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Estimation of One Day Probable Maximum Precipitation for Fafan Zone of Somali Region, Ethiopia

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ABSTRACT

Drought and floods are common in Fafan zone, since study of probable maximum precipitation is exceedingly imperative for design of water resources project. Development of one day probable maximum precipitation (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) for Fafan zone using daily annual extreme values of 5 stations by statistical method of Hershfield formula were implemented. The objectives are to estimate point probable maximum precipitation (PMP) for station and their return period and to select the best fit probability distribution function. Missing data were reconstructed and inconsistency was checked using normal ratio method and double mass curve analysis, respectively. Frequency factor (Km) and PMP were derived using annual maxima, means and standard deviation. Km values varied from 2.93 (Gursum station) to 7.08 (Jigjiga stations) and PMP varied from 74.21mm (Harshin station) to 189.82mm (Awbare station) with an average 126.09mm. The ratio of one day PMP and highest observed rainfall varied from 1.07(Gursum station) to 1.42 (Jigjiga station) with an average 1.19. Normal, Log normal, Log pearson type III and Gumbel distributions were used to predict extreme values. The obtained values from probability distribution functions were tested by chi-square (χ^2) test and coefficient of determination (R^2). Results revealed that the log Pearson type III distribution performed the best (50%) and Gumbel performed second (34%) was the next. PMP estimates for one day durations using log pearson type III have minimum, maximum and average value of 2127.66, 3225.81and 2690.78 return period of years, respectively and the observed variability was found as 5.5%. The depths of rainfall for 5, 10, 50, 100, 1000 and 10000 return periods were found to vary between 37.07 mm and 241.49 mm. The predicted PMP values to a depth of various years return period ratios were found to vary between 0.76 (at 10000 years) and 2.89 (at 5 years). 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 order of between 5, 10, and 50 years for some areas. In order to get very precise results meteorological stations has to be distributed evenly with adequate data range (quality) and length and the study needs to be updated with recent information.

Key Words: Probable Maximum Precipitation, Probability Distribution Function, Goodness of Fit Test, Return Period.

1. Introduction

Floods are extreme natural environmental events which have severe consequence in disruptions on agriculture, ecology, and infrastructure that can lead to interruptions in human activities, result in injuries, and even cause fatalities.

Extreme precipitations are the major causal event of peak flood discharge. Information of extreme precipitation are a big concern nowadays, regarding both environmental and engineering purposes such as public safety, water supply, hydraulic structures design and operation. Water resource projects are designed for a certain design period with their parallel cost. These structures are designed by considering the maximum rainfall datas of the upper catchment area. Hydraulic structures need to be efficient for their entire design period without any stability problem. These structures cannot be stable during their design period without considering these extreme rainfall events in their design. Our world had experience vast number of flooding records which sometimes follow with structural. Among them 1975 Banqiao dam failure and flood in china, 1977s Laurel Run dam failure and flash flood in Johnstown and Pennsylvania,1911s Austin dam failure, 1993s LaJosefina landslide dam failure, 2021s Maharashtra floods in India, 2021s Turkish flood, 2019s Irans flood, 2016s Srilanka flood, 2018s Japan flood can be listed as few (Dartmouth, 2022).

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The flood hit has no exception for east Africa. In 2006 flood peak reaches Kenya, Ethiopian and Somalia (Dartmouth, 2022). In Ethiopia alone Heavy rain born flash flood in 2006 in Diredawa, Gode, Tena and Omo River Delta causes 705 people to die (Dartmouth, 2022). In 2018 again higher flash flood hits Kenya, Ethiopia, Uganda, Rwanda and Somalia with toll death of greater than 500 people (Okiror, 2018).

PMP refers to the maximum amount of precipitation that can realistically occur in a specific area and location during a particular time of year for a defined duration (WMO, 1986). It is an old concept but recently attracts water resource project designers and planners.

Hydraulic structures are very sensitive to different phenomenon such as flood. These structures drop a titanic risk to where its downstream area lies. Based on the PMP High flood peaks can be managed and employed to different engineering structures design and operation. The use of PMP is important in engineering practices to design water resources projects in areas where the likelihood of rainfall is above normal. Therefore, analyzing the maximum precipitation over a catchment area or zone for a single day is crucial for the planning and design of hydraulic structures like check dams, storage reservoirs, and earthen dams. Understanding extreme rainfall and probable maximum precipitation is fundamental in engineering practices for designing these structures and implementing strategies to mitigate disaster impacts.

Employing PMP is much adopted method of estimating high peak discharge in our world today, since it has very accurate results than frequency sample based method. Examples are USA, Neither land, India, Most European countries and Asia. In contemporary engineering, extreme rainfall estimation relies on statistical frequency analysis of maximum precipitation records, utilizing available sample data to determine the parameters of a chosen frequency distribution. This distribution is subsequently applied to estimate event magnitudes for return periods that may exceed or fall below those of the recorded events. Thus, precise estimation of extreme rainfall can mitigate storm-related damage and contribute to the more effective design of hydraulic structures.

Concepts of PMP are also hired in Ethiopia at different locations to estimate maximum peak flood records. Alemayew and Ayalew (2010) have estimated point PMP using rainfall records of 15 and more years in Malaysia and Ethiopia respectively. In addition to this, Regasa (2010) for Benishangul-Gumuz, Mulugeta (2012) for West Shewa Zone of Oromia and Yohannes (2013) for Tigray Region, Ethiopia had attempted to develop one day PMP and isohyetal map.

Fafan zone is one of highly vulnerable areas of flooding. The construction of big storage hydraulic structures in the zone may enable to store additional water for irrigation to agricultural lands with a view to make them more productive and commercial. These works must be designed and built to withstand the maximum floods that would be expected to occur at the structure site. To mitigate casual floods in the zone, safety measures require hydraulic structures to be designed based on the estimation of PMP (EEWS, 2007). A lot of informations such as rainfall depth, duration, frequency, etc. are required in area that are bounded by lower elevation, flat nature and common flood zones like Fafan zone. However, no study was carried out so far to develop any hydrological method that could provide easy, reliable and quick information on the PMP values in the zone.

With this regard, Spatial and temporal PMP distribution is essential for calculating probable maximum flood for the safe design of dams, disaster mitigation and preparedness measures. Thus estimation of probable maximum precipitation could be an input for estimation of probable maximum flood for water resources planning and designing in the zone. It also delivers accurate and timely information on the PMP values for the area. Consequently, the primary goal of this study is to estimate point PMP, which is frequently essential for effective planning, management, and design of various water resource projects, along with the following specific aims:

- To estimate point PMPs and their return periods for rain gauge stations in the zone.
- To identify best fit probability distribution function for stations and for the zone.

2. Materials and Methods

2.1. Description of the area

2.1.1. Geographical location

Fafan is a zone of Somali regional state of Ethiopia, previously called Jigjiga zone. The geographical location of Fafan zone lies between $10°10'$-$8°40'$ North latitude and $42°32'$-$44°00'$ East longitude having nearly 1.2 million total population. It has bordered on the south by Jarar, on the southwest by Nogob, on the west by the Oromia region, on the north by Sitti and on the east by Somaliland. According to the current administrative structure, the zone is structured under six weredas, namely Awbare, Jigjiga, Kebri Beyah, Harshin, Tuli Guled and Gursum. It covers 12,126 square kilometers with 3.7% areal contribution in regional scale. It takes 631 kms from Capital town of zone, Jigjiga to Addis Ababa.

