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ORIGINAL PAPER

Frequency curves of high and low flows in intermittent river basins for hydrological analysis and hydraulic design

Gokhan Sarigil[1] · Yonca Cavus[2] · Hafzullah Aksoy[3] · Ebru Eris[4]

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Abstract

Upper and lower percentiles of Flow Duration Curves (FDCs) of daily streamflow data were investigated to develop frequency curves. Upper percentiles with exceedance probability of 1, 5 and 10% (Q_1, Q_5, Q_{10}) were used for high flows, and lower percentiles with non-exceedance probability of 10, 5 and 1% (Q_{90}, Q_{95}, Q_{99}) for low flows. Median value (Q_{50}) was covered to represent the average conditions of streamflow. A mixed frequency analysis based on the total probability theorem taking zero values into account was applied for the lower percentiles of FDC. Case studies were performed for three intermittent Streamflow Gauging Stations (SGSs) from Kucuk Menderes River Basin in western Turkey. An overall assessment of results shows that the best-fit probability distribution function does not change from one SGS to another considerably for low flows while each SGS has its own probability distribution function for high flows. Upper and lower percentiles, and median value were calculated at various return periods by using the identified probability distribution functions. The calculated values were plotted in the form of frequency curves of high flow percentiles and low flow percentiles. The frequency curves have a practically significant potential use in hydrological analysis, water resources management and hydraulic design under high and low flow conditions. They are yet open to further development for regionalization and their applicability can be extended to ungauged sites in river basins.

Keywords Frequency curve · High flow · Intermittency · Low flow · Percentile · Total probability theorem

1 Introduction

1.1 Scope of the study

Within the scope of this study, we analyze high and low flows in river basins, which are important for the planning, management, design and operation in hydrological and hydraulic practice. Although they are linked, high flow is not necessarily the same as flood, and low flow as drought (Dracup et al. 1980; Tokarczyk 2013). Flood and drought are extreme events of high and low flows, respectively, and they are not only engineering or environmental problems but also social issues because of their human-water relevance (Terti et al. 2019; Cavus et al. 2022). Furthermore, they are among the unsolved problems in hydrology (Bloschl et al. 2019). They are expected to become worse as flash floods with high peaks and prolonged droughts severe in intensity will likely be dominating among the hydrological phenomena in the future (Brunner 2023).

Quantitatively, high flow and low flow correspond, respectively, to the upper and lower percentiles of the discharge of the streamflow record. Flow duration curve (FDC) is commonly used in the determination of the percentiles. It shows the variation of streamflow ranked at descending order at the vertical axis with the percentage of time the specified discharge is equaled or exceeded at the horizontal axis. Kotei et al. (2016) define high flow as values at the upper end of FDC in the 0–10% range of exceedance probability. More specifically, Huh et al. (2005) suggest the 75th percentile as the lower boundary of high flows and the 25th

✉ Ebru Eris
ebru.eris@ege.edu.tr

[1] Graduate School, Istanbul Technical University, Istanbul, Türkiye

[2] Department of Civil Engineering, Beykent University, Istanbul, Türkiye

[3] Department of Civil Engineering, Istanbul Technical University, Istanbul, Türkiye

[4] Department of Civil Engineering, Ege University, Izmir, Türkiye

percentile as the upper boundary of low flows. The detailed classification of Pfannerstill et al. (2014) divides flow into five classes as very high flow (with exceedance probability $<$ 5%), high flow (with exceedance probability 5–20%), average flow (with exceedance probability 20–70%), low flow (with exceedance probability 70–95%), and very low flow (with exceedance probability $>$ 95%). The range between high and low flows is larger in dry regions, and it is expected to widen with future projections of climate change, i.e., upper extremes will be larger and lower extremes will be smaller (Tavakoli et al. 2014), which will likely be more pronounced in terms of their effects.

As the peak event of high flows, flood demonstrates hydrological regime of the river basin. High flows in dry regions can create only minor disturbances if they are not large in magnitude but they may have permanent effects if their magnitude is large enough to reshape the vegetation of the river basin and the morphology of the stream channel and to clear silt and debris from the stream (Stromberg et al. 2007). They affect agricultural products, and fish species during spawning, and may create floods by which properties, water infrastructures such as reservoirs and channels might heavily be damaged and human lives are likely lost (Forsee and Ahmad 2011; Zhang et al. 2016). Flood discharge of a given return period, which is needed in engineering design practice can be obtained from flood frequency analysis (Griffis and Stedinger 2007; Machado et al. 2015; Rao and Hamed 2019).

High flows (flood discharges) are used in the design of road-crossing culverts among many of their practical uses. For example, in United States, culverts are designed by using the 25-year flow event provided that the ratio of the headwater to the diameter does not exceed 1.25. The 100-year flow event should pass without overtopping the roadway if the culvert is under a major route (WSDOT 2023). In Turkey, culverts are designed by using similar guidelines. Flood discharges with return periods from 10 years to 100 years are used for the culvert design, and discharges with return periods from 100 years to 500 years for the river-crossing bridges (KGM 2019). In the determination of these design criteria, FDC plays an important role. However, in the strict sense, FDC is based on the data over the period-of-record (Searcy 1959; Castellarin et al. 2004). The design discharges derived from FDC are therefore limited with the observed probabilities. Consequently, the sole use of FDC is insufficient for practical purposes. The upper and lower percentiles of FDC are expected to be higher than their recorded values if the period-of-record coincides with a wet period, and they are lower if it does with a dry period. In such a case, percentiles extracted from FDC may under- or over-design hydraulic structures. In order to go beyond the observed probabilities, theoretical distributions are used through frequency analysis, which has served for high flows (flood) since 1960s even 1950s (Benson 1950; Dalrymple 1960) in accordance with practice. This is what we call flood frequency analysis, which is used for the design of civil structures under flood conditions for which region- or country-specific codes exist (Chow et al. 1988). For example, in United States, the use of Log-Pearson Type III probability distribution function is recommended for high flow (flood) frequency analysis (England et al. 2018).

