Turk J Agric For
26 (2002) 187-194

Determining Suitable Probability Distribution Models For Flow and Precipitation Series of the Seyhan River Basin

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Received: 18.10.2000

Abstract: The frequency analysis of the largest, or the smallest, of a sequence of hydrologic events has long been an essential part of the design of hydraulic structures. Therefore, the question of better fit among countless probability models used in frequency analysis is always a fresh one. The purpose of this study was to make a statistical comparison of currently popular probability models. Therefore, Gumbel, log-Logistic, Pearson-3, log-Pearson-3 and log-Normal-3 distributions were applied to the series of annual instantaneous flood peaks and annual peak daily precipitation for 13 flow gauging and 55 precipitation gauging stations in the Seyhan basin, respectively. The parameters of the distributions were estimated by the methods of moments (MOM) and probability weighted moments (PWM). A detailed chi-squared and Kolmogorov-Smirnov (K-S) goodness-of-fit tests were also applied. According to the evaluations of chi-squared tests, Gumbel (MOM) for both flow and precipitation stations in the Seyhan river basin were found to be the best models. As a result of the K-S test, log-Normal-3 (MOM) and log-Pearson-3 (MOM) models were determined to be the best for flow and precipitation stations, respectively.

Key Words: Frequency Analysis, Goodness-of-Fit Tests, Flow and Precipitation Series

Seyhan Havzası Akım ve Yağış Verileri İçin Uygun Olasılık Dağılım Modellerinin Belirlenmesi

Özet: Hidrolojik olaylar dizininin en büyük veya en küçüğünün frekans analizi uzun zamandır hidrolik yapıların projelendirilmesinin önemli bir kısmını oluşturmaktadır. Bu yüzden, frekans analizinde kullanılan sayısız olasılık modelleri arasında en iyi uyum sorusu daima güncelliğini korumaktadır. Bu çalışmanın amacı, son zamanlarda çok kullanılan olasılık modellerinin istatistiksel kıyaslamasını yapmaktır. Bu amaçla, Gumbel, log-Logistic, Pearson-3, log-Pearson-3 ve log-Normal-3 dağılımları, Seyhan havzasında 13 akım gözlem istasyonunun yıllık anlık maksimum akım serilerine ve 55 yağış gözlem istasyonunun 24 saatlik yıllık maksimum yağış serilerine uygulanmıştır. Dağılım parametreleri momentler (MOM) ve olasılık ağırlıklı momentler (PWM) yöntemleri ile tahmin edilmiştir. Detaylı khi-kare ve Kolmogorov-Smirnov (K-S) uygunluk testleri de kullanılmıştır. Khi-kare uygunluk testi değerlendirmesine göre, Seyhan nehir havzası akım ve yağış gözlem istasyonları için Gumbel (MOM) modeli en iyi model olarak bulunmuştur. K-S testi sonucunda, akımlar için log-Normal-3 (MOM), yağışlar için log-Pearson-3 (MOM) olasılık modellerinin en iyi modeller olduğu belirlenmiştir.

Anahtar Sözcükler: Frekans Analizi, Uygunluk Testleri, Akım ve Yağış Serileri

Introduction

Hydrological and meteorological data such as flow rate and rainfall are used in the engineering design of hydraulic structures. Although meteorological satellites and early flood warning systems exist, the dates of occurrence and magnitudes of extreme events cannot be forecasted yet. Hence, frequency analysis is an established method for determining critical design discharge for small to moderate sized hydraulic structures (Haktanır, 1992).

The earliest attempts to determine extreme events sought to establish a model for frequency analysis. At present there is no single universally accepted model. Rather a whole group of models, such as the Gumbel, the log-Logistic, the log-Normal, the Pearson-3 and the log-Pearson-3 distributions, have been suggested for predicting the magnitude of such extreme events. Therefore, the question of better fit among these countless models is always a fresh one, and many studies with this theme have been reported (e.g. Bilgin, 1981; Haktanır, 1982; Özcan, 1990; Aydurak, 1994; Karaş, 1996; Atar, 1996; Özdemir and Kırmızıgül, 1997; Kişi et al., 2001).

