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Development of One Day Probable Maximum Precipitation (PMP) and Isohyetal Map for Tigray Region, Ethiopia

Yohannes Gerezihier Gebremedhin[1] Shoeb Quraishi[2] Habtamu Itefa[3]
1.Department of Natural Resources Management, College of Agriculture and Environmental Sciences, Adigrat University, Adigrat, 50, Ethiopia, (Lecturer)-author
2.Department of Soil and Water Engineering, Institute of Eriengineering, Haramaya University, Haramaya, 138, Ethiopia, (Professor Dr. Lecturer)-co-author
3.Department of Natural Resources Management, Institution of Science and Technology, Addis Ababa University, Addis Ababa, 16417, Ethiopia, (Assistant Professor, Dr. Lecturer) - co-author

Abstract
Water is a prime requirement for the existence of life; however uncontrollable amounts of water can adversely affects the survival of living beings. Due to wide range of precipitation variability, drought and extreme floods, the study of one day Probable Maximum Precipitation (PMP) for Tigray region is necessary. In an attempt to develop PMP and Isohyetal map for one day duration, using annual daily extreme rainfall series of 22 stations were subjected to statistical analysis using Hershfield formula adapted version of chow. Stations having inadequate daily records were identified and estimated using Normal Ratio Method, and Double mass curve was employed to check for the consistency of the data. An appropriate frequency factor (K_m) was displayed as a function of the mean of the annual maxima for rainfall observations and the PMP for one day duration, and the highest value of K_m was found to be 5.91. It was found that PMP vary from 70.06 to 144.51 mm, and the ratio of estimated one-day PMP and highest observed rainfall varied from 1.04 to 1.42. To predict extreme daily rainfall for each station normal, log normal, log Pearson type-III and Gumbel probability distribution functions were used, and values were subjected to goodness of fit tests of chi-square, correlation coefficient and coefficient of determination tests to assess how best the fits had been. Results revealed that the log Pearson type-III distribution performed the best, with average return period $2.7*10^3$ years. The ratio of one-day PMP to rainfall depth for frequencies return period of 5, 10, 50, 100, 1000 and 10000 year floods had been estimated and found to vary from 33.29 to 175.92 mm. The predicted PMP value to depths of various years return period ratios were computed and found to vary between 0.5132 and 2.712. Isohyetal map over Tigray region was generated by means of Arc Map10, IDW interpolation approach and the PMP Isohyetal lines were vary from 80 to 135mm. The high PMP Isohyetal values were observed in the Southern, Central and Eastern Zone and decreases in South-East Zone. For more reliable finding it is better to deal with uniformly distributed stations and larger update data as the climate pattern of the region is dynamic.
Keywords: PMP[1], Probability Distribution Function, Goodness of Fit Test, Return Period, Isohyetal Map, Tigray Region

1. Introduction

Assessment of extreme precipitation is an important problem in hydrologic risk analysis and design. Water is a prime requirement for the existence of life; however uncontrollable amounts of water can adversely affect the survival of living beings (Wanniarachchi [1] and Wijesekera [2], 2012). Extreme natural environmental events, such as floods, rainstorms, high winds and droughts, have severe consequences for human society and cause significant damage to agriculture, ecology and infrastructure, disruption to human activities, injuries and loss of lives. Planning for weather-related emergencies such as design of engineering structures, reservoir management, pollution control, and insurance risk calculations, all rely on knowledge of the frequency of these extreme events. (Einfalt *et al.,* 1998).

Ethiopia has very diversified pattern in different climatic conditions, ranging from semi-arid desert type in low lands to humid and warm temperate type in the southwest, which means higher in the south west and gradually decreases to north east of the country. Rainfall is mainly controlled by the seasonal migration of ITCZ in associated with atmospheric circulation, as well as complex topography of the country (NMSA, 2004).

Flooding is common in Ethiopia during rainy season between June and September and the major types of floods are flash floods and river floods (FDPPA, 2006). Flash floods are mainly linked with isolated, localized intense and short duration event caused by high peak discharge (Few, 2006). This type of flood could pose a big damage to human life and property because they occur suddenly with very high intensity (Greenough *et al,* 2001). There were flash floods in many parts of Ethiopia at different times. For example, due to the phenomenon of extreme rainfall events in Dere-Dawa in 2006 when 9,956 people were displaced and 256 were killed (FDPPA, 2007). In South Omo, Gode, Afar, Gambella, Oromia, Tigray and Amahra regions, nearly 118,000

[1]***Probable Maximum Precipitation-PMP***

peoples were affected, 35,000 were displaced and 1,000 faced fatalities (EEWS, 2007). Similarly, Tigray regional state had also faced massive floods in the past resulted in crop damage and livestock losses (NMSA, 2004).

In recent days, Ethiopia is heading with the transformation plan of progressive philosophy. To make this dream true, the county requires tapping and conserving natural resources like land, water and generation of hydro-electricity and development of much more water resources to meet the needs in very near future. A number of water projects are started all over the country. Some are at the feasibility stage and some others are at the detail design and construction phase. As northern part of the country, no exception for Tigray regional state, the need for hydroelectricity, irrigation conservation practices has become the primary motivation in large-scale water resource projects. In this regards, construction of dams and other hydraulic structures on major rivers of the region is one of the priorities for the regional authorities. In the past, a lot had been invested for the construction of water resource projects such as soil and water conservation measures, dams, diversion weirs, barrages and other hydraulic structures across rivers.

In the design of major hydraulic structures, hydrologists and hydraulic engineers would like to keep the failure probability as low as possible *i.e.* virtually zero. This is because the failure of such a major structure will cause damage to life, property, economy and national morale. In the design and analysis of such structures, the probable maximum precipitation (PMP) is expected at a given location used. Works must be designed and built to withstand the maximum floods that would be expected to occur at the structure site. Therefore, to mitigate casual floods because of extreme events in the region requires safety measures for hydraulic structures to be designed based on the estimation of PMP.

Getting reliable long consistent and complete river and stream discharge data, which would be used in water resource project development, is still a problem in Tigray (Mahdi Osman, 2001). Therefore, hydrologic designs such as peak flow rates and/or flow hydrographs depend more on rainfall data. In doing so, the common problem encountered is to identify the upper limit of rainfall amount for particular duration to estimate the probable maximum flood. Furthermore, there were no developed hydrological procedure and reliable complete data sets in the past that could provide easy, reliable and quick information on the PMP values in the region.

Studies of one-day PMP over a region or a catchment area are essential for the planning and designing of hydraulic structures such as check dams, storage reservoirs and earthen dams and also now a day in soil and water conservation measures, although the probability analysis of annual maximum daily rainfall for different return periods has been suggested. Hence, knowledge on extreme rainfall events and PMP would be the basis in engineering practices for designing hydraulic structures and set up measures for reducing the impact of the disaster (Chow.V.T., 1952).

Therefore, to overcome the limitations of the frequency based storm in the regional state, estimation of one-day PMP and the corresponding Isohyetal map are valuable options for the design rainfall inputs for computing probable maximum flood. This information may provide preliminary basis for designing of hydrologic structures to minimize the damages on hydraulic structures and the consequent loss of properties due to the failure or overtopping of the structures under flood conditions. Considering the importance of the issue in the region, an attempt will be made to estimate point PMP and to generate the corresponding Isohyetal map, which often needed for proper planning, management and designing of different types of water resource and conservation projects. Therefore, this study was planned with following specific objectives;

- To estimate one day point PMP and their return periods for selected station in Tigray Region
- To identify best fit probability distribution function for Tigray Region
- To develop one day PMP Isohyetal map for Tigray Region

2. Materials and Methods

2.1. Description of the Study Area

2.1.1. Location and Population

Geographically Tigray Region is located between latitude 12°15 ′N and 14° 57′ N and longitude 36° 27 ′ E and 39° 59′ E and bordered by Eritrea to the north, Sudan to the west, the Afar region to the east, and the Amhara region to the south and southwest. According to the new administrative set up, the region is structured in to 7 administrative zones these are Western, North-Western, Central, Eastern, Southern, South-East and Mekelle (Regional Capital City). It has 46 wereda/districts, total area of Tigray estimated around 53,000 km^2, accounts 4.82% of the total area of the country. According to Ethiopia Central Statistics Authority (2008), the population of Tigray was 4,314,456 (2008 census) and the projection for the 2011 is 4,803,000 inhabitants, of whom 85% of the population lives in rural areas, which depends on rain-fed agriculture. Annual population growth is 2.5%, which is near to at national level (Tewelde Yideg, 2012).

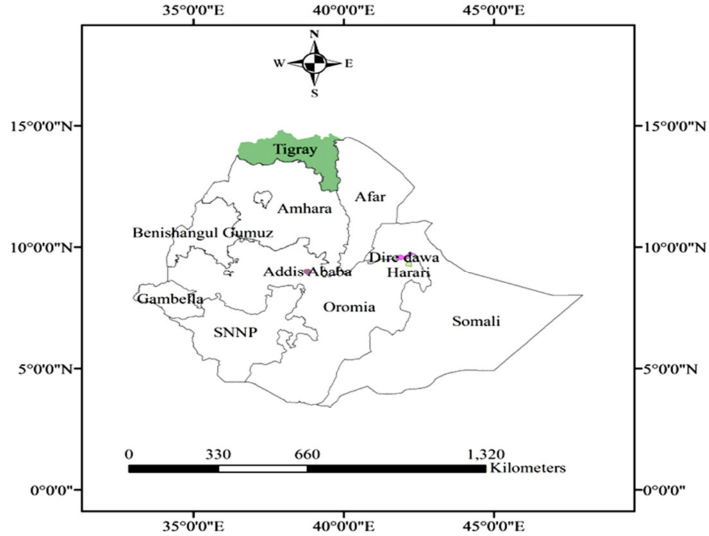

Figure 2.Location of Tigray Region in Ethiopia

2.1.2. Climate and Weather

Climate conditions of Tigray vary from arid to semi-arid and characterized as Kolla (semi-arid), Weyna-dega (warm temperate) and Dega (temperate).The area coverage of the climate sub-regions are 53%, 39% and 8% with low, medium and high rainfall, and have high, medium and low temperature respectively (USAID, 2009, BFED, 2007). The rainfall in the Tigray is bi-modal which contains *Meher (Kremt)* and *Belg* seasons and the average annual rainfall of the region ranges between 400 to 700 mm and about 84% of the annual rainfall is received during the *Meher* or main rain season. The effective rainy season covers 50 to 60 rain days (June to August), while the dry period covers the months December to April. The average annual temperature of the region ranges from 13.4°C and 28°C in the highland of South West and Western lowlands respectively (Gebrehiwot *et al*., 2011). The *Belg* rainy season is observed in only a small part of the region and occurs from March to May (Kiros *et al.,* 2009).

