Check for updates

Frequency analysis of low flows in intermittent and non-intermittent rivers from hydrological basins in Turkey

Ebru Eris, Hafzullah Aksoy, Bihrat Onoz, Mahmut Cetin, Mehmet Ishak Yuce, Bulent Selek, Hakan Aksu, Halil Ibrahim Burgan, Musa Esit, Isilsu Yildirim and Ece Unsal Karakus

ABSTRACT

This study attempts to find out the best-fit probability distribution function to low flows using the up-to-date data of intermittent and non-intermittent rivers in four hydrological basins from different regions in Turkey. Frequency analysis of $D = 1$-, 7-, 14-, 30-, 90- and 273-day low flows calculated from the daily flow time series of each stream gauge was performed. Weibull (W2), Gamma (G2), Generalized Extreme Value (GEV) and Log-Normal (LN2) are selected among the 2-parameter probability distribution functions together with the Weibull (W3), Gamma (G3) and Log-Normal (LN3) from the 3-parameter probability distribution function family. Selected probability distribution functions are checked for their suitability to fit each D-day low flow sequence. LN3 mostly conforms to low flows by being the best-fit among the selected probability distribution functions in three out of four hydrological basins while W3 fits low flows in one basin. With the use of the best-fit probability distribution function, the low flow-duration-frequency curves are determined, which have the ability to provide the end-users with any D-day low flow discharge of any given return period.

Key words | frequency analysis, intermittent river, low flow, low flow-duration-frequency curve

Ebru Eris (corresponding author)
Department of Civil Engineering,
Ege University,
Izmir, Turkey
E-mail: *ebru.eris@ege.edu.tr*

Hafzullah Aksoy
Bihrat Onoz
Halil Ibrahim Burgan
Isilsu Yildirim
Ece Unsal Karakus
Department of Civil Engineering,
Istanbul Technical University,
Istanbul, Turkey

Mahmut Cetin
Department of Agricultural Structures and Irrigation,
Cukurova University,
Adana, Turkey

Mehmet Ishak Yuce
Department of Civil Engineering,
Gaziantep University,
Gaziantep, Turkey

Bulent Selek
General Directorate of Water Management,
Ankara, Turkey

Hakan Aksu
General Directorate of State Hydraulic Works,
Ankara, Turkey

Musa Esit
Department of Civil Engineering,
Adiyaman University,
Adiyaman, Turkey

INTRODUCTION

Low flow frequency analysis is a useful practice for estimating the probability of water availability in streams during critical low flow periods such as drought. Low flow statistics can be used in water supply planning to determine allowable water transfers and withdrawals. Their use also includes minimum downstream release from hydropower plants, water supply and cooling systems, etc. A certain duration-low flow discharge with a certain return period is important information for engineering design practice. As an example, $Q_{7,10}$, the 7-day low flow with 10 years of return period, is one of the most-used (design or reference) low flow indices. It is used for many design practices such as the protection or regulation of water quality from waste water discharges or waste load allocations (Riggs *et al.*

doi: 10.2166/ws.2018.051

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

1980), the regulation of water withdrawals and discharges into streams (Carter & Putnam 1978), and the comparison of the impacts of climate change and irrigation on low surface streamflows (Eheart & Tornil 1999; Eheart *et al.* 1999). It is also used as a local extinction flow (Ontario Ministry of Natural Resources 1994), and considered as the worst-case scenario in water quality modelling (Mohamed *et al.* 2002).

The comprehensive literature review performed by Smakhtin (2001) is a benchmark study on low flow hydrology in which low flow was discussed in all aspects. For characterizing and evaluating low flows, flow duration curves, recession analysis, low flow indices and frequency analysis have frequently been used (Bayazit & Onoz 2008). Frequency analysis has focused on fitting a theoretical probability distribution function to the observed data, and providing low flow estimates for any given return period. Frequency analysis has been combined with the recession process in order to consider human activities such as groundwater pumping (Gao *et al.* 2017). A quite high number of probability distribution functions are used for the purpose of low flow frequency analysis (Caruso 2000; Hewa *et al.* 2007; Liu *et al.* 2015). Durrans (1996) applied a conditional Weibull tail model to low flow data lower than or equal to an upper threshold. The same model was applied by Durrans *et al.* (1999) to ephemeral streams where the data are censored (with zeroes). A case study from Alabama in the USA has shown that the log Pearson Type III distribution can be proposed on a regional basis (Durrans & Tomic 1996). Selection of the parameter estimation method is another important issue in the low flow frequency analysis literature (Durrans & Tomic 2001; Chen *et al.* 2006; Modarres 2008; Dodangeh *et al.* 2014).

Streamflow records are frequently inadequate in terms of length; no records are available at all for ungauged basins. Therefore, local or regional low flow estimation through synthetic streamflow time series or regression equations become useful important tools to use. Hydrometeorological, geological and morphological basin characteristics used in case data are not available (Smakhtin 2001; Laaha & Bloschl 2006). Contour maps have also been derived for estimating low flow characteristics at ungauged sites and evaluating spatial trends (Caruso 2000). The change or variability in hydrology in general (Montanari *et al.* 2013; Ceola *et al.* 2016; McMillan *et al.* 2016) and the nonstationary of low flows as a particular case (Du *et al.* 2015; Liu *et al.* 2015; Ahn & Palmer 2016) should be taken into account in the frequency analysis or modelling studies of low flows, because higher effects on low flows than high flows could be expected (Schaake & Chunzhen 1989).

