RAINFALL INTENSITY-DURATION-FREQUENCY RELATIONSHIP FOR NORTHERN ETHIOPIA

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ABSTRACT

Intensity-Duration-Frequency (IDF) relationship provides essential information for the planning, design and evaluation of hydraulic structures, highways, urban drainage works and flood plain management. The objective of this paper is to develop IDF relationship that will enable estimation of intensity of rainfall (I) corresponding to any required rainfall duration (D) and frequency (F). Once this basic information of a given location is obtained, flood magnitude of various frequencies can be easily estimated which are essential for hydraulic and hydrologic works.

This paper describes the formulation of mathematical relationships of IDF developed for northern portion of Ethiopia (NE). The annual maximum rainfall magnitudes of varying duration were abstracted from rainfall charts and fitted to theoretical frequency distributions and then extrapolation of values for larger return periods were made. The analysis of rainfall intensities was expressed using the IDF equation of the generalized mathematical form.

The parameters of the mathematical form were generated for some selected eleven stations. The performance of the method was evaluated based on the historical and computed values of intensities using graphical and statistical methods. The results of this evaluation showed good agreement between the observed and the computed ones, implying that the method is reliable.

This IDF relationship, being an important hydrologic tool, will bridge the gap between the design need and the unavailability of design information especially in planning and design of water resources systems.

INTRODUCTION

Rainfall of a given point in space can be completely defined if the intensity, duration and frequency of various storms occurring at that point are known. The intensity of rainfall is the time rate at which it is falling, duration D is the time for which it is falling with that given intensity I and frequency F expressed in terms of return period T, is the average recurrence time of that rainfall intensity.

The rainfall Intensity-Duration-Frequency (IDF) relationship is one of the most commonly used tools in water resource engineering. Adequate knowledge of rainfall magnitude, its duration, and frequency has indispensable use for the planning, designing, operating of water resources projects, and for the protection of various properties, settlements and engineering projects against flood damage. IDF relations have been developed since 1932 [1]. Since 1960s many sets of relationships have been developed and the geographic distribution of this relationships were studied and maps have been constructed for several developed countries like those maps developed by the US Weather Bureau [5].

This paper discusses the procedures and methodologies used in data collection, and processing and steps involved in IDF relationship development. The result is a formulation of IDF relationship and derivation of the parameters for eleven stations in the Northern Ethiopia (NE).

DATA SETS

Eleven first class representative recording stations were selected from the northern Ethiopia. Sampling of stations was made based on non-random sampling technique using some judgment criteria. These criteria were made based on three factors. These are: the stations should be geographically representative; type of station need to be first class, and length of record has to be more than ten years. However, the period of the records of the stations was a combination of different time series. Very few stations had records of longer period. Most of the stations were having medium and short length of records. For these reason four of the stations didn't satisfy the long-period requirement and are below 10 years (Table 1). Figure 1 shows name and location of these stations used in the analysis.

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Figure 1 Name and Location of Meorological Stations Used for IDF Analysis (symbolized with circular dot)

Table 1: Rainfall data recording period and sample size

No.	Station	Recording period	Sample size (year)
1	Addis Ababa (OB)	1961 - 1990	30
2	Debre Brehan	1980 - 1990	10
3	Combolcha	1966 - 1990	24
4	Assaita	1977 - 1982	6
5	Dubti	1977-1982, 1988-1990	9
6	Mekele	1991 - 2001	10
7	Shire Indeselasie	1992 - 2001	6
8	Bahir Dar	1964, 1971 - 1996	26
9	Gonder	1976 - 1996	15
10	Assosa	1965 - 1987	15
11	Lima	1990-1991, 1994-1998	7

The rainfall data were read for each station for some selected duration of 1, 2, 3, 5 and 24 hours directly from daily and hourly-recorded rainfall charts except for Addis Ababa (which includes duration of 30 minutes). Since the recording on chart is made on daily basis, for most of the stations, reading of rainfall values for duration of less than 1 hour was not possible.

