Addis Ababa University

Addis Ababa institute of technology

School of Civil and Environmental Engineering

Estimation of Probable Maximum Precipitation (PMP)
(Case Study on Upper Awash Sub River Basin)

A thesis submitted and presented to the school of graduate studies of Addis Ababa University in partial fulfilment of the degree of Masters of Science in Civil and Environmental Engineering (Major Hydraulic Engineering)

By

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BY

Birhan Tekuame

Approval by Board of Examiners

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Advisor Signature

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Internal Examiner Signature

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External Examiner Signature

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Chairman (Department of Graduate Committee) Signature

CERTIFICATION

The undersigned certify that he has read the thesis entitled Estimation Probable Maximum Precipitation (PMP) (A Case Study on Upper Awash Sub River Basin) and hereby recommend for acceptance by the Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science.

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Yilma Seleshi (PhD)

(Supervisor)

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Date

DECLARATION AND COPY RIGHT

I, Birhan Tekuame, 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 degree award.

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Date_____________________________

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My sincere appreciation goes to the almighty God for giving me abundant life, health and Peace.

DEDICATION

FOR ALL MOTHERS

ABSTRACT

Probable Maximum Precipitation (PMP) is defined as theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a particular time of year. The probable maximum precipitation helps for the design a civil structure appropriately in the study area. PMP value should be estimated by more than one method for critical hydrologic regulations, and preferably by both statistical and moisture maximization methods. The PMP for rainfall stations in Ethiopia have been estimated by Hershfield statistical method with frequency factor (K) determined by the Hershfield's chart. But different studies show that the value of frequency factor founded from the chart was not reliable. Therefore the main purpose of this study was to estimate the value of PMP using the frequency factor obtained from both the statistical equation and Hershfield's chart for 1-day, 2-days and 3-days duration and compare the results. In addition to this estimate the PMP values using both the statistical method and moisture maximization methods for first class meteorological stations in the Upper Awash sub river basin and compare the results. In this paper, yearly maximum one day, two days and three days duration rainfall data of 30 years for 11 stations in the Upper Awash sub river basin were analysed to estimate PMP based on statistical method. The study shows that the maximum frequency factor (Km) founded from the statistical equation is 6.2 and the PMP value obtained using the Hershfield chart maximum frequency factor (Km) deviated around 54% from the PMP Value obtained from the Hershfield's frequency equation. This result clearly indicated that Hershfield's chart overestimated PMP value which leads to uneconomical designs in the Upper Awash Sub River Basin. The maximum dew point temperature is very essential parameter to estimate PMP using moisture maximization method and for any location it is chosen by surveying long record period (50 years or above) of a highest value of persisting dew point of the station. But in this study the maximum record period is 30 years, so the maximum dew point temperature is calculated by performing the frequency analysis on annual series of monthly maximum persisting temperature with 100 year return period as a recommendation of (WMO, 2009). According to this paper Hershfield's Statistical Procedure is well-matched method in the Upper Awash Sub Basin.

Key words: probable maximum precipitation, statistical method, Hershfield's Statistical procedure, moisture maximization method, Upper Awash Sub River Basin

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ABBREVIATIONS and ACRONYMS

AM	Annual Maximum
EV1	Extreme Value 1
EXP	Exponential
GEV	Generalized Extreme Value
ITCZ	Inter-Tropical Conversance Zone
K	Frequency factor
Km	maximum Frequency factor
KS	Kolmogorov-Smirnov
LLG	Log Logistic
LN3	Log Normal 3
m asl	meter Above sea level
ML	Maximum Likelihood
MMF	Moisture Maximization Factor
MOM	Method of Moment
NMSA	National Meteorological Service Agency
P III	Pearson 3
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
T_{dm}	Maxim Dew Point Temperature
T_{ds}	Storm Dew Point Temperature
UASRB	Upper Awash Sub River Sasin
UBNB	Upper Blue Nile River Basin
USA	United States of America
WM	Maximum Precipitable Water
WMO	World Meteorological Organization
WS	Precipitable Water

1. INTRODUCTION AND BACKGROUND

1.1. Background

Probable Maximum Precipitation (PMP) is generally used to arrive at estimates for Probable Maximum Flood (PMF) for planning, design and risk assessment of high hazard hydraulic structures. Probable Maximum Precipitation (PMP) is theoretically defined as the greatest depth of precipitation for a given duration which is physically possible over a given size storm area at a particular geographical location and at a particular time of year (WMO, 2009). Hydrologists use a PMP magnitude together with its spatial and temporal distributions for the catchments of a dam to calculate the Probable Maximum Flood (PMF).

Different procedures are available to compute the PMP based on the location of the project basin, availability of data and other considerations have been proposed. Most of them are based on meteorological analysis, where as some are based on statistical analysis (Casas, Rudriguez, Prohom, & Gazquez, 2010), but Moisture maximization method and Hershfield (statistical) method are two widely used methods (Srinivas & Chavan, 2015). Statistical approach is preferred in those areas where meteorology parameters such as daily relative humidity, dew point temperature and wind speed data are unavailable (Rakhecha, 1994).

Moisture maximization method requires more site specific data and thus provides more reliable estimate than the other methods where site specific data are not available statistical (Hershfield) method can be applied that requires data for annual maximum rainfall series in the region for required storm durations. Factors that influence calculation of PMP values are rainfall records of intended storm durations, temperature, relative humidity, altitude, wind direction, dew point temperature (Hashim & Al-Mamun, 2004).

Different studies on Estimation of probable maximum precipitation (PMP) have been made at different regions in the world and different countries have reliable frequency factor (Km) and the studies show that the frequency factor (Km) found from Hershfield's graphical procedure was overestimate the actual value [India (Srinivas & Chavan, 2015), Iran (Gharaman, 2008) , Spain (Casas, Rudriguez, Prohom, & Gazquez, 2010) are some examples].

(Abenezer & Dereje, 2015) , (Alemayehu & Semu , 2010) have been made estimation of PMP on Upper Blue Nile river basin and they concluded that the Km value obtained from Hershfield's statistical procedure and the chart is far from each other. While most of the Km values obtained from the chart are about 15, the maximum value obtained using statistical method for 1 day duration is limited to 11. So the result of their study shows that these PMP estimates were considerably high and were not economical. Due to this reason (Abenezer & Dereje, 2015) recommended that like other country, further researches should be conducted on the rest basins of Ethiopia for fixing the country's reliable maximum frequency factor (km).Therefore, the purpose of this study focuses on estimation of PMP in the Upper Awash Sub River Basin using Hershfield's statistical procedure and Hershfield's chart and compare the results. In addition to this estimate the PMP values using both the statistical method and moisture maximization methods for first class recording meteorological stations in the Upper Awash Sub River Basin (UASRB) and compare the results.

1.2. Description of the study Area

1.2.1. Awash River Basin

The Awash River basin with a total area of 110,000 km^2 drains the northern part of the rift valley in Ethiopia. It has no outlet to the oceans, the terminal point being Lake Abe on the border with Djibouti. The basin is almost entirely within the boundaries of Ethiopia, the portion within Djibouti being negligible. The river rises at an elevation of about 3 000 m in the central highlands, West of Addis Ababa and flows north-east wards along the Rift Valley. The main river length is about 1 200 km.

The river rises on the High plateau near Ginchi town west of Addis Ababa and flows along the rift valley into the Afar triangle, and terminates in salty Lake Abbe on the border with Djibouti, being an endothecia basin. Based on physical and socio-economic factors the Awash Basin is divided into Upland (all lands above 1500m asl), Upper Valley, Middle (area between 1500m and 1000m asl), Lower Valley (area between 1000m and 500m asl) and Eastern Catchment (closed sub -basin are between 2500m and 1000m asl), and the Upper, Middle and Lower Valley are part of the Great Rift Valleys systems.

The Awash basin is geographically located in between 38^{o}E to 43.50^{o}E longitudes and 8^{o}N to 12.2^{o}N latitudes. Based on the division of governmental administration, wholly or partly contributing regions of the basin are Oromia, Addis Ababa, Afar, Amhara, Dire Dawa and Somali regional states. Due to the geological conditions, high runoff, and deforestation and over exploitation, high erosion is predominant in the basin. The basin is bordered on its western side by the Blue Nile basin, to the south west by the Omo-gibe and rift valley lakes river basins and to the south east by the Wabi-Shebele river basin. The Awash Basin is the most utilized in Ethiopia. 70% of the irrigate agriculture and 90% of the nations irrigated cotton production depend on the Awash, mainly down stream of Koka (Gobena, 2010).

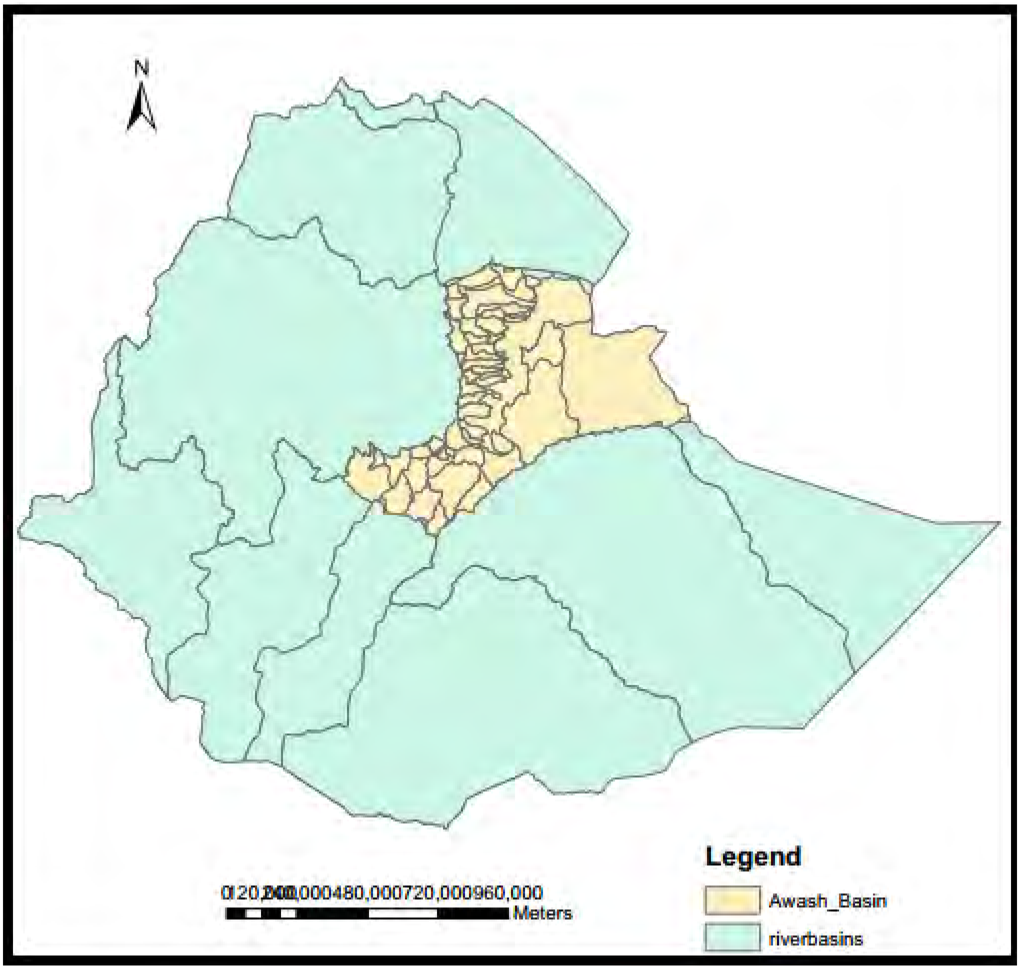

Figure1- 1: Awash River Basin

1.2.2. Upper Awash Sub River Basin

The Upper Awash Basin lies in the Ethiopian highland plateau in elevation ranging from 1500 to 3000 m above sea level. It is located upstream of Koka dam.

The Upper Awash catchment is found in the highlands of central Ethiopia with all lands above 1500m asl. The land use condition in the Upper Awash catchment includes mainly of cultivated agricultural land, forest land, rural and towns. The Upper Awash River covers the river section from its source up to Koka Reservoir. The Upper Awash River drains a catchment area close to 11,300 km^2 and the length of the river up to Koka is around 220 km (Halrcow, 1989).The major tributaries to the upper Awash are Akaki and Mojo rivers. Akaki River starts from the mountainous areas of the northern part of Addis Ababa and join the main Awash River between Melka-Kunture and Melka-Hombole gauging stations.

Mojo River, the other main tributary to Awash, originates from the high lands northeast of Addis Ababa. It drains a catchment area close to 1,900 km^{2}and travels a total length of about 105 km before joining Awash (Gobena, 2010).

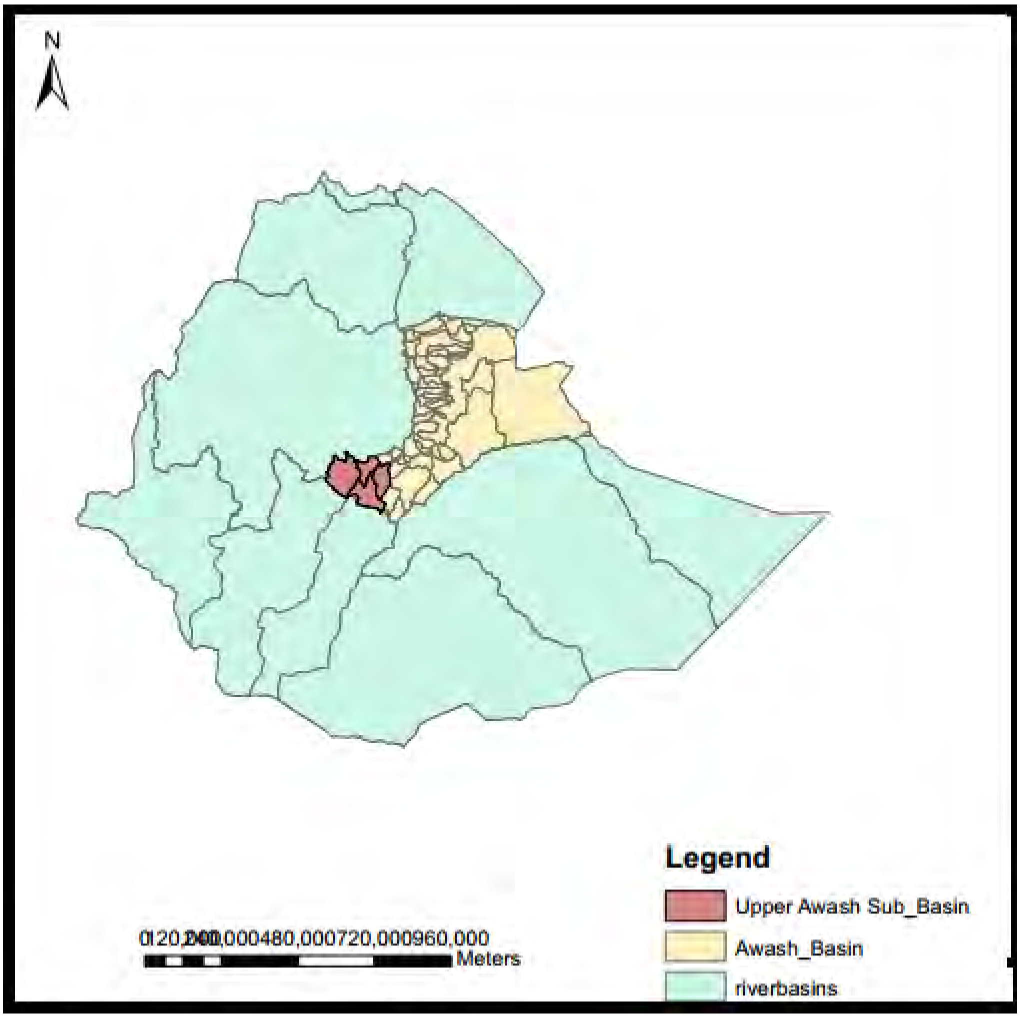

Figure1- 2: Upper Awash Sub Basin

Climate

According to the definition given by the World Meteorological Organization (WMO),Climate is defined as the synthesis of weather condition in a given area characterized by long-term statistics (mean, variance, probabilities of extremes, etc.) of the meteorological elements in an area .The WMO usually accepts 30 years of statistical data series to define climate.

In January, when the inter-tropical convergence zone (ITCZ) is in its most southerly position, most of Ethiopia comes under the influence of North East trade winds , resulting in a pronounced dry season. In March, when the ITCZ crosses the basin from the south, the small spring rain occurs. In, June and July the ITCZ reaches its most northerly location. This is associated with relatively humid south west monsoon air, which is responsible for the main rainy season in July and August with heavy rains. The climate of the Upper Awash Basin, in general, comes under the influence of the Inter Tropical Convergence Zone (ITCZ).This zone of low pressure makes the convergence of dry tropical easterlies and moist equatorial westerly. The explanation of the seasonal rainfall distribution within the basin lies in the annual migration of the ITCZ across the basin. The ITCZ starts its advance across the basin from the south in March, bringing the small or spring rains. In June and July the ITCZ reaches the most northerly location beyond the basin which then experiences the heavy or summer rains throughout. The ITCZ returns southwards during August, September and October, restoring drier, easterly airstreams that prevail until the ITCZ resumes its northward migration in March (Halrcow, 1989). Apart from this general pattern, there is a high spatial variance within the Upper Awash Basin due to the height dependence of the climatic parameters and the varying topography.

The mean annual temperature range in the basin is around 15^0C. The temperature at Addis Ababa ranges from a mean monthly maximum of 22.5^0C to a mean monthly minimum of 9.6^0C (Halrcow, 1989).

The wind flow pattern is influenced by the seasonal variation of the ITCZ. The predominant wind direction during June to September is southerly to south westerly. The wind speed pattern is distinctly bimodal in Addis Ababa region with peaks occurring in March and September and minimum speeds being recorded in July and August. The mean annual wind speed at Addis Ababa is 0.9m/s. The Awash basin experiences 2700 hours of sunshine annually. The monthly variation closely follows the rainfall pattern as would be expected with more sunshine hours in the dry months than in the wet months. Sunshine hours vary from a daily mean of 9.4 hours in December to 3 hours in July at Addis Ababa. The mean annual relative humidity of the basin is 60.2% measured at Addis Ababa. The monthly variation in relative humidity at Addis Ababa ranges from 50.9% in March to 78.5% in August (Gobena, 2010).

1.3. Statement of Problems

Due to lack of properly established probable maximum flood (PMF) procedure, professionals and practitioners alike tend to use the Hershfield’s graphical procedure to estimating the PMP and convert it into PMF (Alemayehu & Semu , 2010).

Different studies on estimation of probable maximum precipitation (PMP) have been made at different region in the world and different countries have reliable frequency factor (Km) and the studies show that the frequency factor (Km) found from Hershfield's graphical procedure is overestimate the actual value, India (Srinivas & Chavan, 2015), Iran (Gharaman, 2008) , Spain (Casas, Rudriguez, Prohom, & Gazquez, 2010) are some examples.

(Abenezer & Dereje, 2015) , (Alemayehu & Semu , 2010) have been made estimation of PMP on Upper Blue Nile river basin using statistical method and they concluded that the Km value obtained from Hershfield's statistical procedure and the chart is far from each other. While most of the Km values obtained from the chart are about 15, the maximum value obtained using statistical method for 1 day duration is limited to 11. So the result of their study shows that these PMP estimates were considerably high and were not economical. Due to this reason (Abenezer & Dereje, 2015) recommended that like other country, further researches should be conducted on the rest basins of Ethiopia for fixing the country's reliable maximum frequency factor (km).

The researches on Blue Nile River basin (Alemayehu & Semu , 2010) and (Abenezer & Dereje, 2015) indicates that for our country Ethiopia Hershfield's graphical procedure is not well tested, due to this reason it is big challenge to design and construct large dams in Ethiopian River basins. So it is necessary to estimate the PMP in every Ethiopian basin.

Therefore the main purpose of this study focuses on estimation of the probable maximum precipitation of the stations in the basin for 1-day, 2-day 3-day duration in the Upper Awash River basin, evaluation of the frequency factor (Km) founded from Hershfield's chart with that of the frequency factor (Km) calculated from Hershfield's statistical procedure using historical daily rainfall data in the basin and also estimate the PMP using statistical and hydro meteorological methods and compare the results for first class recording meteorological stations in the Upper Awash Sub River Basin.

1.4. Objectives of the Study

The main objective of this study is to estimate the point probable maximum precipitation (PMP) values for Upper Awash sub river basin.

The followings are specific objectives of this study.

- To estimate the frequency factor (Km) using Hershfield's statistical method and compare the result with the value found from Hershfield's Chart.
- Distinguish the best frequency distribution model for the stations.
- To estimate the PMP using hydro meteorological method and compare the result with the value obtained by statistical method in first class recording meteorological stations' in the Upper Awash Sub River Basin.
- To compare the probable maximum precipitation (PMP) values with the 10,000 years return period Quantiles for different durations.

1.5. Significances of the Study

This paper will create good awareness for hydrologists and engineers about how to design economical spillways in our river basin using reliable PMP. It is also helpful for researchers who have an interest for doing further research on Estimation of PMP using both Moisture maximization and statistical method on Ethiopian river basins.

The estimation of Probable Maximum Precipitation (PMP) for the basin is an important task for various engineering works such as spillway design for dams of the highest hazard category. It is therefore, anticipated that institutions and individuals involved in these sector will utilize the result of this study.

2. LITERATURE REVIEW

2.1. Definition of PMP and PMF

According to World Meteorological Organization PMP is defined as 'the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at certain time of the year with no allowance made for long term climatic trends' (WMO, 2009) . PMP is very essential for the design of large hydraulic structures especially for spillways of large dams. Now a day PMP is practiced in different countries like India, China, USA, and UK (Wickramasuriya & Fernando, 2011). The probable maximum precipitation helps design a civil structure properly in the study area. PMP value should be estimated by more than one method for critical hydrologic regulations, and preferably by both statistical and physical methods. Therefore, statistical method was used and recommended to estimate the PMP due to limitation of data availability .

PMF is the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed. Such a flood could plausibly occur in a locality at a particular time of year under current meteorological conditions (WMO, 2009). Estimates of extreme floods have long been used to design the flood-handling facilities of major dams whose failure might cause loss of life or extensive property damage.

In world Meteorological Organization (WMO, 2009) there are various methods of estimating probable maximum precipitation (PMP) ,which are storm model approach; storm maximization and transposition; statistical analysis; use of generalized data; use of empirical formulae and relationships. Storm maximization and Statistical analysis is the two most widely used methods globally (Srinivas & Chavan, 2015) .

2.2. Probable Maximum Precipitation (PMP) Estimation Methods

The various methods which can be used for estimating probable maximum precipitation amounts are classified into three major groups.
These are:

1. the statistical approach,
2. the physical approach, and
3. the empirical approach

In the statistical approach the estimates of PMP are derived from frequency analysis of the annual maximum rainfall series for different durations. Statistical method for estimating PMP has been developed by Hershfield (1961, 1965) based on a general frequency equation given by Chow (1951). The use of statistical method in different countries has shown that the computed PMP estimates are closely comparable to those obtained by the meteorological method. (WMO, 2009) Has suggested this method for estimating PMP for stations having long period of daily rainfall data. Considering this, many countries have employed the statistical method extensively for estimating PMP for stations having a long period of rainfall records (Rakhecha, 1994), (Wickramasuriya & Fernando, 2011). The statistical method is useful when there is insufficient meteorological data to apply other methods.

The physical approach is primarily concerned with the estimation of probable maximum precipitation (PMP) which can be defined as the theoretical highest precipitation amount which is physically possible over a locality for a given duration. Values of PMP are therefore dependent on the humidity content of the air and maximum efficiency of release. Values of PMP are usually estimated by the physical method of storm transposition and maximization described by (Ridel, Schreiner, & John, 1980).

The storm model approach uses physical parameters, such as surface dew point, height of storm cell, and inflow and outflow, to represent the precipitation process (WMO, 2009). Storm transposition involves translating observed storm characteristics from one or more gauged locations to the location where the PMP estimation is required (typically an ungauged location). Storm maximization consists of adjusting observed precipitation amounts upward to account for maximum atmospheric moisture convergence.

Generalized PMP methods are often developed by maximizing and translating classes of storms over a broad region; storm classification in turn is based on the storm type, and storm efficiency defined as the ratio of maximum observed rainfall to the amount of Precipitable water in the storm column (Rakhecha, 1994) .