Similar to high flows, low flow conditions are also needed for water resources planning and management, and for the design of hydraulic structures (Ashkar et al. 1998). Specifically, they are used in the determination of minimum discharge released from hydropower plants, water supply schemes, cooling systems, among many other purposes. Water withdrawal from the river can safely be regulated, the life cycle and water quality in the river can be protected if low flow conditions are sustained (Hoque et al. 2022). Lower discharge in the river decreases flow velocity, thus the ventilation potential of the river is reduced and pollutants may become hazardous. Certain duration-low flow discharges with a certain return period are used in engineering design practice. For example, fish ladders are designed by using Q_{95} and Q_5 as low and high flow criteria, respectively (USFWS 2019). Here, Q_{95} and Q_5 are the percentiles of the FDC with exceedance probabilities 95 and 5%, respectively. Alternatively, low flows are averaged over D-day period of time. The common notation for the low flow discharges is $Q_{\mathrm{D,\,T}}$ to show the D-day low flow with return period T. In United States, the most widely used low flow value is the 10-year annual minimum 7-day discharge, $Q_{7,10}$, which is the minimum of 7-day moving average discharge expected to be reached once every 10 years on average (ASCE Task Committee 1980).

For the lower tail of FDC (low flows), so far, there is no unique generally applicable probability distribution function. Instead, different forms of Weibull (W), Gumbel (Gu), Pearson Type III (P3) and log-normal (LN) distributions were frequently used (Smakhtin, 2001). A few examples can be mentioned here. The low flow frequency analysis of Riggs (1972), ASCE Task Committee (1980) and USACE (1993) are the most comprehensive yet outdated studies from the U.S., and Gustard et al. (1992) from the U.K. The WMO (2008) manual and the joint analysis of the volume and the durations of low flow events (Ashkar et al. 1998) are two more examples to mention. Some other efforts not as comprehensive as the above studies were reviewed by Smakhtin (2001), Ouarda et al. (2008) and Hulley et al. (2014). Results are site-specific and cannot be generalized. Therefore, efforts towards development of a low flow estimation procedure or an operational index for monitoring drought (Laaha and Bloschl 2007; Cammalleri et al. 2017) are not satisfactory enough in producing a design code or guideline. The issue is already overdue for low flows and, thus, an emerging hot topic in hydrology with ever increasing demand globally (Vogel and Kroll 2021).

1.2 Need for the study

FDC and frequency curve are different from each other. FDC may only approximate frequency curve if the streamflow during the period on which the FDC is based represents the long-term flow of the stream. If the FDC represents long-term flow conditions, the estimated percent of time that a specified high flow discharge will be exceeded or equaled at the upper tail of FDC or that a specified low flow discharge will not be exceeded at the lower tail of FDC can be used as the probability that these events will be observed in the future (Searcy 1959). However, in practice, FDCs are insufficient to represent the long-term characteristics as they are based on records with limited length, and frequency analysis becomes unavoidable to apply to any specified percentile to obtain frequency curves. Probabilities extracted from FDC are limited with the period-of-record, and they are biased tending towards streamflow characteristics of this particular period-of-time. Therefore, frequency curves based on the best-fit theoretical probability distribution function are valuable to calculate the best-approximated values of discharges with various return periods. Regional low flow curves of the Peninsular Malaysia (Mamun et al. 2010), low flow duration-frequency curves of the Gediz River Basin in Turkey (Orta and Aksoy 2022), and low flow quantity-duration-frequency curves of the upper Yellow River Basin in China (Ma et al. 2023) can be mentioned here as examples.

Furthermore, variability in the percentiles is missing when the long-term FDC is used as each percentile is represented by one single value. The variability is more pronounced in low flows than high flows. This is particularly so in intermittent rivers where low flows are bounded with zero. For example, for the real-data case in Fig. 1, Q_{95} is a non-zero value in the long-term FDC while at the annual FDCs, Q_{95} is zero for one of the years in the observation period. For Q_{99}, the situation is more pronounced, i.e., the percentile is zero considering the long-term FDC; however, it takes non-zero values for most of the years in the observation. Despite its wide range, even $Q_{70} = 0$ for one of the years in the period of records which is represented by a single non-zero value. Similarly, high percentiles vary

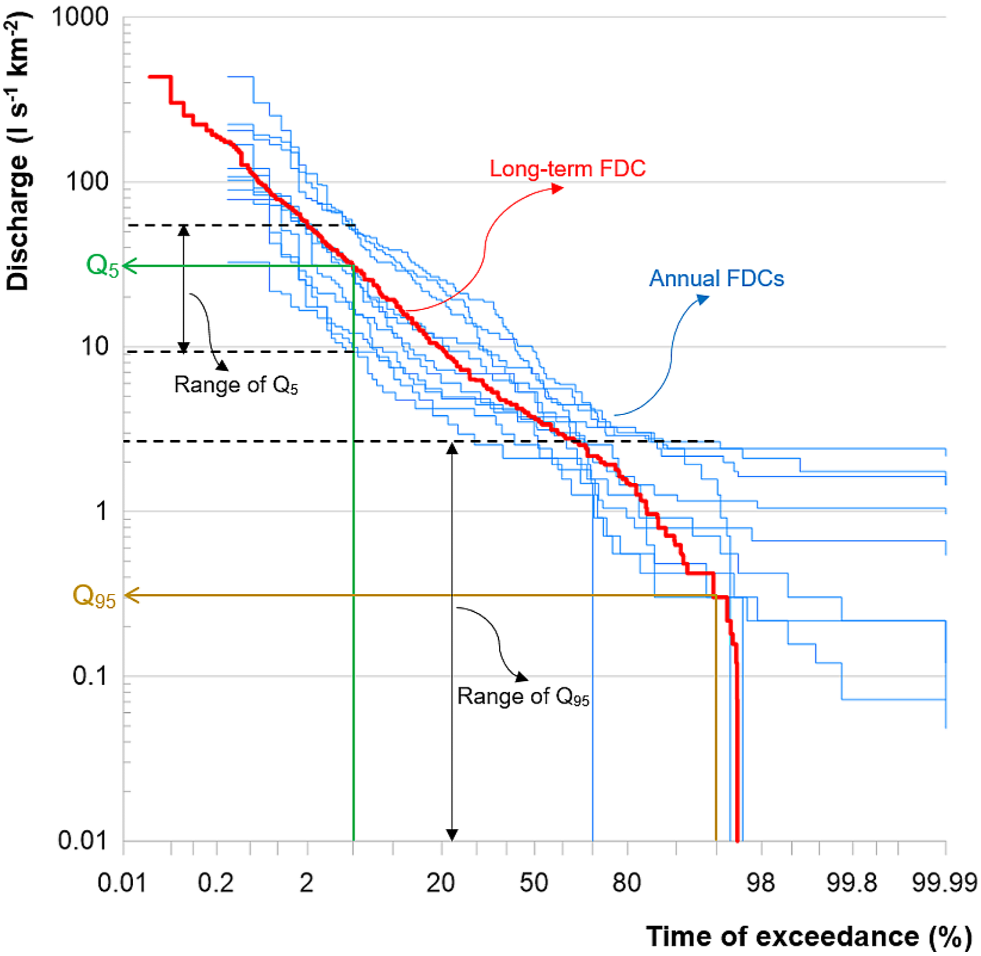

Fig. 1 Long-term flow duration curve (thick curve) and annual flow duration curves (thin curves) of a real daily streamflow data set. The long-term flow duration curve assigns one single value to each of the percentiles, which are indeed varying within a range obtained from annual flow duration curves

within a range. This variability in the percentiles is missing in the long-term FDC. This is another concern of this study for which we present frequency curves instead of using one single value taken from the FDC for each percentile. Frequency curves provide values of the percentiles with return periods from 2 years up to 100 years.

