	45.1
1977	23.2	33.5	37.6	39.9	40.7	41	57.8	57.8
1978	22.8	23.9	38	39.7	41.9	44.4	46.4	46.4
1979	20.1	30.7	37.4	38.4	38.4	38.4	41.5	47.4
1980	15.3	18.7	21.5	21.5	30.4	30.4	32.2	32.2
1981	30	45.7	46.5	46.5	46.7	46.7	46.7	46.7
1982	26.7	49.4	52.6	52.6	52.6	52.6	52.6	52.6
1983	23.6	28.1	28.8	28.9	29.8	38.8	42.2	42.7
1984	32.5	32.5	33.4	33.4	33.4	33.4	33.4	33.4
1985	16.1	24.9	31.7	38.4	39.9	39.9	39.9	47.8
1986	20.2	22.2	22.2	34.2	35.5	35.7	36	36
1987	19.2	29.1	49.1	59.5	59.5	59.5	59.5	59.5
1988	18.5	18.7	18.7	19.2	27.7	27.7	27.7	27.7
1990	10.2	14.8	24.4	24.4	32.1	41.7	51.8	51.8
2003	17.8	19.6	21.6	22.4	24.1	27.7	32.9	35
2004	10.3	20	30	34.4	44.9	47.4	47.4	51.5
2005	14.7	27.1	30.1	32.1	32.9	33.4	33.8	33.8
2006	23.7	25.9	29.7	36.5	36.5	36.5	36.6	44
2007	18.6	27.8	30.7	30.7	30.7	30.7	46.3	54.4
Mean	**20.90**	**27.27**	**31.86**	**34.28**	**38.76**	**40.42**	**43.89**	**46.48**
STDEV	**5.74**	**9.49**	**10.52**	**11.16**	**10.68**	**10.30**	**9.40**	**9.21**

Station: Lalibela

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1989	16.8	21.7	25.1	31.6	37	39.3	39.7	39.7
1992	17.5	19.9	25.8	25.8	26.7	26.7	27.8	29.2
1993	10.6	12	16.5	18.2	23	27.5	43.4	43.4
2000	28.3	41.4	51.4	51.4	51.4	51.4	51.4	51.4
2001	12.4	15.5	18.7	22	22.6	22.6	22.6	22.6
2003	14	19.6	23.8	30.2	32.1	35.4	35.7	37.8
2004	11	15.5	17.1	20.1	20.4	20.7	24.6	29.1
2005	16.3	17	18.4	22.1	24.4	24.6	28.3	28.8
2006	8.9	10.5	10.5	11.4	15.7	15.7	15.7	15.7
2007	18.9	26.9	30.6	30.7	30.7	30.7	30.8	33.8
Mean	**15.47**	**20.00**	**23.79**	**26.35**	**28.40**	**29.46**	**32.00**	**33.15**
STDEV	**5.59**	**8.90**	**11.27**	**10.83**	**10.16**	**10.35**	**10.65**	**10.38**

Station: Majete

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1991	29.1	32.3	32.5	32.5	32.5	32.5	32.5	40.9
1992	22	40.2	65.4	70.4	73.9	76.7	79	83.2
1993	19.6	28.6	33.1	34.6	42.5	48.7	53.4	62.1
1995	30.1	33.7	45.8	48.4	56.2	57.9	58.1	64.1
1996	29.4	31.9	35	38.6	44.7	47.7	55.1	58.1
1997	46.2	47.4	47.4	56.3	59.2	60.8	61.3	70.3
1998	22.8	28.3	29.8	31.5	39.6	52.4	58.4	67.4
1999	28.2	39.8	59.8	61.3	70.7	71.9	72	84.3
2000	20.1	22.4	36.7	36.7	36.7	36.7	36.7	38.1
2001	30	36	38	40.1	46.4	62.4	73.6	79.2
2002	19.3	23.6	27.9	29.8	43	46.6	47	48.6
2003	19.5	33.8	36	36.7	37.6	38.2	38.6	58.4
2004	34.7	46.2	47.8	48.2	48.4	48.4	48.4	71.6
2005	13	16.8	24.3	26.6	29	29	29	35.9
Mean	**26.00**	**32.93**	**39.96**	**42.26**	**47.17**	**50.71**	**53.08**	**61.59**
STDEV	**8.32**	**8.75**	**11.91**	**12.93**	**13.43**	**14.17**	**15.48**	**16.03**

Station: Mehal Meda

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1987	13.2	15	19.8	25.5	31.4	35.2	41.7	52.6
1988	12.7	18.6	20.6	20.6	29.9	30.4	35.5	47.3
1989	22.5	27.1	33.4	39.1	39.2	39.6	39.6	39.6
1990	10.2	13.2	13.2	15.3	19	19.2	26.1	34
1999	12	12	20	24	25.8	29.2	35.6	47.8
2000	13.8	16	22.8	27	28.1	30.9	36	49.9
2001	17	17.3	20.7	29.2	33	34.4	61.9	65.3
2002	13	13.8	23	28.6	43.6	44.1	52.1	74.3
2003	14.3	15.4	15.4	15.4	15.4	18.4	18.4	23.4
2004	16.2	21	23.2	25	26.4	29.2	29.2	29.2
2005	16.9	16.9	17.2	18.8	23.7	25.8	29.3	33.1
2006	20.3	23.6	24	24.5	31	31.9	41.1	41.1
Mean	**15.18**	**17.49**	**21.11**	**24.42**	**28.88**	**30.69**	**37.21**	**44.80**
STDEV	**3.56**	**4.46**	**5.08**	**6.57**	**7.83**	**7.42**	**11.61**	**14.73**

Station: Mekane Selam

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1988	15.8	16.9	20.1	24.8	25.2	26.1	32.8	33
1989	22.5	23.1	24.8	26.2	27.9	28.3	29.7	30.2
1999	17.5	18.5	19.2	19.4	19.5	19.5	22	24.6
2000	17	17.2	17.9	18.1	18.3	18.3	25.6	32.2
2001	18.8	21.2	24.5	28.3	31	31	31.3	39.1
2002	19.4	20.4	21.4	22.8	23.6	23.6	24.8	24.8
2003	18.2	25.2	29.2	31.5	31.8	31.8	32.1	32.6
2004	17	23.6	26.8	27.5	28.3	28.3	28.3	28.3
2005	19	23.1	29.2	31.6	32.5	32.5	32.5	32.5
2007	20.6	20.9	22.8	23.1	23.3	24.9	26.3	26.3
Mean	**18.58**	**21.01**	**23.59**	**25.33**	**26.14**	**26.43**	**28.54**	**30.36**
STDEV	**1.95**	**2.81**	**4.01**	**4.60**	**5.00**	**4.92**	**3.74**	**4.49**

Station: Mekele

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1991	24.3	43.3	43.7	50.2	50.2	50.2	50.6	52.3
1992	15.2	17.2	20.6	20.6	29.6	29.6	29.6	29.6
1993	22.7	36.8	37.8	37.8	37.8	37.8	37.8	37.8
1999	23	30.8	36.4	36.4	36.7	38.4	38.4	38.4
2000	16.8	17	18.2	18.2	24.2	24.2	24.2	32.5
2001	20.5	25.7	32.9	34.2	34.2	34.2	40.9	53.4
2002	18.4	26	26	26.7	28.5	28.7	32.8	32.8
2003	19	27.7	27.7	27.7	27.7	28.2	28.2	28.6
2004	26.4	34.7	44	44.3	44.8	44.8	45.1	45.1
2005	27.1	27.1	30	34.2	34.2	34.2	35.3	44
2007	28	31	40	40	40	40	50.2	65.7
Mean	**21.95**	**28.85**	**32.48**	**33.66**	**35.26**	**35.48**	**37.55**	**41.84**
STDEV	**4.31**	**7.83**	**8.80**	**9.72**	**7.78**	**7.76**	**8.69**	**11.62**

Station: Metema

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1976	15.4	29.9	43.4	46.8	54.1	54.2	55.5	61.8
1977	11.8	30.3	47.8	52.2	62.2	62.3	63.8	66.1
1978	25.3	28.7	31.5	32.4	34.0	34.2	34.9	49.5
1979	27.7	28.4	28.6	28.8	29.5	29.7	30.3	46.3
1980	7.9	30.7	52.4	57.8	71.1	71.2	72.9	73.5
1982	16.3	29.8	42.3	45.5	52.1	52.3	53.4	60.7
1985	19.8	29.4	38.1	40.4	44.8	45.0	46.0	56.5
1986	22.7	29.1	34.6	36.1	38.9	39.1	39.9	52.8
1987	21.5	29.2	38.9	39.5	45	45.1	46.2	46.2
1988	26	29.6	33.7	36.2	43	44.3	46.6	55.3
1989	27.1	28.5	29.3	29.7	30.6	30.8	31.4	47.1
1995	24.3	29	31.5	31.5	31.9	31.9	31.9	41
2004	25.6	27.9	27.9	27.9	28	28.2	28.8	40.5
2005	19.4	29.2	37.2	40.7	41.7	41.7	42	42.2
Mean	**20.78**	**29.27**	**36.96**	**38.95**	**43.34**	**43.58**	**44.54**	**52.83**
STDEV	**6.03**	**0.76**	**7.43**	**9.05**	**12.88**	**12.85**	**13.25**	**10.01**

Station: Michew

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1992	18.2	23	24.9	26.9	42.4	42.9	52.5	52.5
1994	22	22.3	22.4	22.4	28	28.4	39.5	39.6
1995	19.5	23.5	25.2	28.9	31.2	34.9	57.7	66.9
1996	24.5	32.5	32.5	34.5	40.8	40.8	40.8	51.1
1997	24.6	24.9	27.9	28	28	28	28	47.9
1999	19	21.8	21.9	23.7	29.8	33.1	33.1	48.9
2000	24	40	45	45	45	45	45	45
2001	14.6	19.6	33.6	33.6	33.6	33.6	33.6	34.1
2002	17	22.3	24.4	31.6	33.9	39.8	39.8	39.8
2003	28.2	35.2	47.5	51.2	52.8	56.2	57	57
2004	27.4	30.9	31.4	31.5	33.5	33.6	51.8	51.8
2005	17.7	25.2	26.7	26.7	28.5	28.6	28.6	39.8
2007	16.7	18.8	20.5	23.5	29.7	34.7	35.2	36.6
Mean	**21.03**	**26.15**	**29.53**	**31.35**	**35.17**	**36.89**	**41.74**	**47.00**
STDEV	**4.36**	**6.46**	**8.46**	**8.44**	**7.75**	**7.97**	**10.29**	**9.16**

Station: Pawi

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1987	16.2	30	41.2	41.2	41.7	41.7	41.7	41.7
1988	24.5	38.5	54	55.3	55.3	55.3	55.3	65.8
1989	16.3	17	24.9	26.9	36.9	36.9	46.5	55.4
1990	33.4	42.1	46.9	46.9	49.8	50.5	53.3	56.2
1992	17.7	27.5	27.5	27.5	27.5	28.5	35.5	40.3
1993	16	19.5	21.4	21.4	30	32.2	34.6	35.8
1997	19.2	25	26.9	26.9	29.7	29.7	30.1	30.1
1999	23.8	34.5	38.9	39.2	39.3	39.3	39.5	46.1
2001	28.7	42.6	51.1	52.2	53.1	53.1	53.3	53.9
Mean	**21.76**	**30.74**	**36.98**	**37.50**	**40.37**	**40.80**	**43.31**	**47.26**
STDEV	**6.25**	**9.38**	**12.19**	**12.36**	**10.46**	**10.14**	**9.23**	**11.40**

Station: Motta

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1964	18.7	23.2	24.8	25.9	27.4	27.4	27.7	32.0
1971	20.4	26.3	30.2	31.2	34.1	34.2	34.4	37.3
1972	20.7	26.9	31.2	32.3	35.4	35.6	35.8	38.3
1973	18.2	22.4	23.4	24.5	25.8	25.9	26.0	30.7
1974	19.4	24.5	27.0	28.0	30.1	30.1	30.4	34.2
1975	19.4	24.5	27.0	28.1	30.1	30.2	30.4	34.2
1976	19.2	24.1	26.3	27.4	29.3	29.3	29.6	33.5
1978	19.1	23.9	25.9	27.0	28.8	28.9	29.1	33.2
1979	19.5	24.6	27.2	28.2	30.3	30.4	30.6	34.4
1980	19.1	23.9	26.0	27.0	28.9	28.9	29.1	33.2
1981	19.3	24.3	26.7	27.8	29.8	29.8	30.0	33.9
1982	21.9	29.0	35.2	36.2	40.4	40.7	40.9	42.1
1983	21.5	28.3	33.9	34.9	38.8	39.0	39.2	40.8
1984	21.4	28.0	33.4	34.4	38.1	38.4	38.5	40.4
1985	20.4	26.2	30.0	31.0	33.8	33.9	34.1	37.1
1986	20.4	26.3	30.1	31.2	34.0	34.2	34.4	37.3
1987	19.8	25.2	28.3	29.3	31.7	31.8	32.0	35.5
1988	20.2	25.9	29.6	30.6	33.3	33.4	33.6	36.7
1989	22.8	24.8	27.4	28.2	28.3	28.3	28.3	39.7
1990	19.2	24.2	26.4	27.5	29.4	29.4	29.7	33.6
1991	21.9	29.0	35.3	36.2	40.5	40.8	40.9	42.1
1992	20.8	27.0	31.5	32.5	35.7	35.9	36.1	38.5
1994	19.7	24.9	27.8	28.9	31.1	31.2	31.4	35.0
1996	21.2	29.4	32.4	32.7	46.6	47	47.1	47.3
1998	21.3	30.7	34.7	38.7	40.7	40.7	40.7	40.7
1999	16.2	21.1	25	28	29.7	29.7	29.7	29.7
2001	20.3	29.1	43	43	53.7	55.6	55.6	55.6
2002	23.8	33.3	41.3	41.3	41.3	41.3	41.5	41.5
2005	18.8	24	26.8	26.8	27.7	28	28.7	32.7
2006	26	29.7	31.9	31.9	33.5	33.5	33.5	33.5
Mean	**20.35**	**26.16**	**29.98**	**31.02**	**33.94**	**34.12**	**34.30**	**37.16**
STDEV	**1.83**	**2.73**	**4.66**	**4.55**	**6.29**	**6.54**	**6.49**	**5.30**

Station: Nefas Mewcha

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1964	15.8	19.2	21.9	26.2	29.7	30.3	39.0	45.0
1971	17.7	22.2	28.0	34.2	38.6	39.6	44.6	47.7
1972	17.4	21.8	27.1	33.0	37.3	38.2	43.8	47.3
1973	14.8	17.6	18.9	22.2	25.3	25.8	36.0	43.6
1974	16.4	20.2	23.9	28.7	32.6	33.3	40.9	45.9
1975	16.7	20.6	24.7	29.8	33.7	34.5	41.6	46.3
1976	16.0	19.5	22.5	27.0	30.6	31.3	39.6	45.3
1978	16.3	20.0	23.5	28.3	32.1	32.8	40.6	45.8
1979	16.7	20.7	24.8	30.0	34.0	34.7	41.8	46.3
1980	16.3	20.1	23.5	28.3	32.1	32.8	40.6	45.8
1981	15.7	19.0	21.4	25.6	29.0	29.6	38.6	44.8
1982	19.2	24.6	33.7	41.6	46.9	48.2	49.2	49.8
1983	16.6	20.4	24.4	29.4	33.3	34.0	41.3	46.1
1984	18.6	23.6	31.4	38.6	43.5	44.6	47.3	49.0
1985	17.4	21.7	27.0	32.9	37.2	38.1	43.7	47.3
1986	17.6	22.1	27.8	34.0	38.4	39.3	44.4	47.6
1987	21	23.3	26.3	32.6	39.2	41.9	43.3	54.3
1988	15.2	17.8	23.6	27.6	33.5	33.7	45.7	49.2
1989	20	20.4	20.4	22.2	29	30.7	37.5	37.5
1990	16.4	20.1	23.7	28.5	32.3	33.0	40.7	45.8
1991	19.1	24.5	33.5	41.5	46.7	47.9	49.1	49.8
1992	18	23	33.5	40.9	43.8	43.8	43.8	44.2
1993	13.5	16.7	21	25.6	26.1	26.1	32.3	44.9
1994	16.9	21.0	25.5	30.9	35.0	35.8	42.4	46.6
1996	17.1	21.2	26.0	31.5	35.7	36.5	42.8	46.8
1997	16.5	20.4	24.2	29.2	33.1	33.8	41.2	46.1
1998	18.2	23.1	30.1	36.9	41.6	42.7	46.3	48.5
1999	16.3	22.8	24	31	32	32	47.7	47.7
2000	15.1	18.0	19.6	23.1	26.3	26.8	36.7	43.9
2001	20.3	26.5	38.4	47.9	53.8	55.4	56.7	59.7
2005	16.3	20.0	23.4	28.1	31.9	32.6	40.5	45.7
2006	18.4	23.4	30.8	37.8	42.6	43.7	46.9	48.7
Mean	**17.11**	**21.11**	**25.89**	**31.42**	**35.53**	**36.35**	**42.70**	**46.97**
STDEV	**1.65**	**2.21**	**4.58**	**6.06**	**6.61**	**6.87**	**4.61**	**3.55**

Station: Shambu

Year	Observed annual max. Rainfall depth(mm) for the indicated durations(hr)							
	0.5	1	2	3	5	6	12	24
1987	34.5	45	48.4	48.4	63	68.9	68.9	74.3
1988	20.4	24	28.5	31.2	31.2	31.2	53.6	53.6
1989	22.7	23.2	28.2	29.1	29.1	29.1	35.3	61.8
1990	29.7	31.5	33.2	33.6	34.2	34.2	40.7	59.8
1991	19.4	26.4	32	36.5	38.6	38.5	40.2	49.8
1992	19.5	26.6	30.4	31.4	31.4	31.4	31.4	31.4
1993	30	44.5	47	47.5	71.6	75.6	77.3	77.3
1998	25.3	29.8	31.9	31.9	32.1	42.1	68.4	71
1999	28.5	32.8	32.9	32.9	32.9	32.9	54.7	63.2
2000	29.3	31.8	37.7	41.1	46	46	46	46.4
2001	23	37.5	37.5	37.5	40.2	40.2	41.3	43.6
2002	33.9	54.5	65.8	66.3	66.3	66.5	66.5	66.5
2003	19.6	19.6	40.3	40.3	42.1	42.1	42.1	58.1
2006	18.8	24	28	29.5	34.5	35	37.3	37.3
Mean	**25.33**	**32.23**	**37.27**	**38.37**	**42.37**	**43.84**	**50.26**	**56.72**
STDEV	**5.59**	**9.95**	**10.48**	**10.15**	**14.22**	**15.25**	**14.70**	**13.77**

Station: Shire Endasilase

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1992	21.4	29.8	36.1	45.6	45.6	45.6	45.6	45.6
1993	14.5	15.1	21.5	21.5	27	27.2	27.2	27.2
1994	19	19	20.2	20.2	20.2	20.2	20.2	23.5
1995	28	28.3	28.3	29.5	51.6	53.2	53.9	53.9
1996	14.7	18.6	25	30.2	30.2	30.2	30.2	30.2
1997	20.2	28.1	28.4	29.4	29.4	29.4	29.4	29.4
1998	19.7	20.7	22.7	24.3	40.2	40.7	42.3	44.2
1999	24	27.2	30.8	32.8	35.8	37.2	41.8	42.4
2000	22	28.5	33	40	47.4	47.6	47.6	52.2
2001	24	27.9	38.1	47.4	47.4	47.4	47.4	57.8
2002	24.5	33.7	35.6	35.6	35.6	35.6	35.6	55.3
2003	17.1	31.1	31.5	34	35.3	35.9	35.9	35.9
2004	21.5	28.5	38	39.5	50.5	50.5	57.1	59.6
2005	19.1	27.3	27.3	27.3	27.3	30	53	54.9
Mean	**20.69**	**25.99**	**29.75**	**32.66**	**37.39**	**37.91**	**40.51**	**43.72**
STDEV	**3.79**	**5.40**	**6.00**	**8.32**	**9.92**	**9.91**	**11.11**	**12.47**

Station: Shola Gebeya

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1990	19.9	20.1	20.6	20.6	20.6	20.6	24.6	32.7
1991	17.4	19.6	19.9	25.5	28.9	33.4	41	58
1992	6	10.6	12.6	17.6	17.6	17.6	17.6	17.6
1993	9.5	18.6	27.9	35.9	43.9	46	47.3	60.7
1994	22.7	24.2	30.2	30.2	30.2	30.2	30.2	46
1995	18.2	18.6	18.6	18.6	18.6	18.6	18.6	24.9
1996	12.8	24.6	24.7	24.7	24.8	25.5	41.1	50.1
1997	20.1	23.1	24.1	28.1	30	32	35.5	35.5
1998	15.7	15.7	24.4	29.8	35.2	35.2	35.7	36.5
1999	19.5	34.6	47.5	56	57.7	57.7	62.8	71.1
2000	7.5	9.4	11	11.4	17.5	18	23.5	30.7
2001	9.6	12	12.5	17.3	19	19	28.3	28.3
2002	14.8	16.2	21.3	23.5	27.1	29.2	34.2	39.4
2003	11.5	15.5	25.2	30.6	44	46.4	59.7	71.2
2004	18.3	23.3	33.5	43.3	47.2	47.2	49.2	50.7
2005	15.6	15.6	17.6	18.3	20.2	20.2	26.6	32.9
2007	20.8	23.1	23.1	29.3	33.7	36.3	36.7	36.7
Mean	**15.29**	**19.11**	**23.22**	**27.10**	**30.36**	**31.36**	**36.04**	**42.53**
STDEV	**5.02**	**6.17**	**8.75**	**10.77**	**11.92**	**12.23**	**13.10**	**15.69**

Station: Sinkata

Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1992	27.3	30.9	32.5	32.6	32.8	32.9	37.9	43.1
1994	23.5	25.5	27.4	27.8	28.0	28.1	30.1	32.4
1995	31.1	36.5	37.6	37.3	37.5	37.7	46.5	55.0
1996	26.9	30.4	31.9	32.1	32.3	32.4	37.0	41.9
1997	26.0	29.1	30.7	30.9	31.1	31.3	35.1	39.3
1999	26.3	29.5	31.1	31.3	31.5	31.6	35.7	40.1
2000	25.7	26.7	27.1	28.8	29.5	29.5	29.5	29.5
2001	23.5	27.3	27.3	27.3	27.9	27.9	33.6	33.6
2002	19.2	21.2	22.2	22.2	22.2	22.2	22.2	28
2003	24.4	32.5	38.9	39	39.2	39.6	39.6	47.6
2004	27.4	27.4	27.4	27.4	27.4	27.4	39.5	46.1
2005	34.2	35.6	35.6	35.6	35.6	35.6	37.1	39.1
2007	19.1	19.6	24.9	25.3	25.3	25.3	25.3	25.3
Mean	**25.73**	**28.63**	**30.35**	**30.59**	**30.79**	**30.88**	**34.54**	**38.55**
STDEV	**4.14**	**4.91**	**4.95**	**4.82**	**4.82**	**4.91**	**6.48**	**8.55**