The empirical approach to the estimation of extreme rainfalls utilizes the available data just like the statistical approach. The US Weather Bureau has carried out some studies utilizing data on heavy rainfall occurrences extracted from autographic records. From these, an enveloping curve can be drawn to show the maximum rainfall likely to be obtained in any given time.

The reliability of such estimates obviously depends on the duration and quality of rainfall records as well as the number of gauges involved especially if a catchment is being considered.

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

This paper used Storm maximization and Statistical analysis because they are widely used methods globally.

2.3. Storm Maximization

2.3.1. Definition

The storm maximization method means maximizing the meteorological conditions (e.g., moisture content or Precipitable water) that control the existence of convective precipitation above the target station. The storm maximization method, which is a deterministic approach, is used to increase the observed precipitation data to get maximum moisture inflow theoretically possible at the site, either '*in-situ*' or by 'transposition'.

If the station has not sufficient number of severe storm, it is reasonable to transpose storms from another area (Wickramasuriya & Fernando, 2011) .Storm maximization method requires more site specific data and thus provides more reliable estimates than the other method (Hashim & Al-Mamun, 2004).

According to WMO the storm maximization procedure describes two maximization factors, namely, moisture maximization factor (MMF) and wind maximization factor (WMF). However, most studies on storm maximization throughout the world have used only moisture maximization ((Rakhecha, 1994), (Wickramasuriya & Fernando, 2011), (Hashim & Al-Mamun, 2004)) because It is believed that maximum possible wind convergence is impractical either empirically or theoretically.

2.3.2. Assumption of a Saturated Pseudo-Adiabatic Atmosphere

The moisture in the lower layers of the atmosphere is the most important for producing precipitation, both because most atmospheric moisture is in the lower layers and because it is distributed upward through the storm early in the rainfall process (Schwarz, 1967; United States Weather Bureau,1960). Theoretical computations show that, in the case of extreme rains, moving up rates in the storm must be so great that air originally near the surface has reached the top of the layer from which precipitation is falling within an hour or so.

The most realistic assumption seems to be that the air ascends dry-adiabatically to the saturation level and thence moist-adiabatically. For a given surface dew point, the lower the level at which the air reaches saturation, the more moisture a column of air will contain. The greatest Precipitable moisture occurs when this level is at the ground. For these reasons, hydro meteorologists generally postulate a saturated pseudo-adiabatic atmosphere for extreme storms (WMO, 2009).

2.3.3. Atmospheric Moisture

Radio stone observation is the best way to measure the atmospheric moisture. But many severe storms was occurred before the establishment of radio stone network and the radio stone network is too far to detect the narrow parts of moisture that is very important for the formation of storms. In order to solve the above problems of using atmospheric moisture (Ridel, Schreiner, & John, 1980), an assumption of pseudo-adiabatic atmosphere is taken, tied to surface dew point, which fixes the moisture and its distribution.

The storm dew point (T_{ds}) it is the representative of moisture inflow during the storm and Maximum recorded dew point (T_{dm}) (the maximum dew point for the same location time of the year) are required for moisture maximization.

2.3.4. Precipitable Water

Moisture or humidity is the degree of wetness. Moisture available for precipitation can be measured using Precipitable water, which is defined as the equivalent linear depth of water within a column of air if all the water vapour is condensed over the base area of the column (Wickramasuriya & Fernando, 2011).

Precipitable Water (PW) indicates the amount of moisture there is above a fixed point. It does not indicate how much it will rain but rather how much moisture is in the air. For example, a Precipitable Water value of 1 inch does not indicate it will rain 1 inch but rather indicates all the moisture above a location if condensed would be 1 inch. The Precipitable Water value is also an instantaneous value of the amount of moisture in the air above a location. It can precipitate more than the Precipitable value amount since moisture convergence can occur and precipitation falls over a span of time and is not instantaneous. The Precipitable Water value gives a forecaster an idea of the amount of moisture in the air.

Higher values of Precipitable water indicate greater availability of moisture to make rainfall if precipitation develops. Generally, Precipitable water indicates that the total amount (mass) of water vapour in the vertical column of the atmosphere. Air contains 4cm of Precipitable water implies that each vertical column of 1 cm^2 cross section from the surface of the top of the atmosphere contains 4 g of water in vapour form. If all the water vapour were to be condensed into liquid water and deposited at the base of the column, the accumulated liquid would be 4 cm deep, since the density of water is 1 g/cm^3.

2.3.5. Storm Dew Point (Representative Storm Dew Point)

Moisture maximization of a storm needs empathy of two saturation adiabatic-process. One characterizes that vertical temperature distribution that occurred in the storm to be maximized. The other is the warmest saturation adiabatic to be predictable at the similar time of year and place as the storm. It is necessary to identify these two saturation adiabatic-process with an indicator.

The conventional label in meteorology for saturation adiabats is the wet-bulb potential temperature, which corresponds to the dew point at 1 000 hPa. Tests have shown that storm and extreme values of Precipitable water may be approximated by estimates based on surface dew points, when saturation and pseudo-adiabatic conditions are assumed (Miller, 1963; United States Weather Bureau, 1960).Dew points are determined from the warm humid air flowing in to the storm, both distance and directions of the dew points from the stations are recorded.

The dew points from a set of stations used to obtain a representative persisting 12-hour storm dew point are unlikely to be in the most intense moisture inflow for more than 12–24 hours. After this time the stations where the dew points were observed are very likely to be in the cold air because of the displacement of the storm. The selection of different representative 12-hour dew points for every 12 hours of a storm is a very tedious task, especially for storm durations of 72 hours and longer. Storm rainfall values adjusted on the basis of 12-hour dew points from different sets of stations compared with values from a single set indicate that differences are too small to justify the additional time required in obtaining representative 12-hour dew points for different storm intervals.

To get the appropriate value of persisting storm dew point the average dew point values from different stations were taken (Ridel, Schreiner, & John, 1980).where the dew point temperatures are not readily available we can calculate the persisting storm dew from the maximum surface temperature.

When surface dew point temperature is not recorded we can use the following formula (Smith, 1966).

$$Td = \frac{237.3\ln(Rh) + 237.3(\frac{17.27T}{237.3+T})}{17.27 - \ln(Rh) - \frac{17.27T}{237.3+T}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots..2.2$$

Where:

Td=surface dew point temperature in Fahrenheit

T=maximum surface temperature in degree Celsius

Rh=relative humidity (g/kg)

2.3.6. Maximum persisting Dew point

The highest dew point detected for a given location and time of the year is known as Maximum persisting dew point .These dew points are based on seasonal and regional envelopes of maximum observed surface dew points that have persists for 12or 24 hours.

Maximum values of atmospheric water vapour used for storm maximization are usually estimated from maximum persisting 24-hour 1000-hPa dew points. These dew points are generally obtained from surveys of long records – 50 or more years – at several stations in the problem area. In some regions, the maximum dew points for each month of the year or critical season may be adequate to define the seasonal variation of maximum atmospheric moisture, but it is generally advisable to select maximum persisting 12-hour dew points using semi-monthly or 10-day intervals. Dew point records appreciably shorter than approximately 50 years are unlikely to yield maximum values representative of maximum atmospheric moisture. The usual practice in such cases is to perform a frequency analysis on an annual series of monthly or shorter interval maximum persisting 24-hour dew points.

Generally maximum persisting dew point is the maximum value from the historical surface dew point temperatures (T_d).

2.3.7. Moisture Maximization

Moisture maximization is estimated by multiplying the observed rainfall by the moisture maximization factor (MMF), which the ratio is of wm is maximum Precipitable water indicated for storm reference location and Ws is the Precipitable water estimated for the storm. Hence to estimate the above two parameters two dew point temperatures are required (24-h persisting storm dew point temperature-T_{ds} and 24-h persisting maximum storm dew point temperature (T_{dm}).

$$MMF = \frac{Wm}{Ws} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.3$$

In most hydro meteorological work the atmosphere is assumed to contain the same amount of water vapour as saturated air with saturation pseudo adiabatic temperature lapse rate. The Precipitable water in various layers of the saturated atmosphere can be determined and listed in tables or in nomogram form (WMO, 2009).

WMO monograph presents values of Precipitable water (mm) between the 1 000-hPa surface and various pressure levels up to 200-hPa in a saturated pseudo-adiabatic atmosphere as a function of the 1 000-hPa dew point (WMO, 2009).

In maximizing storm rainfall, only the depth of Precipitable water from the ground to some arbitrarily selected level between 400 hPa and 200 hPa is used. The 200-hPa level is generally accepted as the top of the storm. From the 400-hPa level upwards, the selected level make little difference as there is very little moisture and the effect on the moisture adjustment is negligible. In cases where a mountain barrier lies between the storm area and the moisture source, the mean elevation of the ridge or crest is selected as the base of the moisture column. In most cases, it is advisable to select the storm and maximum dew points between the barrier and the storm location.

2.3.8. Wind Maximization

Most studies on storm maximization throughout the world have used only moisture maximization ((Rakhecha, 1994), (Wickramasuriya & Fernando, 2011), (Hashim & Al-Mamun, 2004)) .because It is believed that maximum possible wind convergence is impractical either empirically or theoretically. However, when moisture maximization yields inadequate or unrealistic results, incorporating wind maximization is recommended.

WMF is the ratio of maximum average wind speed (F_m) for some specific duration and critical direction, to the average wind speed (F_s) for the same duration and direction for the observed storm:

$$WMF = \frac{Fm}{Fs} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2.4$$

The 24-h wind run is used as an alternative for average wind speed but care must be taken to select critical wind direction in deriving WMF. Maximum wind speed is selected from a long record of observations as in moisture maximization.

2.4. Statistical Method

Storm maximization and transposition method provides more reliable data because it requires more site specific data, but where site specific data are not available statistical (Hershfield) method can be applied because it requires annual maximum rainfall data of the region (Hashim & Al-Mamun, 2004).

If adequate precipitation data is available on the region Statistical method is useful for estimation of PMP because once a statistical model is constructed, its application is simple and fast. The statistical method aims at the determination of the point probable maximum precipitation (PMP) for a given gauge position or grid point. Corrections that transform the point PMP to an area rainfall are necessary for determining an area PMP.

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

2.4.1. Frequency Factor (Km)

The Hershfield method is used to find out the appropriate frequency factor that can give reliable PMP values for stations in the study area for practical application. But here the annual maximum rainfall amounts series of the stations found in the study area is used for the analysis. This involves standardizing the residual (maximum rainfall minus mean of annual maxima) by dividing it by the standard deviation to obtain the frequency factor. The frequency factor is analogous to the normal deviate or reduced variate when normally distributed or extreme-value data are analysed, respectively.

After determining the appropriate frequency factor (Km) values for the study area different adjustments have to be carried out for the maximum observed events before using them for subsequent calculations.

Extreme rainfall amounts of rare magnitude or occurrence, such as with return periods of 500 or more years, are often found to have occurred at some time during a much shorter period of record, e.g.,30 years. Such a rare event, called an outlier, may have an appreciable effect on the mean and standard deviation of the annual series. The magnitude of the effect is less for long records than for short, and it varies with the rarity of the event, or outlier. This has been studied by Hershfield (1961) using the hypothetical series of varying length, and developed the figure. Using the Hershfield figure adjustments were made to mean and standard deviations to compensate for outliers and this type of adjustment is called Adjustment of Mean and Standard deviation for Maximum Observed Events.

The mean and standard deviation of the annual series tend to increase with length of record, because the frequency distribution of rainfall extremes is skewed to the right so that there is a greater chance of getting a large than a small extreme as length of record increases.so adjustment is necessary for mean and standard deviation for a length of a record.

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

Studies of thousands of station-years of rainfall data indicate that multiplying annual maximum hourly or daily rainfall amounts for a single fixed observational interval of one to 24 hours by 1.13 will yield values closely approximating those to be obtained from an analysis of true maxima ((WMO, 2009) .

2.5. Use of PMP in Spillway Design

The hydrologic problem typically addressed in dam safety analysis is the determination of the capacity of the spillway needed to prevent catastrophic failure of the dam due to overtopping. The PMF is generally accepted as the design inflow for evaluating the spillway when there is potential loss of life due to dam failure in high hazard situations.

As per the first edition of Dam Safety Guidelines by the Canadian Dam Association (CDA 1999) dams are classified into four categories according to the perceived incremental consequences of failure these are very high, high, low and very low dams. The criteria for the design flood as stated in CDA, 1999 are as follows.

- For very high dams: the PMF developed as a result of PMP is mandatory.
- For high dams: the design flood may be selected between the PMF and the 1000-years flood.
- For low dams: the design flood may be selected between the 1000-year and the 100-year floods.
- For very low dams the design flood selected is less than100-year floods.

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

2.6. Extreme Flow Quantiles Estimation

Hydrologic Systems are influenced by extreme events, for example excessive rainfall, runoff and severe drought. The occurrences of extreme events are inversely proportional with its frequency of occurrences. The purposes of frequency analysis of hydrologic events are to correlate the magnitude of extreme events to their frequency of occurrences (Chow, Maidment, & Larry, 1988).

Extreme flow quantiles estimation is estimating a future high and low flow magnitude from the available gauged flow data or from the available reanalysis flow data. They are essential for the efficient operation of water infrastructure, the mitigation of natural disasters such as floods and droughts and design of hydraulic structure such as culvert, spillway, and bridge. In addition, they are becoming increasingly important in supporting integrated water resources management and reducing flood induced losses. Estimates of flow having given recurrence intervals or probabilities of exceedance are needed for design of hydraulic structures and flood plain management.

For any hydraulic structure the critical flood peaks to be designed mostly based on the extreme rainfall events with the return period 10,000 years (Haktanier, Cobaner, & Kisi, 2010).

The distribution models which are suggested by WMO for annual maximum data series (Cunnane, 1989) are listed below.

- Normal distribution (NOR)
- Two parameter Log-Normal distribution (LN2)
- Three Parameter Log-Normal distribution (LN3)
- Exponential distribution
- Two parameter Gamma distribution
- Pearson three distribution (PIII)
- Log Pearson three distribution (LP3)
- Generalized extreme value distribution(GEV)
- Extreme value type one distribution (EVI)
- Weibull distribution(W)
- The five parameter Wakeby distribution(WAK5)
- The four parameter Wakeby distribution(WAK4)

In this study Easy-Fit statistical computer software was used for selecting the best fit distribution of the stations.

The frequency analysis methods used in this study are as follows

Normal Distribution

The normal distribution is suitable in hydrology for describing well-behaved occurrences like average yearly stream flow. According to central limit theorem if a random variable X is the sum of n independent and identically distributed random variables With finite variance, then with increasing n the distribution of X becomes normal regardless of the distribution of the original random variables (Stendinger, Rechard, & Georious).The normal distribution is unbounded bell-shaped curve with the maximum value at the central point and extending from -∞ to +∞.

Annual precipitation events tend to follow the normal distribution, and distribution varies over a continuous range and is symmetric about the mean but allows negative values. However, hydrologic variables tend to be skewed and all are non-negative.

Log Normal Distribution (LN)

Many hydrologic processes have a tendency to follow the normal distribution, and the distribution fluctuates over a nonstop range and is symmetric about the mean but permits negative values. Nevertheless, hydrologic variables have a tendency to be skewed and all are non-negative. The log normal Distribution eradicates the problem of non-negative variables as the data are greater than zero, permits the skewness of the data, and does require the data to be symmetric about the logarithm of the mean (Stendinger, Rechard, & Georious).

Hydrologic processes are positively tilted and are not normally distributed. However, in many cases for strictly positive random variables $X > 0$ their logarithm

$$Y = lnX \quad \ldots 2.5$$

$$X = \exp(Y)$$

In several cases the logarithms of the random variables X are not fairly normally distributed, so in order to solve this problem subtracting an inferior bound μ before taking the logarithm.

Thus

$$Y = \ln(X - \mu) \quad \ldots 2.6$$

$$X = \mu + \exp(Y)$$

Log Pearson Type 3

The statistical distribution commonly used in the hydrologic system United States of America is the log-Pearson Type I11 (LP3) distribution because it was mentioned by the U.S. Water Resources Council in Bulletin 17B. The Pearson Type I11 distribution is a probability density function. It is commonly recognized because it is simple to apply when the parameters are estimated using the method of moments and because it usually provides a good fit to measured data. LP3 analysis needs a logarithmic transformation of the data (McCuen & Richard, 1989).

General Extreme Value

The GEV distribution is continuous probability distributions that associations the Gumbel (EV1), Frechet and Weibull distributions. GEV is three parametric distributions: location, scale and shape. The variation of distribution in a specified direction on the horizontal axis is described by the location parameter. How the distribution is spread out and where the bulk of the distribution lies is defined by scale parameter. If the scale parameter increases, the distribution will becomes more spread out. The shape parameter strictly shakes the shape of the distribution, and rules the tail of each distribution. When shape parameter (k) =0, this is the EV1 distribution. When k>0, this is EV2 (Frechet), and when k<0 is the EV3 (Weibull) (Millington, Das, & Simonovic, 2011)

Goodness of Fit (GOF) Tests

In easy fit statistical software Three goodness of fit tests (GOF), including Kolmogorov-Smirnov test, Anderson Darling test, Chi-square test, were employed to check whether the hypothesized distribution function fitted the sample data. The most common methods are Kolmogorov-Smirnov and Chi-square test (Chen, 2000).

A. Kolmogorov-Smirnov Test

KS test is based on the deviation of the sample distribution function from the specified continuous hypothetical distribution function, providing a comparison of a fitted distribution with the empirical distribution. The K-S test calculates the maximum difference between the hypothesized distribution function and the empirical distribution.

The Kolmogorov-Smirnov statistic (D) is based on the largest vertical difference between the theoretical and the empirical cumulative distribution function: The test statistic D is defined in equation 2.3.

$$D = \max_{1 \le i \le n} |F_n(x_i) - F_0(x_i)| \quad \text{.......} 2.7$$

Where, i = rank of data and n = number of the sample data

The values of F_n (x_i) are estimated as n_i/n where n_i is the cumulative number of sample events in class interval I. F_0 (x_i) is then 1/k, 2/k…..etc. The value of D must be less than a tabulated value of D at the specified confidence level for the distribution to be accepted.

The hypothesis regarding the distributional form is rejected at the chosen significance level (α) if the test statistic, D, is greater than the critical value obtained from a table. A value of (α) 0.05 is typically used for easy fit applications. (Chen, 2000).

B. Chi-Squared Test

In Chi-square test, the observed data values of the relative frequency or the cumulative frequency function are compared with the corresponding value of the assumed theoretical distribution to test the goodness of fit of a probability. In the test, the data are divided into k class intervals (k is recommended to be more than 5).

The Chi-Squared test is used to determine if a sample comes from a given distribution. It should be noted that this is not considered a high power statistical test and is not very useful (Cunnane, 1989). The test is based on binned data, and the number of bins (k) is determined by:

$$k = 1+\log_2 n \qquad \text{.......... 2.8}$$

In which n = sample size

The test statistic (χ^2) is:

$$\chi^2 = \sum_{i=1}^{k} \frac{(Oi-E_i)}{Ei} \qquad \text{.......... 2.9}$$

Where,

In equation 2.9, Oi is the observed number of events in the class interval i, Ei is the number of events that would be expected from the theoretical distribution, and k is the number of classes to which the observed and re-analysis data are sorted.

If the class intervals are chosen such that each interval corresponds to an equal probability, then Ei = n/k where n is the sample size and k is the number of class intervals and, equation 2.9 reduces to equation 2.10

$$\chi^2 = \frac{k}{n}\sum_{i=1}^{k} O_i{}^2 - n \qquad \text{.......... 2.10}$$

Class intervals can be computed by using the inverse of the distribution function corresponding to different values probability F, Similar to estimation quintiles.

2.7. Previous Studies on PMP

Different studies on Estimation of probable maximum precipitation (PMP) have been made at different region in the world. A paper edited by Daniela Rezacova, Peter pesice and Zbynek Sokol on 2004 estimate the probable maximum precipitation for river basins in the Czech Republic. They were used two techniques of PMP estimation suitable for Czech Republic territory, and they were applied them with respect to the precipitation duration (Rezacova, Pesice, & Sokol, 2004) .The PMP was estimated by Storm model approach for precipitation duration shorter than 1 day, and the world meteorological organization (WMO) statistical techniques was modified in order to determine the PMP for the precipitation duration of 1 day and longer. Daniela Rezacova, Peter pesice and Zbynek Sokol were modified the world meteorological organization statistical model for Czech Republic territory because they believed that correction factors from WMO manual were derived from the data collected mostly in the United States (Rezacova, Pesice, & Sokol, 2004).

W.C.D.K.Fernado and S.S.Wickramasuriya estimate the probable maximum precipitation in Sri Lanka using Storm maximization method_(Wickramasuriya & Fernando, 2011). In this study seven meteorological station covering several agro ecological zones of Sri Lanka were selected and hydro-meteorological data such as daily rainfall, dew point temperature and wind runs with directions were used in the computation. According to W.C.D.K.Fernado the 24-h point PMP values for seven meteorological stations in Sri Lanka were derived using hydro-meteorological method come closest to the Statistical method (Wickramasuriya & Fernando, 2011).

Demetris Koutsoyiannis have been made on a probabilistic view of Hershfield’s method for estimating probable maximum precipitation using all the data Hershfield used for his study for determining the PMP estimation method. After the end of his study Demetris Koutsoyiannis conclude that Hershfield’s estimate of probable maximum precipitation (PMP) may be obtained by using generalized extreme value (GEV) distributing with the shape parameter given as a specific function of the average value of annual maximum precipitation series, and for a return period of about 60,000years (Koutsoyiannis D. , 1998).According to figure 2.1, the maximum observed value of Hershfield’s frequency factor Km=15 but it is not at all a physical upper limit and it would be greater in case that more records were available (Koutsoyiannis D. , 1998). But according to his data Hershfield found that the maximum observed value of Km was 15 (Koutsoyiannis D. , 1998).

A paper written by S.M.Papalexion and D.Koutsoyiannis tried to apply the probable maximum precipitation (PMP) estimation method (focus on Storm maximization method) and a probabilistic analysis of its results. And they conclude that a probabilistic approach, based on the generalized extreme value (GEV) model, seems to be more consistence tool for studying hydrological extremes (Koutsoyiannis & Papalexiou, 2006).They conclude that concept of probable maximum precipitation (PMP) is based on the assumption that (a)there exists an upper physical limit of the precipitation depth over the given area at a particular geographical location at certain time of year, and (b) that this limit can be estimated based on deterministic consideration (Koutsoyiannis & Papalexiou, 2006).

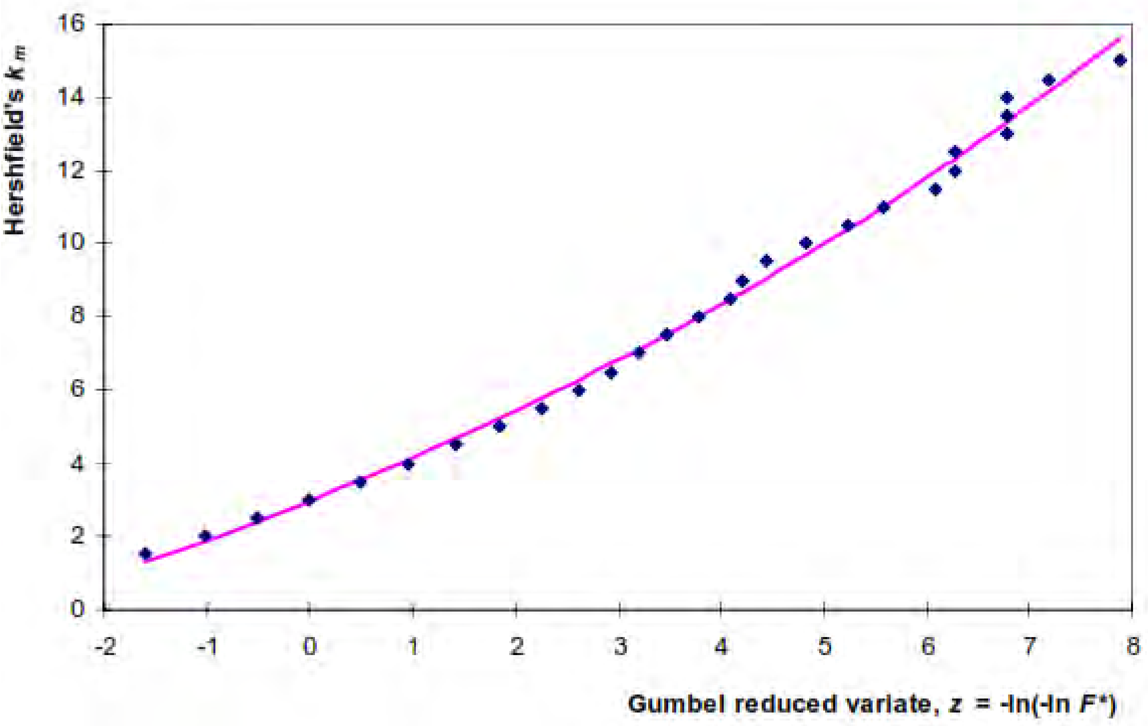

Figure 2- 1: Hershfield's Km Vs Gumbel reduced variate

Abdullah Al-Mamun and Alias Hashim prepared Isohyetal map to estimates the PMP for Peninsular Malaysia .Historical storms of 1,3 and 5-day durations from 21 rainfall recording stations operated by Malaysian Meteorological Service were identified and analysed to calculate the PMP values using Storm maximization method. They used storm maximization method over the other methods because they were enough meteorological data and they believed that Storm maximization and transposition method requires more site specific data and thus provides more reliable estimates than the other methods (Hashim & Al-Mamun, 2004).

