# Streamflow Duration Curves: Focus on Low Flows

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***Abstract:*** *Flow duration curves (FDCs) express the link between a selected streamflow and the percentage in time such value is exceeded. The curves provide a graphical insight into hydrological regimes, though, the absence of time-series data is a significant shortcoming. Conversely to what happens with hygrograms, flows in FDCs are represented without regard of sequence of occurrence. This paper explores FDCs of 19 catchments for which, at least, 10 years of daily discharges are available. FDCs can be built for any temporal scale (i.e. daily, weekly, monthly). In this study daily discharges have been adopted because daily scale better represents the variation in flow. A particular focus is on low flow data which are useful to the design: fish ladders, environmental passages and low flow diversions. The work also introduces a unique hydrological area having the inner catchments similar response among themselves in terms of low flow data. For such an hydrologically homogeneous area, environmental flow, namely the amount of water released uniquely for biological requirements, is appropriately detected.*

***Keywords:*** *Biological demands, characteristic durations, environmental structures, fish passages, flow duration curves, low flow data.*

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## 1. INTRODUCTION

Analysis of watercourse regimes, with a focus on low flows and droughts, is important for designing storage and capture works, managing regulation devices and dealing with qualitative standards for the ecosystem. Runoff data would ideally be obtained from the hydrometrical gauges but in most cases is obtained through regional analysis that extrapolates available data at a number of measured sites to the rest of a catchment. Searcy (1959) demonstrated that with a sufficiently long record of reliable information curves can be derived that represent the cumulative frequency and enable data analysis that can inform probabilistic modelling of future scenarios. Other work on Flow Duration Curves (FDCs) is attributed to Vogel and Fennesey (1994,1995) who provide a brief history of their widespread use in hydrology. More recent efforts tend to focus on the problem of curve regionalization. Vogel and Fennessey (1994) introduced the idea of annual flow duration curves which have shown to be quite useful for drawing probabilistic considerations on wet and dry years and for computing confidence intervals associated with the curves. Following these conclusions, Castellarin et al. (2004a) modelled the relationship between FDCs and Annual Flow Duration Curves (AFDCs) built on daily streamflow series. His results provide an evaluation of the reliability of the regional FDCs for ungauged sites and show that the reliability of the three best performing regional models are similar to one another. A generation of time series of daily streamflows for ungauged sites has been also detected. Castellarin (2004) tested the procedure over three catchments varying from 400 to 3000 km$^2$ of size. LeBoutillier and Waylen (1993) tried to relate FDCs to AFDCs through a five-parameter stochastic model of daily streamflows. Albeit a widespread application of different forms of FDCs, curves based upon daily discharges seem yet to be of principal use. This work provides a focus on low flow data dealing with FDCs expressed in the form of ''*characteristic durations*'' detailing a procedure explained by Searcy (1959). In more recent efforts attributed to Claps (1997) and Verma et al (2017) there are attempts to estimate environmental flow (EF) using FDCs. Verma made use of two different approaches, the former one based on a period of record and the second on stochastic approaches for daily: 7-, 30-, 60-day moving averages, and 7-daily mean annual flows. The procedure has been tested on 6 Indian catchments. The results of the study presented here demonstrate a practical and appropriate tool for assessing adequate EF for river courses characterized by similar precipitation pattern but different catchments responses.

## 2. STUDY AREA AND DATA

The study area, known as Liguria region, is located along the north eastern side of Italy (see Figure 1). Major city is Genova which separates the eastern from the western river courses. The analysis considers a group of 19 catchments for which at least 10 concurrent years of daily data are available. The period of analysis belongs to 1951-1971. After 1977 the dismantlement of the *Ufficio Idrografico Statale* , namely the National Bureau in charge with hydrometrical information,  has limited data  only to level observations and streamflows are no longer at disposal.


Figure 1 - Liguria Region with highlighted monitored catchments.