In Turkey, statistical analysis of low flows was investigated by Bulu *et al.* (1995) and Onoz & Bulu (1996) for the Thrace Region, the European part of the country. Sertbas (1996), Bulu & Onoz (1997) and Saris (2016) analyzed the Sakarya and Meric basins in the northwestern part of the country. Duran (2000) studied the Aegean Region in the west, Saracoglu (2002) the Mediterranean Region in the south, Yurekli *et al.* (2005) the Yesilirmak Basin in the north, and Koken (2009) the Tigris Basin in the southeastern parts of the country. Frequency analysis of low flows in these particular basins was dealt with separately by different researchers individually considering different data sets. However, a low flow frequency analysis considering various basins at once with recent flow observations does not exist. Therefore, this study attempts to find out the best-fit probability distribution function for low flows using up-to-date data of intermittent and non-intermittent rivers in four hydrological basins from different regions in Turkey.

MATERIALS AND METHODS

Study area

Turkey is divided into 25 hydrological basins (Figure 1) with different topographical characteristics as well as morphological and meteorological conditions. Daily streamflow data of gauging stations from Meric-Ergene, Gediz, Seyhan and Ceyhan basins are used in this study. Meric-Ergene Basin is located in the Thrace Region, in the northwestern part of Turkey, with a drainage area of 14,510 km^2. Land in the basin is mostly used for agriculture followed by forests and semi-natural areas. The rest of the basin has been urbanized together with some wetlands and reservoirs. The long-term average of annual precipitation in the basin is 665 mm,

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

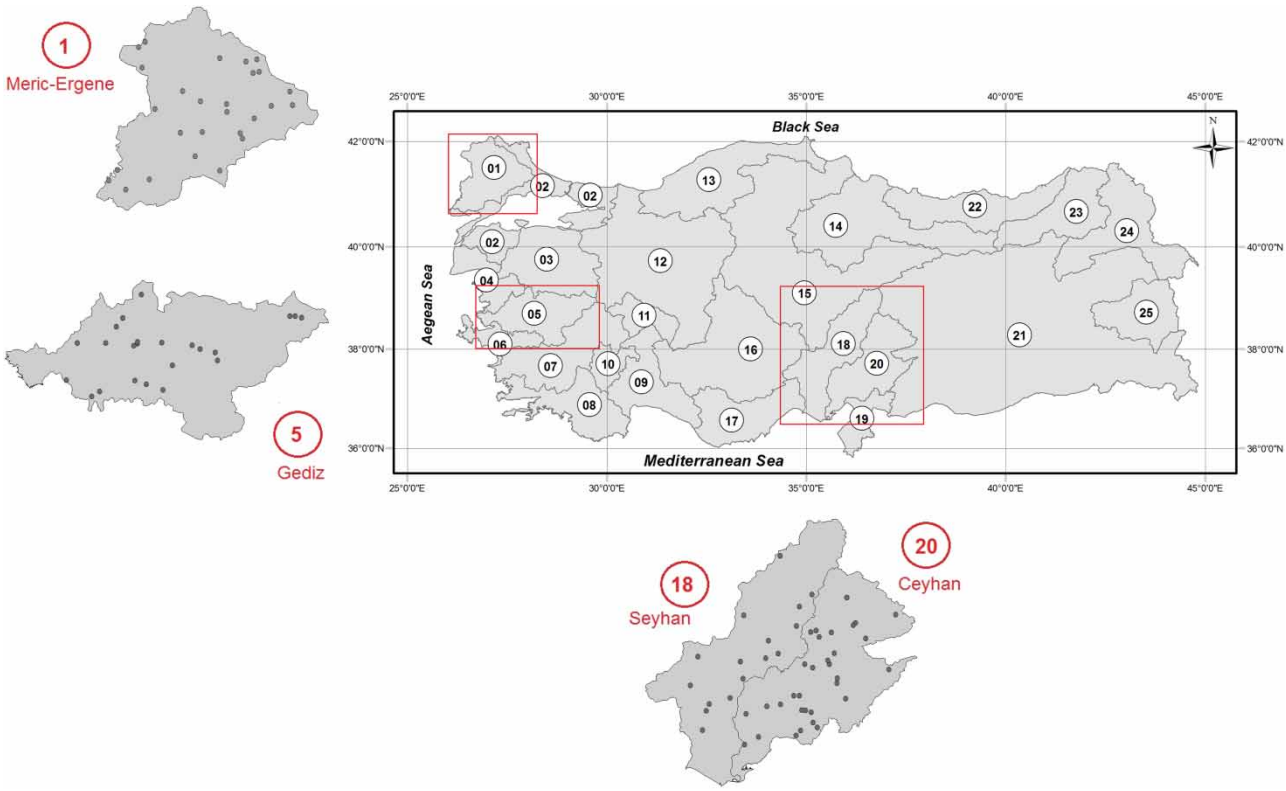


Figure 1 | Location of the basins with flow-gauging stations.