All these recording rain gauge stations have the information on the time of beginning and end of the individual rainstorms as well as the time and intensity of rainfall bursts during the storm. The rainfall data were read from the charts beginning from the start or from some point, which provides the largest reading on a given chart for 1-hour duration. Once the 1-hour reading is fixed, the rest of the duration was read continuously.

The annual maximum rainfall values were extracted from these readings for the subsequent years based on the annual maximum series method and were fitted to probability distribution function (PDF).

DATA ANALYSIS

Fitting the Probability Distribution Function

There are a number of probability frequency distributions in use. Annual maximum hourly or daily amounts ordinarily conform to a Gumbel

Type I, Log Pearson, Lognormal and Gamma distributions [8]. Among these, the most commonly used distributions namely Lognormal, Extreme Value Type I, and Log Pearson Type III are discussed briefly as follows.

Lognormal Distribution

The two parameter (the mean and standard deviation) lognormal distribution has been some times used for rainfall intensity duration analysis. If the random variable $y = \log(x)$ is normally distributed, then x is said to be log normally distributed. This logarithmic transformation of the normal distribution (i.e. the probability density function) is given as follows.

$$f(x) = \frac{1}{x\delta_y\sqrt{2\pi}}\exp\left(-\frac{(y-\mu_y)2}{2\delta_y^2}\right) x > 0 \qquad (1)$$

where

$y = \log x$, μ_y and δ_y are the mean and standard deviation of the population which are equivalent to $\bar{x}$ and s for the sample.

Lognormal distribution has been used to describe the distribution of hydraulic conductivity in porous medium and distribution of raindrop sizes in a storm and other hydrologic variables [3]. The lognormal distribution has advantage over normal distribution that it is bounded as $x > 0$ and the log transformation tends to reduce the positive skewness.

Log-Pearson Distribution

Log Pearson Type III distribution is a logarithmic transformation of the Gamma distribution. If $\log(x)$ follows a Pearson Type III distribution, then x is said to follow a Log Pearson distribution. It has a special feature that when $\log x$ is symmetric about its mean, the Log Pearson distribution will be reduced to normal distribution. This distribution is the standard distribution for frequency analysis of annual maximum floods and has got also wide application in the analysis of rainfall intensities. The fit of the distribution to data can be checked using the chi-square test or by probability plotting.

The probability density function f(x) is given by;

$$f(x) = \frac{\lambda^{\beta}(y-\varepsilon)^{\beta-1}e^{-\lambda(y-\varepsilon)}}{x\Gamma(\beta)} \log x \geq \varepsilon \qquad (2)$$

Where λ, β and ε are the scale, shape and location parameters respectively.

And $y = \log(x)$, $\lambda = \frac{s_y}{\beta}$, $\beta = \left(\frac{2}{Cs(y)}\right)^2$, $\varepsilon = \bar{y} - s_y\sqrt{\beta}$

and $\Gamma(\beta) = (\beta-1)!$ assuming the skewness $Cs(y)$ is positive.

The parameters λ, β and ε are used to compute the mean μ_y, standard deviation σ_x, and coefficient of skew Cs of sample estimates of the population as follows.

$$\mu_y = \varepsilon + \lambda\beta, \sigma_y = \lambda\sqrt{\beta}, \text{ and } Cs(y) = 2\sqrt{\beta} \qquad (3)$$

Chow [3] gave that the following general equation for any distribution from which the T -year event magnitude can be computed.

$$x_T = \mu + K\delta_x \text{ or } x_T = \bar{x} + Ks_x \qquad (4)$$

where x is event magnitude of the record, $\bar{x}(\mu)$ and s_x or (σ_x) are mean and standard deviation of the series and K is the frequency factor defined by a specific distribution, is a function of the probability level of x.

The Extreme Value Distribution

The Gumbel Extreme-Value frequency distribution is the most popular distribution and has received the highest application for estimating large events in various part of the world. Hershfield and Kohler[5] tested its application to rainfalls of 10-minute to 24 hours duration from 128 stations throughout the United States and found that the method yields of acceptable accuracy [4]. This distribution has been used for rainfall depth-duration-frequency studies [5] as well as for the distribution of the yearly maximum of daily river flows. Extreme value distribution has been also widely used in hydrology and storm rainfall most commonly by the EVI distribution [2].