This area is characterized by river courses of intermittent and torrential flow regime where major flash floods occur about twice a year, namely, in: November and April. During summer period, conversely, flows are a consequence of a long sequence of non-rainy days (roughly more than 90) which highly limit the water availability necessary for irrigation and potable purposes. The intermittent behavior is entailed in those courses which are sharply dry almost all the yearlong and rebirth after intensive precipitation events, thus flowing for several days before vanishing again. Torrential river courses have an extremely variable flow regime with stream flows going from negligible values along the year to high peaks of hundreds of $m^3/s$ in half a day. The floods, coupled with the high urbanizations, cause severe havoc in the cities located next to their delta, both in term of moral and material damages.  A paradigmatic example of high damages is expressed by the photo below.

Figure 2 - Flood in Genova: November 2011

High slopes, short concentration times during the floods (generally in less than 8 hours the flood reaches the delta at sea level originating from 700 m of height) and fast continuous alternation of sediment and erosion areas along the riverbeds characterize hazardous and highly unpredictable response to sudden precipitations.

In general, all 19 catchments have average slope varying from 3 up to 8% and catchment sizes around 150 $km^2$ and river lengths less than 80 km. Three courses have been selected (see ‘Table 3’) being representative of: extreme eastern (Roya), eastern (Argentina) and western (Petronio) rivers respect the city of Genova. The former one closed at the hydrometrical section is 480 $km^2$ squared and origins from 3050 m of height and reaches the delta after 60 km. The river course is located at the extreme eastern side of the region next to the French border. Only one third of its total catchment is in Italian territory and the remaining part has been acquired by France after the Italian defeat of WWII. Its delta is in Ventimiglia. Argentina catchment (total size S=220 km$^2$) stretches along 39 km from Mountain Saccarello (2000 m of height) to its delta at sea level near the city of Sanremo. Major tributaries have intermittent patterns. In the upper part of the valley there are many slates, limestone and conglomerates quarries. Average overall slope equals to 5.6 %. Petronio is located near the city of Genova and has mean slope of 3.4% with highest altitude of 870 m above sea level.

Table 1 lists the 19 catchments under study. Columns report, respectively: the catchment's area, the period of absent information detected inside the total period considered, the driest month in the year and the corresponding minimum flow value.

Table 1 - Catchments studied from 1951 to 1971, in * catchments with missing data.

| **Catchment's number** | **Catchment's name and area (km$^2$)** | **Missing Data between 1951-1971** | **Month with lowest rainfall and minimum corresponding flow Q (m$^3$/s)** |
|---|---|---|---|
| 1 | Roya*; 477.78 | 1960-1961 | September; *5.264* |
| 2 | Bevera*; 155.40 | 1951-1956; 1960-1963; 1971 | September; 0.419 |
| 3 | Nervia*; 123 | 1956 | September; *0.217* |
| 4 | Argentina; 192 | No missing data | September; *0.474* |
| 5 | Impero*; 69 | 1951 | August; *0.111* |
| 6 | Arroscia*; 202 | 1959: December<br>1960: January-February<br>1962: July-September | September; *0.442* |
| 7 | Lerrone*; 47 | 1951-1955; 1967; 1970-1971 | September; *0.117* |
| 8 | Neva*; 124 | 1955-1964<br>1954: October, December | September; *0.31* |
| 9 | Sansobbia*; 32 | 1966 | August; *0.033* |
| 10 | Bisagno*; 34 | 1955-1963<br>1954: September-December | August; *0.09* |
| 11 | Lavagna*; 163 | 1969-1971 | August; *0.229* |
| 12 | Graveglia*; 41 | 1953: September-December;<br>1955-1959<br>1960: January-March | August; *0.193* |
| 13 | Entella; 364 | No missing data | August ; *0.497* |
| 14 | Petronio*; 57 | 1951-1956;<br>1960: May-December<br>1961 | August; *0.0431* |
| 15 | Piccatello*; 77 | 1951-1956 | August; *0.369* |
| 16 | Bagnone; 51 | No missing data | August; *0.432* |
| 17 | Aulella*; 208 | 1951-1954<br>1955: June-July<br>1959: May-December<br>1960-1961<br>1963: January-August | August; *1.692* |
| 18 | Calamazza*; 939 | No missing data | August; *5.340* |
| 19 | Vara* ; 206 | 1954: November-December;<br>1958: August-November | August; *0.768* |