M Carmen Casa and his friends try to estimate the PMP in Barcelona (Spain) using storm maximization method and Hershfield's statistical method .According to their study the PMP values obtained using the two techniques are very similar (Casas, Rudriguez, Prohom, & Gazquez, 2010). The PMP in Barcelona is very reliable because they used both the hydro-meteorological and statistical analysis. The 66-year true maximum rainfall annual series was fitted by the Gumbel distribution, using the L-moments method.

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

Statistical approach is preferred in those areas where meteorology parameters such as hourly precipitation, dew point temperature and wind speed data are unavailable (Rakhecha, 1994).Sagar Rohidas Chavan and V.V.Srinivas estimate the Probable maximum precipitation (PMP) for Mahanadi river basin, India, using two methods of PMP estimation namely moisture maximization method and Hershfield method (Statistical method). The result indicates that the Hershfield approach tends to give higher estimates for PMP when compared to the storm model approach (moisture maximization) (Srinivas & Chavan, 2015) .They are prepared PMP maps for Mahanadi river basin, as the basin is prone to frequent floods.

The estimation of one day duration probable maximum precipitation over Atrak water shed in Iran was done by Ghahraman because the probable maximum precipitation (PMP) for many stations in Iran and other places using the Hershfield formula is routinely estimated as the mean plus 15 times the standard deviation processed from one –day yearly maximum rainfall value. However, the value of 15 may not be suitable for all stations with different climatic specifications (Gharaman, 2008).but based on the actual maximum daily rainfall data of Atrak watershed stations ,the highest value of frequency factors was found to be 9.63 for one day duration (Gharaman, 2008).

2.8. Previous Studies in Ethiopia

A paper edited by Alemayehu tried to estimate the 24-h, 48-h, 72h probable maximum precipitation (PMP) for Blue Nile Basin. PMP obtained using the Km from the Hershfield chart is 46% greater than the application of new Km value. This difference of PMP as a result of difference in new Km and the Chart Km has far reaching consequence in the total cost of dam projects when dam design is considered based on PMF. Therefore, high attention should be provided for the estimation of Km values (Alemayehu & Semu , 2010).According to Alemayehu and Semu the comparison of the Km value obtained from Hershfield's statistical procedure and the chart is far from each other. While most of the Km values obtained from the chart is about 15, the maximum value obtained using statistical method for 1 day duration is limited to 11 (Alemayehu & Semu , 2010).So far in Ethiopia the frequency factor used for the PMP estimate were made using the Hershfield's chart, but the result of this study shows that these PMP estimates were considerably high and were not economical therefore, Fresh and reliable estimates are made through this study for the Blue Nile basin (Alemayehu & Semu , 2010).Alemayehu Deme and Semu Ayalew (2010) recommended that for those first class stations in the study area having automatic gauges their PMP values should be carried out using the meteorological method of estimation and there results should be checked before using them for further calculation (Alemayehu & Semu , 2010).

Muez Berhane (2014) tried to estimate the probable maximum precipitation (PMP) for North Shewa region using Hershfield statistical method and Gumbel EVI model. And the highest value of frequency factor was found to be 5.2 which correspond to Debresina station (Muez, 2014).Muez develop one day PMP isohyetal map and identify the best fit frequency distribution model for each rain gauge station for the zone.

Abenezer Endale and Dereje Hailu (2015) Estimate the probable maximum precipitation (PMP) using In-situ and Re-analysis global precipitation product on Upper Blue Nile Basin and according to their paper PMP value using the new Km and the chart values for both in situ and reanalysis products exhibited difference 38% up to 96.4%, this result confirmed the Hershfield's chart overestimated PMP value which leads to uneconomical designs in the Upper Blue Nile Basin (Abenezer & Dereje, 2015).

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

3. METHODOLOGY

3.1. Methods for Estimation of PMP

In world meteorological organization (WMO, 2009) there are various methods of estimating probable maximum precipitation (PMP) ,which are storm model approach; storm maximization and transposition; statistical analysis; use of generalized data; use of empirical formulae and relationships. Storm maximization and Statistical analysis is the two most widely used methods globally (Srinivas & Chavan, 2015).The probable maximum precipitation helps design a civil structure properly in the study area. PMP value should be estimated by more than one method for critical hydrologic regulations, and preferably by both statistical and physical methods.

This study used Storm maximization and Statistical analysis because they are widely used methods globally.

3.2. Storm Maximization

The storm maximization method means maximizing the meteorological conditions (e.g., moisture content or Precipitable water) that control the existence of convective precipitation above the target station.

According to WMO the storm maximization procedure describes two maximization factors, namely, moisture maximization factor (MMF) and wind maximization factor (WMF). However, most studies on storm maximization throughout the world have used only moisture maximization. Due to shortage of available data of wind this paper used only moisture maximization method.

3.2.1. Precipitable water

A total mass of water vapour in a vertical column of the atmosphere is known as Precipitable water (WMO, 2009).

The general formula for computing the Precipitable water, W is:

$$W = \frac{\bar{q}}{g\rho} \Delta P \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..3.1$$

Where

W=Precipitable water in cm

$\bar{q}$= the mean specific humidity in g/kg of a layer of moist air

ΔP=the depth of the layer in h-pa (in maximization rainfall 1000h-pa and 200h-pa pressure level are used)

g=gravitational acceleration in $^{cm}/_{s^2}$

ρ=density of water which is equal to $^{1g}/_{cm^3}$

3.2.2. Representative Storm Dew Point (T_d)

Dew points are determined from the warm humid air flowing in to the storm, both distance and directions of the dew points from the stations are recorded. But in the study area of this paper surface dew point temperature is not recorded, so to find the surface dew point temperature we can use equation 3.2 (Smith, 1966)

$$Td = \frac{237.3\ln(Rh) + 237.3(\frac{17.27T}{237.3+T})}{17.27 - \ln(Rh) - \frac{17.27T}{237.3+T}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots..3.2$$

Where:

Td=surface dew point temperature in Fahrenheit

T=maximum surface temperature in degree Celsius

Rh=relative humidity (g/kg)

To find the appropriate value of persisting storm dew point (T_{ds}) the average value of the representative storm dew point of different stations were taken.

The highest dew point detected for a given location and time of the year is known as Maximum persisting dew point (T_{dm}). Generally maximum persisting dew point (T_{dm}) is the maximum value from the historical surface dew point temperatures (T_d).

Maximum values of atmospheric water vapour used for storm maximization are usually estimated from maximum persisting 24-hour 1000-hPa dew points. These dew points are generally obtained from surveys of long records – 50 or more years – at several stations in the problem area. In some regions, the maximum dew points for each month of the year or critical season may be adequate to define the seasonal variation of maximum atmospheric moisture, but it is generally advisable to select maximum persisting 24-hour dew points using semi-monthly or 10-day intervals.

Dew point records appreciably shorter than approximately 50 years are unlikely to yield maximum values representative of maximum atmospheric moisture. The usual practice in such cases is to perform a frequency analysis on an annual series of monthly or shorter interval maximum persisting 24-hour dew points.

3.2.3. Moisture Maximization

To find the maximized moisture first it is mandatory to calculate the moisture maximization factor (MMF) properly. Which is calculated by dividing the maximum Precipitable water (wm) to the Precipitable water estimated for the storm (Ws). Therefore to estimate the above two parameters two dew point temperatures are required (24-h persisting storm dew point temperature-T_{ds} and 24-h persisting maximum storm dew point temperature (T_{dm}).

(WMO, 2009) Prepare a monograph to estimate the value of maximum Precipitable water (wm) from 24-h persisting maximum storm dew point temperature (T_{dm}), and also to estimate the value of Precipitable water (Ws) from 24-h persisting storm dew point temperature-T_{ds}

The monograph presents values of Precipitable water (mm) between the 1 000-hPa surface and various pressure levels up to 200-hPa in a saturated pseudo-adiabatic atmosphere as a function of the 1 000-hPa dew point. And different studies show that for maximization studies 1000h-pa and 200h-pa pressure level are used.

The (WMO, 2009) monograph is attached in appendix N

$$MMF = \frac{Wm}{Ws} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3.3$$

In most hydro meteorological work the atmosphere is assumed to contain the same amount of water vapour as saturated air with saturation pseudo adiabatic temperature lapse rate. The Precipitable water in various layers of the saturated atmosphere can be determined from the monogram. Finally Moisture maximization is estimated by multiplying the observed rainfall by the moisture maximization factor (MMF).

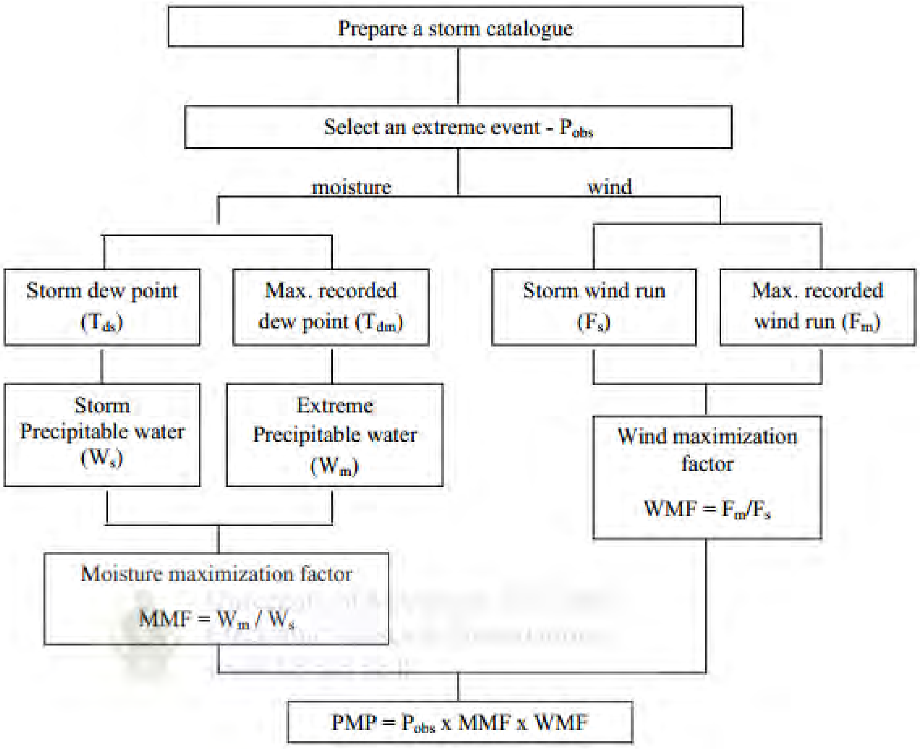

Figure 3- 1: The flow chart for storm maximization

Some correction for storm elevation may be required if the storm elevation is not at mean sea-level. Some studies have not made an adjustment for storm elevation (Hart, 1982; Schreiner and Riedel, 1978) if the elevation of the storm is less than 300 m. This decision is based on the distance to the moisture source, the storm characteristics and the topography of the region. Appendix N provides values for adjustment of Precipitable water for storm elevation.

3.3. Statistical Method

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

$$PMP = \bar{X}n + Km\,\delta n \text{ …………………………………………………………………….} 3.4$$

$$Km = \frac{XM - \bar{x}_{n-1}}{\delta_{n-1}} \text{ ………………………………………………………………………….} 3.5$$

Where $X_M, \bar{X}_n$ and δ_n are the highest, mean and standard deviation for a series of n annual maximum rainfall values of a given duration; $\bar{x}_{n-1}$and δ_{n-1} are the mean and standard deviation of the series excluding the highest value from the series; and Km is a frequency factor (WMO, 2009).

3.3.1. Development of Frequency Factor (Km)

The Hershfield method is used to find out the appropriate frequency factor that can give reliable PMP values for stations in the study area for practical application. But here the annual maximum rainfall amounts series of the stations found in the study area is used for the analysis.

3.3.2. Adjustment of Mean and Standard Deviation for Maximum Observed Events

Extreme rainfall events may occur at some time during a much shorter period of record, e.g. 50 years. Such unusual event, called an outlier, might have a visible effect on the mean and standard deviation of the annual series. Hershfield (1961) has been studied the hypothetical series of varying length, and the following figures were made to show the adjustments to be made to mean and standard deviations to compensate for outliers. In the figures X_{n-m} and S_{n-m} refer, respectively, to the mean and standard deviation of the annual series computed after excluding the maximum item in the series.

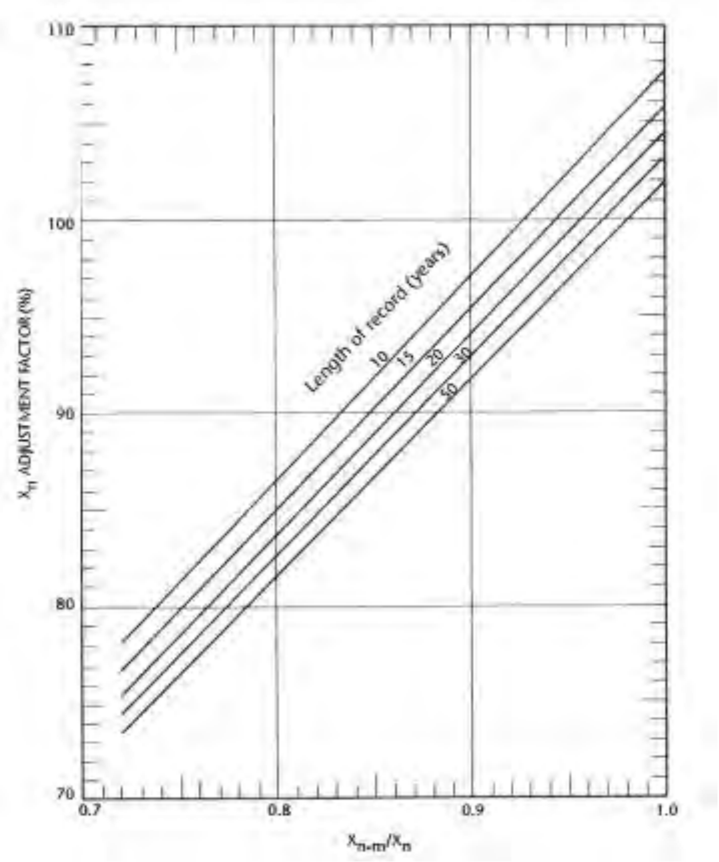

Figure 3- 2: Adjustment of mean of annual series for maximum observed rainfall (Hershfield, 1961b)

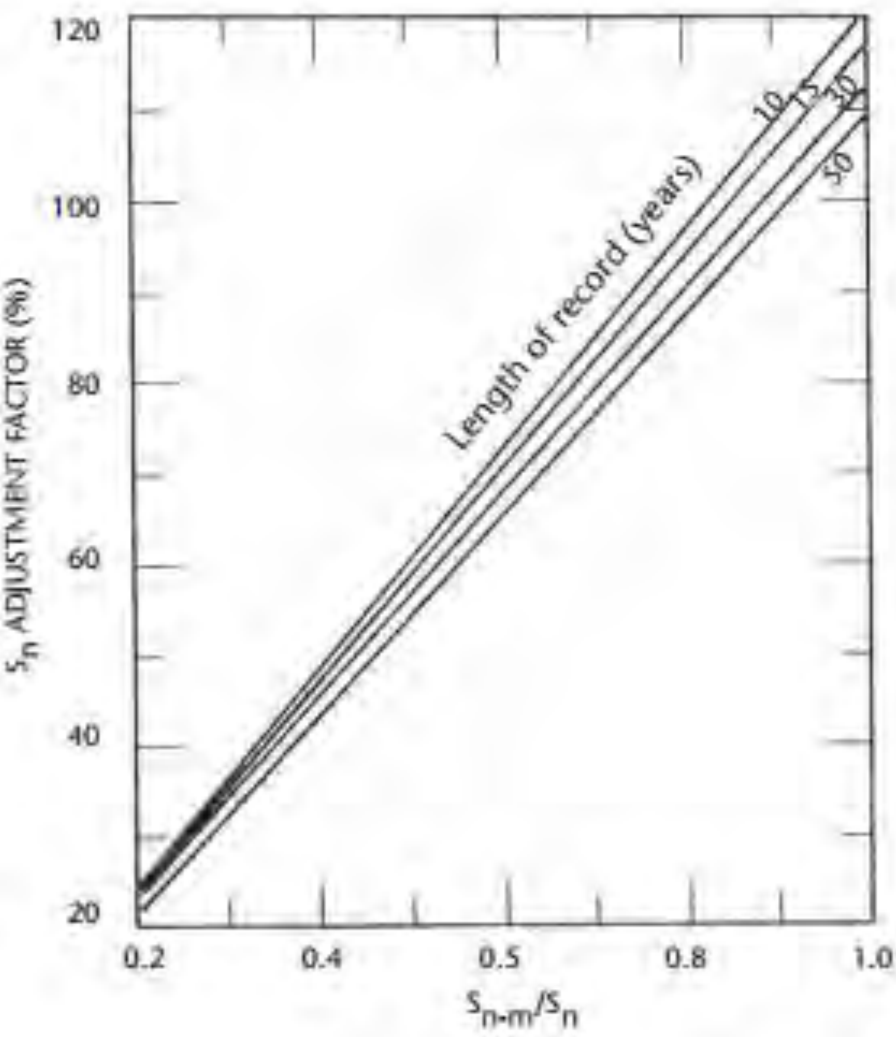

Figure 3- 3: Adjustment of standard deviation of annual series for maximum observed Rainfall (Hershfield, 1961b)

3.3.3. Adjustment of Mean and Standard Deviation for Sample Size

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

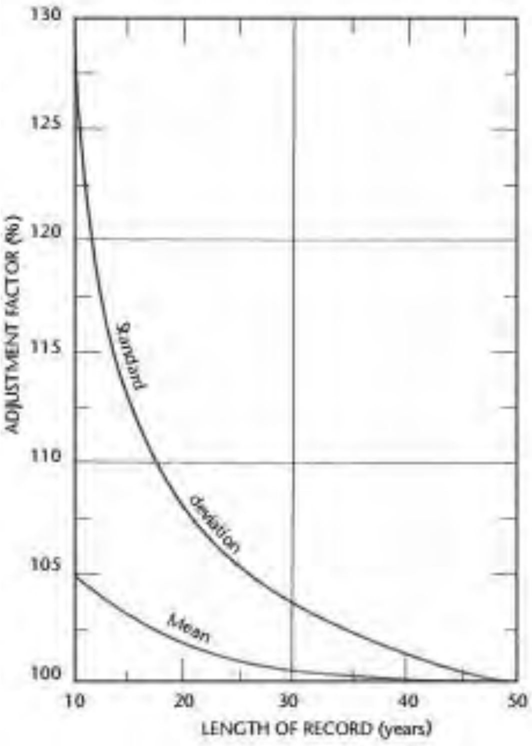

Figure 3- 4: Adjustment of mean and standard deviation of annual series for length of record (Hershfield, 1961b)

3.3.4. Adjustment of Data for Fixed Observational Time Intervals

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

Studies of thousands of station-years of rainfall data indicate that multiplying annual maximum hourly or daily rainfall amounts for a single fixed observational interval of one to 24 hours by 1.13 will yield values closely approximating those to be obtained from an analysis of true maxima ((WMO, 2009) .

3.3.5. Development of Frequency Factor (Km) from Hershfield's Chart

Hershfield prepare a curve for estimation of frequency factor by analysing data from 2700 stations 90% of which were in United States and he found that the maximum observed value of km was 15. Then, he decided that an estimate of the PMP values can be calculated by using km= 15, but in 1995 he proposed that the Km value equal to 15 is not compatible for all areas in USA .Therefore ,he constructed a chart indicating that Km varies between 5 and 20 depending on the rainfall duration and the mean (WMO, 2009).

Different studies show that the frequency factor (Km) found from Hershfield's graphical procedure was overestimate the actual value.

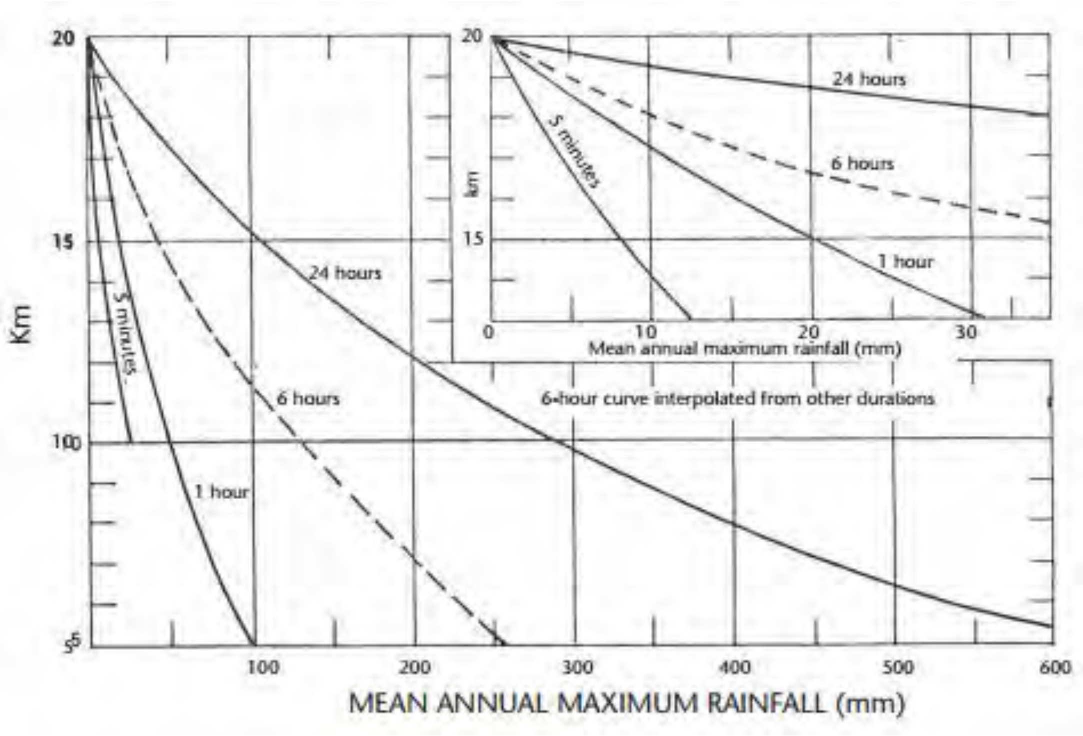

Figure 3- 5: The Hershfield's chart for determination of frequency factor Km

The study on Upper Blue Nile river basin indicates that the Km value obtained from the statistical procedure and the chart is far from each other. Hence a suitable Km value based on in-situ data of particular study area would give well estimates of PMP than Hershfield's chart (Abenezer & Dereje, 2015).

The research outputs of countries like China and Romania also showed that that their frequency factor (Km) value varies between 6 and 8.5 for their respective countries and rejected the Hershfield's chart as it over estimates the PMP ((Drobort, 2010).

