Annual flow duration curve model for ungauged basins

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ABSTRACT

A flow duration curve (FDC) plots the percentage of time that flow in a stream is equal to or exceeding a given value. In a gauged basin, it is obtained by sorting the observed flow from the largest to the smallest, and plotting against the corresponding exceedance probability. At ungauged basins where no data exist, the need for developing empirical methods emerges. This study aims at developing an FDC model for ungauged basins. The model is based on the normalized nondimensional annual mean flow quantiles. The annual mean flow is empirically calculated by a regression equation that takes drainage area and annual precipitation as input. Slope of the channel is additionally considered in the regression, however no better performance is achieved. Seyhan and Ceyhan basins in the Mediterranean region in southern Turkey are chosen as the study area. Data from 109 gauging stations are used for the calibration and validation of the model. Gauging stations on the tributaries are studied with a view to limiting anthropogenic activities on the rivers. Results of the application are found so promising that the model can be considered a good foundation for the development of FDCs at ungauged basins.

Key words | drainage area, flow duration curve, precipitation, regression, ungauged basin

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INTRODUCTION

A flow duration curve (FDC) is used to determine the discharge of a certain time percentage (quantile) in hydrological basins. It can simply be obtained by sorting the observed streamflow time series in the ascending order and plotting it against its corresponding duration (Castellarin *et al.* 2013). FDCs are useful tools for characterizing hydrological regimes and flow variability (Booker & Snelder 2012). They are widely used in the determination of the upper extreme events (floods) as well as in the calculation of low-flow characteristics of streams as mentioned by Vogel & Fennessey (1994, 1995), Smakhtin (2001); Castellarin *et al.* (2004) and Lane *et al.* (2005). The urban stormwater modelling (Petrucci *et al.* 2014), environmental flow allocation (Yang & Yang 2014) and the determination of hydropower potential and water availability at ungauged sites (Quimpo *et al.* 1983; Baltas 2012; Kim *et al.* 2014) are performed by using FDCs.

FDC-related studies started in the first half of the 20th century by Saville & Watson (1933) for producing weekly FDCs in North Carolina rivers. Searcy (1959) presented step-by-step how a long-term FDC is produced from short-term records. Due to the importance of water resources, FDCs have always been studied in the water-related development and planning projects for which extensive hydrological engineering practice is needed. Therefore, there are quite a high number of studies in the literature based on a wide range of methodologies such as regression equations, probabilistic and empirical approaches, analytical and statistical methods, and soft computational techniques applied at individual gauging stations or used at regional scale.

For example, Singh (1971), Dingman (1978) and Singh *et al.* (2001) established FDC models using regression equations based on morphological characteristics such as

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drainage area and elevation of the hydrological basin. Risley *et al.* (2008) estimated low-flow frequency and FDC at ungauged basins by a regression equation between mean flow, drainage area and precipitation.

Probability distribution functions have widely been used in the FDC literature. For example, a conjugate gradient algorithm was employed by Fennessey & Vogel (1990) to fit lognormal probability distribution function to the lower half of the observed FDCs. Cigizoglu (2000), Atieh *et al.* (2015) and Boscarello *et al.* (2016) can also be given as recent examples using the probabilistic approach. Muller *et al.* (2014), Zhang *et al.* (2015) and Muller & Thompson (2016) studied FDC with analytical and statistical methods. Recently, soft computational techniques such as artificial neural networks, gene expression programming and geostatistical methods have widely been applicable in the FDC literature (Pugliese *et al.* 2016; Atieh *et al.* 2017).

Not all hydrological basins are properly gauged. Therefore, regional FDCs have been studied widely with the aim of transferring information at gauged sites to ungauged sites. For example, Mimikou & Kaemaki (1985) developed regional FDCs for Greece by using morphological characteristics of the hydrological basin; Wittenberg (1987) combined the basin characteristics with the parameter of the probability distribution function in calculating the FDC quantiles; Yu & Yang (1996) calculated the quantiles based on regression equations using drainage area as input; Yu *et al.* (2002) compared this technique with the polynomial method; Mohamoud (2008) and Doulatyari *et al.* (2015) identified the dominant landscape and climate characteristics to develop regional FDC models for ungauged basins; Yasar & Baykan (2013) applied a regionalization procedure on karstic and non-karstic basins in Turkey for the determination of FDC; Niadas (2005) obtained a regional FDC model in nondimensional form for homogenous small basins. Similarly, Ganora *et al.* (2009) developed a regional model for the estimation of dimensionless FDC in sites with no or limited data. The comparative study of Swain & Patra (2017) on the regional FDCs for estimating streamflow in ungauged basins should finally be mentioned. As a last point, it should be emphasized that delineation of homogeneous regions by the so-called region of influence, principal component analysis, cluster analysis, discriminant analysis, etc., is an important issue when FDC is studied at regional scale (Holmes *et al.* 2002; Hsu & Huang 2017).

