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NOTE

A GENERAL DIMENSIONLESS RAINFALL DEPTH-DURATION-FREQUENCY RELATIONSHIP

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ABSTRACT

The frequencies of high-intensity rainfalls may be required for several engineering purposes. The analyzed and dependable rainfall intensities of durations up to 24 hrs with frequencies of up to 100 yr from 126 stations in Iran were used in this study. The results of this survey showed that (a) probability density function for coefficient of variation (CV) at each rain duration was approximately normal, (b) the ratios of rain depth with different frequencies to that of 10-yr frequency [P(T)/P(10)] was constant, averages of these constants are comparable with those in other countries, and P(T)/P(10) and rain duration are significantly related to each other at each frequency, (c) the ratio of rain depth with different durations to that of 1-hr duration [P(D)/P(60)] was constant, and in spite of good agreement between average of these empirical constants with those of other countries, it was shown

1. Instructor.

that a highly significant relationship exists between P(D)/P(60) and return period at each specified rain duration, (d) a dimensionless relationship was derived between P(D,T)/P(60,10) and two independent variables of return period and rainfall duration for climatological conditions of Iran .Therefore, intensity-duration-frequency (IDF) or depth-duration-frequency (DDF) relationship can be obtained at any point in Iran knowing the value 10-yr hourly rainfall.

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یک رابطه عمومی بدون بعد مقدا ر-مدت-فراوانی بارندگی

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چکیده

تناوب های باران های شدید برای برخی از هدف های مهندسی مورد نیازاست. از آمار تجزیه و تحلیل شده شدت های باران درتداوم های تا ۲۴ ساعت و تناوب های تا ۱۰۰ سال در ایران در این بررسی استفاده شده است . نتایج این بررسی نشان داد: (الف) توزیع چگالی احتمال ضریب تغییرات درهرمدت تداوم تقریبا نرمال است، (ب) درمدت دوام ثابت بین مقدار باران بادوره های بازگشت مختلف به دوره بازگشت پایه ۱۰ سال [P(T)/P(10)] نسبت های ثابتی بدست آمد، میانگین این نسبت های ثابت با نتایج گزا رش شده در سایر نقاط دنیا هماهنگی دارد و رابطه

معنی داری بین P(T)/P(10) ومدت دوام باران درهر دوره بازگشت ثابت وجود دارد، (ج) در دوره بازگشت ثابت، بین مقدار باران درمدت های دوام مختلف به مقدار باران ساعتی [P(D)/P(60)] نسبتهای ثابتی حاصل گردید، و با وجود یک هماهنگی قابل قبول بین میانگین این نسبت ها با نسبت های مشابه در سایر نقاط دنیا، نشان داده شد که در هر مدت دوام ثابت یک رابطه معنی داری بین P(D)/P(60) ودوره بازگشت وجوددارد، (د) یک رابطه بدون بعد بین نسبت P(D,T)/P(60,10) و متغیرهای مستقل دوره بازگشت و مدت تداوم برای شرایط آب و هوایی ایران بدست آمد . بنابراین روابط شدت-مدت-تناوب (IDF) و یامقدار-مدت -تناوب (DDF) بارندگی در هر نقطه ایران با داشتن مقدار عددی باران ساعتی ۱۰ ساله قابل محاسبه خواهد بود.

INTRODUCTION

The frequencies of high-intensity rainfalls are required for several engineering purposes, one of the most important being the estimation of extreme floods for inadequately gauged streams. In general, the rainfall associated with the extreme floods of large streams has relatively long duration while the rainfall associated with the floods of the smaller streams has shorter duration. As stream sizes decrease, their chances of being adequately gauged also decrease, and so it may be argued that short - duration rainfalls of less than 2 to 3 hr are of special importance in flood prediction for small streams.

Unfortunately, short-duration rainfall data are deficient in many parts of the world because their proper collection requires continuous-recording of precipitation gauges, which have not been readily available until recent years In many cases, the available data are now sufficient to provide reasonable estimates of high-intensity rainfalls with return periods of up to 10 yr.

However, for engineering design purposes, it is generally necessary to estimate values with return period of at least 50 yr. Depth-duration-frequency (DDF) is required especially for areas of insufficient short-duration rainfall data.