Chow [3] has given EVI cumulative distribution function in the following form.

$$F(X) = \exp\left(-\exp\left(-\left(\frac{X-u}{\alpha}\right)\right)\right), \quad -\infty \leq X \leq \infty \qquad (5)$$

where α and u are parameters and u is the mode of the distribution point of maximum probability density and 'X' is the variate (historically observed data) and estimated from the following relations for large population size.

$$\alpha = \frac{\sqrt{6}*S}{\pi} = 0.797*S \text{ and } u = \bar{X} - 0.5772*\alpha \qquad (6)$$

A reduced variate' Y' can be defined as $Y = \frac{X-u}{\alpha}$ and substituting Y into Eq. (3.5) yields,

$$F(X) = \exp(-\exp(-Y)) \quad (7)$$

And the reduced variate YT, for the return period T will be;

$$Y_T = -\ln\left(\ln\left(\frac{T}{T-a}\right)\right) \quad (8)$$

Therefore, for the EVI distribution, X_T is related to Y_T by Eq. (9) as follows;

$$Y = \frac{Y-u}{\alpha} \Rightarrow Y_T = \frac{X_T - u}{\alpha}$$

Hence, $X_T = u + \alpha * Y_T$ (9)

Comparison of the Probability Distribution Function

For the purpose of comparison, the annual maximum rainfall data of Addis Ababa station (of the 1 and 24-hours rainfall depth) were fitted to EVI, lognormal and log Pearson type III frequency distributions as shown in the Figs. 2(a) to 2(c).

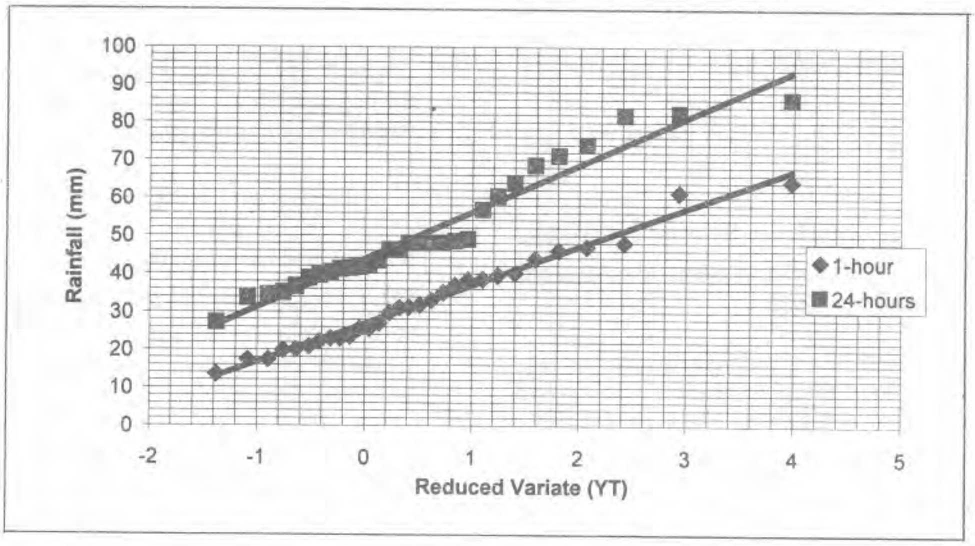

Figure 2(a) Fitting EVI probability distribution to observed value [9]

