A parametric approach to estimate streamflow quantiles using annual flow–duration curves

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Abstract

The flow–duration curve (FDC) is a significant instrument used in solving many hydrological and environmental problems such as evaluating water quality, examining water supply and use for hydroelectric generation and irrigation, and investigating sedimentation and low flows. However, the insufficiency of flow data allows FDCs to be used only for gauged basins or gauged locations in a basin. Therefore, obtaining regional relationships that provide effective estimates about a region, by using the records of existing stations in the region, becomes necessary. This paper illustrates a simple parametric approach, where droughts are characterized by using the lower part of the annual flow–duration curve. The paper uses the actual instantaneous flow data of 30 basins in Western Anatolia and 21 basins in Southwestern Anatolia, Turkey to offer a new perspective for the estimation of streamflow quantiles using Areal Scale Factors (*ASF*s), which efficiently represent the relationship between flow quantile and basin area.

1 Introduction

Various approaches have been adopted to determine the flow variability by considering low flows, high flows (floods), annual flows, and the seasonal variation of flows in different ways. The variability of the flow in a basin and/or a stream is related to many climatic and hydrological factors (precipitation, evapotranspiration, infiltration, surface storage, land slope, vegetation, and soil type), and one of the most common tools used by hydrology and environmental sciences in examining this variability is the flow–duration curve (FDC). Flow period is also an important factor that significantly affects flow variability. FDC graphs the relationship between a certain flow magnitude and a time period at which the flow magnitude is equalized or exceeded (Vogel and Fennessey 1995).

The first use of FDC dates back to Clemens Herschel in 1880, and FDCs have been widely used in many environmental and hydrology studies worldwide. A very comprehensive study of FDC applications is presented by Vogel and Fennessey (1994). The main and most common problem in FDC application has been the scarcity of flow data. Therefore, the regionalization of FDCs emerges as an important instrument when dealing with ungauged basins or short flow records.

The estimation methods of regional FDCs are usually categorized into three groups (Castellarin et al. 2004 ; Shu and Ouarda 2012):

i. Statistical methods, which assign a regional parent frequency distribution by estimating regional FDCs at ungauged sites (Fennessey and Vogel 1990; Leboutillier and Waylen 1993; Yu and Tang 2000; Singh et al. 2001; Yu et al. 2002; Croker et al. 2003; Claps et al. 2005)
ii. Parametric methods, in which the FDCs of the study area are assumed represented by analytical equations (Quimpo et al. 1983; Mimikou and Kaemaki 1985; Franchini and Suppo 1996; Yu et al. 2002; Mohamoud 2008)
iii. Graphical methods, which construct regional dimensionless FDCs standardized by an index flow (Smakhtin et al. 1997)

In terms of their production, two different types of FDCs are encountered in the literature. The first, the traditional one, represents a long-term demonstration of the flow regime using all the long-term flow records and is reported in the literature as period-of-record FDC (Vogel and Fennessey 1994). The second one is based on the annual interpretation of FDCs (LeBoutillier and Waylen 1993; Vogel and Fennessey 1994) and considers FDCs for separate years (annual flow–duration curves, AFDCs); each one is constructed similarly to FDC, using only annual hydrometric information (Castellarin et al. 2013). A conjunctive evaluation of AFDCs provides a perspective of the inter annual variability of the FDCs, which allows the estimation of the median of the AFDCs. The median AFDC is a hypothetical FDC representing the annual flow regime for a typical hydrological year. AFDCs are presented to be less sensitive to the period of record than traditional FDCs, specifically in the region of low flows, and can be efficiently applied in generating flood and low flow indices (Vogel and Fennessey 1994; Castellarin et al, 2013).

This paper belongs to the second group (parametric methods) in the categorization of FDC studies made by Castellarin et al. (2004) and proposes a methodology that uses the lower part of AFDCs obtained from daily flow records. The relationship between basin characteristics and streamflow quantiles (Q_{30}, Q_{40}, Q_{50}, Q_{60}, Q_{70}, Q_{80}, Q_{90}, Q_{95}, and Q_{99}) is examined, and the findings reveal that the flow quantiles could be estimated significantly depending on the basin area. Accordingly, areal scale factors (*ASF*s) are calculated for each streamflow quantile. Afterward, the regional envelope curves, which successfully represent the relationship between *ASF*s and exceedance probabilities, are obtained. A regional envelope curve provides the estimation of the flow of a certain exceedance probability related to the basin size for an ungauged location of a region.

2 Study Area And Dataset

This study was carried out for the basins located in the western and southwestern regions of the Anatolian peninsula, which forms a large part of Turkey (Fig. 1). The climate of both regions is Mediterranean on the coasts. Summers are hot and dry. Winters are mild and rainy. Interiors are cold and usually see some snowfall during the winter. The climate is semi-arid continental. The average annual rainfall is about 596 mm (1938–2020) in Western Anatolia and 608 mm (1938–2020) in Southwestern Anatolia. Precipitations are concentrated in the winter period, and no precipitation usually occurs in July and August.

Although the two regions in the study show similar climatic features, they differ geologically. In Western Anatolia, 85% of topographic surfaces is composed of metamorphic and volcanic rocks, whereas in Southwestern Anatolia, 80% of the surface is composed of sedimentary rocks (limestone). The vast majority of groundwater resources in Southwestern Anatolia are due to the existence of complexes characterized by high infiltration. The geological formation of the region clearly highlights the significance of the outcropping of limestone complexes in relation to the infiltration and circulation of rainwater. In such basins, finding a direct relationship between the area and the amount of water flowing into the basin outlet is difficult (Franchini and Suppo 1996). Therefore, the effect of limestone complexes on the drainage mechanism and low flow characteristics is significant, which remarkably differs from non-karstic regions such as Western Anatolia.

Daily streamflow data are provided for the study by State Water Works of Turkey. Only unregulated river basins with a minimum 10 years of data are considered. Thus, the number of flow gauging stations used in the study decrease to 30 in Western Anatolia and 21 in Southwestern Anatolia. The average daily flows of the basins range from 0.43 m^3/s to 39.64 m^3/s in Western Anatolia and from 0.08 m^3/s to 27.47 m^3/s in Southwestern Anatolia. A substantial number of the rivers in southwestern Anatolia are fed by groundwater. The minimum record length is 10 years, the maximum record length is 54 years, and the mean sample size is approximately 20 years in both regions. The basin areas range from 32 km^2 to 15.848 km^2 in Western Anatolia and from 8 km^2 to 2.448 km^2 in Southwestern Anatolia. The average annual rainfall varies between 556 and 658 mm in Western Anatolia and between 526 and 729 mm in Southwestern Anatolia. The main hydrological and geographical characteristics of the basins and flow gauging stations are given in Tables 1 and 2 for Western Anatolia and Southwestern Anatolia, respectively.