The FDC model of Singh *et al.* (2001), based on an empirical regression equation between the annual mean flow and the watershed drainage area, was improved here at the annual time scale by taking precipitation and slope of the channel into account as additional inputs. A case study for Seyhan and Ceyhan basins from the Mediterranean region in southern Turkey was implemented to show its applicability. Ungauged basins are expected to benefit from the developed model.

METHODS

FDCs are produced from the daily, weekly, 10-daily, monthly or annual flows depending on the need of the hydrological problem in hand. In this study, the annual time scale is used to improve the model of Singh *et al.* (2001). The improvement is that annual precipitation is taken as an input variable together with the drainage area in the empirical model to calculate the annual mean flow. It is expected that the ability of the model increases to better approach the annual mean flow of the basin. The model has the following steps as shown in Figure 1.

(a) Nondimensionalization: Annual mean flow time series of each gauging station is nondimensionalized by dividing with the long-term mean streamflow of the gauging station as:

$$q = \frac{Q}{\bar{Q}} \tag{1}$$

in which q is the nondimensional annual mean flow, Q is the observed annual mean flow (dimensional) and $\bar{Q}$ is the long-term mean flow (dimensional) of the gauging station.

(b) Normalization: The nondimensional annual mean flow is transformed to fit normal distribution using a proper transformation such as:

$$W = q^{\theta} \tag{2}$$

where parameter θ is determined by trial-and-error.

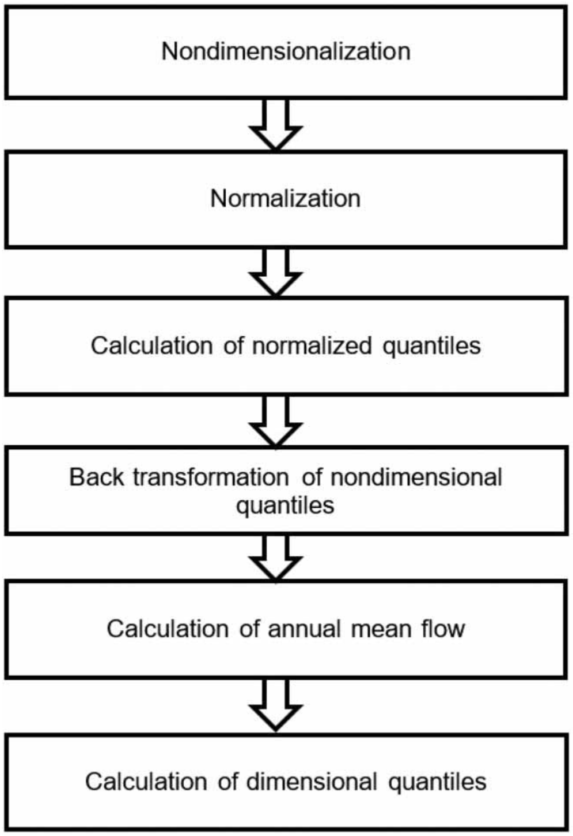

Figure 1 | Steps of the model.

(c) Calculation of normalized quantiles: The mean value and standard deviation of the normalized streamflow time series are calculated. For the normal variable:

$$W_D = \mu_w + Z_D\sigma_w \tag{3}$$

in which Z_D is taken from the standard normal distribution. In this case, W_D gives the transformed streamflow corresponding to the exceedance probability D.

(d) Back transformation of nondimensional quantiles: For the known W_D and θ, the q-quantile of exceedance probability D, q_D, can be derived by inverse transformation of:

$$q_D = W_D^{1/\theta} \tag{4}$$

(e) Calculation of annual mean flow: An empirical model is proposed, which accommodates the drainage area of the basin (A in km^2), annual precipitation (P in mm) and topographical slope of the river channel (S) to calculate the annual mean flow of each basin. Power functions given as:

$$\bar{Q} = C_1A^m \tag{5a}$$

$$\bar{Q} = C_2A^mP^n \tag{5b}$$

$$\bar{Q} = C_3(AP)^m \tag{5c}$$

$$\bar{Q} = C_4A^mS^n \tag{5d}$$

$$\bar{Q} = C_5(AP)^mS^n \tag{5e}$$

were considered for alternative use in calculating annual mean flow ($\bar{Q}$). In Equation (5a)–(5e), C_1, C_2, C_3, C_4 and C_5 are coefficients, m and n are powers to be determined through regression.