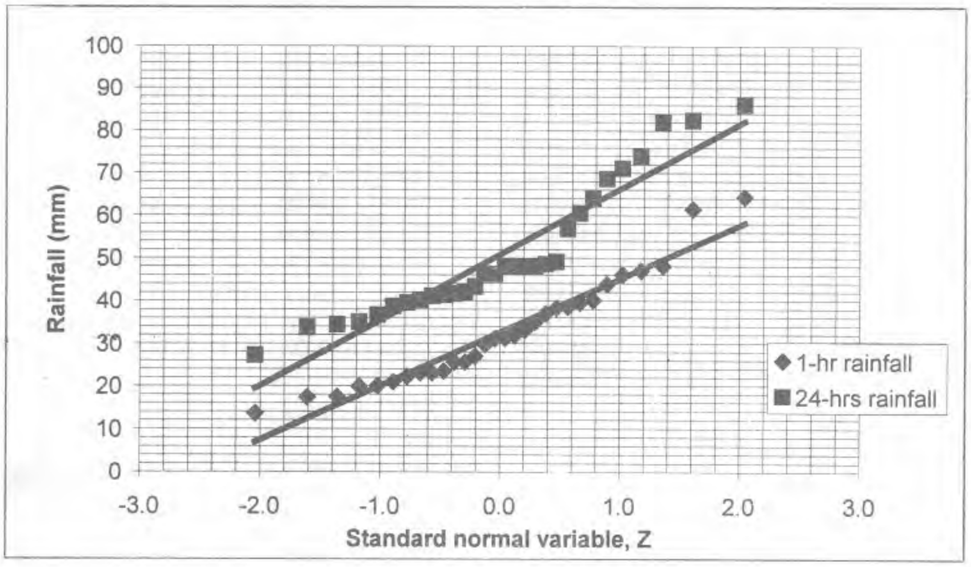

Figure 2(b) Fitting Lognormal Probability Distribution to observed value [9]

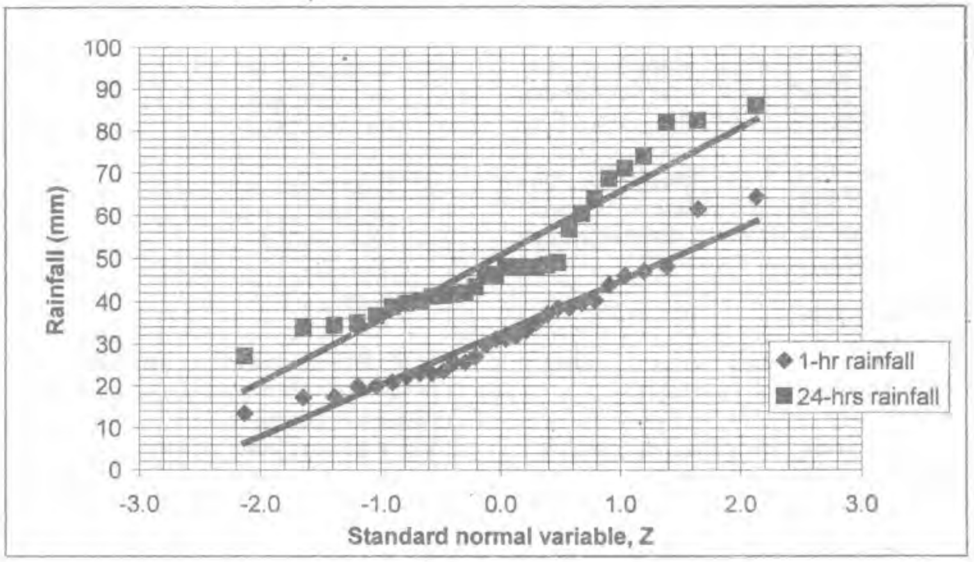

Figure 2(c) Fitting Log Pearson Type III Distribution to observed value [9]

Of all distributions the EVI is generally most commonly used for extreme value distributions, such as for annual maximum rainfall analysis as it is suitable to model maximum values. And from Fig. 3(a) to 3(c), though three of the distributions have fitted the data values almost in a similarly way, EVI distributions has better described the given data sets. Hence, data analysis, and fitting the theoretical probability distribution to the observed data as well as numerical computation of the rainfall magnitude (X_T) for frequencies larger than the recording period was made based on EVI distribution.