Tomlinson (16) analyzed 86 stations in New Zealand and concluded that for the durations of 10 minutes to 1 hr CV does not depart significantly from 0.3448, and for durations of 2 hrs to 72 hrs it does not depart significantly from 0.3047. He also concluded that CV does not depend on the geographic location of raingauge station. In contrast on Tomlinson (16), Hershfield (8) reported that the CV of many hydrometeorological quantities, including rainfall, shows a well defined geographical pattern. Analysis of rainfall data for 200 raingauge stations in the USA showed that on the average the rainfall CV for durations of 5 minutes to 1 hr was 0.30, and for durations of 2 hrs to 3 days was 0.375 (9).

Bell (2) argues that, from physical viewpoint, the parameters of short-duration rainfall would be related only indirectly to parameters of long-duration rainfall because different storm mechanisms are associated with the two sets of values. Empirical relationships, which are more directly dependent on physical laws and which should consequently have greater generality, will require separate analytical treatments of rainfall from different sources. Because short-term high intensity rainfall is generally of local convective origin, this requirement is partly satisfied if separate treatment is given to rainfall with durations of less than 2 hr.

Bell (2) has analyzed 40-yr of hourly rainfall from 126 stations within the USA and derived simple ratios between T-yr and 10-yr rainfall depth return periods. He further claimed that these ratios are valid for other rainfall durations and will be applicable all over the world. These ratios have also been recorded for other countries such as USA (14), South Africa (14), New Zealand (16), Saudi Arabia (10) and Iran (4). Although these depth ratios seems more or less constant for any rainfall duration, none of the researchers reported on rainfall duration depended ratios. Instead a simple average was reported for a range of rainfall durations under consideration.

Hathaway [6] , Reich [14] and Bell (2) found a simple ratio between rainfall depth at any duration (up to 2 hr) to hourly rainfall at every return period for the contiguous of the USA and recommended that these ratios be valid throughout the world. Similar constants were reported for other regions such as USSR (2), Czechoslovakia (2), USA (1,7), Australia (1,13), South Africa (14), Saudi Arabia (10), New Zealand (16) and Iran (4,15). The probable dependence of these ratios to return period and at any fixed rainfall duration has not been studied by any of these researchers. A simple arithmatic average has been used instead .

Bell [2] has recommended the following simple equation for rainfall depth at specific duration and return period, P(D,T), based on constant ratios from the USA data:

$$P(D,T)=[0.21Ln\ (T) + 0.52]\ [0.54\ D^{0.25}-0.5]\ P(60,10) \qquad [1]$$

Similar relationships based on constant ratios from Iran data (4) are:

$$P(D,T) = [a_1 + a_2\ Ln\ (T-a_3)]\ [b_1+ b_2\ \ t \wedge b_3]P(60,10) \qquad [2]$$

where all constants have been reported elsewhere (4) . These equations have been derived based on separate terms. These terms (depth- return period ratios and depth-duration ratios, respectively) are assumed independent of time duration and return period, respectively. Otherwise, their validity is questionable.

MATERIALS AND METHODS

In the analysis that follows, the main aim was to derive a dimensionless DDF relationship to estimate up to 50 yr return period for Iran and compare the results with those of other countries.

A. Vaziri (18) reported rainfall depth at specific time duration (6 min to 24 hr) and return periods (2 to 100 yr) from Gumbel distribution for 126 raingauge stations in Iran. These data were saved for further analysis.

B. Simple linear regression of an independent variable (x) and a dependent one (y) should read as:

$$y = a + b\,x \qquad [3]$$

in which a and b are intercept and slope of regression line, respectively. These values may be computed by means of a least square procedure. A t-test was used to examine the hypothesis that the slope (b) was not significantly different from zero, i.e. $H_0 : b=0$ (5). Rejection of the null hypothesis implies that y is dependent on x.