(f) Calculation of dimensional quantiles: Q_D at any exceedance probability D for an ungauged basin can be determined by:

$$Q_D = \bar{Q}q_D \tag{6}$$

STUDY AREA

Seyhan and Ceyhan River basins in the Mediterranean region located in southern Turkey were selected as the study area (Figure 2). The Seyhan and Ceyhan River basins have drainage areas of 20,450 and 21,982 km^2, respectively. Zamanti, Goksu and Seyhan are the main rivers in the Seyhan basin and Ceyhan River in the Ceyhan basin all flow southerly and discharge into the Mediterranean Sea. The upper and middle parts of the Seyhan basin are characterized with rain-fed agriculture that spreads over hilly regions while the lower flat part of the basin has mainly irrigated agriculture of such as maize, wheat, fruits and other cash crops (Watanabe 2007). The main sectoral activities in the two basins include agriculture on the Zamanti River; hydroelectric power generation on the Goksu River; and agriculture, hydroelectric power generation and

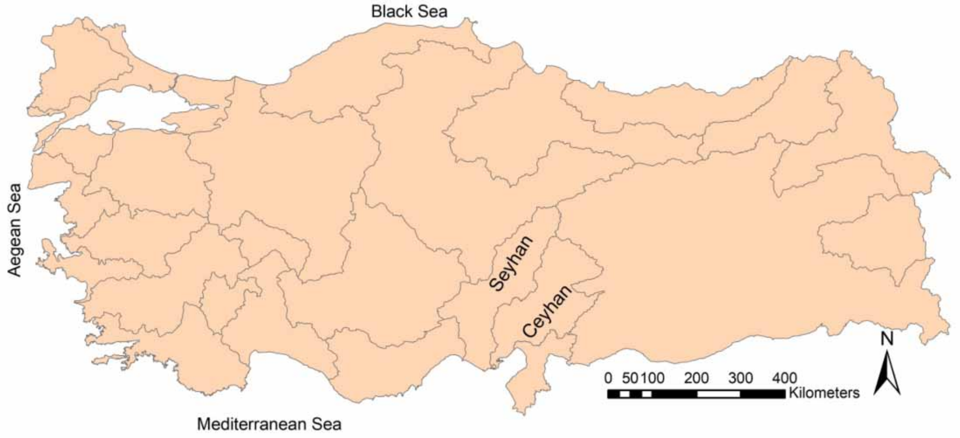

Figure 2 | Location map of Seyhan and Ceyhan basins in Turkey.

industrial sector on the Seyhan River (Tuncok 2016). The Ceyhan basin is bordered by the Seyhan basin in the west and northwest, the Asi (Orontes with its ancient name) in the south, and the Euphrates in the east and northeast (Tanriverdi *et al.* 2010). Forty-one percent of the basin is covered by the actively used agricultural lands. The southern part of both basins is called Cukurova Plain, which is one of the most important agricultural production areas in Turkey (Gumus & Algin 2017).

DATA

Streamflow data used in this study were taken from State Hydraulic Works (DSI) of Turkey. Annual mean flow data of streamflow gauging stations with practically no anthropogenic interruption were considered. In case a reservoir exists at the upstream of the gauging station, data before the reservoir is established were taken into account while any data after the reservoir were omitted. In total, 109 gauging stations were used, 20 of which were selected for the validation of the model while the remaining 89 were used for the calibration (Table 1). Particular attention has been paid while selecting the validation gauging stations, such that they are distributed over the basins as homogeneous as shown in Figure 3. The shortest record of streamflow data is only one year while the longest has 60 years of recorded data. In total, 1,792 station-year annual flow data were used for the modelling; 1,452 station-years for calibration and 340 station-years for validation.

Precipitation data were taken from 14 meteorological stations of General Directorate of Meteorology (MGM) and 24 stations of State Hydraulic Works (DSI) with the shortest and longest recorded data of 11 and 57 years, respectively. Each meteorological station was assigned to the nearest streamflow gauging station. Topographical slope of the river channel was calculated by using the freely available ASTER GDEM with a resolution of 30 m and accuracy of 7–14 m.

Statistical characteristics of the annual mean flow data are provided in Table 2 for the calibration and validation gauging stations separately. The minimum and maximum values of the annual mean flow change at two orders of magnitude from 0.68 to 46.24 L/s-km^2 for the gauging stations in Ceyhan basin while it is three orders of magnitudes for the Seyhan basin within the range of 0.40–102.34 L/s-km^2. Not only the mean flow but also the minima and maxima

Table 1 | Streamflow data used in the study

	Basin	Number of gauging stations	Shortest record (year)	Longest record (year)	Station-Year
Calibration	Seyhan	35	1	48	443
	Ceyhan	54	1	60	1,009
Subtotal		89			1,452
Validation	Seyhan	8	5	17	90
	Ceyhan	12	3	49	250
Subtotal		20			340
Total		109			1,792

