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ORIGINAL RESEARCH ARTICLE

A new method for estimating flood peak discharge and extreme rainfall: Case study of Firat basin

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ABSTRACT

The commonly-used design parameter for hydraulic structures is the annual maximum instantaneous streamflow recorded by conventional gauging stations. Increased hydroclimatic variability in recent years and the resultant flooding raise questions concerning the flood risk estimations from the short flow records in Turkey. The method described in this study has been selected according to the likely estimates for the peak flow values at different return periods for the gauged basins. Hence, estimation of the peak flow values for regions with poor or rich discharge datasets could be implemented. In theory, this developed method may be used to estimate the peak flow values at any point on a river network, and not only at basin outlets. In this research, a case study has been conducted on the Firat basin, on which the largest dams in Turkey have been built, by employing a novel approach for developing a new method that calculates the peak flood flows and extreme rainfall. The results demonstrate that the approach is sound and can be employed in the prediction of peak rainfall and flow parameters in river basins.

Keywords: Extreme Rainfalls; Goodness-of-fit Test; New Estimation Method; Peak Discharge

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1. Introduction

From time immemorial, investigations have been made into the probability of occurrence of river floods. Based on that knowledge, river-engineering works have been designed and flood protection measures have been taken. Yet, the data available are insufficient to draw firm conclusions on the future effectiveness of these interventions. The more reliable the discharge data from the past, the smaller the risk of failure of the design conditions for flood protection measures. The estimation of the probability of occurrence of peak floods is open to improvement. To that end, other estimation methods will be used, the data series will be extended and different methods of data processing will be used.

Peak discharge information is required to determine the dam design and appropriate size water conveyance systems such as natural channels, diversion canals, bridge openings, etc. The accurate prediction of stream flows is essential to the planning of our water resource systems. This paper addresses the practical state of the art of techniques to predict flood peaks and their associated frequency of occurence. Statistical relationships will be investigated as means of predicting the peak discharges. The statistical graphical or analytical methods of flood flow estimation seem to be well established in the literature, Gumbel[1], Chow[2], Benson[3], Yevjevich[4], Haan[5]. Generally, a graphical method by plotting annual peak flow on a log-normal probability paper using the Weibull plotting position formula, or an analytical method using the log Pearson type distributions is recommended.

Rossi *et al*.[6] describe the theoretical considerations to obtain a parent flood distribution that closely represents the real flood experience, the existence of the annual flood series of Italian river basins.

Keim and Faiers[7] explored heavy rainfall distributions by season and the associated differences in seasonal quantile estimates for selected recurrence intervals in Louisiana, as a result of the findings of other investigators.

Adamowski[8] considers the currently used parametric analysis of the " annual maximum" flood series. They reveal unimodal and multi-modal probability density functions for floods in two Canadian Provinces Ontario and Quebec.

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Nonparametric frequency analysis has been introduced as an alternative method. This method also revealed unimodal and multimodal "annual maximum" and "peak over threshold" flood probability density function shapes in both Provinces.

Luxemburg *et al*.[9] analyzed the statistical properties of flood runoff of North Asian rivers under conditions of climate change.

Bakker and Luxemburg[10] consider the problem of heterogeneous distributions of floods, as research in the area of frequency analysis has been rather limited on this item, although several investigators confess that the assumption of homogeneity of flood distributions may not be valid. Therefore, the estimates of probabilities of exceedance are often very unreliable. The heterogeneity of the series of annual maximum runoffs can be explained by the fact that different extreme floods are caused by different mechanisms (ice melt, rains, cyclones, etc.).

Mantje *et al*.[11] try to identify the different homogeneous subsets in a heterogeneous distribution (although the latter is often regarded as homogeneous in flood frequency analysis).

2. Goodness-of-fit test

It is the work of determining the magnitudes of hydrological variables corresponding to given frequencies or recurrence intervals. Procedures involved in frequency analysis include: (1) collecting a random sample of the interested hydrological variable; (2) finding the best-fit distribution for the sample by a goodness-of-fit (GOF) test or other appropriate methods; and (3) determining the magnitude of the hydrological variable corresponding to a given probability of exceedance using the best-fit distribution. Two GOF tests, namely the chi-square test and the Kolmogorov–Smirnov test, are often used for the selection of probability distributions for hydrological variables[12]. Another method of goodness-of-fit test is the method based on ordinary moment-ratio diagrams[13].