As a response to this practical need, in this study, we performed frequency analysis of high and low flows for several percentiles frequently used in practice. The study aims (i) to develop frequency curves of high and low flow percentiles of daily streamflow discharges, and (ii) to assess frequency curves in terms of their practical use in hydrologic analysis and hydraulic design. As the methodology, we extended the total probability theorem used for the D-day low flows (Eris et al. 2019) to the upper and lower streamflow percentiles to develop frequency curves. Streamflow percentiles with 1, 5 and 10% exceedance probabilities (Q_1, Q_5, and Q_{10} of FDC) are taken as the upper percentiles. From the lower part of FDC, streamflow percentiles with 90, 95 and 99% exceedance probabilities (Q_{90}, Q_{95}, Q_{99}) are used. This is what we call "percentile frequency analysis" in this study. With the completion of frequency analysis of the upper and lower percentiles, high- and low-flow frequency curves of each streamflow gauging station (SGS) were constructed for the upper and lower percentiles separately. Median values were also covered by the upper percentile frequency curves.

2 Study area and data

To achieve the goals of the study, we performed case studies on Kucuk Menderes River Basin in western Turkey (Fig. 2). The Mediterranean climate of the river basin is typically hot and dry in summers, and warm and rainy in winters. Almost half of the total annual precipitation falls in winter. The river basin receives the least precipitation in August, and the most in December showing a strong seasonality (SYGM 2016). Snowfall and frost are rare in the coastal zone of the river basin. Precipitation in the east and southeast (the upstream) of the river basin is higher than the other parts. It is expected that the average temperature in coastal parts will increase and precipitation will decrease (MGM 2014). Moreover, water per capita in the basin will lower down to a level at which people will feel stress of water shortage. Agricultural lands cover about 41% of the river basin, which has fertile soils producing high-quality crops. Agricultural activities have a large share in the economic development of the region and in the water consumption, which is affected by

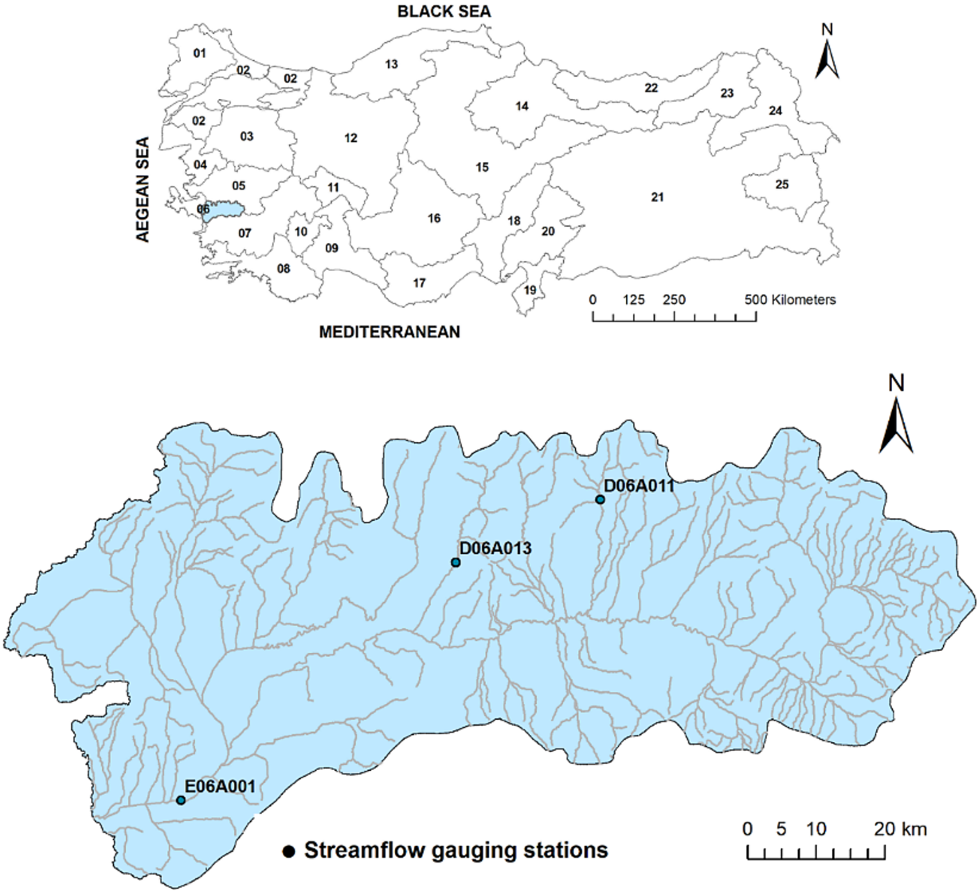

Fig. 2 Kucuk menderes river basin in western Turkey and layout of selected streamflow gauging stations

less water available than required for irrigation (Albek et al. 2004; Durdu, 2010).

Eris et al. (2020) studied the river basin and found that severe prolonged droughts were experienced with an almost uniform distribution over the entire river basin. The river basin was under the effect of drought varying temporally within a year and changing significantly over years, which indicates more severe droughts in the future (Aksu et al. 2022). Frequency analysis was applied on the annual low flow time series. The log-Pearson Type III (LP3) was found the best-fit probability distribution function of low flows in majority of the cases tested (Aksoy et al. 2022).

In this study, daily streamflow data of three SGSs acquired from State Hydraulic Works of Turkey (DSI with its Turkish acronym) were used (Table 1). The SGSs have record length of 10 years at minimum. Two of the SGSs are on two different upstream tributaries, and one is at the downstream on the main river (Fig. 2). The upstream tributaries are close to each other. They have comparable mean streamflow and intermittency. The downstream SGS has higher mean streamflow and intermittency than the upstream SGSs. The streamflow time series are complete for the record period considered. No missing data exist.