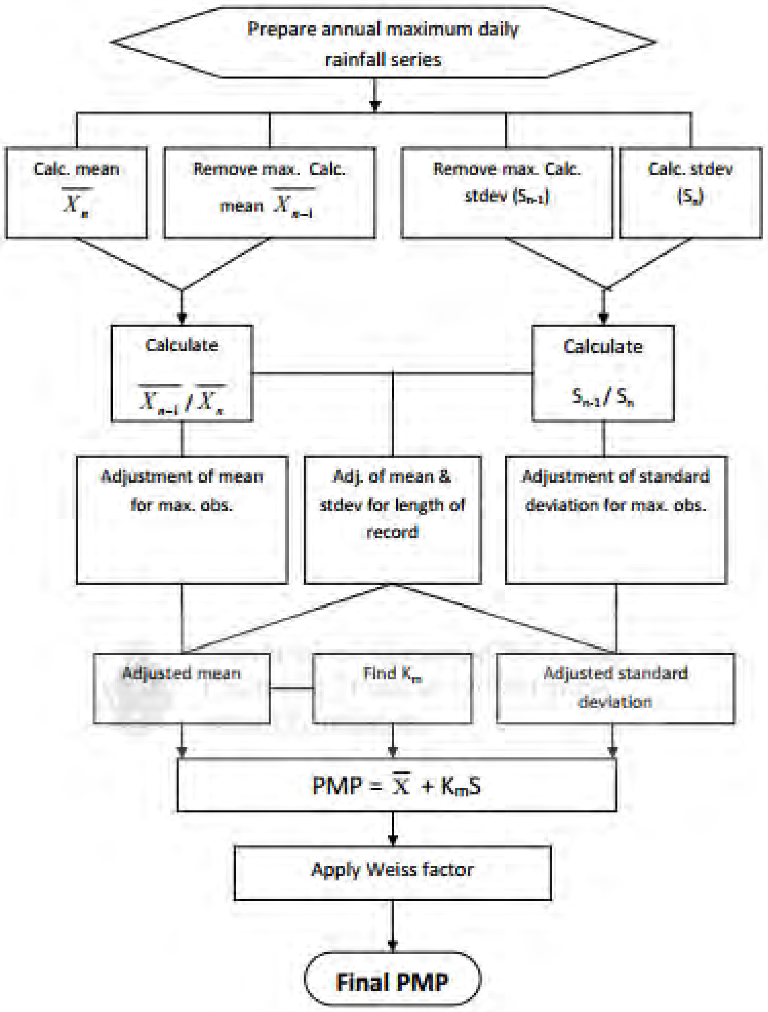

Figure 3- 6: The flowchart to estimate PMP using Hershfield's method

3.4. Parameter Selection for Frequency Analysis

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

Easy-Fit statistical computer software with proper parameter estimation method suitable for each distribution within the interface.

3.4.1. Parameter Estimation

Several methods can be used for parameter estimation. The method of moments (MOM), the method of maximum likelihood (MML) and the L-moment method (LMM) are used for parameter estimation in the statistical computer software (Easy-Fit).

The method of maximum likelihood (MML) is considered to be the most accurate method, especially for large data sets since it leads to efficient parameter estimators with Gaussian asymptotic distributions. It provides the smallest variance of the estimated parameters, and hence of the estimated quintiles, compared to other methods. However, with small samples the results may not converge.

The method of moments (MOM) is relatively easy and is more commonly used. It can also be used to obtain starting values for numerical procedures involved in ML estimation. However, MOM estimates are generally not as efficient as the ML estimates, especially for distributions with large number of parameters, because higher order moments are more likely to be used to obtain starting values for numerical procedure involved in ML estimation. However, MOM estimates are generally not as efficient as the ML estimate especially for distribution with large number of parameters, because higher order moments are more likely to be highly biased for relatively small samples.

Easy-Fit software uses the least computationally intensive methods. Thus, it employs the method of moments for those distributions whose moment estimates are available for all possible parameter values, and do not involve the use of iterative numerical methods. For many distributions, Easy-Fit uses the ML method involving the maximization of the log-likelihood function. For some distributions, such as the 2-parameter Exponential and the 2 parameter Weibull, a closed form solution of this problem exists. Given the initial parameter estimates vector, this method tries to improve it using subsequent iteration. In this study Easy-Fit statistical computer software were used for parameter estimation of selected distributions. Easy-Fit software use MML for Generalized Extreme Value (GEV) distributions.

4. DATA AVAILABLITY AND ANALYSIS

4.1. Data Availability

For this study 30years of daily rainfall, relative humidity and temperature data from the meteorological stations of Upper Awash sub river basin were taken.

The basic information for available stations are listed on appendix A and the annual maximum for 1-day,2-days and 3-days of the rainfall data prepared from the daily rainfall data are listed in appendix B.

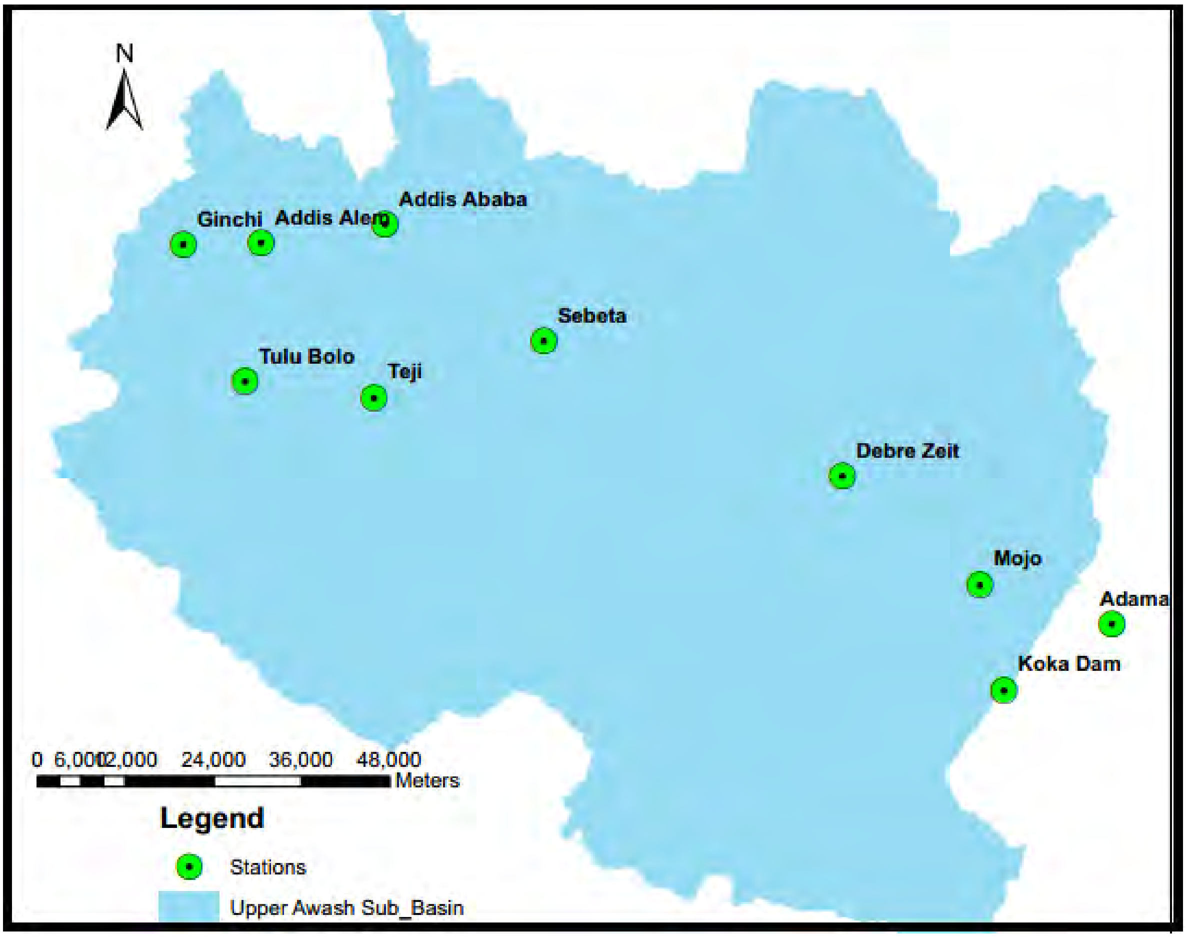

Fig 4-1-Meteorological Stations over the Upper Awash Sub basin

4.2. Data Quality Control

In order to get good results, the qualities of the data should be investigated though different methods of checking. Under flood frequency analysis the following tests are commonly used, test for Consistency, homogeneity, and independence of data which are discussed below.

4.2.1. Test for Independence

It is usually assumed that all the peak magnitudes in the AM series are mutually Independent in the statistical sense. This assumption is usually justified. A hydrologic time series is stationery if it is free of trends, shifts or periodicity (cyclist) which implies that the statistical parameters of the series, such as the mean, variance, and autocorrelation structure do not change over time (Hanssen-Bauer, 1991).

The statistical analysis for dependence is carried out for all the 1-day 2-day and 3-day durations of rainfall record with in each station.

The statistical analysis for dependence is carried out for all the 1-day, 2-day and 3-day durations of rainfall record with in each station.

In this paper Wald –Wolfowitz (W –W) test is used to check the independency of the data set.

For the data set $X1, X2, X3 \dots\dots X_n$

$$\mathrm{R}{=}\sum_{i=1}^{n-1} X_i\, X_{i+1} + X_1 X_n$$

$$\dddot{\boldsymbol{R}} = \left(\frac{\boldsymbol{X_1}^2 - \boldsymbol{S_2}}{\boldsymbol{n-1}}\right)$$

$$Var(R) = \frac{\boldsymbol{S_2}^2 - \boldsymbol{S_4}}{\boldsymbol{n-1}} - \ddot{\boldsymbol{R}}^2 + \left(\frac{\boldsymbol{S_1}^4 - \boldsymbol{4S_1}^2\boldsymbol{S_2} + \boldsymbol{4S_1S_3} + \boldsymbol{S_2}^2 - \boldsymbol{2S_4}}{(\boldsymbol{n-1})(\boldsymbol{n-2})}\right.$$

$$U = \frac{\boldsymbol{R} - \ddot{\boldsymbol{R}}}{\boldsymbol{var(R)}^{1/2}}$$

$$U_{critical} = 1.96$$

Table 4- 1: Independent Test for Tulu Bolo Station

	Independent Test for Tulu Bolo Station		
Duration	Statistics(U)	Critical Statistics(Ucritical)	Remark
1-Day	0.503737	1.96	Independent
2-Day	0.268833	1.96	Independent
3-Day	0.30688	1.96	Independent

4.2.2. Homogeneity Test for the Data Series

"A Data set is Homogeneous if the measurements have been consistently done by the same procedure, with the same instrumentation, at the same time and place, and the same environment" (Hanssen-Bauer, 1991).

In this paper the homogeneity test is done by Mann-Whitney (M-W) test. In this test two samples of size p and q with $p \leq q$ are compared. The combined data set of size $N = p + q$ was ranked in increasing order. The Mann-Whitney (M-W) test considers the quantities V and W (Mann & Whitney, 1974; Mann & Whitney, 1974).

Where

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

$$W = pq - V$$

R is the sum of the ranks of the elements of the first sample (size p) in the combined series (size N), and V and W are calculated from R, p, and q. V represents the number of times an item in sample 1 follows an item in sample 2 in the ranking. Similarly, W can be computed for sample 2 following sample 1. The M-W Statistic U is defined by the smaller of V and W. When $N > 20$ and p, $q > 3$, and under the null hypothesis that the two samples came from the same population, is approximately normally distributed with mean and variance.

Where

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

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

Where $T = J^3 - J/12$ and J is the number of observations tied at a given rank. T is summed over all groups of tied observations in both samples of size p and q. The statistic $u = (U - U_{mean})/[Var(U)]^{1/2}$ is used to test the hypothesis of homogeneity at significance level α by comparing it with the standard normal variate for that significance level.

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

Table 4- 2:2- Day Homogeneity Test of Adama Station

2-Day Homogeneity test of Adama Station	
Sample Size	34
Sample1 (p)	16
Sample 2 (q)	18
Number of Observation tied (J)	1
Sum of the tied	0
$Var(U)$	835.5080214
Standard test result for 5% significant level (u)	0.594<1.96 (Homogeneous)

As shown in the table 4-2 the standard test for Adama station for 5% significant level was found to be less than 1.96 therefore no significant trend in the annual maximum rainfall values exist. Hence, the annual maximum rainfall series for the station is treated as homogeneous for subsequent calculation, for all the rest of stations shown in appendix C.

5. RESULT AND DISCUSSION

5.1. Probable Maximum Precipitation (PMP) Using Statistical Method

Different studies show that the frequency factor (Km) found from Hershfield's graphical procedure was overestimate the actual value.

The study on Upper Blue Nile river basin indicates that the Km value obtained from the statistical procedure and the chart is far from each other (Abenezer & Dereje, 2015). Hence a suitable Km value based on in-situ data of particular study area would give well estimates of PMP than Hershfield's chart. So in this study the Km value of Upper Awash sub river basin was calculated by both statistical procedure and Hershfield's chart, then the study also put how much the Hershfield's chart overestimate the actual value in the basin.

In sight of the stated problems in the statement of problem part and current research outputs moisture maximization and transposition method requires more site specific data and thus provides more reliable estimate than the other methods and where site specific data are not available statistical (Hershfield) method can be applied that requires data for annual maximum rainfall series in the region for required storm durations. Due to the above reasons this paper used two methods (storm maximization and statistical method) for estimating PMP on the basin.

5.1.1. Determination of Frequency Factor (K) Values Using Hershfield's Frequency Equation

The values of mean, standard deviation, and highest observed precipitation were calculated for annual maximum series of each station corresponding to each duration. Mean and standard deviation were adjusted for sample size and maximum observed event. Adjustments were made based on Figure 3.2, 3.3 and 3.4 (in the methodology part of this paper) (WMO, 2009).

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

The results of this study show that the maximum frequency factor (Km) of the basin found from the statistical procedure was approximately six. The maximum frequency factor (Km) for 1-Day, 2-Day, and 3-Day durations are 6.17, 6.02 and 5.81 respectively. This indicates that in the upper Awash River basin the value of maximum frequency factor (Km) is closely the same in different durations.

Studies show that Ethiopia use the maximum value of the frequency factor from Hershfield's chart (Km=15), but table 5-1 show that most stations have frequency factor (K) below 5.So this show that we constructed uneconomical Hydraulic structures in our river basins.

Table 5- 1: The value of frequency factors K for 1, 2, and 3-Days duration.

Stations	The frequency factor K for (1,2,and 3-DayS) duration		
	K (1-Day duration)	K(2-Days duration)	K(3-Days duration)
Adama	3.36	4.55	3.34
Addis Ababa	3.05	2.33	2.31
Addis Alem	6.17	5.69	4.85
Debre Berhan	4.18	3.98	4.87
Debre Zeit	2.49	4.35	3.2
Ginchi	2.66	3.43	2.2
Koka	2.6	6.02	5.81
Mojo	2.79	2.63	2.6
Sebeta	4.92	3.92	3.5
Teji	4.39	1.91	2.83
Tulu Bolo	3.48	1.96	2.267

As shown in the above table around 36.4% of the stations have a frequency factor below 3 and 54.6% of the stations have the value of frequency factor between 3 and 5, only 9% of the stations have the frequency factor above 5. Different research in the world indicated that the frequency factor Km=15 exaggerated, India (Srinivas & Chavan, 2015), Iran (Gharaman, 2008) , Spain (Casas, Rudriguez, Prohom, & Gazquez, 2010) are some examples. The research edited by (Abenezer & Dereje, 2015) , (Alemayehu & Semu , 2010) on UBNB also indicates that this value was overestimated in the river basin. However Ethiopia use Hershfield's frequency factor (Km) fifteen for estimating the PMP for all river basins. This paper indicates that using the frequency factor Km=15 without detailed study of estimating the PMP leads the country to construct uneconomical hydraulic structures (spillways).

5.1.2. Estimation of Frequency Factor (K) Using Hershfield's Chart

The adjusted values of mean ($\bar{X}_n$) and standard deviations σn of the stations with the Hershfield's chart were taken to calculate the frequency factor of each station for 1-day duration. Hershfield prepare a chart using data from 2 700 stations (90 per cent of which are located in the United States of America) ,due to this reason the frequency factor estimated from the chart may not reliable.

The results in this paper shows that all the stations have a value of the frequency factor (Km) larger than 15 and the maximum frequency factor (Km) is 17.4.

Table 5- 2: Frequency factor (Km) from Hershfield's chart

Station	Adama	Addis Ababa	Addis Alem	Debre Berhan	Debre Zeit	Ginchi	Koka	Mojo	Sebeta	Teji	Tulu Bolo
Km	16	16.28	17.3	17.15	17.04	17.03	16.39	16.51	16.02	17.21	17.4

The value of 1-day duration maximum frequency factor (Km) founded from Hershfield's chart is 3 times larger than the value of the maximum frequency factor (Km) founded from the Hershfield's statistical method. So in this basin the frequency factor (Km) found from Hershfield's graphical procedure was 3 times overestimate the actual value.

5.1.3. Estimation of PMP Using statistical method

Hershfield's method or statistical method of estimating probable maximum precipitation (PMP) is a very valuable, common and reliable method for hydrologic design because it is based on the analysis of a huge amount of rainfall information (Koutsoyiannis D. , 1998).If adequate precipitation data is available statistical methods are useful for the PMP estimation. The statistical method aims at the determination of the point PMP for a given gauge station.

Due to lack of meteorological data in developing country like Ethiopia using statistical method is the best way to estimate PMP. In this study daily rainfall data of 11 stations from the Upper Awash sub river basin were taken with the adjusted values of mean ($\bar{X}_n$) and standard deviations σn of the stations to estimate point PMP. The maximum frequency factor (Km) was also taken to estimate the probable maximum precipitation of the stations.

Table 5- 3: Procedure to estimate the probable maximum precipitation of Addis Alem Station

No	Descriptions	Symbol	Values
1	Station Name	Addis Alem	
2	Sample Size	N	31
3	Mean(mm)	$\bar{X}_n$	43.8
4	Standard Deviation(mm)	σ_n	16.6
5	Mean after Excluding the maximum rainfall depth from the series(mm)	$\bar{X}_{n-1}$	41.6
6	Standard deviation after Excluding the maximum rainfall depth from the series(mm)	σ_{n-1}	11.3
7	The ratio of 5 and 3	$\bar{X}_{n-1}/X_n$	0.95
8	The ratio of 6 and 4	σ_{n-1}/σ_n	0.68
9	Adjustment of mean for the maximum observed series (see section 3)	From fig(3.2),	0.98
10	Adjustment of mean for length of record (see section 3)	From fig (3.4)	1.01
11	Adjustment of standard deviation for the maximum observed series (see section 3)	From fig(3.3)	0.82
12	Adjustment of standard deviation for length of record	From fig(3.4)	1.04
13	Adjusted mean(mm)	adj. mean	43.4
14	Adjusted standard dev(mm)	adj. standard dev	14.19
15	Frequency factor	Km	6.2
16	1-day probable maximum precipitation(mm)	1-day PMP	148.001

As shown in table5.4 the highest value of probable maximum precipitation (PMP) for 1-day duration is observed in Sebeta station with the value of 317.88mm. The highest value of estimated rainfall depth for a return period 10,000 years for 1-day duration in the study area using generalize extreme value method (GEV) was 161.9 mm. this show that there are 51% difference between the two result.

Table 5- 4:1-Probable maximum precipitation of the stations for 1-day duration

Station	Adjusted ($\bar{X}_n$)	Adjusted (σ_n)	K	1-day PMP
Adama	71.7753	17.8227	3.35819	205.4
Addis Ababa	56.9912	16.195	3.04735	177.4
Addis Alem	43.3662	14.1913	6.17336	148.0
Debre Berhan	46.6875	11.185	4.1766	130.8
Debre Zeit	49.154	13.807	2.49308	151.9
Ginchi	49.2498	11.9624	2.66399	139.1
Koka	58.0404	20.3166	2.60389	207.3
Mojo	56.1877	18.0469	2.78713	189.4
Sebeta	58.747	36.0527	4.91528	317.9
Teji	46.9757	12.8016	4.38777	142.4
Tulu Bolo	44.8922	11.2084	3.47655	128.9

Overtopping of dams due to inadequate spillway discharge capacity to pass flood waters. This is one of the most common causes of dam failures. Dam will fail if the spillway is too small and flood waters raise high enough to flow over the top of the dam wall. PMF is used to determine the design characteristics of flood protection works. The PMF as the upper limit of flood potential at a site, for storm duration and magnitude defined by the Probable Maximum Precipitation (PMP) is the common method to determine the spillway discharge capacity.

In this study the calculated PMP values are around 1.72 times higher than the recorded maximum rainfall values on the stations of Upper Awash Sub basin; in the other word we can say that the estimated PMP values have a factor of safety around 1.72.

In general the values of PMP estimated by this method have 1.72 higher than the maximum rainfall record; it is also higher than the rainfall depth for 10,000 year return period. This indicates that we can design the structures using the above PMP values and should not be any risk for overtopping of the structures.

5.1.4. Estimation of PMP Using Hershfield's Chart

To evaluate the frequency factor (Km) Hershfield[1961] initially analysed a total of 95 000 station-years of annual maximum rainfall belonging to 2645 stations of which about 90% were in the USA, and found that the maximum observed value of Km was 15. Then, he decided that an estimate of the PMP values can be calculated by using Km= 15, but in 1995 he proposed that the Km value equal to 15 is not compatible for all areas in USA .Therefore ,he constructed a chart indicating that Km varies between 5 and 20 depending on the rainfall duration and the mean (WMO, 2009).

Different studies show that experts in Ethiopia have been using Hershfield's Chart for estimation of PMP and their results indicates that for our country Ethiopia Hershfield's graphical procedure is not well tested (Alemayehu & Semu , 2010). Now in this paper estimation of PMP were made by both Hershfield's chart and Hershfield's frequency equation for 1-day duration and tried to give reasonable justification.

Table 5- 5: 1-day duration probable maximum precipitation (PMP) founded from Hershfield's chart

Station	Adjusted ($\bar{X}_n$)	Adjusted (σ_n)	K(From Chart)	PMP (Using Chart)
Adama	71.78	17.82	16	431.60
Addis Ababa	56.99	16.19	16.28	382.89
Addis Alem	43.366	14.19	17.30	328.08
Debre Berhan	46.69	11.19	17.15	272.72
Debre Zeit	49.15	13.81	17.04	327.07
Ginchi	49.25	11.96	17.03	290.90
Koka	58.04	20.32	16.39	465.13
Mojo	56.18	18.05	16.51	418.40
Sebeta	58.74	36.05	16.02	775.39
Teji	46.98	12.80	17.21	304.84
Tulu Bolo	44.89	11.21	17.40	271.15

According to Abenezer Endale and Dereje Hailu the PMP estimated from the frequency factor founded from the Hershfield's chart was overestimated in UBNB (Abenezer & Dereje, 2015).

The above table indicates that the maximum frequency factor (Km) founded from the Hershfield's chart is 17.4 ,So this result clearly showing the Maximum frequency factor obtained from Hershfield's chart is over estimated.

The PMP value obtained using the chart maximum frequency factor (Km) deviated around 54% from the PMP Value obtained from the Hershfield's frequency equation.

Table below clearly indicated that estimated value of probable maximum precipitation (PMP) using the maximum frequency factor (Km) is around three times of the PMP values obtained from the Hershfield's frequency equations. This large difference of PMP as a result of difference in frequency factor (K) founded from Hershfield's statistical procedure and Hershfield's chart has significant consequence in the total cost of dam projects when dam design is considered based on PMF. Therefore, high attention should be provided for the estimation of Km values because Km constant is very sensitive in the estimating PMP.

Table 5- 6: Comparison of the resulted PMP of the Hershfield's frequency equation with the PMP from the graphical method

Station	For 1-Day duration				
	K	K(from Chart)	PMP	PMP (Using Chart)	Deviation (%)
Adama	3.36	16	205.44	431.6	110.1
Addis Ababa	3.05	16.28	177.38	382.89	115.86
Addis Alem	6.20	17.3	148.00	328.08	121.67
Debre Berhan	4.18	17.15	130.78	272.72	108.53
Debre Zeit	2.49	17.04	151.86	327.07	115.4
Ginchi	2.66	17.03	139.10	290.9	109.1
Koka	2.60	16.39	207.31	465.13	124.4
Mojo	2.79	16.51	189.39	418.4	120.9
Sebeta	4.92	16.02	317.89	775.39	143.9
Teji	4.39	17.21	142.39	304.84	144.0
Tulu Bolo	3.48	17.4	128.92	271.15	110.32

5.2. Frequency Analysis

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

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

5.2.1. The Probability Distribution

The distribution models which are suggested by WMO for annual maximum data series (Cunnane, 1989) are listed below.