Table 1
Basin characteristics in Western Anatolia. The basins used for the validation are bolded.

	Catchment	Drainage Area (km^2)	Mean Flow (m^3/s)	Annual Rainfall (mm)	Altitude (m)	Latitude (ºN)	Longitude (ºE)
1	Orhaneli Creek at Kucukilet	1622	5,14	631	795	39,62	29,46
2	Atnos Creek at Balikli	1384	7,67	601	94	39,63	28,03
3	**Emet Creek at Dereli**	**1126**	**4,61**	**579**	**557**	**39,46**	**29,26**
4	Kille Creek at Buyukbostanci	544	2,66	609	105	39,57	27,94
5	**Simav Creek at Osmanlar**	**1254**	**7,74**	**571**	**271**	**39,26**	**28,32**
6	Dursunbey Creek at Sinderler	975	5,86	622	294	39,63	28,73
7	**Zeytinli Creek at Zeytinli**	**123**	**3,18**	**572**	**35**	**39,62**	**26,95**
8	Manastir Creek at Kavaklar	32	1,02	576	55	39,59	26,83
9	Inonu Creek at Inonu	73	0,86	580	65	39,58	27,15
10	**Cumalidere Creek at Cumali**	**85**	**0,21**	**562**	**115**	**39,13**	**27,48**
11	Yagcili Creek at Yagcili	86	0,63	564	210	39,34	27,64
12	Medar Creek at Kayalioglu	902	3,34	561	77	38,89	27,77
13	**Kum Creek at Killik**	**3189**	**7,94**	**562**	**54**	**38,77**	**27,67**
14	Selendi Creek at Derekoy	690	2,38	598	345	38,70	28,70
15	Deliinis Creek at Topuzdamlari	735	3,29	596	381	38,72	28,56
16	Murat Creek at Sazkoy	176	1,66	585	790	38,96	29,51
17	**Yigitler Creek at Yigitler**	**64**	**0,72**	**579**	**158**	**38,41**	**27,61**
18	Tabak Deresi at Çaltılı	81	1,09	600	137	38,46	28,05
19	**Gediz River at Muradiye Bridge**	**15848**	**39,64**	**556**	**17**	**38,68**	**27,33**
20	Ahmetli Creek at Derekoy	95	0,74	590	125	38,49	27,94

	Catchment	Drainage Area (km^2)	Mean Flow (m^3/s)	Annual Rainfall (mm)	Altitude (m)	Latitude (ºN)	Longitude (ºE)
21	Uladi Creek at Yakapinar	69	0,43	572	120	38,24	27,55
22	**Cine Creek at Kayirli**	**948**	**4,79**	**636**	**262**	**37,42**	**28,13**
23	Buyukmenderes River at Burhaniye	12799	21,40	630	120	37,95	28,74
24	Buyukmenderes River at Citak Bridge	3946	6,88	598	802	38,16	29,64
25	**Yenidere Creek at Calikoy**	**669**	**1,14**	**647**	**855**	**37,59**	**28,92**
26	Akcay Creek at Degirmenalani	855	7,66	653	397	37,34	28,72
27	Sarhos Creek at Goktepe	236	1,16	648	390	37,42	28,56
28	**Buyukmenderes River at Cogasli**	**4664**	**7,28**	**610**	**617**	**38,19**	**29,39**
29	Mortuma Creek at Yemisendere	170	1,63	658	478	37,26	28,62
30	Banaz Creek at Ulubey	2286	4,85	605	531	38,37	29,31

Table 2
Basin characteristics in Southwestern Anatolia. The basins used for the validation are bolded.

	Catchment	Station Nr	Drainage Area (km^2)	Mean Flow (m^3/s)	Annual Rainfall (mm)	Altitude (m)	Latitude (ºN)	Longitude (ºE)
1	Yenice Creek at Zindan Bogazi	D09A002	62	3,068	561	1250	37,81	31,09
2	Dim Creek Irrigation Channel	D09A006	195	0,967	580	38	36,55	32,12
3	**Korkuteli Creek at Salamur Bogazi**	**D09A011**	**131**	**0,974**	**595**	**1190**	**37,13**	**30,05**
4	Kucukaksu Creek at Gebiz	D09A034	239	4,36	587	62	37,13	30,94
5	Aglasun Creek at Aglasun	D09A042	49	0,566	**582**	1100	37,64	30,53
6	**Duden Creek at Weir**	**D09A056**	**1782**	**16,587**	**685**	**96**	**36,94**	**30,76**
7	Sücüllü Creek at Dam Inlet	D09A065	103	0,594	**526**	1198	38,39	31,13
8	Karpuz Creek at Uzunlar	D09A067	303	4,192	576	100	36,74	31,62
9	**Kargi Creek at Turkler**	**D09A068**	**336**	**6,801**	**567**	**16**	**36,61**	**31,80**
10	Oba Creek at Kadipinari	D09A084	46	2,071	580	91	36,59	32,08
11	Aksu River at Belence	D09A086	349	4,88	584	1000	37,62	31,12
12	**Degirmendere River at Sutculer**	**D09A088**	**131**	**1,453**	**591**	**750**	**37,47**	**30,98**
13	Çandir Creek at Yemisli Pinar	D09A095	164	1,788	**700**	160	36,83	30,47
14	Basak River at Yanikkoy	D09A100	223	3,315	584	1085	37,66	31,16
15	**Doyran River at Doyran**	**D09A111**	**106**	**0,773**	**700**	**145**	**36,89**	**30,51**
16	Esen Creek at Kinik	815	2448	27,471	609	8	36,36	29,32
17	Ballik River at Ballik	D08A018	126,2	0,757	**641**	1091	37,22	29,67
18	**Basgoz Creek at Gokbuk**	**D08A049**	**222,2**	**3,47**	**554**	**208**	**36,46**	**30,46**

	Catchment	Station Nr	Drainage Area (km^2)	Mean Flow (m^3/s)	Annual Rainfall (mm)	Altitude (m)	Latitude (ºN)	Longitude (ºE)
19	Akcay Creek at Gombe	D08A078	114,5	1,243	**602**	80	36,53	29,67
20	Cataloyuk River at Karaculha	D08A106	8	0,075	637	1340	36,95	29,64
21	**Geyik Creek at Nif**	**D08A109**	**8,2**	**0,233**	**729**	**1035**	**36,85**	**29,17**

3 Construction Of Afdcs

As explained in the previous section, FDCs provide significant information about streamflows and usually appear in the literature in two different forms as period-of-record FDCs and AFDCs. The difference between traditional FDCs and AFDCs is that the former is obtained by using streamflows over the whole available record period, whereas the latter is constructed by using the flow records of separate years. The use of a traditional period-of-record FDC for regionalization limits the representation of the flow regime to the specific record period for which the FDC is constructed (sampling error, Copestake and Young 2008; Taye and Willems 2011; Mendicino and Senatore 2013). For similar reasons, Niadas (2005) suggested that for regional analysis involving multiple sites, AFDCs represent regional conditions better compared with traditional FDCs for which concurrent data are more important.

