Indian J. Dryland Agric. Res. & Dev. 2022 37(1): 35-41 10.5958/2231-6701.2022.00008.2

Rainfall Intensity-Frequency-Duration Relationship for Solapur in Scarcity Zone of Maharashtra

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ABSTRACT: The characteristics of rainfall, viz., intensity, duration, frequency of rainfall, time distribution and geographical distribution are responsible for producing runoff. Rainfall intensity-frequency-duration equations are required for design of soil and water conservation and runoff disposal structures and for planning flood control projects. The rainfall intensity-duration-return period relationship as $I = (KT^a) / (t+b)^d$ has been developed for Solapur region under scarcity zone of Maharashtra. The constants K, a, b and d in this equation are location specific. The values of parameters a and b were determined by using graphical method and the values of K and d by least squares method. The daily automatic rain gauge charts of Solapur were analyzed in the form of annual maximum series of various durations, viz. 5, 10, 15, 30 minutes, 1, 3, 6, 12 and 24 hours. The constants K, a, b and d for Solapur were found earlier as 11.08 0.1892, 1.01 and 1.2066 respectively by analyzing 17 years daily automatic rain gauge charts of Solapur. These constants K, a, b and d were now modified to 4.57, 0.1934, 0.40 and 0.9187 respectively by analyzing 37 years (1970 to 2020 except 1973, 1978, 1983-1988, 1992, 1993, 1997-2000) daily automatic rain gauge charts. The modified constants will be helpful in design of runoff disposal structures in the Solapur region.

Key words: IFD, rainfall intensity-frequency-duration relationship, rainfall intensity

Introduction

Intensity duration frequency (IDF) relationship of observed rainfall is one of the most common mathematical relations used in water resources engineering for planning, design and operation of water related designs. One of the first steps in many hydrologic design projects, such as drainage design, is the determination of the rainfall event or events and this process is generally done with intensity-duration-frequency curves (IDF) which shows intensity and duration of a design storm at the same time (Chow *et al.,* 1988). It was predicted that by the end of 21st century, a significant reduction in the return period of an annual maximum precipitation amount with frequent occurrence of extreme rainfall events would take place (IPCC, 2012; Fadhel *et al.,* 2017). The sensitivity of urban storm water collection systems can be negatively affected by such changes (Willems 2013; Fadhel *et al.,* 2017). Therefore, in order to prevent damages due to storm water collection systems, intensity-duration-frequency analysis must be done cautiously (Yuce and Deger, 2019).

The hydrologic phenomena that directly influence the interest of an engineer are rainfall, runoff, flood and drought. The characteristics of rainfall, which are of importance for a soil and water conservation structure design engineer are those which are responsible for producing runoff. These characteristics are intensity, duration, frequency of rainfall, time distribution and geographical distribution. It is not possible to predict accurately the future occurrences of these events from given facts and data in a mathematical manner due to complex nature of hydrologic cycle.

Rainfall is one of the most important factors responsible for soil erosion. The characteristics of rainfall, viz., amount, intensity and duration play an important role in determining the rate of soil erosion. Greater the intensity of rainfall, greater is the kinetic energy it possesses. The kinetic energy of rainfall dislodges soil particles and splashes them. Among other factors, the amount of runoff is determined by rainfall intensity, duration and rainfall amount. The rainfall of longer duration reduces the infiltration capacity of soil as a result produces considerable runoff regardless of its intensity. The capacity of runoff conveyance system is usually based on certain depth of rainfall to be expected during a selected period time. Farm terraces, culverts, bridges and flood control structures are thus designed on the basis of safely conveying runoff expected from rainstorms of specified frequency, intensity and duration.

The significance of rainfall intensity-duration-return period analysis is also important from economic considerations. An overdesigned structure involves excessive cost and under designed structure will be unsafe and involve high recurring expenditure on repair, maintenance and replacement. An appropriate design would provide a structure with reasonable initial and maintenance cost. In order to have optimization in hydraulic design of any structure, the peak rate of runoff expected during the recurrence interval should be correct. This necessitates the knowledge of rainfall intensity-frequency-duration relationship for a particular location.