3. The scope of the study

This study was developed, to yield a satisfactory first estimate of the discharge and corresponding water level at a certain point along the river starting from rainfall forecasts. An improved estimation method for the probability of occurrence of flood peak discharges. Improved accuracy of the probability of exceedance estimates of flood peak as a result of this determination. Identification of the flood properties at rivers that determine further downstream. A method to determine these downstream water levels, their probability of exceedance, and accuracy. Operational flood discharge prediction, especially early forecasting, enhances operational decision-making. As the flood event proceeds, the availability of more elaborate data and the use of more sophisticated flood forecasting models may enable more accurate predictions.

In this study, a new methodology, different from the distribution analyses, was developed to estimate the annual maximum instantaneous stream flows and the precipitation depths measured by weather stations in 100, 200, 500, 1,000, and 10,000 years, and a correlation was obtained. Then the values determined by the assistance of this correlation have been compared with the GOF test results.

4. Methodology

If the annual maximum precipitation values measured for river basins are arranged in ascending order as $Q_1 < Q_2 < Q_3 \ldots < Q_N$, a Q-T variation curve would be obtained as seen in **Figure 1**. For a time period of T years, the T years-recurrence peak-flow Q-T is defined as a value of discharge, which statistically occurs every T year.

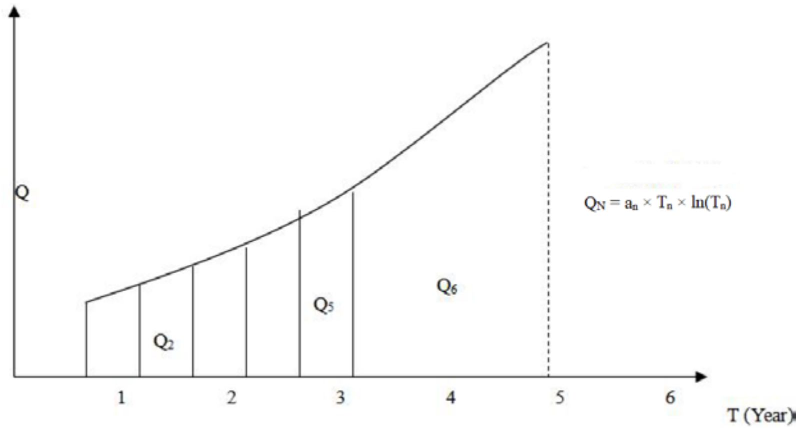

Figure 1. Q-T variation curve.

For any Q_i in **Figure 1**, the equation below could be asserted:

$$Q_i = a_i \times T_i \times \ln(T_i) \quad (1)$$

The variables employed in the equation above stand for the following:

Q_i = value of the measured streamflow, precipitation depth or similar variable at the i^{th} year;

a_i = the coefficient of i^{th} year;

T_i = i^{th} year.

Consequently, $Q_2 = a_2 \times T_2 \times \ln(T_2)$ or in short, $Q_2 = a_2 \times 2\ln(2)$.

Similarly, equations like $Q_{10} = a_{10} \times T_{10} \times \ln(T_{10})$ could be stated briefly as $Q_{10} = a_{10} \times 10\ln(10)$.

In these equations, the ai values for the years of measurement period are obtained by the following relation:

$$a_i = Q_i/(T_i \times \ln(T_i)) \quad (2)$$

For instance:

$a_2 = Q_2/(T_2 \times \ln(T_2))$ or $a_2 = Q_2/(2 \times \ln(2))$

$a_5 = Q_5/(T_5 \times \ln(T_5))$ or $a_5 = Q_5/(5 \times \ln(5))$

$a_n = Q_n/(T_n \times \ln(T_n))$ or $a_n = Q_n/(N \times \ln(N))$.

The a_i values are as shown in **Figure 2**.

The values of a_{50}, a_{100}, a_{200}, a_{500}, $a_{1,000}$, and $a_{1,0000}$ are required for determining the values such as Q_{50}, Q_{100}, Q_{200}, Q_{500}, $Q_{1,000}$, and $Q_{10,000}$ that are beyond the scope of the N-year observation period for which measurements have been taken, could be determined in turn by the assistance of the chart in **Figure 2** as well as the main values determined from the a_i calculations. The equation below holds between the values of a_i, and a_{i+1}:

$$a_{(i+1)} = a_i\,(1 - 1/(i+1))$$

Simplifying, $(i + 1) \times a_{(i+1)} = a_i - 1$ is obtained.