2.1.3. Relief and Topography

Topography of the region has been shaped by geomorphology processes and by centuries of natural geological erosion and more recently by man-made soil erosion, deforestation and overgrazing. Many sequences of steep hills and valleys are some of the important physical features of the region. Topography of Tigray contains three main physiographic divisions of Ethiopia, the kola-lowlands (1400-1800 m.a.s.l) with relatively low rainfall and high temperatures; the Woina-dega middle highlands (1800-2400 m.a.s.l.) with medium rainfall and medium temperatures; Dega or highlands (2400-3400 m.a.s.l.) with somewhat higher rainfall and cooler temperatures (USAID, 2009).

2.1.4. Agro-Ecological Zones and Farming System

Tigray presents a diversification of agro-ecological zones characterized as a function of soils, geology, vegetation, local climate and other natural resources. Mixed farming (crop and livestock) is the dominant system in the region. Rain-fed agriculture is dominant in the region but currently the irrigation coverage of the region is improving through time. Barley, Wheat, Tiff, Sorghum and Maize are the dominant crops growing in the region (USAID, 2009).

2.2. Method of Data Analysis

For each station, daily maximum rainfall was selected and an array of annual daily maximum values of rainfall was formed. All the annual daily and annual total rainfall data of the stations was arranged in Excel-2007, SAS version 9.1.3 (for Windows.exe) and Easy Fit version5.5 standard software's were very useful tools for data analyzing and interpreting. In additional to this to develop PMP Isohyetal map, Arc Map 10 software was used. Any oddities in the data were checked and identified using the appropriate measures taken.

2.3. Data Collection and Organization

According to the Ethiopian Meteorological Agency web set (in 2015), there were 61 stations in the Tigray region, out of those 22 stations (36%) were considered for this study (Figure 2). Area coverage of the region is about 53,000 km^2 and with this station density is approximately one per 870 km^2 (for this study 2,409 km^2, this is far from the WMO and FAO recommendation) and the mean distance between stations is approximately 81.8 km^2 (for this study 114.5km^2). Based on the FAO guideline 10% of the rain gauge stations are equipped with self recording type which is the need for any research study, where as in this study 22.73% of the stations are self recording (first class). The nature and class properties of gauging stations for this study are given in Table 1. As per the requirement for PMP estimation, all classes of stations were considered.

Secondary data was collected from Ethiopia National Meteorology Service Agency head office (Addis Ababa) and Tigray Region sub-branch (Mekelle). Data collected includes, daily annual rainfall, daily extreme rainfalls (which were extracted from the daily annual data of rainfall), annual totals rainfall and GPS location of each gauging stations (Table 1 and 2, and Figure 2). The criteria for rainfall data collection were for those stations having 15 or more year's (Table 2) with an average 22 years record length (max. for Edaga-hamus 39 years and min. for Adi-shehu and Agibe both 15 years) were sued. Missed data were estimated and reconstructed by Normal Ratio Method and Double mass curve to check for the consistency of the data.

$$P_x = \frac{A_x}{n}\left(\frac{P_1}{A_1} + \frac{P_2}{A_2} + \frac{P_3}{A_3} + \ldots \frac{p_i}{A_n}\right) \quad (2.7)$$

where, the ratio (P_i/A_n) is the proportion of rain gauge station (i) of the mean annual catch that occurs in specific storms.

$$P_a = \frac{M_a}{M_o} P_o \quad (2.8)$$

where,

P_o - the observed value
P_a - the adjusted value
M_o - slope of the double mass curve corresponding to the value, to which the observed values are being adjusted.

Table 1. Selected Stations in Number, Percentage and their Properties

Class Type	Stations no.	Stations %	Description of Class Properties
First Class Station	5	22.73	consists of manual and automatic recording rain-gauges, evaporation pan, screen thermometer, wind vane, sunshine hours recording, and intensity recording and well trained personnel
Second Class Station	1	4.55	consists recording rain-gauges, evaporation pan, screen thermometer, wind vaneand somewhere trained personnel
Third Class Station	9	40.91	This class is equipped with manual rain-gauge, thermometer, and with trained as well as part time workers.
Fourth Class Station	7	31.81	This class stations are equipped with only manual type rain gauge
Total	22	100	

Table 2. Meteorological Stations and their Locations in Tigray

S/N	Station Name	Latitude (^{O}N)	Longitude (^{O}E)	Altitude (m.a.s.l)	Class Type	Years Record	Region
1	Abi-adi	13.61	39.00	1829	3	18	Tigray
2	Adi-da'ero	13.31	38.17	1772	4	18	Tigray
3	Adigrat	14.28	39.45	1970	1	21	Tigray
5	Adi-gudom	13.25	39.51	2100	4	21	Tigray
4	Adi-remets	13.75	37.32	2014	3	18	Tigray
6	Adi-shehu	12.93	39.53	2465	4	15	Tigray
7	Adwa	14.18	38.88	1911	1	21	Tigray
8	Agibe	13.54	39.04	1550	4	15	Tigray
9	Alamata	12.42	39.56	1589	3	21	Tigray
10	Axum	14.11	38.73	2105	3	21	Tigray
11	Aynalem	13.46	39.49	2195	4	21	Tigray
12	Dengolet	13.32	39.32	2371	4	21	Tigray
14	Edaga-hamus	14.18	39.56	2708	4	39	Tigray
13	Endaba-guna	13.94	38.18	1761	3	18	Tigray
15	Hawzen	13.97	39.43	2242	3	21	Tigray
16	Humera	14.10	36.52	604	1	31	Tigray
17	Korem	12.51	39.51	2450	3	23	Tigray
18	Maichew	12.78	39.53	2432	1	21	Tigray
19	Mekelle	13.47	39.53	2257	2	21	Tigray
20	Sherie	14.10	38.29	1897	1	21	Tigray
21	Waja	13.28	39.60	1458	3	29	Tigray
22	Wukro	13.79	39.60	1987	3	21	Tigray
Average						21.64	

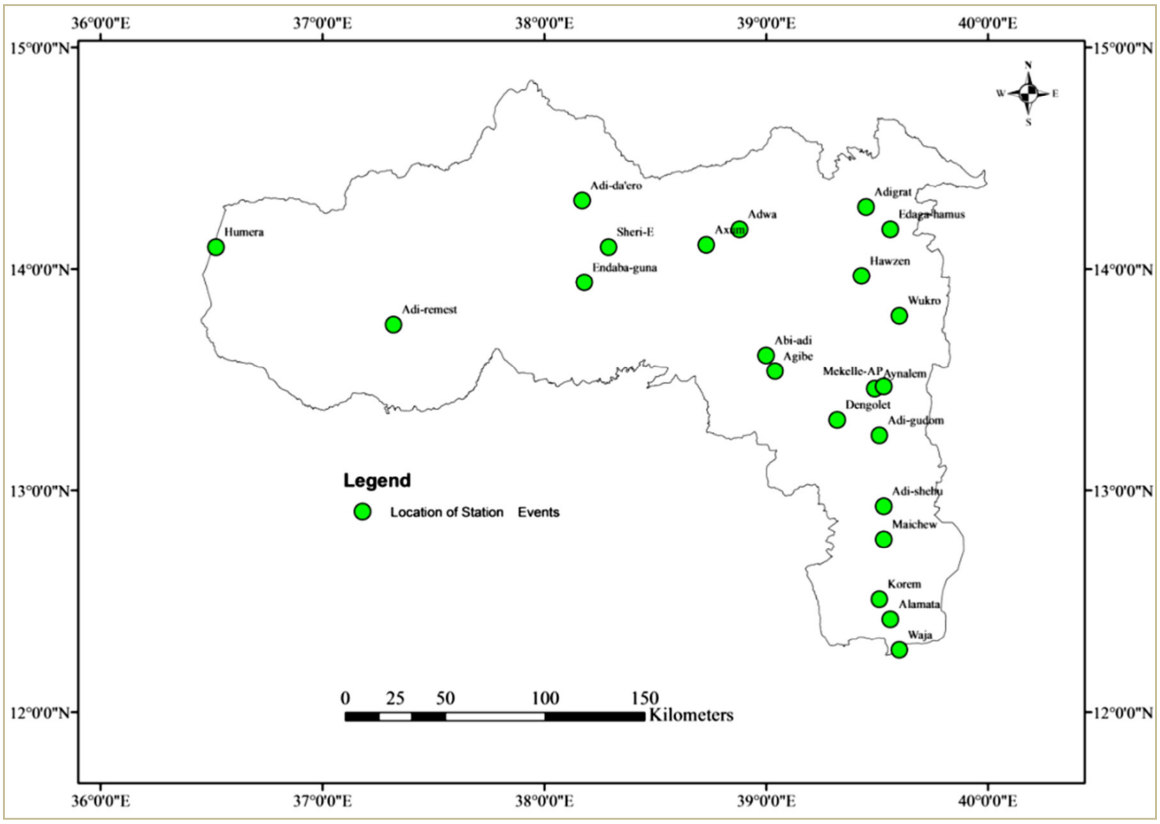

Figure 3. Distribution of Selected Rain Gauge Stations in Tigray Region

2.4. PMP Estimation

The Hershfield (1961, 1965) technique, an adapted version of Chow (1952), for the frequency analysis of rainfall was used for PMP computation. The values of $\bar{x}$, $\bar{x}_{n-1}$, σ_n, σ_{n-1} and CV were estimated using equation (2.11 and 2.12). The maximum frequency factor (K_m) was estimated for each station using equation (2.13); hence frequency table for K_m was prepared. Then, upper limit of the estimated K_m was chosen from the extremely high values. One-day annual maximum rainfall values of all stations were analyzed to extract the station based PMP estimates using equation (2.10). Then estimated values of series rainfall stations were summarized to observe one-day highest rainfall, as well as the ratio of estimated PMP to these rainfall values, to facilitate comparisons.

$$X_{PMP} = \bar{X}_n + S_n K_m \tag{2.10}$$

where,

X_{PMP} - PMP estimate for a station
$\bar{X}_n$ - mean of the annual extreme series
S_n - standard deviation of the annual extreme series
K_m - maximum frequency factor

The sample mean ($\bar{X}$) and standard deviation (S_n) could be computed by:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{2.11}$$

$$Sn = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}} \tag{2.12}$$

where,

$\bar{X}$, - mean for the random variable
X_i - the ith value of the random variable
S_n - sample standard deviation

The maximum frequency factor (K_m) can be calculated as (Hershfield, 1961, 1965)

$$K_m = \frac{X_1 - \bar{X}_{n-1}}{\sigma_{n-1}} \tag{2.13}$$

Where,

X_1 - highest observed annual maximum rainfall in the series

$\overline{X}_{n-1}$ - mean of the annual maximum, excluding the highest value

σ_{n-1} - Standard deviation of the annual maximum, excluding the highest value

2.5. Fitting Data to the Probability Distribution Functions

Frequency analysis techniques (Tao *et al,* 2002) were employed to analyze the annual daily maximum rainfall data. Fitting the theoretical probability distribution to the observed data was done by applying corresponding plotting position given in Table 3.