2.2. Topography and Rainfall

At the Station, the highest recorded rainfall was 1825 mm in 1976, while the lowest was just 321 mm in 1999. This significant variation highlights the necessity of water storage for dry periods. Typically, every five years, there is a rainfall event of 60 mm per day, and every 7.5 years, the area experiences a downpour exceeding 100 mm per day. Although these totals are not particularly high, the stormy nature of these events often leads to rainfall concentrated within one or two hours. Such intense rainfall can result in substantial surface runoff, increasing erosion and the likelihood of flooding. Consequently, peak discharges can lead to severe flood events. The region's elevation varies from 1,141 to 2,157 meters above sea level, with the western central areas being predominantly hilly, while the northern, southern, and eastern corners are at lower elevations. In addition to

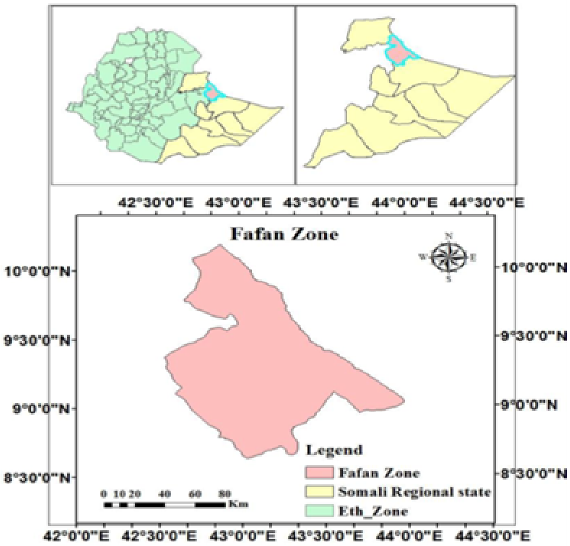

Figure 1: Location of Fafan zone with respect to Somali Regional Map and Ethiopian boundary

the division between highlands and lowlands, the Ethiopian landscape is marked by the Great Rift Valley that traverses the country (Reinier et al., 2006).

2.3. River Basins and Existing Hydraulic Structures

A number of hydraulic structures; mainly earthen dams, sand dam and bridges have been constructed in the Fafan zone. Though, among them many are overtopped and destroyed by flood. The zone lies in between Awash, Ogaden and Wabi shebele river basins. There is one seasonal stream in the zone, Fafan River.The Fafan River has an average runoff of 90 Mm³ and exhibits a higher rainfall-runoff ratio compared to neighboring rivers such as Jarar. While the steepest slopes are found in the Amora Mountains, the greatest runoff percentages are observed in the downstream areas of the Fafan Catchment. This high runoff is closely associated with sparse vegetation cover. Just 1% of the total average runoff from the upper Fafan and Jerer catchments could meet the water needs of Jijiga Town. This suggests that the water access issue is more related to seasonal availability and inadequate infrastructure rather than insufficient rainfall. Enhancing water storage could significantly improve availability during dry periods and even support irrigation efforts (Reinier et al., 2006).

2.4. Data Collection and Analysis

For this study, precipitation data were used on a daily basis. The rainfall dataset and location of each gauge were collected from the National Meteorological Agency in Addis Ababa, Ethiopia. The data analysis was done from stations that have 10 or more years of daily rainfall data. Current statistics of rain gauge stations in the zone shows six stations, of which three stations recently became non-functional after 2014 and 2015 G.C., and two were installed in 2003 and 2007. Among the six stations, only one station has 8 years of data; others have longer data records ranging from 13-29 years. The distribution of rain gauges that have long-term daily rainfall records in the zone is nearly uniform in all parts. Table 1 shows the locations and data ranges of Fafan rain gauge stations.

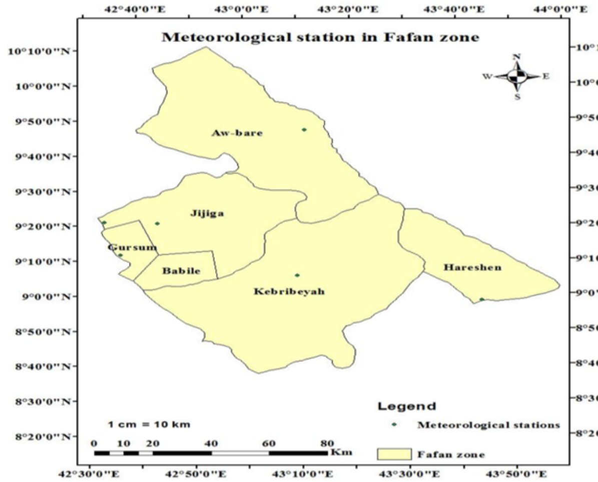

Figure 2: Distribution of meteorological stations in Fafan zone

Missing data and inadequacy of data are among the major problems encountered in hydrological studies. Precipitation record from a particular rain gauge is not 100 percent complete throughout the year. Before using raw data, datas from stations should get their qualification by improving the data that arisen from manual and environmental errors. There are many data filling methods such as normal ratio, arithmetic mean method, inverse distance method etc. As the error percentage is beyond 10%, normal ratio method of missed data filling method was employed using equation (1).

$$P_x = \frac{A_x}{n}\left(\frac{P_1}{A_1} + \frac{P_2}{A_2} + \frac{P_3}{A_3} + \cdots + \frac{P_i}{A_i}\right) \tag{1}$$

where the ratio $\frac{P_i}{A_i}$ is the proportion of rain gauge station i of the mean annual catch that occurs in specific storms.

For the consistency analysis, double mass curve was adopted for checking the consistency of rainfall datas. Double mass curve analysis plots accumulated values of one station against accumulated values of another station, or accumulated values of the average of other stations for the same period of time. In the data series, the change of proportionality in the trend line which is inconsistent is adjusted to consistent values. Most of the stations in this study were found inconsistent and converted into consistence value by applying Double mass curve analysis using equation (2).

$$P_a = \frac{M_a}{M_o} P_o \tag{2}$$

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

Table 1: Data ranges of rain gauge stations in the Fafan zone.

Station Name	Longitude (°E)	Latitude (°N)	Elevation (m)	Data Period (years)
Aw-Bare	43.0286	9.7642	1611	2003–2015 (13)
Jigjiga	42.8914	9.3683	1175	1989–2016 (28)
Kebri Beyah*	43.1749	9.0306	1753	2007–2015 (8)
Hareshen	43.6939	9.7451	1441	1988–2014 (27)
Gursum	42.6406	9.2333	1900	1988–2016 (29)
Babile	42.7843	9.1209	1600	1988–2016 (29)

2.5. PMP Estimation

The Hershfield technique, based on Chow's method, was utilized for frequency analysis of rainfall in order to compute PMP. Values were determined using equations (3) and (4). The maximum frequency factor (K_m) for each station was calculated using equation (5), which led to the creation of a frequency table for K_m. The upper limit for the estimated K_m was selected based on the highest observed values. One-day annual maximum rainfall data from all stations was analyzed to derive station-based PMP estimates via equation (6). Finally, the estimated values for the series of rainfall stations were compiled to identify the highest one-day rainfall and the ratio of estimated PMP to these rainfall figures, enabling effective comparisons.