For instance, concerning the relationship between the 16^{th} and 17^{th} years; $17 \times a_{17} = 16 \times a_{16}$, hence,

$N \times a_{min} = 100 \times a_{100} = 1000 \times a_{1,000} = 10,000 \times a_{10,000}$. Therefore, the equation below could be derived since the product of $N \times a_{min}$ must be constant:

$$Q_T = a_{min} \times N \times \ln(T) \quad (3)$$

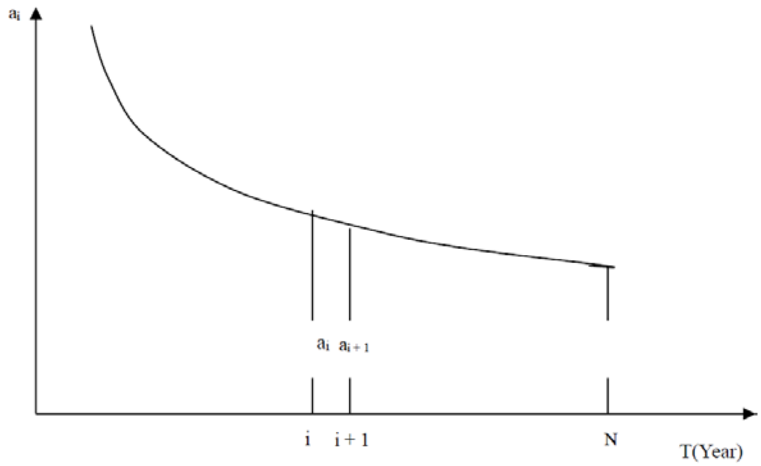

Figure 2. Evolution of ai values during the period of measurement.

The T-year streamflow as well as any time-dependent variable could be determined by equation 3. With N denoting the measurement year, the following streamflow values have been obtained;

$Q_{50} = a_{min} \times N \times \ln(50)$ yields 50-year streamflow

$Q_{100} = a_{min} \times N \times \ln(100)$ yields 100-year streamflow

$Q_{200} = a_{min} \times N \times \ln(200)$ yields 200-year streamflow

$Q_{500} = a_{min} \times N \times \ln(500)$ yields 500-year streamflow

$Q_{1,000} = a_{min} \times N \times \ln(1,000)$ yields 1,000-year streamflow

$Q_{10,000} = a_{min} \times N \times \ln(10,000)$ yields 10,000-year streamflow

In the equations given above:

a_{min} = The minimum value obtained from the graph of measured values in **Figure 2** or from equation 2 using the a_i calculations. If no observation in excess of the N-year value has been made within the year of measurement, the value of a_{min} is reached at year N as seen in **Figure 2**. However, this situation is encountered rarely. Generally, amin is reached before the Nth year since some measurements greater than N-year values are observed within a particular observation year. In this case, if we denote the year where amin has been reached as N_{amin}, the product of ($a_{min} \times N_{amin}$) stays constant. Therefore, the following equations hold: $(a_{min} \times N_{amin}) = 100 \times a_{100} = 1,000 \times a_{1,000} = 10,000 \times a_{10,000}$. Consequently, equation 3 could be stated in the following form:

$$Q_T = a_{min} \times N_{amin} \times \ln(T) \quad (4)$$

5. Study case

The study area is situated adjacent to Keban Township, approximately 40 km to the west of Elazig province in eastern Turkey (**Figure 3**). The drainage system is characterized primarily by ephemeral streams of limited widths. The Euphrates is the main river in the study area, flowing from north to south. The elevation of the region ranges from about 1,000 m to over 2,500 m. The vegetation comprises scarce scrub grass and stunted trees. The area has a semi-arid climate characterized by dry summers and cold winters. According to the meteorological data for the period 1923 to 2010 (Turkish State Meteorological Service, Elazig), the average annual rainfall is 399 mm, with snowfall accounting for more than half of this precipitation. The lowest mean precipitation has been recorded in the months of July and August (6 and 4 mm, respectively), whereas the highest mean precipitation has been recorded in the months of April and May (58 and 60 mm, respectively). The mean annual temperature is 14.8 °C, with July and August being the warmest months, with average temperatures around 28 °C, whereas January and February are the coldest months, with temperatures around 3 °C.