Station: Sirinka

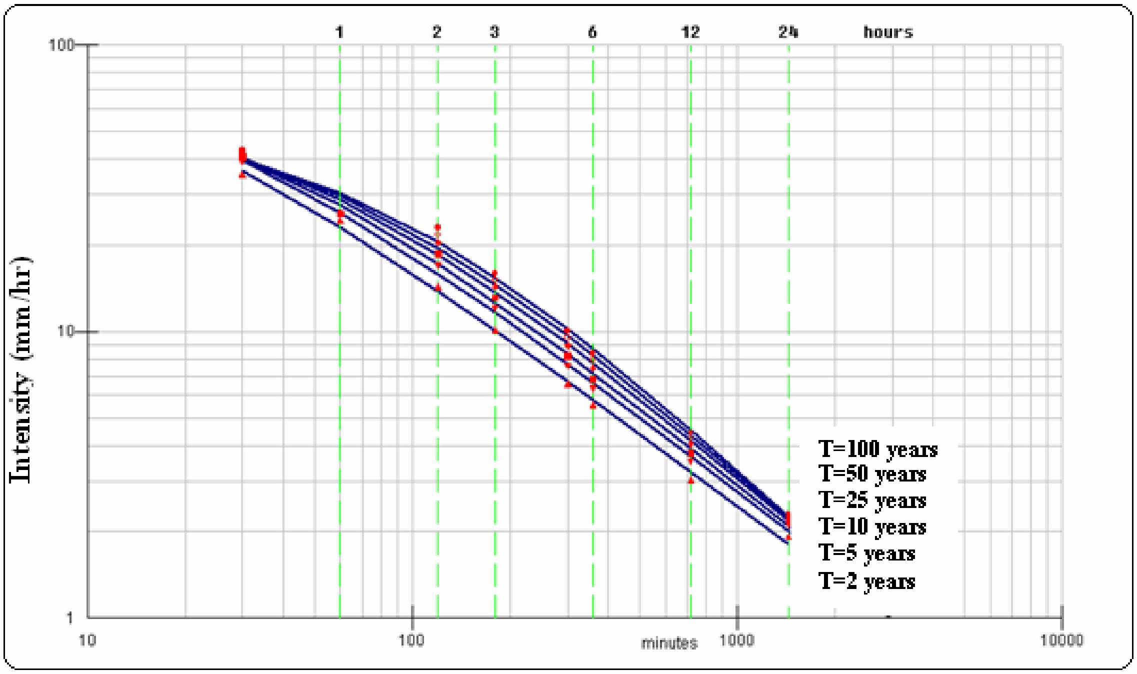
Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1987	17.2	18.2	23.2	23.2	23.2	28	43.4	57.7
1988	27.7	30.3	32.6	51.7	52.4	52.7	62.7	78.3
1989	28.2	28.2	30.7	35.2	44.6	44.6	47.7	48.1
1991	25	33.4	33.9	35.1	35.1	35.1	35.9	36.9
1992	11.2	20	23.1	28.4	38.4	39.2	44.2	50.9
1993	15.8	22.3	23.8	23.8	37.4	39.5	61.1	74.1
1994	15.7	21.5	33.5	37.5	46.2	47.1	47.6	48.5
1995	21.4	25.4	30.2	31.1	36.6	47.4	57.4	62.5
1996	17.6	21.1	32.5	34.5	60.6	75.3	78.9	88.9
1997	19.4	25.7	27.2	30.1	40.5	44.6	56.2	57.2
1998	27.6	30	39	48.2	48.2	48.2	52.4	73.3
1999	24.2	31.8	37.5	37.5	37.5	37.5	39.3	46.6
2000	19.5	24	24.5	25	25.7	25.7	41.6	46.2
2001	20.1	26.6	27.5	30.5	30.5	30.5	31.7	32.1
2002	25.5	31.5	35.1	39	39	39	40.5	41.6
2003	17.6	18.7	32.5	32.8	33	33	35.2	36
2004	14.8	18.3	28.5	37	49.7	51	51.3	51.4
2007	16	24	26.5	34.2	48.3	50.2	51.6	52.4
Mean	**20.25**	**25.06**	**30.10**	**34.16**	**40.38**	**42.70**	**48.82**	**54.59**
STDEV	**5.06**	**4.96**	**4.86**	**7.46**	**9.53**	**11.47**	**11.67**	**15.58**

Station: Wegel Tena

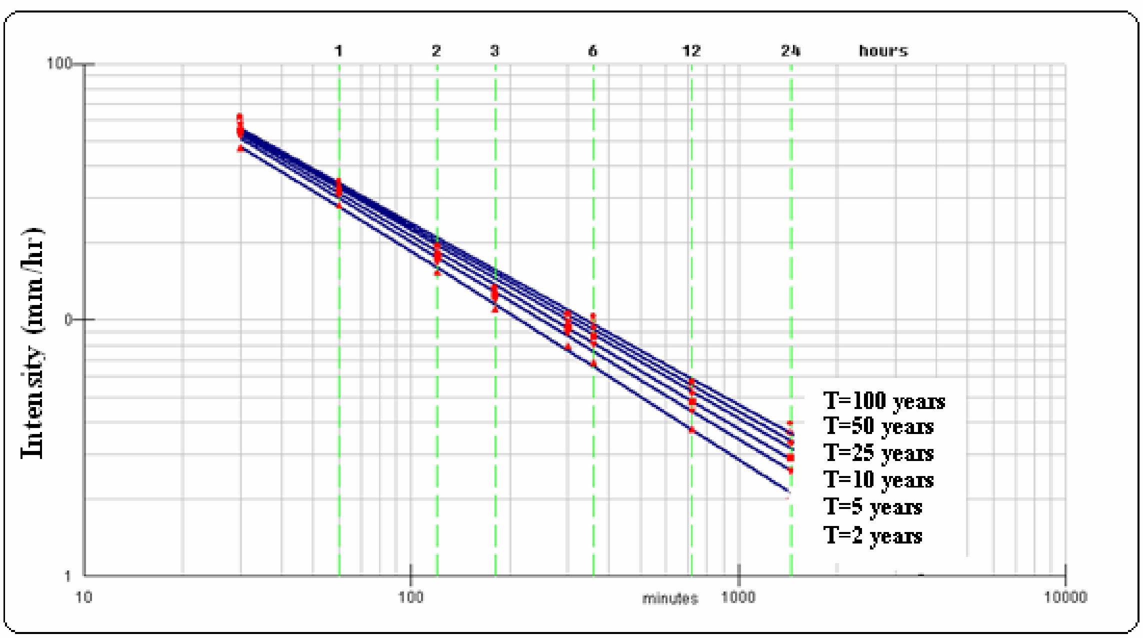
Year	Observed annual maximum rainfall (mm) for the indicated duration (hr)							
	0.5	1	2	3	5	6	12	24
1987	15.9	19.5	23.7	26.5	29.5	29.9	31.4	34.2
1988	11.9	14.1	16.6	17.2	17.4	17.4	23.1	23.1
1989	8.5	10.8	12.1	15.8	18.4	19.7	20.5	24.5
1991	7.9	10.7	12.6	15.2	16.1	16.8	18.6	21.1
1992	15.7	18.8	21.8	26.3	29.4	29.4	29.4	42.1
1993	13.8	17.1	20.7	23.5	25.9	26.4	28.0	30.8
1994	14.2	17.6	21.3	24.1	26.6	27.1	28.7	31.5
1995	12.1	15.3	18.4	21.2	23.2	23.7	25.5	28.2
1996	14.4	17.8	21.5	24.4	27.0	27.4	29.0	31.8
1997	12.0	15.2	18.2	21.0	22.9	23.5	25.2	27.9
1998	9.7	12.6	15.1	17.8	19.1	19.7	21.6	24.2
1999	8.7	11.6	13.8	16.4	17.5	18.2	20.0	22.5
2000	12.9	16.1	19.4	22.3	24.4	24.9	26.6	29.4
2001	9.6	13.8	18.5	23.7	30.9	32.8	35	39.2
2002	9.8	12.2	12.2	12.7	13.4	13.6	14.7	15.7
2003	15.3	18.1	27.2	32.3	35.3	35.4	35.4	35.4
2004	17.4	20.2	22.4	23.2	23.8	23.8	25.4	27.9
2005	20.3	23.9	23.9	25.4	27.1	27.3	27.3	28.7
2007	11.4	17.9	27.7	32.8	35.3	36.3	38.9	39.9
Mean	**12.71**	**15.97**	**19.31**	**22.20**	**24.38**	**24.91**	**26.55**	**29.37**
STDEV	**3.33**	**3.54**	**4.75**	**5.45**	**6.26**	**6.33**	**6.11**	**6.83**