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \quad (3)$$

$$S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}} \quad (4)$$

where $\bar{X}$ is the mean for the random variable, X_i is the i^{th} value of the random variable, and S is the sample standard deviation.

$$K_m = \frac{X_1 - \bar{X}_{n-1}}{S_{n-1}} \quad (5)$$

where X_1 is the highest observed annual maximum rainfall in the series.

$$X_{\text{PMP}} = \bar{X}_n + K_m S_n \quad (6)$$

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

2.5.1. Fitting to probability distribution function

The estimated values of PMPs were fitted to different probability distribution functions in order to get the best fit for all the stations. Frequency analysis techniques (Tao et al., 2002) were employed to analyze the annual daily maximum rainfall data.

Normal Distribution

Plotting probability was estimated using the Weibull method using equation (7). The standard normal deviate (Z) values for exceedance probability other than those in Table 2 were interpolated, which were then used for estimation of extreme value (X_T) using equation (8).

Table 2: Daily extreme precipitation indices

Exceedance probability (%)	Return period	Z
50	2	0.00
20	5	0.81416
10	10	1.2816
4	25	1.7507
2	50	2.0538
1	100	2.3264
0.2	500	2.8782

$$P = \frac{m}{n+1} \quad (7)$$

where m is the rank of rainfall order, and n is the total number of recording years.

$$X_T = \bar{x} + \sigma K_T \quad (8)$$

Log-Normal Distribution

After rearranging the annual daily maximum values in descending order of magnitude and assigning a rank m with '1' for the highest value, the values of Z and w were estimated using equations (9) and (10), respectively. Other parameters were estimated using the expressions given in Table3.

Table 3: Expressions used to estimate parameters of log-normal probability distribution

Parameter	Formula
Y_T	$Y_n + K_T S_y$
X_T	10^{Y_T}

$$Z = K_T = w - \frac{2.516 + 0.8028w + 0.0103w^2}{1 + 1.4328w + 0.1893w^2 + 0.0013w^3} \quad (9)$$

where w is an intermediate variable calculated using the formula:

$$w = \left[\ln\left(\frac{1}{p^2}\right)\right]^{1/2}, \qquad (0 < p \leq 0.5) \quad (10)$$

where p is the probability of exceedance. For $p > 0.5$, $1 - p$ is substituted for p, and the value of Z computed is given a negative sign.

Log Pearson Type III Distribution

The procedure for fitting the LPT-III distribution is similar to that for the normal and log-normal distributions. For performing LPT-III analyses, the following steps were used as given by Raghunath (2006):

1. A logarithmic transformation was made for all events of the series ($Y_i = \log X_i$).
2. The probability plotting positions were calculated using the Weibull formula.
3. The mean ($\bar{Y}$), standard deviation (S_y) was calculated using equation (3) and (4), and standardized skew coefficient (C_s) of the logarithms, as given by Apipattanavis et al. (2005), were computed using Equation (11).
4. K_T and k were calculated using equations (12) and (13), respectively.

$$C_s = \frac{n \sum_{i=1}^{n} (Y_i - \bar{Y})^3}{(n-1)(n-2)S_y^3} \quad (11)$$

$$K_T = Z + (Z^2 - 1)k + \frac{1}{3}(Z^3 - 6Z)k^2 + Zk^4 + \frac{1}{3}k^5 \quad (12)$$

where,

$$k = \frac{C_s}{6} \quad (13)$$

Gumbel Distribution

Gumbel distribution analysis was achieved by plotting the ranked annual maximum rainfall values and estimating the exceedance probability. The following steps were followed for derivation of extreme value, as given by Raghunath (2006):

1. The reduced variate (Y_T) was calculated using equation (15).
2. The value of the return period was obtained by taking the inverse of the probability plotting position, which was obtained using the Weibull method.
3. The frequency factor K_T was derived (where $\bar{y}_n$ and S_n were obtained from the reduced variate table) using equation (14).
4. Finally, the extreme value is calculated as $X_T = \bar{X} + K_T \cdot S$.

$$K_T = \frac{Y_T - \bar{y}_n}{S_n} \quad (14)$$

where,

- $\bar{y}_n$ = reduced mean of y_n (a function of sample size n; values are given in the concerned table, maximum value is 0.577 at $n = \infty$)
- S_n = reduced standard deviation (a function of sample size n; values are given in the concerned table, maximum value is 1.2825 at $n = \infty$)
- Y_T = reduced variate, estimated as:

$$Y_T = -\ln\left[\ln\left(\frac{T}{T-1}\right)\right] \quad (15)$$

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

To identify the most suitable model at each station, various probability distribution models underwent three goodness-of-fit tests, including the chi-square test (χ^2) and the coefficient of determination (R^2). The selection of these models was guided by the total score achieved from all tests, with scores ranging from zero to four $(0 - 4)$ assigned based on specific criteria. Models that received the highest total scores were deemed the best fit for the data at each station. The model that consistently ranked highest across all stations was ultimately designated as the best fit for the region. Generally, the distribution that performed best in a test received a score of four, while the second-best got three, and so forth, in declining order. Any distribution that showed a significant discrepancy between its estimated rainfall values and the actual observed data received a score of zero (0) for that test. For each test category, the overall rankings for each distribution were calculated by summing individual scores across the five stations.

2.5.3. Estimation of Return Period Values for PMP

Equation (16) along with the estimated location and scale parameters using equations (17)-(22) were used for the computation of return period values corresponding to estimated PMP value for durations of one day for all stations.

$$T = \frac{1}{1 - F(x)} \quad (16)$$

where,

- T is the return period
- $F(x)$ is the value of the cumulative distribution function

A common issue with hydrologic data is that it does not evenly distribute around the mean. The lower values only extend from the mean down to zero, while the upper values can rise indefinitely, resulting in a skewed distribution. To address the skew that may be present in the data, the log Pearson type III distribution was created to enhance the fit. This distribution relies on three parameters: mean, standard deviation, and skew coefficient (Izinyon & Ajumuka, 2013).

This distribution differs from most distributions in that three parameters (mean, standard deviation, and coefficient of skewness) are necessary to describe the distribution function. Mathematically, it is the logarithmic transformation of the Gamma distribution.

The probability density function is given by:

$$f(X) = \frac{\lambda^{\beta}(y-\varepsilon)^{\beta-1}e^{-\lambda(y-\varepsilon)}}{X\Gamma(\beta)}, \quad \text{where } \log X \geq \varepsilon \tag{17}$$

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

$$y = \log x \tag{18}$$

$$\lambda = \frac{S_y}{\sqrt{\beta}} \tag{19}$$

$$\beta = \left(\frac{2}{C_S(Y)}\right)^2 \tag{20}$$

$$\varepsilon = \bar{y} - S_y\sqrt{\beta} \tag{21}$$

$$\Gamma(\beta) = (\beta - 1)! \tag{22}$$

The mean and standard deviation are given by:

$$\bar{y} = \frac{\sum y}{n} \tag{23}$$

$$S_y = \sqrt{\frac{\sum(y-\bar{y})^2}{n-1}} \tag{24}$$

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

$$C_S = \frac{n\sum(y-\bar{y})^3}{(n-1)(n-2)S_y^3} \tag{25}$$

3. Results and Discussion

3.1. Missing Data Construction

Stations having inadequate daily records were identified and considered to have missing data. Almost all stations have missing data ranging from incomplete to relatively complete remarks, as shown in Table 4.

3.2. Consistency Test

Changes in slope might occur by chance or due to meteorological and climate properties, malfunctioning of gauges, and unknown reasons. Most of the stations were found to have data inconsistency in their series. These stations were adjusted to consistent values as presented in the appendix. A plot of the double mass curve for Babile station is shown in Figure 3 as a sample.