Keban dam, which is one of the largest dams in Turkey and the world, was built on the Euphrates River in the Upper Euphrates region. Keban Dam Reservoir spans an area of 67,500 km^2. The construction of the dam had been launched in 1964 and the dam had become operational by 1974. The maximum streamflow values of Euphrates River for a period of N = 43 years between 1932 and 1974 (prior to the completion of Keban Dam) as measured by AGI owned by EIE[14] located in Keban have been displayed in **Figure 4** and the streamflow analysis conducted by the new method is given in **Table 1**. Since the construction of Keban Dam has been fully completed in 1975, no streamflow measurements have been carried out in 1975. The obtained values have been given in **Table 2** in addition to the GOF test results of the measured stream flows for 43 years.

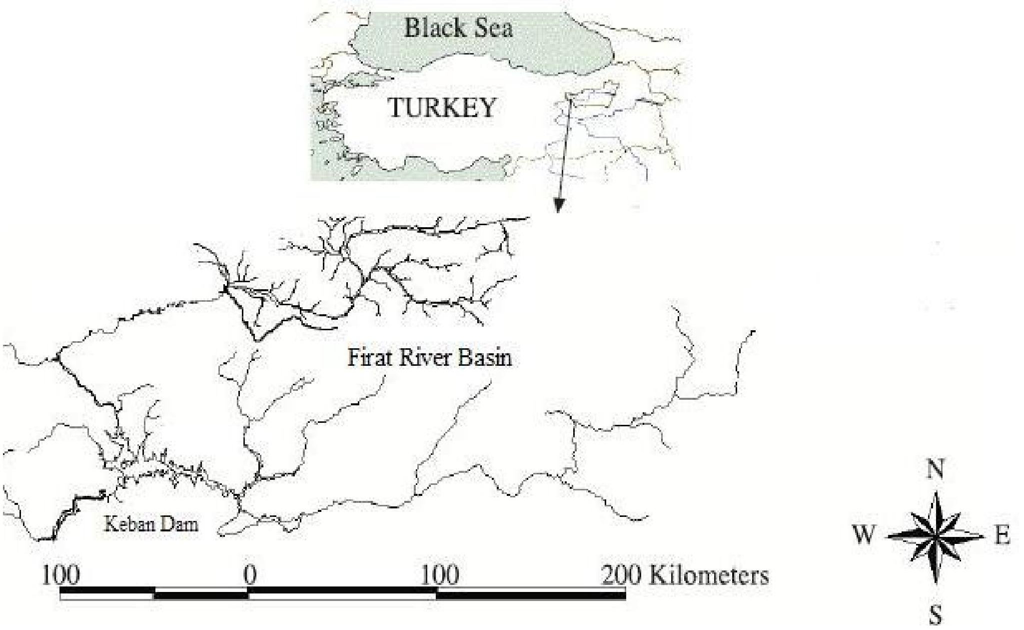

Figure 3. Location of the study area.

