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

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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 functions family. Selected probability distribution functions are checked for their suitability to fit each D-day low flow sequence. LN3 mostly conforms 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 has 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

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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 the engineering design practice. As an example, $Q_{7,10}$, the 7-day low flow with 10 years of return period, is one of the mostly used (design or reference) low flow indices. It is used for many design practice such as the protection or regulation of water quality from waste water discharges or waste load allocations (Riggs *et al.*

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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 Smakthin (2001) is a benchmark study on low flow hydrology in which low flow have been 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) on ephemeral streams where the data are censored (with zeroes). A case study from Alabama in the US has shown that the log Pearson Type 3 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 the length; no records are available at all in an ungauged basin case. 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 are used in case data are not available (Smakthin 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), Onoz & Bulu (1996) for the Thrace Region, the European part of the country. Sertbas (1996), Bulu & Onoz (1997) and Saris (2016) analyzed Sakarya and Meric basins in the north-western 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 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 to low flows using up-to-date data of intermittent and non-intermittent rivers in four hydrological basins from different regions in Turkey.

MATERIAL 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, the north western 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

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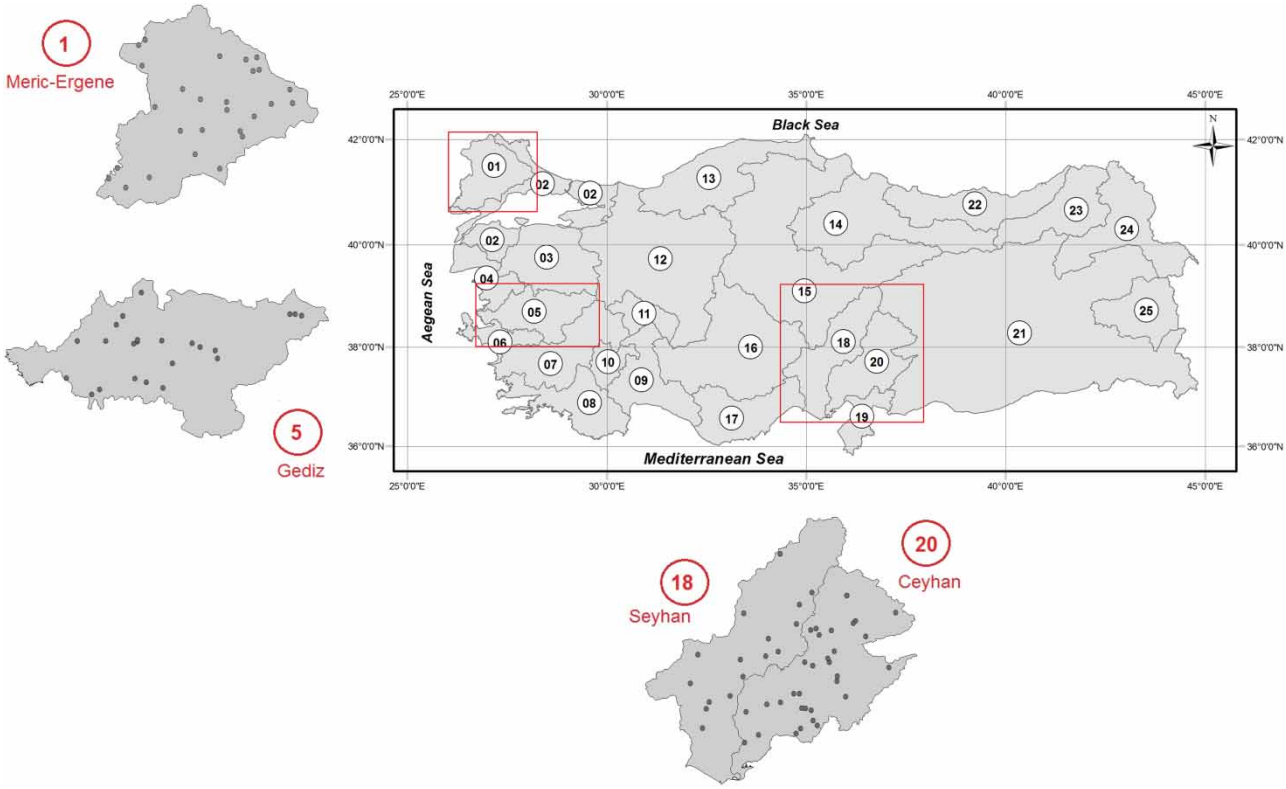


Figure 1 | Location of the basins with flow gauging stations.

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 to drain 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 into the Mediterranean Sea southerly. To the west of Ceyhan River basin is the Seyhan River. 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 in 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

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Ceyhan basins, respectively. Most of the streamflow gauges has 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 years 1939 to 2015. In total, 99 gauging stations with total of 2,627 station-year data were analyzed. This is a considerable amount of data for the low flow frequency analysis. In selecting the streamflow gauges, a particular attention was paid for taking data from the natural conditions with either no or least human-made influence. 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 in the unit l/s-km^2. The range of 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 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 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 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 (Smakthin 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

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(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 functions can be found in van Gelder (1999).

On semi-arid and arid regions, hydrologists may encounter streamflow time series that contain zero values. The same problem arises in the cold regions where the rivers are frozen during the winter season. Such data sets are called censored samples (Stendinger *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 nonzero 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 to 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 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 the D-day low flow data. The least square 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. 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, 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 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 $X > 0$.