In this paper, a methodology based on the use of AFDCs is adopted, which describes FDCs with a time span of 1 year, as advocated by Vogel and Fennessey (1994). The median AFDC characterizes the distribution of daily streamflows that are not significantly affected by extremely dry or wet periods. Obtaining the median AFDCs for each station consists of a few simple steps described below:

(a) sorting daily observed flows Q_i for each year from largest to smallest to produce an ordered series (i = 1,2, ..., 365)

(b) plotting each sequential observation Q_i against its duration d_i corresponding to exceedance probability P_i, which is calculated with Weibull plotting position

$$P_i = \frac{i}{366}$$

1

(c) obtaining the typical annual FDC of that stream (or basin) by calculating the median of N AFDCs, where N is the observation length in years

In particular, the methodology addresses the analysis of the lower part of the FDC that refers to low flows because hydrologic droughts motivate this paper. Therefore, the range of P = 0.30–0.99 of the probability of exceedance is considered. For similar reasons, Fennessey and Vogel (1990), Franchini and Suppo (1996), and Castellarin et al. (2004) suggested describing the lower part of the FDCs of daily streamflows (i.e., $P \geq 0.5$ or $P \geq 0.3$). The lower portion of FDCs has generally been used for hydroelectric engineering, water quality assessment, sedimentation, low flow analysis, or drought-related studies.

4 Parametric Approach For Modeling Afdcs

The main idea of a parametric approach is to represent FDCs with analytical relationships. Thus, the procedure evolves to obtain the parameters of these analytical relations. The parameters are usually related to the physical, hydrological, and/or meteorological characteristics of the relevant stream basin. Parametric approaches have widely been used in various forms (simple linear regression, multi linear regression, exponential regression, and logarithmic regression) for basins in various parts of the world, and scientists have dealt with the problem of estimating FDCs at ungauged or partially gauged basins using regression methods for a long time (e.g., Quimpo et al. 1983; Mimikou and Kaemaki 1985; Fennessey and Vogel 1990; Franchini and Suppo 1996; Singh et al. 2001; Yu et al. 2002; Castellarin et al. 2004; Mohamoud 2008; Viola et al 2011; Müller et al. 2014; Pugliese et al. 2016; Ridolfi et al. 2018).

Quimpo et al. (1983) conducted a regionalization study to estimate water availability at small hydroelectric plants in the Philippines. They first parameterized the flow–duration characteristics and mapped the geographical variation of one of the parameters to cover the entire archipelago. They then defined another parameter related to the basin area.

Mimikou and Kaemaki (1985) parameterized the monthly flow–duration characteristics of flow measurement stations in the western and northwestern regions of Greece. Then, using multiple regression methods, they obtained the parameters of the flow–duration model depending on characteristics such as geographical variability, average annual precipitation, and basin drainage area.

Fenensey and Vogel (1990) stated that the aim is to develop regression models that relate the parameters of the daily FDC at a site to basin characteristics. To obtain such regression models, they aimed to define the FDC with as few parameters as possible. They argued that a complex trade-off between the number of parameters needed to define FDCs and the ability to develop regional regression models that uses parameters related to the basin characteristics exists. Fennessey and Vogel modeled the lower portion of the FDC (only the portion of the probability of exceedance within $P = 0.50–0.99$ range) in their study.

Franchini and Suppo (1996) proposed a methodology that addresses the regional analysis of the lower part of the FDC that refers to low flows. This methodology requires deriving an equation characterized by a set of parameters that define the lower part of the FDC and defining the statistical model that allows the parameters of the chosen equation to be estimated correctly. Unlike other parametric approaches, Franchini and Suppo regionalized streamflow quantiles (Q_{30}, Q_{70}, Q_{90}, and Q_{95}) instead of parameters. They considered Molise Region (Italy) in applying the methodology to a real-world case.

Singh et al. (2001) developed models for the 1,200 unmeasured basins of the Lower Himalayan region of India. The formulation of the models is based on empirical regional relationship and data transfer between measured basins of the same region. They used a simple power relationship for the average flow estimation.

Yu et al. (2002) applied the parametric method (polynomial) and the area-index method to produce FDCs, and estimate their uncertainties at ungauged sites for the upper reaches of the Cho-Shuei Stream in Taiwan. They used annual precipitation, altitude, and drainage area in the parametric method to explain regional variation.

Castellarin et al. (2004) conducted a regionalization study based on statistical, parametric, and graphical approaches for a large region of East Central Italy to regionalize the lower portion of FDCs (the region of FDC for probability of exceedance P = 0.3–0.99). They showed that all three approaches were equally successful.

Mohamoud (2008) presented a method for estimating FDCs for ungauged basins in the Mid-Atlantic Region, USA. Using a stepwise multiple regression analysis, they identified important geographic and meteorological characteristics in constructing the flow–duration relationship.

Viola et al. (2011) developed a regional model to predict FDCs in ungauged basins in Sicily, Italy. They analyzed a large flow dataset and derived the parameters of FDCs for nearly 50 basins. They developed regional regression equations to construct FDCs.

Müller et al. (2014) derived a process-based analytical expression for FDCs in seasonally dry climates. They applied their FDC model to 38 basins of Nepal, California coast of USA, and Western Australia, and showed that FDCs were successfully demonstrated using five significant parameters.

Pugliese et al. (2016) compared two methods, one based on geostatistics and the other based on regional multiple linear regression, to estimate FDC in ungauged basins. They compared these two methods in 182 unregulated basins in Southeastern USA. Their findings revealed that the geostatistical and linear regression models performed similarly.