C. Coefficients of variation of rainfall series at a specific duration. As the original rainfall series are not available , the statistical specefications of each series should be determined indirectly. Chow (3) has defined the following relationship:

$$x_T = x_M + S\,K_T = x_M\,[1 + (CV)\,K_T] \qquad [4]$$

in which x_T is the amount of hydrologic variable at T yr return period, K_T is frequency factor and x_M, S and CV are the average, standard deviation and coefficient of variation of the series, respectively. K_T value for Gumbel distribution is a function of return period and sample size. Since 6 values of x_T are known for return periods of 2, 5, 10, 25, 50 and 100 yr (18) , and only two unknown values of x_M and S (or x_M and CV) are present, their determination must be made via normal equations (12).

RESULTS AND DISCUSSION

1. Coefficients of Variation of Rainfall Series

Coefficient of variation for every time period D and for each raingauge station was calculated. Variation in each rain duration series and for all stations are not small. Probability density function (PDF) corresponding to each time duration was derived . The results showed that the CV for all rain durations have nearly normal distribution (skewness ~ 0 and kurtosis ~ 3). Although at each rain duration CV varies, its variation are normally distributed around its expected value (the mean). Variation of CV at any rain duration to another one is not great. For the durations of 10 min to 1 hr, CV does not depart significantly from 0.4364, and for durations of 2 hr to 24 hr it does not depart significantly from 0.3652. These figures are higher than those of New Zealand (14). The possible causes may be explained by: 1) New Zealand is a small country completely surrounded by South Pacific ocean with highly uniform storm mechanisms, but Iran is a wide country with highly variable sources of storm mechanisms, 2) Iran has lower length of records at each rain duration as compared to New Zealand, and 3) measurement errors for Iran are not small (17,18). Unequal CVs at a specified duration for Iran and the USA may be due to different storm mechanisms for such wide countries, in contrast to small country of New Zealand. Measurment errors for Iran is a cause for higher rainfall CV at lower duration as compared to corresponding values for USA.

2) Depth-Frequency Ratios, P(T)/P(10)

Ratios of T-yr to 10-yr rainfall depths at different durations were computed (Table 1).

a) Constant ratios. It is believed that D-hr, T-yr to D-hr, 10-yr rainfall depths are constant (2). Therefore, ratios in Table 1 were averaged in different time periods of less than 2 hr, greater than 2 hr, and less than 24 hr (Table 2). The coefficients of variation for all groups are small but, since

Table 1. P(T)/P(10) ratios for Iran at different rainfall durations and return periods.

Rainfall duration min (hr)	Return period (yr)				
	2	5	25	50	100
6	0.514	0.807	1.240	1.411	1.596
12	0.528	0.814	1.248	1.420	1.595
15	0.520	0.808	1.246	1.428	1.606
30	0.526	0.814	1.240	1.419	1.603
45	0.532	0.811	1.236	1.415	1.594
60	0.536	0.814	1.232	1.404	1.579
(2)	0.558	0.825	1.226	1.394	1.560
(3)	0.568	0.827	1.220	1.383	1.548
(4)	0.574	0.830	1.217	1.374	1.535
(5)	0.576	0.831	1.214	1.374	1.534
(6)	0.579	0.830	1.210	1.371	1.528
(8)	0.583	0.836	1.210	1.364	1.522
(10)	0.592	0.838	1.202	1.358	1.511
(12)	0.588	0.834	1.203	1.361	1.514
(14)	0.582	0.832	1.214	1.367	1.524
(16)	0.572	0.830	1.187	1.374	1.532
(18)	0.578	0.833	1.212	1.372	1.528
(24)	0.611	0.846	1.196	1.343	1.468

different mechanisms are associated with rainfall of low and high durations (2), these groups can not be combined. A comparison was made between the up to 2 hr results from this survey with those of previous research for Iran (4) , USA and Australia (2) , and New Zealand (16) (Table 3). The results show that the differences between Iran ratios and those of other countries

Table 2. Statistical parameters for P(T)/P(10) ratios of Iran at different rainfall duration groups.