3.3. Annual Total and Annual Daily Maximum

Relatively high rainfall coverage in the west and central parts of the zones and relatively low rainfall records in the east and north parts of the zone were observed. Conversely, the maximum daily annual rainfall in Awbare station was found to be the highest, followed by Jigjiga station. The distribution of annual and annual daily maximum rainfall of selected five stations is indicated in Tables 5 and 6.

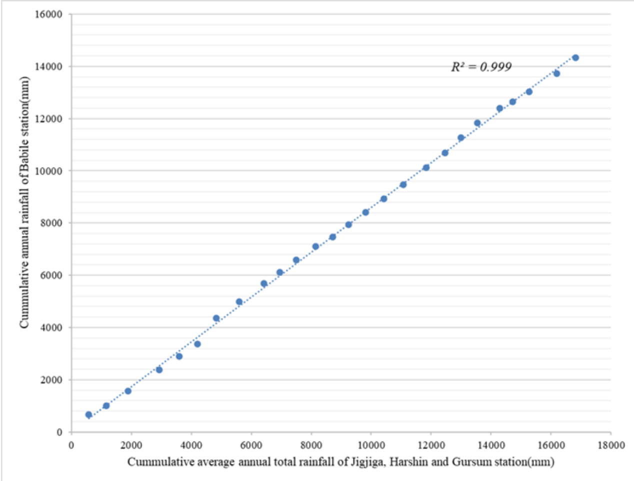

Figure 3: Double mass curve for Babile station

3.4. Maximum Frequency Factor (K_m)

The maximum frequency factor values for the stations ranged from 2.93 at Gursum station to 7.08 at Jigjiga station, with an average of 3.98 and a coefficient of variation (CV) of 43.7%. The K_m result, exceeding 20%, indicates significant data variability. This variation could stem from differences in record length or the micro-climatic conditions of the rain gauge stations. Table 7 presents the K_m factor for each station.

As shown in Table 11, the maximum frequency factor (K_m) values were primarily below 3.5, with only one instance (20%) of a value exceeding 3.5, specifically 7.08 at Jigjiga, which represents the upper limit of the estimated K_m. A frequency table for K_m was created, revealing that the most common quintiles ranged from 3.00 to 4.00, while the least common quintiles were above 4.00 and between 2.00 and 3.00. Since PMP focuses on atypical rainfall values, the corresponding frequency factor of 7.08 estimated at the Jigjiga station is considered an extremely high K_m value.

3.5. Comparison of K_m with Previous Studies

The observed enveloping of K_m (7.08) shows changes of 52.8, 26.2, 18.6, 21.3 and 13.6 from the largest Hershfield frequency, Atrak Watershed, Humid Regions Malaysia, Blue Nile Basin and Benishangul-Gumuz, respectively. The change of the estimated K_m from Hershfield's largest frequency factor implies that considering $K_m = 15$ for estimation of PMP will give an overestimated value. Table 9 shows the percentage difference between the maximum K_m values of Fafan zone with worldwide historical K_m observations.

3.6. Probable Maximum Precipitation (PMP)

The relation between the highest observed rainfall (HOR) and estimated maximum precipitation (PMP) is indicated in

Table 4: Selected stations' properties, data series, and missing percentage

Station Name	No. of years in series	No. of years missed	% missed years	Missed years	Remark
Babile	29	8	28	1992, 1993, 1997–2001, 2004	Incomplete
Harshin	27	13	48	1993–2005	Incomplete
Jigjiga	28	2	7	1992, 1999	Rel. complete
Awbare	13	2	15	2003, 2007	Incomplete
Gursum	29	1	3	1992	Complete
Average	–	–	20	–	Incomplete

Table 5: Annual total rainfall (mm) of selected meteorological stations in Fafan zone

	Annual Rainfall (mm)				
Year	**Babile**	**Harshin**	**Jigjiga**	**Awbare**	**Gursum**
1988	890.16	401.50	–	–	808.20
1989	675.02	384.12	545.20	–	778.30
1990	546.36	327.00	618.70	–	819.10
1991	314.20	336.30	688.90	–	1169.90
1992	819.31	616.96	828.75	–	1636.92
1993	558.24	564.33	570.70	–	872.40
1994	806.90	481.03	595.55	–	764.50
1995	644.10	529.37	528.98	–	849.30
1996	617.00	598.28	710.42	–	972.70
1997	697.83	662.88	917.30	–	870.57
1998	432.07	410.43	418.89	–	750.90
1999	471.72	448.09	509.75	–	745.30
2000	517.40	490.80	495.10	–	906.20
2001	483.77	458.85	585.10	–	673.50
2002	124.28	349.08	604.50	–	663.50
2003	309.60	459.93	575.60	600.12	687.50
2004	515.93	492.61	544.41	541.08	740.80
2005	685.46	656.94	694.20	934.55	606.26
2006	893.40	439.90	828.30	543.16	1043.11
2007	577.46	532.58	570.10	336.82	793.80
2008	587.18	245.13	508.26	270.24	825.50
2009	556.72	507.10	536.30	338.98	603.80
2010	572.60	592.40	710.03	896.10	930.10
2011	234.20	494.60	380.10	442.60	426.42
2012	386.10	678.00	406.90	383.20	565.30
2013	705.10	1419.20	603.00	417.90	712.10
2014	596.30	399.48	711.10	246.50	792.43
2015	453.05	–	457.70	350.99	614.88
2016	654.40	–	494.10	–	692.23

Table 6: Maximum annual observed daily rainfall (mm) of selected meteorological stations in Fafan zone

	Observed Maximum Rainfall (mm)				
Year	**Babile**	**Harshin**	**Jigjiga**	**Awbare**	**Gursum**
1988	56.2	66.0	61.9	–	71.9
1989	30.8	27.0	53.7	–	58.8
1990	56.6	32.0	50.8	–	43.3
1991	13.6	63.0	41.6	–	82.8
1992	37.9	46.4	46.4	–	70.1
1993	24.9	23.7	54.9	–	45.1
1994	41.7	22.9	39.9	–	54.4
1995	49.7	22.7	37.5	–	42.2
1996	41.6	23.9	62.0	–	52.3
1997	52.6	50.0	38.8	–	82.0
1998	21.7	20.7	35.3	–	64.2
1999	32.2	30.6	31.3	–	50.2
2000	22.6	21.5	38.0	–	45.0
2001	28.0	26.6	40.0	–	63.8
2002	14.2	20.8	59.0	–	60.0
2003	22.4	34.0	40.4	127.0	40.0
2004	26.4	25.1	61.2	39.2	82.3
2005	40.0	40.0	43.5	108.1	37.3
2006	60.0	24.6	45.0	40.3	89.0
2007	68.0	36.4	46.5	22.4	58.2
2008	50.0	16.6	48.0	26.2	62.7
2009	35.0	24.3	115.0	42.0	37.2
2010	83.1	29.6	30.4	152.0	104.0
2011	20.0	26.6	40.1	43.0	63.7
2012	30.5	24.6	47.2	32.5	37.2
2013	31.0	28.9	60.3	42.3	65.0
2014	28.9	17.8	32.1	27.4	75.3
2015	25.5	–	54.6	40.0	48.5
2016	41.5	–	–	–	34.4

Table 10. The estimated value of PMP was found to vary from 74.21 mm (Harshin station) to 189.82 mm (Awbare station) with an average value of 126.07 mm and CV of 38.62%. Normally, higher PMP estimates correspond to stations having higher variability, as reported from dry areas. Indeed, this was observed in this case due to the presence of stations that have dry conditions and the largest variability of rainfall records. The PMP to HOR ratio was found to vary from 1.07 (Gursum station) to 1.42 (Jigjiga station) with an average value of 1.19.