We visited the list of dams and ponds in operation from the Regional Directorate of DSI to check if they affect the streamflow data we used for the study (DSI 2023). Rahmanlar Dam is currently under construction on the same tributary with the Bebekler SGS (D06A011), and Burgaz (Zeytinova) Dam on the same tributary with the Falaka SGS (D06A013) has been completed in 2015. The dams have no effect on the record periods of these two SGSs because of no overlap with their periods of record. Completed in 2009 the Beydag Dam at the most upstream of the river basin was taken into operation in 2010 (CYGM 2016) overlapping with the last 2 years only of the 52-year record period of the Selcuk SGS (E06A001). The dam may have negligible influence only because of the almost no time overlap with the period of record.

3 Method

The method of the study is composed of four steps (Fig. 3): (1) Determination of the upper and lower percentiles of FDC, (2) Frequency analysis of the percentiles, (3) Development of frequency curves of the percentiles.

In Step 1, we use daily streamflow data of the selected SGSs to plot FDCs from which we obtain percentiles corresponding to certain exceedance probabilities. FDC is obtained by ranking the streamflow time series at descending order and assigning a rank to each element of the ranked time series such that the largest discharge value has rank 1. For the daily streamflow data, the percentage of streamflow exceeding a given value is defined as

$$p = \frac{i}{N} \tag{1}$$

Here, i represents the number of days, i.e., the position (rank) of each element of the discharge vector; N is the total number of days in the streamflow time series. Thus, the ratio in Eq. (1) represents a cumulative frequency of exceedance, yet it is not a probability distribution function. Information about the sequence of streamflow is lost in FDCs as the streamflow time series is ordered. However, they resemble the cumulative distribution of flow rate and, once plotted, streamflow discharge exceeded in a certain percentage of time can be determined from the FDC. The discharge value exceeded in a percentage of time t is called the t-percentile of the FDC and it is represented by Q_t.

In this study, we considered the upper and lower 10% exceedance probabilities for high and low flows, respectively. As the upper percentiles, we used high flow values corresponding to 1, 5 and 10% exceedance probabilities (Q_1, Q_5 and Q_{10}). Similarly, we used percentiles corresponding to 90, 95 and 99% exceedance probabilities of time (Q_{90}, Q_{95} and Q_{99}) for low flows. Also, the median value (Q_{50}) were used in the analysis. We determined these percentiles for each water year (starting on October 1st of the previous year to end on September 30th of the current year). The percentiles are informative to display relationship between the streamflow discharge and its frequency for high and low flows (Castellarin et al., 2004; Burgan and Aksoy 2022).

Table 1 Streamflow gauging stations (SGSs) selected from Kucuk Menderes River Basin and statistical characteristics calculated from the daily streamflow data

SGS	Name	Drainage Area (km^2)	Elevation (m)	Record Period	Record Length (year)	Mean (m^3/s)	Min (m^3/s)	Max (m^3/s)	Zero values (%)
D06A011	Bebekler	37	220	1990–2014	24	0.31	0.00	9.44	4.3
D06A013	Falaka	83	130	1979–1990	11	0.68	0.00	36.00	3.3
E06A001	Selçuk	3255.2	4	1960–2012	52	9.23	0.00	614.0	16.1

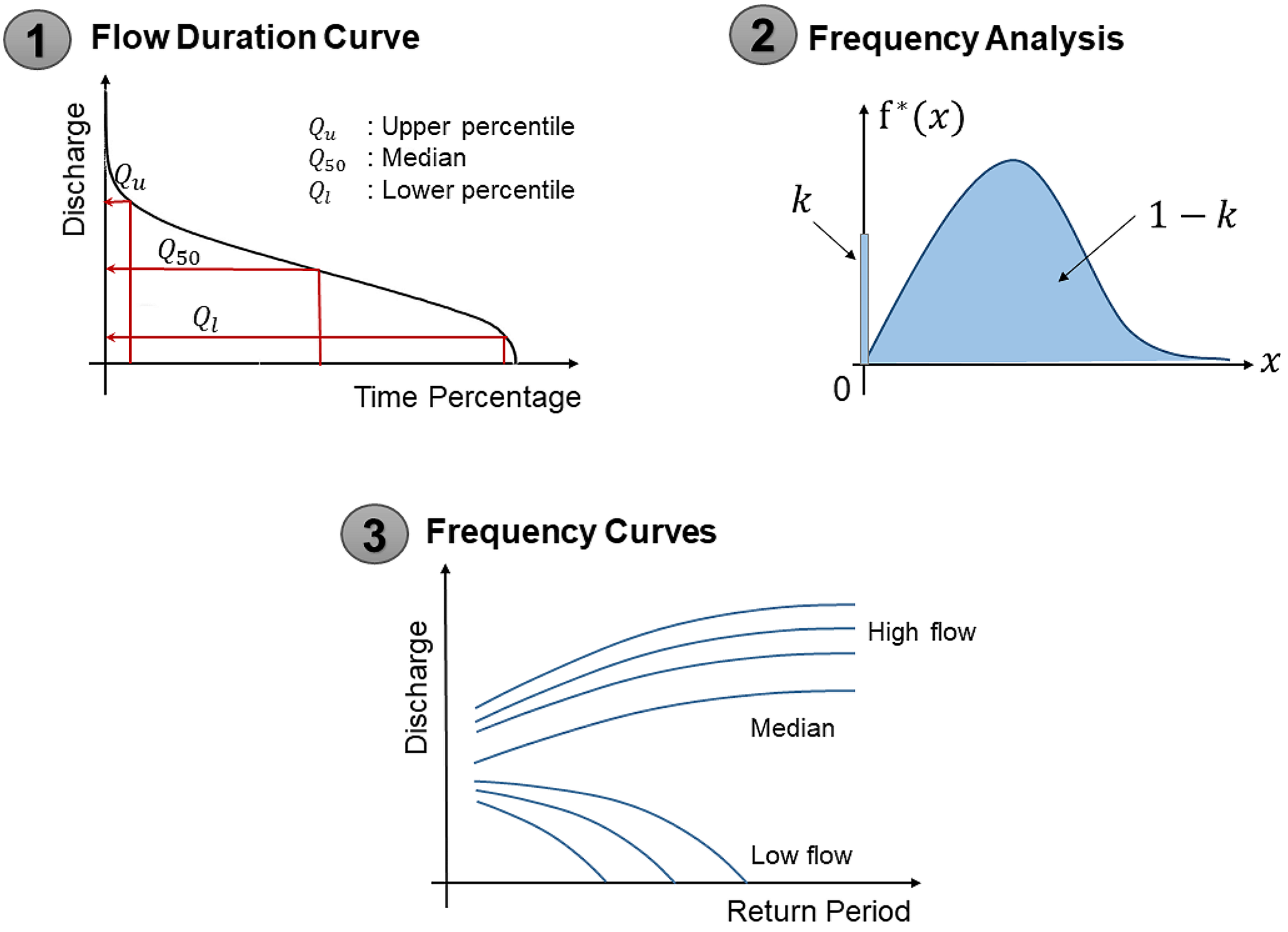

Fig. 3 Storyline showing steps of the method

In Step 2, we apply frequency analysis to the upper and lower percentiles, and the median values to determine the probability density function of each. Low flow percentiles of an intermittent river contain zero values. Frequency analysis for the so-called censored time series is applied according to the total probability theorem, which discards zero values from the time series but takes their probability into account. From the total probability theorem,