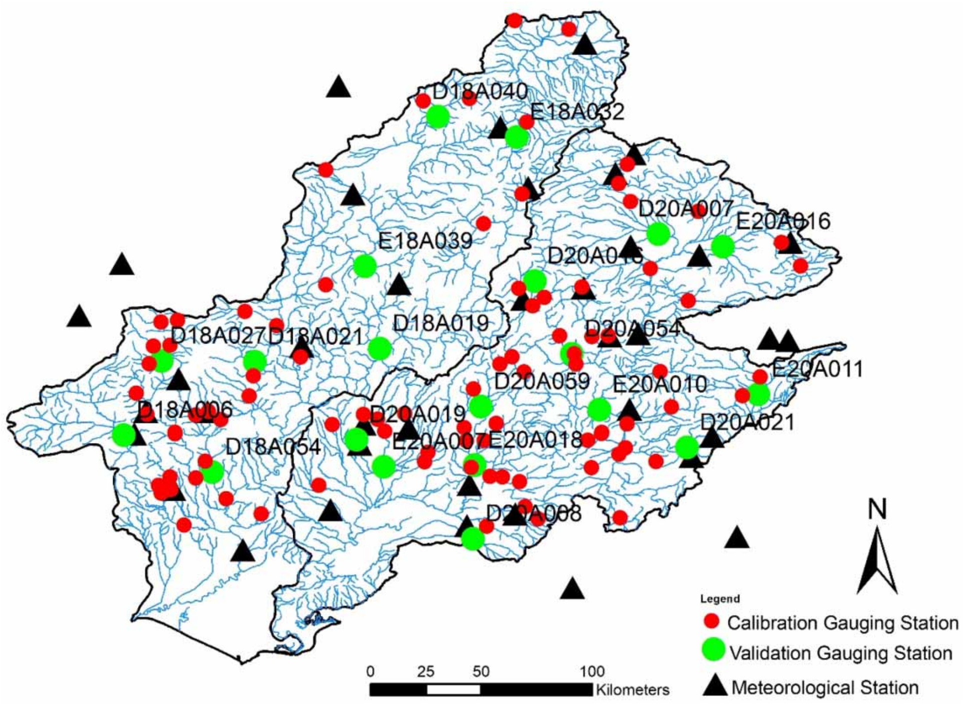

Figure 3 | Streamflow gauging stations and meteorological stations in the study area.

of the data set changes within wide ranges. The range is within three orders of magnitude for minima, four orders of magnitude for maxima of the gauging stations selected from the two basins for the calibration stage. This variability is reflected by the standard deviation and coefficient of variation. Also the skewness coefficient has great variability. Figure 4 is given for a better understanding of the skewness behavior of the annual mean flow data. It is seen that only 15% of the data set is non-skewed while the rest is mostly positively skewed.

Characteristics of the input variables of the empirical model (drainage area, slope and precipitation) are provided in Table 3. When the variability in the input variables are concerned, the behavior is not very much different than the annual mean flow. The variability in the input variables is obvious as it is seen that the drainage area of the basins changes at four orders of magnitudes, slope and precipitation have ranges within two orders of magnitude.

APPLICATION OF THE MODEL

As illustrated in Figure 1, first, annual mean flow data in each gauging station were converted to a nondimensional

Table 2 | Statistical characteristics of annual mean flow data

		Mean (L/s-km^2)		**Min (L/s-km^2)**		**Max (L/s-km^2)**		**Std. dev (L/s-km^2)**		**C_v**		**C_s**	
Stage	**Basin**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Calibration	Seyhan	0.40	102.34	0.03	41.95	0.78	174.41	0.23	31.05	0.12	0.82	−1.08	1.74
	Ceyhan	0.68	46.24	0.31	43.01	0.88	117.31	0.10	20.60	0.01	0.74	−1.87	2.75
Validation	Seyhan	0.47	19.51	0.13	11.44	0.90	28.46	0.24	5.54	0.24	0.52	−1.14	0.72
	Ceyhan	5.00	32.01	0.97	10.62	10.00	54.13	2.00	11.80	0.26	0.71	−1.15	1.73

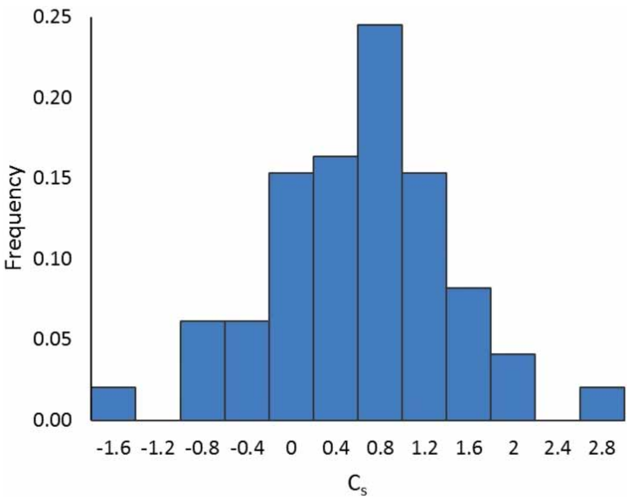

Figure 4 | Histogram of the skewness coefficient of the annual mean flow data.

form by dividing with the long-term average of the gauging station. The nondimensional annual mean flow time series was transformed into normal distribution with the power transformation in Equation (2) by taking $\theta = 0.405$ determined after trial-and-error. The histogram of the normalized nondimensional flows is given in Figure 5, showing that flow data fit the normal distribution well. The normality was checked by the Chi-square and Kolmogorov-Smirnov tests, both accepts that the transformed annual mean flow data set has normal distribution.