Ridolfi et al. (2018) proposed a new methodology for estimating FDCs and applied this methodology to sub-basins located in two different basins from different parts of the world. Ten basins are situated in the upper Neckar River basin of Germany, whereas 10 are located in Eastern USA. They indicated that FDC is characterized by the basin and the weather.

In the study of Castellarin et al. (2004), one of the most comprehensive of the studies summarized above, three different parametric approaches were applied (Quimpo et al. 1993; Mimikou and Kaemaki 1985; Franchini and Suppo 1996). They noted that all analytical expressions with two or more parameters successfully reproduced FDCs. By contrast, the validation stage showed controversial results. Especially in analytical expressions where the physical meaning of the parameters is uncertain, not all parameters could be defined through multiple regression analyses. However, Franchini and Suppo's (1996) parametric approach, unlike other parametric approaches, regionalizes flow quantiles (Q_{30}, Q_{70}, Q_{90}, and Q_{95}) instead of parameters, and probably because of this feature, it outperformed all other parametric approaches in the validation phase. Considering this, our paper intends to establish a relationship between the streamflow quantiles (Q_{30}, Q_{40}, …,Q_{99}) and the hydrological, geographical, and meteorological characteristics of the basins.

5 Application And Results

5.1 Parametric Approach Using AFDCs

Flow observations of 30 Western Anatolia basins, with observation lengths varying between 10–54 years, are compiled to prepare AFDCs, as described in Chap. 2. The observations are arranged in descending order from 1 to 365 for N years of data in each basin. Then, the typical AFDC, which is the median of these N series, is obtained.

The streamflow quantiles (Q_{30}, Q_{40}, ...,Q_{99}) of each basin to be used in the parametric approach are obtained from typical AFDCs.

At this stage, how streamflow quantiles (Q_{30}, Q_{40}, ...,Q_{99}) are affected by the basin characteristics is investigated using a multivariate linear regression relationship in the following form:

$$Q_P = a_0 + a_1X_1 + a_2X_2 + \cdots + a_nX_n + \epsilon,$$

2

where Q_p is the pth quantile (or percentile), X_i, for $i = 1,2,.. . ,n$, are the explanatory variables, and ϵ is the residual of the model. When these variables are replaced by the basin characteristics, Eq. (1) turns into the following:

$$Q_P = a_0 + a_1A + a_2q + a_3MAP + a_4h + a_5Lat + a_6Long + \epsilon,$$

3

where A is the basin area (km^2); q is the average flow (m^3/s); MAP is the mean annual precipitation (mm); h is the altitude (m); Lat is the latitude (°); and $Long$ is the longitude (°).

In the evaluation of the multivariate linear regression relationship, the significance of the basin characteristics in the regression relationship is examined, and the results are given in Tables 3 and 4.

Table 3
p values of the variables in multivariate regression in Western Anatolia. Significant variables for α= 0.05 are bolded.

	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{95}	Q_{99}
	R^2 = 0,989	**R^2 = 0,995**	**R^2 = 0,988**	**R^2 = 0,982**	**R^2 = 0,980**	**R^2 = 0,975**	**R^2 = 0,972**	**R^2 = 0,968**	**R^2 = 0,961**
	p-values								
A	**3,4E-06**	**7,3E-11**	**1,8E-07**	**1,10E-06**	**9,71E-09**	**1,05E-08**	**5,81E-08**	**1,96E-07**	**6,71E-06**
q	**8,1E-07**	**3,1E-09**	**2,3E-05**	**7,48E-04**	0,26	0,97	0,71	0,68	0,22
MAP	0,88	0,73	0,36	0,32	0,09	**0,05**	0,10	0,12	0,29
h	0,24	0,38	0,15	0,14	0,42	0,77	0,35	0,27	0,16
Lat	0,63	0,11	0,38	0,39	0,10	**0,05**	0,06	**0,03**	0,08
Long	**0,05**	0,88	0,08	0,07	0,27	0,43	0,28	0,40	0,27

Table 4
p values of the variables in multivariate regression in Southwestern Anatolia. Significant variables for α=0.05 are bolded.

	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{95}	Q_{99}
	R^2 = 0,992	**R^2 = 0,988**	**R^2 = 0,983**	**R^2 = 0,979**	**R^2 = 0,976**	**R^2 = 0,969**	**R^2 = 0,972**	**R^2 = 0,974**	**R^2 = 0,977**
	p-values								
A	**0,03**	**0,01**	**3,7E-03**	**1,37E-03**	**4,14E-04**	**5,01E-04**	**3,06E-04**	**3,33E-04**	**6,74E-04**
q	**3,0E-05**	**0,01**	0,18	0,77	0,57	0,35	0,31	0,38	0,79
MAP	0,59	0,65	0,52	0,67	0,82	0,91	0,95	0,92	0,57
h	0,65	0,42	0,43	0,43	0,48	0,53	0,54	0,56	0,51
Lat	0,48	0,48	0,49	0,63	0,66	0,76	0,72	0,68	0,54
Long	0,44	0,47	0,33	0,41	0,53	0,82	0,69	0,52	0,20

Tables 3 and 4 show a strong multivariate regression relationship for each quantile. However, only one of the six basin characteristics (*A*, basin area) has a significant effect on the regression relationship for each of the nine quantiles. This result raises the question of whether streamflow quantiles can be determined solely in terms of basin area.

5.2 Areal Scale Factor (*ASF*)

To answer the question "whether streamflow quantiles can be determined solely in terms of basin area," the relationship between streamflow quantiles Q_P and basin size *A* is examined, and this analysis indicates a strong linear relationship of the following form:

$$Q_P = a_p . A,$$

4

where a_p is the coefficient of the linear regression relationship and referred to as the *ASF*. Eq. (4) indicates a linear regression line that intersects the origin. The *ASF*s of each quantile and the results of the simple linear regression relationship are given in Tables 5 and 6 for Western Anatolia and Southwestern Anatolia, respectively.