3.6.1. Ratio of PMP to Highest Observed Rainfall (HOR)

The ratio of rainfall magnitude at each individual station did not exceed three times the maximum recorded rainfall depth, which supports Hershfield (1962) findings. Consequently, the PMP values predicted in this study were accurate, without overestimation or underestimation. However, it is important to note that providing an exact predicted PMP value is not feasible, as it fluctuates over time with new data from severe storms in the same catchment area. Thus, the PMP values estimated here are the best possible estimates based on the available knowledge, methodologies, and data. Variations in these estimates may arise from differences in micro-

Table 7: Maximum Frequency Factor (K_m) of the stations

Station name	HOR	$\bar{X}_{n-1}$	σ_{n-1}	K_m
Harshin	66.00	29.24	10.60	3.47
Jigjiga	115.00	45.94	9.76	7.08
Babile	83.10	35.85	14.33	3.30
Gursum	104.00	57.75	15.79	2.93
Awbare	152.00	49.20	32.93	3.12
Mean	–	–	–	3.98
S_n	–	–	–	1.74
CV	–	–	–	0.44

Table 8: Frequency factor table for K_m

No.	Quintile interval	Frequency	Frequency (%)
1	$2.00 \leq K_m \leq 3.00$	1	20.00
2	$3.00 < K_m \leq 4.00$	3	60.00
3	$K_m > 4.00$	1	20.00

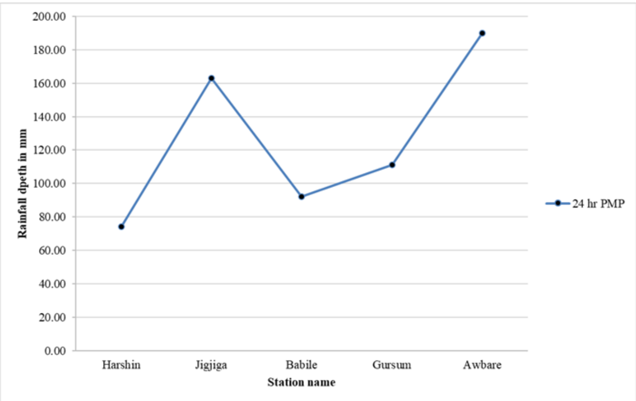

Figure 4: Stations with their corresponding PMP values

climates between stations and the varying lengths of their records, as noted by Hershfield (1961).

3.7. Comparison of the Probability Distribution Functions

3.7.1. Normal Probability Distribution Function

The standard normal deviate value (Z) for exceedence probability for the annual maximum rainfall data of Babile station were interpolated and computed as shown in Table 11. The result shows that the standard normal variate of records of all stations 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.

3.7.2. Log-Normal Probability Distribution Function

The values of the standard normal variate (Z) for exceedance probability related to the annual maximum rainfall data from the Babile station were calculated and are shown in Table 12. The findings indicate that the standard normal variable decreases as the recurrence interval decreases (which corresponds to an increase in plotting probability), and the extreme values observed demonstrate a linear relationship with the standard normal variable.

3.7.3. Log Pearson Type III Probability Distribution Function

The standard normal variable (Z) for the exceedance probability related to the annual maximum rainfall data from Babile station has been calculated and is displayed in Table 13. The findings indicate that the standard normal variable values for all stations decline as plotting probability increases (leading to a shorter recurrence interval), and the extreme values observed exhibit a linear relationship with the standard normal variable.

3.7.4. Gumbel EV1 Distribution

Table 14 presents the calculated reduced variate values for the exceedance probability of the GEV1 probability distribution based on the annual maximum rainfall data from the Babile station. The findings indicate that the reduced variate values decline as the recurrence interval decreases (or as the plotting probability increases).

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

3.8. Goodness of Fit (GOF)

3.8.1. The Coefficient of Determination (R^2)

The variation in the values obtained for specific P_i values was analyzed using a linear regression line. The coefficient of determination was computed using equation (26). For the Babile station, the log-normal and log Pearson III models were found to have equal significance (1), while the normal distribution model received the lowest ranking with a value of 0.95.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \right)^2 \quad (26)$$

where,

- O_i = observed rainfall values
- P_i = predicted rainfall values
- $\bar{O}$ = mean of the observed rainfall data
- $\bar{P}$ = mean of predicted rainfall data

3.8.2. Chi-Square Test

The chi-square goodness of fit test is one of the most widely used methods for assessing how well observed data matches expected values from various probability distribution functions. This is done by calculating the chi-square statistic (χ^2) using equation (27) and comparing it to the tabulated

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

Basin/Region	$K_{envelop}$	$\left(\frac{K_{envelop}-7.08}{K_{envelop}}\right) \times 100$	**Source**
Largest Hershfield frequency	15.0	52.8	Hershfield (1961)
Atrak Watershed, Iran	9.6	26.2	Ghahraman (2008)
Humid Regions Malaysia	8.7	18.6	Desa and Rakhecha (2006)
Blue Nile Basin, Ethiopia	9.0	21.3	Alemayew and Ayalew (2010)
Benishangul Gumuz region, Ethiopia	8.2	13.6	Regasa (2010)

Table 10: Probable Maximum Precipitation (mm) and Ratio of PMP to HOR

Station Name	$\bar{X}_n$	σ_n	**PMP (mm)**	**PMP:HOR**
Harshin	30.60	12.57	74.21	1.12
Jigjiga	48.41	16.19	162.97	1.42
Babile	37.48	16.58	92.16	1.11
Gursum	59.34	17.73	111.26	1.07
Awbare	57.11	42.50	189.82	1.25
Mean	–	–	126.09	1.19
S_n	–	–	48.69	0.14
CV	–	–	38.62	11.86

chi-square value at a 5% significance level and with the appropriate degrees of freedom. Since the calculated chi-square value was lower than the tabulated one, it indicates there is no significant difference between the observed and expected values. The model with the lowest chi-square value was identified as the best fit. Tables 15 and 16 indicate that the Gumbel EVI distribution function, with the lowest estimated chi-square value of 2.64 for the Babile station, should be considered the best fit model, receiving a score of 4 points. In contrast, the Normal distribution, with a calculated chi-square value of 89.2, is regarded as a weak model and was assigned only 1 point.

$$\chi_c^2 = \sum n \cdot \left[\frac{(f_s(x_i) - p(x_i))^2}{p(x_i)}\right] \tag{27}$$

where n is the number of intervals, and $f_s(x_i)$ and $p(x_i)$ are the observed and expected number of occurrences in interval i, respectively. The calculated χ_c^2 will be compared with tabulated χ^2, with $1-\alpha$ level of confidence and ν degrees of freedom. ν is given as $\nu = m - p - 1$, where $m =$ the number of intervals and $p =$ the number of parameters used in fitting the proposed distribution.

Based on the results from Table 16, Gumbel's EV1 probability distribution and log-normal have equal weights against chi-square and coefficient of correlation, hence they are the best model for Babile area.

From the results of four frequency distribution models applied in this study (Table 17), it could be concluded that Log-Pearson type III distribution was the best fit distribution for Harshin, Jigjiga station and Awbare weredas, which accounted for 50% of the total station number, followed by Gumbel distribution accounting for 34%, and Log normal accounting for 16% and no station fitted with Normal distribution.