The rational formula is one of the extensively used empirical formulae due to its simplicity for estimating runoff to be expected from small drainage areas. In USA the generalized charts of rainfall intensity-frequency-duration, developed earlier by Yarnell (1935) and revised by US Weather Bureau (Hershfield, 1961) are being used for obtaining the value of rainfall intensity 'I' in the rational formula (Ram Babu *et al.,* 1979). Since such generalized charts are not available in our country because of insufficient density of automatic rain gauge stations, some empirical assumed values of 'I' are used for estimating runoff, which needs improvement.

Rainfall intensity-duration-return period equations on regional basis are required in the country for design of soil conservation and runoff disposal structures and for planning flood control projects. Such relationships and nomographs have been developed at a few stations scattered over the country (Gupta *et al.*, 1968; Raghunath *et al.*, 1969; Khuller *et al.*, 1975 and Senapati *et al.*, 1976). Nemec (1973) developed the general form of the rainfall intensity- duration- return period equation.

Selection of data

Jarvis (1936) stated that use of annual maximum value is the most practical rain independent events, which are essential in hydrologic frequency analysis. Beard (1974) has shown that the relationship between annual series and partial duration series, flood peak varies throughout the U.S. and recommends the use of empirically derived, regionalized relationship. Raghunath *et al.* (1969), Patel *et al.* (1969), Kharche (1970), Ram Babu *et al.* (1979) and Ranade & Gupta (1988) used the annual duration series method for frequency analysis.

Adequacy of length of record

While analyzing the rainfall data, the adequacy of the length of available record must be ensured for reliable results. Mockus (1960) gave the equation for finding the minimum acceptable years. The values for minimum acceptable years for this study were found less than 28 years for all durations.

Method for frequency analysis

Dalrymple (1960) suggested that for the period of record more than 30 years, the use of mathematical model might be advisable, while for short period of record the graphical method should be preferred.

Probability paper

In order to linearize the frequency distribution, use of probability paper is recommended. Hazen (1914) suggested the use of probability paper for linearization of normal distribution. The linearization makes the extrapolation and comparison easy. Ram Babu *et al.* (1979) and Ranade and Gupta (1988) used the lognormal probability paper for frequency analysis.

Curve plotting

Ogrosky and Mockus (1957) developed the 'computing method' for plotting the frequency line by computation of plotted points, which was used by Gupta *et al.* (1968), Handa and Misra (1968), Raghunath *et al.* (1969), Singh *et al.* (1971), Sharma (1973) and Ranade and Gupta (1988).

Analytical procedure

Various equations that were found to represent the rainfall intensity-duration-return period relationship in India and abroad are summarized and discussed by Raghunath *et al.* (1969). However, the most satisfactory general equation is of the form as given in equation (1).

$$I = \frac{KT^a}{(t+b)^d} \quad (1)$$

where, I = rainfall intensity, cm/hr; T = return period, yr.; t=duration up to 24 hours; K, b = derived constants; a, d = derived exponents.

Materials and Methods

Ram Babu *et al.* (1979) worked out intensity - duration-return period equations and developed nomographs for the whole country using the relevant data from a large number of rain gauge stations. The relationship was developed for Central Zone of India as a whole, which covers a large area. It is necessary to develop such relations that are site specific. In central zone of India, Solapur is not included. In Maharashtra, the values have been determined for Aurangabad, Mahabaleshwar, Mumbai, Nandurbar, Nagpur and Vengurla stations by Ram Babu *et al.* (1979). Since the relationship between rainfall intensity duration and return period is specific for a particular location and mainly depends upon the physical characteristics of rainfall, the relationship developed for one particular location cannot be superimposed on the other. It is necessary to determine the values of constants K, a, b and d for as many locations as possible. Hence, it is necessary to develop such relationship for small units in order that their reliability and applicability will have greater practical significance. Barai (2004) analyzed 17 years rainfall data (1970 to 2003) of Solapur and found the values of constants K, a, b and d as 11.08, 0.1892, 1.01 and 1.1081 respectively. An effort has been made to modify these constants for Solapur region in the scarcity zone of Maharashtra by analyzing 37 years data from 1970 to year 2020 (except 1973, 1978, 1983-1988,1992,1993, 1997-2000).