Table 3 Different plotting positions formulae

Plotting Positions	Formulae
Hazen (1930)	$\frac{(m-0.5)}{n}$
Weibull (1939)	$\frac{m}{(n+1)}$
Gringorton (1963)	$\frac{(m-0.375)}{n+0.25}$
Cunnane (1978)	$\frac{(m-0.4)}{n+0.2}$
California (1923)	$\frac{m}{n}$
Blom (1958)	$\frac{(m-0.44)}{n+0.12}$
Chegodajev (1955)	$\frac{(m-0.3)}{n+0.4}$

Normal Distribution: Plotting Probability was estimated using Weibull method (Table 3), value of Extreme value *(X_T)* and standard normal deviate *(Z)* were estimated using equation (2.27 and 2.28) respectively. The standard normal deviate *(Z)* values for exceedence probability other than the equation 2.28 were interpolated.

$$X_T = \overline{x} + \sigma K_T \quad (2.27)$$

$$K_T = \frac{x_T + \overline{x}}{Sn} \quad (2.28)$$

where, x_T is the variate, $\overline{x}$ is the mean and *Sn* is the standard deviation of the sample data.

Log Normal Distribution: After rearranging the annual daily maximum values in the descending order of magnitude and assigning a rank '*m'* with '1'for the highest value (Table 3), values of the '*Z'* and '*W'* were estimated using equation (2.29 and 2.30) respectively and the other parameters were estimated using equations given in Table 4.

$$Z=K_T= w-\left[\frac{(2.516+0.8028w+0.0103w^2)}{(1+1.4328w+0.1893w^2+0.0013w^3)}\right] \quad (2.29)$$

where *w* is intermediate variable which is calculated using the formula:

$$w = \left[ln\frac{1}{p^2}\right]^{\frac{1}{2}} \quad (0 < p \leq 0.5) \quad (2.30)$$

where *p* is the probability of exceedence, and *p>0.5, 1-p* is substituted for *p* and the value of *Z* which is computed is given a negative sign.

Table 4. Expressions Used to Estimated Parameters of Log Normal Probability Distribution

Parameter	Formula
Y_T	$\overline{Y}_n + K_T S_y$
X_T	10^{Y_T}

Log Pearson Type-III Distribution: The procedure for fitting the LPT-III distribution is similar to that for the normal and log-normal. For making LPT-III analyses the following steps were used given by Raghunath (2006) as;

- A logarithmic transformation was made for all events of the series ($Y_i = log X_i$)
- The probability plotting positions were calculated using Hazen formula (Table 1)
- Mean ($\overline{Y}$), standard deviation (*Sn*), and standardized skew (*Cs*) of the logarithms were computed using equations (2.23, 2.24 and 2.25) respectively, and

$$\overline{y} = \frac{\sum y}{n} \quad (2.23)$$

$$S_y = \sqrt{\frac{\sum(y-\overline{y})^2}{n-1}} \quad (2.24)$$

The coefficient of skewness (C_s) is estimated given by Apipattanavis *et al*. (2005) as:

$$C_S = \frac{n\sum(y-\overline{y})^3}{[(n-1)(n-2)S_y^3]} \quad (2.25)$$

- K_T and K were calculated using equation (2.31) and (2.32) respectively

$$K_T = Z + (Z^2 - 1)k + \frac{1}{3}(Z^3 - 6Z)k^2 + Zk^4 + \frac{1}{3}k^5 \quad (2.31)$$

where, $$k = {C_s}/{6} \quad (2.32)$$

Gumbel Extreme Value Type-I Distribution: this distribution was achieved by plotting the ranked annual maximum rainfalls values and exceedence probability was estimated. The following Steps were followed for derivation of extreme value, given by Raghunath (2006);

- The reduced variate (Y_T) was calculated using equation (2.34)

$$Y_T = -\ln\left[\ln\left(\frac{T}{T-1}\right)\right] \quad (2.34)$$

- The value of the return period was obtained by taking the inverse of the probability plotting position which was obtained by using Weibull method
- Frequency factor K_T was derived (where Y_n and S_n were obtained from the reduced variate table) using equation (2.33), and

$$K_T = \frac{Y_T - \bar{y}_n}{S_n} \quad (2.33)$$

- Finally $X_T = \overline{X} + K_T{*}S$ which is the extreme value

2.6. Testing the Goodness of Fit of Data to Probability Distribution

In order to determine the best-fit model at each station, probability distribution models were subjected to three goodness of fit tests, chi-square test (x^2), coefficient of correlation (r) and coefficient of determination (R^2). Determination of the probability distribution models was based on the total test score obtained from all the tests. Test scores ranging from zero to four (0-4) was awarded to each distribution model based on the criteria that the distribution/s with the highest total score were chosen as the best distribution model for the data of a particular station. Later on, model which was selected repeatedly for each station was selected as best fit model for the region. In general, the distribution best supported by a test was awarded a score of four; the next best was awarded three, and so on in descending order. A distribution was awarded a zero (0) score for a test if the test indicates that there was a significant difference between the rainfall values estimated by the distribution model and the observed rainfall data. For every test category, overall ranks of each distribution were obtained by summing the individual point rank at each of the 22 stations (Adegboye and Ipinyomi, 1995).

2.7. Estimation of Return Period Values for PMP

Equation (2.43) along with the estimated location and scale parameters using equation (2.20-2.25) were used for the computation of return period values corresponding to estimated PMP value for durations of one day for all stations.

$$T = \frac{1}{1-F} \quad (2.43)$$

where,

T-return period

F-value cumulative distribution function

$$f(X) = \frac{\lambda^{\beta}(y-\varepsilon)^{\beta-1}e^{-\lambda(y-\varepsilon)}}{X\Gamma(\beta)} \qquad where, logX \geq \varepsilon \quad (2.20)$$

where ε, β and λ are the location, shape and scale parameters respectively and estimated as:

$$y = \log x, \quad \lambda = \frac{S_y}{\beta} \quad \text{and} \quad \beta = (\frac{2}{C_S(Y)})^2, \quad (2.21)$$

$$\varepsilon = \overline{y} - S_y\sqrt{\beta} \quad \text{and} \quad \Gamma(\beta) = (\beta-1)! \quad (2.22)$$

$$\overline{y} = \frac{\sum y}{n} \quad (2.23)$$

$$S_y = \sqrt{\frac{\sum(y-\overline{y})^2}{n-1}} \quad (2.24)$$

The coefficient of skewness (C_s) is estimated given by Apipattanavis *et al*. (2005) as:

$$C_S = \frac{n\sum(y-\overline{y})^3}{[(n-1)(n-2)S_y^3]} \quad (2.25)$$

2.8. Developing PMP Isohyetal Map

Point PMP was located over base map of the region using ArcMap10 software to develop PMP Isohyetal maps. Over the base map of Tigray region, shape file was created with PMP data throughout the stations, shape file was selected and zoomed, then a grid file was created by using Arc View, finally layout of contour lines map were generated by inverse distance weighting(IDW) interpolation method and generalized PMP map was prepared (Ben Willardson *et al,* 2004).

3. Results and Discussions

3.1. Estimation of Missed Data

Stations having inadequate daily records were identified and considered to be missed. Based on the criteria given in section (2.5.1.), out of the 22 stations four station had missed data (Table 5). Missed data were estimated using Normal Ratio Method (Equation 2.7).

Table 5. Stations Having Missed Data

S/N	Station Name	No. of Years Recorded	No. of Years Missed	Missed Years in %	Specified Missed Year
1	Adigrat	21	2	9.52	2000, 2007
2	Edaga-hamus	39	2	5.13	1991, 2000
3	Humera	31	2	6.45	2000, 2007
4	Waja	29	2	6.90	1997, 2003

3.2. Consistency Test

Double mass curve (Equation 2.8) was employed to check for the consistency of the data. Accordingly, there were a little slope changes (average 0.17%) that were not persistence significant period change in the double mass curves; therefore the little change in slope might be occurred by chance or due to micro meteorological and climate properties. In addition to this report obtained from Regional Meteorological Agency Mekelle Branch, there were no historical evidences for station/s change from their original position or first established place. But there were long time stations not functional because of lack of skilled man power, war and unknown reasons. Therefore, the changes were not significant for the existence of inconsistency of records. Hence, relative homogeneity of records was observed for the precipitation.

3.3. Average Annual Total and Annual Daily Maximum

Based on the average recorded length (22 years) the average annual total and annual daily maximum of the region was decreasing trend (Table 6). Relatively high rainfall coverage in the west, north-west and central zones and low rainfall record in the east and south-east part of Tigray region was observed.

3.4. Estimation of Maximum Frequency Factor (K_m)

Maximum frequency factor (K_m) values for stations were estimated using equation (2.13) and found to vary from minimum 1.91 (Agibe station) to maximum 5.91 (Aynalem station) with average value of 3.10 and coefficient of variation as 28.20% (Table 7). K_m result obtained is higher than 20% (indicates the variability of the data). This variation may be due to the variability in record length or the variation in micro climatic conditions of the rain gauge stations.