Computation of Extreme Value (X_T) and Intensity of Rainfall

Once the type of the distribution is known, the rainfall events (X_T) exceeding the observed values can be either extrapolated from the graph or calculated numerically. For instance, the 100 years return period values of a 3D-minute rainfall of mean (X = 24.4) and the standard deviation (8=9.97) can be estimated using Eq. 6 and 9 as follows:

Once the X_T values are known, the rainfall intensities of given duration (D_i) and a set of selected frequencies (T_j) can be calculated. For instance the intensity of rainfall of a 30minute duration and 100-year frequency estimated in the above example will be;

$$i = \frac{\text{Rainfall depth (mm)}}{\text{Time duration (hr)}} = \frac{X_T}{D_i} = \frac{55.65(\text{mm})}{0.5(\text{hr})} = 111.30 \text{ mm/hr}$$

INTENSITY - DURATION - FREQUENCY REGIME

In practice, the construction of the series of maximum intensities is performed simultaneously for a number k of durations $D_i = 1, ..., k$, starting form a minimum durations equal to the time resolution 8 of observations (e.g. from 5-10 minute to 1 hour depending on the measuring device) and ending with a maximum duration of interest in – engineering problems typically 24 or 48 hours [7].

The IDF curves can be produced for the given return periods and for the respective duration from a series of maximum rainfall intensities observed. The resulting IDF graphs can be published for the major stations and the regime of the recording stations can be summarized by means of maps (like that of the U.S. Weather Bureau, 1955 and 1957maps). Interpolation for various storm duration and return period for ungauged (no recording station) can be made from these maps, though there are large uncertainties in doing this for areas of strong relief.

According to WMO [10], the analysis of rainfall intensity data for a long series of storm may be summarized and expressed either by:

i. Families of curves for given frequencies (return periods) showing the maximum rainfall intensity for each of a number of durations.

ii. Empirical formula or mathematical form expressing the relationship portrayed by such curves.

iii. Maps providing rainfall frequencies for various return period and duration from which rainfall intensities can be derived.

In this particular case, a combination of IDF curves construction and mathematical formulation along with methods of parameter estimation are discussed as follows.

Construction of IDF Curves

The typical IDF curve construction procedure consists of the following three basic steps.

1. Fitting a probability distribution function to each group of data values for a specific duration, *Di*
2. Calculating or extrapolating the rainfall depth X_T for the given D_i and a set of selected return periods such as (1,2,5, 10,20,50,100 years etc).
3. Plotting sets of IOF curves with duration D_i as abscissa and the intensity I as ordinate on a log-log graph, which relates the intensity of rainfall I as a function of duration D and frequency T.

As an example to IDF curve construction, a graph was plotted on a log-log scale (with duration D_i as an abscissa and the intensity I as an ordinate) using data for Addis Ababa station as in Fig. 4 below.

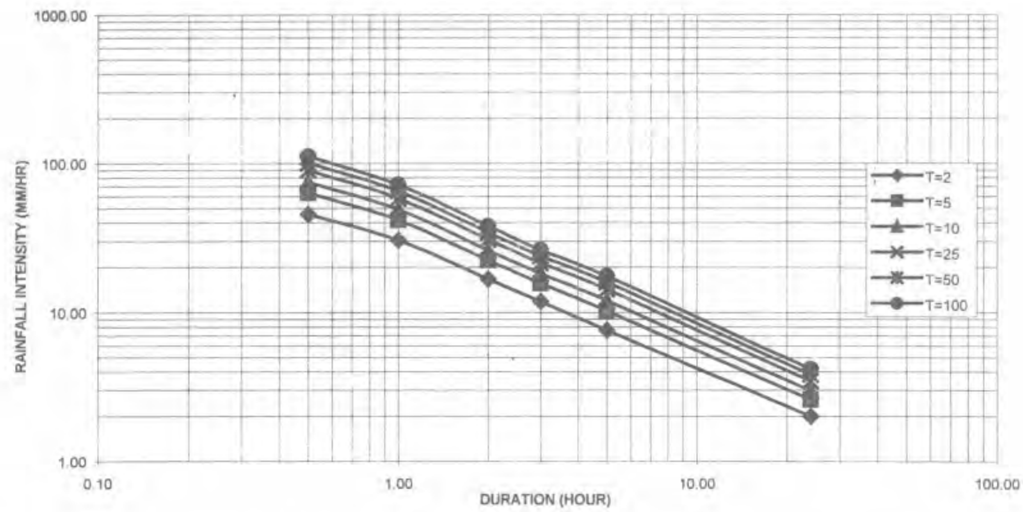

Figure 4 IDF Curves plotted on a log-log graph, Addis Ababa OBS [9]