The objective of this study was to apply most of the currently popular probability models to the series of annual instantaneous flood peaks and annual peak daily precipitation of the Seyhan river basin, and to attempt to reach a conclusion about the best- or better-fitting models.

Materials

The annual instantaneous flood peaks and the annual peak daily precipitation series longer than 15 and 14 years were picked for 13 flow gauging (FS) and 55 precipitation gauging (PS) stations of the Seyhan river basin, respectively. Precipitation and flow data were taken from the publications of the DSİ (1990) and DSİ (1994), respectively. Details of all 13 FSs and 55 PSs are given in Tables 1 and 2, respectively.

Methods

Statistical Screening Tests

Hydrological and meteorological data showing no random behaviour need to be analysed by some statistical screening tests so that they can be used in frequency analyses, regional flood frequency analyses etc. Many statistical screening tests such as turning point, trend, stationary of means and variances, autocorrelation and homogeneity tests have been proposed and used in the literature (Siegel, 1956; Kottegoda, 1980; Lye and Lin, 1994; Topaloğlu, 1999; Topaloğlu et al., 1999).

Frequency Analysis

Many references are also available about the probability distributions (PD) and their parameter estimation methods (Greenwood et al., 1979; Phien, 1987; Ahmad et al., 1988; Özcan, 1990; Haktanır, 1991; Haktanır, 1992).

In the study, it was decided to use PDs thought to fit better the peak flow and precipitation series of Turkey. These PDs are Gumbel (GB), log-Logistic (LL), Pearson-3 (P3), log-Pearson-3 (LP3) and log-Normal-3 (LN3). The parameters of the distributions were estimated by the methods of moments and probability weighted moments except the LN3. Detailed information has been given in the cited references.

Because many PDs and parameter estimation methods have been proposed, the question of best fit has always been of concern (Haktanır and Horlacher, 1993). The fit is usually determined by means of a criterion depending on the differences between the observed and theoretical density functions or distributions (Kottegoda, 1980). In the present study, the most popular [the chi-squared and Kolmogorov-Smirnov (K-S) goodness-of-fit tests (GOF)] were chosen. Nevertheless, the chi-squared statistic was explained in more detail because of the detailed features of the software package developed by Haktanır (1991).

Table 1. Some Characteristics of the Selected Flow Gauging Stations (DSİ, 1994)

Gauge Number	Name of River	Name of Gauge Site	Drainage Area (km^2)	Elevation (m)	Years of Record	Number of Peaks Used
1801	Göksu River	Himmetli	2683.2	665	1936-91	56
1802	Zamantı R.	Faraşa	7615.2	858	1936-54	19
1804	Zamantı R.	Söğütlü	4800.8	1345	1941-55	15
1805	Göksu R.	Gökdere	4492.8	350	1940-91	52
1806	Zamantı R.	Ergenuşağı	8920.8	347	1961-79	19
1812	Zamantı R.	Pınarbaşı	2708.0	1425	1955-73	19
1817*	Çakıt R.	Arapali	1609.6	150	1964-85	17+5
1818*	Seyhan R.	Üçtepe	14484.0	180	1966-91	25+1
1820	Körkün R.	Hacılı Köprüsü	1460.7	170	1970-91	22
1821	Eğlence R.	Sarımehmetli	664.0	75	1971-86	16
1822	Zamantı R.	Fıraktin Köpr.	6528.0	1270	1970-91	22
1823	Zamantı R.	Emeğil	2847.2	1451	1974-90	17
18-12*	Körkün R.	Kamışlı	1107.2	1109	1971-90	19+1

* Discontinued site

Table 2. Properties of Precipitation Gauging Stations Within and Nearby the Seyhan River Basin (DSİ, 1990)