Table 6. Average Annual Total and Annual Daily Maximum

Station name	Average annual total rainfall (mm)	Annual daily maximum (mm)
Abi-adi	1096.66	63.27
Adi-da’ero	808.71	56.84
Adigrat	625.99	47.35
Adi-gudom	504.57	40.31
Adi-remets	1296.06	74.44
Adi-shehu	647.06	45.58
Adwa	813.24	56.30
Agibe	634.57	47.61
Alamata	772.01	50.26
Axum	755.88	58.46
Ayenalem	535.39	43.01
Dengolet	680.00	48.42
Edaga-hamus	656.89	62.04
Endaba-guna	982.91	56.27
Hawzen	535.08	42.80
Humera	691.28	58.39
Korem	952.15	67.13
Maichew	782.20	54.65
Mekelle	600.39	48.92
Sherie	1014.20	57.48
Waja	643.97	45.93
Wukro	637.88	58.68
Average	707.60	53.83

Table 7.Derivation of Maximum Frequency Factor (K_m)

Station Name	HOR	$\bar{X}_{n-1}$	σ_{n-1}	K_m
Abi-adi	86.7	61.89	11.84	2.10
Adi-dae'ro	86.8	55.08	14.08	2.25
Adigrat	81.5	45.64	12.43	2.88
Adi-gudom	80.5	38.31	8.88	4.75
Adi-remets	102.3	72.80	9.90	2.98
Adi-shehu	78.0	43.26	12.99	2.67
Adwa	105.5	53.85	17.23	3.00
Agibe	70.1	46.00	12.63	1.91
Alamata	80.2	48.76	10.29	3.06
Axum	115.4	55.61	17.87	3.35
Aynalem	102.8	40.02	10.62	5.91
Dengolet	82.5	46.72	11.10	3.22
Edaga-hamus	126.2	60.35	23.31	2.82
Endaba-guna	91.8	54.18	12.72	2.96
Hawzen	66.0	41.64	9.66	2.52
Humera	105.9	56.81	15.42	3.18
Korem	109.3	65.22	14.16	3.11
Maichew	92.1	52.78	11.92	3.30
Mekelle	77.5	47.50	11.51	2.61
Sherie	101.8	55.26	11.99	3.88
Waja	71.1	45.03	9.97	2.61
Wukro	100.5	56.59	16.38	2.68
Mean				3.10
Sn				0.87
CV				28.20

As indicated in Table 7, the values of maximum frequency factor (K_m) were mostly less than 3.35. Only three values (13.64% of the total) 5.91 (Aynalem station), 4.75 (Adigu-dom station) and 3.88 (Sherie station) were greater than 3.35, with the latter being the upper limit of the estimated K_m. The frequency table for K_m was also formed and the most frequent quintiles were found to be between 3.00 and 4.50 and the least was found to be greater than 4.80 (Table 8). As PMP deals with unusual rainfall values, the corresponding frequency were chosen from the extremely high values, as 5.91 estimated in Aynalem station, and this is chosen as extremely high K_m value.

Table 8. Frequency Factor Table for Km

No	Quintile interval	Frequency	Frequency (%)
1	$1.50 \leq K_m \leq 3.00$	8	50.00
2	$3.00 < K_m \leq 4.50$	6	37.50
3	$4.50 < K_m \leq 6.00$	1	6.25
4	$K_m > 6.00$	1	6.25

Plots were made for the estimated maximum frequency factors (K_m) against daily annual maximum rainfall depths to observe the trend. As it could be observed from Figure 3, the trend line shows an inverse relation *i.e*. the value of K_m was generally decreasing for increased mean of annual daily maximum and average annual total rainfall. Hence, the finding of this study is in agreement with "the largest Hershfield frequency factor as it found high for humid countries and low for arid areas" (Hershfield, 1965; NWS, 1977; Desa et al., 2001).

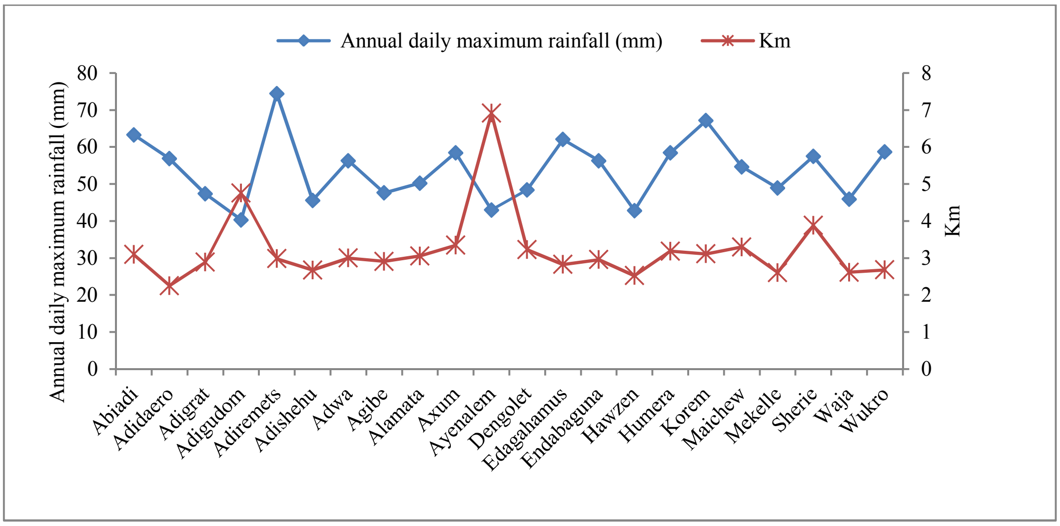

Figure 4. Comparing Values of K_m and Annual Daily Maximum Rainfall (mm)

4.4.1. Comparisons of K_m with the Previous Studies

The observed enveloping of K_m (5.91) has 60.6%, 38.4%, 32.1%, 34.3%, 27.9% and 13.1% change from the largest Hershfield frequency, Atrak Watershed, Humid Regions Malaysia, Blue Nile Basin, Benishangul-Gumuz, and West Shewa Zone Oromia region, respectively (Table 9). The smaller value of K_m from the findings for Blue Nile basin, Benishangul-Gumuz region and West Shewa Zone under local condition is not as such significant. The change of the estimated K_m from Hershfield largest frequency factor implies that, considering (K_m=15) for estimation of PMP will give an overestimated value for PMP.

Table 9. The maximum frequency factors for different basins or regions

Basin/Regions	K-envelop	$(\frac{K_{envelop}-5.91}{K_{envelop}})*100$	Source
Largest Hershfield Frequency Factor	15.0	60.6	Hershfield (1961)
Atrak Watershed, Iran	9.6	38.4	Ghamhraman(2008)
Humid Regions Malaysia	8.7	32.1	Desa and Rakhecha (2006)
Blue Nile Basin, Ethiopia	9.0	34.3	Alemayehu and Semu (2010)
BenishangulGumuz region, Ethiopia	8.2	27.9	Mulualem (2010)
West Shewa Zone Oromia region, Ethiopia	6.8	13.1	Mulugeta (2012)

3.5. Estimation of Probable Maximum Precipitation (PMP)

The estimated value of PMP was found to vary between minimum 70.06 mm (Hawzen station) and maximum 144.51 mm (Aynalem station) with average value 101.67 mm (15.7% of the annual average rainfall of the region) and coefficient of variability 19.87% (Table 10). Normally the higher PMP estimates correspond to stations having higher variability is reported from dry areas. Indeed in this study, this was observed due to the presence of station that has the dry conditions and largest variability for rainfall record, as compared to a station with the highest observed variability.

Table 10 .Derivation of probable maximum precipitation (PMP)

Station Name	$\bar{X}_n$	σ_n	HOR	$\bar{X}_{n-1}$	σ_{n-1}	PMP (mm)
Abi-adi	63.27	12.89	86.7	61.89	11.84	90.28
Adi-dae'ro	56.84	15.57	86.8	55.08	14.08	91.92
Adigrat	47.35	14.42	81.5	45.64	12.43	88.95
Adi-gudom	40.31	12.64	80.5	38.31	8.88	100.36
Adi-remets	74.44	11.86	102.3	72.80	9.90	109.78
Adi-shehu	45.58	15.40	78.0	43.26	12.99	86.77
Adwa	56.3	20.22	105.5	53.85	17.23	116.91
Agibe	47.61	13.67	70.1	46.00	12.63	73.69
Alamata	50.26	12.15	80.2	48.76	10.29	87.38
Axum	58.46	21.76	115.4	55.61	17.87	131.27
Aynalem	43.01	17.17	102.8	40.02	10.62	144.51
Dengolet	48.42	13.34	82.5	46.72	11.10	91.42
Edaga-hamus	62.04	25.30	126.2	60.35	23.31	133.51
Endaba-guna	56.27	15.20	91.8	54.18	12.72	101.22
Hawzen	42.80	10.81	66.0	41.64	9.66	70.06
Humera	58.39	17.54	105.9	56.81	15.42	114.23
Korem	67.13	16.61	109.3	65.22	14.16	118.84
Maichew	54.65	14.45	92.1	52.78	11.92	102.32
Mekelle	48.92	12.99	77.5	47.50	11.51	82.78
Sherie	57.48	15.48	101.8	55.26	11.99	117.57
Waja	45.93	10.92	71.1	45.03	9.97	74.48
Wukro	58.68	18.62	100.5	56.59	16.38	108.59
Mean						101.67
Sn						20.21
CV						19.87

Table 11. Ratio of PMP to HOR

Station Name	PMP (mm)	HOR	PMP:HOR
Abi-adi	90.28	86.7	1.04
Adi-dae'ro	91.92	86.8	1.06
Adigrat	88.95	81.5	1.09
Adi-gudom	100.36	80.5	1.25
Adi-remets	109.78	102.3	1.07
Adi-shehu	86.77	78.0	1.11
Adwa	116.91	105.5	1.11
Agibe	73.69	70.1	1.05
Alamata	87.38	80.2	1.09
Axum	131.27	115.4	1.14
Aynalem	144.51	102.8	1.41
Dengolet	91.42	82.5	1.11
Edaga-hamus	133.51	126.2	1.06
Endaba-guna	101.22	91.8	1.10
Hawzen	70.06	66.0	1.06
Humera	114.23	105.9	1.08
Korem	118.84	109.3	1.09
Maichew	102.32	92.1	1.11
Mekelle	82.78	77.5	1.07
Sherie	117.57	101.8	1.15
Waja	74.48	71.1	1.05
Wukro	108.59	100.5	1.08
Mean			1.11
Sn			0.08
CV			7.23

3.6. Estimation of PMP to Highest Observed Rainfall (HOR) Ratio

Estimated PMP values were compared with maximum operations and enveloping world rainfall record as well as PMP estimations of humid and dry regions. PMP to one day HOR ratio was estimated in Table 11.This ratio was found to vary between minimum 1.04 (Abi-adi station) and maximum1.42 (Aynalem station) with an average value of 1.11.

The magnitude ratio at an individual station was not exceeded three times the highest observed rainfall depth; hence, confirm with Hershfield (1962). Therefore, the predicted PMP values for this study were neither overestimated nor underestimated. However, in reality, it is not possible to give the exact suggestion for the predicted PMP value while, it keeps on changing for the same catchment with the time and new records of heavy storms. Hence, the estimated PMP values only represent the best estimation with the available knowledge, technique and data support. Such variation may originate from stations with different micro-climates and a different record length of the stations (Hershfield, 1961).