which becomes significant in winter and decreases in summer. Gediz Basin is located in the Aegean Region, the western part of Turkey. Gediz River is about 275 km long and drains from an area of 17,200 km^2. It has a hot dry summer and a cool winter. Precipitation in the basin is concentrated in the winter season and it ranges from over 1,000 mm per year in the mountains to 500 mm near the coast. The Ceyhan River Basin is in the semi-arid Eastern Mediterranean Region located in the southern part of Turkey. The basin covers 20,670 km^2. Mountains in the basin are as high as 2,500 m. The basin drains southerly into the Mediterranean Sea. To the west of Ceyhan River Basin is the Seyhan River. The drainage area of the basin is more than 21,000 km^2. The lower part of the basin is dominated by the Mediterranean climate, while the middle and upper parts are influenced by the Continental climate. The annual precipitation is about 700 mm in the coastal area; it increases to approximately 1,000 mm at higher elevations in the north and decreases to about 400 mm at the most upstream area further north.

Data

State Hydraulic Works of Turkey (DSI with its Turkish acronym) operates and maintains hydrometric stations for gauging streamflow all over the country. Daily streamflow data were obtained from the DSI-operated streamflow gauges in Meric-Ergene, Gediz, Seyhan and Ceyhan basins. Table 1 shows the characteristics of the data used in this study. For the analysis, 27, 23, 16 and 33 streamflow gauges were selected from Meric-Ergene, Gediz, Seyhan and

Table 1 | Stream gauges, record period and years considered

Basin	Number of gauging stations	Earliest record year	Latest record year	Station-year
Meric-Ergene	27	1957	2014	501
Gediz	23	1939	2015	586
Seyhan	16	1954	2015	436
Ceyhan	33	1954	2015	1,104
Total	99			2,627

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

Ceyhan basins, respectively. Most of the streamflow gauges have an intermittent character in Meric-Ergene, Gediz and Ceyhan basins while rivers in Seyhan Basin are mostly perennial. The selected streamflow gauges have uninterrupted time series with record lengths from 10 years at minimum up to 59 years at maximum between the years 1939 and 2015. In total, 99 gauging stations with total of 2,627 station-years of data were analyzed. This is a considerable amount of data for the low flow frequency analysis. In selecting the streamflow gauges, particular attention was paid to taking data from the natural conditions with either no or the least human-made influence. The record period for each gauging station was selected such that the influence of any upstream dam or water-related structure was excluded.

Statistical characteristics calculated from the daily streamflow time series of each gauging station are also given in Table 2. For comparability, the daily streamflow data were calculated with the units l/s-km^2. The range of the following characteristics were calculated from the observed daily streamflow time series: zero-flow percentage, the mean, minimum and maximum values; standard deviation, coefficient of variation (C_v), coefficient of skewness (C_s), and lag-one autocorrelation coefficient (r_1).

D-day low flow

The D-day average time series is obtained by taking the overlapping D-day average of the daily streamflow time series under consideration. For one year-portion of the daily streamflow time series, the number of the D-day average flow is 365-(D-1). The minimum of the calculated D-day low flow sequence at each year is taken as the D-day low flow of the year; hence a D-day low flow sequence with N items is obtained. Frequency analysis is performed on the D-day low flow sequences (one value per year). In the low flow practice, minima of $D = 1$, 3, 7, 10, 15, 30, 60, 90, 120, 150, 180 or 183, 273 and 284 days are frequently used. In this study, minima of $D = 1$-, 7-, 14-, 30-, 90- and 273-day average flows calculated from the daily flow time series of stream gauges in Meric-Ergene, Gediz, Seyhan and Ceyhan hydrological basins are used.

Using the above methodology on the data described, minima of $D = 1$-, 7-, 14-, 30-, 90- and 273-day low flows were extracted, for each year of the records' length, from the daily streamflow time series of each gauging station taken from the study area. Each D-day low flow sequence has the same number of items as the length of the observed time series of each particular time series; i.e., a streamflow gauging station with a 25 year-record will have sequences of $D = 1$-, 7-, 14-, 30-, 90- and 273 days each with 25 D-day low flow. It was seen that the $D = 1$-, 7-, 14-, 30-, and 90-day low flow sequences of some gauging stations in Meric-Ergene, Gediz and Ceyhan basins have a considerable amount of zero values. However, no zero-low flow was observed in the streamflow data taken from stream gauges in Seyhan Basin.

Frequency analysis

There is no unique and universally accepted probability distribution function for low flows. However, in the literature, several theoretical distribution functions are frequently fitted to low flow data. Different forms of Weibull, Gumbel, Pearson Type III, and log-normal distributions are the most frequently used probability distribution functions in the low flow literature (Smakhtin 2001). Therefore, in this study, the 2- and 3-parameter Weibull (W2, W3), Generalized Extreme Value (GEV), 2- and 3-parameter Gamma

Table 2 | Statistical characteristics of daily streamflow data

	Zero-flow (%)		Mean (l/s-km^2)		Min (l/s-km^2)		Max (l/s-km^2)		St Dev		C_v		C_s		r_1	
Basin	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Meric-Ergene	0.00	43.39	1.93	17.78	0.00	0.49	37.14	2,386.64	3.69	38.56	0.87	6.24	2.73	39.37	0.28	0.99
Gediz	0.00	38.86	0.95	19.03	0.00	0.19	4.12	1,243.75	1.22	33.61	1.07	4.35	1.03	31.09	0.32	0.92
Seyhan	0.00	2.56	2.82	84.43	0.00	6.06	24.63	431.59	2.22	60.52	0.72	1.61	0.95	6.71	0.81	0.99
Ceyhan	0.00	15.23	5.27	34.87	0.00	5.08	30.40	994.70	4.67	60.61	0.64	2.91	1.34	8.96	0.70	0.99

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

(Pearson Type III) (G2, G3), and 2- and 3-parameter Log-Normal (LN2, LN3) distributions were fitted to the D-day low flow observations after they were checked with statistical tests such as Kolmogorov–Smirnov and Anderson–Darling. Details about the expression, validity range and parameter estimation methods for each probability distribution function can be found in van Gelder (1999).