Location and climate

The geographic location of the rain gauge station of Solapur, which was used for the study is latitude 17° 41'N and longitude 75° 57'E. The altitude of rain gauge station at Solapur is 483.63 m above mean sea level. The climate is usually hot, pan evaporation (PE) far exceeds the precipitation and climatically the area falls under scarcity zone. The annual average rainfall is 723.4 mm. The rainfall is scanty, erratic and ill distributed. The September rains are more assured with relatively high intensity, which are responsible for severe soil erosion.

Data acquisition (Automatic rain gauge charts)

The daily automatic rain gauge charts of Solapur for the period 1970 to 2020 (except 1973, 1978, 1983-1988, 1992-2000) (total 37 years) were obtained from the observatory established under National Agricultural Research Project (NARP), Solapur and maintained by AICRP on Agrometeorology, Solapur and analyzed.

Collection and preparation of data for analysis

The daily automatic rain gauge charts were analyzed in the form of annual maximum series of various durations viz. 5, 10, 15, 30 minutes, 1, 3, 6, 12 and 24 hours.

Plotting positions for development of frequency line

The plotting positions were obtained by using the 'computing method' suggested by Ogrosky and Mockus (1957). The values of antilog of mean, antilog of mean plus and antilog of mean minus are the plotting positions corresponding to 50 per cent, 15.9 per cent and 84.1 per cent of abscissa, respectively (Table 1).

Table 1: Plotting positions for development of frequency lines of rainfall intensities of selected durations

Duration, h	Rainfall intensity, mm/h		
	50% chance line	15.9% chance line	84.1% chance line
0.08	90.23	133.11	61.16
0.16	72.93	109.09	48.76
0.25	67.45	100.93	45.08
0.50	49.05	73.34	32.80
1.0	35.02	55.19	22.22
3.0	16.21	24.33	10.80
6.0	9.22	13.27	6.40
12.0	5.04	7.42	3.43
24.0	2.66	3.83	1.84

Development of frequency line

The rainfall intensities were plotted on lognormal probability paper, with rainfall intensities on log scale and per cent chance of occurrence on probability scale. A straight line passing through all the three points was extended so that it intersected with ordinate (Fig. 1). This line is called as frequency line of rainfall intensity. The frequency lines were drawn for nine durations and designated as $I_{0.08}$, $I_{0.16}$ and I_{24} for 0.08, 0.16 … and 24.0 h durations, respectively. The rainfall intensities for each duration against selected per cent chance (1%, 2%, 4%, 10%, 25% and 50%) were obtained. Return period in years was obtained with the help of following equation,

$$T = \frac{100}{PC} \text{ ----------- (2)}$$

where, T = return period, years and PC = per cent chance

The rainfall intensities for selected frequencies and return period for selected durations are given in Table 2.