Appendix B: IDF curves on double logarithmic scale

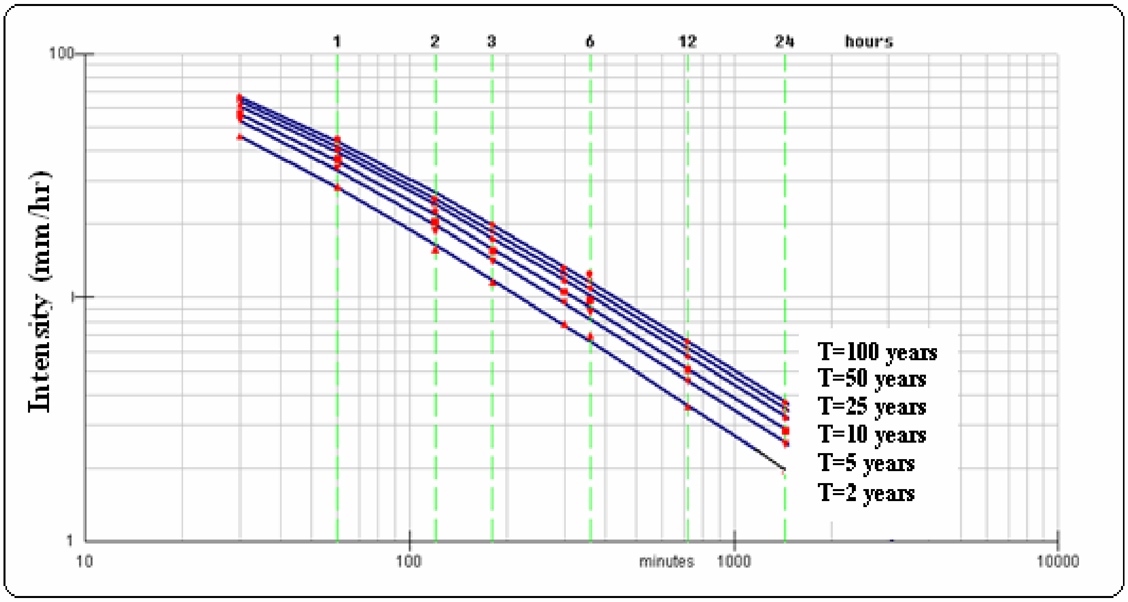
Station: Adigrat



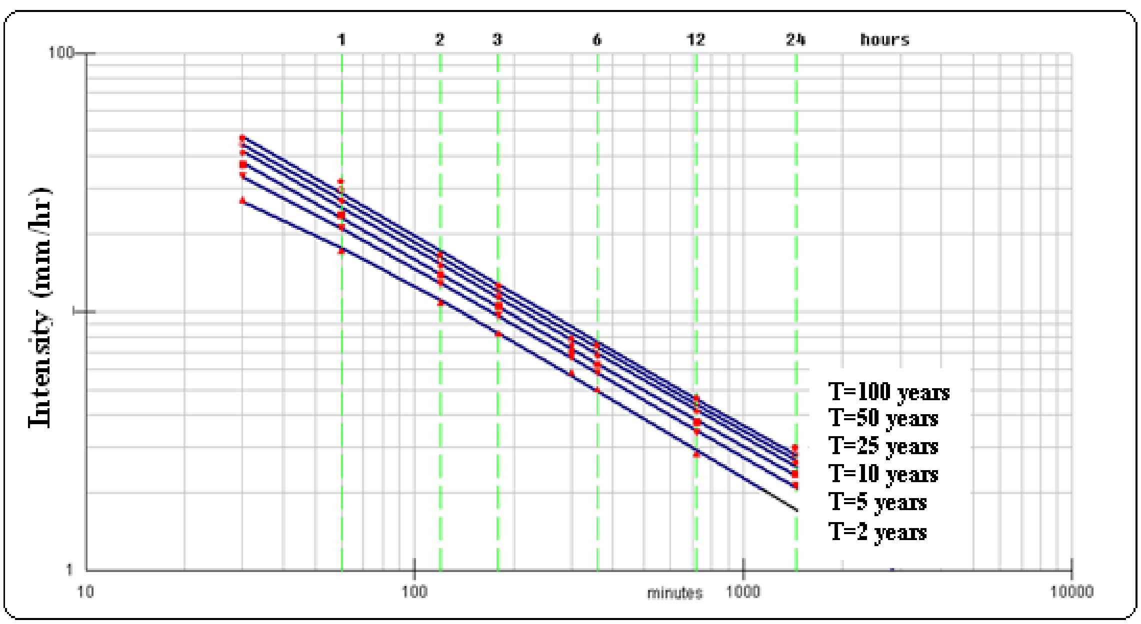
Station: Adwa



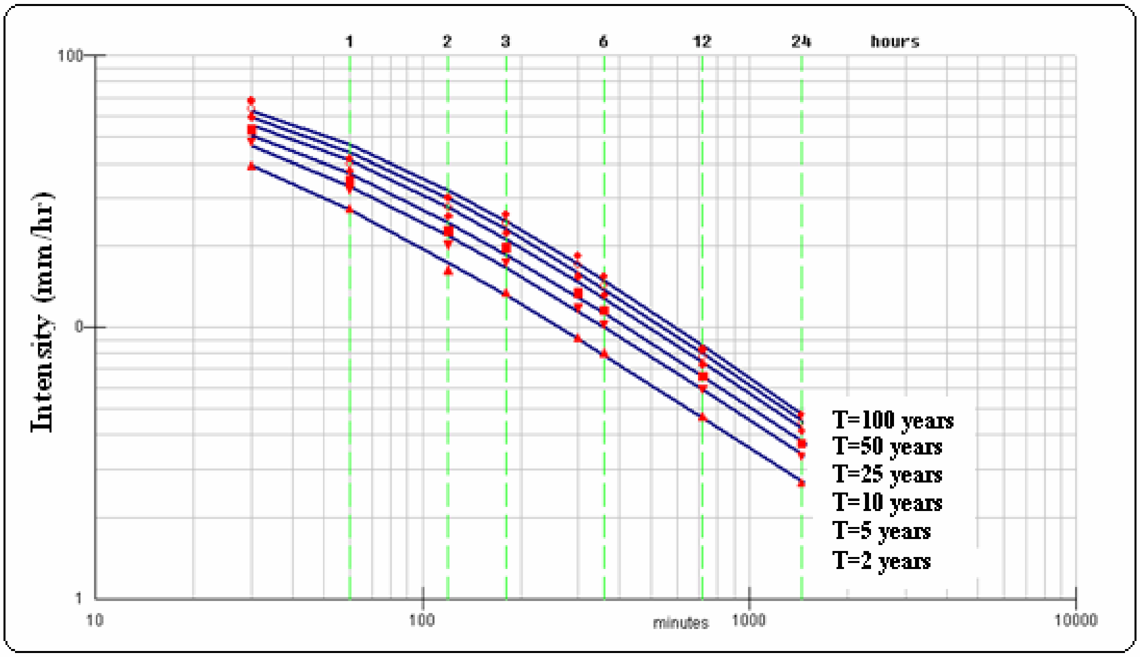
Station: Alem Ketema



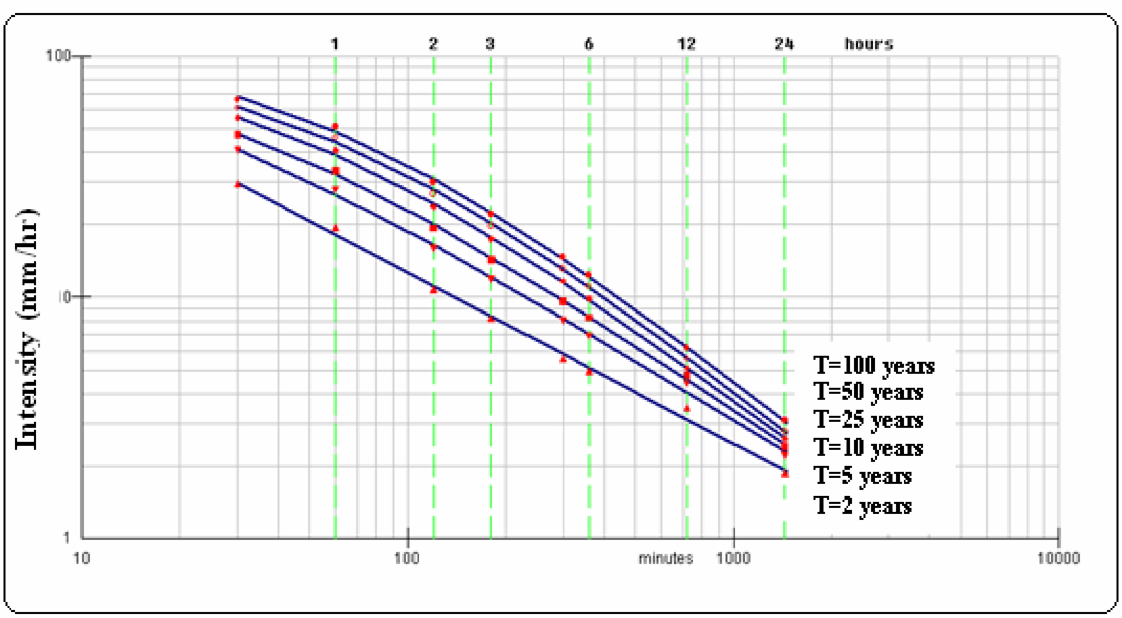
Station: Amba Mariam



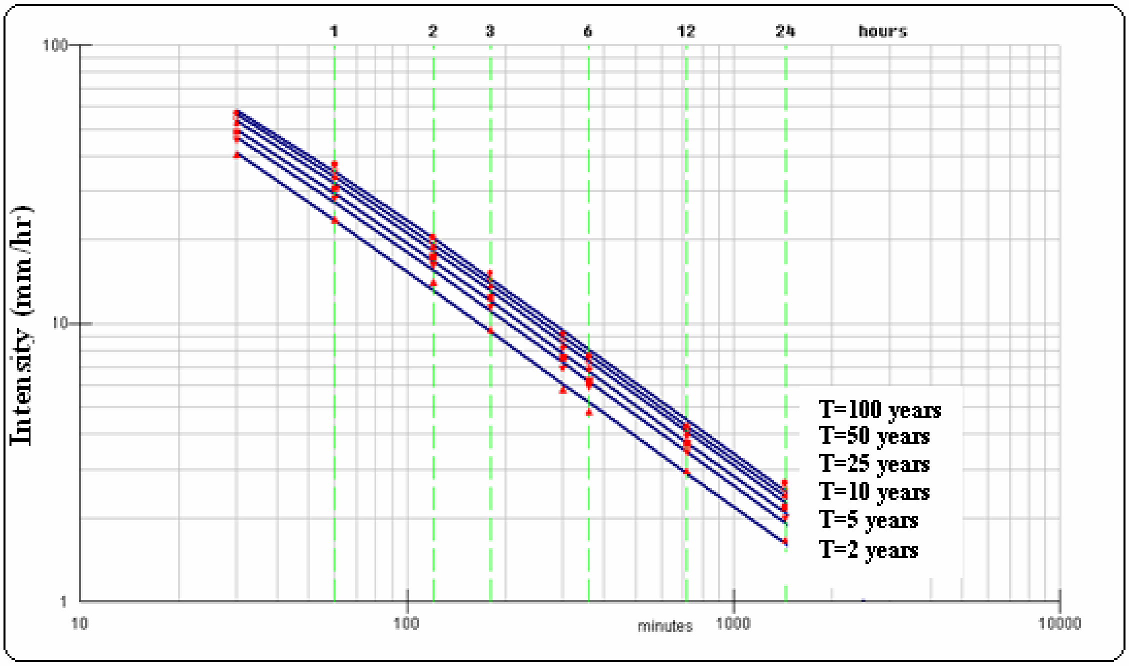
Station: Bati



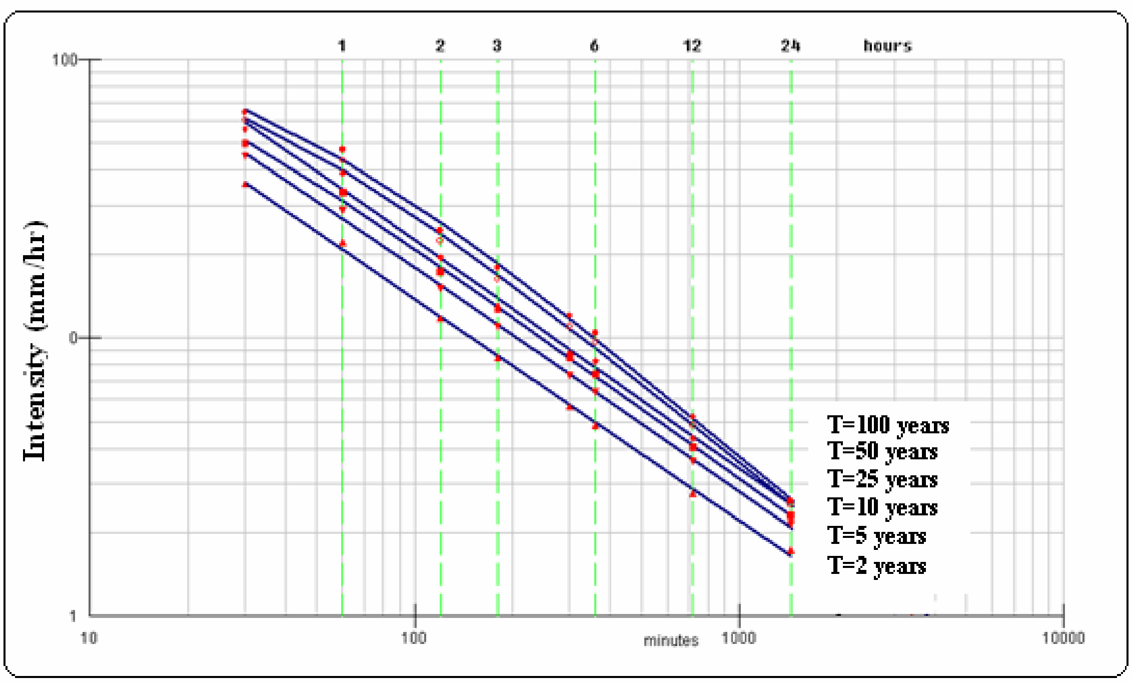
Station: Cheffa



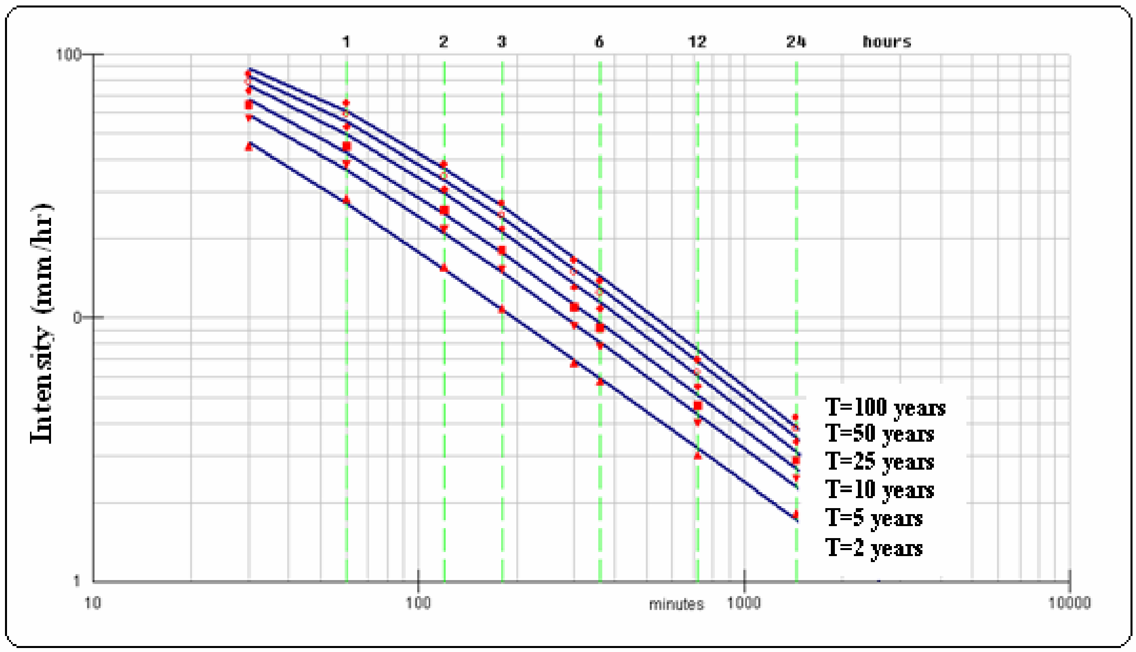
Station: Dangla



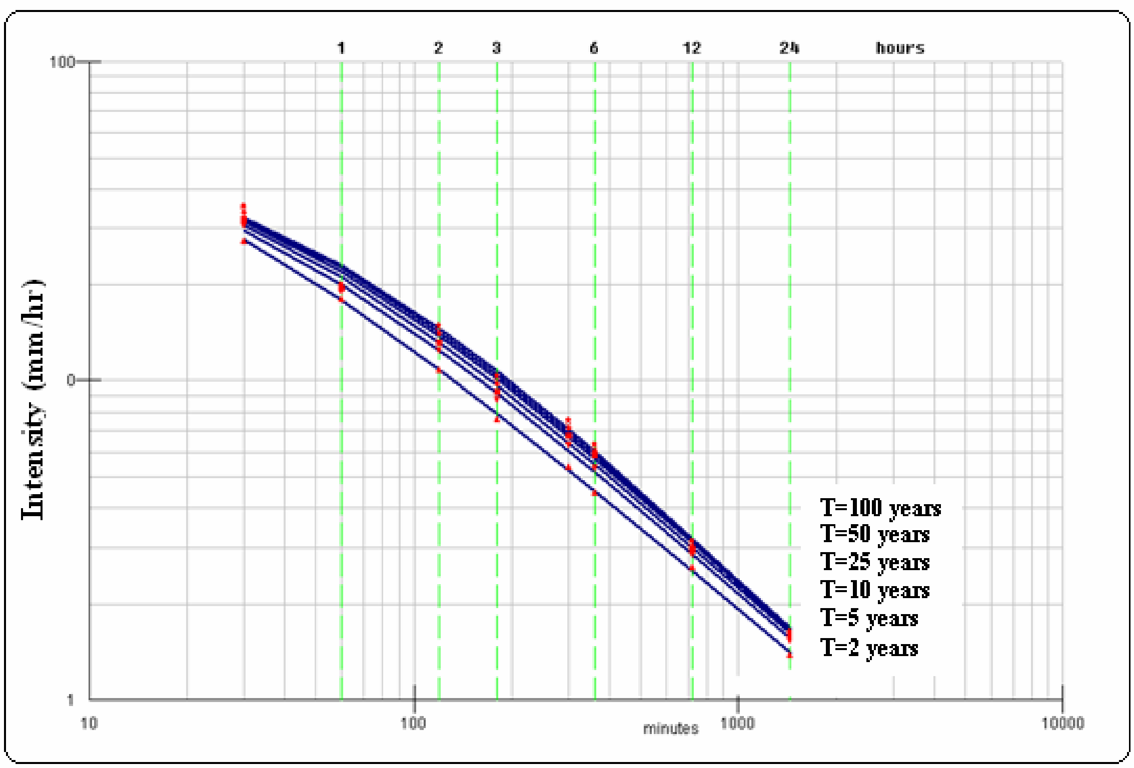
Station: Debre Berhan



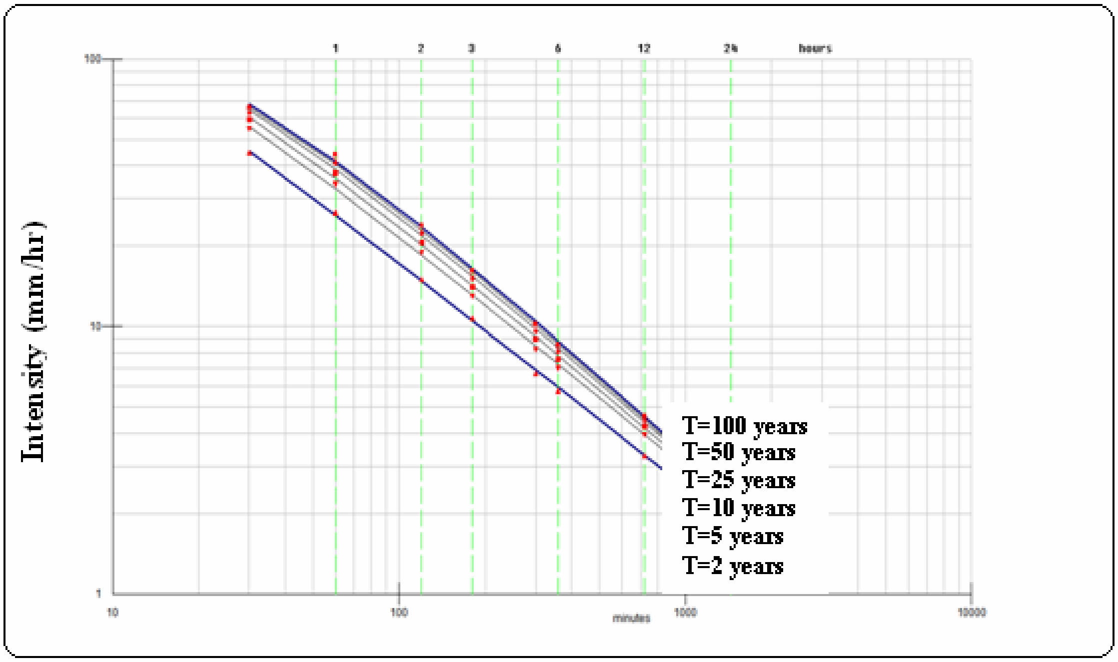
Station: Debre Markos



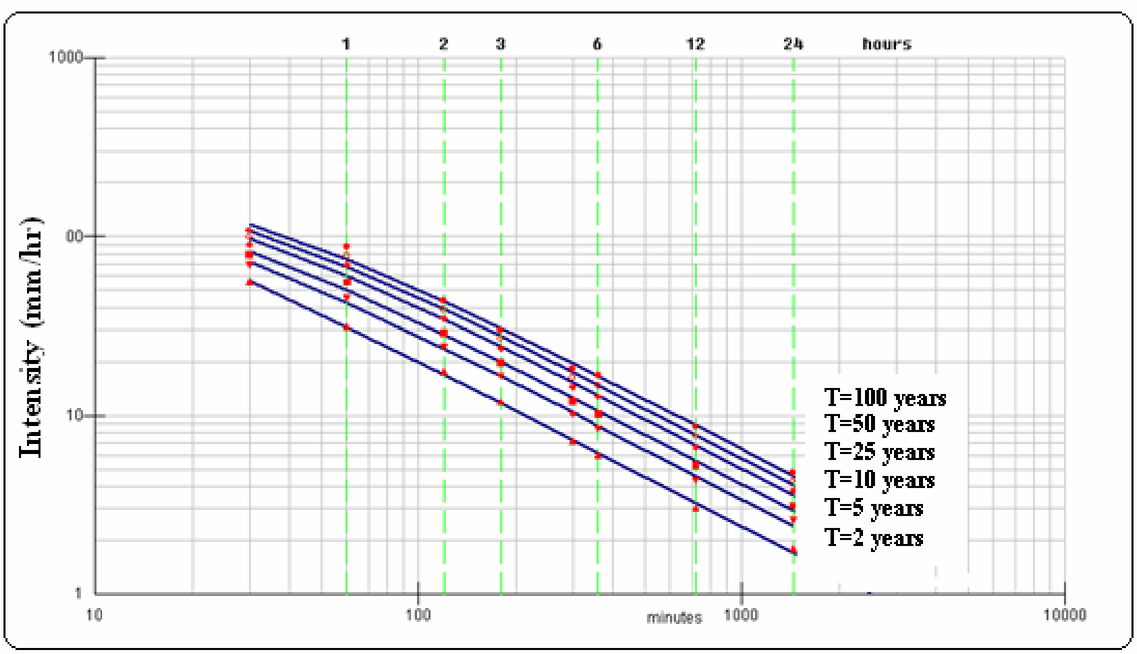
Station: Finote Selam



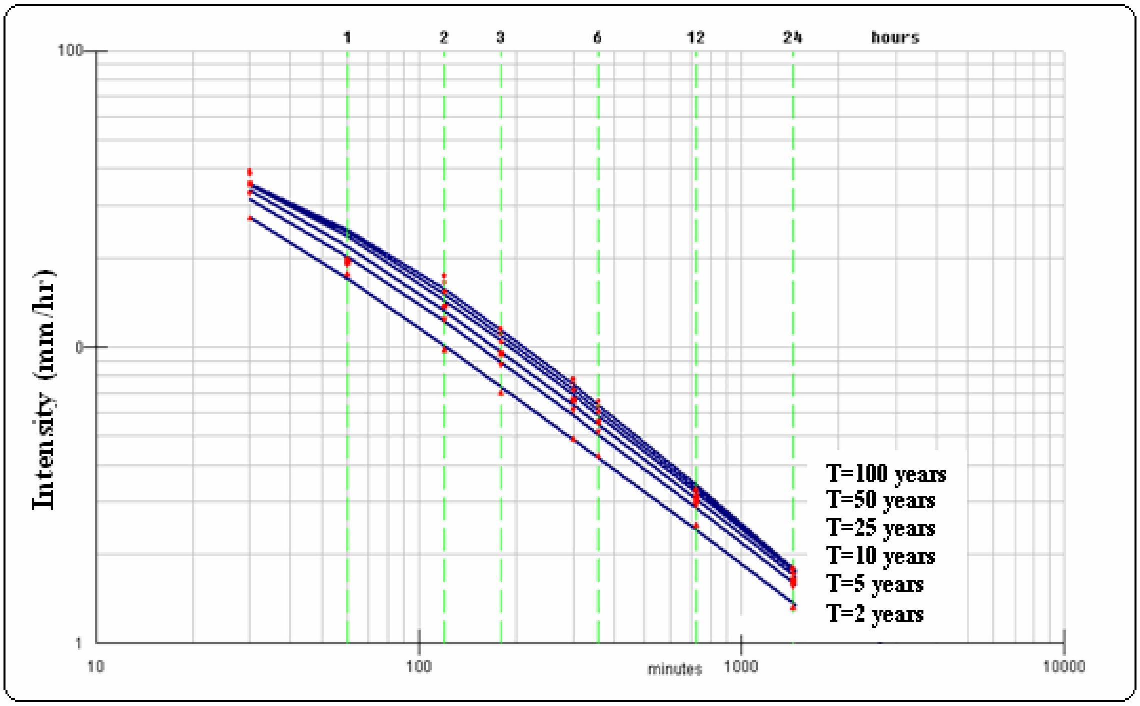
Station: Gebre Guracha



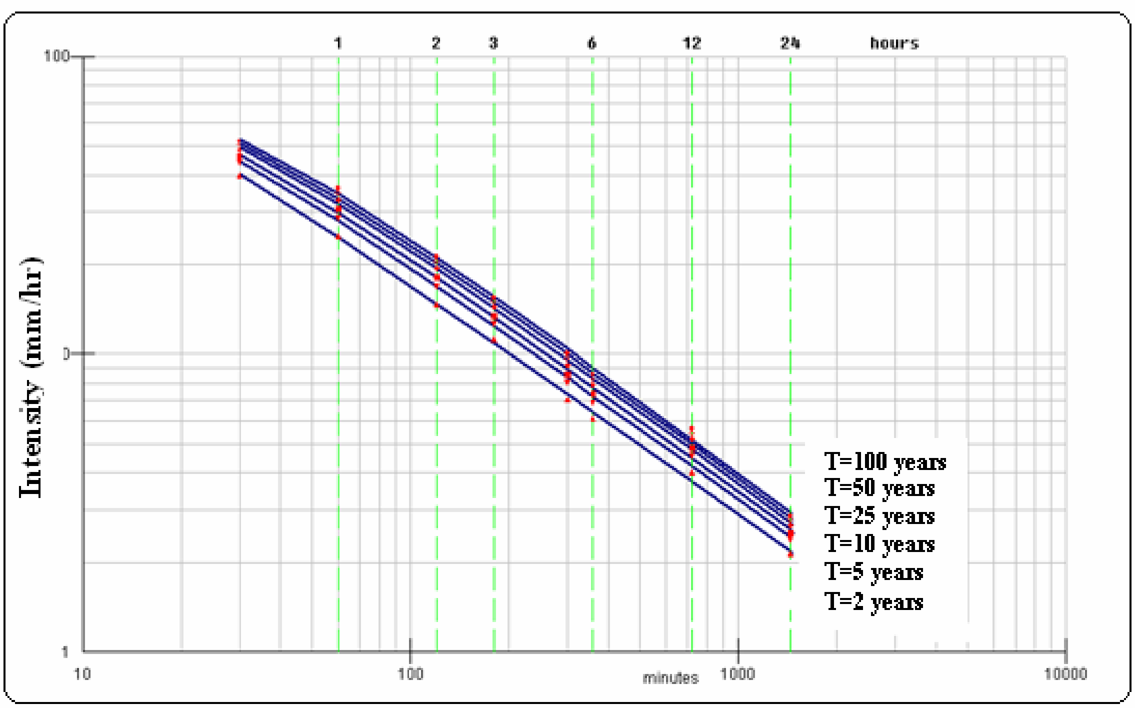
Station: Gewane



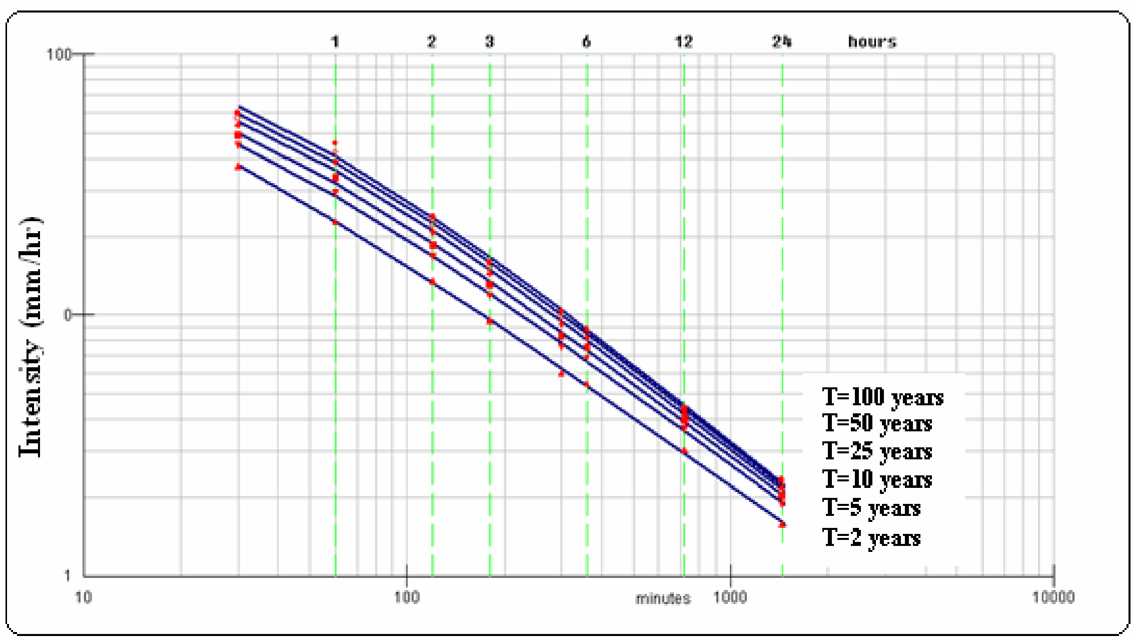
Station: Gondar



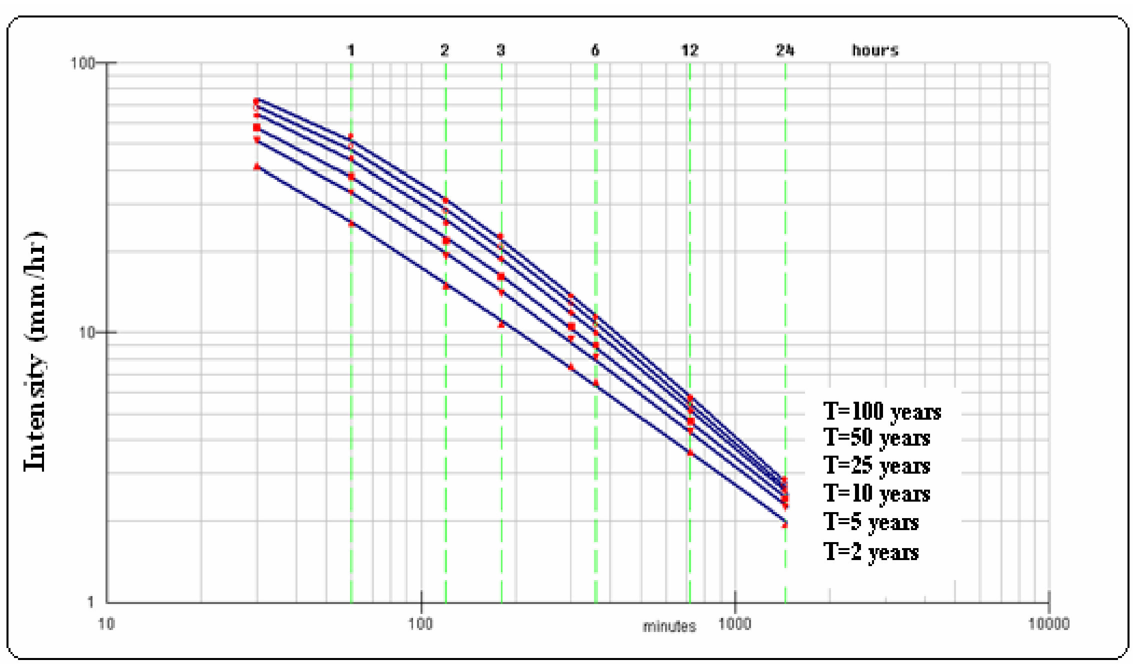
Station: Haike