## 3. ADOPTED METHODOLOGY

For each of the above-mentioned catchments the FDC with duration referred to such known long-*term period* has been built having ranked the daily recorded streamflows for ten years at disposal into a descendent order. FDCs are synthesized at official *characteristic durations* (according to the National Hydrographic Bureau custom, Annali Idrologici (1951, 1971)) which correspond to runoff values available: 10, 91, 182, 274 and 355 days/year. To these values the National Hydrographic Bureaus attribute the meaning of: runoff Q10 as maximum flood of reference, namely: the value available (or exceeded) 10 days a year, Q355 is minimum drought of reference, Q91 and Q274 being ordinary flood threshold and ordinary drought threshold. Q182 is the semipermanent flow, namely, the streamflow available half the year. The remaining durations: 10, 91, 274, 355 are specularly complementary within a year. Shape factors are obtained from the ratio of streamflows set at the characteristic durations and briefly describe the shape of the plotted FDCs. Durations between 274 and 355 deal with droughts going from ordinary 274 to extraordinary 355-day limits. Q335 has been here additionally inserted as the complementary runoff value of the month with minimum flow a year. Q335 represents, on the plot of FDC, a pivot point for most of the 19 catchments which have the remaining data (Q336-to Q365) all recorded into the driest month of the year. Results show that for the tail of FDCs the hypothesis that low flow values follow the corresponding chronological sequence of observations is respected. The novelty of the work is to introduce a link between the bottom part of FDCs and the corresponding temporal sequence of low streamflows, which is known to lack by nature. Table 2 summarizes FDCs information reporting: Q335 as the low flow value available, or exceed, 335 days/year in the hydrological year *of long term period* (1951-1971), the shape factors (Q182/Q335 and Q274/Q335) evaluated in respect of Q335 as the value of reference and the number of day/year the average minimum flow (reported in column 4 of Table 1) is available on FDCs. In case such minimum flow (column 4 of Table 1) matches totally to Q335 (column 2 of Table 2) the days/ year (column 5 of Table 2) naturally equal to 335. Such coincidences have been highlighted in bold. The corresponding basins are, therefore, identified as a unique homogeneous hydrographic area in respect of low flows. Shape factors can be detected for any duration of reference and briefly summarize the shape of FDCs. However, the comparisons among Q335 to Q10 and Q91 have been disregarded for lack of useful information since Q335 and Q10, Q91 belong to different hydrological regimes.

Table 2 - FDCs set at *characteristic durations*. Discharges expressed in $m^3/s$.

| **Catchment's number** | **Q(335)** | **Q(182)/Q(335)** | **Q(274)/Q (335)** | **Duration (days/year)** |
|---|---|---|---|---|
| **1** | **5.26** | **1.869** | **1.3118** | **335** |
| **2** | **0.38** | **3.39** | **1.58** | **333-335** |
| **3** | **0.22** | **3.955** | **1.773** | **335** |
| **4** | **0.47** | **3.745** | **1.723** | **335** |
| **5** | **0.11** | **4.637** | **2** | **335** |
| 6 | 0.53* | 3.811 | 1.811 | 343 |
| 7 | 0.06 | 4.50 | 2.333 | = 296- 306= 338 |
| 8 | 0.39 | 3.333 | 1.872 | =350-351 |
| **9** | **0.03** | **10** | **2.667** | **335** |
| 10 | 0.1 | 5.10 | 1.70 | =340-354 |
| 11 | 0.15 | 13.933 | 4.667 | 322 |
| 12 | 0.16 | 5.188 | 2.438 | 327 |
| 13 | 0.66 | 8.485 | 3.182 | 342 |
| 14 | 0.06 | 12.33 | 4.33 | 348 |
| 15 | 0.38 | 4.132 | 1.579 | 340 |
| 16 | 0.42 | 3.048 | 1.738 | 333 |
| 17 | 1.82 | 3.028 | 1.643 | 343 |
| 18 | 5.5* | 3.709 | 1.735 | 338 |
| 19 | 0.65 | 5.539 | 2.431 | 322 |