$$\begin{aligned}P(X>x)=P(X>x|\,X=0)\,P(X=0)\\+P(X>x|\,X>0)\,P(X>0)\end{aligned}\tag{2}$$

can be written where X is a non-negative variable, x is a non-zero positive value that the variable can take, and P stands for the probability. The conditional probability satisfies

$$P(X>x|X=0)=0\tag{3}$$

which reduces Eq. (2) to

$$P(X>x)=P(X>x|X>0)\,P(X>0)\tag{4}$$

$P(X>0)$ in Eq. (4) is the fraction of non-zero values and $P(X>x|X>0)$ is estimated by frequency analysis of non-zero values. The fraction of zero values (Fig. 4) can be expressed in terms of probability as:

$$k=P(X=0)\tag{5}$$

Equation (4) can then be written as:

$$1-F(x)=[1-F^*(x)]\,(1-k)\tag{6}$$

in which $F(x)$ is the cumulative probability distribution function of all values $(X\geq 0)$ and $F^*(x)$ is the cumulative probability distribution function of non-zero values $(X>0)$, which are expressed, respectively, as:

$$F(x)=P(X\leq x|X\geq 0)\tag{7}$$

$$F^*(x)=P(X\leq x|X>0)\tag{8}$$

This is a mixed distribution which has a probability mass at $X = 0$ and a continuous probability distribution function for $X > 0$ (Fig. 4). Percentiles with return period T can be estimated by solving Eq. (6) for $F^{*}(x)$ and using its inverse transformation. Return periods of high and low flows are linked to the exceedance and non-exceedance probabilities, respectively, as

$$T = \frac{1}{1 - F(x)} \tag{9}$$

$$T = \frac{1}{F(x)} \tag{10}$$

Return periods are calculated in years. By combining Eq. (6) with Eqs. (9–10) we obtain:

$$F^{*}(x) = \frac{1 - \frac{1}{T} - k}{1 - k} \tag{11}$$

$$F^{*}(x) = \frac{\frac{1}{T} - k}{1 - k} \tag{12}$$

for high- and low-flow percentiles, respectively. $F^{*}(x)$ takes positive values only if

$$k \leq 1 - \frac{1}{T} \tag{13}$$

$$k \leq \frac{1}{T} \tag{14}$$

are satisfied for high and low flows, respectively. High and low flow percentiles can be calculated for as short return periods as T satisfying Eqs. (13–14). Negative values are obtained for percentiles with shorter return periods than this least value. These percentiles are indeed zero as a percentile cannot take a physically unrealistic value lower than zero.

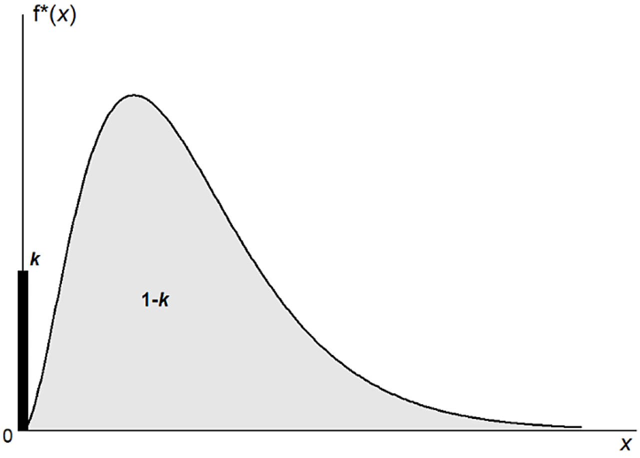

Fig. 4 Mixed probability distribution of flows with zeros. Zero values have a probability mass (*k*). The complementary probability (1-*k*) of the non-zero values is represented by the probability distribution function, $f^{*}(x)$

Important information on high- and low-flow percentiles is derived from the frequency analysis (Chow et al. 1988; Smakhtin 2001; Eris et al. 2019; Aksoy et al. 2021; Jafari et al. 2023) but no universally applicable probability distribution function exists for low flows. In this study, we checked the Generalized Extreme Value (GEV), LP3, Gamma with 2 and 3 parameters (G2, G3), Log-Normal with 2 and 3 parameters (LN2, LN3), and Weibull with 2 parameters (W2) for the lower percentiles (Q_{90}, Q_{95}, and Q_{99}). In the same way, the LN2, LN3, G2, G3, LP3 and Gumbel (Gu) probability distribution functions were tested for high flow percentiles (Q_{1}, Q_{5} and Q_{10}). The Normal (N) probability distribution function was additionally considered for the median value (Q_{50}). Frequency analysis was applied to sequences with 10 years of non-zero values at minimum. The probability distribution functions were checked by the Anderson-Darling test at 5% significance level to either accept or reject the hypothesis that the tested probability distribution function fits the data best. The exceedance probability was considered in the calculation of high flows and median value in plotting the frequency curves. For low flows, the non-exceedance probability was used.

Based on the probability distribution function of each sequence, in Step 3, we developed frequency curves in the form of discharge-return period for the upper and lower percentiles and the median values. The selected probability distribution functions were used to calculate the upper and lower percentiles and the median values of 2, 5, 10, 25, 50 and 100-year return periods.