In Table 4, the standard normal variable is given for different exceedance probability D. Having the mean and standard deviation of the transformed flow in hand, the transformed flow corresponding to any exceedance probability is calculated by Equation (3). Finally, Equation (4) is performed and the nondimensional annual mean flow corresponding to any exceedance probability D is

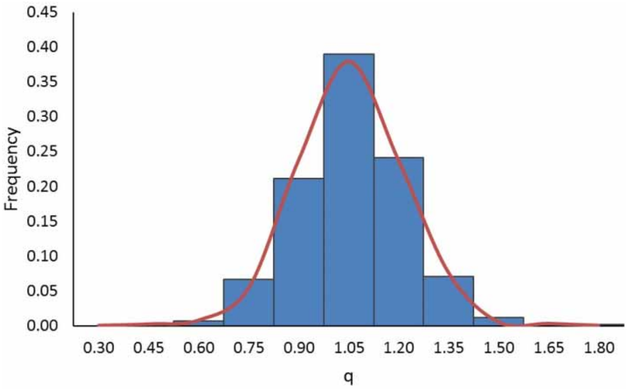

Figure 5 | Histogram of the normalized nondimensional flows.

calculated. This is the tabular form of the FDC visualized as in Figure 6 for the calibration and validation gauging stations. The nondimensional FDC fits both the calibration and validation data sets quite well.

In order to calculate the dimensional quantiles of the FDC, an empirical model needs to be developed. This has been performed by Singh *et al.* (2001) empirically through a nonlinear regression between the mean flow and the drainage area of the hydrological basins. As an improvement in this study, annual mean flow was calculated by the same technique in the form of Equations (7a)–(7e). The models best-fit to the calibration data were obtained as:

$$\bar{Q} = 0.0493A^{0.768} \tag{7a}$$

$$\bar{Q} = 0.000225A^{0.750}P^{0.838} \tag{7b}$$

$$\bar{Q} = 0.000378(AP)^{0.755} \tag{7c}$$

Table 3 | Statistical characteristics of drainage area, slope and precipitation

		A (km²)		*S*		*P* (mm)	
Stage	**Basin**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Calibration	Seyhan	9.9	1896.9	0.01347	0.12749	269.7	1006.3
	Ceyhan	23.0	2787.3	0.01021	0.13190	304.8	1083.3
Validation	Seyhan	103.2	1833.0	0.01989	0.06313	373.7	1006.3
	Ceyhan	131.1	3498.8	0.00671	0.07301	400.5	1083.3

Table 4 | Normalized nondimensional flows corresponding to the exceedance probability *D*

D (%)	z_D	w_D	q_D
5	1.64	1.25	1.72
10	1.28	1.19	1.53
15	1.04	1.15	1.41
20	0.84	1.12	1.31
25	0.67	1.09	1.23
30	0.52	1.06	1.17
35	0.39	1.04	1.11
40	0.25	1.02	1.05
45	0.13	1.00	1.00
50	0.00	0.98	0.95
55	−0.13	0.96	0.90
60	−0.25	0.94	0.86
65	−0.39	0.92	0.81
70	−0.52	0.90	0.76
75	−0.67	0.87	0.72
80	−0.84	0.85	0.66
85	−1.04	0.81	0.60
90	−1.28	0.77	0.53
95	−1.64	0.72	0.44

$$\bar{Q} = 0.0901A^{1.017}S^{0.606} \tag{7d}$$

$$\bar{Q} = 0.000332(AP)^{0.813}S^{0.175} \tag{7e}$$

in which the basin area (A) was used in km^2, annual precipitation (P) in mm and slope (S) as the ratio to calculate annual mean flow ($\bar{Q}$) in m^3/s.