Name of Gauge Site	Years of Record	Number of Peaks Used	Elevation (m)	Name of Gauge Site	Years of Record	Number of Peaks Used	Elevation (m)
Adana	1929-95	67	20	Karataş	1963-88	26	5
Afşin	1954-83	30	1180	Karsantı	1960-75	16	860
Akkışla	1964-87	24	1500	Kaynar	1964-82	19	1550
Andırın	1953-83	31	1250	Konaklı	1966-81	16	1265
Bakırdağ	1960-81	22	1300	Kozan	1951-95	45	150
Bor	1964-83	20	1100	Mansurlu	1964-85	22	1050
Bünyan	1957-87	31	1300	Niğde	1935-95	61	1208
Ceyhan	1942-95	54	30	Örenşehir	1964-87	24	1600
Çamardı	1969-82	14	1500	Pazarören	1964-87	24	1500
Çamlıyayla	1967-86	20	628	Pınarbaşı	1950-95	46	1470
Çardak	1967-84	18	1175	Pozantı	1960-86	27	778
Çatalan	1964-86	23	65	Saimbeyli	1957-87	31	1100
Çiftehan	1967-82	16	1000	Sarıoğlan	1964-87	24	1150
Çokak	1969-87	19	1350	Sarız	1951-87	37	1500
Develi	1951-95	45	1180	Şarkışla	1939-87	49	1180
Doğankent	1968-87	20	20	Talas	1970-86	17	1100
Elbaşı	1965-87	23	1425	Tanır	1968-88	21	1200
Feke	1942-93	52	620	Tarsus	1941-62	22	33
Gemerek	1957-95	39	1173	Toklar	1965-83	19	1400
Gezi	1965-87	23	1250	Tomarza	1963-88	26	1400
Göksun	1954-91	38	1344	Tufanbeyli	1957-73	17	1350
Gülek	1957-78	22	950	Tuzla	1966-87	22	10
Hacılar	1964-84	21	1500	Ulukışla	1937-95	59	1451
Hacıali çift.	1963-79	17	12	Yahyalı	1969-87	19	1260
İmamoğlu	1963-86	24	100	Yazyurdu	1965-87	23	1750
Kadirli	1956-87	32	100	Yeşilhisar	1957-87	31	1150
Kamışlı	1963-87	25	1225	Yumurtalık	1965-95	31	3
Karaisalı	1957-95	39	400	-	-	-	-

Chi-Squared Test: This test is based on the density function, which is divided into slices through class intervals. The number of slice divisions for histograms to be compared was determined using the Sturges equation and the Williams equation (Kottegoda, 1980). Both equations give the slice number as a function of the sample length. The Williams equation usually yields a value greater by two than that of Sturges. Hence, the value of the chi-squared GOF statistic depends on the number of subdivisions. The program developed by Haktanır (1991) can compute the chi-squared GOF statistic three times for consecutively increasing different sub-interval divisions in order to account for this disadvantage to some extent. Although originally the chi-squared GOF test was executed on the basis of equal-length sub-intervals, equal-probability-area sub-intervals have also been used. Kottegoda (1980) states that the latter version is more meaningful. The program also does the chi-squared GOF test for both equal-length sub-intervals and equal-probability-area sub-intervals, and repeats the computations for three sequentially increasing interval divisions, such as 5, 6 and 7, for each case (Haktanır, 1991).

In the chi-squared GOF test, the main idea is to ascertain whether a theoretical distribution can be fitted to a distribution observed through a set of measurements. Therefore, the smaller the value of the chi-squared statistic, the better the expected fit of the model to the sample at hand, which is computed by

$$\text{chi-squared} = \sum_{j=1}^{k} (NO_j - NE_j)^2 / NE_j \qquad (1)$$

where NO_j and NE_j symbolize the number of elements in the *ith* sub-interval of the observed and expected histograms, which are sliced into k subdivisions.

This statistic computed by equation (1) approximately obeys a chi-squared distribution with a degree of freedom (DOF) defined as

$$DOF = k\text{-}1\text{-}mp \qquad (2)$$

where k is the number of slice divisions and mp is the number of parameters present in the model. Classically, the 90% confidence interval is computed with this DOF, and the adopted model is said to be acceptable if the chi-squared value calculated with equation (1) is within this interval. In the program, 80% and 60% one-sided confidence intervals can also be computed (Haktanır, 1991). Obviously, the larger this confidence interval, the better the chance of any model being accepted.