For semi-arid and arid regions, hydrologists may encounter streamflow time series that contain zero values. The same problem arises in cold regions where rivers are frozen during the winter season. Such data sets are called censored samples (Stedinger *et al.* 1993) or intermittent time series. The recorded flow is composed of two different-character data; a subset of zero-low flows, and a subset of non-zero low flows. Zero-flows should be taken into consideration in estimating the probabilities of low flows (Haan 1977) and flow-duration-frequency curves. This makes the frequency analysis of intermittent rivers of arid or cold regions more complex compared with the perennial rivers of humid regions.

In this study, the D-day low flow sequences were checked for the best-fit probability distribution function. Zero low flows were extracted from the D-day low flow sequence before the best-fit probability distribution function is checked. In fitting the probability distribution function, any D-day low flow sequence with a minimum 10 years of non-zero low flow is used. Zero-flows in each D-day sequence were taken into account for calculating the low flow of a given return period once the probability distribution function was fitted to the D-day low flow data. The least-squares method was used to calculate the parameters of W2; the method of moments for GEV, G2, LN2, LN3 and maximum likelihood method for W3 and G3. The Kolmogorov–Smirnov test was performed to check the goodness-of-fit of the selected distributions at significance level $\alpha = 0.05$.

Low flow-duration-frequency curves of intermittent streams

Once the best-fit probability distribution of a D-day low flow sequence is determined, the D-day low flow of any return period can be calculated. The so-called low flow-duration-frequency curve is used for this purpose. In the case of an intermittent stream, zero D-day low flows were taken into account in the development of the low flow-duration-frequency curve.

For considering the zero D-day low flow records, the total probability theorem given as

$$P(X \geq x) = P(X \geq x|X = 0)P(X = 0) + P(X \geq x|X \neq 0)P(X \neq 0) \quad (1)$$

was used. Since

$$P(X \geq x|X = 0) = 0 \quad (2)$$

Equation (1) is reduced to

$$P(X \geq x) = P(X \geq x|X \neq 0)P(X \neq 0) \quad (3)$$

in which $P(X \neq 0)$ is the fraction of non-zero values, and $P(X \geq x|X \neq 0)$ would be estimated by a standard analysis of the non-zero values with the same size taken to be equal to the number of non-zero values. Equation (3) can also be written in terms of cumulative probability distributions as

$$1 - F(x) = k[1 - F^*(x)] \quad (4)$$

In Equation (4), $F(x)$ is the cumulative probability distribution of all X and $F^*(x)$ is the cumulative probability distribution of the non-zero values of X; which are expressed, respectively, as

$$F(x) = [P(X \leq x|X \geq 0)] \quad (5)$$

$$F^*(x) = [P(X \leq x|X \neq 0)] \quad (6)$$

The fraction of non-zero values, k in Equation (4), can be expressed in terms of probability as

$$k = P(X \neq 0) \quad (7)$$

This is a mixed distribution which has a probability mass for $X = 0$ and a continuous probability distribution for $X > 0$.

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

Equation (4) can be used to estimate the magnitude of an event with return period T by solving first for $F^*(x)$ and then using the inverse transformation of $F^*(x)$ to get the value of X. This depends on the probability distribution function applied to the non-zero flow values.

Considering that the return period of low flows can be estimated by

$$T = \frac{1}{F(x)} \tag{8}$$

Equation (4) changes then to

$$F^*(x) = \frac{1/T - 1 + k}{k} \tag{9}$$

The applicability of Equation (9) depends on getting positive values for the probability $F^*(x)$. This means, the application of the total probability theorem to the low flow analysis depends on the relation between T and k. It is valid for a return period that satisfies

$$k \geq \frac{T-1}{T} \tag{10}$$

Indeed, negative values obtained for $F^*(x)$ in Equation (9) mean that, for the given return period T and fraction k, the probability of observing the flow value, x, is zero for the river under consideration. For the commonly used return periods, the fractions of non-zero values, k, that would be greater are given in Table 3.

RESULTS AND DISCUSSION

Based on the review of the low-flow literature, the 2- and 3-parameter Weibull (W2, W3), Generalized Extreme Value (GEV), 2- and 3-parameter Gamma (Pearson Type III) (G2, G3), and 2- and 3-parameter Log-Normal (LN2, LN3) distributions were selected in this study to fit the D-day low flow sequences. The best-fit probability distribution function was determined for each D-day low flow sequence of streamflow gauging stations in the Meric-Ergene, Gediz, Ceyhan and Seyhan basins after being properly checked with statistical tests.