Rainfall duration groups (hr)	Statis. param.	Return period (yr)					
		2	5	25	50	100	Mean
0.1- 2	Mean	0.5306	0.8132	1.2383	1.4128	1.5903	
	C V	0.027	0.007	0.006	0.008	0.010	0.011
2.1-24	Mean	0.5819	0.8332	1.2078	1.3672	1.5238	
	C V	0.020	0.006	0.008	0.008	0.011	0.011
0.1-24	Mean	0.5621	0.8254	1.2197	1.3850	1.5497	
	C V	0.051	0.014	0.014	0.018	0.024	0.024

have decreased relative to previous research (4). The earlier research was conducted on limited number of stations with shorter length of records.

b) Variable ratios. Dependency of T-yr to 10-yr rainfall depth ratios to rainfall duration is illustrated in Fig. 1. A linear regression was established between these ratios (as y) and rainfall durations (as x) on three different duration groups. Highly significant trends were noted (Table 4). As a result,

Table 3. Comparisons between P(T) /P(10) of Iran for rain durations of up to 2 hr with other researches for hourely rainfall.

Reference	Return period (yr)				
	2	5	25	50	100
Present survey	0.5307	0.8132	1.2383	1.4128	1.5903
Iran, 1990 (4)	0.525	0.805	1.244	1.434	1.631
USA, 1969(2)	0.630	0.850	1.170	1.310	1.460
Australia, 1969(1)	0.650	0.850	1.180	1.330	1.500
New Zealand, 1980(16)	0.614	0.846	1.194	1.338	1.481

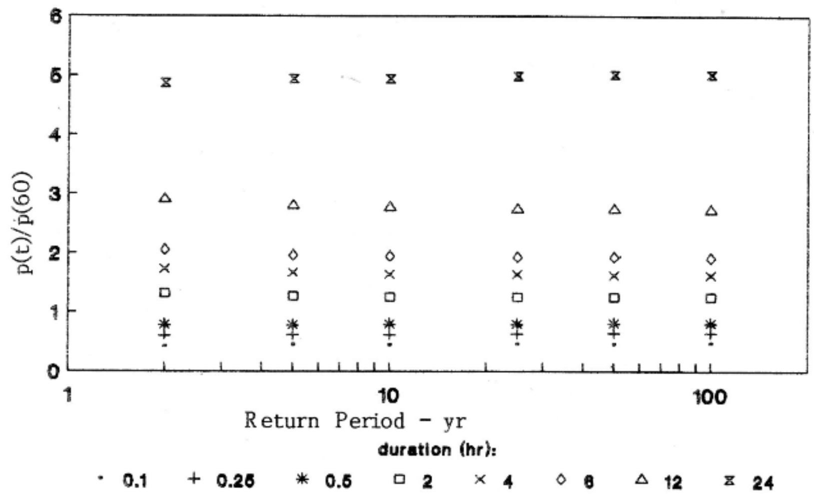

Fig. 1. Dependency of P(T)/P(10) to rain duration.

Table 4. Testing the hypothesis of b=0 for regression line between P(T)/P(10) versus rainfall duration.

	Rain duration groups (hr)					
	D≤2		2≤D<24		D≤24	
Return period (hr)	Significant level (df=5)§	t†	Significant level (df=9)§	t†	Significant level (df=16)§	t†
2	¶	8.01	0.02	2.60	¶	5.38
5	¶	4.58	0.02	2.86	¶	5.58
25	¶	-4.63	0.02	-2.52	¶	-5.74
50	0.01	-3.50	0.02	-2.69	¶	-5.54
100	¶	-4.98	0.01	-3.06	¶	-5.84

† Student's t-test

§ df=degrees of freedom

¶ Less than 0.01

computation of average between these ratios is not valid in either rainfall duration groups.

3. Depth-Duration Ratios,P(D)/P(60)

Ratios of rainfall depth at different durations to hrly rainfall depth were computed from a range of return periods. The results are listed in Table 5.

a) Constant ratios. A comparison was made between average of Iran empirical ratios (Table 5) with those of other countries (Table 6). The coefficients of variation for these ratios are less than those of previous research for Iran (4), but they are higher than for other countries. Differences between the constant ratios and those of previous research (4) are explained by:

(1). Changes of statistical properties as length of records and number of stations increased (11).