3.6.1. Comparisons of PMP to HOR Ratio with the Previous Studies

The observed ratios were far from the corresponding ratios obtained for Dry Atrak Watershed, near to Humid Regions of Malaysia, Benshangul-Gumuz, West Shewa Zone, and Blue Nile Basin, and almost similar to Southern Banswar District (Table 12). This may be due to relative homogeneity in climatic conditions of the areas.

Table 12. PMP to HOR Ratios of Some Dry and Wet Regions/Basins

Regions/Basin	One-day PMP (mm)	PMP:HOR (mean)	Source
Humid Regions of Malaysia	400-1000	2.00	Desa and Rakhecha (2006)
Dry Atrak Watershed, Iran	97-296	2.50	Ghamhraman (2008)
Southern Banswar District, India	350	1.05	Durbude (2008)
Blue Nile River Basin, Ethiopia	180-420	1.90	Alemayehu and Semu (2010)
BenshangulGumuz Region Ethiopia	170 -284	1.80	Mulualem (2010
West Shewa ZoneOromia, Ethiopia	105-243	1.75	Mulugeta (2012)

3.7. Comparison of the Probability Distribution Functions

The selection of an appropriate model depends mainly on the characteristics of available data at the appropriate site (Ewemoje and Ewemooje, 2011).

3.7.1. Normal Probability Distribution Function

The standard normal deviate value *(Z)* for exceedence probability for the annual maximum rainfall data of Adi-adi station (alphabetically selected station to show the process) was interpolated and computed as shown in Table 13. The result shows that the standard normal variate of records of all station decrease with decrease in recurrence interval (increase in plotting probability) and extreme value obtained using the normal distribution function shows linear proportionality with the standard normal variate.

Table 13. Standard Normal Deviate (Z) and Its Extreme Values Derived By Normal Probability Distribution for Abi-Adi Station (mm)

Record years	Rainfall	RF. order	Rank	*P (%)*	*Z*	$\bar{X}$	*Sn*	$Z*S_n$	$X_T = \bar{X} + Z*S_n$
1994	50.5	86.7	1	5.26	1.65	63.27	12.89	21.27	84.54
1995	45.0	80.0	2	10.53	1.26	63.27	12.89	16.24	79.51
1996	64.7	78.5	3	15.79	1.03	63.27	12.89	13.28	76.55
1997	67.0	72.8	4	21.05	0.81	63.27	12.89	10.44	73.71
1998	57.4	70.8	5	26.32	0.66	63.27	12.89	8.51	71.78
1999	44.2	70.6	6	31.58	0.52	63.27	12.89	6.70	69.97
2000	80.0	70.0	7	36.84	0.37	63.27	12.89	4.77	68.04
2001	70.0	67.8	8	42.11	0.22	63.27	12.89	2.84	66.11
2002	58.3	67.0	9	47.37	0.07	63.27	12.89	0.90	64.17
2003	60.5	64.7	10	52.63	0	63.27	12.89	0	63.27
2004	70.8	60.5	11	57.89	0	63.27	12.89	0	63.27
2005	72.8	58.3	12	63.16	0	63.27	12.89	0	63.27
2006	86.7	57.4	13	68.42	0	63.27	12.89	0	63.27
2007	67.8	50.5	14	73.68	0	63.27	12.89	0	63.27
2008	78.5	50.4	15	78.95	0	63.27	12.89	0	63.27
2009	43.6	45.0	16	84.21	0	63.27	12.89	0	63.27
2010	50.4	44.2	17	89.47	0	63.27	12.89	0	63.27
2011	70.6	43.6	18	94.74	0	63.27	12.89	0	63.27
Mean		63.27							
Sn		12.89							
CV (%)		20.37							

n=18, **RF**=rainfall***,*** ***p***= plotting probability, $\bar{x}$ = Mean, ***Sn***=standard deviation, ***Z***=Standard normal deviate variate

3.7.2. Log normal probability distribution function

The standard normal variate value*(Z)* for exceedence probability for the annual maximum rainfall data of Abi-adi station were estimated and presented in Table 14.The result shows that the standard normal variable of all stations records decrease with decrease in recurrence interval (increase in plotting probability) and extreme value obtained shows linear proportionality with the standard normal variable.

Table 14. Standard Normal Variable *(Z)* and Its Extreme Values Derived By Log Normal Distribution for Abi-Adi Station (mm)

Record years	RF.	RF. order	Log RF.	Rank	*P*	*W*	*Z*	Y_T	X_T
1994	50.5	86.7	1.94	1	0.03	2.60	1.82	1.96	90.70
1995	45.0	80.0	1.90	2	0.09	2.20	1.35	1.91	82.02
1996	64.7	78.5	1.89	3	0.14	1.97	1.06	1.89	77.24
1997	67.0	72.8	1.86	4	0.20	1.80	0.85	1.87	73.77
1998	57.4	70.8	1.85	5	0.25	1.66	0.66	1.85	70.97
1999	44.2	70.6	1.85	6	0.31	1.53	0.50	1.84	68.56
2000	80.0	70.0	1.85	7	0.36	1.42	0.35	1.82	66.41
2001	70.0	67.8	1.83	8	0.42	1.32	0.21	1.81	64.43
2002	58.3	67.0	1.83	9	0.47	1.22	0.07	1.80	62.56
2003	60.5	64.7	1.81	10	0.53	1.13	-0.07	1.78	60.77
2004	70.8	60.5	1.78	11	0.58	1.04	-0.21	1.77	59.01
2005	72.8	58.3	1.77	12	0.64	0.95	-0.35	1.76	57.25
2006	86.7	57.4	1.76	13	0.69	0.86	-0.50	1.74	55.45
2007	67.8	50.5	1.70	14	0.75	0.76	-0.66	1.73	53.57
2008	78.5	50.4	1.70	15	0.80	0.67	-0.85	1.71	51.54
2009	43.6	45.0	1.65	16	0.86	0.56	-1.06	1.69	49.22
2010	50.4	44.2	1.65	17	0.91	0.43	-1.35	1.67	46.36
2011	70.6	43.6	1.64	18	0.97	0.26	-1.82	1.62	41.92
$\bar{Y}_n$			1.79						
S_n			0.09						

n=18, **R.F** – rainfall (mm)

3.7.3. Log Pearson Type-III Probability Distribution Function

The standard normal variable value *(Z)* for exceedence probability for the annual maximum rainfall data of Abi-adi station was calculated and presented in Table 15.The result shows that the standard normal variable of all stations records decrease with increase in plotting probability (decrease in recurrence interval) and the extreme value obtained shows linear proportionality with the standard normal variable.

Table 15. The Standard Variable *(Z)* and Extreme Value Derived By Log Pearson Type III Probability Values for Abi-Adi Station (mm)

Record Years	RF	RF. order	Log R.F	Rank	*P*	*W*	*Z*	K_T	Y_T	X_T
1994	50.5	86.7	1.94	1	0.03	2.68	1.91	1.75	1.95	88.60
1995	45.0	80.0	1.90	2	0.08	2.23	1.38	1.32	1.91	81.08
1996	64.7	78.5	1.89	3	0.14	1.99	1.09	1.07	1.89	76.94
1997	67.0	72.8	1.86	4	0.19	1.81	0.86	0.87	1.87	73.87
1998	57.4	70.8	1.85	5	0.25	1.67	0.67	0.70	1.85	71.33
1999	44.2	70.6	1.85	6	0.31	1.54	0.51	0.55	1.84	69.10
2000	80.0	70.0	1.85	7	0.36	1.43	0.36	0.41	1.83	67.06
2001	70.0	67.8	1.83	8	0.42	1.32	0.21	0.27	1.81	65.16
2002	58.3	67.0	1.83	9	0.47	1.22	0.07	0.13	1.80	63.33
2003	60.5	64.7	1.81	10	0.53	1.13	-0.07	-0.01	1.79	61.54
2004	70.8	60.5	1.78	11	0.58	1.04	-0.21	-0.15	1.78	59.75
2005	72.8	58.3	1.77	12	0.64	0.95	-0.36	-0.30	1.76	57.94
2006	86.7	57.4	1.76	13	0.69	0.85	-0.51	-0.46	1.75	56.05
2007	67.8	50.5	1.70	14	0.75	0.76	-0.67	-0.64	1.73	54.03
2008	78.5	50.4	1.70	15	0.81	0.66	-0.86	-0.84	1.71	51.80
2009	43.6	45.0	1.65	16	0.86	0.55	-1.09	-1.09	1.69	49.19
2010	50.4	44.2	1.65	17	0.92	0.42	-1.38	-1.43	1.66	45.84
2011	70.6	43.6	1.64	18	0.97	0.24	-1.91	-2.07	1.60	40.16
$\bar{y}$			1.79							
Sn			0.09							
Cs			-0.38							
K			-0.06							

3.7.4. Gumbel /EVI Probability Distribution Function

The reduced variate value for exceedence probability for the annual maximum rainfall data of Abi-adi station were calculated and presented in Table 16. Results shows that the reduced variate value of all stations records decreases with increase in recurrence, and extreme value obtained shows linear proportionality with the reduced variate.

Table 16. Computation of Extreme Values Using Gumbel for Abi-Adi Station (mm)

Record years	Rainfall	RF. order	Rank	*P*	*T*	Y_T	K_T	X_T
1994	50.5	86.7	1	0.05	19.00	2.92	2.28	92.70
1995	45.0	80.0	2	0.11	9.50	2.20	1.60	83.84
1996	64.7	78.5	3	0.16	6.33	1.76	1.18	78.50
1997	67.0	72.8	4	0.21	4.75	1.44	0.88	74.59
1998	57.4	70.8	5	0.26	3.80	1.19	0.63	71.45
1999	44.2	70.6	6	0.32	3.17	0.97	0.43	68.78
2000	80.0	70.0	7	0.37	2.71	0.78	0.25	66.43
2001	70.0	67.8	8	0.42	2.38	0.60	0.08	64.30
2002	58.3	67.0	9	0.47	2.11	0.44	-0.07	62.33
2003	60.5	64.7	10	0.53	1.90	0.29	-0.22	60.46
2004	70.8	60.5	11	0.58	1.73	0.15	-0.36	58.66
2005	72.8	58.3	12	0.63	1.58	0.00	-0.49	56.90
2006	86.7	57.4	13	0.68	1.46	-0.14	-0.63	55.14
2007	67.8	50.5	14	0.74	1.36	-0.29	-0.77	53.34
2008	78.5	50.4	15	0.79	1.27	-0.44	-0.92	51.44
2009	43.6	45.0	16	0.84	1.19	-0.61	-1.08	49.36
2010	50.4	44.2	17	0.89	1.12	-0.81	-1.27	46.92
2011	70.6	43.6	18	0.95	1.06	-1.08	-1.52	43.63
$\bar{y}$		63.27	Y_n				0.52	
Sn		12.89	S_n				1.05	

Generally the comparison of probability distribution function stations shows, as the variate of stations records decrease the plotting probability increase (recurrence interval decrease) and extreme value obtained shows linear proportionality with the standard normal variable.