Table 4 shows the percentage of probability distribution functions for each D-day low flow sequence with the highest underlined in bold. It is seen that mostly the LN3 distribution conformed to low flows in the Meric-Ergene, Gediz and Ceyhan basins as it has the highest percentage for most of the D-day low flow sequences. On the other hand, for Seyhan Basin, among the tested probability distribution functions, W3 appears to be the most appropriate for all D-day low flow sequences except for $D = 273$ days, for

Table 3 | The k values depending on return period, T

T (year)	2	5	10	25	50	100
$k \geq$	0.5	0.8	0.9	0.96	0.98	0.99

Table 4 | Percentage of probability distribution functions for different D-day low flows

		D					
		1	7	14	30	90	273
Meric-Ergene	G2	18	15	15	12	28	***22***
	G3	0	0	8	6	4	4
	LN2	9	0	23	18	8	7
	LN3	27	***38***	***38***	***35***	***40***	19
	W2	0	15	8	12	8	11
	W3	***36***	23	8	18	12	19
	GEV	9	8	0	0	0	19
Gediz	G2	36	36	33	***40***	***32***	26
	G3	0	7	7	13	5	4
	LN2	7	7	7	0	5	4
	LN3	***43***	***43***	***40***	20	***32***	***39***
	W2	0	0	0	13	16	13
	W3	7	7	13	13	11	9
	GEV	7	0	0	0	0	4
Seyhan	G2	13	0	6	13	6	0
	G3	13	0	19	13	19	0
	LN2	6	6	13	6	0	13
	LN3	13	19	13	6	13	19
	W2	6	6	6	0	19	***25***
	W3	***38***	***56***	***25***	***50***	***31***	19
	GEV	13	13	19	13	13	***25***
Ceyhan	G2	13	9	6	15	6	15
	G3	6	13	13	12	15	0
	LN2	6	3	9	15	12	12
	LN3	***25***	22	***28***	***21***	***24***	***24***
	W2	19	16	13	15	18	21
	W3	16	***31***	***28***	6	21	18
	GEV	16	6	3	15	3	9

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

which W2 and GEV were found equally the best. G2 has been the best twice (for the 273-day low flow sequence in Meric-Ergene, and the 30-day low flow sequence in Gediz) and one of the best two probability distribution functions once (for the 90-day low flow sequence in Gediz). Also W3 has been the best twice (for 1-day low flow in Meric-Ergene and 7-day low flow in Ceyhan). It has also been one of the two best probability distribution functions for 14-day low flow in Ceyhan. LN2 and G3 have never been the best in this analysis although each has either been the second best or shared the second-best place in some cases. For example, LN2 is the second best for 14-day low flow in Meric-Ergene, and G3 is one of the three second-best probability distribution functions for 30-day low flow in Gediz.

In the past, Bulu *et al.* (1995), Sertbas (1996), and Bulu & Aksoy (1998) found that W2, among LN2, N and W2 distributions, were well fitted to the low flows of the Thrace Region and Sakarya Basin. W2 and exponential distributions were found suitable for the Aegean Region in the study by Duran (2000). With use of recent flow observations in this study, W3 but mainly LN3 appeared to be more suitable for low flows of the mentioned basins; namely Meric-Ergene and Gediz. From this comparison, it becomes inevitable to stress that a higher number of parameters in the probability distribution functions are more advantageous for better fitting the D-day low-flow sequences compared with probability distribution functions with a lower number of parameters.

Once the best-fit probability distribution of the D-day low flow sequence is determined, the D-day low flow discharge corresponding to any given return period can be calculated. It should be emphasized that the analysis in this study is station-based. Therefore, the low flow-duration-frequency curves were obtained on a gauging station basis. The low flow-duration-frequency curves are useful tools for many purposes but particularly for practicing engineers. An engineer can get any low-flow design discharge from the low flow-duration-frequency curves. In estimating low flows for a given return period, zero D-day low flows were considered through the total probability theorem as explained above.

One streamflow gauging station per hydrological basin was selected to demonstrate the suitability of the fitted probability distributions (Figure 2). No matter what probability distribution function was found to be the best for any D-day low flow sequence of individual gauging stations, LN3 was applied to all D-day low flows of all stations in the Meric-Ergene, Gediz and Ceyhan basins while W3 was used for the Seyhan Basin. Parameters of the selected probability distribution functions (LN3 and W3) were determined for each of the streamflow gauging stations and used in calculating the D-day low flows in every individual gauging station for return periods of 2, 5, 10, 25, 50 and 100 years.

It is important to notice that for a threshold of zero flow, lower frequency low flows cannot be calculated by the probability distribution function due to the constraint in Equation (10). For example, the non-zero fraction of low flows allows one to calculate the 10-year return period 1-day low flow in station D01A031 of Meric-Ergene Basin. Indeed, for higher return periods such as 25, 50 and 100 years, the D-day low flow is simply taken to be zero. One more point worth mentioning is that no zero D-day low flow was observed in the Seyhan Basin. Therefore, the fraction of non-zero flows is always 100%, which allows one to calculate up to 100-year return period D-day low flow discharges in this particular basin.