(2). The previous research was based on Vaziri (17) in which best distribution was made for each station. But only the Gumbel was used for all stations by Vaziri (18) in the new series of data. Different frequency distibutions would change the rainfall depth at specific return period. Table 6 shows that as rainfall duration decreases, computed ratios deviate more from universal ratios. This may be attributed to greater measurement errors at low durations.

b. Variable ratios. Fig. 2 shows the dependency of P(D)/P(60) ratio to log (return period). A curvilinear (and not a linear) relationship between P(D)/P(60) ratio and return period, however, would be expected. To quantify this dependency, a regression of P(D)/P(60) versus log (return period) was conducted. Correlation coefficients were higher than 0.84 for all cases , except two (Table 5). The last two columns of Table 5 shows the results of testing the null hypothesis of b=0 for regression line. It can be concluded that all lines have significant slope (Table 5). Therefore, averaging between

Table 5. P(D)/P(60) ratios at different rain durations and frequencies.

Rainfall duration min (hr)	Return period (yr) 2	5	10	25	50	100	Mean	R†	t§	Significant level
6	0.44	0.44	0.44	0.45	0.45	0.46	0.45	0.91	4.51	0.01
12	0.55	0.56	0.57	0.58	0.58	0.58	0.57	0.94	5.66	¶
15	0.60	0.62	0.62	0.63	0.64	0.64	0.62	0.96	7.10	¶
30	0.77	0.78	0.79	0.79	0.80	0.80	0.79	0.96	7.09	¶
45	0.89	0.90	0.90	0.90	0.91	0.91	0.90	0.92	4.86	¶
(2)	1.30	1.26	1.25	1.25	1.25	1.24	1.26	-0.84	-3.09	0.02
(3)	1.53	1.47	1.45	1.44	1.44	1.43	1.46	-0.88	-3.80	0.01
(4)	1.72	1.66	1.63	1.63	1.62	1.61	1.64	-0.90	-4.08	0.01
(5)	1.89	1.81	1.79	1.78	1.77	1.77	1.80	-0.87	-3.52	0.02
(6)	2.04	1.96	1.94	1.92	1.92	1.91	1.95	-0.89	-3.92	0.01
(8)	2.33	2.26	2.23	2.22	2.22	2.20	2.24	-0.90	-4.23	0.01
(10)	2.62	2.54	2.50	2.48	2.48	2.47	2.52	-0.90	-4.20	0.01
(12)	2.90	2.80	2.76	2.74	2.73	2.72	2.78	-0.91	-4.38	0.01
(14)	3.36	3.30	3.29	3.26	3.28	3.28	3.30	-0.79	-2.55	0.05
(18)	4.03	4.05	4.04	4.04	4.06	4.05	4.04	0.67	1.82	0.1
(24)	4.87	4.94	4.95	4.98	5.01	5.01	4.96	0.96	6.95	0.01

† Correlation coefficient.

§ Student t-test.

¶ Less than 0.01.

Table 6. Comparisons between P(D)/P(60) of Iran and those of different countries.

	Rain duration (min)									
	15			30			120			
Country	a†	b†	c†	a	b	c	a	b	c	d§
Iran (present survey)	0.62	0.200	-	0.79	0.120	-	1.26	0.130	-	-
Iran (4)	0.69	0.300	11.29	0.85	0.210	7.59	1.21	0.140	3.97	7.62
USA ††	0.57	0.070	8.06	0.79	0.051	0.00	1.25	0.064	0.79	2.95
Austalia §§	0.57	0.070	8.06	0.78	0.038	1.26	1.24	0.048	1.59	3.64
USSR§§	0.55	0.109	11.29	0.79	0.101	0.00	1.30	0.077	3.17	4.82
Saudi Arabia§§	0.56	0.071	9.68	0.78	0.090	1.26	1.20	0.142	4.76	5.23

† a- Average b- Coefficient of variation c- Percent of changes.

§ d- Average of percent of changes.

†† Reported by Bell (2).

§§- Reported by Jones *et al*. (10).