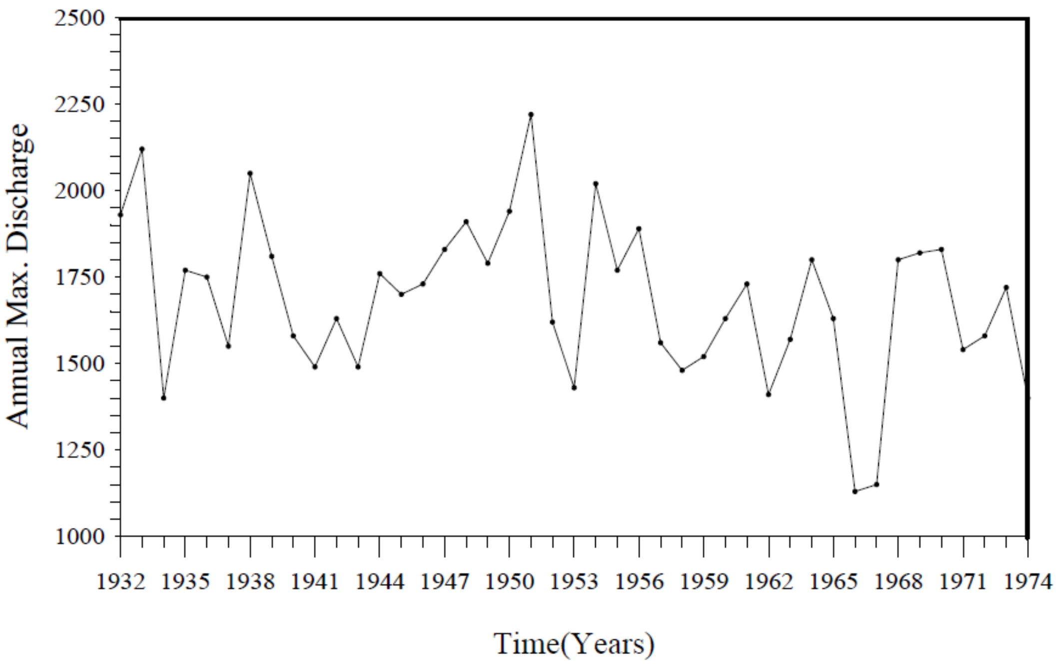

Figure 4. Change of annual maximum discharge for each years.

Table 1. Streamflow analysis conducted by the new method

Year	Max. discharge	Sequential data	a_i	T(Time) N = 43	$Q_T = a_{min} \times N_{amin} \times \ln(T)$
1951	2,220	1,630	27.20	20	1,653,716
1952	1,620	1,700	26.58	21	1,680,649
1953	1,430	1,720	25.29	22	1,706,33
1954	2,020	1,730	23.98	23	1,730,868
1955	1,770	1,730	22.68	24	1,754,362
1956	1,890	1,750	21.74	25	1,776,897
1957	1,560	1,760	20.77	26	1,798,547
1958	1,480	1,770	19.89	27	1,819,381
1959	1,520	1,770	18.97	28	1,839,457
1960	1,630	1,790	18.33	29	1,858,828
1961	1,730	1,800	17.64	30	1,877,543
1962	1,410	1,800	16.90	31	1,895,643
1963	1,570	1,810	16.32	32	1,913,169
1964	1,800	1,820	15.77	33	1,930,156
1965	1,630	1,830	15.26	34	1,946,636
1966	1,130	1,830	14.70	35	1,962,637
1967	1,150	1,890	14.65	36	1,978,188
1968	1,800	1,910	14.29	37	1,993,313
1969	1,820	1,930	13.96	38	2,008,035
1970	1,830	1,940	13.57	39	2,022,374
1971	1,540	2,020	13.68	40	2,036,35
1972	1,580	2,050	13.46	41	2,049,981
1973	1,720	2,120	13.50	42	2,063,283
1974	1,400	2,220	13.72	43	2,076,273
Q50	-	-	-	50	2,159,531
Q100	-	-	-	100	2,542,164
Q200	-	-	-	200	2,924,798
Q500	-	-	-	500	3,430,613
Q1,000	-	-	-	1,000	3,813,247
Q10,000	-	-	-	10,000	5,084,329
Q20,000	-	-	-	20,000	5,466,963

Table 2. Other methods and present study results for QT

Method name	Q_{50}	Q_{100}	Q_{200}	Q_{500}	$Q_{1,000}$	$Q_{10,000}$
Present study	2,159	2,542	2,924	3,430	3,813	5,084
F.Life (3P)	2,152	2,214	2,272	2,341	2,390	2,535
L.Loj (3P)	2,187	2,277	2,367	2,485	2,574	2,869
Burr	2,152	2,226	2,298	2,394	2,468	2,719
John.SU	2,151	2,218	2,281	2,360	2,419	2,605
Chi-squre	2,155	2,218	2,276	2,346	2,395	2,541
Error	2,171	2,243	2,310	2,393	2,452	2,631
Lojistik	2,180	2,269	2,357	2,474	2,562	2,855
Gum max.	2,282	2,408	2,533	2,698	2,822	3,226
Log.Loj	2,310	2,453	2,604	2,816	2,987	3,635
Gam. (3P)	2,172	2,242	2,306	2,385	2,441	2,610
Ge.Gam.	2,150	2,271	2,342	2,430	2,493	2,686
Freched	2,536	2,770	3,025	3,397	3,709	4,964
Rayleigh	3,762	4,081	4,378	4,741	4,999	5,772

The frequency analysis of the maximum streamflows belonging to Euphrates River: N = 43, Q_{avg} = 1,685.6 m^3/s, σ = 230, C_s = -0.126.