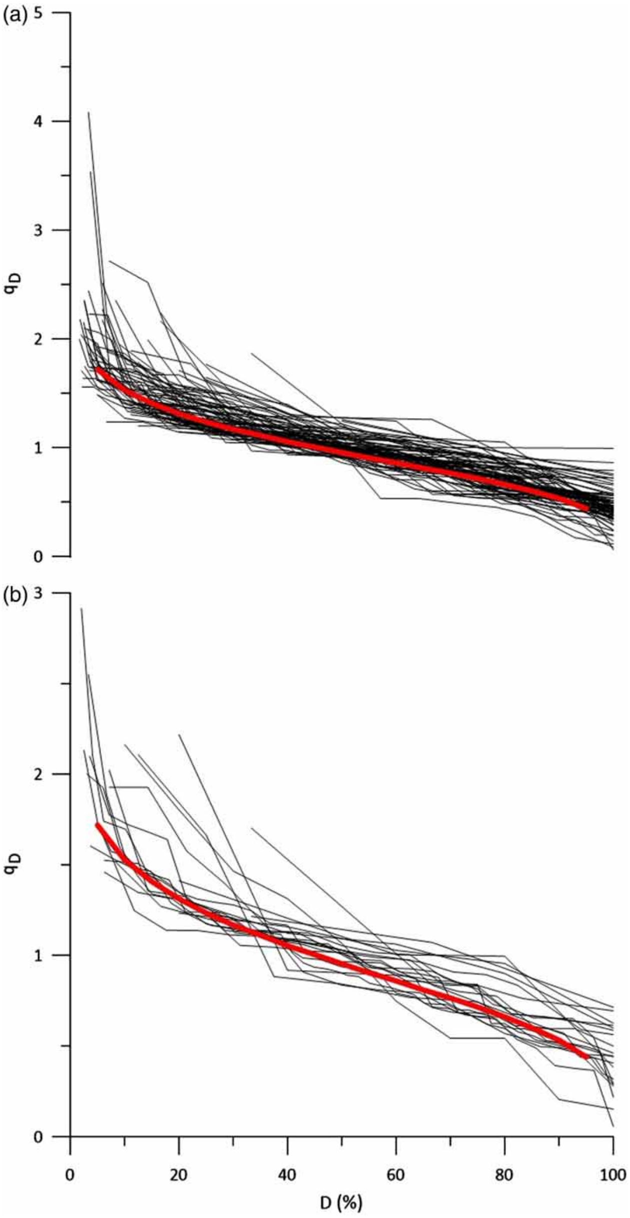

Figure 6 | Nondimensional FDCs fitted to (a) calibration gauging stations and (b) validation gauging stations.

DISCUSSION

Determination coefficient (r^2), root mean square error (RMSE) and mean absolute error (MAE) were calculated as the performance criteria of each empirical model in Equation (7) for the calibration and validation stages separately and are given in Table 5. It is seen that the drainage area-based model (Equation (7a)) has a considerable performance in calculating the annual mean flow. The performance of the models increased with the use of precipitation as an additional variable as in Equations (7b) and (7c). However, the topographical slope of the river channel in Equations (7d) and (7e) did not provide a better performance. It is also seen that Equations (7b) and (7c) are the best among the tested alternatives. In Equations (7b) and (7c), as the input variable, annual precipitation was used together with the drainage area.

Table 5 | Performance criteria between the observed and calculated annual mean flows

		Equation				
Stage	**Criteria**	**7(a)**	**7(b)**	**7(c)**	**7(d)**	**7(e)**
Calibration	r^2	0.815	0.883	0.882	0.868	0.889
	RMSE (m^3/s)	2.025	1.612	1.616	1.712	1.571
	MAE	1.380	1.209	1.217	1.180	1.165
Validation	r^2	0.629	0.738	0.733	0.555	0.702
	RMSE (m^3/s)	4.115	3.414	3.434	4.576	3.634
	MAE	3.055	2.209	2.262	3.187	2.256

Equations (7b) and (7c) perform quite similarly. However, Equation (7c) has a simple structure with one free variable which is the multiplicative form of the drainage area and precipitation (AP). Equation (7c) has two parameters while the number of parameters increases to three in Equation (7b). Equation (7c) is more advantageous as it is a more parsimonious model than Equation (7b) in terms of the number of parameters. Based on its better performance compared to Equation (7a) and its more parsimonious structure compared to Equation (7b), Equation (7c) was preferred to calculate annual mean flow in the development of FDC model. Figure 7 visualizes how well Equation (7c) fits the annual mean flow.

For the validation of the FDC model, Equation (7c) was applied on 20 gauging stations listed in Table 6 to check its ability in obtaining the observed FDC of the annual mean flow. As the performance measure, relative error (RE), RMSE and MAE were considered. RE was used for the comparison of the nine quantiles of the FDC of each gauging station; RMSE and MAE for the assessment of the whole FDC. RE between the modelled and observed quantiles takes reasonable values when stations D18A027 and D18A040 were excluded. The extremely high RE in these two particular gauging stations are due to their annual mean flows which are the lowest two among the 20 validation gauging stations. This should be an expected result because of the definition of RE which takes high values for low annual mean flow data. Due to this disadvantage of RE, RMSE and MAE were also used as performance criteria. When RMSE and MAE are considered, the lowest was found in station E18A032 in Seyhan basin, and D20A008 in Ceyhan.

For the visual demonstration of the performance of the FDC model, from each basin, the four gauging stations with the longest streamflow time series were selected (Figure 8). Reasonable results are mostly seen with the extreme exception that FDC in station D18A027 in the Seyhan River basin was overestimated. The reason for the low performance of the FDC model for this individual gauging station is explained by its different hydrological regime in terms of annual mean flow which is the second lowest of all validation gauging stations in the two basins.