3.9. Probable Maximum Precipitation Return Period

The study area utilized the Log-Pearson type III distribution. Parameters for the distribution function, specifically location, shape, and scale, were estimated based on the sample mean, standard deviation, and coefficient of skewness using equations (2.16–2.19). This allowed for the calculation of the probability of exceeding a specific value in relation to the return period T, leading to the assessment of annual exceedance for the predicted one-day PMP depths $P(X \geq X_0)$ from the Log-Pearson type III distribution for each station, with the relevant return periods detailed in Table 18. It was found that the PMP return periods ranged from 2000 to 3500 years, with a maximum of 3225.81 years at Harshin station and a minimum of 2127.66 years at Gursum station, averaging 2690.78 years and exhibiting a coefficient of variability of 5.47%.

The observed variability in return period (T) was less than 10%, hence the mean value could reasonably represent the overall T value for comparisons. Accordingly, the predicted return period was found to be nearly in the order of 2690 years.

3.10. Rainfall Depths for Various Years of Return Period

The flood frequencies for return periods of 5, 10, 50, 100, 1000, and 10000 years were calculated to compare with the return periods derived from the log Pearson type III distribution. The rainfall depths corresponding to these return periods ranged from 37.07 mm to 241.49 mm. Specifically, the depths for the 10000-year return period were between 97.21 mm and 241.49 mm, while those for the 1000-year period ranged from 64.52 mm to 180.37 mm. The depths for the 5, 10, 50, and 100-year return periods fell between 37.07 mm and 165.40 mm (Table 18).

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

The anticipated PMP values corresponding to various return period depths were calculated (as shown in Table 20), revealing a range from 0.76 for a 10,000-year period to 2.89 for a 5-year period. Al-Mamun and Hashim (2004) suggest that this ratio can be linked to the Factor of Safety (FOS). In civil engineering, the typical FOS values used for structural design range from 1.4 to 1.7, while those for geotechnical design vary between 1.5 and 2.0. Thus, the estimated PMP values present significant uncertainty for 100, 1,000, and 10,000-year periods, but appear to be adequate for designing hydraulic structures with return periods of 10 and 50

Table 11: Standard normal deviate (Z) and its extreme values derived by normal probability distribution for Babile station (mm)

Year	RF order	Rank (m)	P ($m/n+1$)	P (%)	Mean	St. Dev.	Z	X_T
1988	83.1	1	0.03	3.33	37.48	16.58	1.85	68.18
1989	68.0	2	0.07	6.67	37.48	16.58	1.54	63.05
1990	60.0	3	0.10	10.00	37.48	16.58	1.28	58.73
1991	56.6	4	0.13	13.33	37.48	16.58	1.13	56.14
1992	56.2	5	0.17	16.67	37.48	16.58	0.97	53.56
1993	52.6	6	0.20	20.00	37.48	16.58	0.81	50.98
1994	50.0	7	0.23	23.33	37.48	16.58	0.72	49.48
1995	49.7	8	0.27	26.67	37.48	16.58	0.63	47.98
1996	41.7	9	0.30	30.00	37.48	16.58	0.54	46.48
1997	41.6	10	0.33	33.33	37.48	16.58	0.45	44.98
1998	41.5	11	0.37	36.67	37.48	16.58	0.36	43.48
1999	40.0	12	0.40	40.00	37.48	16.58	0.27	41.98
2000	37.9	13	0.43	43.33	37.48	16.58	0.18	40.48
2001	35.0	14	0.47	46.67	37.48	16.58	0.09	38.98
2002	32.2	15	0.50	50.00	37.48	16.58	0.00	37.48
2003	31.0	16	0.53	53.33	37.48	16.58	-0.09	35.98
2004	30.8	17	0.57	56.67	37.48	16.58	-0.18	34.48
2005	30.5	18	0.60	60.00	37.48	16.58	-0.27	32.98
2006	28.9	19	0.63	63.33	37.48	16.58	-0.36	31.48
2007	28.0	20	0.67	66.67	37.48	16.58	-0.45	29.98
2008	26.4	21	0.70	70.00	37.48	16.58	-0.54	28.48
2009	25.5	22	0.73	73.33	37.48	16.58	-0.63	26.98
2010	24.9	23	0.77	76.67	37.48	16.58	-0.72	25.48
2011	22.6	24	0.80	80.00	37.48	16.58	-0.81	23.98
2012	22.4	25	0.83	83.33	37.48	16.58	-0.90	22.48
2013	21.7	26	0.87	86.67	37.48	16.58	-0.99	20.98
2014	20.0	27	0.90	90.00	37.48	16.58	-1.08	19.48
2015	14.2	28	0.93	93.33	37.48	16.58	-1.17	17.98
2016	13.6	29	0.97	96.67	37.48	16.58	-1.26	16.48
Sum	1086.86							
Mean	37.48							
St. Dev.	16.58							

$n = 29$, RF = rainfall, P = plotting probability, St. Dev. = standard deviation, Z = standard normal deviate variate

Table 12: Standard normal variable (Z) and its extreme values derived by log-normal distribution for Babile station (mm)

RF order	**Log RF**	**Rank**	P	W	Z	Y_T	X_T
83.1	1.92	1	0.03	2.61	1.83	1.89	77.08
68.0	1.83	2	0.07	2.33	1.50	1.82	66.49
60.0	1.78	3	0.10	2.15	1.28	1.78	60.32
56.6	1.75	4	0.13	2.01	1.11	1.75	55.91
56.2	1.75	5	0.17	1.89	0.97	1.72	52.46
52.6	1.72	6	0.20	1.79	0.84	1.70	49.61
50.0	1.70	7	0.23	1.71	0.73	1.67	47.17
49.7	1.70	8	0.27	1.63	0.62	1.65	45.02
41.7	1.62	9	0.30	1.55	0.52	1.63	43.09
41.6	1.62	10	0.33	1.48	0.43	1.62	41.33
41.5	1.62	11	0.37	1.42	0.34	1.60	39.71
40.0	1.60	12	0.40	1.35	0.25	1.58	38.20
37.9	1.58	13	0.43	1.29	0.17	1.57	36.78
35.0	1.54	14	0.47	1.23	0.08	1.55	35.44
32.2	1.51	15	0.50	1.18	0.00	1.53	34.15
31.0	1.49	16	0.53	1.12	-0.08	1.52	32.91
30.8	1.49	17	0.57	1.07	-0.17	1.50	31.71
30.5	1.48	18	0.60	1.01	-0.25	1.48	30.53
28.9	1.46	19	0.63	0.96	-0.34	1.47	29.38
28.0	1.45	20	0.67	0.90	-0.43	1.45	28.24
26.4	1.42	21	0.70	0.84	-0.52	1.43	27.11
25.5	1.41	22	0.73	0.79	-0.62	1.41	25.97
24.9	1.40	23	0.77	0.73	-0.72	1.39	24.82
22.6	1.35	24	0.80	0.67	-0.83	1.37	23.64
22.4	1.35	25	0.83	0.60	-0.95	1.35	22.41
21.7	1.34	26	0.87	0.53	-1.08	1.32	21.10
20.0	1.30	27	0.90	0.46	-1.24	1.29	19.68
14.2	1.15	28	0.93	0.37	-1.44	1.26	18.06
13.6	1.13	29	0.97	0.26	-1.71	1.20	16.01
Mean	1.53						
St. Dev.	0.19						
CV	0.13						