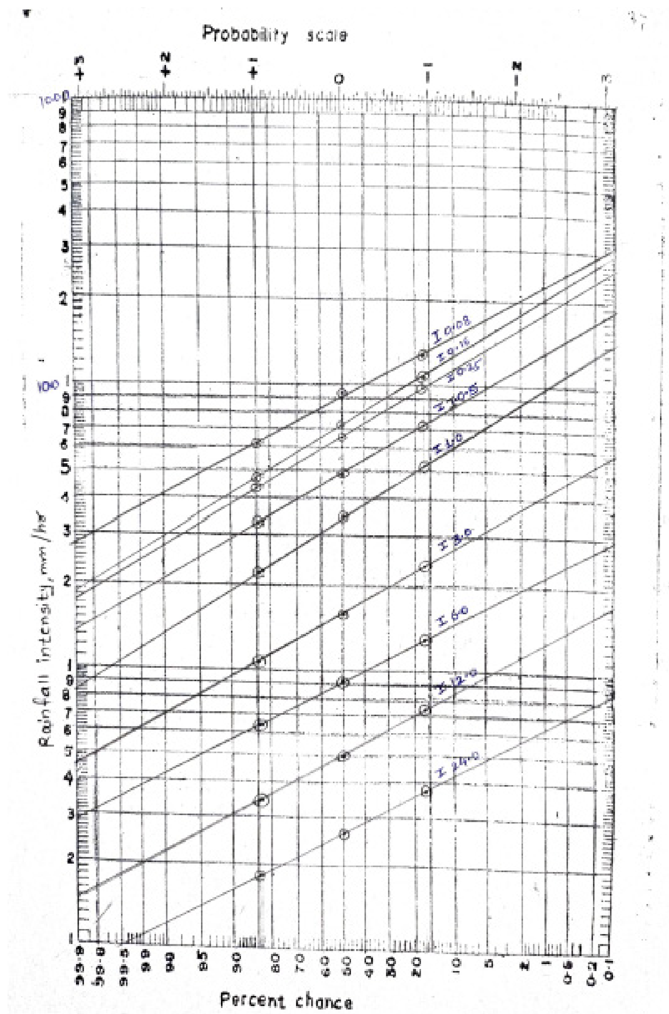

Fig. 1: Frequency distribution of rainfall intensities for various durations at Solapur
(log scale = rainfall intensity, mm/hr)
(probability scale = per cent chance of occurrence)

Table 2: Rainfall intensities for different return period and selected durations

Duration, h	Per cent frequency					
	1%	2%	4%	10%	25%	50%
	Return period, year					
	100	50	25	10	4	2
	Rainfall intensity, mm/h					
0.08	230.0	210.0	185.0	150.0	120.0	90.0
0.16	205.0	180.0	162.0	130.0	98.0	72.0
0.25	182.0	165.0	140.0	115.0	88.0	68.0
0.50	130.0	120.0	102.0	84.0	66.0	50.0
1.0	100.0	88.0	78.0	60.0	47.0	35.0
3.0	42.0	38.0	35.0	28.0	22.0	16.0
6.0	23.0	20.0	18.0	15.0	12.0	9.0
12.0	13.0	12.0	10.0	8.4	7.6	5.0
24.0	6.4	5.8	5.0	4.2	3.4	2.6

Testing for adequacy of length of record

The minimum acceptable years of record were determined by using the equation suggested by Mockus (1960). The test works in terms of numbers of years of record used, that is, in terms of sample size. This method is represented by following equation:

$$Y = (4.30 \; t \log_{10}R)^2 + 6 \quad \text{------------------} \quad (3)$$

where, Y = minimum acceptable years of record; t = Student's 't' at 10 per cent level of significance and R = Ratio of magnitude of the 100 year event to the 2 year event

The values of R and Y were calculated for all the nine durations and tabulated in Table 3. The values of 'Y' for all durations were obtained from the test of the length of record found less than 37 years (Table 3). The data analyzed for the present study are of 37 years, hence the length of record considered found adequate. In order to evaluate the coefficients K, a, b and d for frequency curves, the following steps are involved (Ram Babu *et al.* 1979).

Table 3: Computation of minimum acceptable years of record

Duration, h	Rainfall Intensity, mm/hr		R = (2)/(3)	$\log_{10}R$	$Y = (4.30 \; t \log_{10}R)^2 + 6$
	100 year event	2 year event			
(1)	(2)	(3)	(4)	(5)	(6)
0.08	230	90	2.56	0.41	11.26
0.16	205	72	2.85	0.45	12.54
0.25	182	68	2.68	0.43	11.79
0.5	130	50	2.60	0.41	11.46
1.0	100	35	2.86	0.46	12.59
3.0	42	16	2.63	0.42	11.57
6.0	23	9	2.56	0.41	11.26
12.0	13	5	2.60	0.41	11.46
24.0	6.4	2.6	2.46	0.39	10.85

(t_{10}=1.309 at 31 (n-6=37-6=31) d.f.)

Geometric mean slope

The values of rainfall intensities from table 2 for all durations were plotted on Y-axis and values of return period on X-axis on log-log paper (Fig. 2). All the points were connected by a thin dotted line giving more weightage to points from 10 year to 100 years return period. The dotted line was extended to cut the Y-axis against 1-year return period. The scale distance of all slope lines was measured from X-axis. The slope of the individual dotted lines for each duration was determined. The geometric mean slope for the entire set of lines was determined. The geometric mean slope of the lines represents the exponent 'a' in the equation and was found as 0.1934. The detailed procedure given in Table 4.