- Normal distribution (NOR)
- Two parameter Log-Normal distribution (LN2)
- Three Parameter Log-Normal distribution (LN3)
- Exponential distribution
- Two parameter Gamma distribution
- Pearson three distribution (PIII)
- The four parameter Wakeby distribution(WAK4)
- Log Pearson three distribution (LP3)
- Generalized extreme value distribution(GEV)
- Extreme value type one distribution (EVI)
- Weibull distribution(W)
- The five parameter Wakeby distribution(WAK5)

In this study Easy-Fit statistical computer software was used for selecting the best fit distribution of the stations. Table 5.7 show that the best fit distribution for 1-day, 2-day and 3-day maximum rainfall duration from easy–fit statistical computer software. The result indicates that majority of the station in the basin is fitted with GEV.

GEV	33.33%
Log Normal	18.18%
Weibull	18.18%
Logperson3	12.12%
Lognormal (3P)	9.09%
Normal	6.06%
Weibull (3P)	3.03%

Table 5- 7: Best fit distribution for 1-Day maximum rainfall duration

Station	1-Day
Adama	Lognormal(3P)
Addis Ababa	Log person type 3
Addis Alem	General extreme Value
Debre Berhan	General extreme Value
Debre Zeit	Lognormal
Ginchi	Weibull(3p)
Koka	Weibull
Mojo	General extreme Value
Sebeta	Lognormal
Teji	Weibul1
Tulu Bolo	General extreme Value

5.2.2. Parameter Estimation

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

Table 5- 8 : Estimated parameters of GEV distributions for Addis Alem station.

Name of stations	Selected distributions	Parameters	Value
1-Day duration			
Addis Alem	General extreme value	K	0.153
		σ	7.1629
		μ	36.177
2-Day duration			
Addis Alem	General extreme value	K	-0.0447
		σ	9.7399
		μ	48.442
3-Day duration			
Addis Alem	General extreme value	K	0.00705
		σ	9.5331
		μ	61.043

5.2.3. Estimation of Extreme Rainfall Magnitude from the Observed Rainfall

As the Table 5.7 shown for the 1-Day, 2-Days and 3-Days durations the best fit distribution of the majority stations in the study area was General Extreme Value (GEV).

Paper edited by Koutsoyiannis and Demetries show that Hershfield's estimate of PMP obtained by using the Generalized Extreme value (GEV) distribution with shape parameters given as a specific linear function of the average annual maximum precipitation (Koutsoyiannis D. , 1998),and different researches recommended GEV distribution for determine the extreme rainfall value related with a large return period (Alemayehu & Semu , 2010), (Koutsoyiannis D. , 1998), (Haktanier, Cobaner, & Kisi, 2010).

As shown on the above table GEV is best fit distribution for the majority of the station and according to Koutsoyiannis and Demetries research Hershfield's estimate of PMP obtained by using the Generalized Extreme Value (GEV), due to those reasons this paper uses GEV distribution for estimating the magnitude of 1-Day, 2-Days and 3-Days rainfall durations for 10,000 years return period.

The results of estimated extreme rainfall magnitude from observed daily maximum rainfall for all the stations in the sub-basin are shown in Appendix F for return periods: 2,5,10,25,50,100,200,500,1000,2000,5000,10000 years.

Table 5- 9: Estimated rainfall depth for Addis Alem station

Return Period	Estimated rainfall depth for Addis Alem station(mm)		
	1-Day	2-Days	3-Days
2	44.03	60.45	72.45
5	50.24	72.4	83.11
10	53.79	80.65	90.13
25	57.73	91.48	98.94
50	60.31	99.81	105.45
100	62.6	108.35	111.87
200	64.67	117.12	118.23
500	67.07	126.59	129.11
1000	68.67	132.86	138.52
2000	70.11	139.1	148.21
5000	71.79	147.31	161.49
10000	72.92	153.48	171.9

5.2.4 Comparing the PMP Values with the 10,000 years Return Rainfall Depths

PMP has a theoretical exceedance probability zero, but this is not in the real situation.Hershfield's estimate of PMP may be obtained by using the Generalized Extreme value (GEV) , and for a return period equal to 60,000 years (Koutsoyiannis D. , 1998).

According to Hershfield (1962), the magnitude of point PMP at an individual station should normally not exceed three times the Highest Observation Rainfall from a long period of rainfall data (Rakehacha & Kulkami, 1981).

For any hydraulic structure the critical flood peaks to be designed mostly based on the extreme rainfall events with the return period 10,000 years (Haktanier, Cobaner, & Kisi, 2010).

In this study the value of PMP founded from Hershfield's statistical procedure was around 1.5,1.7,1.6 times that of 10,000 years return period rainfall depth for 1-Day ,2-Days and 3-Days durations respectively.

5.3. Estimation of Probable Maximum Precipitation using Moisture Maximization method

The storm maximized method is used to maximize the observed precipitation data to allow for maximum moisture inflow theoretically possible at the site.

Moisture Maximization method provides more reliable estimate of PMP than the other methods, but it needs more site specific meteorological data like daily Rainfall, daily Relative humidity, daily maximum temperature.

In Upper Awash sub river basin there are many meteorological stations but only four stations (first class recording Meteorological station) have detailed meteorological data .This paper used daily rainfall data from 11 stations for statistical method and daily Rainfall, relative humidity and maximum temperature data from 4 first class recording meteorological stations for moisture maximization method.

In This paper estimation of Probable maximum precipitation were made by using moisture maximization method and compare the result with the value of PMP founded from Statistical method.

5.3.1. Preparation of Storm Catalogue

The objective of establishing a storm catalogue is to identify extreme rain fall from the selected stations. The catalogue was prepared by considering the top 5 extreme rainfall per year for each station. Ten extreme rainfalls of Addis Ababa, Adama and Debre Zeit stations are listed in table 5-10 and the storm catalogues of all statins are attached in appendix L.

The major rainy season of Ethiopia is summer season (from June to August) and the storm catalogue clearly indicates that many extreme rainfall events were occurred during summer and autumn seasons.

Table 5-10: Storm catalogues for selected station.

Addis Ababa		Adama		Debre Zeit	
Date	Rainfall(mm)	Date	Rainfall(mm)	Date	Rainfall(mm)
05/04/1986	83.8	18/02/2006	62.8	05/06/1996	62
09/08/1995	85.3	30/08/2007	55.1	11/06/1996	57.8
10/09/1996	67	09/04/2008	72.5	15/08/1996	54.8
09/10/1998	78.3	15/07/2009	54	26/11/1997	70
12/03/2001	96.3	09/08/2010	56.1	10/02/1998	53.6

27/04/2005	58.6	04/07/2012	69.6	02/01/1998	74
31/03/2006	70.9	16/08/2012	54.8	21/01/2004	55.7
23/09/2006	61.9	06/07/2012	61.6	27/09/2004	74.4
19/08/2007	64	01/07/2013	57.9	16/03/2009	61
11/09/2014	65.4	04/09/2013	59.4	17/12/2009	61

5.3.2. Representative Storm Dew Point

Dew point temperature is the temperature at which the moisture in the air forms possible drops of water. When air is holding all the water it can hold, it is said to be saturated. In Upper Awash sub basin the dew point temperatures are not readily available, so it is calculated from daily relative humidity and maximum surface temperature. The method is described in equation 3.2.

Table 5- 11: Calculated Dew Point Temperature (Td) for some selected days in AA station

Day	Rainfall	Humidity (%)	Surface air temperature (^{O}C)	Dew point temperature(^{O}C)
05/04/1986	83.8	59	22	12.7
09/08/1995	85.3	89	21.2	17.0
10/09/1996	67	47	22.4	10.4
09/10/1998	78.3	90	20.2	16.4
12/03/2001	96.3	87	23	18.1
27/04/2005	58.6	70	24.8	16.7
31/03/2006	70.9	78	22.3	16.2
23/09/2006	61.9	89	24	19.1
19/08/2007	64	84	20.8	16.0
11/09/2014	65.4	86	22.4	17.4

Table 5-11 clearly indicated that dew point temperature never higher than surface air temperature. If the dew point temperature and surface air temperature are equal it is said to be saturated. The maximum dew point for any location is chosen by surveying long record period (50 years or above) of a highest value of persisting dew point of the station. But in this study the maximum record period is 30 years, so the maximum dew point temperature is calculated by performing the frequency analysis on annual series of monthly maximum persisting temperature with 100 year return period. The frequency analysis was done by easy fit statistical software. The maximum dew points in Addis Ababa, Debre Zeit, Debre Berhan and Adama stations are 21, 22, 25 and 21 ^{o}C respectively.

5.3.3. Precipitable Water

Precipitable Water (PW) indicates the amount of moisture there is above a fixed point. It does not indicate how much it will rain but rather how much moisture is in the air. For example, a Precipitable Water value of 1 inch does not indicate it will rain 1 inch but rather indicates all the moisture above a location if condensed would be 1 inch. The Precipitable Water value gives a forecaster an idea of the amount of moisture in the air. Higher values indicate greater availability of moisture to make rainfall. In this study also the maximum Precipitable values and extreme rainfall events were recorded in the summer and autumn seasons.

In most hydro meteorological work the atmosphere contain the same amount of water vapour as saturated air with saturation pseudo-adiabatic temperature lapse rate. The Precipitable water in various layer of the saturated atmosphere can be determined and listed in appendix N. In this paper the value of Precipitable water is determined from appendix N but it is between the 1000hPa surfaces (at mean sea level) up to 200 hPa, so it needs some adjustments.

Table 5- 12: Precipitable water with dew point temperature for five extreme rainfall events at Addis Ababa Station

Date	Rainfall (mm)	Humidity (%)	Dew point temp. (^{o}C)	Precipitable water WS (mm)
05/04/1986	83.8	59	12.66935	25.33871
09/08/1995	85.3	89	16.96973	36.90919
09/10/1998	78.3	90	16.35778	35.07334
12/03/2001	96.3	87	18.03566	41.14264
31/03/2006	70.9	78	16.18426	34.55279

Some correction for storm elevation must be required because the stations in the Upper Awash sub basin is not at mean sea level. For example Addis Ababa station have 2386 m asl and the value of Precipitable water (WS) must be adjusted for its elevation. Appendix N contains the extra amount of water due to elevation.

Table 5- 13: Adjusted Precipitable water for five extreme rainfall events at Addis Ababa Station

Date	Rainfall (mm)	Humidity (%)	Dew point temp. (^oC)	Max. Dew point temp. (^oC)	Adjusted WS(mm)	Adjusted WM (mm)
05/04/1986	83.8	59	12.67	21	8.32	24.14
09/08/1995	85.3	89	16.97	21	13.503	24.14
09/10/1998	78.3	90	16.368	21	12.75	24.14
12/03/2001	96.3	87	18.04	21	15.85	24.14
31/03/2006	70.9	78	16.18	21	12.54	24.14

As indicated in the above table the maximum moisture was not overcome during historical storm (24.14mm) and Precipitable water increases with dew point temperature. There was a chance that condition of maximum possible moisture available may not prevail during historical storm and more precipitation might have occurred if the maximum moistures were available during the extreme rainfall events.

5.3.4. Estimation of Probable Maximum Precipitation (PMP)

As indicated in methodology part Using Precipitable water (WS) and maximum Precipitable water (WM) we can calculate the moisture maximization factor (MMF), and the probable maximum precipitation (PMP) is estimated by multiplying the extreme rainfall events by moisture maximization factor (MMF).

Table 5- 14**:** Moisture maximization factor (MMF) and Probable Maximum Precipitation for six extreme rainfall events at Debre Zeit station

Day	Rainfall(mm)	Humidity (%)	Adjusted WS(mm)	Adjusted WM (mm)	MMF	PMP (mm)
05/06/1996	62	56	7.52	32.5	4.32	267.84
26/11/1997	70	85	18.74	32.5	1.73	121.10
02/01/1998	74	71	21.05	32.5	1.54	114.26
27/09/2004	74.4	54	12.12	32.5	2.68	199.40
16/03/2009	61	31	6.63	32.5	4.90	299.02
17/12/2009	61	40	9.56	32.5	3.34	207.39

In this study the calculated PMP values are around 3 times higher than the recorded storms in the first class meteorological stations of Upper Awash sub river basin. In the other word we can say that the estimated PMP values have a factor of safety around 3. The factor of safety (FOS) usually adopted in engineering activities are 1.4-2.0, so it can be conclude that the estimated values of PMP is reasonable.

Table 5- 15: Calculated 1-Day PMP using statistical and Moisture Maximization methods

Station	PMP- moisture maximization (mm)	PMP-statistical (mm)
Addis Ababa	243.22	177.38
Adama	291.82	205.44
Debre Berhan	272.85	130.78
Debre Zeit	299	151.86

Table 5.14 indicates that the PMP estimated from the moisture maximization method is around 1.7 times higher than the value of PMP founded from statistical method.

Different researches indicated that moisture maximization method is more reliable than statistical method. Due to data limitation in our country statistical method is widely used to estimate the values of probable maximum precipitations. This study shows that the values founded from moisture maximization were overestimated when we compare with the statistical method, so detail study of PMP using moisture maximization method for first class recording meteorological stations are necessary to get reliable information about the reliability of PMP values estimated by Statistical method.

The research edited by Chen and Bradley (2006) show that the moisture maximization method overestimate the PMP values by about 7% on average due to pseudo adiabatic assumptions. This study also used pseudo adiabatic assumption because of lack of radio stone observation to determine the dew point temperature and the Precipitable water in the meteorological stations. The paper edited by M Carmen Casas and his fraínds shows that the statistical method provided PMP values that are slightly higher than the moisture maximization method, all the estimates differ by less than 10% (Casas, Rudriguez, Prohom, & Gazquez, 2010).The study of PMP on Sri Lanka indicated that the values of PMP founded from the moisture maximization method were almost similar with the values of PMP estimated by statistical method (Wickramasuriya & Fernando, 2011).

All the above studies specified that the comparisons of the PMP values of the two mostly used methods: moisture maximization and statistical method were different and it is depending on the region where the research was done. But we can conclude that the difference between the PMP values of two methods is slight (up to 10%).

Because of absence of radio stone observations to determine the dew point temperature, relative humidity and surface temperature with the pseudo adiabatic assumption were used in this study. This might be amplifying the value of PMP. In addition to this relative humidity and surface temperature taken from the meteorological stations for this study were recorded only once on a day, this value may not represent the value of the data on the given day so it have also significant effect on the exaggerated PMP value.

The other assumption for this amplifying result is going to the record period of the data. In this paper the maximum record period of the data was 30 years but the hydro meteorological (moisture maximization) method needs long record period at least 50 years. So to compensate this gap frequency analysis with 100 years return period was done to calculate the maximum dew point temperature as per recommendation of (WMO, 2009).

Different researches indicated that moisture maximization method is more reliable than statistical method. Due to data limitation in our country statistical method is widely used to estimate the values of probable maximum precipitations. This study shows that the values founded from statistical methods are underestimated when we compare with the statistical method, so detail study of PMP using moisture maximization method for first class meteorological stations are necessary to get reliable information about the reliability of PMP values estimated by Statistical method.

5.4. Construction of K and PMP Contour Maps

Isohyetal lines of point PMP maps were prepared to ease estimation of design rainfall for the ungauged catchments. Isohyetal maps to understand precipitation distribution were generated by means of Arc GIS software.

The K and PMP contour map shows the spatial distributions of PMP over Upper Awash Sub river basin. Data from these maps used to characterize the PMP over the Upper Awash Sub river basin. The K and PMP contour maps for the Hershfield's equation of different durations are sited in the Appendix M.

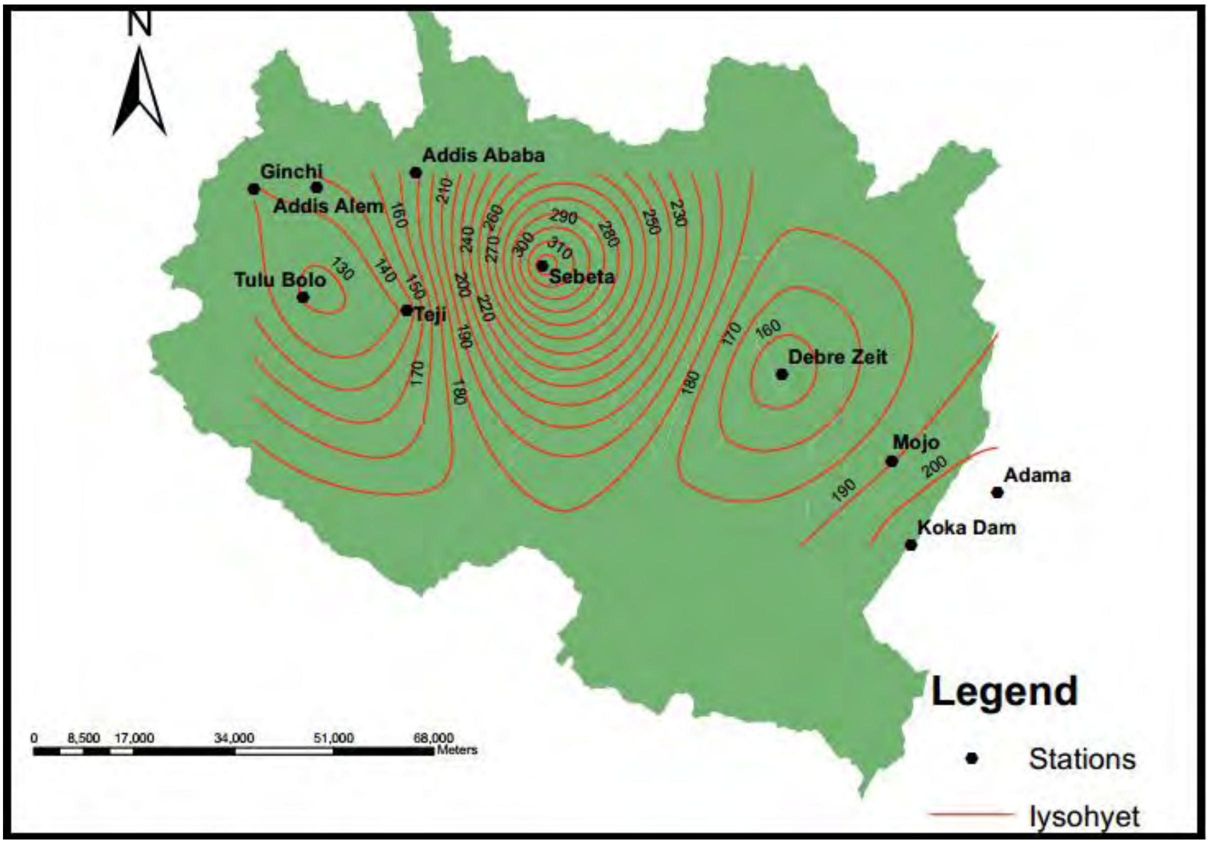

Figure 5- 1: PMP (mm) Contour Maps of the stations in the Upper Awash Sub river basin for 1-Day Durations using Hershfield's statistical equation.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The probable maximum precipitation helps design a civil structure appropriately in the study area. PMP value should be estimated by more than one method for critical hydrologic regulations, and preferably by both statistical and moisture maximization methods. Hence, statistical method was used for all the selected stations in the area to estimate the PMP due to limitation of data availability and for first class recording meteorological stations in the area both moisture maximization and statistical method were used.

The purpose of this study was to estimate the PMP and prepare the Isohyet map of PMP and Frequency factor (K) for the Upper Awash sub basin and compare the values of PMP obtained from statistical and moisture maximization methods for first class meteorological stations in the study area.

The maximum frequency factor (Km) obtained from statistical method on the area was 6.2 and the comparison of the Km value obtained from Hershfield's statistical procedure and the chart is far from each other. Though all the K values calculated using statistical method were below 7 but all the values of Km obtained from the chart were above 15.The studies on Upper Blue Nile River Basin (UBNB) (Alemayehu & Semu , 2010), (Abenezer & Dereje, 2015) also indicated that the values of frequency factor (K) obtained from Hershfield chart were overestimated. The maximum PMP values estimated from statistical method for 1-day, 2-day and 3-day durations were 317.88mm, 465.2mm, and 547.51mm respectively observed at Sebeta station. The PMP value obtained using the Hershfield chart maximum frequency factor (Km) deviated around 54% from the PMP Value obtained from the Hershfield's frequency equation. The PMP values Estimated by statistical method was 1.72 times higher than the maximum rainfall record, it is also higher than the rainfall depth for 10,000 years return period. This indicates that we can design the structures using the above PMP values and should not be any risk for overtopping of the structures.

Moisture Maximization method provides more reliable estimate of PMP than the other methods, but it needs more site specific meteorological data like daily Rainfall, daily Relative humidity, daily maximum temperature (Wickramasuriya & Fernando, 2011).

In Upper Awash sub basin there are many meteorological stations but only four stations have (first class recording Meteorological stations) detailed meteorological data .This paper used daily rainfall data from 11 stations for statistical method and Daily Rainfall, Relative humidity and maximum temperature data from 4 stations. Even if the dew point temperature is the most important parameter to determine the amount of moisture in the atmosphere, there is no record in the meteorological stations of Upper Awash sub river basin. Due to this reason in this paper it is calculated from daily relative humidity and maximum surface temperature. The result clearly indicated that dew point temperature never higher than surface air temperature.

The maximum dew point for any location is chosen by surveying long record period (50 years or above) of a highest value of persisting dew point of the station. But in this study the maximum record period is 30 years, so the maximum dew point temperature is calculated by performing the frequency analysis on annual series of monthly maximum persisting temperature with 100 year return period as a recommendation of (WMO, 2009).

Moisture maximization method was done based on the assumption “There was a chance that condition of maximum possible moisture available may not prevail during historical storm and more precipitation might have occurred if the maximum moistures were available during the extreme rainfall events” (Hashim & Al-Mamun, 2004). In this study also the maximum moisture was not overcome during historical storm.

The calculated PMP values founded from moisture maximization method are around 3 times higher than the recorded storms in the level 1 meteorological stations of Upper Awash Sub basin. In the other word we can say that the estimated PMP values have a factor of safety around 3. The factor of safety (FOS) usually adopted in engineering activities are 1.4-2.0, so it can be conclude that the estimated values of PMP is reasonable.

The PMP estimated from the moisture maximization method is around 1.7 times higher than the value of PMP founded from statistical method. This large difference might be happened because of absence of radio stone observations to determine the dew point temperature, relative humidity and surface temperature with the pseudo adiabatic assumption were used in this study. In addition to this relative humidity and surface temperature taken from the meteorological stations for this study were recorded only once on a day, this value may not represent the value of the data on the given day so it have also significant effect on the exaggerated PMP value. The other assumption for this amplifying result is going to the record period of the data. In this paper the maximum record period of the data was 30 years but the hydro meteorological (moisture maximization) method needs long record period at least 50 years.so to compensate this gap frequency analysis with 100 years return period was done to calculate the maximum dew point temperature as per recommendation of (WMO, 2009).

6.2. Recommendations

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

- Researches should be conducted using storm transposition method for ungagged stations for estimation of PMP.
- There are only limited numbers of first class recording stations in the Upper Awash Sub river basin. Therefore, establishment of additional first class stations within the study area is very essential to get reliable PMP by using moisture maximization method.
- Further researches should be conducted on the rest of basins of Ethiopia for fixing the country's reliable maximum frequency factor (km).
- Different country in the world uses physical (storm maximization) model to get Reliable PMP values because it needs more site specific data. So like other country, further research should be conducted on river basins of Ethiopia on the application of this model and compare the result with the values founded from statistical based model.
- Different studies show that Due to unreliable estimation of PMP Ethiopia constructed uneconomical spillways but their paper can't evaluate the degree of extravagant based on different economic constraints, so further study should be conducted to evaluate the performances (economical) of the spillways.