Mathematical Form of IDF

To establish mathematical relationship for IDF, the historical data are first fitted to theoretical distribution, which is most commonly to EVI. For each durations selected, the annual maximum rainfall depths are extracted from the historical rainfall records and then frequency analysis applied to the annual maximum value. For return periods exceeding the size of the sample, the annual maximum rainfall values can be extrapolated either from the frequency distribution graphs or estimated numerically based on the type of pdf involved.

The IDF relationship can then be expressed in the form of an empirical equation rather than reading the rainfall intensities from graphs or maps. From the mathematical relationship (equation), the IDF parameters can be estimated. The typical empirical formulas among others [11] are;

$$P_i = \frac{a}{b+T} \tag{10}$$

$$P_i = a(T-b)^{-n} \tag{11}$$

$$P_i = a + \frac{b(\log T)}{1+D} \tag{12}$$

where, P_i = maximum mean rainfall intensity for duration of D (mm/hr)

T = the return period (years)

a, b and n are parameters that vary from station to station, within station with selected frequency of occurrence.

In some countries where there is extensive analysis of rainfall intensity data, complete maps showing Isoplateths of the parameters a, b, and n are available which is generally more useful than the curves and the maps.

In addition to the above formulae, [10] also provided method of estimation of coefficients from a number of cities in USA using another empirical equation of the form,

$$I = \frac{c}{T_d^e + f} \qquad (13)$$

The above equation was extended further by Chow[3] to include the return period T using the following equations.

$$I = \frac{cT^m}{T_d + f} \qquad (14)$$

$$I = \frac{cT^m}{T_d^e + f} \qquad (15)$$

where, T_d is the duration, c, e, f and m are coefficients varying with location and return period.

Another generalized typical mathematical relationship of IDF for given frequency was given by Koutsoyiannis et al. [7] as follows:

$$I = \frac{\omega}{\left(d^v + \theta\right)^\eta} \qquad (16)$$

where ω, ν, θ and η are non-negative coefficients with $v\eta \leq 1$ and θ and η are to be estimated and d is rainfall duration.

Simplified form of the above equation was given by different authors by adopting either one or two of the coefficients $v = 1$, $\eta = 1$ and/or $\theta = 0$, and by assuming;

- The duration (d) to be restricted between d min. = 1/12 hour (= 5 min) and d max. = 120 hours.
- The parameter 8 to vary between 0 and 8 max. = 12*d min. = 1 hour
- The parameter v to vary between 0 and 1 but most often, it is assumed to be 1.

Therefore, taking v to be 1, Eq. 16 is reduced to the following fonn

$$I = \frac{\omega}{\left(d + \theta\right)^\eta} \qquad (17)$$

In this equation the parameter ω is dependent on the return period, T and considered as increasing function of T. The various studies carried out in the field indicate that the real world families of IDF curves can be well descried with constant parameters θ, and η as well as with dependent parameter ω.

Parameter Estimation Technique

After fitting the pdf and defining the relationship, the next step is to estimate the parameters of the intensity-duration-frequency regime. There are two methods of parameter estimation suggested by Koutsoyiannis et al. [7]. These are the robust estimation and the one-step least squares methods based on optimization technique. The second method estimates all parameters (θ, η and ω) in one step, by minimizing the total square error of the fitted IDF relationship to the data. The minimization of the total error can be performed using the embedded solver tools of the MS-Excel spread sheet by a trial and error procedure.