4 Results and discussion

4.1 FDCs

FDCs of SGSs were plotted for the entire period of record and for each year (Fig. 5). For comparability, the streamflow discharge values were converted into the discharge from the unit drainage area. The high and low flow percentiles and the median value were obtained from the FDCs of each year. Lower percentiles get zero values, demonstrating that the SGSs have intermittent streamflow records. Any curve down-crossing the horizontal axis indicates a year with a portion of no-flow period. The lower the time of exceedance at the down-cross, the higher the intermittency of the river. Table 1 and Fig. 5 show that, among the three SGSs, E06A001 has the lowest down-crossing at about 10% coinciding with the highest intermittency (16.1%) and D06A013

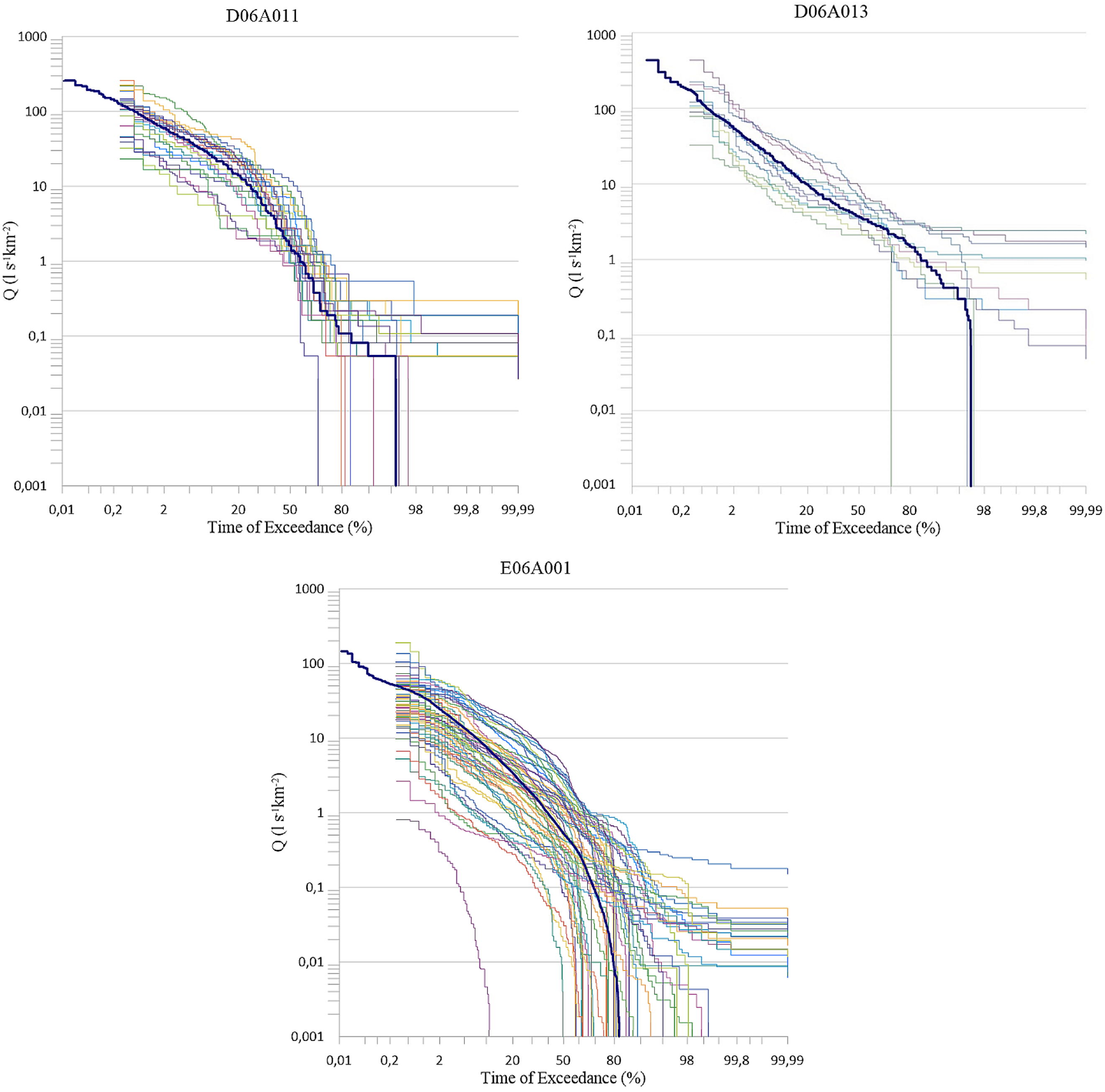

Fig. 5 Flow duration curves (FDCs) of streamflow gauging stations. Thick curve is FDC obtained from the entire length of the daily streamflow time series. Thin curves show FDCs of each water year in the observation period. Water year starts on October 1st of the previous calendar year to end on September 30th of the current year

has the highest down-crossing at about 70% with the lowest intermittency (3.3%).

4.2 Frequency curves of high and low flow percentiles

Table 2 summarizes the frequency analysis of high and low flow percentiles. It shows that each SGS has its own best-fit probability distribution function. The GEV, LP3 and LN3 probability distribution functions fit the upper percentiles for D06A001, D06A013 and E06A001, respectively. The median values of these two SGSs were better fit by the LP3 probability distribution function. For the three lower percentiles, LP3 comes front as the best-fit probability distribution function for two of the percentiles. Results have no agreement to propose a common best-fit probability distribution function for the upper and lower percentiles of the river discharges. Each percentile of each SGS should be investigated individually by means of its own best-fit probability distribution function, i.e., results are case-specific. By using higher number of SGSs, the case-specific results of this study may possibly change to indicate one of the probability distribution functions tested as the best-fit probability distribution function of the upper and lower percentiles.

In terms of the probability distribution function fitted to the upper percentiles, results are comparable with previous studies, for example, Bayazit et al. (1997) who proposed GEV as the best-fit probability distribution function for the annual maximum discharge based on 14 SGSs from 10 different river basins in Turkey. Among the probability distribution functions tested for lower percentiles, LP3 came front by being the best in 4 out of 6 cases (Table 2). Low flows in various river basins in Turkey were best-fit by GEV, P3 and LP3 (Buyukkaracigan 2014; Aksoy et al. 2022; Orta and Aksoy 2022). It can therefore be stated that the outputs of this study are in accordance with the state-of-low flow knowledge of the river basins in Turkey. Similar outcomes of different countries support the finding of the study. For example, the conditional W and LP3 probability distribution functions were found applicable for low flows in the US (Durrans 1996; Durrans and Tomic 1996), the LN2, N and G probability distribution functions were found the best for the majority of sites in Iran (Modarres 2008).

Due to high number of zeros in the lower percentiles, no frequency analysis was applied at E06A001 (Table 2). It is important to identify probability distribution functions of the low flow percentiles to estimate their values at practically significant return periods. The best-fit probability distribution function cannot be identified when the non-zero portion of the data available is not long enough to apply frequency analysis. This difficulty of the low flow percentiles can be solved by data generation techniques. Various techniques exist in the literature to generate the daily streamflow time series of perennial or intermittent rivers. For instance, Claps et al. (2005) used a shot noise model for perennial streams, and Aksoy and Bayazit (2000) performed a method based on the combination of Markov chain, gamma distributed random numbers and an exponential recession function. With these two examples selected among many more in the literature, not only the statistical characteristics but also the non-reversible shape of the daily streamflow hydrograph, e.g., the short and quick ascensions, and the long and slow recessions are preserved. The extended time series can be used for the frequency analysis assuming that the generated data is a statistically similar random realization of the observed daily streamflow, and thus representing the SGS. The short streamflow records are very common in practice. The extended data set can be seen as an opportunity to overcome this difficulty and identify the probability distribution functions which are not obtained otherwise.