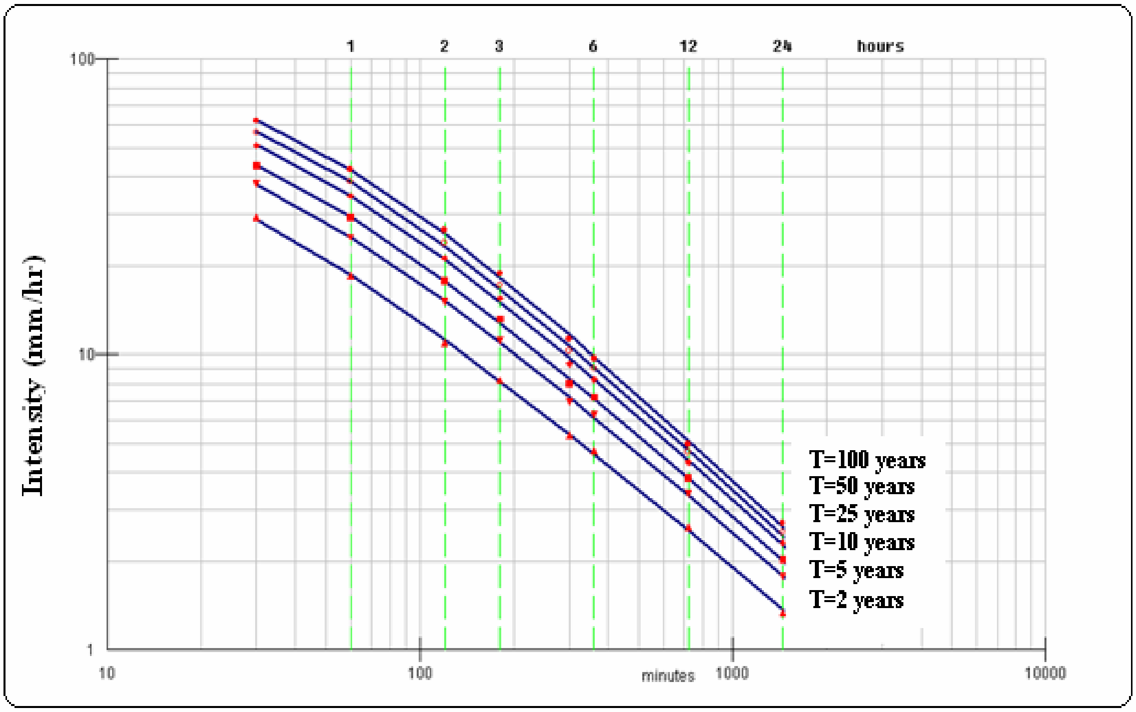
Station: Humera



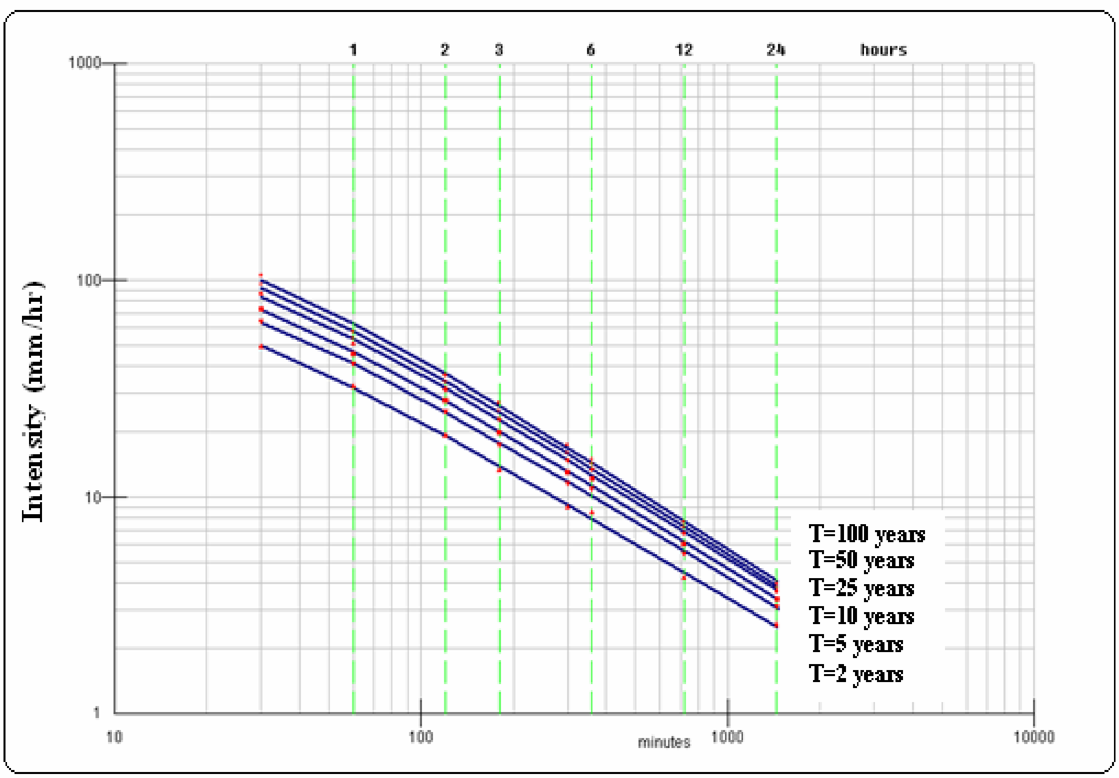
Station: Kombolcha



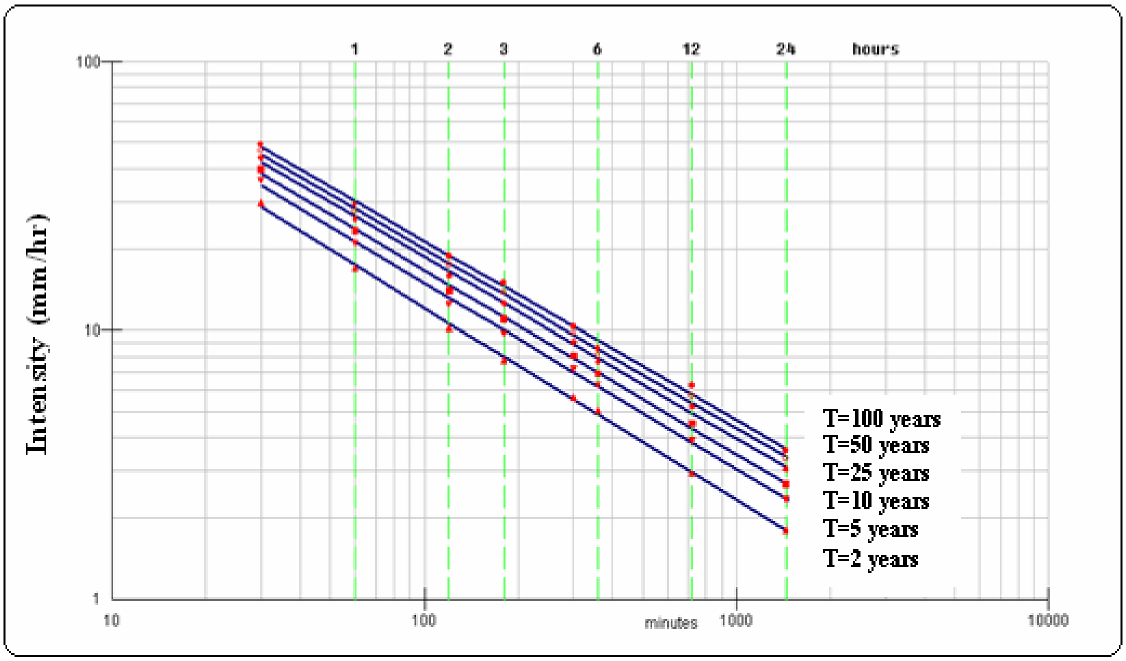
Station: Lalibela



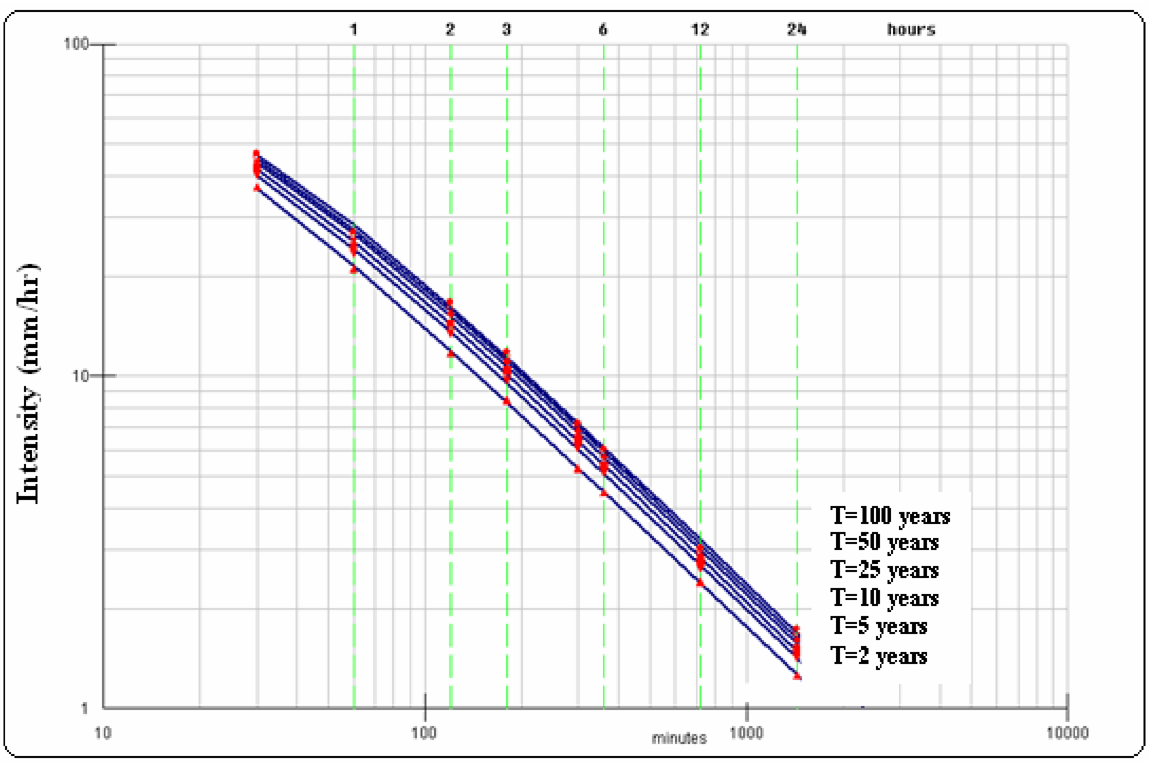
Station: Majete



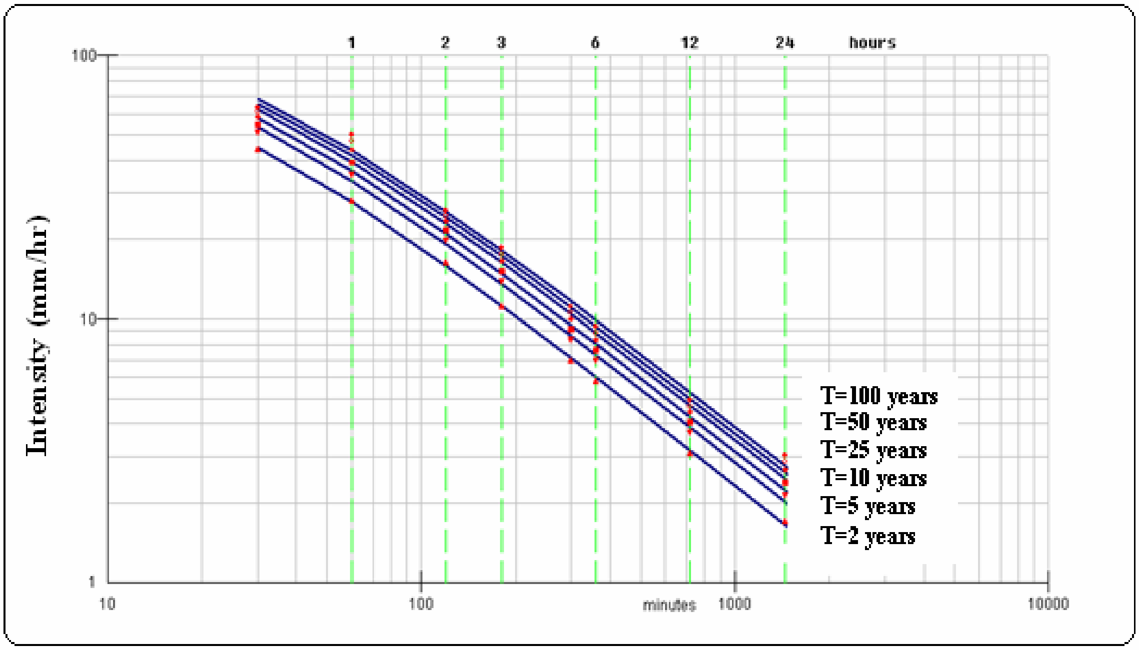
Station: Mehal Meda



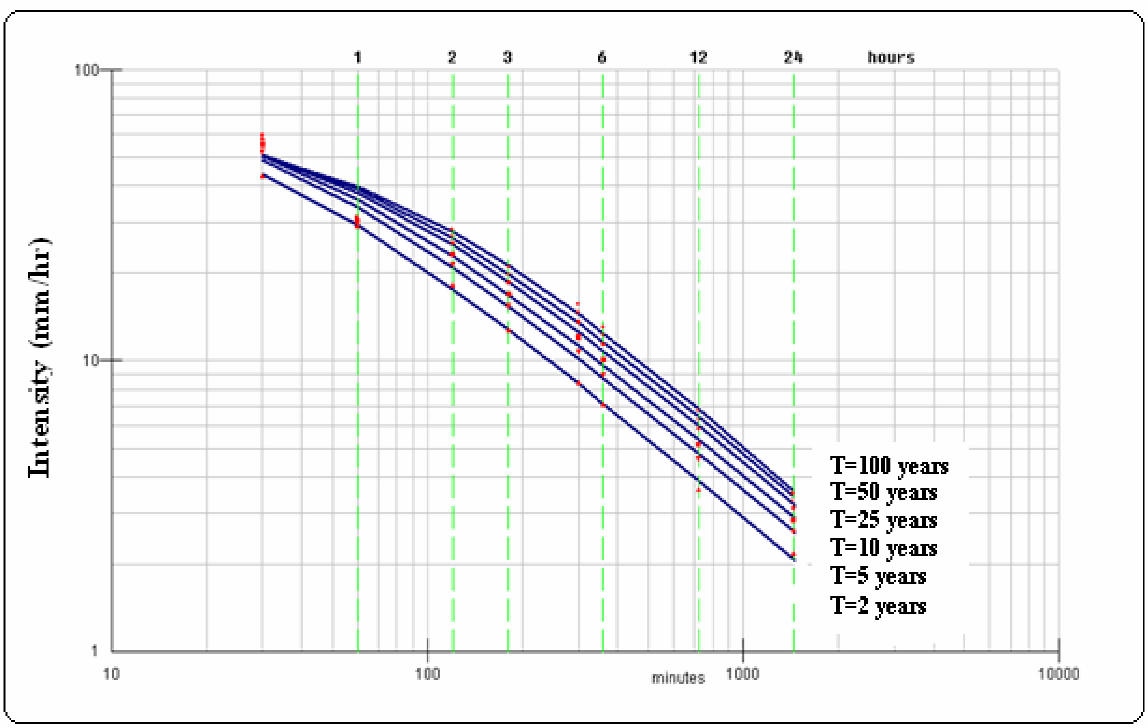
Station: Mekane Selam



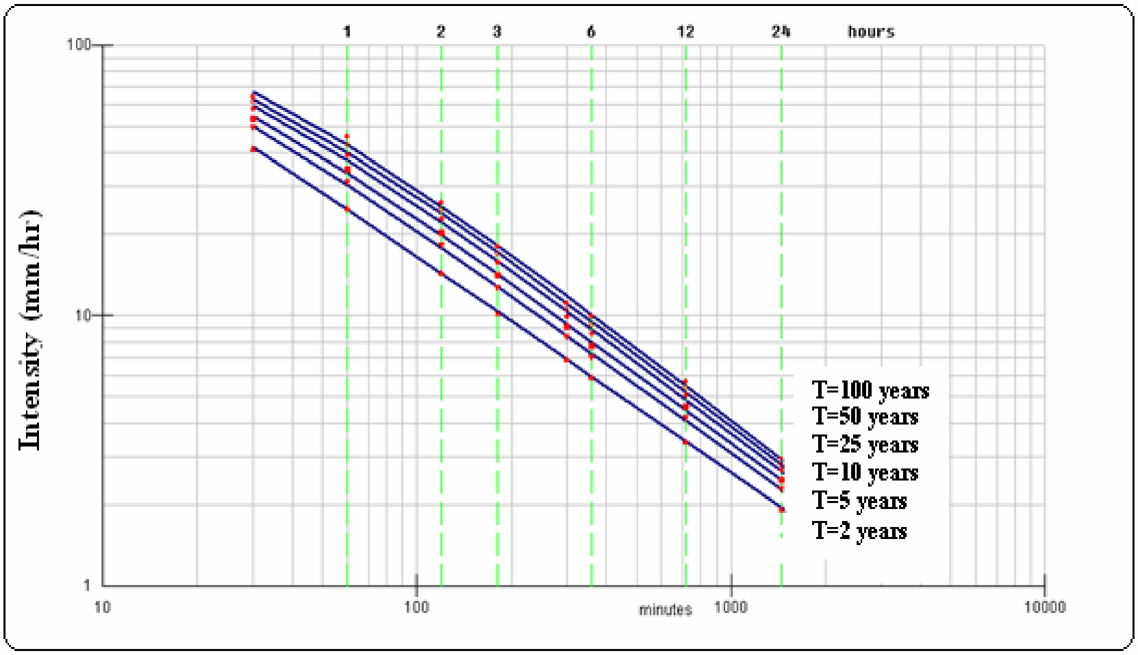
Station: Mekele



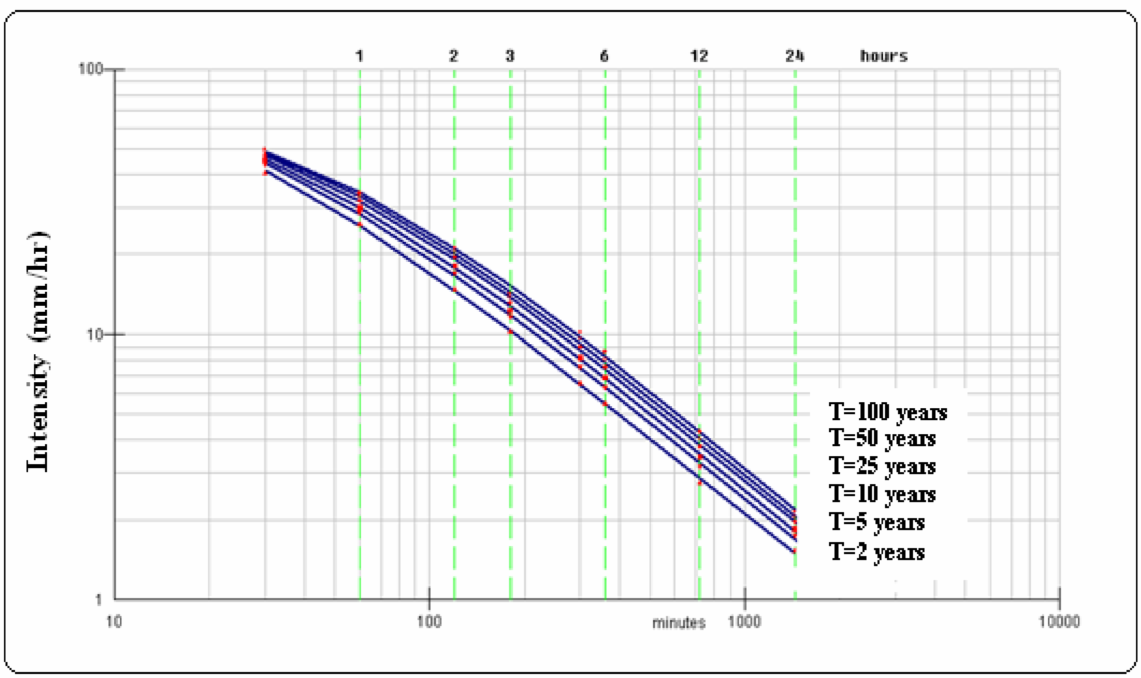
Station: Metema



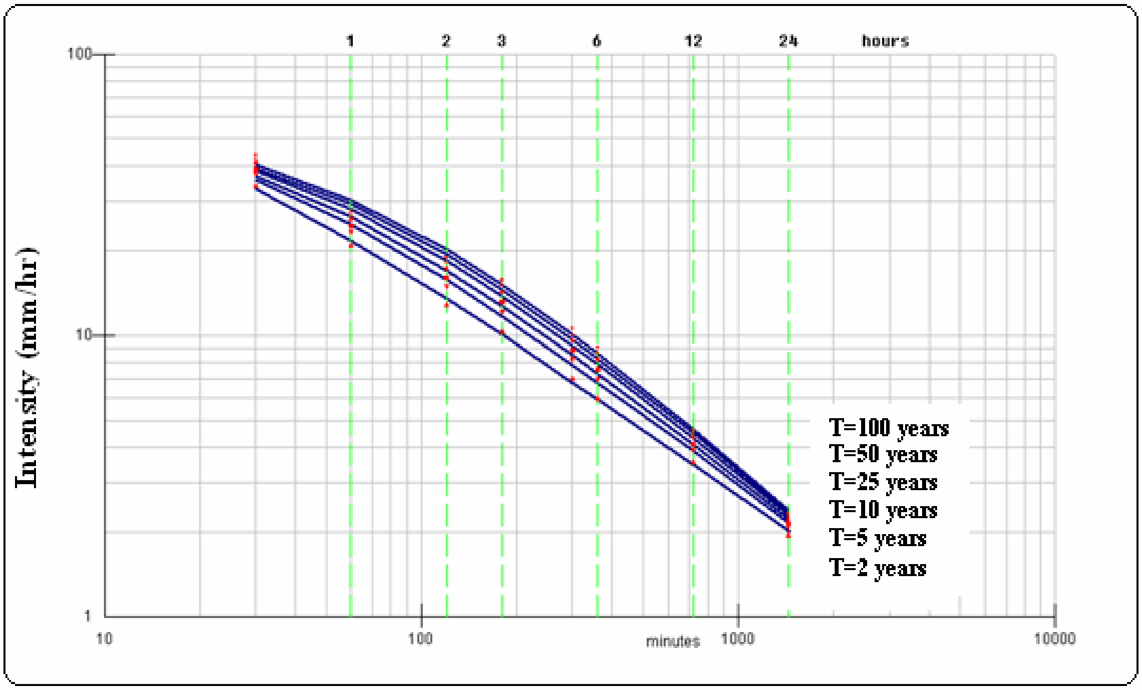
Station: Michew



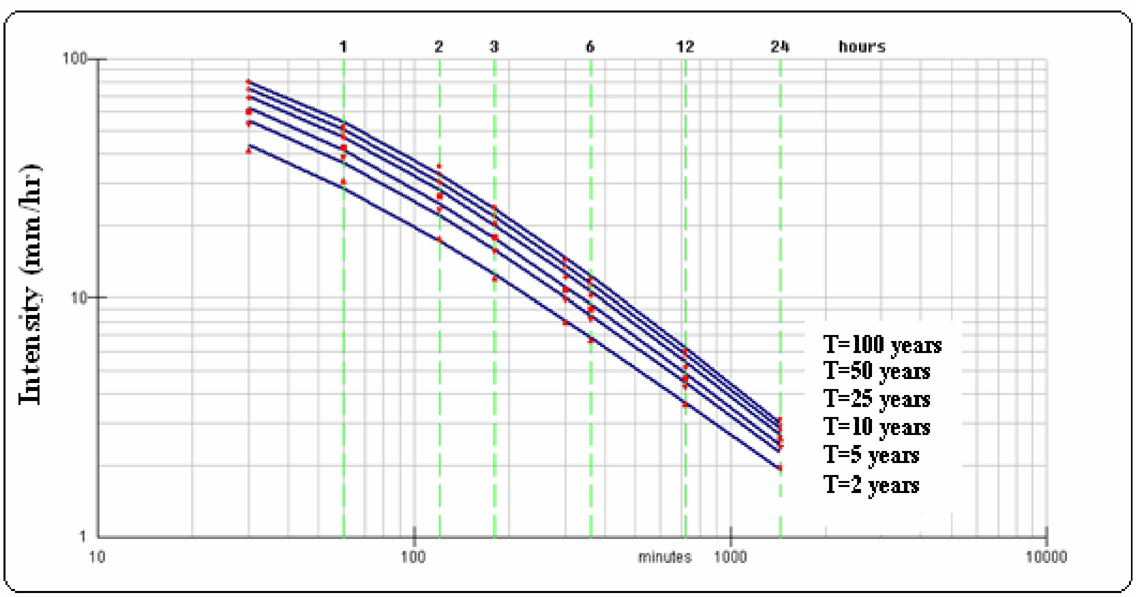
Station: Motta



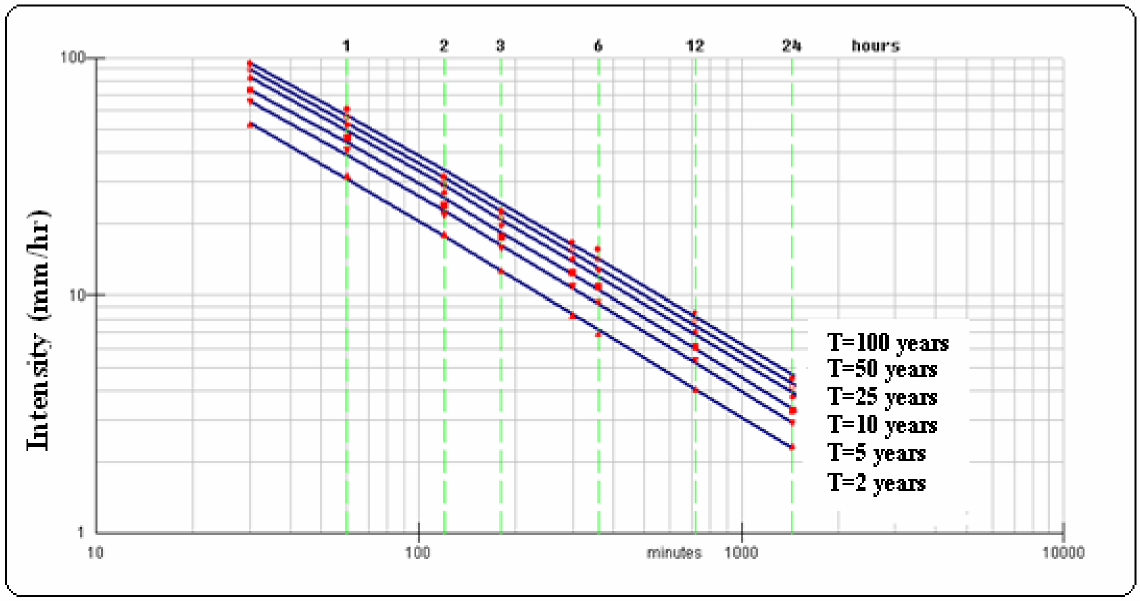
Station: Nefas Mewcha



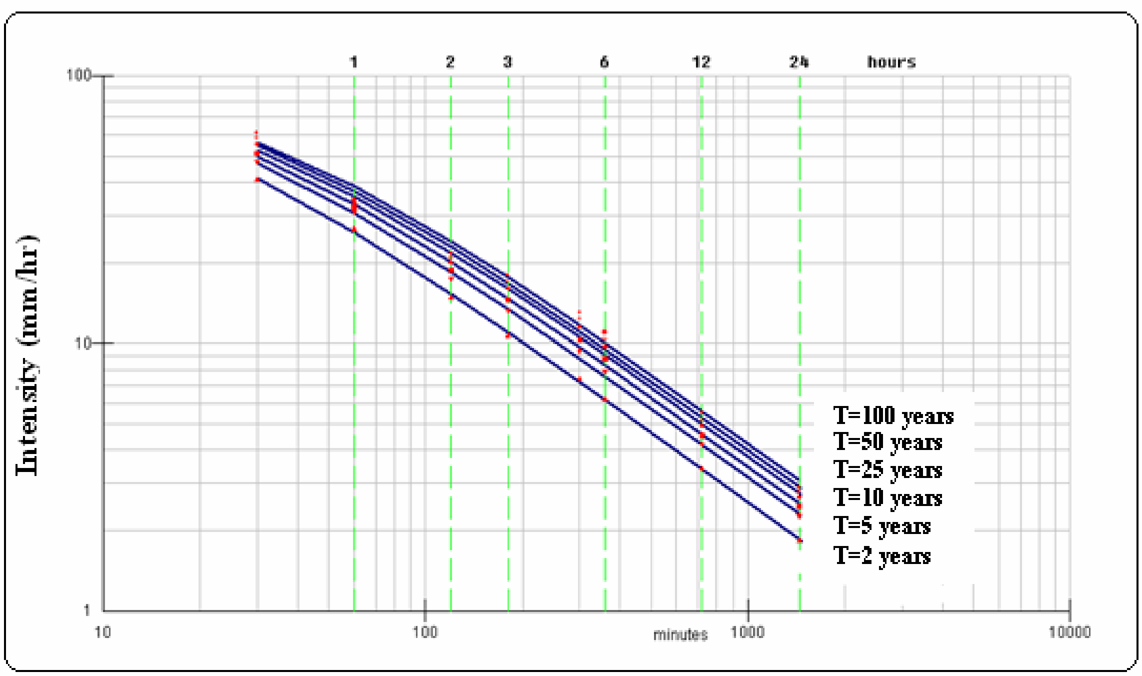
Station: Pawi



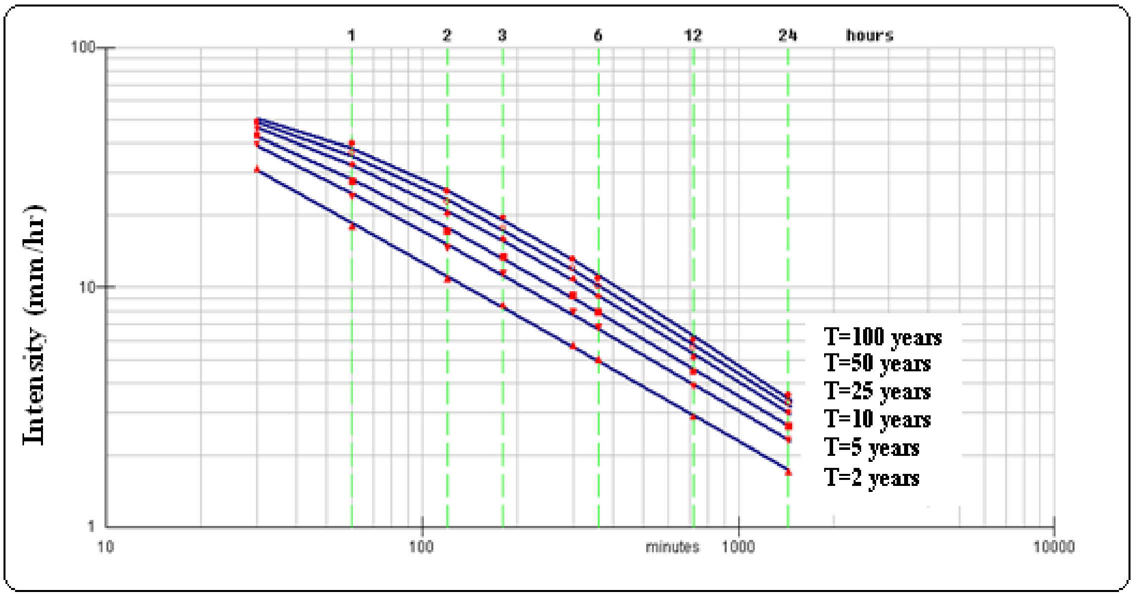
Station: Shambu



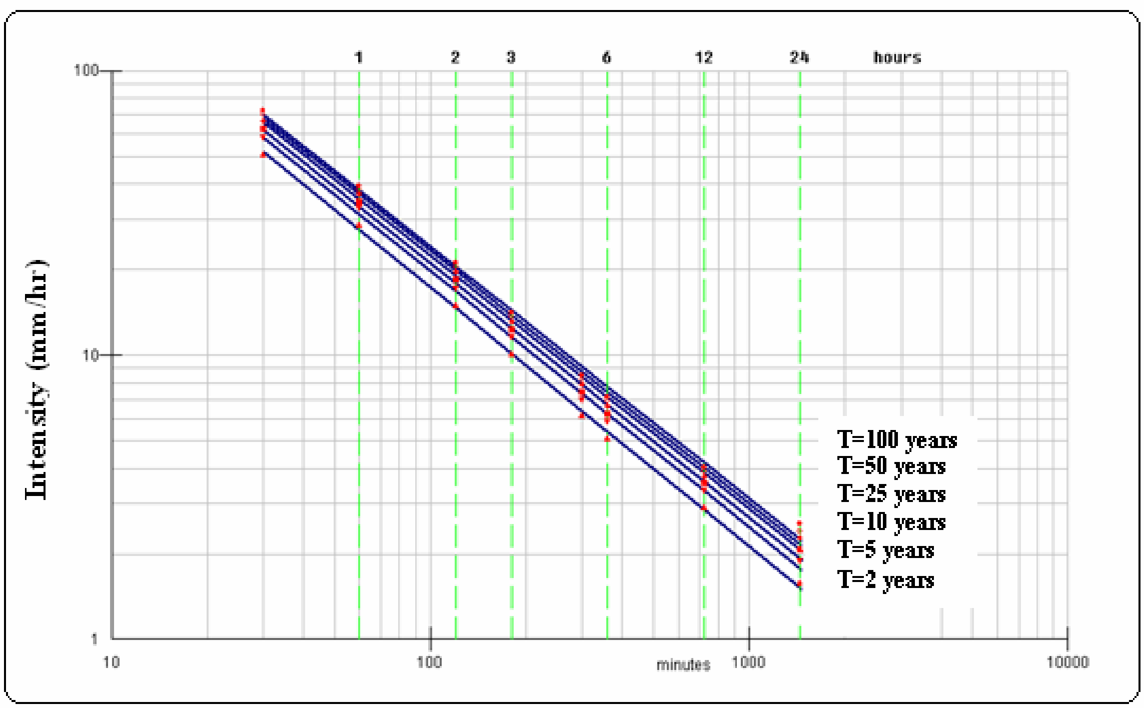
Station: Shire Endasilase



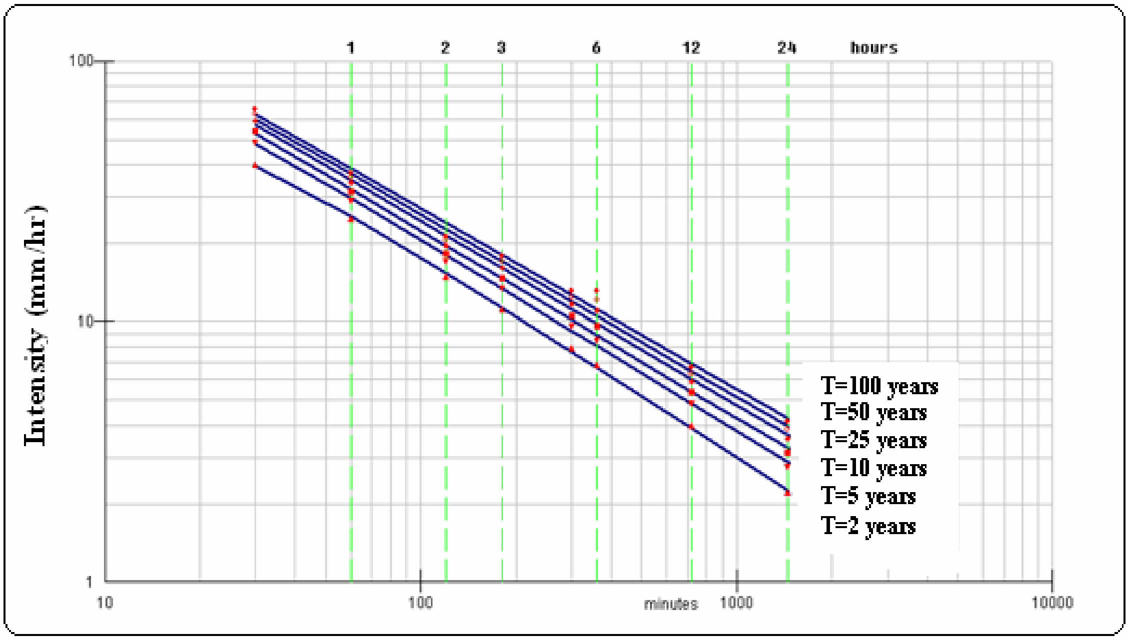