Table 5
p values of *ASF*s in simple linear regression in Western Anatolia

	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{95}	Q_{99}
	R^2 = 0,960	**R^2 = 0,977**	**R^2 = 0,974**	**R^2 = 0,970**	**R^2 = 0,979**	**R^2 = 0,972**	**R^2 = 0,969**	**R^2 = 0,965**	**R^2 = 0,956**
p-values	7,12E-22	2,97E-25	1,81E-24	1,44E-23	8,86E-26	3,76E-24	2,06E-23	9,65E-23	2,89E-21
ASF	0,00219	0,00172	0,00152	0,00134	0,00114	0,00095	0,00078	0,00060	0,00054

Table 6
p values of *ASF*s in simple linear regression in Southwestern Anatolia

	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{95}	Q_{99}
	R^2 = 0,972	**R^2 = 0,980**	**R^2 = 0,976**	**R^2 = 0,970**	**R^2 = 0,965**	**R^2 = 0,957**	**R^2 = 0,955**	**R^2=,954**	**R^2 = 0,953**
p-values	4,71E-17	1,46E-18	1,02E-17	9,51E-17	5,03E-16	3,65E-15	6,38E-15	7,17E-15	8,98E-15
ASF	0,01156	0,01010	0,00894	0,00780	0,00667	0,00568	0,00510	0,00482	0,00425

Tables 5 and 6 show a significant relationship between streamflow quantiles and basin area, and prove that flow quantiles can be successfully predicted depending on the basin area using regionally derived *ASF*s.

5.3 Validation

To test the significance of the proposed parametric model, 10 of the 30 basins in Western Anatolia and 7 of the 21 basins in Southwestern Anatolia are initially retained for validation. In Tables 1 and 2, these stations are bolded. At this stage, the success of the developed model is tested for 10 and 7 validation basins in Western Anatolia and Southwestern Anatolia, respectively.

The empirical quantiles and the quantiles estimated in relation to the basin area using the *ASF*s (Q_P= ASF_P. A) are compared. The graphical representation is given in Figs. 2 and 3 for all the quantiles considered.

In addition, *NSE*, Nash–Sutcliffe Efficiency (Nash and Sutcliffe 1970), and *RSR*, the ratio of RMSE and standard deviation of measured data (Moriasi et al. 2007) criteria are calculated to evaluate the model performance. NSE_p and RSR_p are the criteria of the *P*.th quantile and calculated as follows:

$$NSE_P = 1 - \frac{\sum_{s=1}^{S}(Q_P - Q_p^{est})^2}{\sum_{s=1}^{S}(Q_P - \bar{Q}_P)^2},$$

5

$$RSR_P = \frac{\sqrt{\sum_{s=1}^{S}(Q_P - Q_p^{est})^2}}{\sqrt{\sum_{s=1}^{S}(Q_P - \bar{Q}_P)^2}},$$

6

where *s* is the basin number (*s* = 1,2,...*S*), Q_P is the empirical flow quantile, Q_P^{est} is the estimated flow quantile, and $\bar{Q}_P$ is the mean value of the empirical streamflow quantiles. The classification of *NSE* and *RSD* values according to model performance is given in Table 7 (Moriasi et al. 2007). *NSE* and *RSD* values calculated by model validation are presented in Tables 8 and 9 for Western Anatolia and Southwestern Anatolia, respectively.

Table 7
Performance criteria categorizations

Performace	***NSE***	***RSR***
Very good	$0.75 < NSE \leq 1.00$	$0.00 \leq RSR \leq 0.50$
Good	$0.65 < NSE \leq 0.75$	$0.50 < RSR \leq 0.60$
Adequate	$0.50 < NSE \leq 0.65$	$0.60 < RSR \leq 0.70$
Inadequate	$NSE \leq 0.50$	$RSR > 0.70$

Table 8
Model performance criteria of each quantile in Western Anatolia

	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{95}	Q_{99}
NSE	0,952	0,977	0,975	0,964	0,967	0,963	0,959	0,961	0,951
RSR	0,220	0,151	0,157	0,189	0,183	0,193	0,204	0,197	0,221

Table 9
Model performance criteria of each quantile in Southwestern Anatolia

	Q_{30}	Q_{40}	Q_{50}	Q_{60}	Q_{70}	Q_{80}	Q_{90}	Q_{95}	Q_{99}
NSE	0,917	0,974	0,977	0,974	0,961	0,947	0,946	0,949	0,951
RSR	0,289	0,163	0,152	0,162	0,197	0,230	0,232	0,226	0,222

The empirical quantiles of the validation basins and the quantile estimates of the parametric model are compared, and the performance of the proposed model is evaluated as “very good” visually (Figs. (2) and (3)) and numerically (Tables 8 and 9).

5.4. Regionalization of *ASF*s

The validation results show that *ASF*s successfully represent the study region, and its use is effective in estimating the streamflow quantiles. Based on this, the relationship between *ASF*s and exceedance probabilities, *P*, for the two study regions is obtained. Detailed analysis shows that regional *ASF*s can be obtained depending on the probability of their exceedance, with a logarithmic regression relationship given in Eqs. (7) and (8) for Western Anatolia and Southwestern Anatolia, respectively.

$$ASF_P = 0.0067 - 0.0013\ln(P) \quad (R^2 = 0.987) \quad (7)$$

$$ASF_P = 0.0327 - 0.0061\ln(P) \quad (R^2 = 0.995) \quad (8)$$

P is the exceedance probability in percent. Fig.s 4 and 5 show the relationship between regional *ASF*s and exceedance probabilities (regional envelope curves).

6 Conclusion

The main purpose of this paper is to reveal the regional relationships that enable an effective estimation of streamflow quantiles of low flows (or high exceedance probabilities). A parametric approach is proposed, where droughts are characterized by using the lower part of the AFDCs.

The first step in the parametric approach is to estimate streamflow quantiles using AFDCs. The basic principle in the choice of AFDCs is that traditional FDCs limit the representation of the flow regime to the specific record period for which the FDC is developed. On the one hand, daily flows show a high degree of serial correlation. On the other hand, the time–dependence structure at the daily scale has no influence at all on the AFDC if the inter annual variability of the annual flows is preserved (Castellarin et al. 2007).

The second step is to examine the regional variation of these quantiles in relation to the basin characteristics. Two geographical regions are investigated. The first region covers 30 unregulated river basins in Western Anatolia, and the second region covers 21 unregulated basins in Southwestern Anatolia of Turkey. The application remains the streamflow quantiles obtained for nine fixed-percentage points (30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, and 99%) of the AFDCs because low flow analysis is considered. A strong linear relationship between low-flow quantiles and basin area is demonstrated, and *ASF*s describing this relationship are obtained. The regional parametric model is evaluated with the validation method for both regions (Figs. 2 and 3, Tables 8 and 9).

In addition, the relationship between *ASF*s and exceedance probabilities are presented for both study regions, empirically and graphically (Eqs. (7) and (8); Figs. 4 and 5).