High and low flow percentiles of any given return period can be calculated by using the probability distribution function selected. We calculated the upper and lower percentiles which are expected to be reached every 2, 5, 10, 25, 50 and 100 years and plotted in the form of frequency curves (Fig. 6). While calculating the percentiles, we are interested in the maximum of maxima expected to be exceeded for Q_1, Q_5, Q_{10} and Q_{50}, and the minimum of minima expected not to be exceeded for Q_{90}, Q_{95}, and Q_{99}. Therefore, the exceedance probability was used for the upper percentiles and the non-exceedance probability for the lower percentiles. This is the reason why the high flow percentiles including the median value increase and low flow percentiles decrease as the return period becomes longer. Increasing high flow values indicates higher probability of being wet (flood) and decreasing low flow values indicates higher probability of being dry (drought).

One detailed finding about the frequency curves of D06A013 is that Q_{10} increased with a higher rate than Q_5 as the return period increases. Therefore, Q_{10} gets values closer to (practically the same as) Q_5 at the 100-year return period with a tendency to exceed at return periods longer than 100 years (Fig. 6). This is presumably because of different probability distribution functions chosen for these two percentiles (LP3 for Q_5 and LN3 for Q_{10} in Table 2). For a physically plausible frequency curve, a lower percentile of a given return period is not expected to exceed a higher percentile at the same return period. In order to fulfil this physical reality, LN3 was replaced with LP3, the second best-fit probability distribution function of the percentile Q_{10} (Fig. 6). The detailed discussion made for the percentile frequency curves of D06A013 is applicable to the other two SGSs.

Low flow percentiles may contain zero values, and they, indeed, do so when an intermittent river is concerned. Because of the high fraction of zero values, the 10-, 25-,

Table 2 The best-fit probability distribution functions of streamflow percentiles (The best-fit probability distribution function, LN3, was replaced with the second best-fit probability distribution function, LP3, for Q_{10} of D06A013 as Q_{10} tends to exceed Q_5 at high return periods when LN3 is applied.)

SGS	Percentile						
	Q_1	Q_5	Q_{10}	Q_{50}	Q_{90}	Q_{95}	Q_{99}
D06A011	GEV	GEV	GEV	LP3	LP3	LP3	G
D06A013	LP3	LP3	LN3/LP3	G	LP3	LP3	GEV
E06A001	LN3	LN3	LN3	LP3	-	-	-

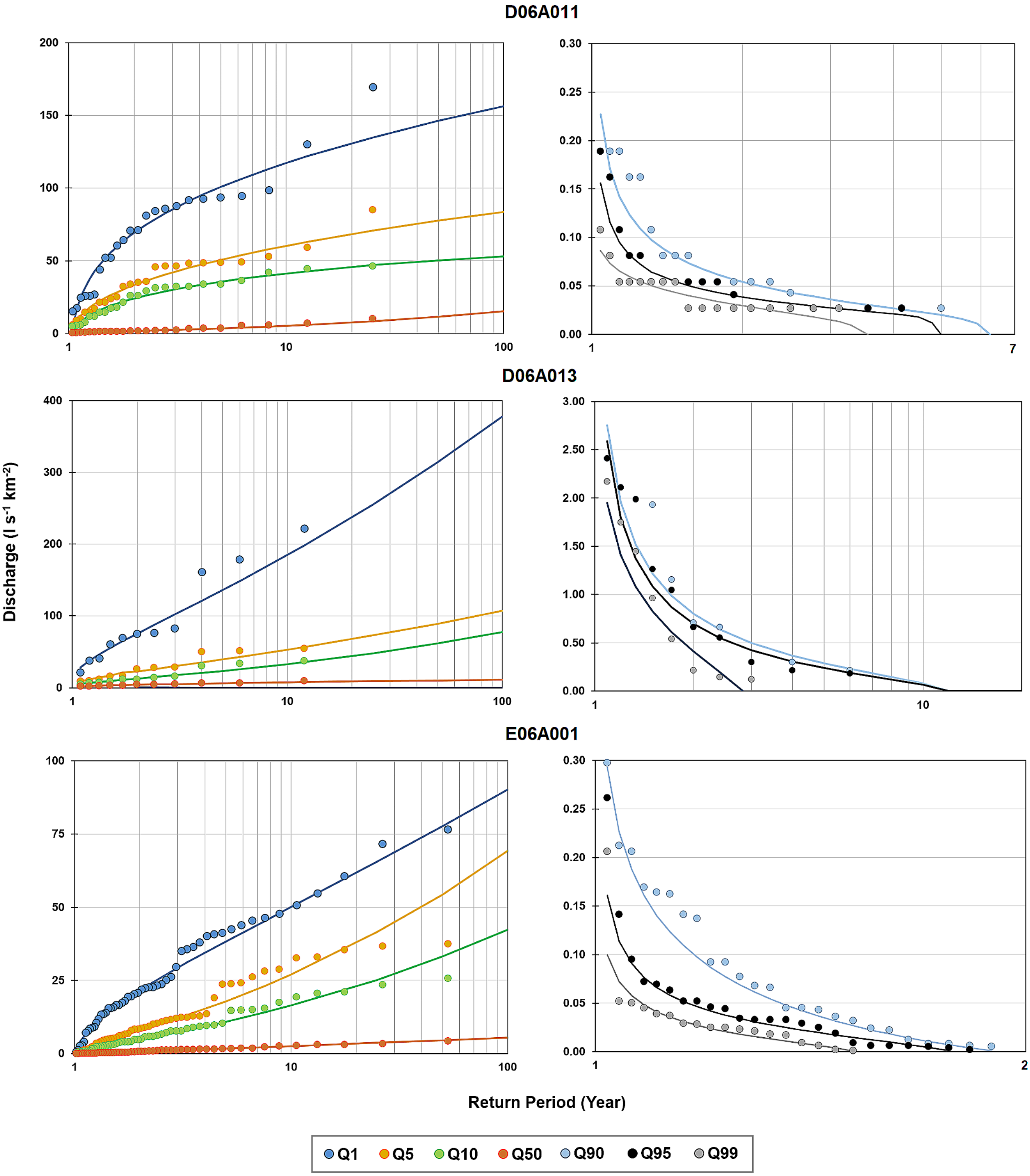

Fig. 6 Frequency curves of high and low flow percentiles. Dots show the observed percentiles while the curves were fitted based on the best-fit probability distribution function of each percentile. The vertical axis is linear and the horizontal axis is in logarithmic scale. Both axis have SGS-specific ranges