It can be noticed that eastern catchments have similar low flow (catchment number: 1-5) behavior conversely to western catchments (catchment number: 14-18) where the minimum flow is experienced at the very tail of the curves. The formers have flatter slopes which denote (see Figure 3) the presence of ground water storage able to balance flow especially during summer periods while the latter (see Figure 4) have steeper slopes which reveal that flows are highly from direct runoff. A flat slope at the very lower end reveals, in general, a large amount of storage while a steep slope indicates a negligible amount.

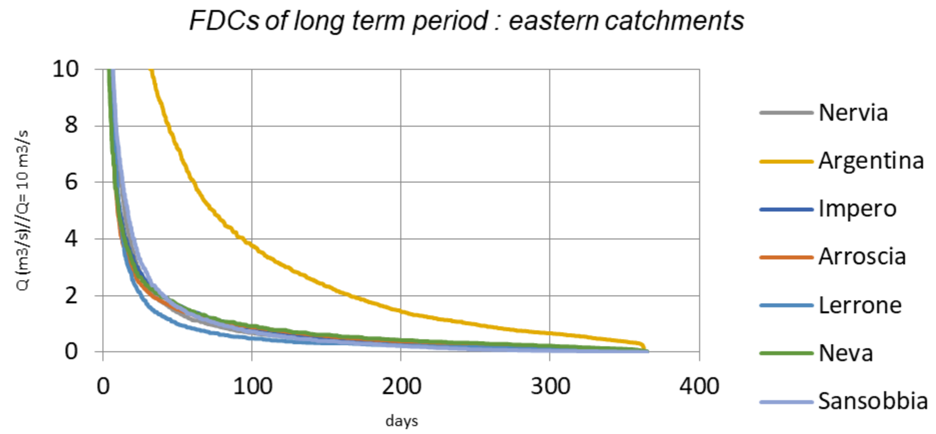



Figure 3 - FDCs extract: eastern catchments respect city of Genova.