3.8. Testing the Goodness of Fit (GOF) of Data to Probability Distribution Functions

3.8.1. Chi-Square Test (X^2)

Comparison of the recorded data and the corresponding values obtained by each of the probability distribution functions tested by calculating x^2 were compared with tabulated x^2 at 5% significance level with the degree of freedom v (two for this case). As the calculated x^2 resulted to be less than that of tabulated x^2 value, there is no significance difference between the observed and predicted ones. The one with the least value of x^2 was selected as the best fit model. From Table 17, it could be revealed that the LPT-III distribution function having least value of estimated x^2 (2.04) could be assumed as best fit model and be assigned with 4 points, where as normal distribution function, a weak model with calculated x^2 value of 23.79 assigned with 1 point.

3.8.2. Correlation coefficient test (r)

The linear relationships between the observed and predicted rainfall data for 18 years record of Abi-adi station for different probability distribution function were developed (Table 18). For the purpose of comparison of best fit model, 4 point was assigned for 'r' value which was closest to 1, and so on. For Abi-adi station, LPT-III was assigned as 4, Log normal 3, Gumbel 2 and normal distribution function obtained 1. In this test also LPT-III was selected as the best fit probability distribution function.

Table 17. Chi-Square Test of GOF for Abi-Adi Station (mm)

S.N	Observed	Gumbel EVI	Log Normal	Log Pearson type III	Normal
1	86.7	92.70	91.69	88.47	84.54
2	80.0	83.84	82.13	82.13	79.51
3	78.5	78.50	77.21	77.21	76.55
4	72.8	74.59	73.71	73.71	73.71
5	70.8	71.45	70.90	70.90	71.78
6	70.6	68.78	68.50	68.50	69.97
7	70.0	66.43	66.37	66.37	68.04
8	67.8	64.30	64.40	64.40	66.11
9	67.0	62.33	62.55	62.55	64.17
10	64.7	60.46	62.55	60.78	63.27
11	60.5	58.66	59.04	59.04	63.27
12	58.3	56.90	57.30	57.30	63.27
13	57.4	55.14	55.54	55.54	63.27
14	50.5	53.34	53.70	53.70	63.27
15	50.4	51.44	51.72	51.72	63.27
16	45.0	49.36	49.49	49.49	63.27
17	44.2	46.92	46.78	46.78	63.27
18	43.6	43.63	42.76	42.76	63.27
Mean	63.27	63.27	63.13	62.85	67.99
Sn	12.89	13.24	12.80	12.40	6.04
Sum	1138.80	1138.77	1136.34	1131.35	1223.81
CV (%)	20.37	20.93	20.27	19.73	9.77
x^2 *cal.*		2.59	2.10	2.04	23.79
x^2 *tab.*		27.59	27.59	27.59	27.59

LPT-III = Log Pearson type III

Table 18. Correlation Coefficient (R) Test of GOF for Abi-Adi Station (mm)

S.N	Observed	Gumbel EVI	Log Normal	LPT-III	Normal
1	86.7	92.70	91.69	88.47	84.54
2	80.0	83.84	82.13	82.13	79.51
3	78.5	78.50	77.21	77.21	76.55
4	72.8	74.59	73.71	73.71	73.71
5	70.8	71.45	70.90	70.90	71.78
6	70.6	68.78	68.50	68.50	69.97
7	70.0	66.43	66.37	66.37	68.04
8	67.8	64.30	64.40	64.40	66.11
9	67.0	62.33	62.55	62.55	64.17
10	64.7	60.46	62.55	60.78	63.27
11	60.5	58.66	59.04	59.04	63.27
12	58.3	56.90	57.30	57.30	63.27
13	57.4	55.14	55.54	55.54	63.27
14	50.5	53.34	53.70	53.70	63.27
15	50.4	51.44	51.72	51.72	63.27
16	45.0	49.36	49.49	49.49	63.27
17	44.2	46.92	46.78	46.78	63.27
18	43.6	43.63	42.76	42.76	63.27
Mean	63.27	63.27	63.13	62.85	67.99
Sn	12.89	13.24	12.80	12.40	6.04
Sum	1138.80	1138.77	1136.34	1131.35	1223.81
CV (%)	20.37	20.93	20.27	19.73	9.77
r- value		0.97132	0.9775	0.9827	0.8430

3.8.3. Coefficient of Determination Test (R^2)

The closer value of coefficient of determination is almost one, the better the regression equation “fits” the data. Based on this LPT-III fits best assigned 4 point, Log normal with 3 point, Gumbel2 point and normal distribution function fits least which assigned 1 as per R^2 was obtained (Table 19).

Table 19. Coefficient of Determination Test of GOF for Abi-Adi Station (Mm)

S.N	Observed	Gumbel EVI	Log Normal	Log Pearson type III	Normal
1	86.7	92.70	91.69	88.47	84.54
2	80.0	83.84	82.13	82.13	79.51
3	78.5	78.50	77.21	77.21	76.55
4	72.8	74.59	73.71	73.71	73.71
5	70.8	71.45	70.90	70.90	71.78
6	70.6	68.78	68.50	68.50	69.97
7	70.0	66.43	66.37	66.37	68.04
8	67.8	64.30	64.40	64.40	66.11
9	67.0	62.33	62.55	62.55	64.17
10	64.7	60.46	62.55	60.78	63.27
11	60.5	58.66	59.04	59.04	63.27
12	58.3	56.90	57.30	57.30	63.27
13	57.4	55.14	55.54	55.54	63.27
14	50.5	53.34	53.70	53.70	63.27
15	50.4	51.44	51.72	51.72	63.27
16	45.0	49.36	49.49	49.49	63.27
17	44.2	46.92	46.78	46.78	63.27
18	43.6	43.63	42.76	42.76	63.27
Mean	63.27	63.27	63.13	62.85	67.99
Sn	12.89	13.24	12.80	12.40	6.04
Sum	1138.80	1138.77	1136.34	1131.35	1223.81
CV	20.37	20.93	20.27	19.73	9.77
R^2- value		0.9435	0.9555	0.9657	0.7107

From the results of four frequency distributions applied in this study, the best frequency distribution obtained for the peak daily rainfall in region was the log-Pearson type III distribution, which accounted 59.1% of the total station number, followed by the Gumbel distribution 18.2%, log normal in the third by 13.6% and in the last Normal distribution function with 4.5% of the total station number (Table 21).

Table 20. Summary of GOF Score Result for Abi-Adi Station

Station	Distribution model	x^2 test	r test	R^2 test	Total
Abi-adi	Normal	1	1	1	3
	Log normal	3	3	3	9*
	Log Pearson type III	4	4	4	12**
	Gumbel EVI	2	2	2	6
**Log Pearson type III selected as best fit distribution model, * Log normal as second fit					

Table 21. Summary of GOF for Stations

Distribution	LPT-III	Gumbel	log normal	Normal	Normal and LPT-III
Station Name	Abi-adi	Adigrat	Adi-gudom	Korem	Axum
	Adi-da'ero	Adwa	Adi-remets		
	Agibe	Alamata	Mekelle		
	Ayenalem	Adi-shehu			
	Dengolet				
	Edaga-hamus				
	Endaba-guna				
	Hawzen				
	Humera				
	Maichew				
	Sherie				
	Waja				
	Wukro				
in number	13	4	3	1	1
in %	59.1	18.2	13.6	4.5	4.5

LPT-III=Log Pearson type IIIdistribution function

3.9. Computation for PMP Return Period

3.9.1. Probable Maximum Precipitations Return Period Values

Log Pearson type III distribution function was fitted to daily annual maximum rainfall. Based on sample mean, standard deviation and coefficient of skewness, the respective parameters of distribution function (location, shape and scale) and corresponding log Pearson type-III *f(x)* was estimated using equations (2.20-2.25). Based on this, the probability of exceedence of a certain value variateis usually expressed in terms of the return period (T) and hence the annual exceedence for the predicted one-day PMP depths $P(X \geq X_o)$ were calculated from the respective log Pearson type-III distribution of each station and the corresponding return period is presented in Table 22.

The PMP return period varies between 2000 and 4000 year's interval with the minimum value at Abi-adi station (2044.15) and maximum value at Waja station (3773.58), at an average value of 2671.83 years and coefficient of variability of 17.56%. The observed variability in return period (T) is less than 20% hence the mean value could reasonably represent the overall T value for comparisons. Accordingly, the predicted return period is nearly in the order of $2.7*10^3$years.

3.9.2. Comparisons of return periods with the previous studies

The average return period of the region falls at the low end out of NERC (1994) but nearly to Deshpande (2008). Hershfield (1981) and Koutsoyiannis (1999) findings (Table 23) were somehow higher than the obtained value, *i.e.* the enveloping frequency factor used for the derivation of PMP in this study is 5.91 that is less than the corresponding frequency factors suggested for the return periods of $6.7*10^5$ and 60000 years by Hershfield (1981) and Koutsoyiannis (1999) respectively. This variation is due to the fact that the probability distribution fitted for the estimated of the return period is different from that used in the for the above previous studies. In addition to this Mulualem (2010), for Benshangul-Gumuz Region,it was found PMP estimates for one-day durations had a return period of the order of $4.9*10^3$ years and Mulugeta (2012) for West Shewa Zone Oromia, was found PMP estimates for one-day durations had a return period of $2.9*10^3$ years, almost similar to this study.