Table 13: Extreme value derived by LP-III probability values for Babile station

RF Order	**Log RF**	**Rank**	P	W	Z	K_T	Y_T	X_T
83.1	1.92	1	0.03	2.61	1.83	1.79	1.88	75.59
68.0	1.83	2	0.07	2.33	1.50	1.48	1.82	65.80
60.0	1.78	3	0.10	2.15	1.28	1.27	1.78	59.98
56.6	1.75	4	0.13	2.01	1.11	1.11	1.75	55.79
56.2	1.75	5	0.17	1.89	0.97	0.97	1.72	52.48
52.6	1.72	6	0.20	1.79	0.84	0.85	1.70	49.72
50.0	1.70	7	0.23	1.71	0.73	0.74	1.68	47.34
49.7	1.70	8	0.27	1.63	0.62	0.63	1.66	45.24
41.7	1.62	9	0.30	1.55	0.52	0.54	1.64	43.34
41.6	1.62	10	0.33	1.48	0.43	0.44	1.62	41.61
41.5	1.62	11	0.37	1.42	0.34	0.36	1.60	40.00
40.0	1.60	12	0.40	1.35	0.25	0.27	1.59	38.50
37.9	1.58	13	0.43	1.29	0.17	0.19	1.57	37.08
35.0	1.54	14	0.47	1.23	0.08	0.10	1.55	35.72
32.2	1.51	15	0.50	1.18	0.00	0.02	1.54	34.43
31.0	1.49	16	0.53	1.12	-0.08	-0.07	1.52	33.18
30.8	1.49	17	0.57	1.07	-0.17	-0.15	1.50	31.96
30.5	1.48	18	0.60	1.01	-0.25	-0.23	1.49	30.77
28.9	1.46	19	0.63	0.96	-0.34	-0.32	1.47	29.60
28.0	1.45	20	0.67	0.90	-0.43	-0.41	1.45	28.44
26.4	1.42	21	0.70	0.84	-0.52	-0.51	1.44	27.28
25.5	1.41	22	0.73	0.79	-0.62	-0.60	1.42	26.11
24.9	1.40	23	0.77	0.73	-0.72	-0.71	1.40	24.92
22.6	1.35	24	0.80	0.67	-0.83	-0.82	1.37	23.70
22.4	1.35	25	0.83	0.60	-0.95	-0.95	1.35	22.43
21.7	1.34	26	0.87	0.53	-1.08	-1.09	1.32	21.08
20.0	1.30	27	0.90	0.46	-1.24	-1.25	1.29	19.60
14.2	1.15	28	0.93	0.37	-1.44	-1.45	1.25	17.91
13.6	1.13	29	0.97	0.26	-1.71	-1.74	1.20	15.77
Mean	1.53			CV	0.13			
St. Dev.	0.19			C_s	-0.11		k	-0.02

Table 14: Extreme value derived by Gumbel EV1 for Babile station

Year	**RF order**	**Rank**	P	T	Y_t	K_T	X_T
1988	83.1	1	0.03	30.00	3.38	2.53	79.35
1989	68.0	2	0.07	15.00	2.67	1.90	68.90
1990	60.0	3	0.10	10.00	2.25	1.52	62.68
1991	56.6	4	0.13	7.50	1.94	1.25	58.18
1992	56.2	5	0.17	6.00	1.70	1.03	54.62
1993	52.6	6	0.20	5.00	1.50	0.86	51.65
1994	50.0	7	0.23	4.29	1.33	0.70	49.08
1995	49.7	8	0.27	3.75	1.17	0.56	46.81
1996	41.7	9	0.30	3.33	1.03	0.44	44.75
1997	41.6	10	0.33	3.00	0.90	0.33	42.87
1998	41.5	11	0.37	2.73	0.78	0.22	41.12
1999	40.0	12	0.40	2.50	0.67	0.12	39.47
2000	37.9	13	0.43	2.31	0.57	0.03	37.92
2001	35.0	14	0.47	2.14	0.46	-0.06	36.43
2002	32.2	15	0.50	2.00	0.37	-0.15	34.99
2003	31.0	16	0.53	1.88	0.27	-0.23	33.59
2004	30.8	17	0.57	1.76	0.18	-0.32	32.23
2005	30.5	18	0.60	1.67	0.09	-0.40	30.89
2006	28.9	19	0.63	1.58	0.00	-0.48	29.55
2007	28.0	20	0.67	1.50	-0.09	-0.56	28.22
2008	26.4	21	0.70	1.43	-0.19	-0.64	26.87
2009	25.5	22	0.73	1.36	-0.28	-0.72	25.50
2010	24.9	23	0.77	1.30	-0.38	-0.81	24.09
2011	22.6	24	0.80	1.25	-0.48	-0.90	22.61
2012	22.4	25	0.83	1.20	-0.58	-0.99	21.03
2013	21.7	26	0.87	1.15	-0.70	-1.10	19.30
2014	20.0	27	0.90	1.11	-0.83	-1.21	17.34
2015	14.2	28	0.93	1.07	-1.00	-1.36	14.96
2016	13.6	29	0.97	1.03	-1.22	-1.56	11.61
$\bar{Y}_n$	37.47			$\bar{Y}_n$	0.54		
Y_s	16.58			Y_s	1.13		

Table 15: Chi-square and correlation coefficient test of GOF for Babile station (mm)

S.No	Observed	Normal	Log Normal	Log Pearson III	Gumbel
1	83.1	68.18	77.08	75.59	79.35
2	68.0	63.05	66.49	65.80	68.90
3	60.0	58.73	60.32	59.98	62.68
4	56.6	56.14	55.91	55.79	58.18
5	56.2	53.56	52.46	52.48	54.62
6	52.6	50.98	49.61	49.72	51.65
7	50.0	49.48	47.17	47.34	49.08
8	49.7	47.98	45.02	45.24	46.81
9	41.7	46.48	43.09	43.34	44.75
10	41.6	44.98	41.33	41.61	42.87
11	41.5	43.48	39.71	40.00	41.12
12	40.0	41.98	38.20	38.50	39.47
13	37.9	40.48	36.78	37.08	37.92
14	35.0	38.98	35.44	35.72	36.43
15	32.2	37.48	34.15	34.43	34.99
16	31.0	37.48	32.91	33.18	33.59
17	30.8	37.48	31.71	31.96	32.23
18	30.5	37.48	30.53	30.77	30.89
19	28.9	37.48	29.38	29.60	29.55
20	28.0	37.48	28.24	28.44	28.22
21	26.4	37.48	27.11	27.28	26.87
22	25.5	37.48	25.97	26.11	25.50
23	24.9	37.48	24.82	24.92	24.09
24	22.6	37.48	23.64	23.70	22.61
25	22.4	37.48	22.41	22.43	21.03
26	21.7	37.48	21.10	21.08	19.30
27	20.0	37.48	19.68	19.60	17.34
28	14.2	37.48	18.06	17.91	14.96
29	13.6	37.48	16.01	15.77	11.61
Sum		1266.68	1074.33	1075.37	1086.61
Mean		43.68	37.05	37.08	37.47
S_n		8.83	15.06	14.86	16.58
χ_c^2 (Calculated)		81.92	3.41	3.60	2.64
χ^2 (Tabulated)		41.34	41.34	41.34	41.34
R^2		0.95	1.00	1.00	0.99

Table 16: Summary of GOF score results for Babile station

Station	Distribution model	χ^2 test	R^2	Total
Babile	Normal	1	2	3
	Log normal	3	4	7*
	Log Pearson type III	2	3	6
	Gumbel EV1	4	3	7*

Table 17: Summary of best fitted distribution model for each station

Distribution model	Stations fitted in number	In %
Log normal	1	16
Log Pearson type III*	3	50
Gumbel EV1	2	34

* The best fitted distribution model for Fafan zone.

years at specific locations. Using PMP for hydraulic structures with a 5-year return period may ensure stability, although it would be relatively expensive. Consequently, the PMP approach may address the limitations of conventional probabilistic methods.