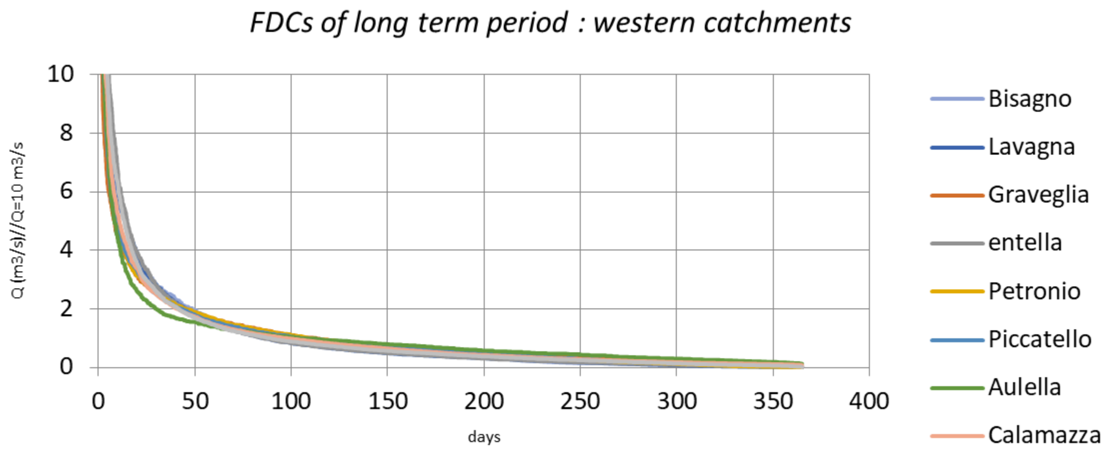


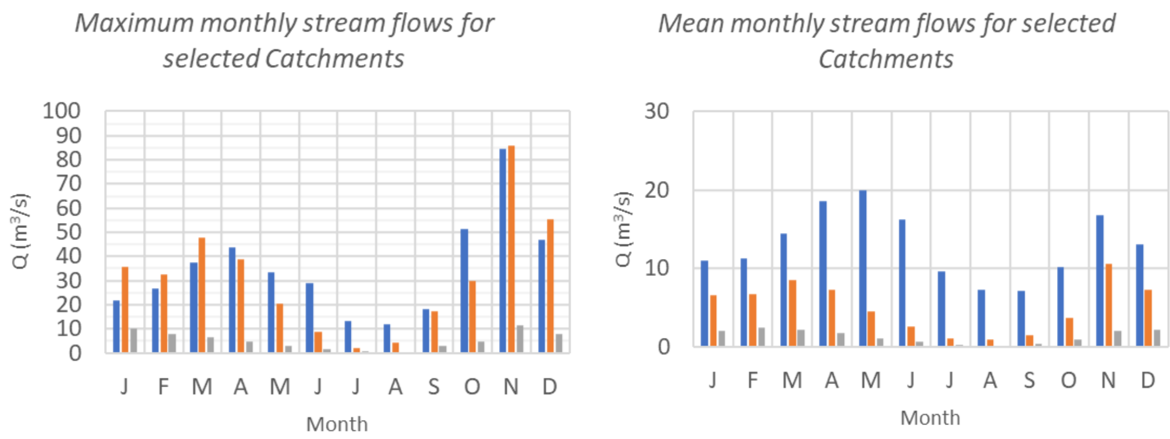

Figure 4 - FDCs extract: western catchments respect city of Genova.

Table 3 reports: maximum, mean and minimum average monthly flow for three selected catchments groups during the period of study which comprehends: 1951-1971. Values are expressed in $m^3/s$. Roya is the unique catchment intensively fed by snow precipitation while Argentina and Petronio are sorted examples of eastern and western catchments.

Table 3 - Monthly averaged stream flows. Discharges expressed in $m^3/s$.

| **ROYA (1st group)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***J*** | ***F*** | ***M*** | ***A*** | ***M*** | ***J*** | ***Jul*** | ***A*** | ***S*** | ***O*** | ***N*** | ***D*** |
| 21.93 | 26.51 | 37.41 | 43.62 | 33.18 | 28.95 | 13.30 | 12.03 | 18.11 | 51.53 | 84.40 | 46.96 |
| 10.93 | 11.23 | 14.50 | 18.64 | 19.97 | 16.19 | 9.66 | 7.32 | 7.16 | 10.16 | 16.74 | 13.13 |
| 7.24 | 7.49 | 8.90 | 11.50 | 13.74 | 10.98 | 7.14 | 5.76 | 5.26 | 5.38 | 6.43 | 7.86 |
| **ARGENTINA (sorted example in 2nd group of similar catchments)** | | | | | | | | | | | |
| 35.70 | 32.46 | 47.84 | 38.70 | 20.57 | 8.61 | 1.94 | 4.32 | 17.23 | 29.60 | 85.93 | 55.31 |
| 6.63 | 6.75 | 8.57 | 7.21 | 4.55 | 2.52 | 1.03 | 0.84 | 1.46 | 3.68 | 10.54 | 7.20 |
| 1.96 | 2.05 | 2.64 | 2.82 | 1.73 | 1.13 | 0.72 | 0.48 | 0.48 | 0.68 | 1.36 | 1.86 |
| **PETRONIO (sorted example in 3rd group of similar catchments)** | | | | | | | | | | | |
| 9.99 | 7.65 | 6.60 | 4.91 | 3.07 | 1.36 | 0.59 | 0.41 | 2.87 | 4.51 | 11.41 | 7.66 |
| 2.04 | 2.41 | 2.12 | 1.78 | 1.02 | 0.59 | 0.25 | 0.14 | 0.35 | 0.92 | 1.98 | 2.18 |
| 0.66 | 0.68 | 0.96 | 0.83 | 0.50 | 0.31 | 0.10 | 0.04 | 0.09 | 0.17 | 0.45 | 0.75 |

Figures 5 and 6 show monthly discharges values which express the hydrological regime of the catchments.