GOF (Goodness-of-fit) test

a) Kolmogorov - Smirnov

1. Fatiqul Life (3P); 2. Log Logistic (3P); 3. Burr; 4. Johnson SU; 5. Chi Squared (2P).

b) Anderson-Darling

1. Burr; 2. Johnson SU; 3. Log Logistic (3P); 4.Error; 5. Log Logistic.

c) Chi-Squared

1. Gumbel max; 2. Log Logistic; 3. Gamma (3P); 4. Gen. Gamma; 5. Log. Logistic (3P).

In **Table 3**, the analysis of the total rainfall for the 79-year period between 1928 and 2006 has been given and a correlation has been empirically developed to predict the annual rainfall depth h_t according to the results of this methodology. This correlation is given in equation 5.

Table 3. Analysis of the total rainfall

Year	Daily max. rainfall	Sequential data	a_i	T(Time), N = 43	$h_T = a_{min} \times N_{amin} \times \ln(T)$
1980	22.1	34.2	0.162528	53	37.15717
1981	18.2	34.3	0.159235	54	37.3321
1982	25.1	34.3	0.155624	55	37.50383
1983	22.8	34.8	0.154379	56	37.67246
1984	20	34.9	0.15144	57	37.83811
1985	38.2	35	0.148616	58	38.00087
1986	29.7	35.7	0.148395	59	38.16086
1987	46.1	36	0.146544	60	38.31815
1988	18	37.2	0.148347	61	38.47285
1989	21.7	37.3	0.14577	62	38.62503
1990	29.7	38.1	0.145967	63	38.77477
1991	30.3	38.2	0.143518	64	38.92216
1992	35.7	38.5	0.141891	65	39.06726
1993	17.6	39.8	0.143933	66	39.21014
1994	61.6	40.3	0.143053	67	39.35088
1995	34.8	41.9	0.14603	68	39.48953
1996	33.5	42.8	0.146498	69	39.62616
1997	28	46.1	0.155013	70	39.76082
1998	20.1	46.2	0.152651	71	39.89357
1999	32	47.9	0.15556	72	40.02446
2000	33.5	48	0.153255	73	40.15355
2001	20.9	48.3	0.151648	74	40.28088
2002	27.2	49.9	0.154102	75	40.40651
2003	48	50.1	0.152217	76	40.53047
2004	33.1	58.2	0.174005	77	40.65281
2005	39.8	61.6	0.181271	78	40.77357
2006	27.7	80.4	0.232918	79	40.89279
h_{50}	-	-	-	50	36.61184
h_{100}	-	-	-	100	43.09887
h_{200}	-	-	-	200	49.58589
h_{500}	-	-	-	500	58.16127
$h_{1,000}$	-	-	-	1000	64.6483
$h_{10,000}$	-	-	-	10,000	86.19773
$h_{2,0000}$	-	-	-	20,000	92.68476

The frequency analysis of maximum daily precipitation for Elazığ Province is as follows: N = 79, h_{avg} = 31.56 mm, σ = 11.45, C_s = 1.348.

Total annual precipitation for Elazığ Province could be given by the following equation:

$$h_t = 127.79 \times T^{-0.011} \times \ln(T) \quad (5)$$

GOF (Goodness-of-fit) test

a) Kolmogorov - Smirnov

1. Beta; 2. Gamma (3P); 3. Fatiq. Life (3P); 4. Gen. Gamma (4P); 5. Gen. Gamma.

b) Anderson-Darling

1. Burr (4P); 2. Burr; 3. Dagum; 4. Log Logistic; 5. P5 (3P).

c) Chi-Squared

1. Cauchy; 2. Weibul; 3. Gen. Gamma; 4. Logistic; 5. Gamma.

Table 4. Other methods and present study results for h_t

Method name	h_{50}	h_{100}	h_{200}	h_{500}	$h_{1,000}$	$h_{10,000}$	$h_{20,000}$
Present study	36.6	43.1	49.5	58.1	64.6	86.2	92.6
Beta	57	62	66.7	72	76	89	93.7
Gamma (3P)	59	64	69	75	79	99	98.5
F.Life (3P)	59.6	65	70	77	82	99	104
Ge.Gam. (4P)	60	65	70.5	77	82.5	99.4	104
Gen.Gamma	58	62	66	72	76	88	92
Burr (4P)	61	68	76	89	99.5	144.5	161
Burr	62	70	79	93	105	158	178
Dagum	62	72	82	97	111	172	196
Log.Loj	63	72	83	99	114	179	206
P5 (3P)	60	66	72	81	87	110	118
Cauchy	Not suitable						
Rayleigh	58	62	66	71	74	84	86.6
Gamma	59	64	68	75	79	92	96.5
Weibull (3P)	58	62	66.5	71	75	85	88
Kumaraswamy	58	62	66	71	74	84.8	87.6
Lojistik	56	60	65	71	75	89	94
Nakagami	61	65	70	75	78	89.5	92.5
Erlang	56	60	65	71	75	88	92

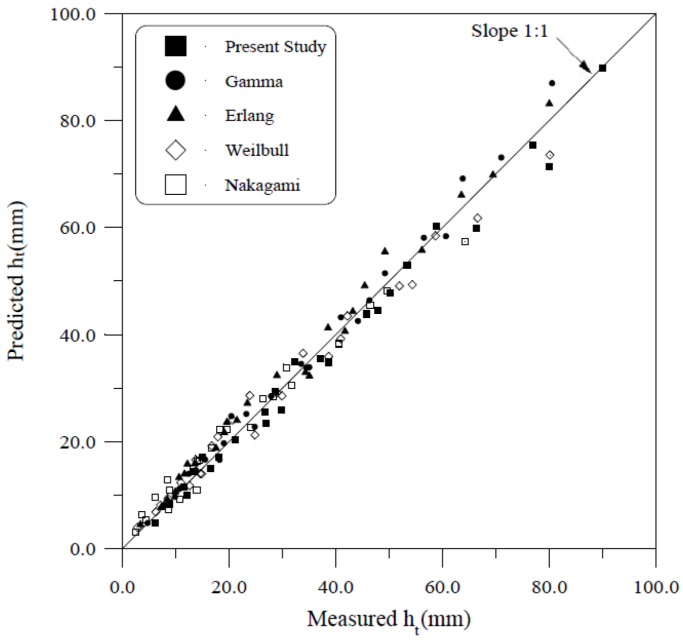

Figure 5. The calculated and measured values for precipitation.

The values obtained from this method have been compared with the calculated values using equation 5.

6. Conclusion

The goal of this study is to improve the understanding of peak flood discharge and extreme rainfall processes in river catchments. Nevertheless, continued hydrologic, hydraulic, and paleohydrologic research on catchments areas is needed that would contribute to a broad range of hydrologic research projects and investigations. An improved understanding of basic hydrologic and hydraulic processes will improve the available methods for the assessment of peak floods and extreme rainfall phenomena. These related studies depend on accurate data and hydrologic methods. The improved hydraulic methods can be incorporated into numerical simulation models of surface-water systems and could be useful to improve the analyses of hydrologic processes. The results of this method are also applicable to other rivers. Moreover, empirical correlations predicting the annual rainfall depths in the gauged catchments have been developed.

In time-related analyses, since the product $a_i.N_i$ remains approximately constant, the results of the distribution analyses obtained from this method and the GOF tests could be compared, and thereby the most convenient results could be determined. Additionally, these results are more practical and reliable than the analysis methods such as MOM and Moment-L. If an observation is conducted for a long enough time and the curves produce reasonable values, the QT and the h_t values of the catchments could be determined with the assistance of a curve. For example, the total rainfall for Elazig could be calculated by the following formula:

$$h_t = 127.79T^{-0.011} \times \ln(T)$$

An extreme rainfall that leads to a flash flood can be approached by a variety of methods. Among others, such methodologies as meteorological analysis, hydrological modeling, hydraulic modeling and analysis, and post-event campaigns for data retrieving (flood marks, peak flow timing through intervals) can be used to provide additional information for reliable annual peak discharge estimations.

Conflict of interest

The author declared no conflict of interest.

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