The general behavior of the low flow-duration-frequency curves in basins other than Seyhan looks similar. A family of upward curves was obtained in Seyhan Basin while families of downward curves were observed for the other three basins. A quick reasoning for this could be that the W3 probability distribution function was found the best-fit for the D-day low flow sequences in Seyhan Basin and LN3 for the other three. The reason for obtaining a different probability distribution function for Seyhan Basin can be linked to the non-intermittent character of stream gauges taken from this particular basin. The D-day low flow sequences of Meric-Ergene, Gediz and Ceyhan basins have, however, zero values whose number increases with decreasing D.

CONCLUSION

Low flow frequency analysis is a commonly used analytical tool to assess low flow characteristics of streams. Different D-day low flows are considered in this study for streamflow gauging stations from four hydrological basins located in different geographical regions in Turkey. The 2- and 3-parameter probability distribution functions commonly used for low flow frequency analysis are applied to fit the D-day

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

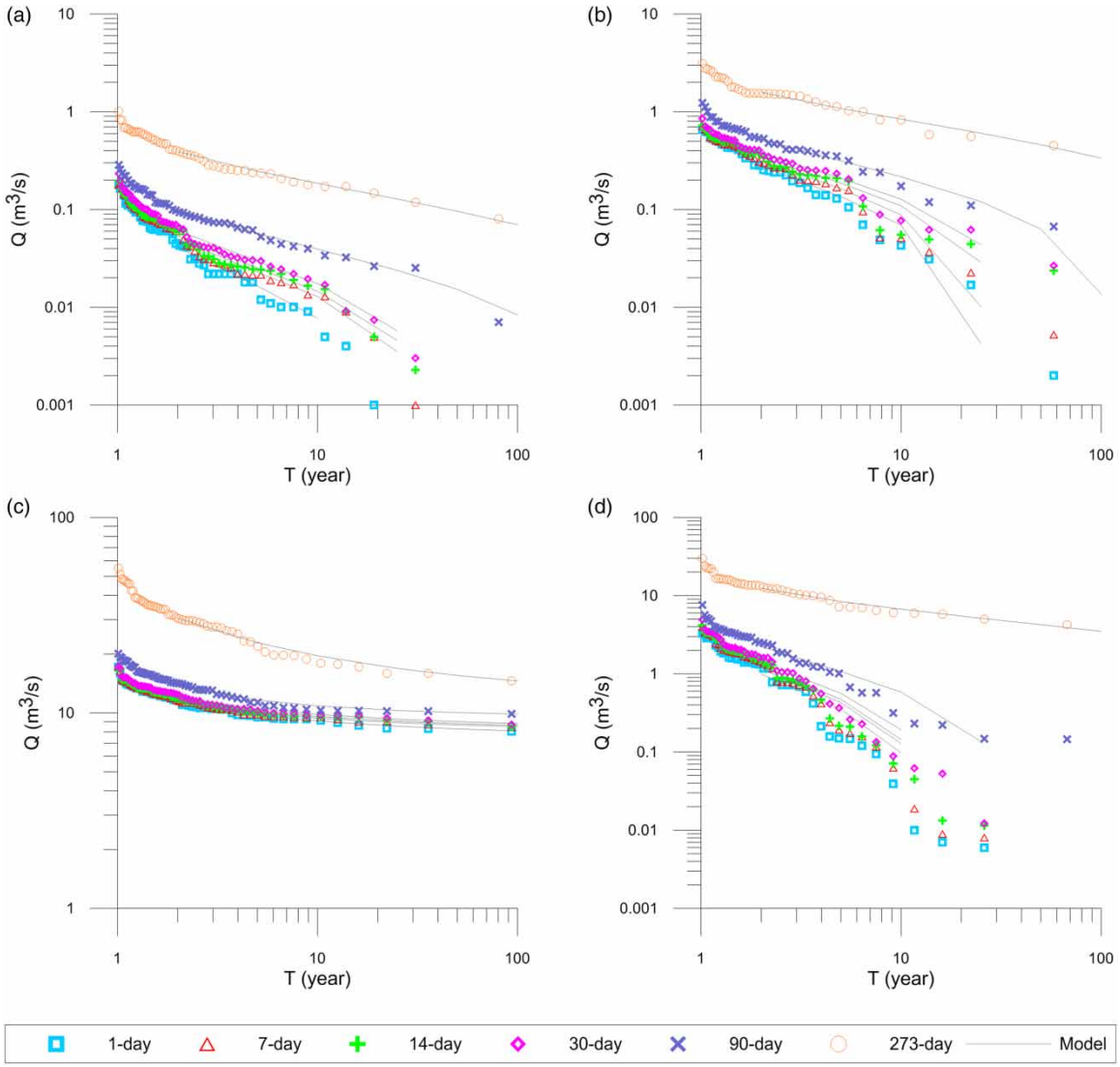


Figure 2 | Low flow-duration-frequency curves for stations (a) D01A031 in Meric-Ergene, (b) E05A024 in Gediz, (c) E18A001 in Seyhan and (d) E20A009 in Ceyhan.

low flow sequences of every gauging station. In total, 2,627 station-year up-to-date daily streamflow data from 99 gauging stations on intermittent and non-intermittent rivers are used. It is found that the 3-parameter Log-Normal (LN3) probability distribution function fits quite well to most of the *D*-day low flows in Meric-Ergene, Gediz and Ceyhan basins in the northwestern, western and southern parts of Turkey, respectively. The 3-parameter Weibull (W3) distribution fits best to the majority of the low flow sequences in Seyhan Basin in the south of the country. Gauging stations of the former basins have zero low-flows, demonstrating their intermittent character, while the latter basin is characterized by non-intermittent gauging stations. The frequency analysis takes into account the zero-flow fraction in the low-flow sequences. It is important that zero-flows are considered in the low flow-duration-frequency curves used for calculating the design low-flow discharges in intermittent rivers.