Figures 5 - Averaged monthly maximum (left) and mean (right) discharges for Roya, Argentina and Petronio.

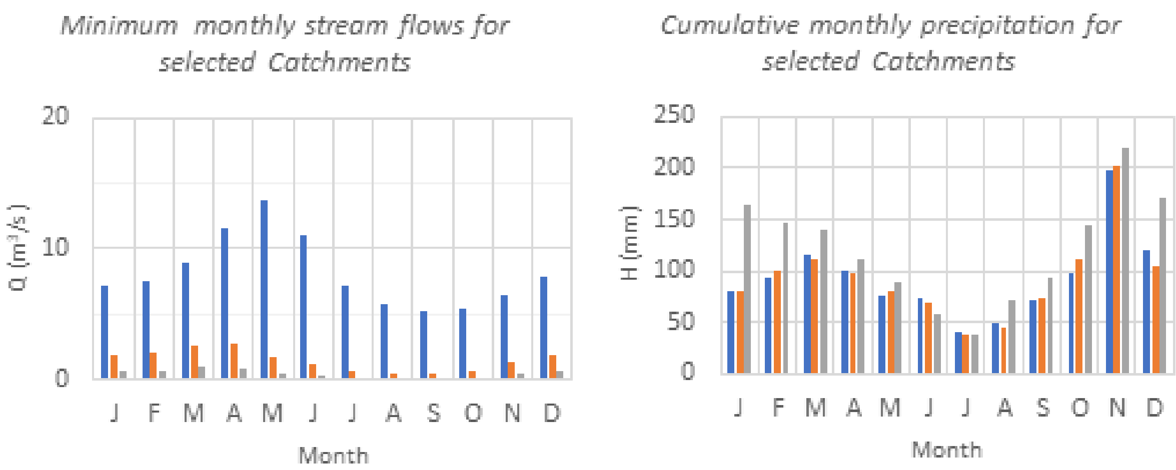



Figure 6 - Averaged monthly minimum discharges (left) and cumulative precipitations (right) for Roya, Argentina and Petronio.

Table 4 displays FDCs synthesized at *characteristic durations*. Q, average is evaluated summing all the observed stream flows for each catchment (record length's equal to 3650+) and dividing the result by the amount of data. Incidentally it must be noticed that the duration associated to Q, average is never known *a priori* but can be stated after its calculation, only. The curves are built according to the *total period* method which requires that all discharges are ranked according to their magnitude and values are, thereafter, sorted to set durations of 10, 30…274 and 355 days. This method is mostly transparent in terms of final curve construction.

The other procedure is known as *calendar year* method which consists in considering the discharges of each singular year ranked according to the magnitude. Subsequently, the discharges of each ordered number are averaged. Shortcoming of this method, although very practical and used also in *Annali Idrologici* is that the final averaged curve has the crest lowered (Q10—Q91) and the tail (Q274-Q355) lifted up. Final values may slightly differ from the more accurate values reported in the *total year's* procedure.