The main results of our paper can be summarized as follows:

1. Streamflow quantiles (Q_{30}, Q_{40}, ...,Q_{99}) representing low flows can be effectively calculated using AFDCs.
2. The proposed regional parametric model successfully estimates the streamflow quantiles corresponding to higher exceedance probabilities depending on the basin area using *ASF*s.
3. The validations indicate that the regional model provides a “very good” performance over both study regions in terms of reliability.
4. The effective identification of the relationship between *ASF*s and exceedance probabilities in a region allows successful estimation of the *ASF* and the streamflow quantile of the corresponding exceedance probability ($Q_P = A.\ ASF_P$).

In summary, the proposed parametric model uses AFDCs that are unaffected by measurement period and sampling errors. As the paper focuses on drought, streamflow quantiles are obtained from the lower part of AFDCs representing low flows. Various basin characteristics are examined with regression relations, and the findings determine that low-flow quantiles could be successfully estimated only depending on basin size. *ASF*s expressing the ratio between quantiles and basin sizes ($ASF_P = Q_P/A$) are obtained, and finally, envelope curves ($ASF_P - P$(%) relationships) for both regions are given (Figs. 4 and 5). Thus, for any sub-basin in the relevant region, quantiles corresponding to a certain exceedance probability can be easily estimated when only basin size is known.

Although the two regions in the paper have similar meteorological characteristics, they are of completely different types geologically. Two different regions with dissimilar geological structure, drainage mechanism, and low-flow characteristics are selected. Thus, the proposed parametric model is tested in terms of adapting to different geohydrological conditions. In Western Anatolia, 85% of the topographic surface consists of metamorphic and volcanic rocks, whereas in Southwestern Anatolia, 80% of the surface is limestone. Outcropping limestone complexes considerably affect the drainage mechanism and the low-flow characteristics, which are significantly different in a non-karstic region (i.e., Western Anatolia). Thus, the successful representation of the model for these two geologically different regions is promising in terms of the robustness of the model and its use in future studies. However, further examination in different geographical areas of dissimilar meteorological characteristics is needed to generalize the results.

Declarations

Acknowledgments

The streamflow data provided by DSI are publicly available and downloadable from https://www.dsi.gov.tr/Sayfa/Detay/744. The website is in Turkish.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Authors' contributions

Both authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Tugce Narin] and [Omer Levend Asikoglu]. The first draft of the manuscript was written by [Omer Levend Asikoglu] and both authors commented on the manuscript. Both authors reviewed the results and approved the final version of the manuscript.