Table 4: Geometric mean slope of frequency lines or the value of exponent 'a' in the formula, $I=K\,T^a / (t+b)^d$ at Solapur

Frequency Line	Scale distance (cm) from x-axis		Difference (col.2-col.3)	length of Line AB	Slope = Col 4 / Col 5	Logarithmic value of col. 6
	B[1]	A[1]				
1	2	3	4	5	6	7
$I^{0.08}$	17.5	14.7	2.8	14.9	0.1879	-0.726
$I^{0.16}$	17.1	13.9	3.2	14.9	0.2148	-0.668
$I^{0.25}$	16.6	13.6	3.0	14.9	0.2013	-0.696
$I^{0.50}$	15.5	12.8	2.7	14.9	0.1812	-0.742
$I^{1.0}$	14.7	11.2	3.5	14.9	0.2349	-0.629
$I^{3.0}$	12.0	9.0	3.0	14.9	0.2013	-0.696
$I^{6.0}$	10.0	7.0	3.0	14.9	0.2013	-0.696
$I^{12.0}$	8.1	5.7	2.4	14.9	0.1611	-0.793
1	6.0	3.5	2.5	14.9	0.1678	-0.775
			Sum			-6.421
			Mean			-0.713
			Antilog (Mean)			0.1934
			Geometric mean slope			0.1934
			Hence the factor a			0.1934
			Factor T^a			$T^{0.1934}$

Rainfall intensity of one-year return period

A line representing the geometric mean slope was drawn at the base through origin as shown in Fig. 2. The solid lines parallel to this slope line were drawn by cutting the y-axis against 1-year return period. The rainfall intensities against 1-year return period for the corresponding durations are presented in Table 5. The old and new plotting positions are shown in Fig. 2.

Table 5 : One year rainfall intensity for selected durations at Solapur

Duration, h	Rainfall Intensity, mm/h
0.08	86.0
0.16	74.0
0.25	66.0
0.50	48.0
1.0	37.0
3.0	17.0
6.0	8.6
12.0	4.8
24.0	2.1

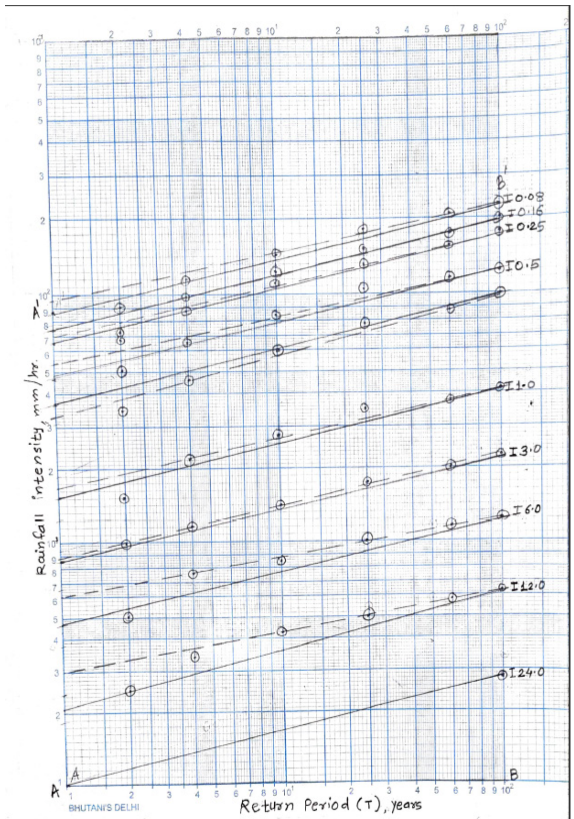

Fig. 2: Rainfall intensities for selected durations and return period at Solapur

Estimation of constant 'b'

The values of rainfall intensities of one-year return period on Y-axis and selected durations on X-axis were plotted on log-log paper (Fig. 3). The points so plotted do not fall in a straight line. To make the points aligned into a straight line, suitable constant 'b' is needed. After adding this constant in the values of durations, the points aligned into a straight line. The estimated value of ‘b’ for Solapur found as 0.40.