Table 22. Annual Exceedence and Return Periods for Predicted PMP

Station Name	$P(X \geq X_o)$	T
Abi-adi	0.9995108	2044.15
Adi-da'ero	0.9996203	2633.66
Adigrat	0.9996640	2976.19
Adi-gudom	0.9996820	3144.65
Adi-remets	0.9996810	3134.80
Adi-shehu	0.9995718	2335.36
Adwa	0.9996123	2579.31
Agibe	0.9995200	2083.33
Alamata	0.9995180	2074.69
Axum	0.9996470	2832.86
Ayenalem	0.9996300	2702.70
Dengolet	0.9996280	2688.17
Edaga-hamus	0.9995807	2384.93
Endaba-guna	0.9995600	2272.73
Hawzen	0.9995900	2439.02
Humera	0.9995730	2341.92
Korem	0.9996790	3115.26
Maichew	0.9995933	2458.81
Mekelle	0.9997250	3636.36
Sherie	0.9996280	2688.17
Waja	0.9997350	3773.58
Wukro	0.9995901	2439.62
Mean		2671.83
CV (%)		17.56

$P(X \geq X_o)$ = value of log Pearson type III function for the depth of PMP, **T**= return period

Table 23. Return Periods for PMP and K Values Observed From Some Previous Studies

S.No.	PMP or K value	The probability distribution used	Return period (years)	Source
1	PMP	EV2	10^5-10^9	NERC (1994)
2	K=10	EV1	$6.7*10^5$	Hershfield (1981)
3	K=15	EV2	$6.0 *10^4$	Koutsoyiannis (1999)
4	PMP	EV1	$10*10^3$	Deshpande (2008)
5	K = 8.1	EVI	$4.9 *10^3$	Mulualem (2010)
6	K = 6.8	LPT-III	$2.9*10^3$	Mulugeta (2012)
7	K = 5.91	LPT-III	$2.9*10^3$	This study (Yohannes, 2013)

According to the report of NERC (1994) the predicted return period's value for PMP in this study is reasonable. However, if rain gauge stations are uniformly distributed in the region and adequate sample of daily annual extreme rainfall series were available, there would be more reliable estimates that would fall in the range.

3.9.3. Estimation of PMP and depths of various years return period

The daily probable maximum annual rainfall amounts were predicted for different stations of the Tigray region and are presented in Figure 4. For the annual rainfall data of the stations with 15-39 years of record the flood frequencies of 5, 10, 50 100, 1000 and 10000 year floods had been estimated for the comparison with the estimated return period developed by log Pearson type III. The depths of rainfall for 5, 10, 100, 1000 and 10000 return periods were found to vary between 33.29 mm and 175.92 mm (Figure 4). The depths of 10000 years were limited between 85.29 mm and 175.92 mm, while depths of 1000 years were between 69.76 mm and 143.89mm, and the depths for 5, 10, 50 and 100 years were between 33.29 mm and 111.79 mm (Figure 4).

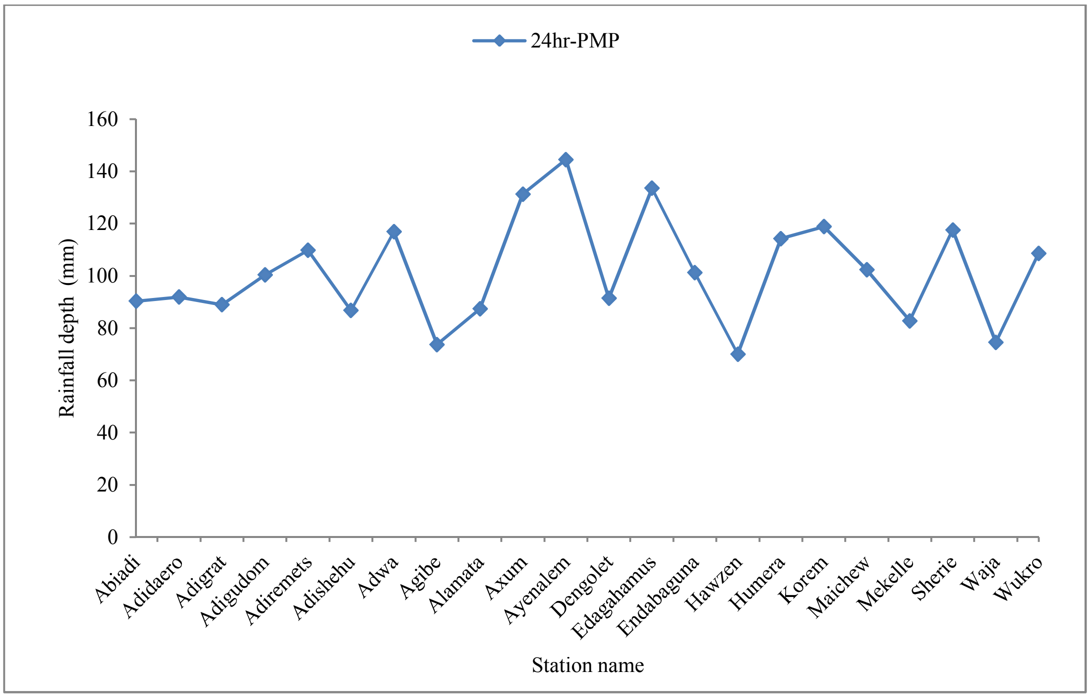

Figure 5. The Estimated Depth for 24 Hr PMP

3.9.4. Estimation Ratios of PMP Value to Various Years Return Period (FOS)

The predicted PMP value to depths of various years return period ratios were computed and presented in Table 25. This ratio was found to vary between 0.5132 (at 5 years) and 2.712 (at 10000 years).

Table 24. Ratio Of PMP to Various Years Returns Period Design Rainfall Depth

Station Name	5 years	10 years	50 years	100 years	1000 years	10000years
Abiadi	2.1046	1.8269	1.4157	1.2927	1.0043	0.8214
Adidaero	2.0670	1.7943	1.3904	1.2696	0.9864	0.8068
Adigrat	2.1361	1.8542	1.4368	1.3120	1.0193	0.8337
Adigudom	1.8932	1.6434	1.2735	1.1628	0.9034	0.7389
Adiremets	1.7308	1.5024	1.1642	1.0631	0.8259	0.6755
Adishehu	2.1897	1.9008	1.4729	1.3450	1.0449	0.8547
Adwa	1.6252	1.4107	1.0932	0.9982	0.7756	0.6343
Agibe	2.5784	2.2381	1.7344	1.5837	1.2304	1.0064
Alamata	2.1744	1.8875	1.4627	1.3356	1.0377	0.8487
Axum	1.4474	1.2564	0.9736	0.8890	0.6907	0.5649
Ayenalem	1.3148	1.1413	0.8844	0.8076	0.6274	0.5132
Dengolet	2.0784	1.8041	1.3980	1.2766	0.9918	0.8112
Edagahamus	1.4231	1.2353	0.9573	0.8741	0.6791	0.5555
Endabaguna	1.8771	1.6294	1.2627	1.1530	0.8958	0.7327
Hawzen	2.7120	2.3541	1.8243	1.6658	1.2942	1.0585
Humera	1.6633	1.4438	1.1189	1.0216	0.7937	0.6492
Korem	1.5988	1.3878	1.0755	0.9820	0.7630	0.6240
Maichew	1.8570	1.6119	1.2491	1.1406	0.8861	0.7248
Mekelle	2.2953	1.9924	1.5439	1.4098	1.0953	0.8959
Sherie	1.6161	1.4028	1.0871	0.9926	0.7712	0.6308
Waja	2.5511	2.2144	1.7160	1.5669	1.2174	0.9957
Wukro	1.7497	1.5188	1.1770	1.0747	0.8350	0.6829
max	2.7120	2.3541	1.8243	1.6658	1.2942	1.0585
min	1.3148	1.1413	0.8844	0.8076	0.6274	0.5132
Mean	1.9402	1.6841	1.3051	1.1917	0.9259	0.7573
Sn	0.3850	0.3342	0.2589	0.2364	0.1837	0.1502

The estimated PMP values have a factor of safety around their corresponding ratio over the design depth of various years return period. According to Al-Mamu and Hashim (2004), this ratio can be used in relation to the Factor of Safety (FOS). To give conclusions that whether PMP values are reasonable for designing hydraulic structures or not, usually the adopted FOS value for engineering practices in Structural Engineering is between 1.4 and 1.7 and for Geotechnical design between 1.5 and 2.0. Accordingly, it can be concluded that the estimated PMP, which is very uncertain values for 100, 1000 and 10000 years and reasonable for designing of hydraulic structures for return periods in the orders of 10and 50years. However, the use of PMP for 5 years of return periods for hydraulic structures will be stable but relatively costly. Therefore, PMP approach could solve the limitations of common probabilistic approach

3.10. Development of PMP Isohyetal Map

Isohyetal lines of point PMP maps were prepared to ease estimation of design rainfall for the ungauged catchments. Isohyetal maps, to understand PMP distribution were generated by means of ArcMap10 GIS software based on the Inverse Distance Weighting (IDW) interpolation approach method. Based on this isohyetal map showing the spatial distribution of one day PMP values in the region was developed as well. Accordingly, PMP grid values were varying between 80 mm and 135 mm at a contour interval of 10mm. The highest PMP isohyetal point values were observed along in the southern, central and eastern zone and decreases towards south-east zone, and with average value at the western zone of the region (Figure 5).

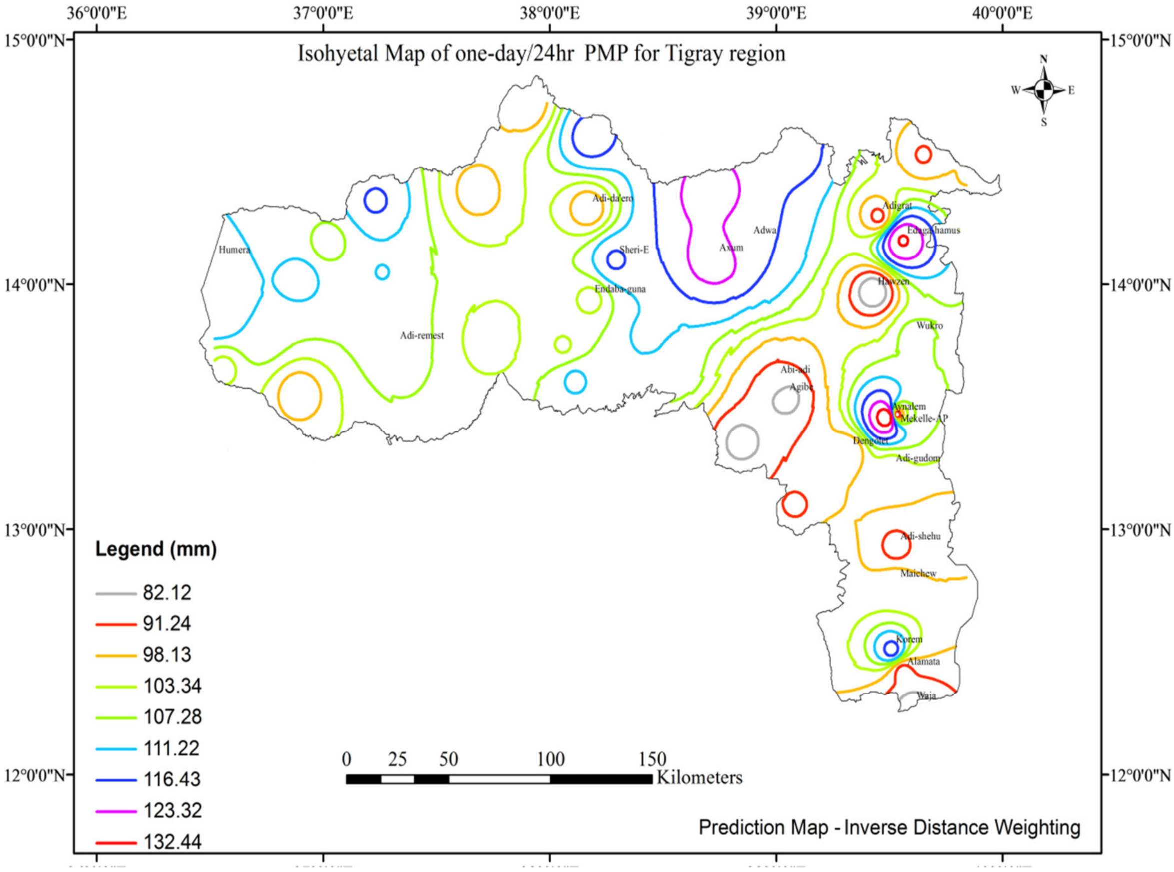

Figure 6. Isohyetal Map of 24hr PMP for Tigray Region

4. Conclusion

PMP is the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location in a certain time of the year. The consequences of precipitation variability, droughts and extreme floods were exhibiting great influence in human life.