50-, 100-year return period low flows were not calculated for Q90, Q95 and Q99 at D06A011. Even the 5-year return period were not calculated for Q99 at this SGS. This is linked to Eq. (14) which should be satisfied for a non-zero low flow percentile be calculated. Under this circumstance, frequency curves down-cross the horizontal axis. Any low flow with a return period longer than the year at the down-cross is zero, because physically implausible negative values cannot be assigned to low flow percentiles. At the least intermittent case of the three SGSs, that is the case of D06A013, Q90 and Q95 can take non-zero values up to return periods longer than 10 years. In the most intermittent SGS (E06A001), however, low flows are expected to take zero values once every 2 years as the return period with non-zero values is almost 2 years. The river may get dry every two years on average over 10% of the time of the year.

4.3 Frequency curves as practical charts

This study can be considered as a step forward in proposing the high and low flow frequency curves as practical charts for operational hydrology and the design of water-related civil structures under flood and drought conditions. They provide flow characteristics, e.g., magnitude, duration, and frequency, to calculate the probability that the civil structure will fail in its lifetime. This is called risk which is pre-selected depending on the project interested.

The project-specific duration is decided in advance. It is linked with the exceedance percentage in FDC. This is what we can call ‘design duration’, which represents the resilience of the structure, the region or society against the water excess for the high flow case, or the tolerance of the water-dependent sector, economy, ecology, society and even individual members of the society to the period of water deficit. The magnitude dictates the amount of water available to the user while the frequency linked with the return period reflects the probability associated with failure in achieving the water needed by the user (Mamun et al. 2010).

More specifically, the magnitude, duration and frequency of high flow and low flow events is crucial in many of the design problems; such as the dike design, reservoir design and operation, river pollution control, and ecological conservation (Engeland et al. 2004). The problem becomes more destructive for high flow conditions. Therefore, higher return periods of less frequently exceeded flows are used. For less destructive high flow design problems, flow with higher probability of exceedance and lower return period can be used. As a practical example, we may compare the dike design with the culvert design. Q_1 with 100 year-return period may serve quite well for the dike design, while Q_5 with 50 year-return period can be sufficient to take as the design discharge for the culvert. This consideration lowers the design discharge by moving downward vertically on the frequency curves chart (Fig. 6) from the Q_1 curve to the Q_5 curve and also by moving from right to left horizontally from the 100 year-return period to the 50 year-return period. This exemplary discussion can be extended to lower percentiles. For example; Q_{90} of a short return period should be used for a fragile aquatic environment. The percentile can be downgraded to, Q_{95} for instance, and the return period can be taken longer when a more sensitive issue is concerned.

The frequency curves can be assessed from two points of view; hydrologic analysis and hydraulic design of civil structures. With hydrologic analysis, we target more non-structural engineering problems than the structural problems. Determination of specific low flow discharge values used as the aquatic life criteria and the design flow for ecological or environmental concerns are among many examples to be given for the hydrological analysis (EPA 2023). Design discharges used for fish-ladders allowing fishes to migrate (O’Connor et al. 2017), and spillways allowing flood to pass safely over the structure (Chanson 2004) are examples for the hydraulic design.

From the frequency curves, the design discharge of a given exceedance probability can be identified for any return period upto 100 years. The choice of the exceedance probability is related to the magnitude of high flow (flood discharge) against which the structure can resist (the resilience). The return period shows if the structure can afford when the selected high flow is exceeded during its lifetime. The exceedance probability is the percentage of time during which the discharge is exceeded (the time span with water surplus over the selected threshold discharge) in the upper part. In the lower part, it is the non-exceedance probability, which is the percentage of time during which the discharge is not exceeded (the time span with water deficit below the threshold discharge). The resilience of the river during the low flow period is important, among many others, for instance, in the conservation of aquatic life for which the environmental flow should be guaranteed.

From the lower percentile frequency curves, we can find if the low flow of a given duration can be reached or not during the lifetime of the project. Low flows of various durations serve for various purposes. Frequency curves of lower percentiles can be used to substitute for the D-day low flows, which are frequently used in hydrology since ASCE Task Committee (1980) proposed $Q_{7,10}$ as the low flow criteria. As a specific example, the Illinois Environmental Protection Agency often uses estimates of the $Q_{7,10}$ as the baseflow condition in Illinois streams at which certain water quality standards apply. In particular, these flows are used for defining permit limits for effluent standards and mixing zones as defined by Illinois Pollution Control Board regulations (ISWS 2023). Provided that its criteria are known as in this practical example, the ecological flow (or environmental flow) can be determined from the frequency curves of the lower percentiles.

The duration over which a given low flow discharge is not exceeded is informative about water availability (or non-availability). This is a major component needed for water planning and management particularly when their values for return periods up to 100 years are obtained from the frequency curves. By using the proposed frequency curves, it is expected that water planners and managers can make proper future projections for water resources planning and management strategies. The upper and lower percentiles demonstrate the applicability of frequency curves as operational hydrology charts to use in improving the resistance of civil structures against floods and in increasing the resilience of water-related sectors against drought.

5 Conclusions

High and low flow percentiles of the daily streamflow are overviewed to develop their frequency curves, which carry a potential for practice in hydrology and hydraulics. The methodology employed in this study is based on one of the fundamental statistical tools, the frequency analysis, which is combined with the total probability theorem to account for the probability of zero values. The LP3 probability distribution function comes to front as the best-fit probability distribution function of the percentiles. This particular probability distribution function is more dominant in the lower percentiles including the median value. Due to the limitation in the data, this might be taken as a site-specific result rather than a general conclusion. The main outputs of this study are the high- and low-flow frequency curves. They can be used for hydrologic analysis, water resources management and hydraulic design. The applicability of frequency curves is limited to gauged sites which can be further studied for regionalization to cover a spatial extend from gauged sites to ungauged sites in river basins. Furthermore, they may contribute to engineering problems in practice under low flow conditions for which design codes do not exist.

Author contributions H.A. conceptualized and supervised the research; G.S. performed the research; Y.C. collected the data and contributed to the data analysis; E.E. made contributed to data analysis and visualization. All authors were involved in the discussion of results, original draft preparation, review and editing the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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