Table 4 - Streamflow data expressed in $m^3/s$ and synthesized at characteristic durations.

| Catchment's number | Q(10) | Q(30) | Q(60) | Q(91) | Q(135) | Q, average | Q(182) | Q(274) | Q(355) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 36.30 | 25.10 | 18.90 | 15.50 | 11.90 | 13.14 | 9.83 | 6.90 | 4.61 |
| 2 | 12.20 | 5.03 | 3.49 | 2.60 | 1.77 | 2.51 | 1.29 | 0.60 | 0.21 |
| 3 | 19.60 | 6.41 | 3.12 | 2.07 | 1.38 | 2.77 | 0.87 | 0.39 | 0.16 |
| 4 | 31.3 | 11.20 | 6.18 | 4.08 | 2.73 | 4.98 | 1.73 | 0.81 | 0.36 |
| 5 | 8.09 | 3.64 | 2.12 | 1.42 | 0.87 | 1.49 | 0.53 | 0.22 | 0.07 |
| 6 | 21.80 | 9.60 | 6 | 4.37 | 2.93 | 4.50 | 1.99 | 0.96 | 0.32 |
| 7 | 5.47 | 1.65 | 0.84 | 0.55 | 0.35 | 0.83 | 0.27 | 0.15 | 0.03 |
| 8 | 14 | 6.27 | 3.88 | 2.69 | 1.30 | 2.68 | 1.30 | 0.73 | 0.29 |
| 9 | 7.72 | 2.82 | 1.41 | 0.86 | 0.5 | 1.06 | 0.30 | 0.08 | 0.5 |
| 10 | 8.04 | 3.75 | 2.19 | 1.29 | 0.81 | 1.34 | 0.51 | 0.17 | 0.08 |
| 11 | 35 | 16 | 8.32 | 5.30 | 3.21 | 5.66 | 2.09 | 0.70 | 0.07 |
| 12 | 6.73 | 3.76 | 2.46 | 1.77 | 1.24 | 1.49 | 0.83 | 0.39 | 0.10 |
| 13 | 103 | 42.30 | 22.20 | 14.10 | 8.60 | 15.21 | 5.60 | 2.10 | 0.40 |
| 14 | 6.60 | 3.43 | 2.27 | 1.62 | 1.09 | 1.36 | 0.74 | 0.26 | 0.02 |
| 15 | 12.9 | 7.03 | 4.37 | 3.18 | 2.30 | 2.79 | 1.57 | 0.6 | 0.31 |
| 16 | 11.7 | 5.53 | 3.38 | 2.46 | 1.80 | 2.31 | 1.28 | 0.73 | 0.31 |
| 17 | 37.50 | 17.7 | 11.7 | 9.12 | 7.05 | 8.24 | 5.50 | 2.85 | 1.39 |
| 18 | 221 | 105 | 61.9 | 44.6 | 30.9 | 42.03 | 20.4 | 9.54 | 4.46 |
| 19 | 52.20 | 21.3 | 12 | 8.04 | 5.34 | 8.25 | 3.60 | 1.58 | 0.44 |

These data, for all catchments, confirm that monthly average stream flows approximately related to Q91 are higher than the corresponding median value Q182 of reference. This is always true for highly skewed data as daily stream flows is much emphasized in case of river of torrential regime whereas the floods squeeze the average value toward shorter days.

Therefore, having the average value toward high flood (Q91) identifies all the Ligurian catchments being typical of torrential regime and differences consist in catchments sizes, slopes, and precipitations patterns.

Figure 7 show the average FDCs built according to the *calendar year* method.