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APPENDIXES

APPENDIX- A: Available Meteorological Stations Used for Upper Awash River Basin

No.	Name of Stations			
		Elevation (m)	Longitude	Latitude
1	Adama	1622	39.2833	8.55
2	Addis Ababa	2386	38.3833	9.042
3	Addis Alem	2372	38.23	9.02
4	Debre Berhan	2750	39.53	9.633
5	Debre Zeit	1900	38.95	8.733
6	Ginchi	2132	38.133	9.01667
7	Koka Dam	1618	39.15	8.47
8	Mojo	1763	39.12	8.6
9	Sebeta	2240	38.58	8.9
10	Teji	2091	38.37	8.83
11	Tulu Bolo	2190	38.21	8.85

APPENDIX- B: Available Data for 1 day, 2 and 3 days' durations

Adama			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1981	65.1	77	106.4
1982	52.3	69.4	107.1
1983	58.6	116.6	127.1
1984	68	80.5	80.5
1985	57	98	102
1986	50	78	92
1987	44.4	65.3	86.7
1988	31.2	42.9	52.9
1989	55	58.1	58.1
1990	77	77	93
1991	73.8	73.8	76.3
1992	41.1	70.2	72.2
1993	70	85	125.5
1994	51	51	85.6
1995	77.5	97.7	99.8
1996	47.5	70.4	79.3
1997	61.4	68.4	94.7
1998	59.8	70.8	79.3
1999	41.5	56.7	63.4
2000	99.8	152.8	153.3
2001	104.8	104.8	107
2002	48.3	50.4	62.6
2003	70.4	80.4	103.6
2004	43.3	74.6	91.6
2005	42.3	54.5	69.6
2006	62.8	71.2	86
2008	72.5	88.2	93
2009	54	83.4	92.8
2010	56.1	83.4	92.8
2011	46.9	55.1	74.6
2012	69.6	96	131.3
2013	59.4	99.8	107.2
2014	46.6	70.8	76.1
2015	64.8789	83.4421	91.9401

Addis Ababa			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1985	43.2	57.4	80.3
1986	83.8	117.3	117.9
1987	56.8	86.3	101.7
1988	35.5	40.9	64.6
1989	49.2	66.3	100.6
1990	39.6	49	70.4
1991	47.3	59.3	59.6
1992	51.4	56.2	59.9
1993	53.5	67	82.2
1994	57	73.3	78.5
1995	85.3	87.2	105.6
1996	67	101.9	107.1
1997	46.3	47.6	53.5
1998	78.3	87.6	97.2
1999	37.4	37.4	80.3
2000	37.1	56.8	78.1
2001	96.3	110.5	121.5
2002	96.3	110.5	121.5
2003	54.9	59.9	75.6
2004	44.2	45.5	60.6
2005	58.6	106.8	112.2
2006	70.9	82.2	98.4
2007	64	69.3	84.9
2008	53.3	76.2	80.8
2009	54.7	57.1	80.2
2010	44.6	59.7	74.2
2011	55.8	83.3	86.6
2012	36.4	61.6	75.8
2013	47.2	63.4	75.2
2014	65.4	74.4	91.1
2015	66.3782	81.3403	83.7124

Addis Alem			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	36	41	58.05
1981	34	50	65
1982	33	40	65
1983	33.3	47.65	58.75
1984	26	36	50
1985	38	44.6	50
1986	45	61	66
1987	32	41	55
1988	38.5	48.5	54.5
1989	72.6	83.2	97.2
1990	36.2	42.2	51.5
1991	30.3	53.3	76.3
1992	26.2	49.2	67.9
1993	37.5	51	58.2
1994	44.2	64.4	88.6
1995	39.2	74.2	89.2
1996	42.8867	62.6961	64.1049
1997	44.2	46.4	65.3
1998	45	57.2	63.4
1999	44.1	48.1	61
2000	38.6	60.5	72.5
2001	38.1	51.6	67.4
2002	35.5	59.7	75
2003	50.5	52.5	57
2004	44.3	49	55
2005	110.9	118.8	124.4
2006	72.3	72.3	85.3
2007	60.3	63.3	67.5
2008	37.1	37.1	69.9
2009	54.7191	67.4821	75.0707
2010	37.7	54.4	68.7

Debre Berhan			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1984	27.2	53.6	69.5
1985	38.8	58.5	77.2
1986	46.5	58.8	69.4
1987	34.1	41.3	61.9
1988	46.6	67.1	78.3
1989	30	49	67
1990	35.4	56.1	66.2
1991	45.6	66.9	87.5
1992	58	87.3	97
1993	41.2	69.3	105.7
1994	60.2	75.2	93.8
1995	60.2	75.2	93.8
1996	41.5	57.2	74.7
1997	31.6	50.3	63.5
1998	40	53.2	77.7
1999	45.7	57.6	71
2000	43.8	74.8	104.9
2001	38.2	62.3	70.3
2002	40.6	54.4	69.8
2003	47.8	63.1	82.8
2004	45.6	64.5	67.9
2005	46.2	61.8	63.3
2006	43.5	70.7	96.3
2007	57.2	69.2	78
2008	57	69.7	83.6
2009	59.5	84.9	92.7
2010	60	87.3	93.8
2011	84.3	109.9	145.2
2012	41	58	85
2013	34.5	43.5	53.3
2014	38.4	60.6	69.2

Debre Zeit			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1986	46.1001	58.275	66.7625
1987	45.8	55	63.7
1988	32.5	43.6	61.6
1989	37.8	43.9	44.3
1990	42.3	55.3	62
1991	40.2	47.8	51
1992	26.9	35.3	48.6
1993	37.8023	47.2	59.5
1994	34.6	47.2	59.5
1995	32.4	49.9	54.2
1996	62	84.3	89.7
1997	70	80.7	82.9
1998	74	74.2	98.1
1999	39.8	54.3	67.9
2000	44.7	54.9	59.2
2001	45.6	52.4	71.4
2002	46.2	48.8	48.8
2003	37	54.6	70.6
2004	74.4	108.1	108.1
2005	38.1	63.4	71.5
2006	45.9	57.1	57.1
2007	35.7	47.8	60.7
2008	50.7	65.3	73.2
2009	61	68.4	77.4
2010	51	59.1	61.3
2011	55.5	68.02	77.15
2012	52.2	67.24	75.79
2013	56.25	71.22	76.15
2014	56.11	61.31	76.9
2015	53.8	56.95	66.4

Ginchi			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	42.4	51.8	59.7
1981	42.3	56.3	69
1982	37.3	52.3	65.1
1983	56.7	77	90.6
1984	46.5	48.3	50.8
1985	47.4	65.4	71.2
1986	67.1	71.1	84.7
1987	60.8	67.8	69
1988	60	78.5	88.5
1989	74.3	96.3	100.8
1990	38.2	64.2	80.7
1991	36.2	57	63
1992	36.5	47.8	68.2
1993	54.5	75.8	98.9
1994	38.1	62.3	81.1
1995	44	70.6	75.9
1996	35.6	51.2	69.8
1997	54.2	68.9	89.8
1998	36.1	63.3	71.8
1999	66.6	66.6	71.2
2000	34.6	51.4	51.9
2001	40	63.3	76.3
2002	48.5	52.4	71
2003	44.8	53.8	65.2
2004	58.2	69.3	85.4
2005	63.9	78.2	82
2006	40.9	63.9	95.6
2007	39.2	52	59.8
2008	29.4	39.5	54.5
2009	43.3	49.8	74
2010	50	52.5	65.5

Koka Dam			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1985	38.5	66.6	77.9
1986	31.5	42.4	42.4
1987	30.5	42.8	48.5
1988	58.8	60	77.7
1989	51.5	79.7	94.5
1990	100.8	100.8	151.2
1991	35.3	62	67.4
1992	96.3	78.5659	109.575
1993	87	161	223
1994	87	161	223
1995	70.6	76.7798	110.105
1996	67.9375	71.5776	102.212
1997	56.3	75.1	88.5
1998	83.5	109.5	122.7
1999	48.2	76.2	83.7
2000	54.2	79.7	102.9
2001	58.4	77.4	94.6
2002	43.9	64.6	67
2003	51.4	68.1	82.3
2004	48.4	70.3	112.1
2005	35.5	53.2	58.9
2006	37.3	54.2	59.5
2007	36.3	61.2	81.2
2008	40.2	66.9	79.5
2009	63.9443	87.0033	103.419
2010	39.5	48.7	68.3
2011	52	52	73
2012	66.3351	80.3381	109.475
2013	64.4	73.8	80.2
2014	60.4	69	78.3
2015	37	64.7	68.3

Mojo			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1986	34	55.3	63.5
1987	48.2	58	92
1988	44.5	65.2	87.5
1889	60.6	79.1	88.9
1990	62	66.2	90.5
1991	69.2	89	113
1992	35.3	48.1	58.3
1993	47.8	72.4	88
1994	39	46.6	65.4
1995	36.2	56.4	71
1996	45	54	74.5
1997	54.2	61.2	71.7
1998	83	91	105.3
1999	92	92	109.2
2000	44.8	73.1	73.1
2001	42.5	60.4	65
2002	46.8	64.8	72.1
2003	85.1	95.6	127.6
2004	47.2	77.2	79.5
2005	56.3	84.8	101.8
2006	34.8	59.8	74.1
2007	38.8	60.2	76.7
2008	94.9	107.1	112.5
2009	59.1483	77.241	77.4421
2010	56.1	87.3	105.1
2011	44.3	50.5	75.8
2012	57.0872	65.9666	99.9157
2013	62.8	84	110.3
2014	61.8	78	90
2015	44.8	55.7	73.1

Sebeta			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1980	72.4	75.5	87.1
1981	42.1	48.6	53.1
1982	28.8	41.1	58.1
1983	40.6	60.8	76.1
1984	21.5	31.1	33.4
1985	82.3	93.7	134.9
1986	177.5	214.9	297.2
1987	116.7	202.1	223.7
1988	210.6	263.3	286.8
1989	71.6	122.1	130.5
1990	40	50	86.3
1991	52.4	57.7	61.1
1992	55.6	68	82.4
1993	116.3	217.8	260.1
1994	55.4	66.5	91.3
1995	62.0855	110.061	61.226
1996	50.2	76	98.4
1997	50.9	50.9	86.1
1998	35.3	53.2	65.5
1999	23.3	35.6	48.4
2000	38.1	68.2	69.7
2001	33.1	47.1	54.3
2002	55.2655	83.0787	113.172
2003	58.2	64.9	75.4
2004	60.2	61.7	80.8
2005	52.1	67.2	72.6
2006	46.1	53.7	75.8
2007	28.8	51.2	57.5
2008	38.8	51.2	75.6
2009	69.0009	102.658	92.0403
2010	30.2	50.3	59.1
2011	90.2244	90.2835	148.764
2012	54.5684	67.0465	95.952
2013	33.6	41	45.4
2014	35.1	38.9	50.6

Teji			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1986	35	45.6	59.4
1987	46.2	72.9	72.9
1988	48	67.4	102
1989	52.5	72.5	83.5
1990	52.2	75.9	89.8
1991	36	61.7	68
1992	34.3	45.9	54
1993	43.7	68.6	77.3
1994	29.4	44.5	45.7
1995	40.9	40.9	67.3
1996	65.5	66.8	67.7
1997	38.7	44.3	67.9
1998	38	61.5	86.7
1999	49.6	49.9	68.3
2000	37.6	55.9	72.4
2001	45.7	45.7	54.4
2002	37.4	51	68.7
2003	44.8	60	63.5
2004	56.1	56.1	56.3
2005	46.8	56.4	75.7
2006	41.8	61	67.5
2007	43.8	50.4	79.5
2008	40.5	49.3	75.6
2009	48.1	57.3	57.9
2010	29.5	37.3	54
2011	29.5	37.3	54
2012	28.9	34.9	47.9
2013	67.3	68.8	73.2
2014	55	55	59.5
2015	65.8	68	80.6

Tulu bolo			
Year	Rainfall depth having a duration of		
	1-day (mm)	2-days (mm)	3-days (mm)
1972	38.4	66.4	72.9
1973	44.7	63.4	63.4
1974	33	37	47
1975	41.6	55.1	67
1976	45	49	57
1977	42	57	83
1978	40	67	67
1979	50	73	74.5
1980	48	70	103
1981	65	78.5	78.5
1982	58	68.9	90.2
1983	49.6	73	115.6
1984	39.54	65.61	85.53
1985	47.6	61.8	75
1986	56.3	59.3	76
1987	28.2	34.3	42.5
1988	40	71	98.2
1989	28	55	75
1990	32	40.3	55.3
1991	20.4	40.1	45.3
1992	38.2	68.3	98.3
1993	33.1	63.9	91.3
1994	36.3	55.6	78.6
1995	30	45.2	56.5
1996	37.3	64.67	73.24
1997	48.45	61.1	77.61
1998	39.01	65.67	86.94
1999	49.7	84.8	119.2
2000	48	84.3	109.8
2001	29	41.7	48
2002	51.8	61.6	90.6
2003	75.5	75.5	93.3
2004	35.5	52	81

APPENDIX- C: Data Test Results

Independent Test for 1-Day Duration			
Station	Statistic (U)	Critical Statistic(U-critical)	Remark
Adama	0.11029	1.96	Independent
Addis Ababa	0.28191	1.96	Independent
Addis Alem	0.935	1.96	Independent
Debre Berhan	0.61259	1.96	Independent
Debre Zeit	0.47495	1.96	Independent
Ginchi	0.1897	1.96	Independent
Koka Dam	0.7059	1.96	Independent
Mojo	0.33021	1.96	Independent
Sebeta	1.80362	1.96	Independent
Teji	0.14624	1.96	Independent
Tulu Bolo	0.50374	1.96	Independent

Independent Test for 2-Day Duration			
Station	Statistic (U)	Critical Statistic(U-critical)	Remark
Adama	0.0425	1.96	Independent
Addis Ababa	0.02597	1.96	Independent
Addis-Alem	0.20289	1.96	Independent
Debre Berhan	0.49672	1.96	Independent
Debre -Zeit	0.51048	1.96	Independent
Ginchi	0.07085	1.96	Independent
Koka Dam	1.18891	1.96	Independent
Mojo	0.14166	1.96	Independent
Sebeta	2.16418	1.96	dependent
Teji	0.15275	1.96	Independent
Tulu Bolo	0.26883	1.96	Independent

Independent Test for 3-Day Duration

Station	Statistic (U)	Critical Statistic(U-critical)	Remark
Adama	0.0065	1.96	Independent
Addis Ababa	0.09815	1.96	Independent
Addis Alem	0.08397	1.96	Independent
Debre Berhan	0.37001	1.96	Independent
Debre Zeit	0.3567	1.96	Independent
Ginchi	0.26072	1.96	Independent
Koka	1.43359	1.96	Independent
Mojo	0.08507	1.96	Independent
Sebeta	2.06119	1.96	Dependent
Teji	0.17825	1.96	Independent
Tulu Bolo	0.30688	1.96	Independent

Homogeneity Test for 1-Day Duration

Station	Statistic (U)	Critical Statistic(U-critical)	Remark
Adama	0.24152	1.96	Homogeneous
Addis Ababa	0.63246	1.96	Homogeneous
Addis Alem	1.00447	1.96	Homogeneous
Debre Berhan	1.3441	1.96	Homogeneous
Debre Zeit	1.78753	1.96	Homogeneous
Ginchi	0.79057	1.96	Homogeneous
Koka	1.3441	1.96	Homogeneous
Mojo	0.24945	1.96	Homogeneous
Sebeta	1.11246	1.96	Homogeneous
Teji	0.3326	1.96	Homogeneous
Tulu Bolo	1.87471	1.96	Homogeneous

Homogeneity Test for 2-Day Duration			
Station	Statistic (U)	Critical Statistic(U-critical)	Remark
Adama	0.55353	1.96	Homogeneous
Addis Ababa	0.83018	1.96	Homogeneous
Addis Alem	2.21382	1.96	Homogeneous
Debre Berhan	1.42302	1.96	Homogeneous
Debre Zeit	1.91438	1.96	Homogeneous
Ginchi	1.02784	1.96	Homogeneous
Koka	1.26619	1.96	Homogeneous
Mojo	1.16398	1.96	Homogeneous
Sebeta	1.94743	1.96	Homogeneous
Teji	1.1641	1.96	Homogeneous
Tulu Bolo	0.32422	1.96	Homogeneous

Homogeneity Test for 3-Day Duration			
Station	Statistic (U)	Critical Statistic(U-critical)	Remark
Adama	0.17298	1.96	Homogeneous
Addis Ababa	0.51439	1.96	Homogeneous
Addis Alem	1.90343	1.96	Homogeneous
Debre Berhan	0.43486	1.96	Homogeneous
Debre Zeit	1.37198	1.96	Homogeneous
Ginchi	0.27698	1.96	Homogeneous
Koka	1.30457	1.96	Homogeneous
Mojo	0.66513	1.96	Homogeneous
Sebeta	1.8484	1.96	Homogeneous
Teji	1.16449	1.96	Homogeneous
Tulu Bolo	1.22577	1.96	Homogeneous

APPENDIX- D: Mathematical Expressions for Statistical Distributions of Annual Maximum Series

Distribution name	Distribution function F(x)	Variate and parameter ranges
Normal distribution (N)	F(x) = $\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}$	$-\infty < x < \infty$ μ *and* σ are parameters
Two parameter Lognormal distribution (LN2)	F(x) = $\frac{1}{\sqrt{2\pi}\,ax}\exp\left\{-\frac{1}{2}\left(\frac{\log x - b}{a}\right)^2\right\}$	0 < x
Three parameter Lognormal distribution (LN3)	F(x) = $\frac{1}{\sqrt{2\pi}\,a(x-m)}\exp\left\{-\frac{1}{2}\left(\frac{\log(x-m) - b}{a}\right)^2\right\}$	m < x
Exponential distribution (EXP)	F(x) = $\frac{1}{a}\exp\left(-\frac{x-m}{a}\right)$	m < x (i.e. P-III with b = 1)
Two parameter Gamma distribution(Gam2)	F(x) = $\frac{(x/a)^{b-1}}{/a/\Gamma(b)}\exp(-\frac{x}{a})$	0 ≤ x if a > 0 x ≤ 0 if a < 0 (i.e. P-III with m = 0)
Pearson-III distribution (P-III)	F(x) = $\frac{\left(\frac{x-m}{a}\right)^{b-1}}{/a/\Gamma(b)}\exp\left\{-\frac{x-m}{a}\right\}$	m ≤ x if a > 0 x ≤ m if a < 0
Log Pearson-III distribution (LP-III)	F(x) = $\frac{\left(\frac{z-c}{a}\right)^{b-1}}{x/a/\Gamma(b)}\exp\left\{-\frac{z-c}{a}\right\}$ If x P-III and z = log x	$c < z < \infty$ $e^c < x < \infty$ a > 0 $-\infty < z < c$ $0 < x < e^c$ a < 0
Generalized Extreme Value distribution (GEV)	F(x) = $\exp\left\{-\left[1-k\left(\frac{x-u}{\alpha}\right)\right]^{1/k}\right\}$	$\alpha > 0$ u + $\frac{\alpha}{k}$ ≤ x ≤ ∞ if k < 0 $-\infty$ < x ≤ u+ $\frac{\alpha}{k}$ if k >0
Extreme value Type I distribution (EV1)	F(x) = $\exp\left\{-e^{-\left(\frac{x-u}{\alpha}\right)}\right\}$	$-\infty < x < \infty$ $\alpha > 0$

Cont'd

Distribution name	Distribution function F(x)	Variate and parameter ranges
Five parameters Wake by distribution (WAK 5)	$x = m+\alpha\ [1-(1-F)^{b}]-c[1-(1-F)^{-d}$ where $F = F(x)$	Note It is analytically defined only in inverse form
Four parameters Wake by distribution(WAK 4)	$x = \frac{\alpha}{\beta}\left[1-(1-F)^{\beta}\right]-\frac{\gamma}{\delta}\left[1-(1-F)^{-\delta}\right]$	
Generalized Pareto distribution (GPar)	$x = \varepsilon+\frac{\alpha}{k}\left[1-(1-F)^{k}\right]$ $F = F(x) = 1-\left[1-\frac{k}{\alpha}(x-\varepsilon)\right]^{1/k}$	
Log-Logistic distribution (LLg)	$F(x) = \left\{1+\left[\left(\frac{x-a}{b}\right)\right]^{-1/c}\right\}^{-1}$	$x > a,\ c > 0,\ b > 0$
Generalized logistic distribution (GLg)	$F(x) = \left\{1+\left[1-\gamma\left(\frac{x-\alpha}{\beta}\right)\right]^{1/\gamma}\right\}^{-1},\ \gamma\neq 0$ $= \left\{1+\exp\left[-\frac{x-\alpha}{\beta}\right]\right\}^{-1},\ \gamma=0$	$\gamma<0,\ \alpha+\frac{\beta}{\gamma}\le x<\infty$ $\gamma>0, -\infty<x<\alpha+\frac{\beta}{\gamma}$ $-\infty<x<\infty$

APPENDIX- E: Estimated Parameter for GEV Distribution

	For 1-Day duration maximum rainfall		
Name of stations	Selected distributions	Parameters	Value
Adama	General extreme value	K	0.1188
		σ	12.422
		μ	52.303
Addis Ababa	General extreme value	K	0.037
		σ	11.582
		μ	48.383
Addis Alem	General extreme value	K	0.153
		σ	7.1629
		μ	36.177
Debre Berhan	General extreme value	K	0.10253
		σ	12.335
		μ	72.862
Debre Zeit	General extreme Value	K	0.13191
		σ	9.4564
		μ	41.286
Ginchi	General extreme Value	K	-0.0004
		σ	8.6241
		μ	41.469
Koka	General extreme Value	K	0.03608
		σ	13.818
		μ	45.461
Mojo	General extreme Value	K	0.02867
		σ	10.377
		μ	14.184
Sebeta	General extreme Value	K	0.09986
		σ	16.371
		μ	41.521
Teji	General extreme Value	K	0.09986
		σ	16.371
		μ	41.521
Tulu Bolo	General extreme Value	K	0.22336
		σ	9.582
		μ	37.603

	For 2-Days duration maximum rainfall		
Name of stations	Selected distributions	Parameters	Value
Adama	General extreme value	K	0.20181
		σ	16.235
		μ	69.222
Addis Ababa	General extreme value	K	0.07508
		σ	17.633
		μ	61.579
Addis Alem	General extreme value	K	-0.0447
		σ	9.7399
		μ	48.442
Debre Berhan	General extreme value	K	0.14668
		σ	10.819
		μ	58.523
Debre Zeit	General extreme Value	K	0.07852
		σ	9.9731
		μ	52.675
Ginchi	General extreme Value	K	-0.0208
		σ	10.118
		μ	56.661
Koka	General extreme Value	K	0.21666
		σ	14.416
		μ	63.692
Mojo	General extreme Value	K	0.14625
		σ	13.562
		μ	63.185
Sebeta	General extreme Value	K	0.29084
		σ	16.45
		μ	52.61
Teji	General extreme Value	K	0.28269
		σ	11.883
		μ	51.234
Tulu Bolo	General extreme Value	K	0.42545
		σ	13.277
		μ	58.19

	For 3-Days duration maximum rainfall		
Name of stations	Selected distributions	Parameters	Value
Adama	General extreme value	K	0.22652
		σ	18.476
		μ	82.545
Addis Ababa	General extreme value	K	0.11023
		σ	16.799
		μ	77.77
Addis Alem	General extreme value	K	0.00705
		σ	9.5331
		μ	61.043
Debre Berhan	General extreme value	K	0.10253
		σ	12.335
		μ	72.862
Debre Zeit	General extreme Value	K	0.085
		σ	11.204
		μ	61.55
Ginchi	General extreme Value	K	-0.0195
		σ	12.068
		μ	68.355
Koka	General extreme Value	K	0.12689
		σ	21.212
		μ	76.194
Mojo	General extreme Value	K	0.10086
		σ	14.803
		μ	77.818
Sebeta	General extreme Value	K	0.36721
		σ	21.892
		μ	64.975
Teji	General extreme Value	K	0.27521
		σ	11.69
		μ	63.033
Tulu Bolo	General extreme Value	K	0.31088
		σ	19.289
		μ	70.324

APPENDIX- F: Estimated Rainfall Depths for Different Return Periods

Station	**Estimated Rainfall Depths of 1-day duration for the indicated frequency (Years) in mm**											
	2	5	10	25	50	100	200	500	1000	2000	5000	10000
Adama	66.2	77.62	84.38	92.1	97.29	102.03	106.39	111.6	102.03	118.47	122.44	125.15
Addis Ababa	61.98	74.28	82.14	91.77	98.69	105.39	111.9	120.23	126.35	132.3	139.94	145.55
Addis Alem	44.03	50.23	53.79	57.73	60.3	62.61	64.67	67.07	68.67	70.11	71.79	72.92
Debre Berhan	86.79	98.46	105.48	113.6	119.13	124.25	128.99	134.76	138.77	142.5	147.05	150.21
Debre Zeit	51.79	60.28	65.25	70.8	74.59	77.97	81.04	84.68	87.15	89.41	92.09	93.91
Ginchi	51.82	61.6	68.09	76.28	82.36	88.39	94.41	102.34	108.35	114.35	122.28	128.28
Koka Dam	61.67	76.39	85.79	97.32	105.62	113.64	121.45	131.45	138.79	145.95	155.14	161.88
Mojo	26.43	37.61	44.82	53.72	60.14	66.4	72.52	80.4	86.22	91.93	99.3	104.75
Sebeta	60.04	75.6	84.98	95.86	103.29	110.18	116.57	124.35	129.78	134.85	141.02	145.33
Teji	60.04	75.6	84.97	95.86	103.29	110.18	116.57	124.36	129.78	134.85	141.02	145.33
Tulu Bolo	40.97	49.81	54.55	59.5	62.56	65.15	67.35	69.79	71.33	72.65	74.1	75.019