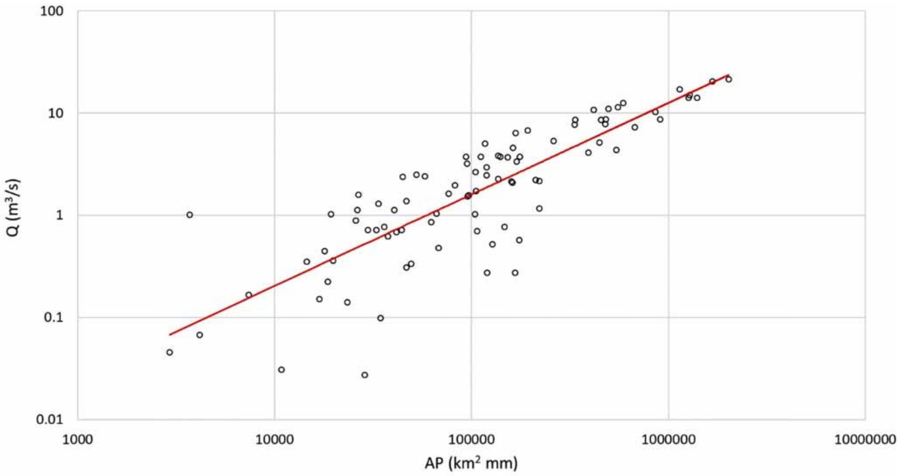

Figure 7 | Empirical model (Equation (7c)) to calculate annual mean flow.

Table 6 | Performance criteria calculated between the observed and modelled FDCs of the validation gauging stations

		RE (%)										
Basin	**Stations**	Q_{10}	Q_{20}	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	**RMSE (m^3/s)**	**MAE**
Seyhan	D18A006		46.42	40.68	37.92	28.35	19.04	14.65	7.98	4.49	2.80	2.31
	D18A019	−28.87	−31.55	−24.49	−28.36	−33.82	−38.18	−35.46	−34.24	−42.27	3.72	3.64
	D18A021	−9.43	−15.67	−15.79	−22.87	−25.32	−29.61	−26.98	−22.58	−32.22	1.70	1.66
	D18A027	316.2	321.54	300.12	272.19	279.48	297.86	261.85	233.86	189.8	11.13	10.55
	D18A040	1281.85	1290.2	1409.64	1711.49	1890.47	1769.15	1791.24	1671.42	1746.35	2.36	2.26
	D18A054		−2.79	−10.78	−16.9	−20.27	−23.56	−29.51	−36.78	−38.44	2.17	1.99
	E18A032	11.16	15.22	4.86	−2.95	−7.32	−12.62	−16.31	−23.07	−21.36	0.23	0.21
	E18A039		39.71	34.15	31.43	29.81	28.74	15.03	−0.18	16.11	0.49	0.42
Ceyhan	D20A007	9.73	12.1	15.12	8.13	3.85	6.84	21.83	15.46	3.03	1.23	1.09
	D20A008	−13.34	−3.59	−6.61	−3.94	1.89	1.83	2.34	4.67	−0.02	0.20	0.13
	D20A016	7.92	9.65	5.83	6.63	2.99	5.62	−2.47	16.02	11.63	0.26	0.23
	D20A019	−37.28	−35.37	−29.26	−28.75	−20.59	2.06	25.17	8.16	130.82	1.96	1.55
	D20A021		−63.26	−53.76	−28.74	−34.5	−40.03	−34.9	−27.87	−32.18	8.07	6.08
	D20A054	−39.59	−38.17	−39.71	−42.65	−44.95	−44.99	−47.55	−44.94	−51.55	2.32	2.29
	D20A059	7.11	10.58	18.42	19.06	14.49	13.32	21.89	32.88	66.15	0.54	0.52
	E20A007		−51.53	−41.24	−18.08	−22.95	−25.26	−30.93	−32.58	−31.55	4.91	3.86
	E20A010	−19.39	−20.19	−25.16	−26.01	−16.54	−10.91	−8.93	−9.17	−11.31	6.63	5.62
	E20A011				−34.27	−38.24	−42.13	−45.3	−47.28	−51.98	4.24	4.23
	E20A016	−9.11	3.03	7.57	5.77	3.23	−2.29	−1.74	−6.59	−6.8	0.38	0.30
	E20A018				−33.44	−27.39	−17.67	−7.42	−6.89	−10.28	1.13	0.85

While the performance of the model is quite changeable in the dimensional FDC, no extreme dissimilarity was seen in its nondimensional form (see Figure 6(b)). It becomes understandable that the dissimilarity in the dimensional FDC is due to the empirical model that does not fit properly to such particular gauging stations. As the gauging station has lower annual mean flow compared to all other stations, the developed model overestimates the FDC. With the same reason, the FDC model underestimates the annual mean flow for station D18A019 which has higher annual mean flow than the average of gauging stations used in the model development.

In order to generalize the results in Figure 8, it can be stated that FDC underestimates for gauging stations with higher annual flow, and overestimates for those with lower annual flow than the average of the 89 calibration stations. This is linked to the empirical model that lumps the calibration gauging stations in one unique model with two parameters and one free variable, the multiplicative form of the basin drainage area and precipitation. However, the results are quite acceptable when a whole picture is considered, and as a general achievement, they are considered encouraging and promising for further improvement.