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Figures

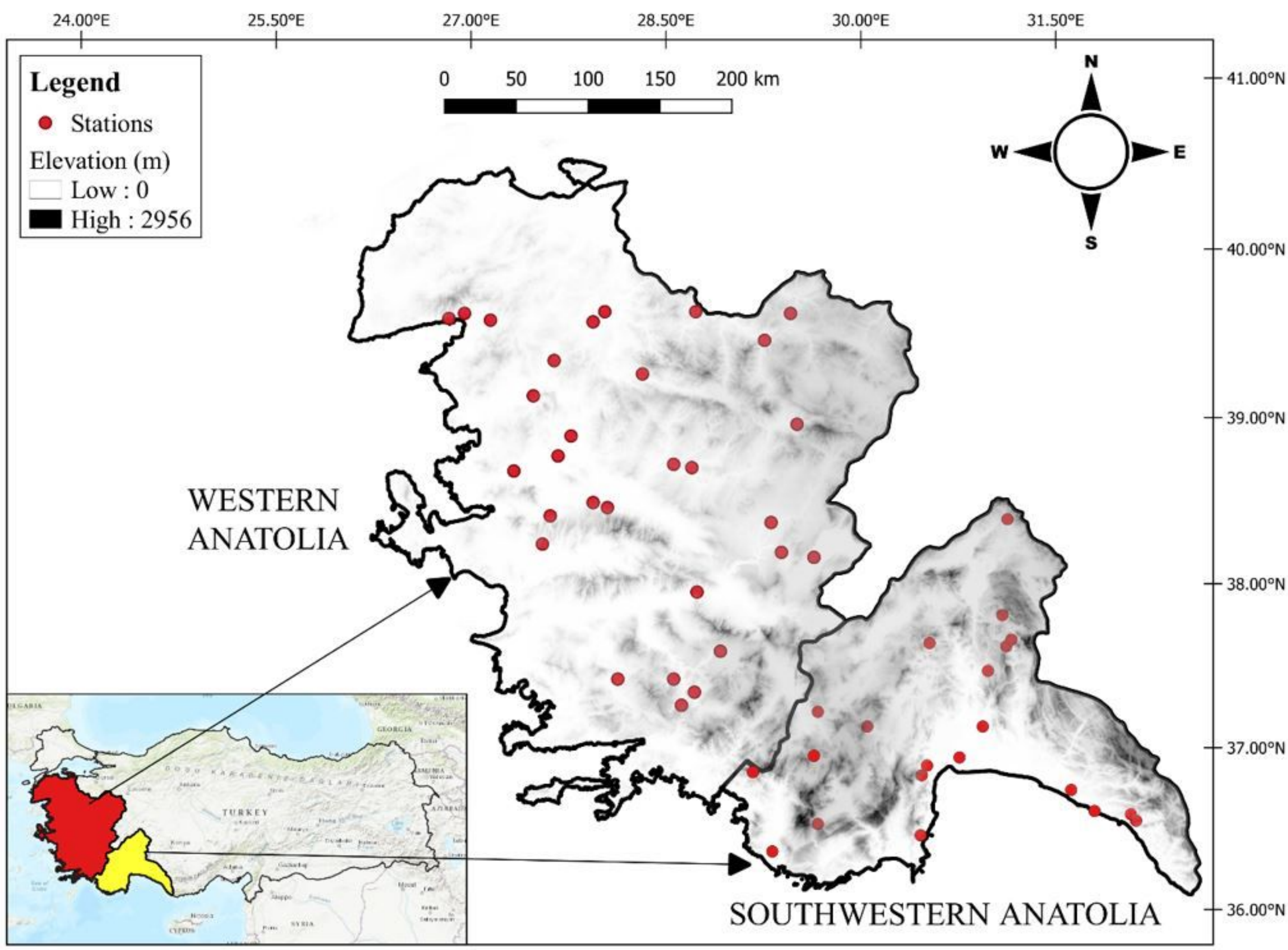

Figure 1

Study area and locations of flow gauging stations

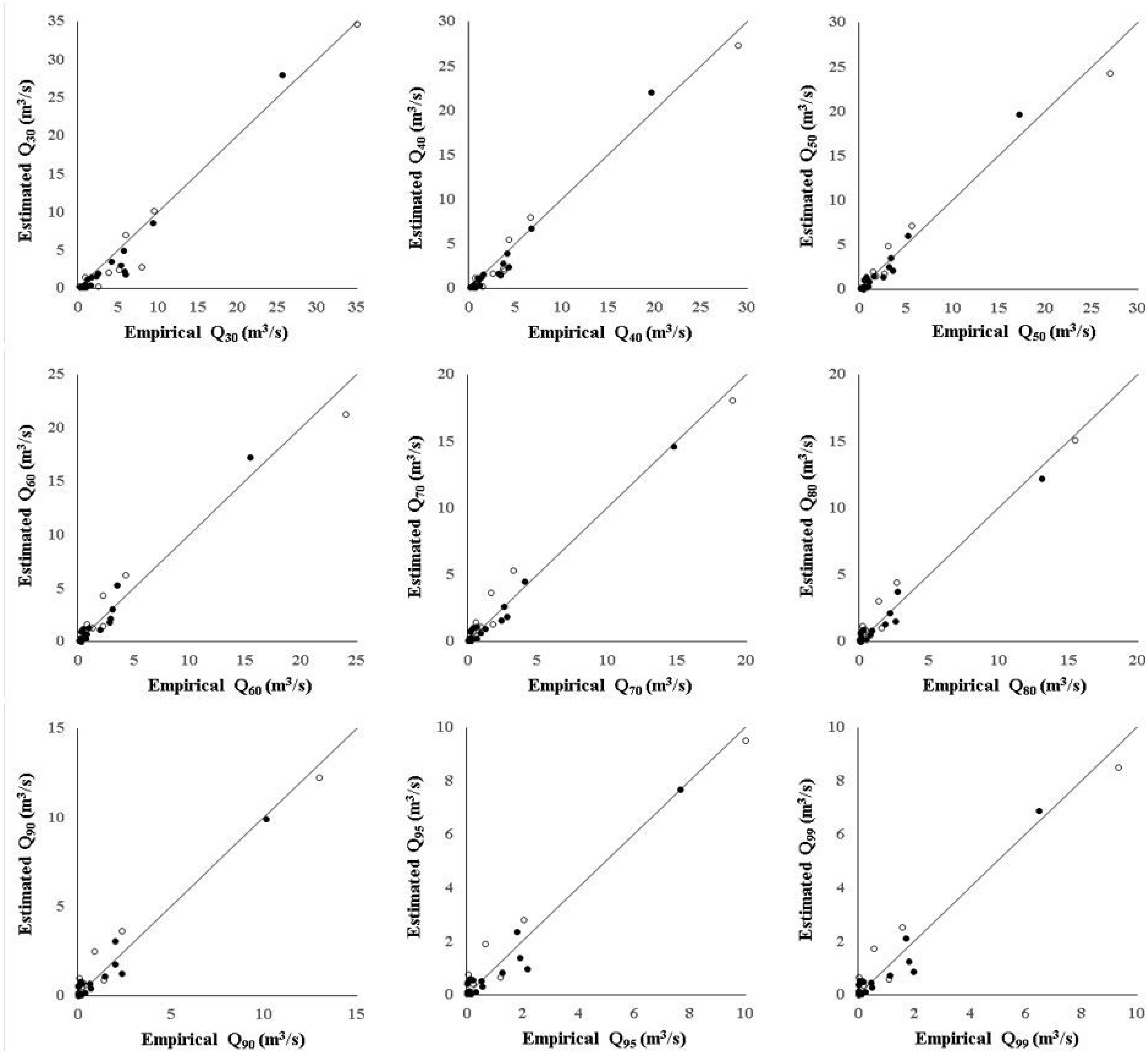

Figure 2

Scatter plots of empirical versus estimated quantiles in Western Anatolia. Calibration data and validation data are represented as dots and circles, respectively.