In the first place, any two-parameter distribution will have an advantage on a three-parameter distribution due to small DOF when the chi-squared GOF test is applied in its classical manner. However, model parameters in the K-S GOF test do not exist. It could be alleged that, regardless of the number of model parameters, the numerical chi-squared value is a direct indication of the closeness of the observed and expected histograms. Furthermore, this number can directly be considered a measure of GOF (Haktanır, 1991). In the program, to satisfy these two thoughts, a ranking can be made on the basis of the values of the average of the three chi-squared's by equation (1) and of the average of the three limit probability values of acceptance in the classical way.

Kolmogorov-Smirnov Test: The Kolmogorov-Smirnov statistic (Δ_{max}) is the greatest absolute deviation of the cumulative probabilities of the observed elements using the adopted model (Tülücü, 1996) and using the Gringorten plotting position formula being the rank number in an ascending order series. This statistic is calculated using equation (3).

$$\Delta_{max} = | F(x=x_i) - [(m_i - 0.44) / (n + 0.12)] | \qquad (3)$$

where $F(x=x_i)$ is the probability of non-exceedance, m_i is the rank number in the ascending order series and n is the record length of the sample.

If Δ_{max} is less than the Kolmogorov-Smirnov table value (Δ_{table}) taken according to the determined level of significance, the probability distribution adopted is accepted.

Results and Discussion

Results of Statistical Screening Tests

Initially, all the available streamflow and precipitation records from 13 FSs and 55 PSs, respectively, in the study area, were considered and screened to determine their suitability for use in the analysis (Topaloğlu, 1999). Statistical screening for turning point, trend, stationary of variance and mean, autocorrelation and homogeneity of flood flow and precipitation data at each gauged site confirmed that 12 FSs' flow data and 43 PSs' precipitation data conform to random and homogeneous samples.

Nevertheless, FS 1801 (among the selected 13 FSs) having the longest record in the basin was not found to be suitable according to the stationary of variance and autocorrelation tests. Therefore, the regression analysis was performed to relate the data from FS 1801 to the data from FS 1805, being on the same river and having the second longest record. The correlation coefficient was found to be 70% and just two sets of flow data were arranged. Later, all the 6 statistical screening tests were applied to 1801 again and it was found to be suitable for the next steps of the analysis. Consequently, in order to complete the discontinued sites, moving averages were used. Thus, one value was added to the FSs of 1818 and 18-12, and five to the FSs of 1817. Statistical screening tests were applied to these three FSs after using moving averages and they were all found to be suitable.

Among the precipitation stations in Table 2, although PSs of Adana, Gemerek, Gezi, Konaklı, Sarıoğlan, Tanır and Tarsus were found to be unsuitable they were used in the frequency analysis so that they were all determined out of the drainage areas of 13 FSs using Thiessen polygons (Topaloğlu, 1999). In addition, PSs of İmamoğlu and Kozan found to be unsuitable were used as they were, since they have very little effect on the drainage areas of some FSs. However, data from Elbaşı, Feke and Kamışlı were adjusted according to the outlier analysis (Chow, 1988) and then they were examined by the statistical screening tests and found to be suitable for the analysis as in the case of 1801.

Results of Frequency Analysis

Frequency analysis was performed for the annual instantaneous flood peaks of 13 FSs and annual peak daily precipitation series of 55 PSs using a software package developed by Haktanır (1991). In the analyses, the Gringorten plotting position formula was used for examining the PDs, GB, LL, P3, LP3 and LN3, whose parameters were estimated by the moments and probability weighted moments. The 9 PDs were evaluated by detailed chi-squared and K-S GOF and the results are given in Tables 3, 4 and 5. In the tables, the number of being first, second and third, and the number of being first three are given twice, which are the three limit probability (AP) and the average of the three chi-squared's (AK), for each PD separately for FSs and PSs.

Conclusions drawn from the tables may be listed as follows:

a) Values of the chi-squared statistic were ranked in ascending order for equal-length-sliced histograms of both FSs and PSs. GB (MOM) PD was found to be the best model, scoring 12 and 8 times the number of firsts among 13 FSs according to both AP and AK, respectively. GB (PWM) PD was the second best scoring model. However, the number of first threes of both PDs was found to be equal to each other for AP while it was not for AK.