Station	**Estimated Rainfall Depths of 2-day duration for the indicated frequency (Years) in mm**											
	2	5	10	25	50	100	200	500	1000	2000	5000	10000
Adama	86.53	99.44	106.5	114.02	118.74	122.8	126.32	130.27	132.8	135	137.48	139.07
Addis Ababa	81.82	99.33	110.13	122.93	131.86	140.26	148.21	158.08	165.1	171.76	180.05	185.95
Addis Alem	44.03	50.24	53.79	57.73	60.31	62.61	64.67	67.07	68.67	70.11	71.8	72.92
Debre Berhan	70.43	79.91	85.36	91.46	95.46	99.04	102.27	106.05	108.59	110.88	113.57	115.38
Debre Zeit	64.1	73.94	79.99	87.15	92.12	96.79	101.2	106.66	110.53	114.19	118.74	121.97
Ginchi	68.96	80.86	88.89	99.22	107.02	114.87	122.81	133.46	141.64	149.95	161.1	169.68
Koka Dam	78.93	90.1	96.12	102.46	106.38	109.73	112.6	115.78	117.79	119.53	121.46	122.68
Mojo	78.12	90	96.85	104.5	109.53	114.03	118.08	122.83	126.03	128.91	132.3	140.68
Sebeta	69.28	80.48	86.11	91.67	94.9	97.53	99.66	101.89	103.22	104.3	105.44	106.12
Teji	63.33	71.54	75.69	79.83	82.25	84.22	85.84	87.54	88.56	89.4	90.28	90.81
Tulu Bolo	62.7	72.91	77.42	81.39	83.46	84.99	86.12	87.18	87.75	88.17	88.56	88.78

Station	Estimated Rainfall Depths of 3-day duration for the indicated frequency (Years) in mm											
	2	5	10	25	50	100	200	500	1000	2000	5000	10000
Adama	101.97	116.04	123.55	131.39	136.21	140.29	143.76	147.58	149.99	152.04	154.3	155.73
Addis Ababa	96.66	112.34	121.7	132.46	139.75	146.45	152.63	160.09	165.25	170.03	175.8	179.8
Addis Alem	72.44	83.11	90.13	98.94	105.45	111.87	118.23	126.59	132.86	139.11	147.31	153.48
Debre Berhan	86.8	98.47	105.48	113.6	119.14	124.25	129	134.76	138.77	142.5	147.05	150.21
Debre Zeit	74.34	85.27	91.95	99.8	105.23	110.31	115.08	120.95	125.1	129.01	133.83	137.24
Ginchi	83.01	97.17	106.72	118.98	128.22	137.53	146.92	159.51	169.18	178.97	192.12	202.22
Koka Dam	99.82	119.04	130.34	143.15	151.71	159.48	166.56	175.01	180.77	186.04	192.33	196.63
Mojo	94.56	108.6	117.06	126.86	133.56	139.75	145.5	152.49	157.36	161.9	167.43	171.29
Sebeta	86.23	99.29	105.38	111.03	114.12	116.49	118.31	120.11	121.12	121.9	122.67	123.1
Teji	74.98	83.16	87.33	91.51	93.97	95.99	97.65	99.4	100.46	101.34	102.27	102.83
Tulu Bolo	89.65	102.34	108.59	114.66	118.14	120.91	123.14	125.43	126.78	127.86	128.98	129.64

APPENDIX- G: Frequency Factor K Values

Appendix G1-Frequancy factor (K) founded from Hershfield's method.

Frequency Factor(K) For 1-Day Duration	
Stations	Frequency Factor (K)
Adama	3.36
Addis Ababa	3.05
Addis Alem	6.2
Debre Berhan	4.18
Debre Zeit	2.49
Ginchi	2.66
Koka Dam	2.6
Mojo	2.79
Sebeta	4.92
Teji	4.39
Tulu Bolo	3.48

Frequency Factor(K) For 2-Day Duration	
Stations	Frequency Factor (K)
Adama	4.55
Addis Ababa	2.33
Addis Alem	5.7
Debre Berhan	3.98
Debre Zeit	4.35
Ginchi	3.43
Koka Dam	6.02
Mojo	2.63
Sebeta	3.93
Teji	1.91
Tulu Bolo	1.96

Frequency factor(K) for 3-day duration	
Stations	frequency factor (K)
Adama	3.35
Addis Ababa	2.32
Addis Alem	4.85
Debre Berhan	4.87
Debre Zeit	3.2
Ginchi	2.2
Koka Dam	5.82
Mojo	2.61
Sebeta	3.51
Teji	2.83
Tulu Bolo	2.27

Appendix G2-Frequancy factor (K) founded from Hershfield's chart.

Frequency Factor(K) For 1-Day Duration	
Stations	Frequency Factor (K)
Adama	16
Addis Ababa	16.28
Addis Alem	17.3
Debre Berhan	17.15
Debre Zeit	17.04
Ginchi	17.03
Koka Dam	16.39
Mojo	16.51
Sebeta	16.02
Teji	17.21
Tulu Bolo	17.4

APPENDIX- H: Probable Maximum Precipitations (PMP) of Different Stations using Hershfield's equation

The values of PMP for 1-Day duration

Station	Adjusted $\bar{X}_n$(mm)	Adjusted $\bar{\sigma}_n$(mm)	Frequency factor (K)	PMP (mm)
Adama	71.78	17.82	3.36	205.435
Addis Ababa	56.99	16.2	3.05	177.375
Addis Alem	43.37	14.19	6.17	148.001
Debre Berhan	46.69	11.19	4.18	130.782
Debre Zeit	49.15	13.81	2.49	151.86
Ginchi	49.25	11.96	2.66	139.101
Koka	58.04	20.32	2.6	207.312
Mojo	56.19	18.05	2.79	189.386
Sebeta	58.75	36.05	4.92	317.884
Teji	46.98	12.8	4.39	142.385
Tulu Bolo	44.89	11.21	3.48	128.917

The Values of PMP For 2-Days Duration

Station	Adjusted $\bar{X}_n$(mm)	Adjusted $\bar{\sigma}_n$(mm)	Frequency factor (K)	PMP (mm)
Adama	73.12	19.9	4.55	218.08
Addis Ababa	73.67	23.06	2.33	240.19
Addis Alem	55.97	14.03	5.7	158.69
Debre Berhan	66.12	13.81	3.98	168.7
Debre Zeit	59.48	13.97	4.35	162.29
Ginchi	63.34	12.14	3.43	154.18
Koka	72.47	19.86	6.02	217.08
Mojo	72.26	16.62	2.63	194.78
Sebeta	79.84	55.1	3.93	465.2
Teji	56.61	12.48	1.91	148.88
Tulu Bolo	62.82	14.33	1.96	168.5

The Values of PMP For 3-Days Duration				
Stations	Adjusted $\bar{X}_n$(mm)	Adjusted $\bar{\sigma}_n$(mm)	Frequency factor (K)	PMP (mm)
Adama	110.94	21.84	3.35	268.89
Addis Ababa	85.88	18.91	2.32	221.33
Addis Alem	68.68	14.32	4.85	171.73
Debre Berhan	76.31	16.42	4.87	194.12
Debre Zeit	67.7	15.37	3.2	177.47
Ginchi	75.64	14.29	2.2	179.36
Koka	88.17	30.76	5.82	301.75
Mojo	86.25	18.74	2.61	220.58
Sebeta	96.26	66.77	3.51	547.51
Teji	68.02	12.91	2.83	161.7
Tulu Bolo	78.06	19.61	2.27	217.06

APPENDIX- I: Probable Maximum Precipitations (PMP) of Different Stations Using Hershfield's Chart for 1-Day Duration

Stations	The Values of PMP For 3-Days Duration			
	Adjusted $\bar{X}_n$(mm)	Adjusted $\bar{\sigma}_n$(mm)	Frequency factor (K)	PMP (mm)
Adama	71.78	17.82	16	431.6
Addis Ababa	56.99	16.2	16.28	382.89
Addis Alem	43.37	14.19	17.3	328.09
Debre Berhan	46.69	11.19	17.15	272.72
Debre Zeit	49.15	13.81	17.04	327.07
Ginchi	49.25	11.96	17.03	290.9
Koka	58.04	20.32	16.39	465.13
Mojo	56.19	18.05	16.51	418.4
Sebeta	58.75	36.05	16.02	775.39
Teji	46.98	12.8	17.21	304.84
Tulu Bolo	44.89	11.21	17.4	271.15

APPENDIX- J: Comparing Probable Maximum Precipitations (PMP) Founded from Hershfield's Chart and Hershfield's Method for 1-Day Duration

stations	PMP - mm	PMP(using chart)-mm	Deviation (%)
Adama	205.44	431.6	52.4
Addis Ababa	177.38	382.89	53.68
Addis Alem	148	328.08	54.89
Debre Berhan	130.78	272.72	52.05
Debre Zeit	151.86	327.07	53.58
Ginchi	139.1	290.9	52.18
Koka	207.31	465.13	55.43
Mojo	189.39	418.4	54.74
Sebeta	317.89	775.39	59
Teji	142.39	304.84	53.29
Tulu Bolo	128.92	271.15	52.46

APPENDIX- K: Ratio of PMP to 10,000 Years Return Period Quantiles

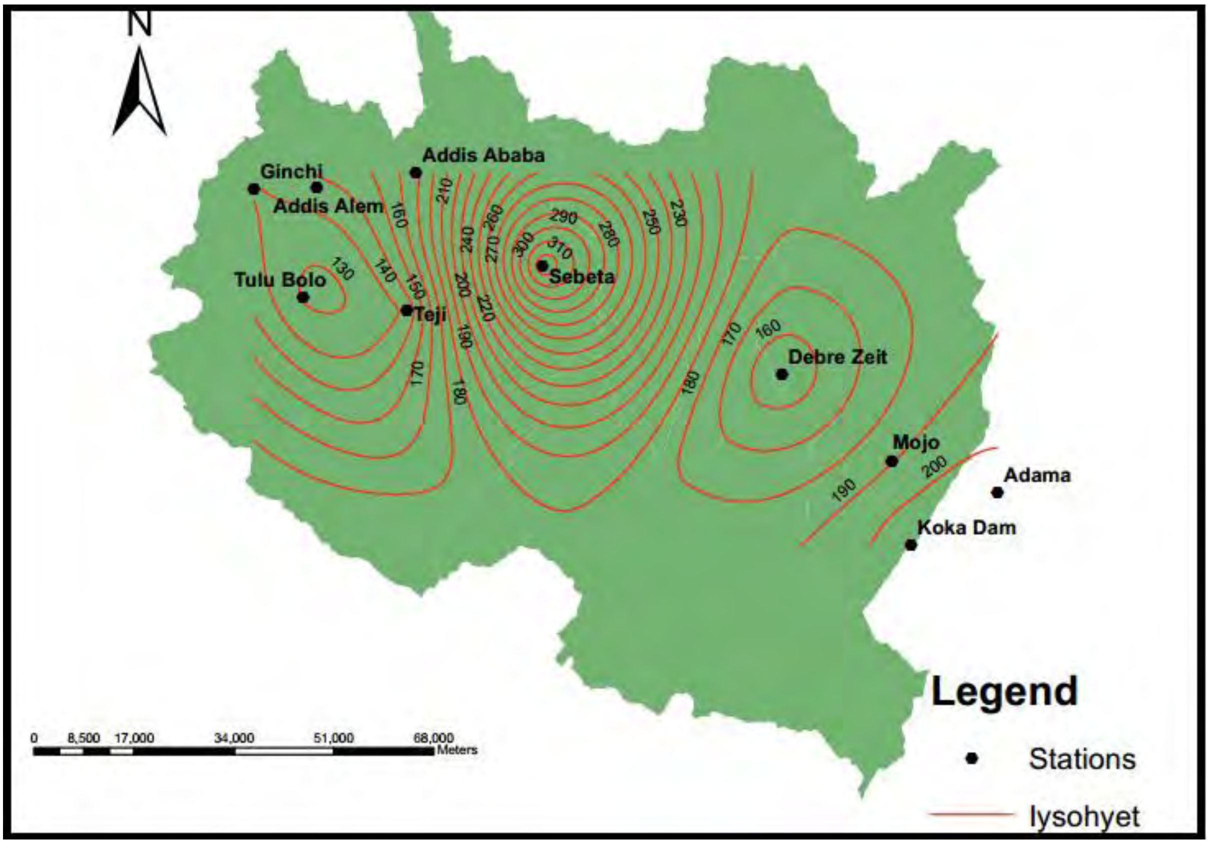
Ratio of PMP to Rainfall Depth for T=10,000 for 1-day duration			
Station	PMP (mm)	Rainfall depth (mm) T= 10,000	Ratio
Adama	205.44	125.15	1.64155
Addis Ababa	177.37	145.55	1.218619
Addis Alem	148	72.92	2.029622
Debre Berhan	130.78	150.21	0.870648
Debre Zeit	151.86	93.91	1.61708
Ginchi	139.1	128.28	1.084347
Koka	207.31	161.88	1.28064
Mojo	189.39	104.75	1.808019
Sebeta	317.88	145.33	2.187298
Teji	142.39	145.33	0.97977
Tulu Bolo	128.92	75.019	1.718498

Ratio of PMP to Rainfall Depth for T=10,000 for 2-day duration			
Station	PMP (mm)	Rainfall depth (mm) T= 10,000	Ratio
Adama	218.08	139.07	1.56813
Addis Ababa	240.19	185.95	1.29169
Addis Alem	158.69	72.92	2.17622
Debre Berhan	168.7	115.38	1.46213
Debre Zeit	162.29	121.97	1.33057
Ginchi	154.18	169.68	0.90865
Koka	217.08	122.68	1.76948
Mojo	194.78	140.68	1.38456
Sebeta	465.2	106.12	4.38372
Teji	148.88	90.81	1.63947
Tulu Bolo	168.5	88.78	1.89795

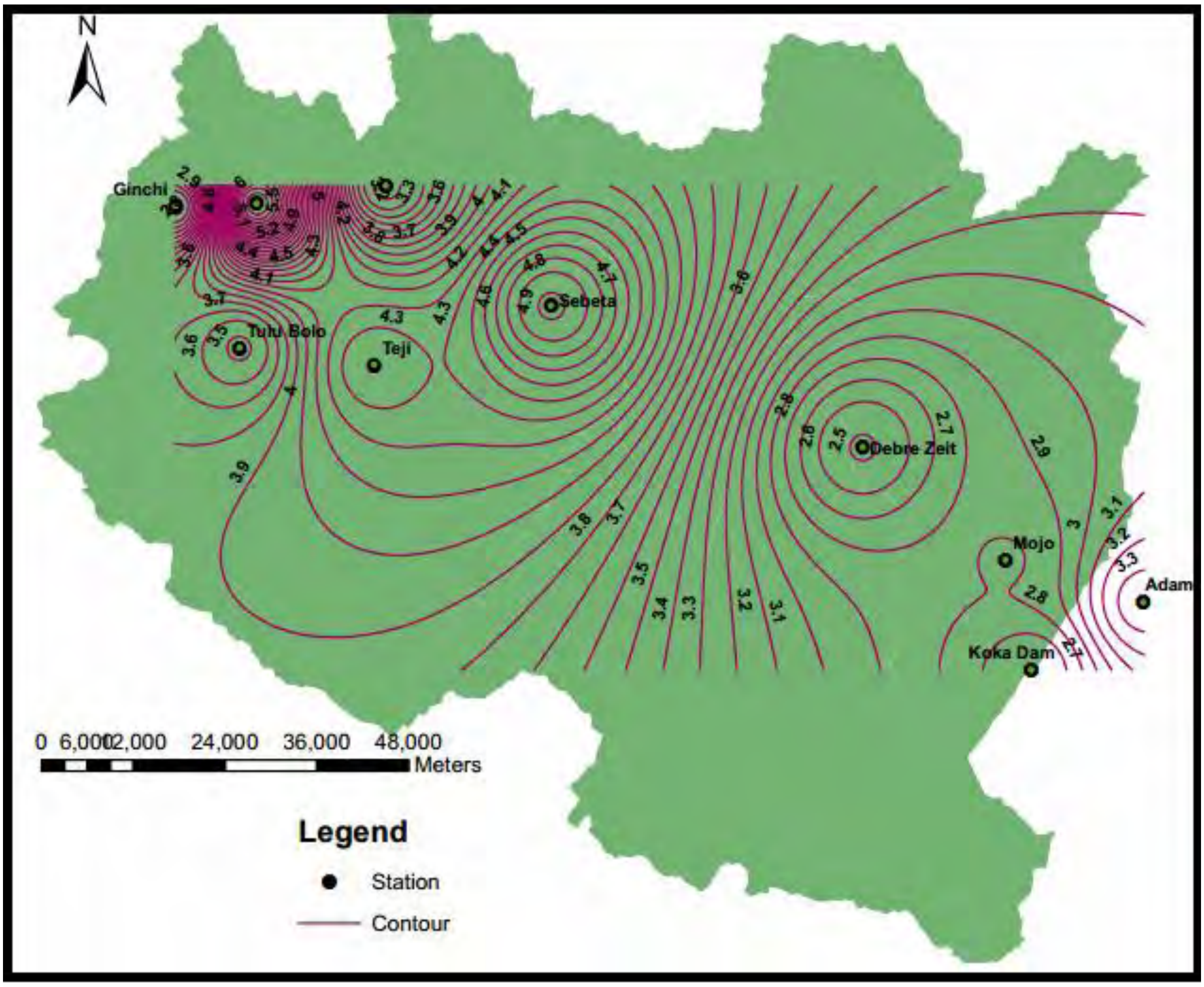
Ratio of PMP to Rainfall Depth for T=10,000 for 3-day duration			
Station	PMP (mm)	Rainfall depth (mm) T= 10,000	Ratio
Adama	268.89	155.73	1.72664
Addis Ababa	221.33	179.8	1.23098
Addis Alem	171.73	153.48	1.11891
Debre Berhan	194.12	150.21	1.29232
Debre Zeit	177.47	137.24	1.29314
Ginchi	179.36	202.22	0.88696
Koka	301.75	196.63	1.53461
Mojo	220.58	171.29	1.28776
Sebeta	547.51	123.1	4.44769
Teji	161.7	102.83	1.5725
Tulu Bolo	217.06	129.64	1.67433