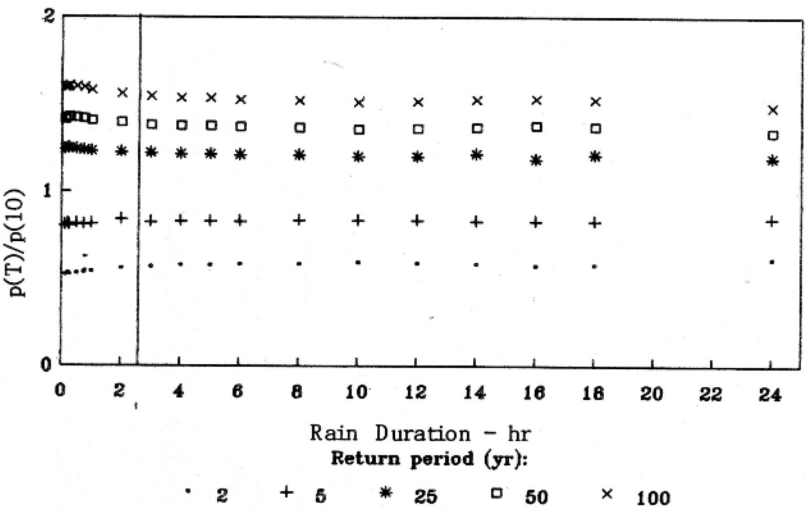

Fig. 2. Dependency of P(D)/P(60) to return period.

these ratios at different return period and at a specific rainfall duration is not valid.

CONCLUSION

A dimensionless DDF relationship has been presented by some researchers (2,4). This relationship, after some manipulation, would read as:

$$P(D,T)/P(60,10) = f(T) \cdot g(D) \quad [5]$$

in which f(T) and g(D) are depth-frequency and depth-duration ratios, respectively. An imbedded hypothesis in equation [5] is that f (T) and g (D) do not depend on rainfall duration and return period, respectively.

It was shown in previous sections that depth-duration and depth - frequency ratios are indeed a function of frequency and duration, respectively. Therefore, instead of averaging these ratios at different return periods and durations, respectively; the whole ratios are needed for deriving a proper general and global relationship. All ratios from Tables 1 and 5 were combined and a multiple nonlinear regression was imposed on these ratios (as dependent variable) with respect to two independent variables of frequency and duration as:

$$P(D,T)/P(60,10) = a D^{b} T^{c} \qquad [6]$$

Constant parameters of this equation were evaluated relative to three different rainfall duration groups (Table 7). Statistical F- tests revealed that all regressions were significant at probability level of less than 0.01.

Estimated versus computed dimensionless ratios from three different rainfall duration groups are illustrated in Figs. 3 to 5. The scatter of points around the line of 1:1 for time durations of less and greater than 2 hr (Figs. 3, 4) are satisfactory, but Fig. 5 presents unacceptable scatter points. This result is attributed to different mechanisms for short and long rainfall durations (2).

Table 7. Consatnt parameters of equation [6] obtained with statistical parameters for climatic conditions of Iran.

	Rainfall duration groups -hr		
parameter	$D \le 2$	$2 \le D < 24$	$D \le 24$
a	0.4813	0.3900	0.5429
b	0.3500	0.5864	0.4168
c	0.2793	0.2296	0.2489
R†	0.97	0.97	0.97
Number of data	42	66	108
F†	744	1168	1891
F§	647	1371	3039
F¶	806	930	707

† F-value for testing the existence of the whole model.

§ F-value for testing the existence of time duration parameter.

¶ F-value for testing the existence of return period parameter.

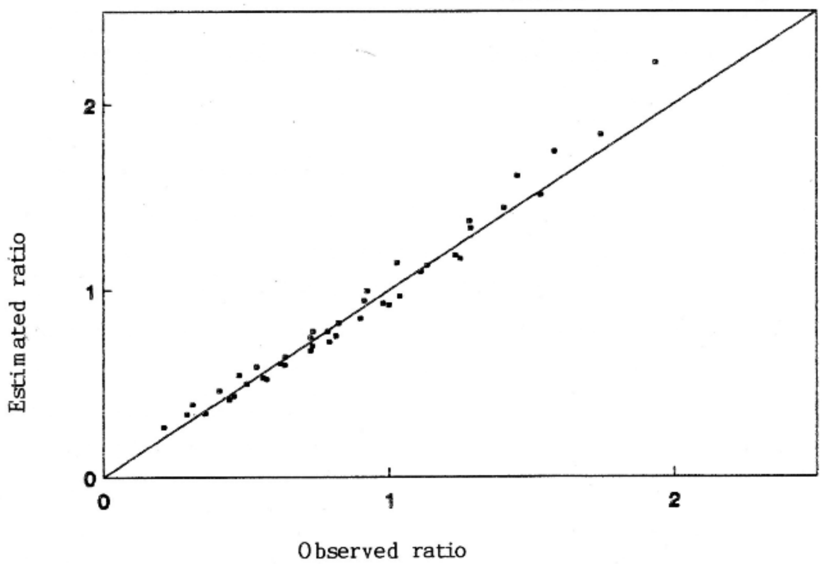

Fig. 3. Reliability test for estimating dimensionless ratio of P(D,T)/P(60, 10) for short rainfall duration of D<=2 hr.