Station: Shola Gebeya



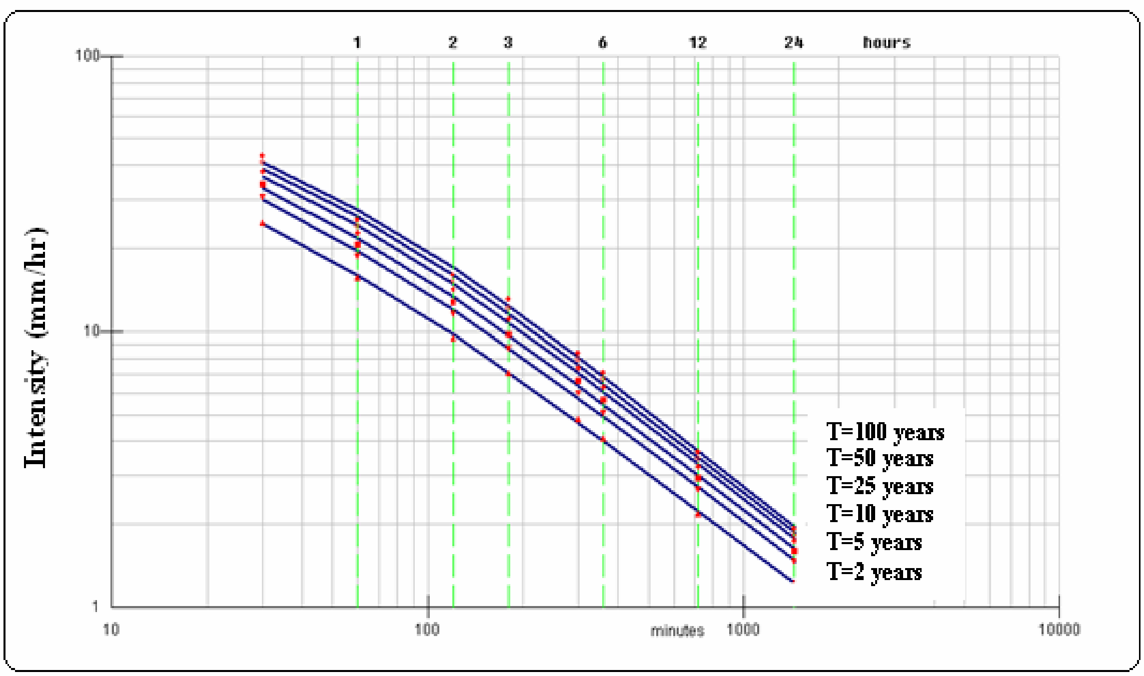
Station: Sinkata



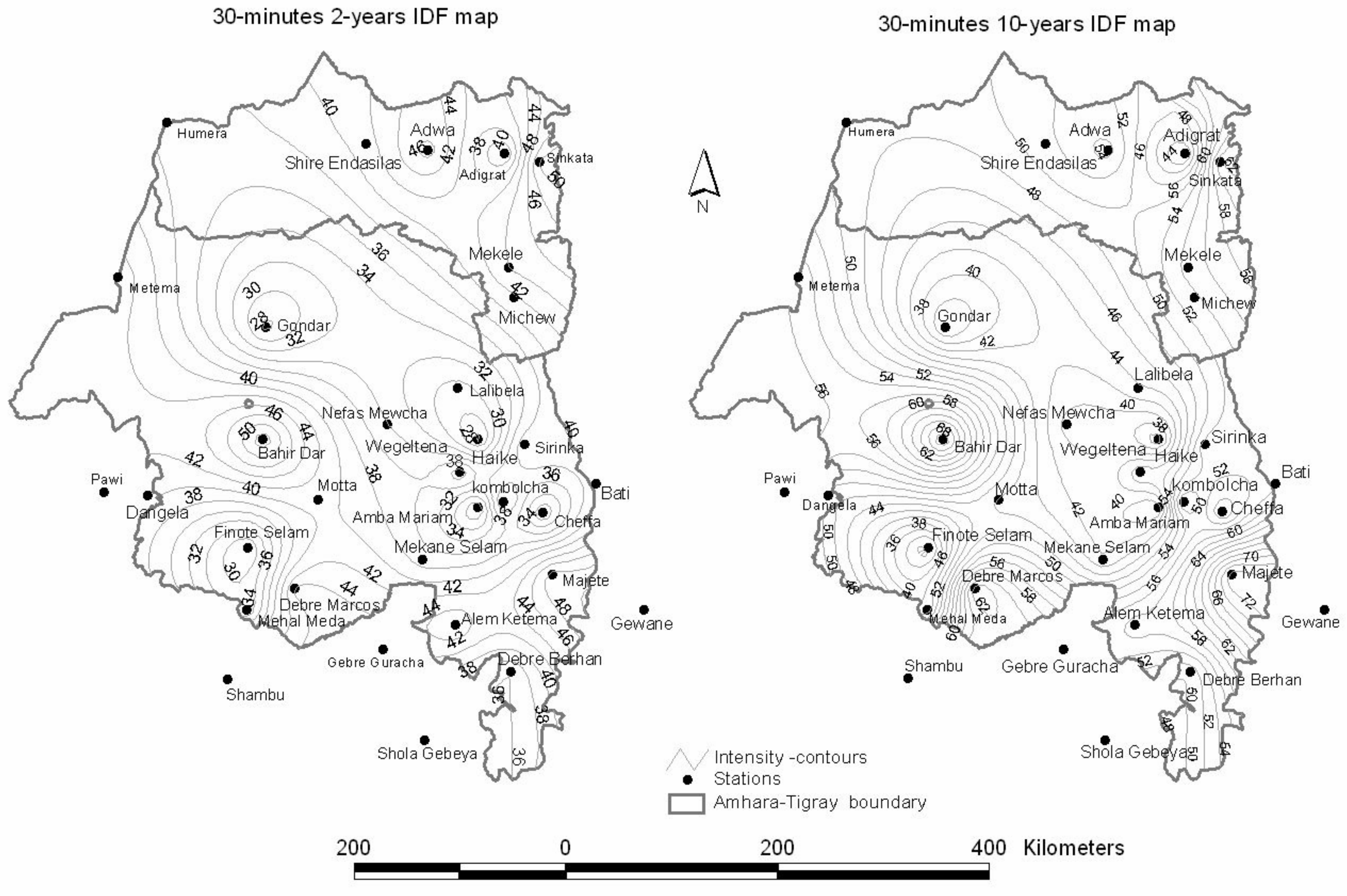
Station: Sirinka

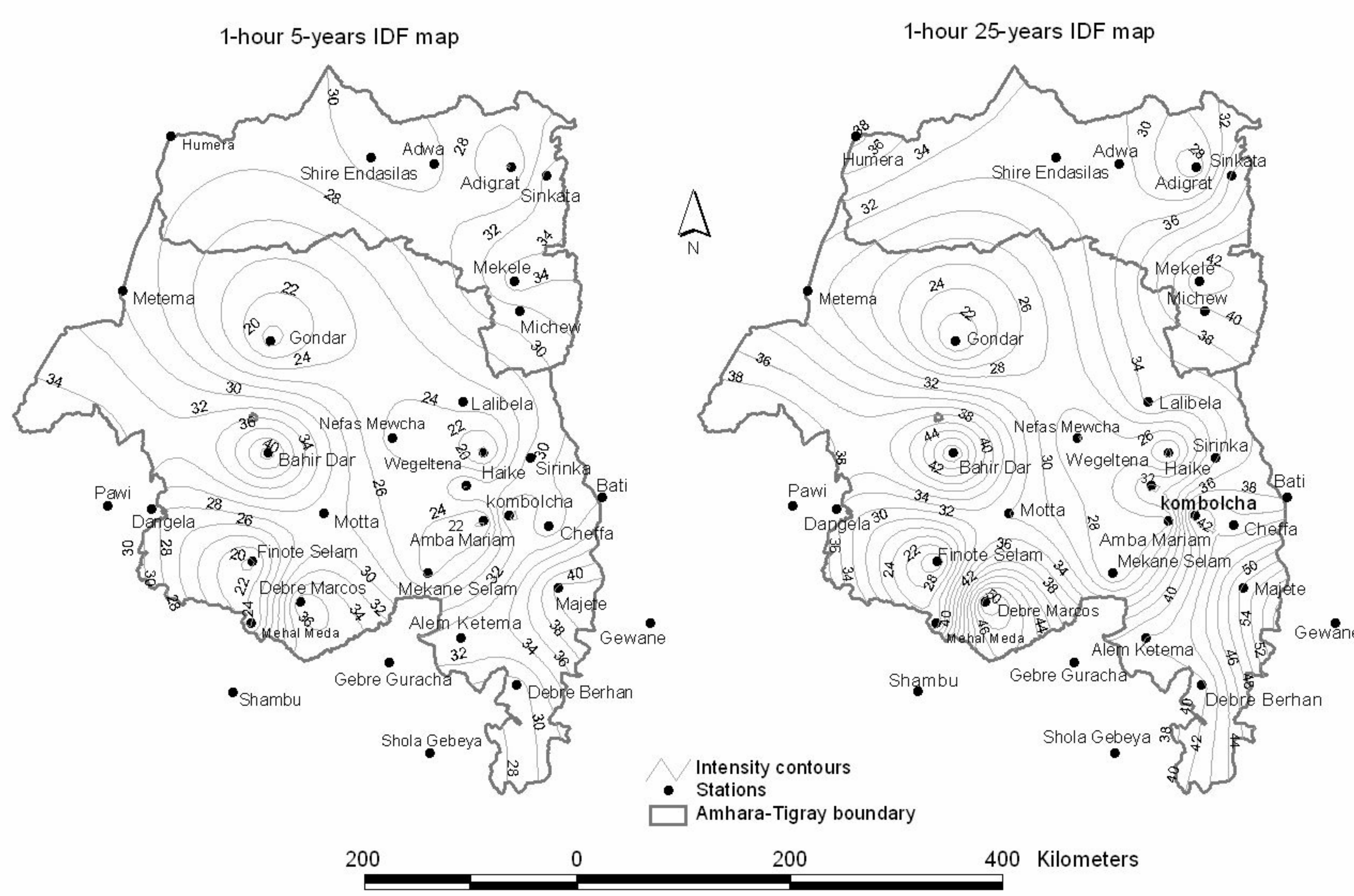


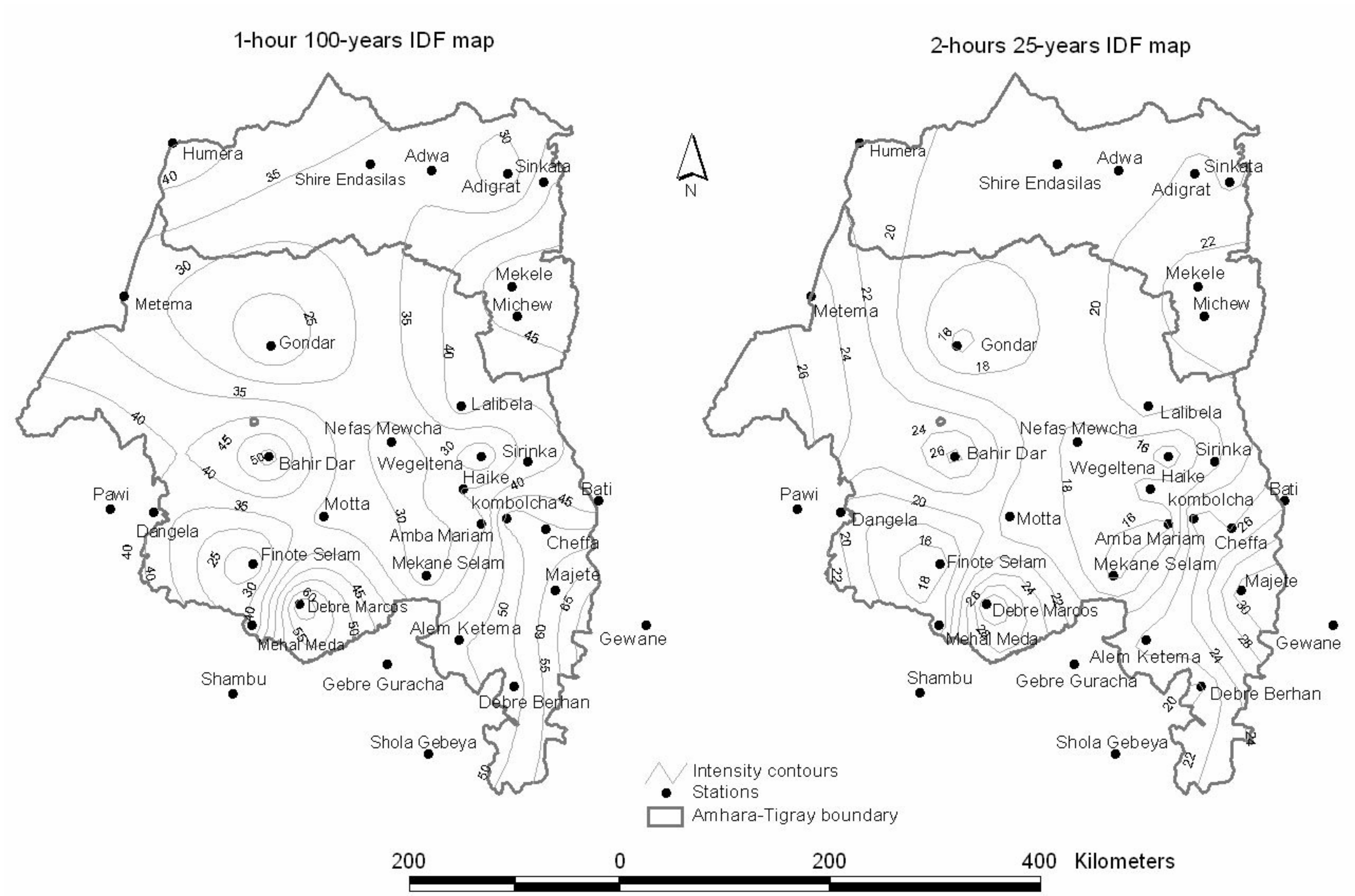
Station: Wegel Tena

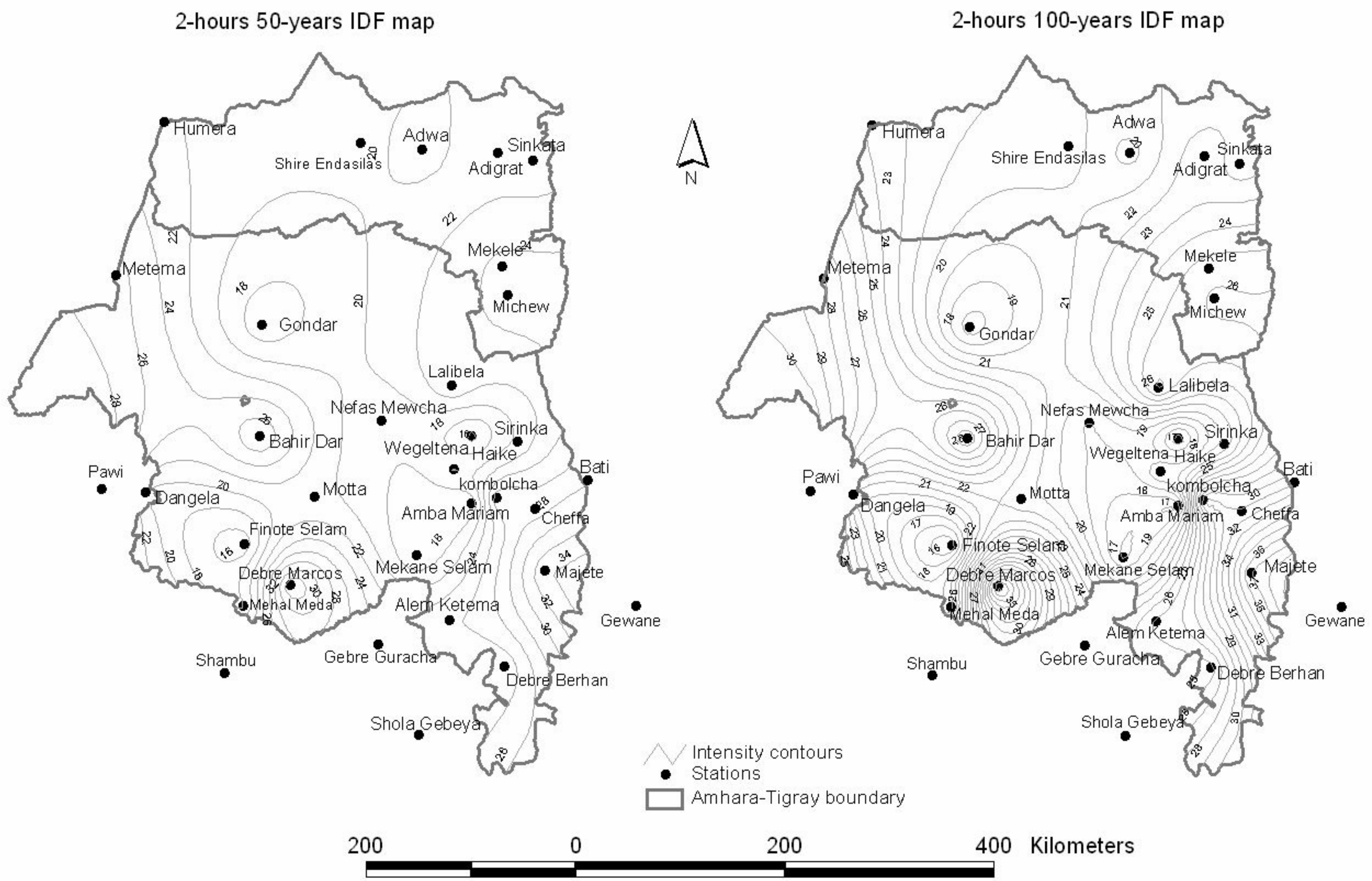


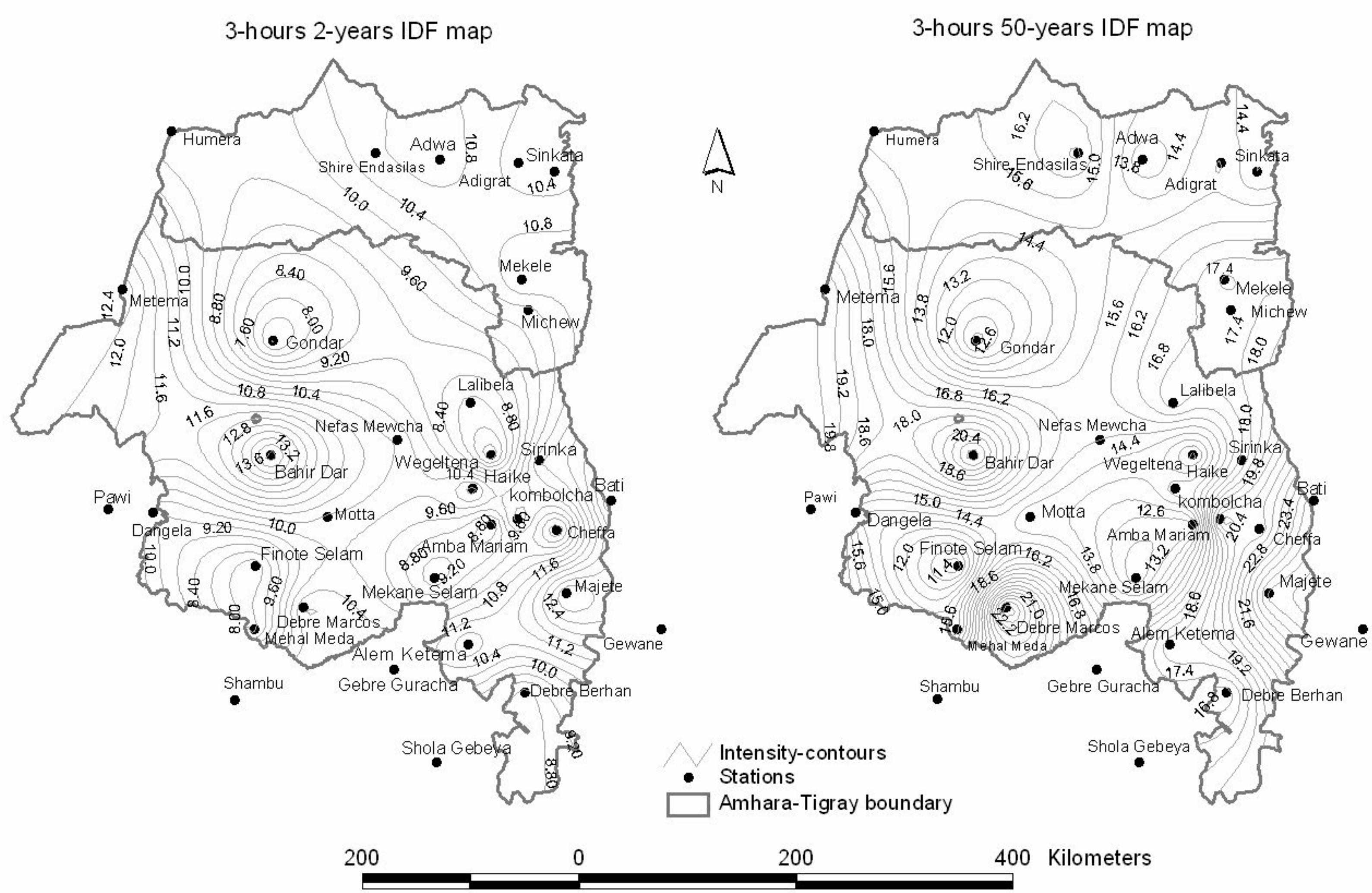
Appendix C: IDF maps for some durations and frequencies

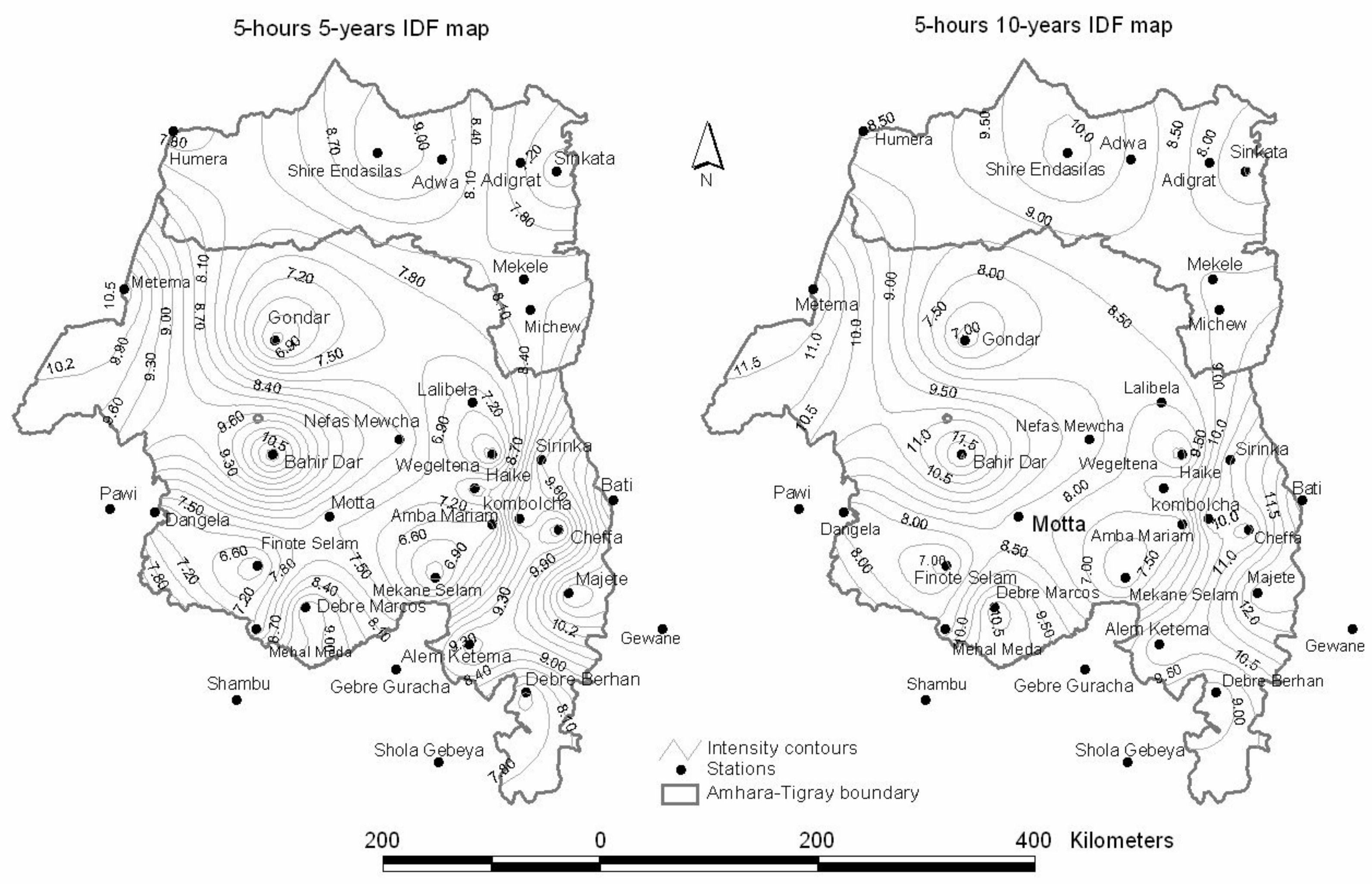


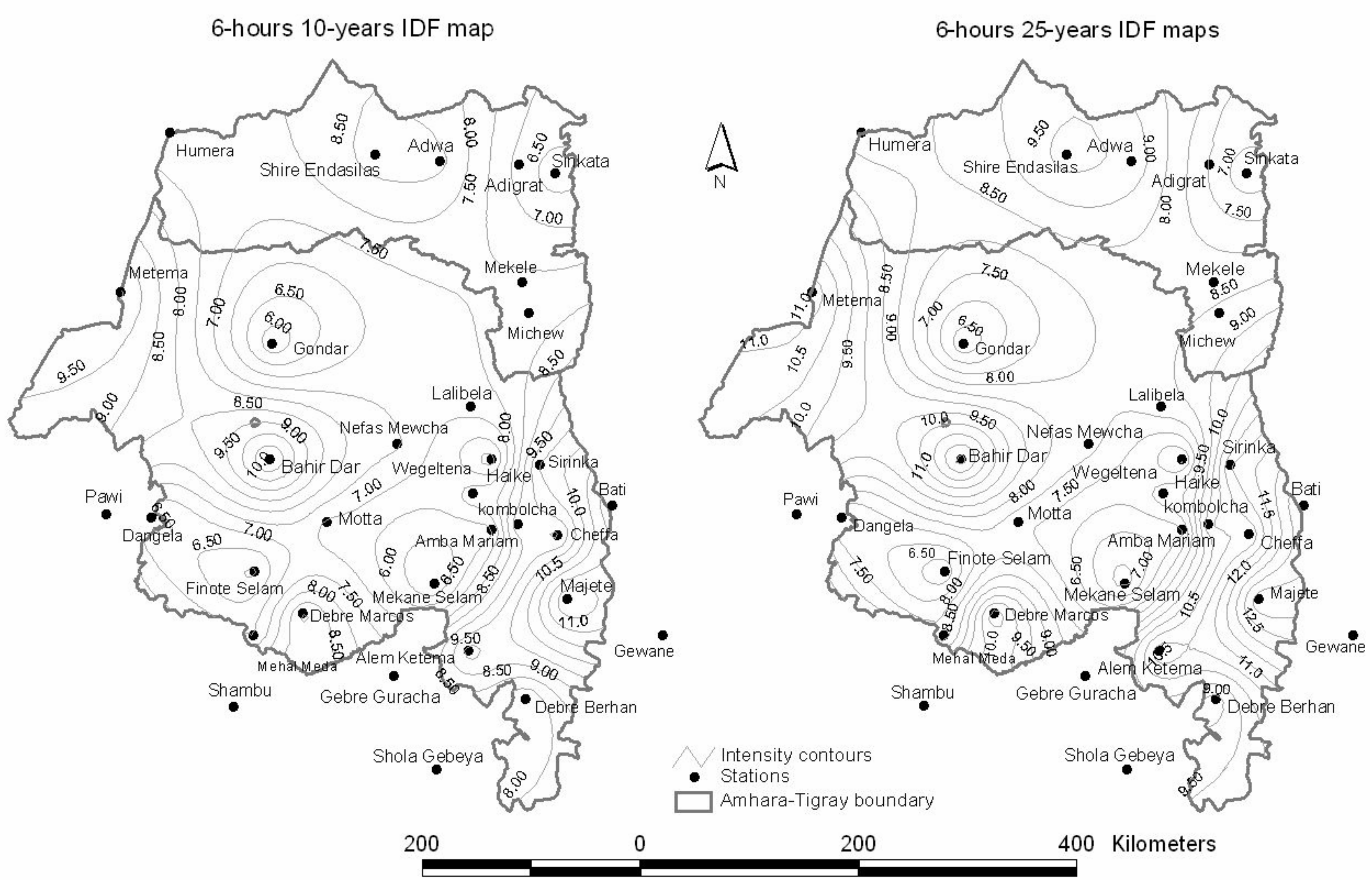

1-hour 5-years IDF map
1-hour 25-years IDF map
Humera
Adwa
Shire Endasilas
Adigrat
Sinkata
Mekele
Metema
Michew
Gondar
Lalibela
Nefas Mewcha
Bahir Dar
Wegeltena
Haike
Sirinka
Bati
Pawi
Dangela
kombolcha
Motta
Cheffa
Amba Mariam
Finote Selam
Debre Marcos
Mekane Selam
Majete
Mehal Meda
Alem Ketema
Gewane
Gebre Guracha
Shambu
Debre Berhan
Shola Gebeya
N
Intensity contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers

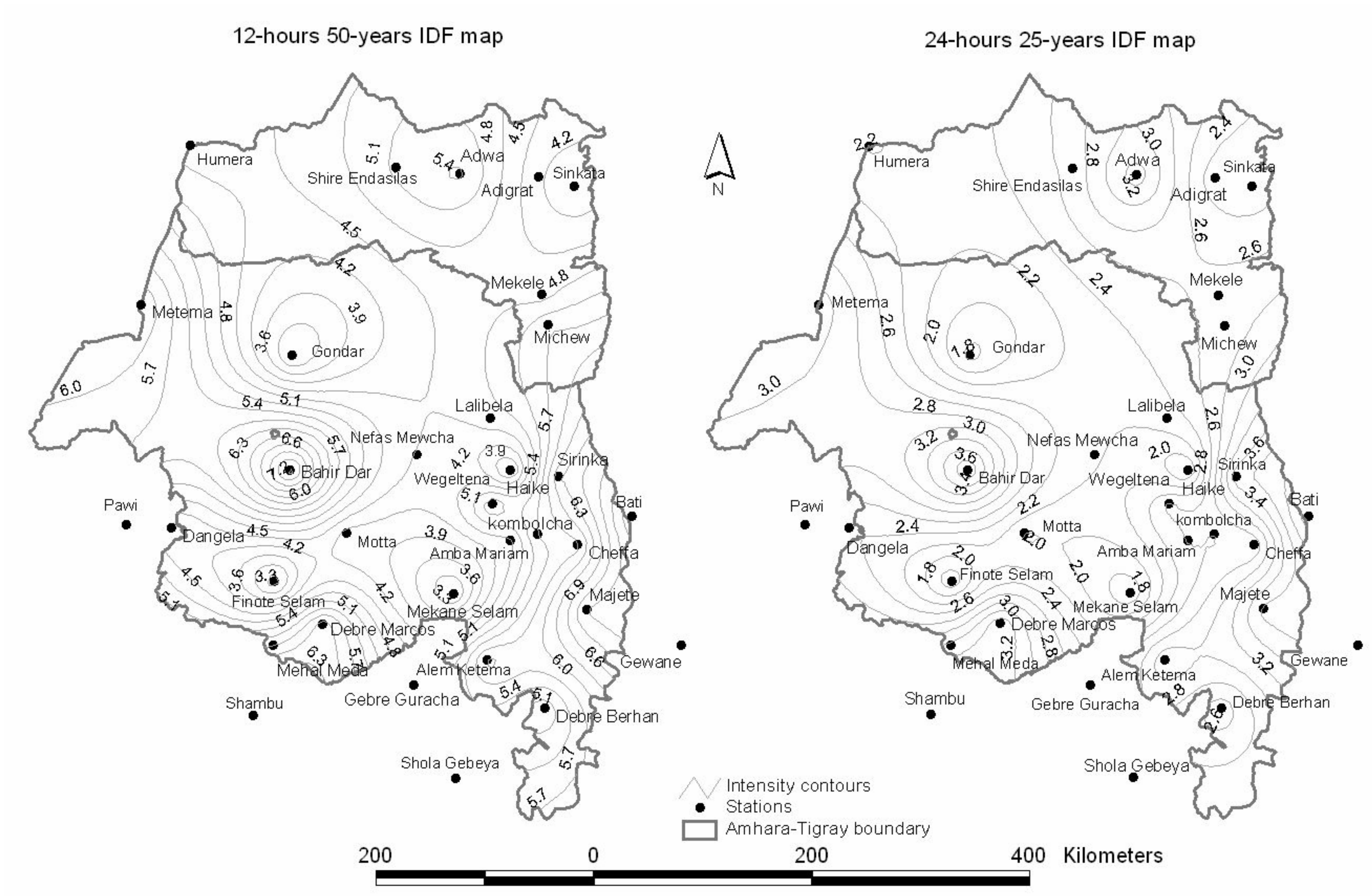