There are also IDF Curve-Fit software developed to estimate the parameters based on the general IDF relationship. One of this software available and used for this case is the IDF Curve-Fit (version 2.49, 1996) developed by Alan A. Smith Inc. The program is a DOS based and operates using either depth or intensity data in either metric or U.S. customary units. The optimization is done using a simple pattern search (Hook and J eeves) and displays a comparison between the synthetic data and the observed data in both tabular and graphical form. Multiple IDF curves can also be plotted on log-log axes for different recurrent intervals. This software enables one to define and solve the parameters (a, b, and c) from a set of pairs of data values (the time duration and rainfall depths /intensities) of an intensity-duration equation of the general form

$$I = \frac{a}{\left(T_d + b\right)^c} \qquad (18)$$

where, I = rainfall intensity (mm/hr)
T_d = D = time duration in minute
a = coefficient with the same unit as I
b = time constant in minute
c = an exponent usually less than 1

IDF PARAMETERS FOR SOME STATIONS IN NE

The parameters (a, b, and c) were estimated using the IDF Curve-Fit Software (version 2.49, 1996) mentioned in the previous section from the given five sets of pairs of data values (the time duration Dj, j = 1,2, ...5 (minute) and rainfall depths dk, k = 1,2...5 (mm)) of an intensity-duration equation of the general form (Eq. 18). The result of the parameters estimation is summarized in Table 5.1 to 5.3 below.

Table 5.1: Values of the IDF Parameters for 11 stations for Return Period, T = 2 & 5 years

No	Name of station	Longitude (degree)	Latitude (degree)	Parameters for T =2 Yrs			Parameters for T =5 Yrs		
				a	*b*	*c*	*a*	*b*	*c*
1	Addis Ababa OB	38.75	9.03	1292	11.7	0.89	1870	11.1	0.906
2	Debre Brehan	39.50	9.63	1422	44.9	0.932	731	5.0	0.816
3	Combolcha	39.73	11.12	1442	11.1	0.886	1709	8.1	0.917
4	Assaita	41.45	11.57	190	13.4	0.849	155	13.4	0.74
5	Dubti	41.10	11.75	1334	39.5	0.995	1319	24.8	0.924
6	Mekele	39.48	13.50	804	4.1	0.895	863	0.0	0.851
7	Shire Indeselasie	38.27	14.10	1237	20.2	0.906	1778	25.4	0.915
8	Bahir dar	37.40	11.60	1619	26.2	0.844	2367	20.2	0.899
9	Gonder	37.42	12.55	505	0.0	0.802	615	0.0	0.789
10	Assosa	34.52	10.02	1412	13.3	0.946	1454	6.1	0.907
11	Lima	36.83	7.67	666	2.2	0.815	910	0.0	0.829

Table 5.2: Values of the IDF Parameters for 11 stations (for T = 10 & 25 years)

No	Name of station	Longitude (degree)	Latitude (degree)	Parameters for T=10 Yrs			Parameter for T =25 Yrs		
				a	*b*	*c*	*a*	*b*	*c*
1	Addis Ababa OB	38.75	9.03	2274	11.1	0.913	2702	10.2	0.916
2	Oebre Brehan	39.50	9.63	728	0.0	0.802	831	0.0	0.806
3	Combolcha	39.73	11.12	2112	7.0	0.932	2643	6.1	0.947
4	Assaita	41.45	11.57	153	13.9	0.702	167	17.6	0.68
5	Oubti	41.10	11.75	1412	20.2	0.901	1540	15.9	0.881
6	Mekele	39.48	13.50	696	0.0	0.841	1130	0.0	0.835
7	Shire Indeselasie	38.27	14.10	2173	28.4	0.922	2550	29.0	0.92
8	Bahir dar	37.40	11.60	2948	19.1	0.909	3635	17.6	0.916
9	Gonder	37.42	12.55	707	0.0	0.787	786	0.1	0.778
10	Assosa	34.52	10.02	1513	2.9	0.890	1642	0.8	0.878
11	Jima	36.83	7.67	1100	0.0	0.839	1378	0.0	0.853

Table 5.3: Values of the IDF Parameters for 11 stations (T=50 & 100 years)