Gumbel PD was also found to be the best among 24 FSs in the East Black Sea by Bilgin (1981). Haktanır (1992) found GB, LN2 and LN3 to be the best PDs for 45 FSs (n 30). Karaş (1996) determined that GB PD among 6 PDs was the best according to chi-squared and K-S tests.

The same PDs were found to be the best model for PSs. GB (MOM) scored 46 and 32 times the number of firsts among 55 PSs according to the AP and AK, respectively. Both models scored the same number of first threes for AP as AP for FSs while they scored close to each other for AK like AK for FSs.

Akar (1993) found that GB PD showed a good fit to annual peak daily precipitation series in Tokat. Atar (1996) determined that GB, LN2 and generalized extreme value (GEV) fit better to one and peak daily precipitation series of 14 PSs (n 22) in the East

Table 3. Results of Chi-Squared Statistic with Equal-Length-Sliced Histograms for All Flow and Precipitation Stations. MOM: Momentler, PWM: Probability weighted moments, AP: Average probability and AK: Average chi-squared

Data	Probability Distribution Models	Number of 1st		Number of 2nd		Number of 3rd		Number of 1st Three	
		AP	AK	AP	AK	AP	AK	AP	AK
Flow Stations	Gumbel (MOM)	12	8	1	4	0	1	13	13
	Gumbel (PWM)	1	5	11	4	1	2	13	11
	log-Logistic (MOM)	0	0	0	0	0	0	0	0
	log-Logistic (PWM)	0	0	0	0	0	0	0	0
	Pearson-3 (MOM)	0	0	0	0	3	4	3	4
	Pearson-3 (PWM)	0	0	0	1	2	2	2	3
	log-Pearson-3 (MOM)	0	0	1	2	5	3	6	5
	log-Pearson-3 (PWM)	0	0	0	0	0	0	0	0
	log-Nornal-3 (MOM)	0	0	0	2	2	1	2	3
Precipitation Stations	Gumbel (MOM)	46	32	10	19	0	1	56	52
	Gumbel (PWM)	9	17	45	25	2	11	56	53
	log-Logistic (MOM)	0	0	0	0	1	1	1	1
	log-Logistic (PWM)	0	0	0	0	2	1	2	1
	Pearson-3 (MOM)	0	0	0	3	10	9	10	12
	Pearson-3 (PWM)	0	0	0	1	11	10	11	11
	log-Pearson-3 (MOM)	0	1	0	1	11	8	11	10
	log-Pearson-3 (PWM)	0	1	0	4	9	4	9	9
	log-Nornal-3 (MOM)	1	5	1	3	10	11	12	19

Table 4. Results of Chi-Squared Statistic with Equal-Probability-Area Sliced Histograms for All Flow and Precipitation Stations. MOM: Momentler, PWM: Probability weighted moments, AP: Average probability and AK: Average chi-squared

Data	Probability Distribution Models	Number of 1st		Number of 2nd		Number of 3rd		Number of 1st Three	
		AP	AK	AP	AK	AP	AK	AP	AK
Flow Stations	Gumbel (MOM)	11	7	2	1	0	4	13	12
	Gumbel (PWM)	2	2	11	5	0	6	13	13
	log-Logistic (MOM)	0	0	0	1	1	0	1	1
	log-Logistic (PWM)	0	0	0	1	0	0	0	1
	Pearson-3 (MOM)	0	4	0	5	7	3	7	12
	Pearson-3 (PWM)	0	0	0	0	0	0	0	0
	log-Pearson-3 (MOM)	0	0	0	0	3	0	3	0
	log-Pearson-3 (PWM)	0	0	0	0	2	0	2	0
	log-Nornal-3 (MOM)	0	0	0	0	0	0	0	0
Precipitation Stations	Gumbel (MOM)	44	35	11	16	1	3	56	54
	Gumbel (PWM)	12	17	41	27	3	9	56	53
	log-Logistic (MOM)	0	0	0	4	9	15	9	19
	log-Logistic (PWM)	0	0	0	1	6	8	6	9
	Pearson-3 (MOM)	0	4	4	8	16	20	20	32
	Pearson-3 (PWM)	0	0	0	0	9	0	9	0
	log-Pearson-3 (MOM)	0	0	0	0	5	0	5	0
	log-Pearson-3 (PWM)	0	0	0	0	1	0	1	0
	log-Nornal-3 (MOM)	0	0	0	0	6	1	6	1