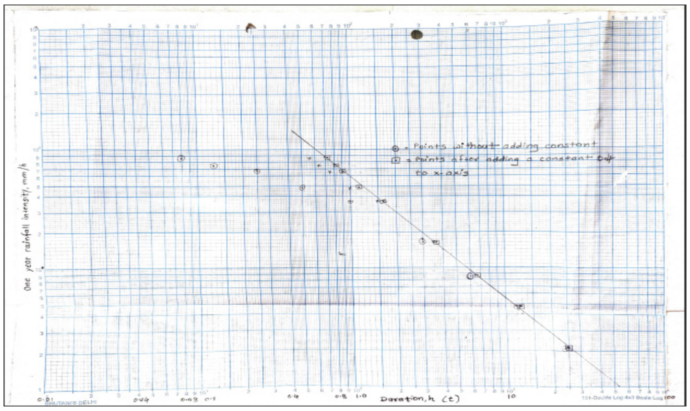

Fig. 3 : Fitting of constant ‘b’ in the equation at Solapur

Estimation of constants ‘K’ and ‘d’

The constants ‘K’ and ‘d’ were solved by least square method. In this method the values of one year (T=1 year) rainfall intensities for selected durations and the values of ‘K’ and ‘d’ were determined by solving the following equation.

$$I = \frac{K}{(t+1.0)^{d}} \quad \text{................................ (4)}$$

The equation in its logarithmic form can be written as, log I = log K- d log (t + 1.0), which is in a straight-line form. The constants ‘K’ and ‘d’ are then solved by least squares method by solving the following equations.

$$\log K = \frac{\sum \log I . \sum [\log\ (t+b)]^2 - \sum[\log I . \log (t+b)] \sum \log\ (t+b)}{n\sum[\log(t+b)]^2 - [\sum \log (t+b)]^2} \quad \text{---- (5)}$$

$$d = \frac{\sum \log I . \log\ (t+b)] - n \sum \log I . \log (t+b)}{n\sum[\log(t+b)]^2 - [\sum \log (t+b)]^2} \quad \text{----------------- (6)}$$

By solving the above equations, the values of K and d are K= 4.57, d = 0.9178. At this stage, the frequency factor, $T^{0.1934}$ as obtained, is included to give the rainfall intensity-duration-return period relationship

$$I = \frac{4.57\ T^{0.1934}}{(t+0.40)^{0.9187}} \quad \text{................................ (7)}$$

Results and Discussion

The constants K, a, b and d in the rainfall intensity-frequency-duration equation developed by Barai (2004) by analyzing 17 years daily automatic rain gauge charts for Solapur were 11.08, 0.1892, 1.01 and 1.2066 respectively. These constants were modified to 4.57, 0.1934, 0.40 and 0.9187, respectively by analyzing 37 years daily automatic rain gauge charts for Solapur. The equation for intensity of rainfall (cm/h) based on duration (h) and frequency (year) for Solapur station with modified constants becomes:

$$I = \frac{4.57\ T^{0.1934}}{(t+0.40)^{0.9187}} \quad \text{................................ (8)}$$

By using above equation, the intensity of rainfall for any duration, t up to 24 hours and any return period T up to 100 years can be determined.

Conclusion

Rainfall intensity-frequency-duration equations are required for design of soil and water conservation and runoff disposal structures, for planning flood control projects and also important from economic considerations. In order to have optimization in hydraulic design of any structure, the peak rate of runoff expected during the recurrence interval should be correct and the rainfall intensity-frequency-duration relationship for a particular location needs to be updated based on the available data. Through the present study, the location specific constants K, a, b and d for Solapur region in the scarcity zone of Western Maharashtra were modified to 4.57, 0.1934, 0.40 and 0.9187, respectively. The results of this study would be useful to different project implementing agencies in designing soil and water conservation structures in Solapur district.

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