1-hour 100-years IDF map
2-hours 25-years IDF map
Humera
Shire Endasilas
Adwa
Adigrat
Sinkata
Mekele
Michew
Metema
Gondar
Lalibela
Nefas Mewcha
Bahir Dar
Wegeltena
Sirinka
Haike
kombolcha
Bati
Pawi
Dangela
Motta
Amba Mariam
Cheffa
Finote Selam
Mekane Selam
Majete
Debre Marcos
Mehal Meda
Alem Ketema
Gewane
Shambu
Gebre Guracha
Debre Berhan
Shola Gebeya
N
Intensity contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers

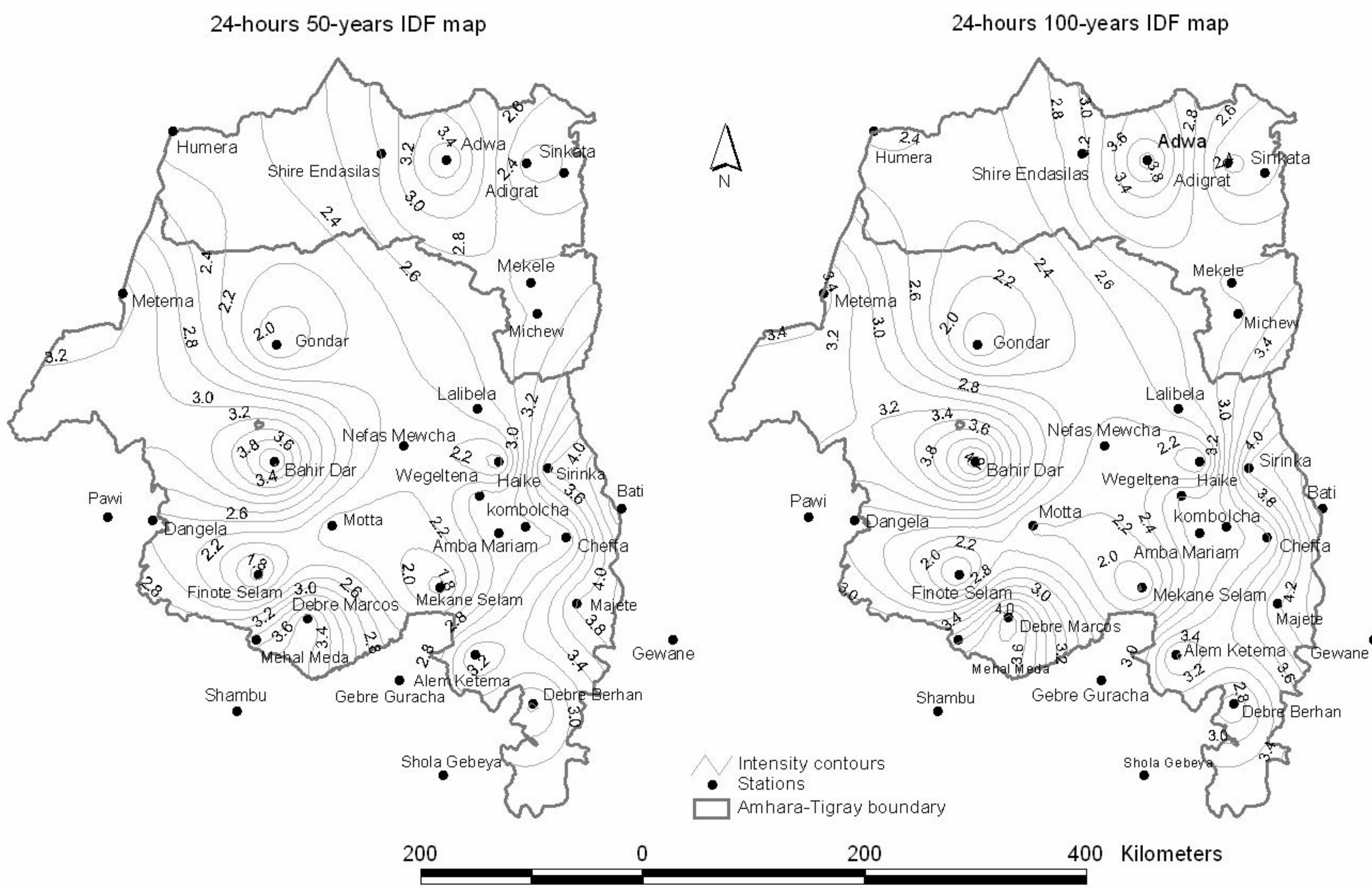

2-hours 50-years IDF map
2-hours 100-years IDF map
N
Humera
Shire Endasilas
Adwa
Sinkata
Adigrat
Mekele
Michew
Metema
Gondar
Lalibela
Nefas Mewcha
Bahir Dar
Sirinka
Wegeltena
Haike
Bati
Pawi
Dangela
Motta
kombolcha
Amba Mariam
Cheffa
Finote Selam
Debre Marcos
Mekane Selam
Majete
Mehal Meda
Alem Ketema
Gewane
Shambu
Gebre Guracha
Debre Berhan
Shola Gebeya
Intensity contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers


3-hours 2-years IDF map
3-hours 50-years IDF map
Humera
Shire Endasilas
Adwa
Adigrat
Sinkata
Mekele
Michew
Metema
Gondar
Lalibela
Nefas Mewcha
Sirinka
Bahir Dar
Wegeltena
Haike
kombolcha
Bati
Pawi
Dangela
Motta
Amba Mariam
Cheffa
Finote Selam
Mekane Selam
Majete
Debre Marcos
Mehal Meda
Alem Ketema
Gewane
Shambu
Gebre Guracha
Debre Berhan
Shola Gebeya
N
Intensity-contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers


5-hours 5-years IDF map
5-hours 10-years IDF map
N
Intensity contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers


6-hours 10-years IDF map
6-hours 25-years IDF maps
N
Humera
Shire Endasilas
Adwa
Adigrat
Sinkata
Mekele
Michew
Metema
Gondar
Lalibela
Nefas Mewcha
Bahir Dar
Wegeltena
Haike
Sirinka
Bati
Pawi
Dangela
Motta
kombolcha
Cheffa
Amba Mariam
Finote Selam
Mekane Selam
Majete
Debre Marcos
Mehal Meda
Alem Ketema
Gewane
Shambu
Gebre Guracha
Debre Berhan
Shola Gebeya
Intensity contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers


12-hours 50-years IDF map
24-hours 25-years IDF map
Humera
Shire Endasilas
Adwa
Adigrat
Sinkata
Mekele
Metema
Gondar
Michew
Lalibela
Nefas Mewcha
Bahir Dar
Wegeltena
Haike
Sirinka
Pawi
Bati
Dangela
Motta
kombolcha
Amba Mariam
Cheffa
Finote Selam
Mekane Selam
Majete
Debre Marcos
Mehal Meda
Gewane
Alem Ketema
Shambu
Gebre Guracha
Debre Berhan
Shola Gebeya
N
Intensity contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers


24-hours 50-years IDF map
24-hours 100-years IDF map
Humera
Shire Endasilas
Adwa
Sinkata
Adigrat
Mekele
Michew
Metema
Gondar
Lalibela
Nefas Mewcha
Bahir Dar
Wegeltena
Haike
Sirinka
Bati
Pawi
Dangela
Motta
kombolcha
Amba Mariam
Cheffa
Finote Selam
Debre Marcos
Mekane Selam
Majete
Mehal Meda
Gewane
Alem Ketema
Shambu
Gebre Guracha
Debre Berhan
Shola Gebeya
N
Intensity contours
Stations
Amhara-Tigray boundary
200 0 200 400 Kilometers

Appendix D: Estimated quantiles for the indicated durations and frequencies

Estimated Quantiles(mm) at Adigrat						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	17.64	19.6	20.35	20.93	21.2	21.37
60	24.4	25.45	25.73	25.89	25.93	25.95
120	28.64	34.04	37.24	40.95	43.48	45.94
180	30.49	36.18	39.41	43.04	45.46	47.77
300	32.93	37.9	40.91	44.74	47.56	50.37
360	33.34	37.91	40.93	44.75	47.58	50.39
720	36.51	42.11	45.24	48.73	51.04	53.23
1440	46.23	50.53	52.27	53.76	54.55	55.17

Estimated Quantiles(mm) at Adwa						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	23.51	26.08	27.49	29.05	30.08	31.04
60	28.23	30.59	31.86	33.23	34.13	34.96
120	30.76	33.62	35.18	36.9	38.02	39.07
180	33.29	35.98	37.29	38.61	39.41	40.12
300	39.58	44.48	47.01	49.66	51.33	52.87
360	41.01	47.98	51.93	56.36	59.31	62.12
720	45.2	52.99	57.4	62.34	65.63	68.77
1440	49.86	61.9	69.87	79.93	87.4	94.81

Estimated Quantiles(mm) at Alem Ketema						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	22.94	26.65	28.57	30.61	31.89	33.08
60	28.52	34.05	37.09	40.43	42.62	44.67
120	31.46	37.46	41.03	45.17	47.99	50.74
180	34.92	42.29	46.83	52.19	55.91	59.56
300	39.2	47.88	52.87	58.53	62.33	65.97
360	42.04	52.51	58.59	65.52	70.2	74.7
720	43.1	54.42	61.03	68.59	73.71	78.64
1440	46.65	59.97	67.8	76.78	82.88	88.77

Estimated Quantiles(mm) at Amba Mariam						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	13.48	16.65	18.49	20.59	22.02	23.38
60	17.17	21.05	23.62	26.86	29.27	31.66
120	21.81	25.53	27.63	29.98	31.55	33.04
180	24.88	29.1	31.49	34.17	35.96	37.67
300	29.28	33.22	35.17	37.16	38.39	39.49
360	30.19	34.94	37.64	40.67	42.7	44.64
720	33.88	41.01	45.09	49.68	52.76	55.7
1440	41.15	50.89	56.56	63.04	67.41	71.63

Estimated Quantiles(mm) at Bati						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	19.66	23.97	26.58	29.65	31.77	33.83
60	27.34	32.05	34.71	37.69	39.67	41.55
120	32.57	40.21	45.16	51.21	55.5	59.79
180	40.22	52.04	58.97	66.92	72.31	77.52
300	45.78	58.57	66.9	77.09	84.36	91.62
360	48.37	61.19	69.2	78.79	85.5	92.13
720	56.3	70.93	78.95	87.74	93.5	98.91
1440	64.03	79.87	89.1	99.65	106.79	113.67

Estimated Quantiles(mm) at Cheffa						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	14.73	20.33	23.73	27.72	30.46	33.15
60	19.55	27.98	33.55	40.6	45.82	51.01
120	21.56	31.89	38.73	47.38	53.79	60.16
180	24.46	35.65	43.07	52.43	59.38	66.28
300	27.88	40.05	48.11	58.29	65.84	73.34
360	29.8	41.64	49.48	59.38	66.73	74.02
720	41.83	52.72	57.28	61.13	66.74	74.04
1440	44.51	53.32	57.73	62.27	66.76	74.07

Estimated Quantiles(mm) at Dangla						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	20.21	22.82	24.34	26.09	27.27	28.4
60	23.62	28.08	30.61	33.44	35.33	37.13
120	28.14	32.36	34.73	37.38	39.14	40.8
180	28.64	34.1	37.21	40.73	43.09	45.34
300	28.9	34.42	37.58	41.14	43.52	45.8
360	28.9	35.42	37.58	41.14	43.52	45.8
720	35.44	41.38	44.37	47.46	49.38	51.12
1440	40.05	47.94	52.46	57.57	61	64.28

Estimated Quantiles(mm) at Debre Berhan						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	17.89	22.41	25.06	28.1	30.16	32.15
60	21.98	28.8	33.32	39.03	43.27	47.47
120	23.5	30.24	34.7	39.03	44.53	48.68
180	25.56	33.03	37.97	44.23	48.86	53.47
300	28.26	36.78	42.41	49.54	54.82	60.07
360	29.22	38.46	44.58	52.31	58.04	62.31
720	33.09	43.16	48.64	54.47	58.11	62.34
1440	41.76	51.59	55.59	58.9	60.51	62.39

Estimated Quantiles(mm) at Debre Markos						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	22.41	28.59	32.24	36.44	39.31	42.08
60	28.44	38.28	44.79	53.02	59.13	65.19
120	31.36	43.46	51.48	61.61	69.12	76.58
180	32.7	45.85	54.55	65.54	73.7	81.8
300	33.9	46.87	55.04	65.56	74.77	82.84
360	34.53	46.89	55.07	65.59	74.79	82.87
720	36.19	48.12	56.01	65.99	74.82	82.91
1440	43.64	58.87	68.96	81.7	91.16	100.54

Estimated Quantiles(mm) at Finote Selam						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	13.77	15.28	16.03	16.79	17.26	17.67
60	18.02	19.1	19.48	19.78	19.91	20
120	21.67	24.91	26.46	28.01	28.94	29.77
180	22.83	26.28	27.85	29.35	30.22	30.96
300	26.88	31.65	33.73	35.69	36.8	37.75
360	26.91	32.09	35.06	36.31	36.82	37.77
720	31.38	34.34	35.44	36.33	36.83	37.79
1440	33.27	36.69	37.93	38.85	39.25	39.51

Estimated Quantiles(mm) at Gebre Guracha						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	22.29	27.5	29.65	31.46	32.34	32.97
60	26.64	34.03	37.52	40.78	42.58	43.98
120	30.04	37.84	41.4	44.6	46.32	47.62
180	32.25	39.03	42.18	45.24	47.07	48.66
300	33.55	41.2	44.8	48.05	49.8	51.15
360	34.56	42.06	45.42	48.42	50.04	51.24
720	39.6	47.52	50.76	53.52	54.84	55.8
1440	45.6	52.8	55.2	57.12	57.84	58.32

Estimated Quantiles(mm) at Gewane						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	27.95	34.84	39.39	45.15	49.42	53.66
60	31.3	45.15	55.46	69.09	78.1	87.19
120	34.98	48.13	57.43	69.38	78.2	87.22
180	35.8	49.88	59.27	71.36	80.28	89.41
300	36.01	50.41	59.97	72.25	81.32	90.6
360	36.03	50.59	61.34	76.39	87.93	100.04
720	36.63	51.62	63.31	79.18	91.34	104.1
1440	42.98	62.16	74.86	90.91	102.81	114.63

Estimated Quantiles(mm) at Gondar						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	13.65	16.37	17.77	19.24	19.61	19.68
60	17.64	18.97	19.37	19.61	19.7	19.75
120	19.69	24.59	27.43	30.68	32.87	34.58
180	21.09	26.09	28.67	31.37	33.07	34.62
300	24.69	30.54	33.3	36.01	37.62	39.02
360	25.79	31.05	33.64	36.28	37.9	39.34
720	30.3	35.03	36.75	38.05	38.62	39.36
1440	31.8	37.17	39.39	41.25	42.41	42.8

Estimated Quantiles(mm) at Haike						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	19.94	21.99	23.12	24.37	25.18	25.95
60	25.02	28.67	30.72	33	34.51	35.95
120	29.48	33.84	36.29	39.02	40.82	42.54
180	33.53	37.91	40.34	43.04	44.83	46.51
300	35.25	40.23	43.01	46.1	48.15	50.09
360	36.54	41.43	44.23	47.39	49.51	51.54
720	48.21	54.73	58.38	62.43	65.11	67.65
1440	51.34	57.18	60.41	63.97	66.32	68.53

Estimated Quantiles(mm) at Humera						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	18.73	22.37	24.44	26.76	28.31	29.79
60	22.92	29.59	33.74	38.68	42.13	45.53
120	27.05	33.58	37.39	41.74	44.69	47.53
180	28.77	35.78	39.43	43.3	45.76	48.02
300	30.05	37.82	41.92	46.3	49.11	51.71
360	32.88	41.19	45.27	49.23	51.49	52.87
720	36.55	44.13	47.44	50.34	51.83	52.92
1440	38.29	45.44	48.87	52.26	54.31	56.11

Estimated Quantiles(mm) at Kombolcha						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	20.65	25.86	28.73	31.9	33.98	35.94
60	25.64	33.1	38.04	44.28	48.9	53.5
120	30.03	38.46	44.05	51.11	56.34	61.54
180	32.38	42.07	48.49	56.59	62.6	68.3
300	37.67	47.25	52.93	59.5	63.88	68.32
360	39.66	48.78	54.01	59.93	63.9	68.35
720	43.3	51.57	56.26	61.52	65.03	68.37
1440	46.7	54.28	58.14	62.14	65.07	68.41

Estimated Quantiles(mm) at Lalibela						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	14.54	18.94	21.85	25.53	28.26	30.97
60	18.5	24.9	29.13	34.48	38.44	42.38
120	21.95	30.19	35.64	42.53	47.65	52.72
180	24.67	33.67	39.62	46.62	51.58	56.49
300	26.72	34.7	39.99	46.66	51.61	56.53
360	28.36	37.66	43.21	49.64	54.03	58.3
720	31.27	40.67	46.03	52.07	56.11	59.97
1440	32.18	42.53	48.55	55.4	60.02	64.47

Estimated Quantiles(mm) at Majete						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	24.69	32.12	37.04	43.26	47.87	52.44
60	32.52	40.95	45.61	50.75	54.12	57.31
120	38.88	49.51	55.74	62.88	67.72	72.39
180	40.21	52.04	59.54	68.58	74.94	81.26
300	45.32	57.54	65.1	74.07	80.32	86.47
360	51.06	65.17	72.91	80.6	85.46	89.98
720	51.09	65.19	72.94	81.44	87.01	92.25
1440	62.27	75.22	81.64	88.18	92.2	95.82

Estimated Quantiles(mm) at Mehal Meda						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	14.92	18.07	19.87	21.91	23.28	24.59
60	17.15	21.1	23.38	25.96	27.7	29.37
120	20.36	25.03	28.12	32.02	34.92	37.8
180	23.34	29.15	32.99	37.85	41.46	45.04
300	28.25	35.96	40.38	45.36	48.7	51.54
360	30.36	37.6	41.58	45.97	48.85	51.57
720	35.39	46.94	54.14	62.72	68.71	74.62
1440	43.28	56.51	64.37	73.46	79.67	85.69

Estimated Quantiles(mm) at Mekane Selam						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	18.52	20.2	21.12	22.13	22.79	23.41
60	21.1	23.4	24.55	25.74	26.47	27.14
120	23.49	26.93	28.79	30.81	32.12	33.34
180	25.43	29.23	31.16	33.17	34.43	35.58
300	26.37	30.39	32.38	34.17	35.21	36.14
360	26.82	30.64	32.43	34.19	35.24	36.15
720	28.81	31.74	33.13	34.51	35.33	36.42
1440	30.15	34.06	36.23	38.63	40.21	41.71

Estimated Quantiles(mm) at Mekele						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	22.01	25.58	27.43	29.36	30.59	31.7
60	28.15	35.14	39.21	43.88	47.04	50.08
120	32.85	39.97	43.5	47.1	49.32	51.32
180	33.75	41.57	45.48	49.91	52.85	55.51
300	34.73	41.59	45.51	49.92	52.88	55.7
360	34.95	41.8	45.7	50.1	53.05	55.86
720	37.32	44.79	48.84	53.26	56.13	58.83
1440	40.85	51.19	57.21	64.07	68.71	73.17

Estimated Quantiles(mm) at Metema						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	21.73	26.12	27.77	29.04	29.62	30
60	29.26	29.9	30.25	30.61	30.85	31.07
120	36.48	43.01	46.71	50.86	53.63	56.27
180	38.31	46.32	50.9	56.09	59.57	62.89
300	42.17	53.67	60.41	68.13	73.37	78.43
360	42.4	53.88	60.6	68.31	73.54	78.58
720	43.32	55.17	62.12	70.1	75.51	80.73
1440	51.97	62.3	68.23	74.93	79.43	83.74

Estimated Quantiles(mm) at Michew						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	20.81	24.62	26.75	29.11	30.67	32.15
60	25.08	31	34.79	39.38	42.64	45.87
120	28.81	36.34	40.72	45.73	49.11	52.36
180	30.67	38.16	42.5	47.42	50.73	53.92
300	34.65	41.48	45.37	49.74	52.66	55.45
360	35.53	41.92	46.15	51.49	55.46	59.39
720	41.19	50.18	55.23	60.84	64.56	68.09
1440	46.44	54.49	59.04	64.14	67.54	70.77

Estimated Quantiles(mm) at Motta						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	20.3	21.87	22.72	23.65	24.25	24.82
60	26.03	28.72	30.2	31.83	32.9	33.91
120	29.72	34.02	36.42	39.11	40.88	42.51
180	30.81	34.78	36.98	39.41	41.02	42.53
300	32.83	37.7	40.92	44.99	48.01	51.01
360	32.97	37.92	41.2	45.34	48.41	51.46
720	33.16	38.08	41.34	45.45	48.51	51.54
1440	36.89	41.64	44.28	47.22	49.15	51.57

Estimated Quantiles(mm) at Nefas Mewcha						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	17.04	18.66	19.55	20.53	21.17	21.77
60	21.01	23.2	24.41	25.74	26.61	27.43
120	25.63	29.64	31.9	34.41	36.08	37.66
180	31.04	36.36	39.37	42.75	44.99	47.13
300	35.14	40.94	44.21	47.87	50.31	52.62
360	35.95	41.98	45.38	49.2	51.73	54.14
720	42.51	46.9	49.32	51.98	53.72	55.37
1440	46.88	49.93	51.57	53.36	54.52	55.61

Estimated Quantiles(mm) at Pawi						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	20.86	26.55	30.1	34.32	37.27	40.19
60	30.92	38.68	42.64	46.78	49.38	51.75
120	35.65	46.63	53.19	60.81	66.03	71.11
180	36.22	47.32	53.92	61.56	66.78	71.85
300	39.94	49.02	54.02	61.58	66.8	71.87
360	40.31	49.15	54.07	61.61	67.11	71.9
720	43.23	51.05	55.2	61.64	67.15	71.92
1440	47.08	56.79	61.99	67.59	71.2	74.57

Estimated Quantiles(mm) at Shambu						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	26.23	32.74	36.64	41.17	44.27	47.29
60	31.92	40.91	46.19	52.26	56.38	60.37
120	36.11	43.31	48.08	54.11	58.58	63.02
180	38.12	47.49	52.96	59.22	63.46	67.56
300	41.51	54.62	62.38	71.35	77.46	83.38
360	41.68	56.05	65.41	76.87	85.05	93.23
720	48.65	63.88	73.52	85.13	93.3	101.39
1440	55.65	69.46	78.61	90.16	98.73	107.24

Estimated Quantiles(mm) at Shire Endasilase						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	20.47	23.79	25.67	27.77	29.16	30.49
60	26.82	30.78	32.28	33.45	33.99	34.35
120	29.86	34.83	37.37	40.03	41.7	43.22
180	32.24	39.51	43.57	48.07	51.05	53.88
300	36.94	46.55	51.85	57.69	61.52	65.14
360	37.41	47.06	52.41	58.32	61.79	65.9
720	40.96	49.96	54.43	59.01	61.83	65.94
1440	44.42	54.35	59.19	64.05	67.01	69.64

Estimated Quantiles(mm) at Shola Gebeya						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	15.69	19.77	21.56	23.13	23.94	24.54
60	18.15	23.99	27.86	32.74	36.37	39.96
120	21.84	29.45	34.49	40.86	45.58	50.26
180	25.35	34.33	40.27	47.78	53.35	58.87
300	28.67	39.52	46.27	54.32	59.93	65.47
360	30.02	41.03	47.62	55.29	60.54	65.65
720	34.68	46.45	53.44	61.52	67.04	72.4
1440	41.13	55.12	63.31	72.68	79.02	85.15

Estimated Quantiles(mm) at Sinkata						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	25.52	29.14	31.17	33.41	34.9	36.31
60	28.83	32.8	34.77	36.8	38.04	39.16
120	30.12	34.44	36.83	39.29	40.87	42.37
180	30.44	34.58	36.84	39.31	40.91	42.42
300	30.7	34.82	37.03	39.43	40.97	42.42
360	30.77	34.97	37.25	39.72	41.32	42.82
720	34.88	40.06	42.59	45.15	46.71	48.11
1440	37.93	45.48	49.8	54.68	57.95	61.08

Estimated Quantiles(mm) at Sirinka						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	20.08	24.44	26.83	29.45	31.16	32.77
60	24.92	29.18	31.5	34.02	35.66	37.2
120	29.84	34.09	36.47	39.12	40.88	42.55
180	33.64	40.23	43.98	48.22	51.05	53.76
300	39.64	48.1	52.97	58.5	62.21	65.78
360	40.91	51.09	57.82	66.34	72.65	78.92
720	47.94	58.28	64.21	70.93	75.45	79.77
1440	52.76	66.83	75.33	85.28	92.14	98.82

Estimated Quantiles(mm) at Wegel Tena						
Duration (minutes)	Estimated quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	12.43	15.39	17.11	19.07	20.39	21.66
60	15.71	18.84	20.63	22.65	24.01	25.3
120	18.94	23.15	25.59	28.37	30.24	32.04
180	21.31	26.12	29.31	33.34	36.33	39.29
300	24.08	30.02	33.31	36.95	39.34	41.6
360	24.55	30.59	33.97	37.73	40.22	42.58
720	26.16	32.02	35.32	39	41.45	43.78
1440	29.25	35.08	38.21	41.6	43.79	45.83

Appendix E: Intensity of rainfall for the indicated durations and frequencies

Intensity of rainfall(mm/hr) at Adigrat						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	35.28	39.20	40.70	41.86	42.40	42.74
60	24.40	25.45	25.73	25.89	25.93	25.95
120	14.32	17.02	18.62	20.48	21.74	22.97
180	10.16	12.06	13.14	14.35	15.15	15.92
300	6.59	7.58	8.18	8.95	9.51	10.07
360	5.56	6.32	6.82	7.46	7.93	8.40
720	3.04	3.51	3.77	4.06	4.25	4.44
1440	1.93	2.11	2.18	2.24	2.27	2.30

Intensity of rainfall(mm/hr) at Adwa						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	47.02	52.16	54.98	58.10	60.16	62.08
60	28.23	30.59	31.86	33.23	34.13	34.96
120	15.38	16.81	17.59	18.45	19.01	19.54
180	11.10	11.99	12.43	12.87	13.14	13.37
300	7.92	8.90	9.40	9.93	10.27	10.57
360	6.84	8.00	8.66	9.39	9.89	10.35
720	3.77	4.42	4.78	5.20	5.47	5.73
1440	2.08	2.58	2.91	3.33	3.64	3.95

Intensity of rainfall(mm/hr) at Alem Ketema						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	45.88	53.30	57.14	61.22	63.78	66.16
60	28.52	34.05	37.09	40.43	42.62	44.67
120	15.73	18.73	20.52	22.59	24.00	25.37
180	11.64	14.10	15.61	17.40	18.64	19.85
300	7.84	9.58	10.57	11.71	12.47	13.19
360	7.01	8.75	9.77	10.92	11.70	12.45
720	3.59	4.54	5.09	5.72	6.14	6.55
1440	1.94	2.50	2.83	3.20	3.45	3.70

Intensity of rainfall(mm/hr) at Amba Mariam						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	26.96	33.30	36.98	41.18	44.04	46.76
60	17.17	21.05	23.62	26.86	29.27	31.66
120	10.91	12.77	13.82	14.99	15.78	16.52
180	8.29	9.70	10.50	11.39	11.99	12.56
300	5.86	6.64	7.03	7.43	7.68	7.90
360	5.03	5.82	6.27	6.78	7.12	7.44
720	2.82	3.42	3.76	4.14	4.40	4.64
1440	1.71	2.12	2.36	2.63	2.81	2.98