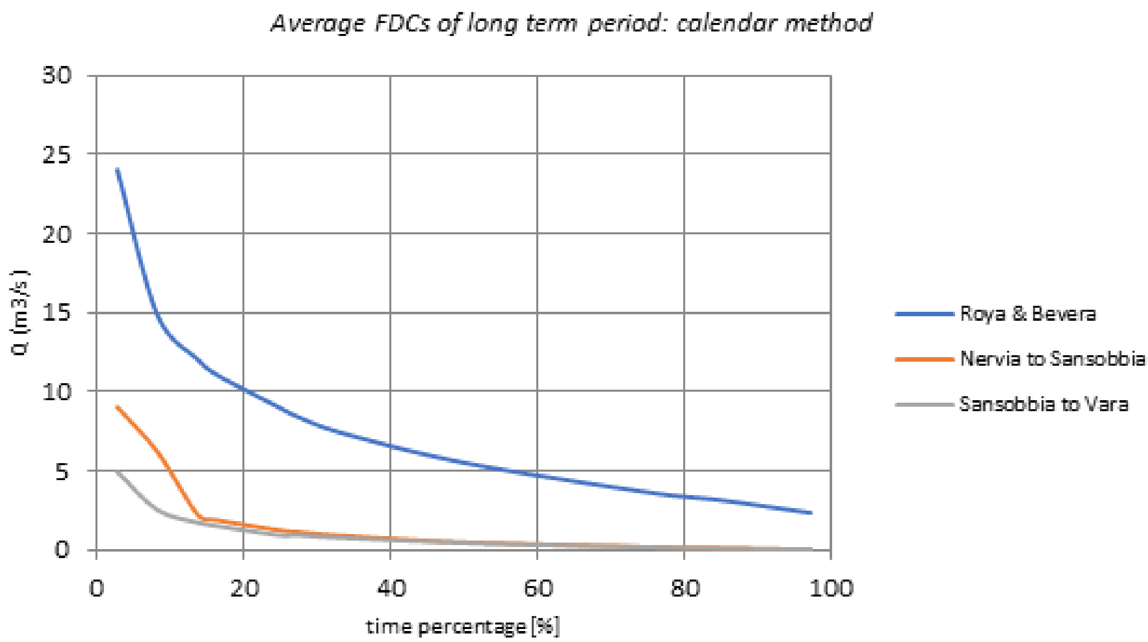



Figure 7 - FDCs represented in long term period and later synthesized at characteristic durations

## 4. RESULTS AND COMMENTS

The information detected from FDCs is more complete in respect to the one corresponding to only streamflow data. FDCs not only provide information about water availability but also about percentage in time such resource is present or generally exceeded either in a singular year, namely, *immediate hydrological scenario*, or in a long-term year of reference, namely, *general hydrological scenario*. As a matter of fact, in practical circumstances comparing a generic withdrawal to the available mean streamflow has very poor strength in terms of water quality and quantity defense of the river body since it is not known *a priori* the duration in a year (either short or long year of reference) associated to such value and furthermore, it is not guaranteed that the streamflow record is thereafter depleted accordingly to the streamflow withdrawn. Although FDCs disregard temporal sequence upon observations the hypothesis that high flow values are independent while low flows are more likely to be strongly timely correlated among themselves is supported by the results. The tails of the curves (from Q335 up to Q365) show that a generic low flow into this last interval is generally followed by a subsequent low flow observed the day after or two days after and all values (into the interval Q335 to Q365) belong to the driest month of the year. (see 'Table 2' highlighted values). The authors suggest the use of Q335 as a proper minimum EF useful to design fish passages and other biological requests. Additional increases initial EF of 10% up to 20% can be added thus introducing a hydrological modulation along the year to better comply the variation of needs. The benefit of the procedure is the detection of a specific duration (335 days/year) whose corresponding streamflow datum, namely Q335, becomes the keystone between non temporal consequential flows (Q1-Q335) to very likely consequential flows (Q335-Q365). Such a value enables a better estimation of EF respect the one achieved using pre-defined formulas based upon catchment's overall: area, precipitation and slope.

## 5. CONCLUSIONS

The study considers the analysis on low flow values for FDCs of long-term period built for 19 catchments under study. The paper is able to provide mean streamflow value estimation for rivers of intermittent and torrential regime having such a value roughly sitting on the Q91 or, in other words, the discharge available almost three months a year (not necessarily 91 consecutive days). A particular focus on the tail of the curve is also provided through the evaluation of shape factors: Q182/Q335 and Q274/Q335 of FDCs. Still, the novelty of the research is that five catchments have the Q335 of long-term period exactly coincident with the average value of minimum flow observed in the driest month of the year. For almost all the catchments the tail of FDCs is represented by likely consecutive observations and in particular the first five nearby catchments represent a unique hydrographic singularity which have similar minimum precipitation pattern and similar minimum catchments responses. This study is a primary and useful example of temporal information on low flows in FDCs.

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