No	Name of station	Longitude	Latitude	Parameters for T =50 Yrs			Parameters for T=100 Yrs		
		(degree)	(degree)	*a*	*b*	*c*	*a*	*b*	*c*
1	Addis Ababa OB	38.75	9.03	3094	10.4	0.921	3443	10.2	0.923
2	Debre Brehan	39.50	9.63	929	0.0	0.811	1004	0.0	0.813
3	Combolcha	39.73	11.12	3080	6.0	0.958	3541	6.1	0.967
4	Assaita	41.45	11.57	174	18.2	0.664	186	20.2	0.655
5	Dubti	41.10	11.75	1630	13.3	0.869	1753	11.9	0.861
6	Mekele	39.48	13.50	1203	0.0	0.826	1306	0.0	0.822
7	Shire Indeselasie	38.27	14.10	2975	31.7	0.927	3266	31.9	0.926
8	Bahir dar	37.40	11.60	4233	17.6	0.923	4648	16.0	0.923
9	Gonder	37.42	12.55	876	0.0	0.778	948	0.0	0.776
10	Assosa	34.52	10.02	1768	0.1	0.873	1972	0.0	0.875
11	Jima	36.83	7.67	1524	0.0	0.854	1750	0.0	0.862

As it can be seen from the above tables, it is difficult to conclude about the trend of the parameters. But generally, the values of 'a' increases with increase in return period T and the value of '*b*' and '*c*' depend on the rate of increase or decrease of '*a*'. There are also cases where all the values of a, b, and c decreases with increase in T with an ultimate goal of optimizing the non-linear function and giving an increased value of intensity I with T.

To insure the reliability of the parameters estimated, evaluation of the method was made to obtain optimum agreement between computed and observed data. Accordingly, goodness of fit test was conducted between observed I_o and computed I_c of rainfall intensities using graphical verification and statistical methods (using coefficient of variation of the residual error and the coefficient of the determination). Both methods showed good agreement indicating the parameter estimation model used performs very well.

Application Procedures

The application of the above tables follows the following general procedures.

1. Define the specific location whereby the rainfall intensities to be estimated.
2. Define the require time span or duration (in minute) such as the time of concentration *Te* of a flood hydrograph of a give catchment.
3. Determine the return period (in years) to be used in the calculation of the rainfall intensity.
4. Read values of the corresponding parameters (a, b and c) from Table 5.1 to 5.3 for the give location and return period.
5. Calculate the rainfall intensities from the relationship given in Eq. (18) by inserting the respective parameters.

Example:

As alternative to the curves and the maps, coefficients of the IDF relationship can be used to estimate rainfall intensities. For instance, the 12-hours rainfall intensity of 100 years return period at Addis Ababa can be computed as follows.

Given: the parameters $a = 3443$, $b = 10.2$, and $c = 0.923$ (from table 5.1)
$T_d = 12$ hours = 720 minutes
$T = 100$ years

Required: I ($T_d = 12$ hrs and $T = 100$ yrs)

Solution:

$$I = \frac{a}{(T_d + b)^c} = \frac{34443}{(720 + 10.2)^{0.923}} = 7.83 \text{ mm/hr}$$

SUMMARY

The planning and use of water resource requires proper hydrologic inputs and adequate design information, which enables to maximize the safe utilization of this limited resource and minimize the risk and damages resulting from extreme events; thus requiring realistic and reliable planning and design tools such as Intensity-Duration-Frequency relationship.

In this paper, the annual maximum rainfall data read from recoding charts were fitted to probability distribution function (PDF). The goodness of fit of the data to pdf was tested based on the Chi Square statistical test. Mathematical relationship of IDF was then developed for eleven stations in northern part of the country.

The values of the IDF parameters were driven from the historic record based on the equation of the general form for the eleven stations of different geographic location and frequencies. The method of parameter estimation was evaluated for consistency and reliability using graphical and statistical methods and the results were found to be very good.

This IDF equation of the general form can be used to determine intensity or depth of rainfall of an area near by the principal eleven stations (within a radius of about 25-km of the respective stations). Since the relief and rainfall variability is great, the direct use of the values for areas farthest from the principal station is not recommended.

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