Table 5. Results of Kolmogorov-Smirnov Test for All Flow and Precipitation Stations

Data	Probability Distribution Models	Number of 1st	Number of 2nd	Number of 3rd	Number of 1st Three
Flow Stations	Gumbel (MOM)	0	1	0	1
	Gumbel (PWM)	0	3	1	4
	log-Logistic (MOM)	3	2	0	5
	log-Logistic (PWM)	1	2	3	6
	Pearson-3 (MOM)	0	0	2	2
	Pearson-3 (PWM)	1	0	1	2
	log-Pearson-3 (MOM)	3	1	2	6
	log-Pearson-3 (PWM)	2	1	2	5
	log-Nornal-3 (MOM)	3	3	2	8
Precipitation Stations	Gumbel (MOM)	0	1	2	3
	Gumbel (PWM)	4	7	4	15
	log-Logistic (MOM)	13	0	5	18
	log-Logistic (PWM)	5	10	10	25
	Pearson-3 (MOM)	4	8	8	20
	Pearson-3 (PWM)	9	5	8	22
	log-Pearson-3 (MOM)	9	8	11	28
	log-Pearson-3 (PWM)	6	2	2	10
	log-Nornal-3 (MOM)	6	15	6	27

Mediterranean region. Özdemir and Kırmızıgül (1997) emphasized that LP3 and GB were the best models for different precipitation intensities of 194 PSs (n 10) in Turkey using chi-squared and K-S tests. Kişi et al. (2001) examined annual peak daily precipitation series using the chi-squared test and found LP3, LN3 and GEV to be the best PDs. GB and P3 PDs, however, did not fit well to the PSs.

Summary for chi-squared statistic, GB (MOM) and GB (PWM) PDs were determined to be the best models for both FSs and PSs. LP3 (MOM) and LN3 (MOM) were found to be the third best model for FSs and PSs, respectively, according to the number of first threes.

b) In the same way, evaluation of the chi-squared GOF with equal-probability-area sliced histograms resulted in similar results as shown in Table 4. However, the third best model determined to be P3(MOM) for both FSs and PSs according to the number of first threes was different from that of the chi-squared with equal-length-sliced histograms.

c) According to the K-S GOF test, LP3 (MOM), LL (MOM) and LN3 (MOM) scored three times the best model each for FSs. However, only LN3 (MOM) PD gave the highest score in the number of first threes. Haktanır (1982) found that log-Gama and LN were the best models as a result of chi-squared tests of 6 FSs for the basins of Seyhan and Ceyhan. Özcan (1990) and Haktanır (1991) determined that LP3 (MOM) and LL (PWM) were the best among 112 FSs (n 21) according to the chi-squared and K-S tests, respectively.

For PSs, LL (MOM) was determined to be the best model, scoring 13 times the number of firsts. LP3 (MOM) and P3 (PWM) followed this model. However, this second best model, LP3 (MOM), scored 28 times the number of first threes. Aydurak (1994) determined that LP3 was the best PD for PS of Ünye using both K-S and chi-squared tests. In a study performed by the DSİ (1990), LP3, LN2 and LN3 PDs were determined to be the best PDs among the annual daily precipitation series of 1777 PSs in Turkey.

As a general result, LN3 (MOM) and LP3 (MOM) PDs were found to be the best models for FSs and PSs, respectively, according to the K-S GOF test. However, both chi-squared tests indicated that GB (MOM) and GB (PWM) PDs for both FSs and PSs were found to be the best models. Cicioni (1973) determined that the chi-squared test was better than K-S and other tests known. After that, a suitable PD from among those above can be selected and used in regional flood frequency analysis, synthetic unit hydrographs, regional regression equations etc. for further analysis of flood and related studies.

Acknowledgement

The author is grateful to Prof. Dr. Tefaruk Haktanır for supplying some references and the software package.

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