Intensity of rainfall(mm/hr) at Bati						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	39.32	47.94	53.16	59.30	63.54	67.66
60	27.34	32.05	34.71	37.69	39.67	41.55
120	16.29	20.11	22.58	25.61	27.75	29.90
180	13.41	17.35	19.66	22.31	24.10	25.84
300	9.16	11.71	13.38	15.42	16.87	18.32
360	8.06	10.20	11.53	13.13	14.25	15.36
720	4.69	5.91	6.58	7.31	7.79	8.24
1440	2.67	3.33	3.71	4.15	4.45	4.74

Intensity of rainfall(mm/hr) at Cheffa						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	29.46	40.66	47.46	55.44	60.92	66.30
60	19.55	27.98	33.55	40.60	45.82	51.01
120	10.78	15.95	19.37	23.69	26.90	30.08
180	8.15	11.88	14.36	17.48	19.79	22.09
300	5.58	8.01	9.62	11.66	13.17	14.67
360	4.97	6.94	8.25	9.90	11.12	12.34
720	3.49	4.39	4.77	5.09	5.56	6.17
1440	1.85	2.22	2.41	2.59	2.78	3.09

Intensity of rainfall(mm/hr) at Dangla						
Duration	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
(minutes)	2	5	10	25	50	100
30	40.42	45.64	48.68	52.18	54.54	56.80
60	23.62	28.08	30.61	33.44	35.33	37.13
120	14.07	16.18	17.37	18.69	19.57	20.40
180	9.55	11.37	12.40	13.58	14.36	15.11
300	5.78	6.88	7.52	8.23	8.70	9.16
360	4.82	5.90	6.26	6.86	7.25	7.63
720	2.95	3.45	3.70	3.96	4.12	4.26
1440	1.67	2.00	2.19	2.40	2.54	2.68

Intensity of rainfall(mm/hr) at Debre Berhan						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	35.78	44.82	50.12	56.20	60.32	64.30
60	21.98	28.80	33.32	39.03	43.27	47.47
120	11.75	15.12	17.35	19.52	22.27	24.34
180	8.52	11.01	12.66	14.74	16.29	17.82
300	5.65	7.36	8.48	9.91	10.96	12.01
360	4.87	6.41	7.43	8.72	9.67	10.39
720	2.76	3.60	4.05	4.54	4.84	5.20
1440	1.74	2.15	2.32	2.45	2.52	2.60

Intensity of rainfall(mm/hr) at Debre Markos						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	44.82	57.18	64.48	72.88	78.62	84.16
60	28.44	38.28	44.79	53.02	59.13	65.19
120	15.68	21.73	25.74	30.81	34.56	38.29
180	10.90	15.28	18.18	21.85	24.57	27.27
300	6.78	9.37	11.01	13.11	14.95	16.57
360	5.76	7.82	9.18	10.93	12.47	13.81
720	3.02	4.01	4.67	5.50	6.24	6.91
1440	1.82	2.45	2.87	3.40	3.80	4.19

Intensity of rainfall(mm/hr) at Finote Selam						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	27.54	30.56	32.06	33.58	34.52	35.34
60	18.02	19.10	19.48	19.78	19.91	20.00
120	10.84	12.46	13.23	14.01	14.47	14.89
180	7.61	8.76	9.28	9.78	10.07	10.32
300	5.38	6.33	6.75	7.14	7.36	7.55
360	4.49	5.35	5.84	6.05	6.14	6.30
720	2.62	2.86	2.95	3.03	3.07	3.15
1440	1.39	1.53	1.58	1.62	1.64	1.65

Intensity of rainfall(mm/hr) at Gebre Guracha						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	44.58	55	59.3	62.92	64.68	65.94
60	26.64	34.03	37.52	40.78	42.58	43.98
120	15.02	18.92	20.7	22.3	23.16	23.81
180	10.75	13.01	14.06	15.08	15.69	16.22
300	6.71	8.24	8.96	9.61	9.96	10.23
360	5.76	7.01	7.57	8.07	8.34	8.54
720	3.3	3.96	4.23	4.46	4.57	4.65
1440	1.9	2.2	2.3	2.38	2.41	2.43

Intensity of rainfall(mm/hr) at Gewane						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	55.90	69.68	78.78	90.30	98.84	107.32
60	31.30	45.15	55.46	69.09	78.10	87.19
120	17.49	24.07	28.72	34.69	39.10	43.61
180	11.93	16.63	19.76	23.79	26.76	29.80
300	7.20	10.08	11.99	14.45	16.26	18.12
360	6.01	8.43	10.22	12.73	14.66	16.67
720	3.05	4.30	5.28	6.60	7.61	8.68
1440	1.79	2.59	3.12	3.79	4.28	4.78

Intensity of rainfall(mm/hr) at Gondar						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	27.30	32.74	35.54	38.48	39.22	39.36
60	17.64	18.97	19.37	19.61	19.70	19.75
120	9.85	12.30	13.72	15.34	16.44	17.29
180	7.03	8.70	9.56	10.46	11.02	11.54
300	4.94	6.11	6.66	7.20	7.52	7.80
360	4.30	5.18	5.61	6.05	6.32	6.56
720	2.53	2.92	3.06	3.17	3.22	3.28
1440	1.33	1.55	1.64	1.72	1.77	1.78

Intensity of rainfall(mm/hr) at Haike						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	39.88	43.98	46.24	48.74	50.36	51.90
60	25.02	28.67	30.72	33.00	34.51	35.95
120	14.74	16.92	18.15	19.51	20.41	21.27
180	11.18	12.64	13.45	14.35	14.94	15.50
300	7.05	8.05	8.60	9.22	9.63	10.02
360	6.09	6.91	7.37	7.90	8.25	8.59
720	4.02	4.56	4.87	5.20	5.43	5.64
1440	2.14	2.38	2.52	2.67	2.76	2.86

Intensity of rainfall(mm/hr) at Humera						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	37.46	44.74	48.88	53.52	56.62	59.58
60	22.92	29.59	33.74	38.68	42.13	45.53
120	13.53	16.79	18.70	20.87	22.35	23.77
180	9.59	11.93	13.14	14.43	15.25	16.01
300	6.01	7.56	8.38	9.26	9.82	10.34
360	5.48	6.87	7.55	8.21	8.58	8.81
720	3.05	3.68	3.95	4.20	4.32	4.41
1440	1.60	1.89	2.04	2.18	2.26	2.34

Intensity of rainfall(mm/hr) at Kombolcha						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	41.30	51.72	57.46	63.80	67.96	71.88
60	25.64	33.10	38.04	44.28	48.90	53.50
120	15.02	19.23	22.03	25.56	28.17	30.77
180	10.79	14.02	16.16	18.86	20.87	22.77
300	7.53	9.45	10.59	11.90	12.78	13.66
360	6.61	8.13	9.00	9.99	10.65	11.39
720	3.61	4.30	4.69	5.13	5.42	5.70
1440	1.95	2.26	2.42	2.59	2.71	2.85

Intensity of rainfall(mm/hr) at Lalibela						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	29.08	37.88	43.70	51.06	56.52	61.94
60	18.50	24.90	29.13	34.48	38.44	42.38
120	10.98	15.10	17.82	21.27	23.83	26.36
180	8.22	11.22	13.21	15.54	17.19	18.83
300	5.34	6.94	8.00	9.33	10.32	11.31
360	4.73	6.28	7.20	8.27	9.01	9.72
720	2.61	3.39	3.84	4.34	4.68	5.00
1440	1.34	1.77	2.02	2.31	2.50	2.69

Intensity of rainfall(mm/hr) at Majete						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	49.38	64.24	74.08	86.52	95.74	104.88
60	32.52	40.95	45.61	50.75	54.12	57.31
120	19.44	24.76	27.87	31.44	33.86	36.20
180	13.40	17.35	19.85	22.86	24.98	27.09
300	9.06	11.51	13.02	14.81	16.06	17.29
360	8.51	10.86	12.15	13.43	14.24	15.00
720	4.26	5.43	6.08	6.79	7.25	7.69
1440	2.59	3.13	3.40	3.67	3.84	3.99

Intensity of rainfall(mm/hr) at Mehal Meda						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	29.84	36.14	39.74	43.82	46.56	49.18
60	17.15	21.10	23.38	25.96	27.70	29.37
120	10.18	12.52	14.06	16.01	17.46	18.90
180	7.78	9.72	11.00	12.62	13.82	15.01
300	5.65	7.19	8.08	9.07	9.74	10.31
360	5.06	6.27	6.93	7.66	8.14	8.60
720	2.95	3.91	4.51	5.23	5.73	6.22
1440	1.80	2.35	2.68	3.06	3.32	3.57

Intensity of rainfall(mm/hr) at Mekane Selam						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	37.04	40.40	42.24	44.26	45.58	46.82
60	21.10	23.40	24.55	25.74	26.47	27.14
120	11.75	13.47	14.40	15.41	16.06	16.67
180	8.48	9.74	10.39	11.06	11.48	11.86
300	5.27	6.08	6.48	6.83	7.04	7.23
360	4.47	5.11	5.41	5.70	5.87	6.03
720	2.40	2.65	2.76	2.88	2.94	3.04
1440	1.26	1.42	1.51	1.61	1.68	1.74

Intensity of rainfall(mm/hr) at Mekele						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	44.02	51.16	54.86	58.72	61.18	63.40
60	28.15	35.14	39.21	43.88	47.04	50.08
120	16.43	19.99	21.75	23.55	24.66	25.66
180	11.25	13.86	15.16	16.64	17.62	18.50
300	6.95	8.32	9.10	9.98	10.58	11.14
360	5.83	6.97	7.62	8.35	8.84	9.31
720	3.11	3.73	4.07	4.44	4.68	4.90
1440	1.70	2.13	2.38	2.67	2.86	3.05

Intensity of rainfall(mm/hr) at Metema						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	43.46	52.24	55.54	58.08	59.24	60.00
60	29.26	29.90	30.25	30.61	30.85	31.07
120	18.24	21.51	23.36	25.43	26.82	28.14
180	12.77	15.44	16.97	18.70	19.86	20.96
300	8.43	10.73	12.08	13.63	14.67	15.69
360	7.07	8.98	10.10	11.39	12.26	13.10
720	3.61	4.60	5.18	5.84	6.29	6.73
1440	2.17	2.60	2.84	3.12	3.31	3.49

Intensity of rainfall(mm/hr) at Michew						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	41.62	49.24	53.50	58.22	61.34	64.30
60	25.08	31.00	34.79	39.38	42.64	45.87
120	14.41	18.17	20.36	22.87	24.56	26.18
180	10.22	12.72	14.17	15.81	16.91	17.97
300	6.93	8.30	9.07	9.95	10.53	11.09
360	5.92	6.99	7.69	8.58	9.24	9.90
720	3.43	4.18	4.60	5.07	5.38	5.67
1440	1.94	2.27	2.46	2.67	2.81	2.95

Intensity of rainfall(mm/hr) at Motta						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	40.60	43.74	45.44	47.30	48.50	49.64
60	26.03	28.72	30.20	31.83	32.90	33.91
120	14.86	17.01	18.21	19.56	20.44	21.26
180	10.27	11.59	12.33	13.14	13.67	14.18
300	6.57	7.54	8.18	9.00	9.60	10.20
360	5.50	6.32	6.87	7.56	8.07	8.58
720	2.76	3.17	3.45	3.79	4.04	4.30
1440	1.54	1.74	1.85	1.97	2.05	2.15

Intensity of rainfall(mm/hr) at Nefas Mewcha						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	34.08	37.32	39.10	41.06	42.34	43.54
60	21.01	23.20	24.41	25.74	26.61	27.43
120	12.82	14.82	15.95	17.21	18.04	18.83
180	10.35	12.12	13.12	14.25	15.00	15.71
300	7.03	8.19	8.84	9.57	10.06	10.52
360	5.99	7.00	7.56	8.20	8.62	9.02
720	3.54	3.91	4.11	4.33	4.48	4.61
1440	1.95	2.08	2.15	2.22	2.27	2.32

Intensity of rainfall(mm/hr) at Pawi						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	41.72	53.10	60.20	68.64	74.54	80.38
60	30.92	38.68	42.64	46.78	49.38	51.75
120	17.83	23.32	26.60	30.41	33.02	35.56
180	12.07	15.77	17.97	20.52	22.26	23.95
300	7.99	9.80	10.80	12.32	13.36	14.37
360	6.72	8.19	9.01	10.27	11.19	11.98
720	3.60	4.25	4.60	5.14	5.60	5.99
1440	1.96	2.37	2.58	2.82	2.97	3.11

Intensity of rainfall(mm/hr) at Shambu						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	52.46	65.48	73.28	82.34	88.54	94.58
60	31.92	40.91	46.19	52.26	56.38	60.37
120	18.06	21.66	24.04	27.06	29.29	31.51
180	12.71	15.83	17.65	19.74	21.15	22.52
300	8.30	10.92	12.48	14.27	15.49	16.68
360	6.95	9.34	10.90	12.81	14.18	15.54
720	4.05	5.32	6.13	7.09	7.78	8.45
1440	2.32	2.89	3.28	3.76	4.11	4.47

Intensity of rainfall(mm/hr) at Shire Endasilase						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	40.94	47.58	51.34	55.54	58.32	60.98
60	26.82	30.78	32.28	33.45	33.99	34.35
120	14.93	17.42	18.69	20.02	20.85	21.61
180	10.75	13.17	14.52	16.02	17.02	17.96
300	7.39	9.31	10.37	11.54	12.30	13.03
360	6.24	7.84	8.74	9.72	10.30	10.98
720	3.41	4.16	4.54	4.92	5.15	5.50
1440	1.85	2.26	2.47	2.67	2.79	2.90

Intensity of rainfall(mm/hr) at Shola Gebeya						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	31.38	39.54	43.12	46.26	47.88	49.08
60	18.15	23.99	27.86	32.74	36.37	39.96
120	10.92	14.73	17.25	20.43	22.79	25.13
180	8.45	11.44	13.42	15.93	17.78	19.62
300	5.73	7.90	9.25	10.86	11.99	13.09
360	5.00	6.84	7.94	9.22	10.09	10.94
720	2.89	3.87	4.45	5.13	5.59	6.03
1440	1.71	2.30	2.64	3.03	3.29	3.55

Intensity of rainfall(mm/hr) at Sinkata						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	51.04	58.28	62.34	66.82	69.80	72.62
60	28.83	32.80	34.77	36.80	38.04	39.16
120	15.06	17.22	18.42	19.65	20.44	21.19
180	10.15	11.53	12.28	13.10	13.64	14.14
300	6.14	6.96	7.41	7.89	8.19	8.48
360	5.13	5.83	6.21	6.62	6.89	7.14
720	2.91	3.34	3.55	3.76	3.89	4.01
1440	1.58	1.90	2.08	2.28	2.41	2.55

Intensity of rainfall(mm/hr) at Sirinka						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	40.16	48.88	53.66	58.90	62.32	65.54
60	24.92	29.18	31.50	34.02	35.66	37.20
120	14.92	17.05	18.24	19.56	20.44	21.28
180	11.21	13.41	14.66	16.07	17.02	17.92
300	7.93	9.62	10.59	11.70	12.44	13.16
360	6.82	8.52	9.64	11.06	12.11	13.15
720	4.00	4.86	5.35	5.91	6.29	6.65
1440	2.20	2.78	3.14	3.55	3.84	4.12

Intensity of rainfall(mm/hr) at Wegel Tena						
Duration (minutes)	Intensity of rainfall(mm/hr) for the indicated frequency(years)					
	2	5	10	25	50	100
30	24.86	30.78	34.22	38.14	40.78	43.32
60	15.71	18.84	20.63	22.65	24.01	25.30
120	9.47	11.58	12.80	14.19	15.12	16.02
180	7.10	8.71	9.77	11.11	12.11	13.10
300	4.82	6.00	6.66	7.39	7.87	8.32
360	4.09	5.10	5.66	6.29	6.70	7.10
720	2.18	2.67	2.94	3.25	3.45	3.65
1440	1.22	1.46	1.59	1.73	1.82	1.91

Appendix F: Pooled quantiles for the classified regions

Pooled Quantiles(mm) for region 1						
Duration (minutes)	Pooled quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	21.02	24.32	26.26	28.51	30.05	31.54
60	25.97	30.84	33.79	37.29	39.73	42.13
120	29.32	35.20	38.78	43.02	45.99	48.93
180	30.79	37.29	41.29	46.07	49.42	52.76
300	33.75	40.52	44.63	49.51	52.91	56.28
360	34.90	41.82	46.03	51.00	54.46	57.89
720	38.00	46.25	51.30	57.30	61.50	65.66
1440	42.57	52.02	57.82	64.74	69.59	74.41

Pooled Quantiles(mm) for region 2						
Duration (minutes)	Pooled quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	16.47	20.87	23.28	26.02	27.93	29.77
60	21.71	25.21	27.40	30.15	32.24	34.37
120	25.20	32.91	38.17	44.80	49.68	54.47
180	27.56	35.58	40.65	46.89	51.42	55.88
300	30.37	39.86	46.08	54.09	60.26	66.64
360	31.26	40.72	46.89	54.71	60.60	66.76
720	34.14	43.72	49.57	56.68	61.82	66.87
1440	38.30	47.16	52.24	58.01	61.91	67.11

Pooled Quantiles(mm) for region 3						
Duration (minutes)	Pooled quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	18.10	21.39	23.64	26.75	29.32	32.16
60	23.20	27.54	30.38	34.19	37.29	40.66
120	27.65	33.08	36.58	41.19	44.85	48.75
180	30.08	36.01	39.82	44.84	48.81	53.04
300	33.34	39.77	43.83	49.14	53.32	57.75
360	34.13	40.64	44.84	50.38	54.80	59.53
720	38.20	45.78	50.74	57.38	62.71	68.45
1440	42.96	51.52	57.06	64.39	70.23	76.46

Pooled Quantiles(mm) for region 4						
Duration (minutes)	Pooled quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	19.04	23.45	26.23	29.61	32.02	34.45
60	23.06	28.92	32.68	37.34	40.72	44.16
120	25.63	33.02	37.92	44.10	48.66	53.38
180	28.00	36.26	41.73	48.63	53.73	58.98
300	30.12	39.06	44.94	52.31	57.72	63.28
360	31.23	40.32	46.23	53.59	58.95	64.42
720	34.17	43.79	50.02	57.73	63.33	69.04
1440	38.31	47.99	54.15	61.68	67.08	72.55

Pooled Quantiles(mm) for region 5						
Duration (minutes)	Pooled quantiles(mm) for the indicated frequency(years)					
	2	5	10	25	50	100
30	21.46	26.39	29.74	34.35	38.16	42.34
60	26.86	33.51	38.25	45.09	50.99	57.75
120	30.81	38.45	44.22	52.93	60.77	70.04
180	33.81	42.59	49.35	59.67	69.09	80.36
300	37.86	47.36	54.41	64.88	74.19	85.12
360	40.36	50.37	57.45	67.59	76.30	86.24
720	44.71	55.70	63.30	73.94	82.89	92.92
1440	50.84	62.58	70.58	81.95	91.89	103.58

Appendix G: Mathematical expression of probability distributions for annual maximum series

Distribution	Probability Density Function (pdf)	Limits and remark
Normal	$f(x) = \frac{1}{\sigma\sqrt{2\Pi}} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}$	$\infty < x < \infty$
Two Parameter Lognormal (LN(2))	$f(x) = \frac{1}{x\sigma_y\sqrt{2\pi}} \exp\left\{\frac{-\left[\log x - \mu_y\right]^2}{2\sigma_y^2}\right.$	$u = \frac{\log(x) - \mu_y}{\sigma_y}$
Three Parameter Lognormal (LN(3))	$f(x) = \frac{1}{(x-a)\sigma_y\sqrt{2\pi}} \exp\left\{-\frac{1}{2\sigma_y^2}\left[\log(x-a) - \mu_y\right]^2\right\}$	$u = \frac{\log(x-a) - \mu_y}{\sigma_y} - (\infty, \infty)$
Exponential	$f(x) = \frac{1}{\alpha^\beta \Gamma(\beta)}(x-\varepsilon)^{\beta-1} e^{-\frac{(x-\varepsilon)}{\alpha}}$	$\Gamma(y+1) = \int_0^\infty t^y e^{-1} dt,\ y+1 > 0$
Two parameter Gamma(G (2))	$f(x) = \frac{1}{\alpha^\beta \Gamma(\beta)} x^{\beta-1} e^{-(\frac{x}{\alpha})}$	$0<x<\infty$
Pearson (3)	$f(x) = \frac{1}{\alpha\Gamma(\beta)}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} e^{-(\frac{x-\gamma}{\alpha})}$	$\gamma < x < \infty$
Log-Pearson (3)	$f(x) = \frac{1}{\alpha x\Gamma(\beta)}\left(\frac{\log(x)-\gamma}{\alpha}\right)^{\beta-1} e^{-(\frac{\log(x)-\gamma}{\alpha})}$	
Generalized Extreme Value (GEV)	$f(x) = \frac{1}{\alpha}\left(1 - k(\frac{x-u}{\alpha})\right)^{\frac{1}{k}-1} e^{-(1-(\frac{x-u}{\alpha}))^{1/k}}$	$u + \alpha / k < x < \infty$ $-\infty < x < u + \alpha / k$
Extreme Value Type I (EV1(2))	$f(x) = \frac{1}{\alpha}\exp\left(-(\frac{x-\beta}{\alpha})\right) - e^{-(\frac{x-\beta}{\alpha})}$	$-\infty < x < \infty$
Weibull	$f(x) = \frac{b}{a}\left(\frac{x-m}{a}\right)^{b-1} e^{-(\frac{x-m}{a})}$	Where a>0 and b>0 X ≥m from GEV k=1/b, α =a/b and u=m-a
Five Parameter Wakeby ((WAK(5))	$x = m + a\left[1-(1-F)^b\right] - c\left[1-(1-F)^{-d}\right]$ $Where F = F(x) = P(X \le x)$ $x = \varepsilon + (\alpha/\beta)\left[1-(1-F)^\beta\right] - (\gamma/\delta)\left[1-(1-F)^\delta\right.$	x is a random variable Re-parameterized form of Wakeby

Four-Parameter Wakeby	$x = a\left[1-(1-F)^{b}\right] - c\left[1-(1-F)^{-d}\right]$ *in the parameterized form* $x = (\alpha/\beta)\left[1-(1-F)^{\beta}\right] - (\gamma/\delta)\left[1-(1-F)^{-\delta}\right]$	x is a random variable Re-parameterized form of Wakeby
Generalized Pareto	$f(x) = \frac{1}{\alpha}\left(1 - \frac{k}{\alpha}(x-\varepsilon)\right)^{1/k-1}$	$x = \varepsilon + (\alpha/k)\left[1-(1-F)^{k}\right]$ $\varepsilon \le x < \infty$ *fork* ≤ 0 *and* $\varepsilon \le x \le \varepsilon + \alpha / k$ *fork* > 0
Logistic	$f(x) = \left(\frac{1}{a}\right) e^{-\left(\frac{x-m}{a}\right)} \left[1 + e^{-\left(\frac{x-m}{a}\right)}\right]^{-2}$	Inverse form $x = m + a\left[\log(F) - a\log(1-F)\right](1-F)^{S}\,dF$ $-\infty < x < \infty$
Generalized Logistic	$f(x) = \frac{1}{\alpha}\left[1 - k\left(\frac{x-\varepsilon}{\alpha}\right)\right]^{\left(\frac{1}{k}-1\right)} \left[1 + \left\{1 - k\left(\frac{x-\varepsilon}{\alpha}\right)\right\}^{1/k}\right.$	Generalized logistic distribution function $F(x) = \left[1 + \left\{1 - k\left(\frac{x-\varepsilon}{\alpha}\right)\right\}^{1/k}\right]^{-1}$