ACKNOWLEDGEMENTS

This study is a part of the project entitled 'Analysis of Low Flow and Drought in Hydrological Watersheds' funded through the Turkish National Meteorological and

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

Hydrological Disasters Program (TUMEHAP) under the Turkish National Union of Geodesy and Geophysics (TUJJB).

REFERENCES

Ahn, K.-H. & Palmer, R. N. 2016 Use of a nonstationary copula to predict future bivariate low flow frequency in the Connecticut river basin. *Hydrological Processes* **30**, 3518–3532.

Bayazit, M. & Onoz, B. 2008 *Flood and Drought Hydrology*. Nobel Publications, Istanbul, Turkey (in Turkish).

Bulu, A. & Aksoy, H. 1998 Low flow and drought studies in Turkey. In: *UNESCO FRIEND-AMHY, Low Flows Expert Meeting*, 10–12 June, Belgrade, Yugoslavia, pp. 123–131.

Bulu, A. & Onoz, B. 1997 Frequency analysis of low flows by the PPCC test in Turkey. In: *UNESCO FRIEND-AMHY'97 – Regional Hydrology: Concepts and Models for Sustainable Water Resource Management* (A. Gustard, S. Blazkova, M. Brilly, S. Demuth, J. Dixon, H. van Lanen, C. Llasat, S. Mkhandi & E. Servat, eds), IAHS Publication No. 246, IAHS Press, Wallingford, UK, pp. 133–140.

Bulu, A., Cigizoglu, H. K. & Cokgor, S. 1995 Statistical analysis of low flows on Thrace Region. In: *UNESCO FRIEND-AMHY Conference*, Thessaloniki, Greece, pp. 91–104.

Carter, R. F. & Putnam, S. A. 1978 *Low Flow Frequency of Georgia Streams*. US Geological Survey Water-Resources Investigations Report No. 77-127, US Geological Survey, USA.

Caruso, B. S. 2000 Evaluation of low-flow frequency analysis methods. *Journal of Hydrology* **39** (1), 19–47.

Ceola, S., Montanari, A., Krueger, T., Dyer, F., Kreibich, H., Westerberg, I., Carr, G., Cudennec, C., Elshorbagy, A., Savenije, H., Zaag, P. V. D., Rosbjerg, D., Aksoy, H., Viola, F., Petrucci, G., MacLeod, K., Croke, B., Ganora, D., Hermans, L., Polo, M. J., Xu, Z., Borga, M., Helmschrot, J., Toth, E., Ranzi, R., Castellarin, A., Hurford, A., Brilly, M., Viglione, A., Blöschl, G., Sivapalan, M., Domeneghetti, A., Marinelli, A. & Baldassarre, G. D. 2016 Adaptation of water resources systems to changing society and environment: a statement by the International Association of Hydrological Sciences. *Hydrological Sciences Journal* **61** (16), 2803–2817.

Chen, Y. D., Huang, G., Shao, Q. & Xu, C.-Y. 2006 Regional analysis of low flow using L-moments for Dongjiang basin, South China. *Hydrological Sciences Journal* **51** (6), 1051–1064.

Dodangeh, E., Soltani, S., Sarhadi, A. & Shiau, J.-T. 2014 Application of L-moments and Bayesian inference for low-flow regionalization in Sefidroud basin, Iran. *Hydrological Processes* **28**, 1663–1676.

Du, T., Xiong, L., Xu, C.-Y., Gippel, C. J., Guo, S. & Liu, P. 2015 Return period and risk analysis of nonstationary low-flow series under climate change. *Journal of Hydrology* **527**, 234–250.

Duran, S. D. 2000 *Low Flow Hydrology and Application to Aegean Area*. MSc thesis, Istanbul Technical University, Istanbul, Turkey.

Durrans, S. R. 1996 Low-flow analysis with a conditional Weibull tail model. *Water Resources Research* **32** (6), 1749–1760.

Durrans, S. R. & Tomic, S. 1996 Regionalization of low-flow frequency estimates: an Alabama case study. *Water Resources Bulletin* **32** (1), 23–37.

Durrans, S. R. & Tomic, S. 2001 Comparison of parametric tail estimators for low-flow frequency analysis. *Journal of the American Water Resources Association* **37** (5), 1203–1214.

Durrans, S. R., Ouarda, T. B. M. J., Rasmussen, P. F. & Bobée, B. 1999 Treatment of zeroes in tail modeling of low flows. *Journal of Hydrologic Engineering* **4** (1), 19–27.

Eheart, J. W. & Tornil, D. W. 1999 Low-flow frequency exacerbation by irrigation withdrawals in the agricultural midwest under various climate change scenarios. *Water Resources Research* **35**, 2237–2246.