In order to estimate the probable maximum precipitation, meteorological data (annual total rainfall and daily maximum rainfall) was collected for 22 stations from NMSA (Addis Ababa) and Tigray regional branch (Mekelle). After checking the missing data and its consistence, Hershfield (1961, 1965) technique for estimating PMP, an adapted version of Chow (1952) for frequency analysis of rainfall was used for PMP computation. Daily annual extreme rainfall data was applied to derive maximum frequency factors (K_m) and the corresponding one day PMP estimation values. Based on this an appropriate enveloping *Km* curve showing the relationship between the *Km* and the mean annual maximum rainfall for duration of 24 hours had been developed. Generally decreasing trend of K_m with rainfall magnitude was observed from the trend (K_m vis-à-vis mean of daily maximum annual rainfall series and annual rainfall) records. As PMP deals with unusual rainfall values, the corresponding K_m used was chosen from the extremely high values i.e. 5.91 and found to vary between 70.06 mm and 144.51 mm at an average value of 101.67 mm. These values were compared with maximum observations, world enveloping records and previous PMP studies for the same duration. The ratio of highest observed rainfall (HOR) to calculated one-day PMP varied from 1.04 to 1.42 with average of 1.11.

From the results of four frequency distributions applied in this study, it found that the best frequency distribution obtained for the extreme daily rainfall in region was the log-Pearson type III distribution. The outcome was relied on the results of three goodness-of-fit tests, Chi-square, correlation coefficient and coefficient of determination. The PMP return period values was derived using log Pearson type III with an average value of $2.7*10^3$ years.

The ratios of daily PMP to the design rainfall varying from 5 year to 10000 year return period were worked out. then the annual rainfall data of the stations with 15 -39 years of record the flood frequencies of 5, 10, 50 100, 1000 and 10000 year floods had been estimated for the comparison with the estimated return period developed by log Pearson type III, and found to vary between 33.29 mm and 175.92 mm.

The predicted PMP value to depths of various years return period ratios were estimated, and it can be concluded that the estimated PMP, which is very uncertain values for the 100, 1000 and 10000 years and reasonable for designing of hydraulic structures for return periods in the orders of 10 and 50 years. However, the use of PMP for 5 years of return periods for hydraulic structures will be stable but relatively costly.

Isohyetal maps, to understand PMP distribution were generated by means of ArcMap10 GIS software based on the IDW interpolation approach. Accordingly, the highest PMP isohyetal values were observed along in the southern, central and eastern zone and decreases out ward south-east zone, and with average at the western zone of the region.

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5. Reference

[1] Adegboye O.S and R.A. Ipinyomi, 1995.Statistical tables for class work and Examination. Tertiary publications Nigeria Limited, Ilorin, Nigeria.
[2] Alemayew Dame and Semu Ayalew, 2010.Development of regional probable maximum precipitation for probable maximum flood development and application in design flood hydrograph. Case study Blue Nile basin, Ethiopia. *The 2010 Conference on* Water Resource in Ethiopia, Addis Ababa, 12-16 January 2010, Ministry of Water Resource.
[3] Al-Mamun, A. and A. Hashim. 2004. General long duration probable maximum precipitation isohyetal map for Peninsula, Malaysia. *Journal of Spatial Hydrology*, 4(1):156-179.
[4] Ben Willardson P.E., 2004. Analysis of 85th percentile 24-hour rainfall depths within the county of Los Angeles, Water Resources Division. Los Angeles.
[5] Bureau Finance and Economic Development (BFED), 2007.Atlasof Tigray regional state.
[6] Chow.V.T., 1952.Design Charts for Finding Rainfall Intensity Frequency, "*Water and Sewage Works*", Vol. 99, No.2.
[7] Desa M.M., A.B. Noriah and R.R., 2001. Probable maximum precipitation for 24 hr duration over Southeast Asian Monson Region-Selangor, Atmospheric Research *J.* 58: 41-54.
[8] Desa, M.M. and P.R. Rakhecha, 2006.Probable maximum precipitation for 24-hr duration over an equatorial region: Part 2-Johor, Malaysia. Humid Tropics Centre (HTC) Kuala Lumpur, Department of Irrigation and Drainage, Malaysia.
[9] Deshpande N.R., B.D. Kulkarni, A.K. Verma and B.N. Mandal, 2008.Extreme rainfall analysis and estimation of probable maximum precipitation (PMP) by statistical methods over the Indus river basin in India. *Journal of spatial hydrology* 8(1).
[10] Durbude D.G., 2008. Estimation of Probable Maximum Precipitation for planning soil and water conservation structure. *Journal of soil and water conservation* 17: 31-35.
[11] EEWS, 2007. Flood Vulnerability and Risks in Ethiopia. *Special report*, 02, July, 2007.
[12] Einfalt T., G. Johann and AP. Fister, 1998.on the spatial validity of heavy point rainfall measurements,

Water Resource Technology 37 (11).

[13] Ethiopian Government's Central Statistics Authority, 2008.*Summary and statically report of the 2007 population and housing census*. Population size by age and sex. Addis Ababa.

[14] Ewemoje T.A. and O.S. Ewemooje, 2011. Best distribution and plotting positions of daily maximum flood estimation at Ona River in Ogun-oshun river basin, Nigeria. *Agricultural Engineering International: CIGR Journal*, Vol.13, Manuscript No.1380.

[15] FDPPA, 2006. Joint Government and Humanitarian Partners Flash Appeal for the 2006 Flood Disaster in Ethiopia, Addis Ababa, Ethiopia.

[16] FDPPA, 2007.Regional summary of Multi-Agency Flood Impact assessment of 2006, Addis Ababa, Ethiopia.

[17] Gebrehiwot T., A. van der Veen, and B. Maathuis, 2011.Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. *International Journal of Applied Earth, Observation and Geo-information,* Doi: 10.1016/j.jag.2010.12.002.

[18] Ghahraman B. 2008. The estimation of one-day duration probable maximum precipitation over atrak watershed in Iran. *Iranian Journal of Science & Technology, Transaction B, Engineering,* Vol. 32, No. B2, pp 175-179, Printed in the Islamic Republic of Iran.

[19] Greenough G., M. Mc Geehin, S. Bernard, J. Trtanj, J. Riad and D. Engelberg, 2001.The Potential Impacts of Climate Variability and Change on Health Impacts of Extreme Weather Events in the United States. Environmental Health Perspective, 109(2).

[20] Hershfield D.M., 1961. Estimating probable maximum precipitation, proceedings ASCE. *Journal of Hydraulics,* Division 87: 99-106.

[21] Hershfield D.M., 1965. Methods of estimating probable maximum precipitation. *Journal of American Water Works Association* 57: 965-972.

[22] Hershfield D.M., 1962. Rainfall frequency atlas of the United State for durations from 30 mints to 24 hours and return periods from 1 year to 100 years. *Tech. Paper no*. 40, U.S. Depart. Commerce, Washington, D.C.

[23] Hershfiled, 1981.The magnitude of the hydrological frequency factor in maximum rainfall estimation. *Hydrological science Bulletin* 26.

*[24]*Kiros M., Gebremichael N., Tesfay B., and Kebede M., 2009.*Seed system impact on farmers income and crop Biodiversity in the Dry lands of southern Tigray*, *Unpublished*.

[25] Koutsoyiannis D., 1999.A probabilistic view of Hershfield method for estimating probable maximum precipitation. Water Resources Research 35(4): 1313-1322.

[26] Mahdi Osman. 2001. Rainfall and its Erosivity in Ethiopia with special consideration of the center highlands, Boon, Bonner Bodenkundliche, Abhandlungen.

*[27]*Mulualem Regassa, 2010. Development of one-day probable maximum precipitation and isohyetal map for Benishangul Gumuz regional state, Ethiopia, M.Sc *thesis submitted to Haramaya University.*

*[28]*MulugetaTesema, 2012. Development of one-day probable maximum precipitation and isohyetal map for west shewa zone, Ethiopia, *M.Sc thesis submitted to Haramaya University.*

[29] NERC, 1994.Estimation Bounds on Extreme Precipitation Events. National Academy Press, Washington, USA.

[30] NMSA, 2004.A ten day Agro meteorological *Bulletin* volume 14, no.22, Addis Ababa, Ethiopia.

[31] NWS, 1977.Probable Maximum Precipitation Estimates, Colorado River and Great Basins Drainages. *NOAA Hydro meteorological Report No.49*. Washington, D.C., U.S. Department of Commerce.

[32] Raghunath H.M., 2006. Hydrology Principles, Analysis and Design. New Age International (P) Limited, Publishers, New Delhi.

[33] Tao D.Q, V.T. Nguyen and A .Bourque, 2002. On selection of probability distributions for representing extreme precipitations in Southern Quebec. *Annual Conference of the Canadian Society for Civil Engineering*, 5th-8th June 2002. pp 1-8.

[34] TeweldeYideg, 2012. Assessing the potential of geneticist earth observation and in-situ data for drought early and monitoring in Tigray, Ethiopia, Enscheda, and the Netherlands.

[35] USAID, 2009.Tigray regional overview and livelihood zone summaries.

[36] Wanniarachchi [1] and Wijesekera [2], 2012.Using SWMM as a Fool for Flood plain Management in ungauged Urban Watershed*, Journal of the Institution of Engineers,* SRILANKA VOL: XXXX V, No. 01.