APPENDIX- L: K and PMP contour Maps

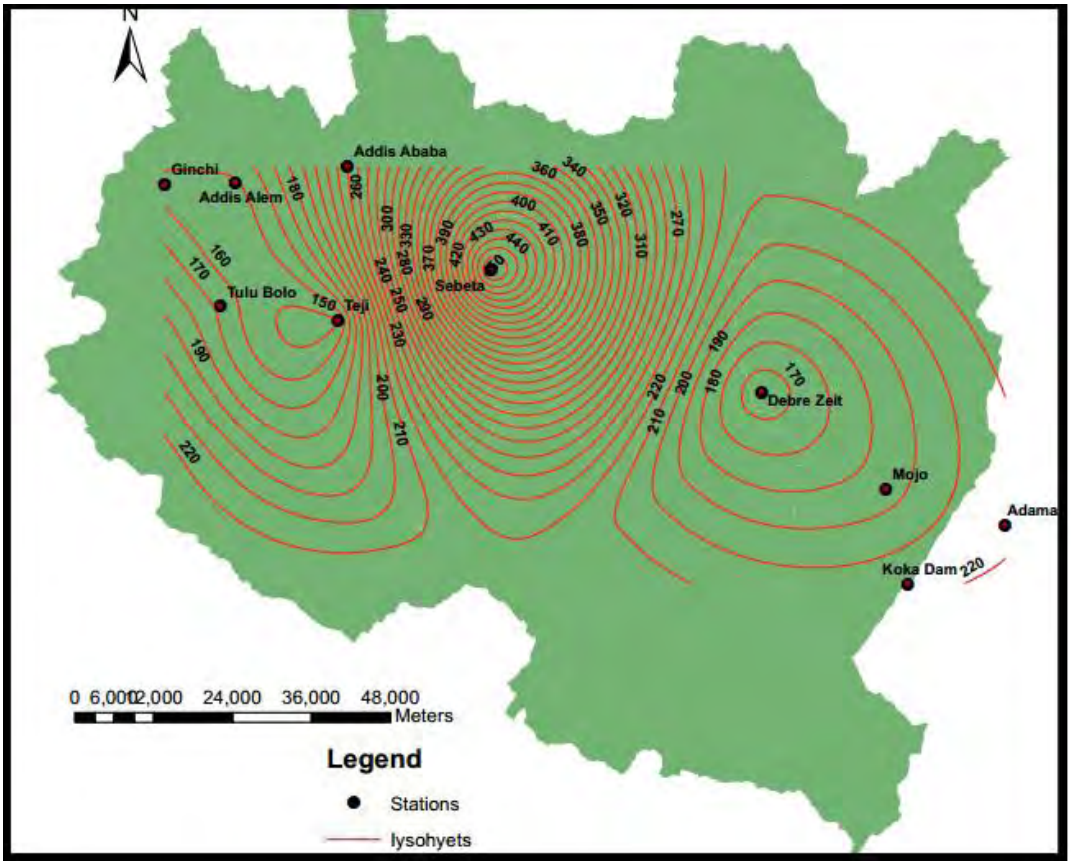
1-Day PMP Contour map



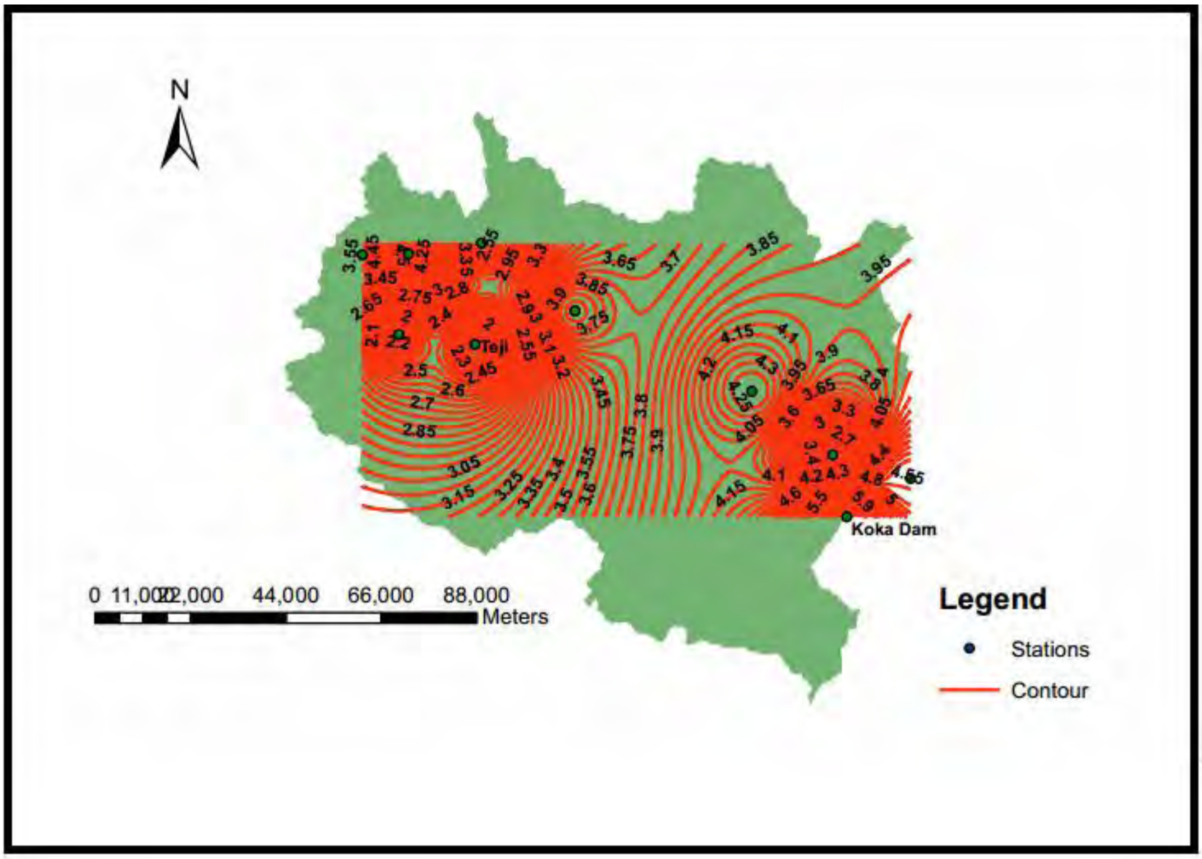
1-Day K contour map



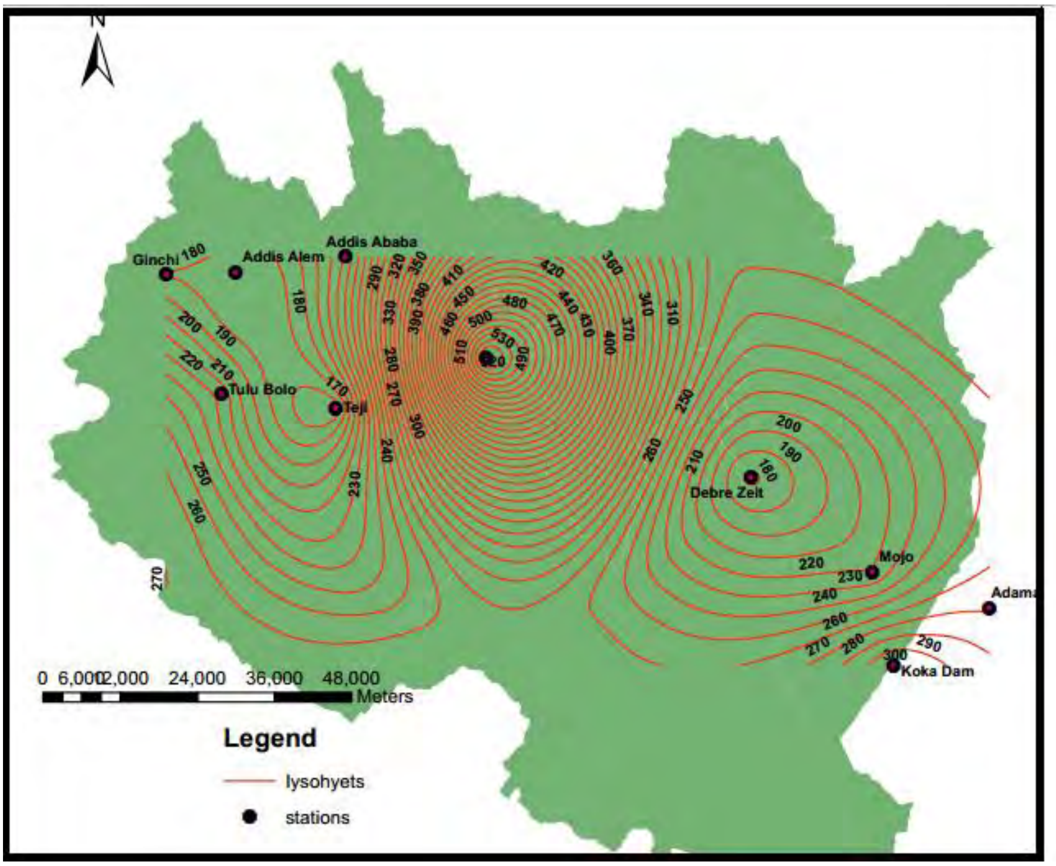
2-Day PMP Contour map



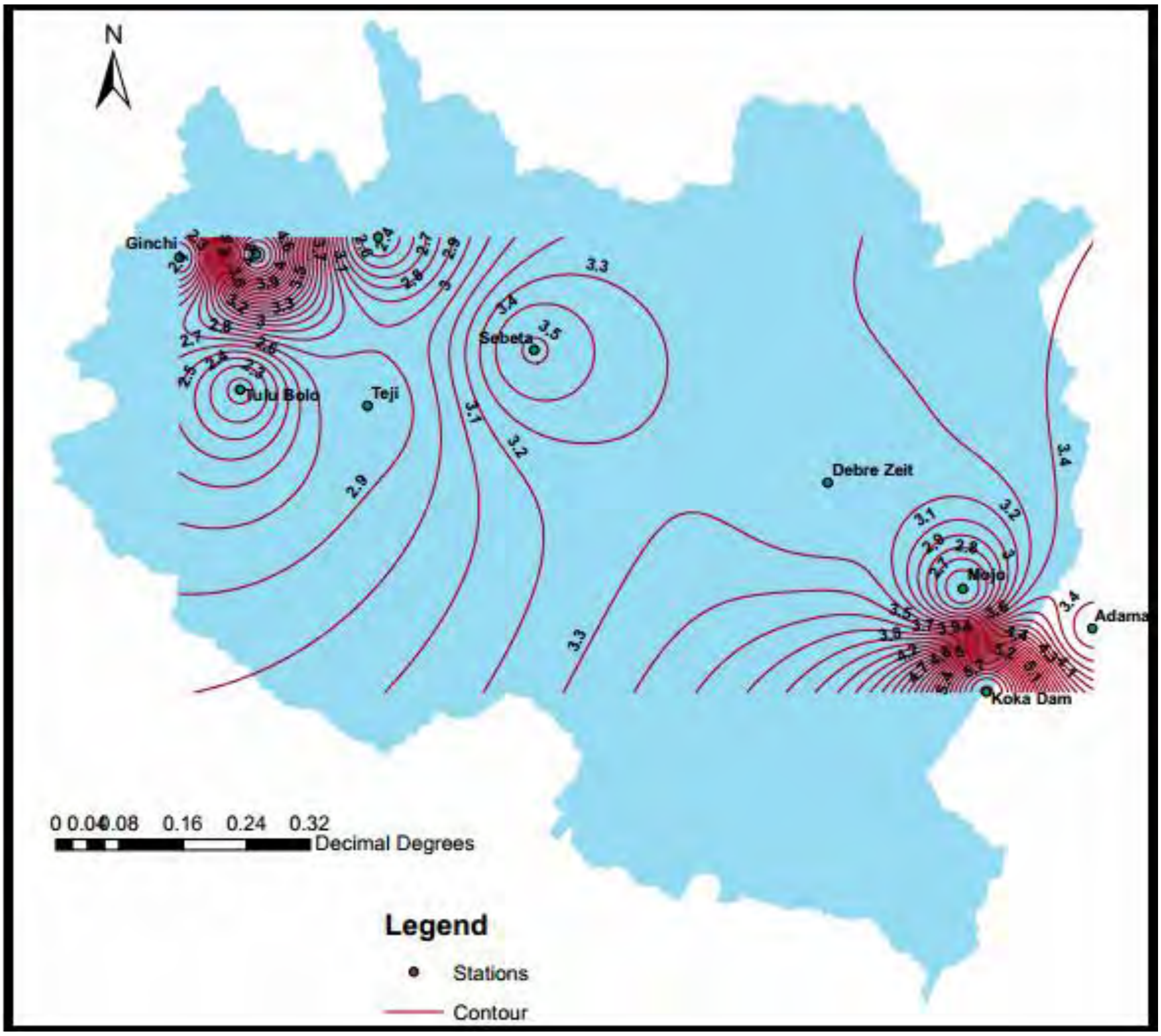
2-Day K Contour map



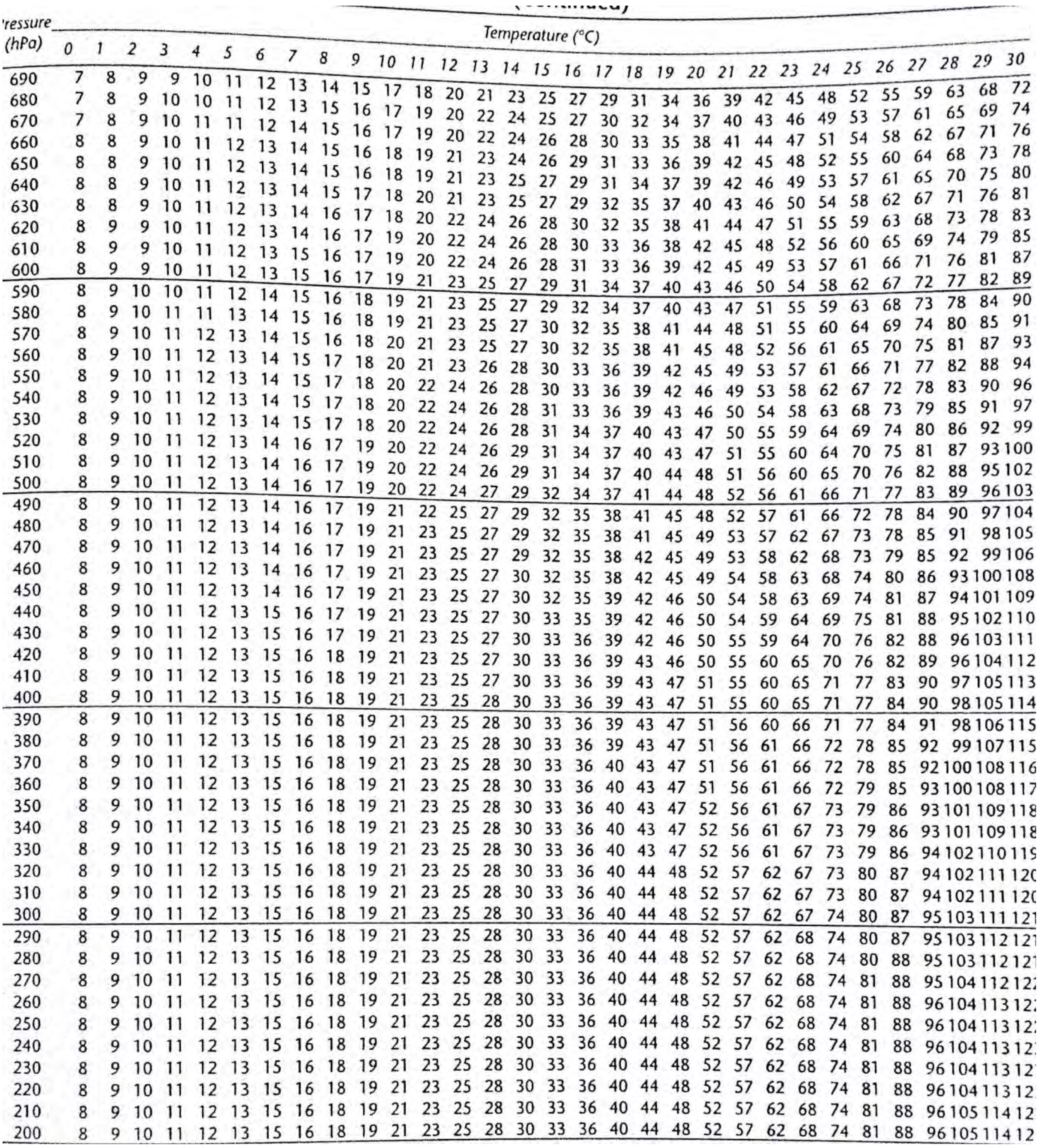
3-Day PMP Contour map



3-Day K contour map

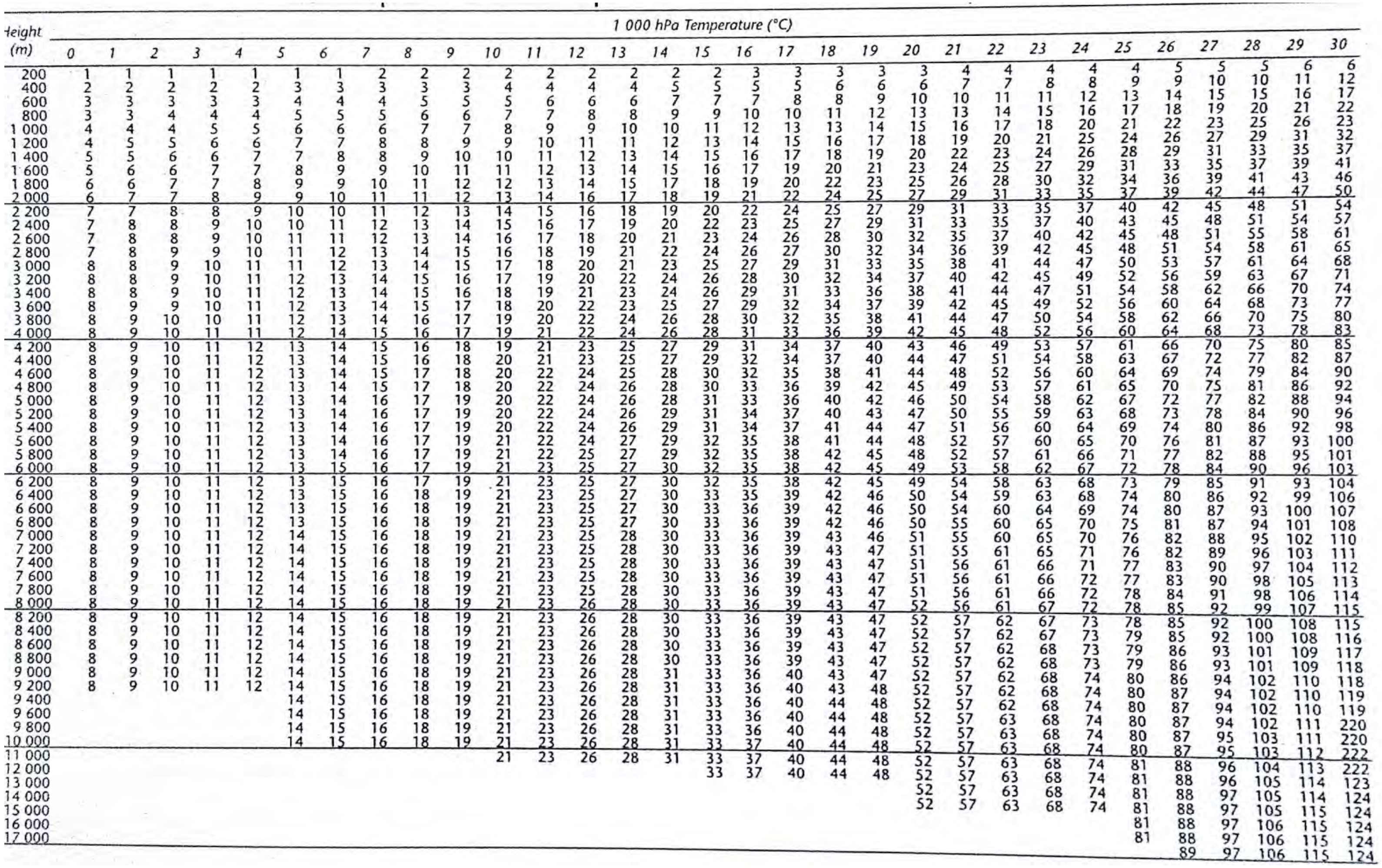


APPENDIX- M-1: Precipitable water (mm) between 1 000-hPa Surface and Indicated Pressure (hPa) in a Saturated Pseudo-adiabatic Atmosphere as a Function of the 1 000-hPa Dew point (°C)



ressure (hPa)	Temperature (°C)																														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
690	7	8	9	9	10	11	12	13	14	15	17	18	20	21	23	25	27	29	31	34	36	39	42	45	48	52	55	59	63	68	72
680	7	8	9	10	10	11	12	13	15	16	17	19	20	22	24	25	27	30	32	34	37	40	43	46	49	53	57	61	65	69	74
670	7	8	9	10	11	11	12	14	15	16	17	19	20	22	24	26	28	30	33	35	38	41	44	47	51	54	58	62	67	71	76
660	8	8	9	10	11	12	13	14	15	16	18	19	21	23	24	26	29	31	33	36	39	42	45	48	52	55	60	64	68	73	78
650	8	8	9	10	11	12	13	14	15	16	18	19	21	23	25	27	29	31	34	37	39	42	46	49	53	57	61	65	70	75	80
640	8	8	9	10	11	12	13	14	15	17	18	20	21	23	25	27	29	32	35	37	40	43	46	50	54	58	62	67	71	76	81
630	8	8	9	10	11	12	13	14	16	17	18	20	22	24	26	28	30	32	35	38	41	44	47	51	55	59	63	68	73	78	83
620	8	9	9	10	11	12	13	14	16	17	19	20	22	24	26	28	30	33	36	38	42	45	48	52	56	60	65	69	74	79	85
610	8	9	9	10	11	12	13	15	16	17	19	20	22	24	26	28	31	33	36	39	42	45	49	53	57	61	66	71	76	81	87
600	8	9	9	10	11	12	13	15	16	17	19	21	23	25	27	29	31	34	37	40	43	46	50	54	58	62	67	72	77	82	89
590	8	9	10	10	11	12	14	15	16	18	19	21	23	25	27	29	32	34	37	40	43	47	51	55	59	63	68	73	78	84	90
580	8	9	10	11	11	13	14	15	16	18	19	21	23	25	27	30	32	35	38	41	44	48	51	55	60	64	69	74	80	85	91
570	8	9	10	11	12	13	14	15	16	18	20	21	23	25	27	30	32	35	38	41	45	48	52	56	61	65	70	75	81	87	93
560	8	9	10	11	12	13	14	15	17	18	20	21	23	26	28	30	33	36	39	42	45	49	53	57	61	66	71	77	82	88	94
550	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	30	33	36	39	42	46	49	53	58	62	67	72	78	83	90	96
540	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	31	33	36	39	43	46	50	54	58	63	68	73	79	85	91	97
530	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	31	34	37	40	43	47	50	55	59	64	69	74	80	86	92	99
520	8	9	10	11	12	13	14	16	17	19	20	22	24	26	29	31	34	37	40	43	47	51	55	60	64	70	75	81	87	93	100
510	8	9	10	11	12	13	14	16	17	19	20	22	24	26	29	31	34	37	40	44	48	51	56	60	65	70	76	82	88	95	102
500	8	9	10	11	12	13	14	16	17	19	20	22	24	27	29	32	34	37	41	44	48	52	56	61	66	71	77	83	89	96	103
490	8	9	10	11	12	13	14	16	17	19	21	22	25	27	29	32	35	38	41	45	48	52	57	61	66	72	78	84	90	97	104
480	8	9	10	11	12	13	14	16	17	19	21	23	25	27	29	32	35	38	41	45	49	53	57	62	67	73	78	85	91	98	105
470	8	9	10	11	12	13	14	16	17	19	21	23	25	27	29	32	35	38	42	45	49	53	58	62	68	73	79	85	92	99	106
460	8	9	10	11	12	13	14	16	17	19	21	23	25	27	30	32	35	38	42	45	49	54	58	63	68	74	80	86	93	100	108
450	8	9	10	11	12	13	14	16	17	19	21	23	25	27	30	32	35	39	42	46	50	54	58	63	69	74	81	87	94	101	109
440	8	9	10	11	12	13	15	16	17	19	21	23	25	27	30	33	35	39	42	46	50	54	59	64	69	75	81	88	95	102	110
430	8	9	10	11	12	13	15	16	17	19	21	23	25	27	30	33	36	39	42	46	50	55	59	64	70	76	82	88	96	103	111
420	8	9	10	11	12	13	15	16	18	19	21	23	25	27	30	33	36	39	43	46	50	55	60	65	70	76	82	89	96	104	112
410	8	9	10	11	12	13	15	16	18	19	21	23	25	27	30	33	36	39	43	47	51	55	60	65	71	77	83	90	97	105	113
400	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	39	43	47	51	55	60	65	71	77	84	90	98	105	114
390	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	39	43	47	51	56	60	66	71	77	84	91	98	106	115
380	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	39	43	47	51	56	61	66	72	78	85	92	99	107	115
370	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	43	47	51	56	61	66	72	78	85	92	100	108	116
360	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	43	47	51	56	61	66	72	79	85	93	100	108	117
350	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	43	47	52	56	61	67	73	79	86	93	101	109	118
340	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	43	47	52	56	61	67	73	79	86	93	101	109	118
330	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	43	47	52	56	61	67	73	79	86	94	102	110	119
320	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	67	73	80	87	94	102	111	120
310	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	67	73	80	87	94	102	111	120
300	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	67	74	80	87	95	103	111	121
290	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	80	87	95	103	112	121
280	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	80	88	95	103	112	121
270	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	95	104	112	122
260	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	96	104	113	122
250	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	96	104	113	12
240	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	96	104	113	12
230	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	96	104	113	12
220	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	96	104	113	12
210	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	96	105	114	12
200	8	9	10	11	12	13	15	16	18	19	21	23	25	28	30	33	36	40	44	48	52	57	62	68	74	81	88	96	105	114	12

APPENDIX- N-2 Precipitable water (mm) between 1000-hPa surface and indicated height (m) above the surface in a saturated pseudo-adiabatic atmosphere as a function of the 1000-hpa dew point (^{o}C)



Height (m)	1 000 hPa Temperature (°C)																														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
200	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	6	6
400	2	2	2	2	2	3	3	3	3	3	4	4	4	4	5	5	5	5	6	6	6	7	7	8	8	9	9	10	10	11	12
600	3	3	3	3	3	4	4	4	5	5	5	6	6	6	7	7	7	8	8	9	10	10	11	11	12	13	14	15	15	16	17
800	3	3	4	4	4	5	5	5	6	6	7	7	8	8	9	9	10	10	11	12	13	13	14	15	16	17	18	19	20	21	22
1 000	4	4	4	5	5	6	6	6	7	7	8	9	9	10	10	11	12	13	13	14	15	16	17	18	20	21	22	23	25	26	23
1 200	4	5	5	6	6	7	7	8	8	9	9	10	11	11	12	13	14	15	16	17	18	19	20	21	25	24	26	27	29	31	32
1 400	5	5	6	6	7	7	8	8	9	10	10	11	12	13	14	15	16	17	18	19	20	22	23	24	26	28	29	31	33	35	37
1 600	5	6	6	7	7	8	9	9	10	11	11	12	13	14	15	16	17	19	20	21	23	24	25	27	29	31	33	35	37	39	41
1 800	6	6	7	7	8	9	9	10	11	12	12	13	14	15	17	18	19	20	22	23	25	26	28	30	32	34	36	39	41	43	46
2 000	6	7	7	8	9	9	10	11	11	12	13	14	16	17	18	19	21	22	24	25	27	29	31	33	35	37	39	42	44	47	50
2 200	7	7	8	8	9	10	10	11	12	13	14	15	16	18	19	20	22	24	25	27	29	31	33	35	37	40	42	45	48	51	54
2 400	7	8	8	9	10	10	11	12	13	14	15	16	17	19	20	22	23	25	27	29	31	33	35	37	40	43	45	48	51	54	57
2 600	7	8	8	9	10	11	11	12	13	14	16	17	18	20	21	23	24	26	28	30	32	35	37	40	42	45	48	51	55	58	61
2 800	7	8	9	9	10	11	12	13	14	15	16	18	19	21	22	24	26	27	30	32	34	36	39	42	45	48	51	54	58	61	65
3 000	8	8	9	10	11	11	12	13	14	15	17	18	20	21	23	25	27	29	31	33	35	38	41	44	47	50	53	57	61	64	68
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3 800	8	9	10	10	11	12	13	14	16	17	19	20	22	24	26	28	30	32	35	38	41	44	47	50	54	58	62	66	70	75	80
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4 200	8	9	10	11	12	13	14	15	16	18	19	21	23	25	27	29	31	34	37	40	43	46	49	53	57	61	66	70	75	80	85
4 400	8	9	10	11	12	13	14	15	16	18	20	21	23	25	27	29	32	34	37	40	44	47	51	54	58	63	67	72	77	82	87
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4 800	8	9	10	11	12	13	14	15	17	18	20	22	24	26	28	30	33	36	39	42	45	49	53	57	61	65	70	75	81	86	92
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9 600						14	15	16	18	19	21	23	26	28	31	33	36	40	44	48	52	57	63	68	74	80	87	94	102	111	220
9 800						14	15	16	18	19	21	23	26	28	31	33	36	40	44	48	52	57	63	68	74	80	87	95	103	111	220
10 000						14	15	16	18	19	21	23	26	28	31	33	37	40	44	48	52	57	63	68	74	80	87	95	103	112	222
11 000											21	23	26	28	31	33	37	40	44	48	52	57	63	68	74	81	88	96	104	113	222
12 000																33	37	40	44	48	52	57	63	68	74	81	88	96	105	114	123
13 000																					52	57	63	68	74	81	88	97	105	114	124
14 000																					52	57	63	68	74	81	88	97	105	115	124
15 000																										81	88	97	106	115	124
16 000																										81	88	97	106	115	124
17 000																											89	97	106	115	124