Eheart, J. W., Wildermuth, A. J. & Herricks, E. E. 1999 The effects of climate change and irrigation on criterion low streamflows used for determining total maximum daily loads. *Journal of the American Water Resources Association* **35**, 1365–1372.

Gao, S., Liu, P., Pan, Z., Ming, B., Guo, S. & Xiong, L. 2017 Derivation of low flow frequency distributions under human activities and its implications. *Journal of Hydrology* **549**, 294–300.

Haan, C. T. 1977 *Statistical Methods in Hydrology*. Iowa State University Press, Ames, IA, USA.

Hewa, G. A., Wang, Q. J., McMahon, T. A., Nathan, R. J. & Peel, M. C. 2007 Generalized extreme value distribution fitted by LH moments for low-flow frequency analysis. *Water Resources Research* **43**, W06301.

Koken, E. 2009 *Regionalization of Low Flow Characteristics of the Tigris Basin in Turkey*. MSc thesis, Dokuz Eylul University, Izmir, Turkey.

Laaha, G. & Blöschl, G. 2006 A comparison of low-flow regionalisation methods: catchment grouping. *Journal of Hydrology* **323**, 193–214.

Liu, D., Guo, S., Lian, Y., Xiong, L. & Chen, X. 2015 Climate-informed low-flow frequency analysis using nonstationary modelling. *Hydrological Processes* **29**, 2112–2124.

McMillan, H., Montanari, A., Cudennec, C., Savenjie, H., Kreibich, H., Krüger, T., Liu, J., Meija, A., van Loon, A., Aksoy, H., Di Baldassarre, G., Huang, Y., Mazvimavi, D., Rogger, M., Bellie, S., Bibikova, T., Castellarin, A., Chen, Y., Finger, D., Gelfan, A., Hannah, D., Hoekstra, A., Li, H., Maskey, S., Mathevet, T., Mijic, A., Acuña, A. P., Polo, M. J., Rosales, V., Smith, P., Viglione, A., Srinivasan, V., Toth, E., van Nooyen, R. & Xia, J. 2016 Panta Rhei 2013–2015: global perspectives on hydrology, society and change. *Hydrological Sciences Journal* **61** (7), 1174–1191.

Modarres, R. 2008 Regional frequency distribution type of low flow in north of Iran by L-moments. *Water Resources Management* **22**, 823–841.

Mohamed, M., Stednick, J. D. & Smith, F. M. 2002 Comparison of field measurements to predicted reaeration coefficients, k_2, in the application of a water quality model, QUAL2E, to a tropical river. *Water Science and Technology* **46**, 47–54.

Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C.,

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest

Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S. J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D. A., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z. & Belyaev, V. 2013 'Panta Rhei – Everything Flows': change in hydrology and society – the IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal* **58** (6), 1256–1275.

Onoz, B. & Bulu, A. 1996 Frequency analysis of low flows on Thrace Region. *IMO Technical Journal* **93**, 1243–1254 (in Turkish).

Ontario Ministry of Natural Resources 1994 *Natural Channel Systems: An Approach to Management and Design*. Queen's Printer for Ontario, Ontario Ministry of Natural Resources, Peterborough, Ontario, Canada.

Riggs, H. C., Caffey, C. E., Orsborn, J. F., Schaake Jr, J. C., Singh, K. P. & Wallace, J. R. 1980 Characteristics of low flows, report of an ASCE Task Committee. *Journal of Hydraulic Engineering* **106** (5), 717–731.

Saracoglu, O. 2002 *Low Flow Hydrology and Application in Mediterranean Area*. MSc thesis, Istanbul Technical University, Istanbul, Turkey.

Saris, F. 2016 Low flow analysis in Porsuk Creek basin. *Istanbul Universitesi, Edebiyat Fakultesi Cografya Dergisi* **33**, 73–81 (in Turkish).

Schaake, J. C. & Chunzhen, L. 1989 Development and application of simple water balance models to understand the relationship between climate and water resources. In: *New Directions for Surface Water Modeling* (M. L. Kavvas, ed.), IAHS Publication No. 181, IAHS, Wallingford, UK, pp. 343–352.

Sertbas, Y. D. 1996 *The Investigation of the Most Suitable Probability Distribution for the Low Flows of the Sakarya Basin River Flows*. MSc thesis, Istanbul Technical University, Istanbul, Turkey.

Smakhtin, V. U. 2001 Low flow hydrology: a review. *Journal of Hydrology* **240**, 147–186.

Stedinger, J. R., Vogel, R. M. & Foufoula-Georgiou, E. 1993 Frequency analysis of extreme events. In: *Handbook of Hydrology* (D. Maidment, ed.). McGraw-Hill Book Company, New York, USA.

van Gelder, P. H. A. J. M. 1999 *Statistical Methods for Risk-Based Design of Civil Structures*. PhD thesis, Delft University of Technology, The Netherlands.

Yurekli, K., Kurunc, A. & Gul, S. 2005 Frequency analysis of low flow series from Çekerek Stream Basin. *Journal of Agricultural Sciences* **11** (1), 72–77.

First received 9 May 2017; accepted in revised form 16 February 2018. Available online 2 March 2018

Downloaded from http://iwaponline.com/ws/article-pdf/19/1/30/507154/ws019010030.pdf
by guest