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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 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 return periods 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 common used return periods, the fractions of non-zero values, k that would be greater are given in Table 3.

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

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 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 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 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

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which W2 and GEV was found equally the best. G2 has been the best twice (for 273-day low flow sequence in Meric-Ergene, 30-day low flow sequence in Gediz) and one of the best two probability distribution functions once (for 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 both 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, 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), Bulu & Aksoy (1998) found that W2, among LN2, N and W2 distributions, 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 using 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 higher number of parameters in the probability distribution functions are more advantageous to fit better the *D*-day low-flow sequences compared to probability distribution functions with lower number of parameters.

Once the best-fit probability distribution of the D-day low flow sequence was 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 at gauging station basis. The low flow-duration-frequency curves are useful tools for many purposes but particularly for practicing engineers. An engineer could 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 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 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 zero. One more point worth to mention is that no zero *D*-day low flow was observed in the Seyhan Basin. Therefore, the fraction of non-zero flows is always 100% that allow 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. As a quick reasoning for this could be the W3 probability distribution function 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

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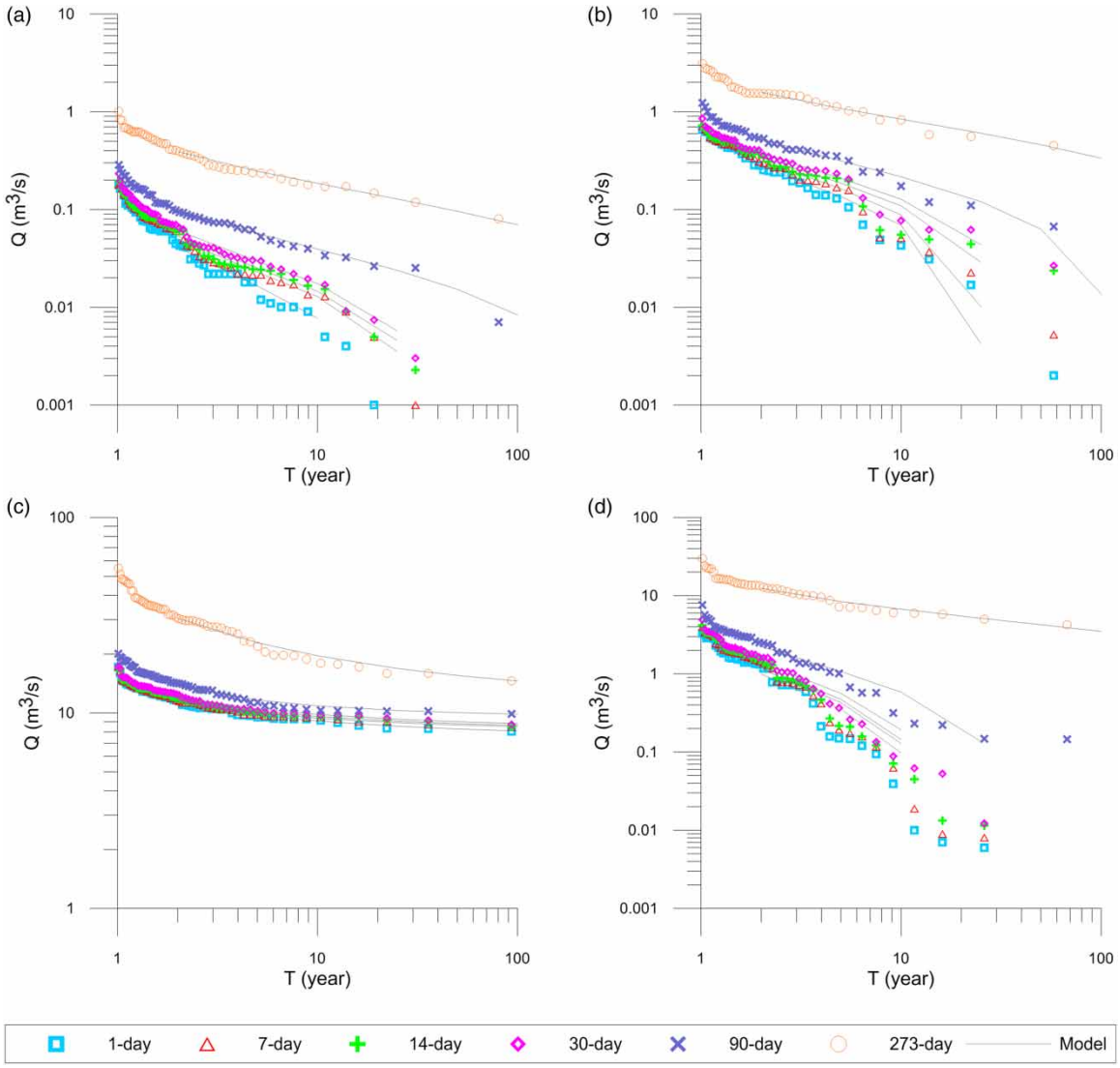


Figure 2 | Low flow-duration-frequency curves for stations (a) D01A031 in Meric-Ergene, (b) E05A024 in Gediz, (c) E18A001 in Seyhan and (d) E20A009 in Ceyhan.

low flow sequences of every gauging stations. 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 fit the 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 with 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 fo calculating the design low-flow discharges in intermittent rivers.

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