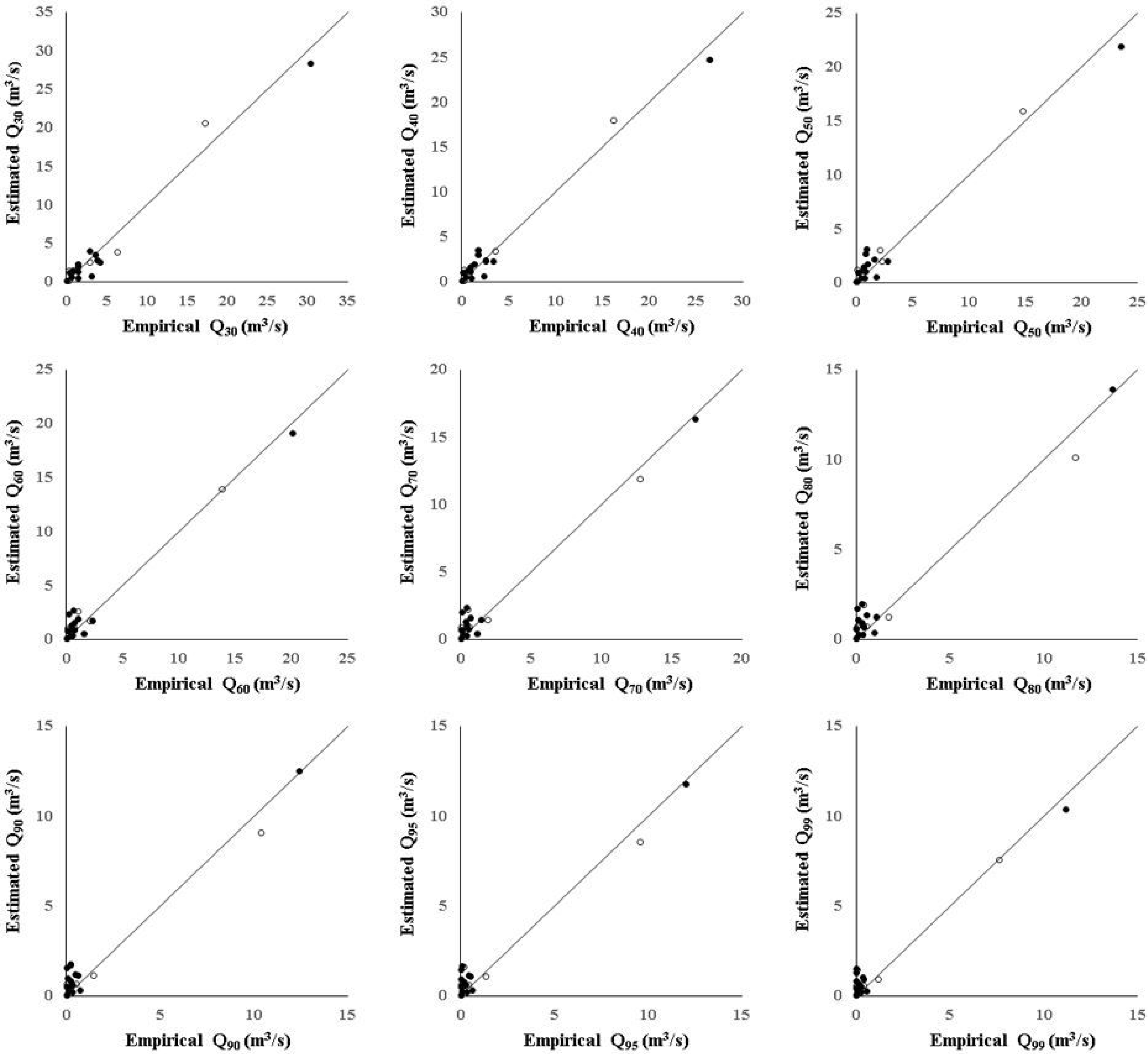

Figure 3

Scatter plots of empirical versus estimated quantiles in Southwestern Anatolia. Calibration data and validation data are represented as dots and circles, respectively.

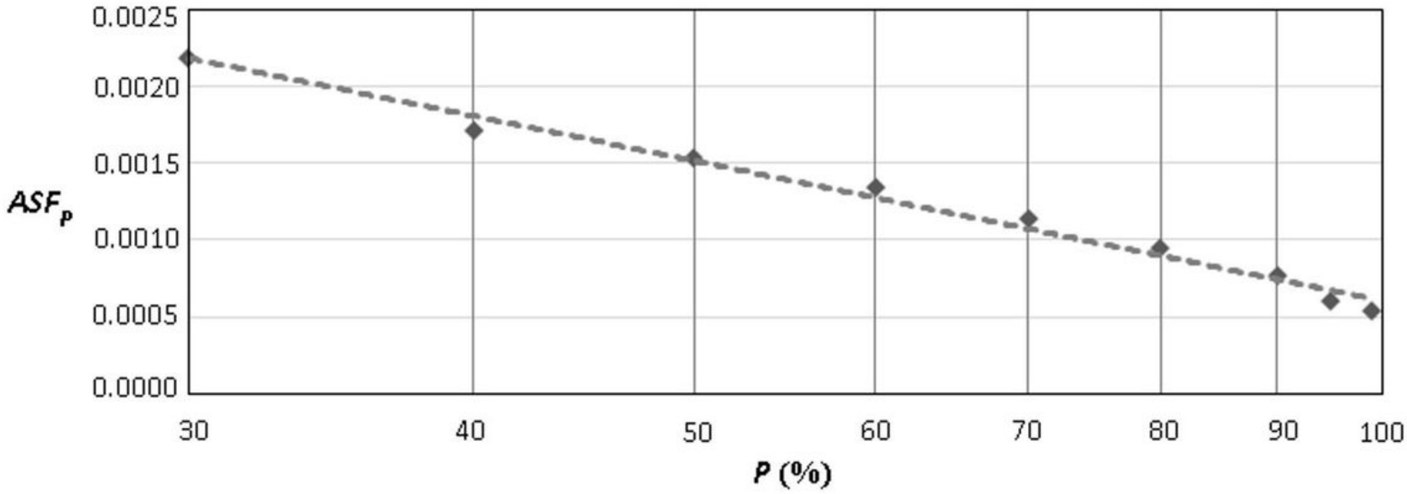

Figure 4

Regional *ASF*s related to exceedance probabilities *P* (%) in Western Anatolia

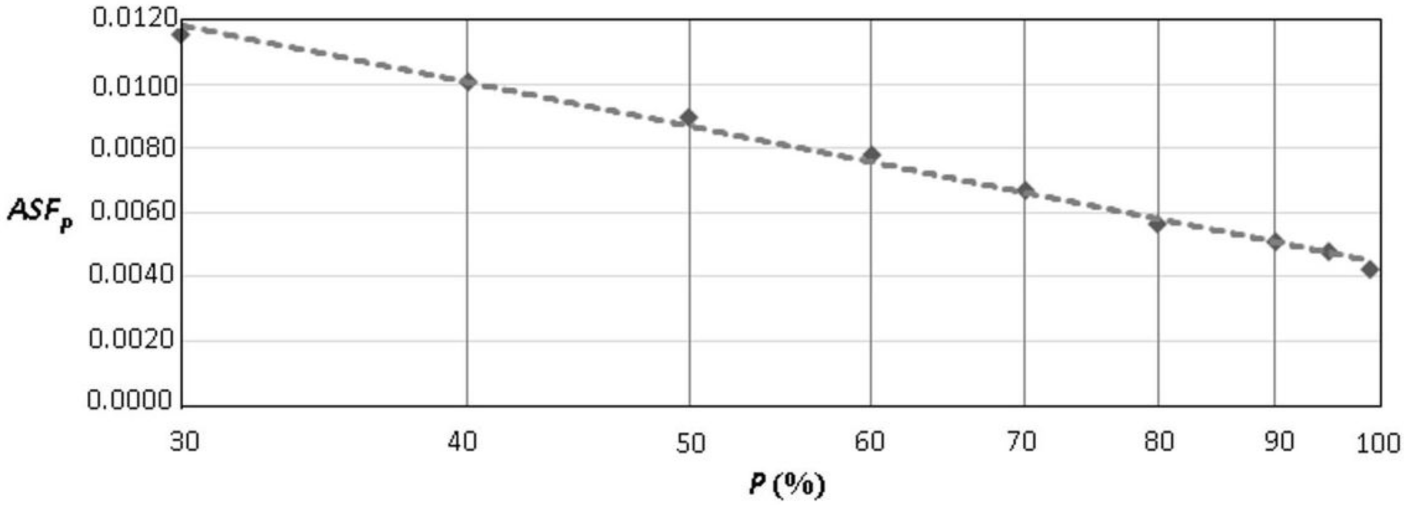

Figure 5

Regional *ASF*s related to exceedance probabilities *P* (%) in Southwestern Anatolia