CONCLUSIONS

An FDC model is presented in this study as an effort to make a slight contribution to the existing FDC literature. The model is based on the normalized nondimensional annual streamflow data. It accommodates an empirical regression model that counts not only on the drainage area of the hydrological basin as usual but also precipitation as an additional independent variable to calculate the annual mean flow. Slope of the basin is also considered among the independent variables, nevertheless its inclusion does not improve the results. Therefore, drainage area and precipitation as one unique variable in multiplicative form is considered. The model is applied on almost 1,800 station-year data at annual scale compiled from 100+ stream gauges from two neighboring basins in southern Turkey. The results are found promising although the model may have a low performance in some particular stations,

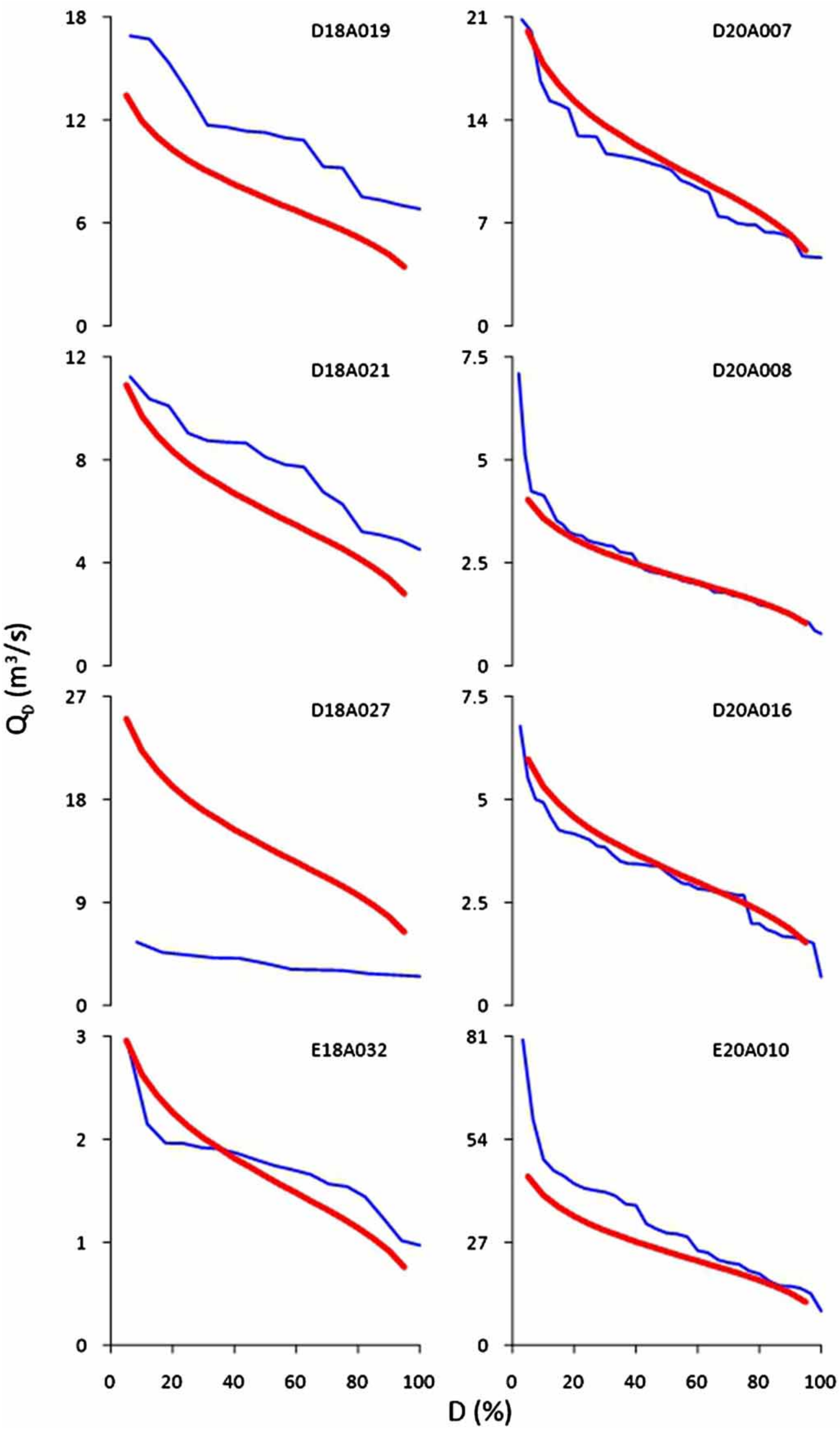

Figure 8 | Observed (broken line) and modelled (continuous line) FDCs for selected validation gauging stations.

deviating from the average hydrological behavior of the basin. Higher performance might be expected with empirical models better approaching the annual mean flow. This is the key issue of the FDC development methodology to be further analyzed.

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