3.12. Perception of Water Resource Sectors on the Associated Factors of Flood

Flood is an extreme event of natural disaster which affects social life and sometimes results in destruction of many infrastructures. Beyond its effects, quantifying and scaling many factors from a water resource sectors point of view is essential at watershed or zonal scale. Four correspondents were asked to rate the significant factors at the zonal scale. Based on the analysis, the following indicational points and measurement thoughts were identified.

Among the suggestions provided by the sectors, the areal characteristics, sloping conditions, and soil characteristics can be listed as major factors that influence flood occurrence in the Fafan zone. Most of them suggested that lack of watershed management, lack of river training works (since this prevents flood water from flowing in a single streamlined direction), and lack of upstream flood protection structure construction are the foremost listed factors. Based on the

Table 18: Return period of each station in Fafan zone

Station	PMP(x)	$P(X \geq X_0)$	T (Years)	Parameter name		
				Location (ε)	Shape (β)	Scale (λ)
Harshin	74.21	0.99969	3225.81	1.21	3.46	0.07
Jigjiga	162.97	0.99963	2702.70	1.52	1.80	0.08
Babile	92.16	0.99968	3125.00	1.15	4.95	0.08
Gursum	111.26	0.99953	2127.66	1.54	3.58	0.06
Awbare	189.82	0.99956	2272.73	1.28	3.00	0.13
Mean	126.09	–	2690.78	–	–	–
S_n	48.69	–	491.63	–	–	–
CV	2.59	–	5.47	–	–	–

$P(X \geq X_0)$ = value of log Pearson type III function for the depth of PMP, T = return period.

Table 19: Rainfall depths (mm) for various years of return period

S.No	Station Name	24hr PMP	5 yr	10 yr	50 yr	100 yr	1000 yr	10,000 yr
1	Babile	92.16	47.79	56.47	75.61	83.70	86.63	111.06
2	Harshin	74.21	37.07	42.92	55.80	61.25	64.52	97.21
3	Jigjiga	162.97	56.38	69.53	90.37	99.19	128.30	193.27
4	Awbare	189.82	87.68	112.10	145.82	165.40	180.37	241.49
5	Gursum	111.26	72.10	79.47	88.30	96.57	105.33	141.44
	Max	–	87.68	112.10	145.82	165.40	180.37	241.49
	Min	–	37.07	42.92	55.80	61.25	64.52	97.21
	Mean	–	60.20	72.10	91.18	101.22	113.03	156.89
	S_n	–	20.00	26.25	33.50	38.89	44.38	59.96

Table 20: Ratio of PMP to various years return period design rainfall depth

S.No	Station Name	5 yr	10 yr	50 yr	100 yr	1000 yr	10,000 yr
1	Babile	1.93	1.63	1.22	1.10	1.06	0.83
2	Harshin	2.00	1.73	1.33	1.21	1.15	0.76
3	Jigjiga	2.89	2.34	1.80	1.64	1.27	0.84
4	Awbare	2.16	1.69	1.30	1.15	1.05	0.79
5	Gursum	1.54	1.40	1.26	1.15	1.06	0.79
	Max	2.89	2.34	1.80	1.64	1.27	0.84
	Min	1.54	1.40	1.22	1.10	1.05	0.76
	Mean	2.11	1.76	1.38	1.25	1.12	0.80
	S_n	0.49	0.35	0.24	0.22	0.09	0.03

analysis, the most influential factor was identified as lack of lower watershed management practices, since the zone is bounded by the hilly topographic nature of the west Oromia region which accumulates water into it.

From the point of view of water resources designers, many suggested that lack of data can be quantified as a major factor since it affects inappropriate estimation of design inputs. For instance, the gauging stations are not sufficient, many have a huge number of missing data, and adoption of software weather generator tools rather than statistical observation is another factor, since those types of data give the same mean of daily or monthly data over large years. Among different reasons, problems due to data collection, problems in analysis and interpretation, and practicing of insufficient hydrological studies were repeatedly outlined among the respondents. Another issue was correlated with not practicing construction according to the design.

We also asked about the measures that have to be taken to address such problems. Introducing watershed management practices, construction of different reservoirs in upstream areas, and upgrading urban and rural drainage systems are the foremost solutions suggested by water resource sectors.

According to UN reports, the recent flash floods have been exacerbated by illegal logging, deforestation, and land degradation. These issues, along with overgrazing, conflict, and climate change, have rendered many regions vulnerable to devastating flash floods triggered by intense rainfall, which results in a rapid rise in river levels followed by a quick decline. This phenomenon typically occurs during the Gu rainy season from March to June and the Dayr season from October to December (Faruk, 2022).

4. Conclusion and Recommendations

Extreme precipitation data is crucial for environmental safety and the design and operation of engineering structures. This study aimed to estimate one-day probable maximum precipitation (PMP) and their return periods, as well as to identify the most suitable frequency distribution model for each rain gauge station. Meteorological data, specifically annual total rainfall and daily maximum rainfall, was gathered from five stations operated by the NMSA. After addressing any missing data and ensuring its consistency, the Hershfield (1961, 1965) method was employed for PMP estimation, alongside an adapted version of Chow (1952) method for rainfall frequency analysis.

Daily annual extreme rainfall data were used to derive maximum frequency factors (K_m), which ranged from 1.91 to 5.91, averaging 3.1 with a coefficient of variation (CV) of 28.2%. Given that PMP relates to extreme rainfall events, a high K_m value of 7.08 was selected. The estimated PMP values ranged from 74.21 mm to 189.82 mm, averaging 126.09 mm with a CV of 38.62%. These findings were compared against maximum observations, global records, and previous PMP studies covering the same period, revealing that the ratio of one-day PMP to the highest observed rainfall (HOR) ranged from 1.07 to 1.42, with an average of 1.19.

The log-Pearson type III distribution was determined to be the best model for extreme daily rainfall in the region, accounting for 50% of cases, followed by the Gumbel distribution at 36%, based on two goodness-of-fit tests, Chi-square and coefficient of determination. The return periods for PMP using the log Pearson type III distribution ranged from 3225.81 to 2127.66 years, averaging 2690.78 years with a variability of 5.5%. The daily PMP values for design rainfall across return periods of 5 to 10,000 years ranged from 37.07 mm to 241.49 mm, with ratio variations in predicted PMP values from 0.76 (at 10,000 years) to 2.89 (at 5 years). Thus, the estimated PMP appears suitable for designing hydraulic structures for return periods of 10 to 50 years in certain areas, though utilizing it for 5-year return periods can be costly.

Based on the study's findings, the following recommendations are suggested:

- Improved self-recording rainfall stations should be established to ensure high-quality management of rainfall data in the study area.
- A greater distribution of gauging stations and longer records of rainfall data are necessary for verifying results and obtaining reliable PMP documentation.
- While the log-Pearson type III model is the best fit for the Fafan zone, due to the country's weather variability, future statistical analyses should confirm the PMP outcomes.

Conflict of Interest

Authors declare that there is no conflict of interest involve in publishing this research paper.

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