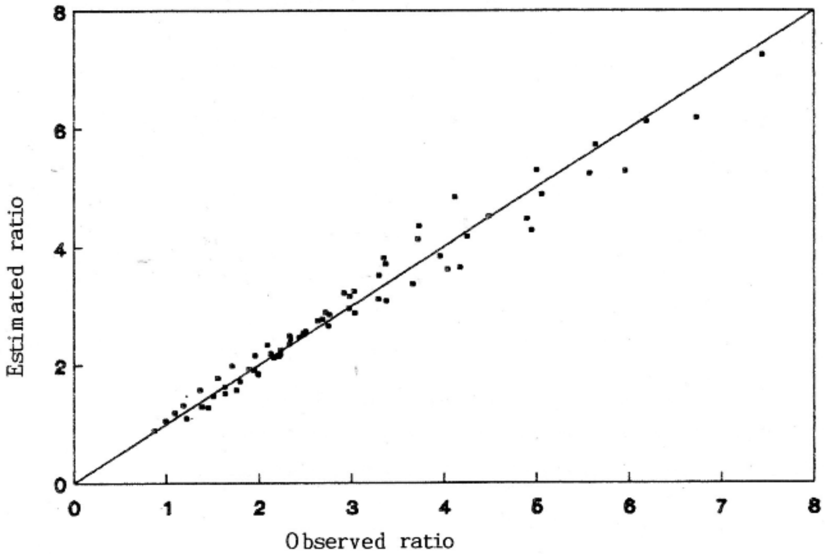

Fig. 4. Reliability test for estimating dimensionless ratio of P (D,T)/P (60,10) for long rainfall duration of D>2 hr.

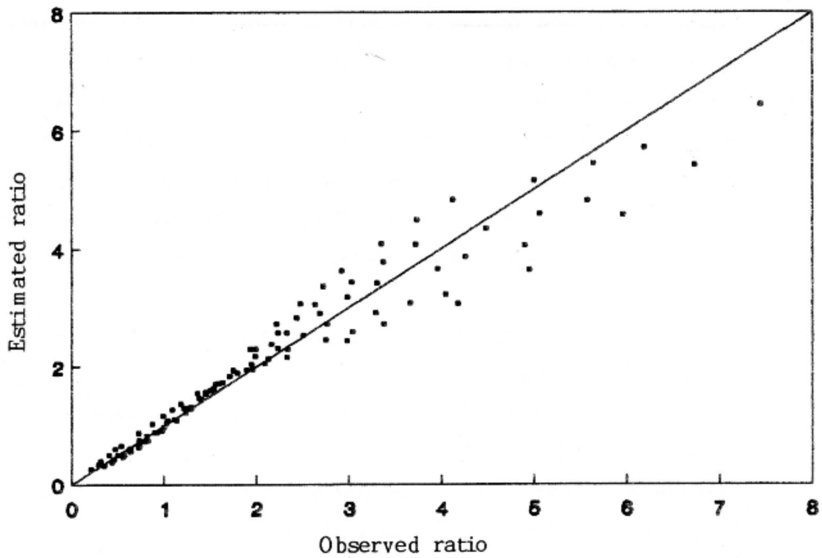

Fig. 5. Reliability test for estimating dimensionless ratio of P (D,T)/P (60,10) for general rain duration of D<24 hr.

Equation (6) is the general dimensionless DDF relationship for different climatic conditions of Iran which is based on variable depth-duration and depth-frequency ratios. A DDF or intensity-duration-frequency (IDF) could be computed for different climatic conditions of Iran knowing the value of P(60,10).

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