ROYÉ, D. (2018). *The application of a Concentration Index on river discharge: a case study of selected stations in Spain*, The overarching issues of the european space - preparing the new decade for key socio-economic and environmental challenges, Porto, Fac. Letras Univ. Porto. pp. 451 - 461

THE APPLICATION OF A CONCENTRATION INDEX ON RIVER DISCHARGE: A CASE STUDY OF SELECTED STATIONS IN SPAIN

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Abstract

The frequency distribution of daily river discharge amounts almost conforms to a negative exponential distribution, reflecting the fact that there are small daily totals and few large ones. Positive exponential curves, which plot the cumulative percentages of days with discharges against the cumulative percentage of the discharge amounts that they contribute can be evaluated through the Concentration Index (CI). The higher the value, the larger the concentration of daily average river discharges. The Concentration Index has been applied as an initial trial to a selected number of stations in Spain. The spatial-temporal distribution of the CI for the selected stations is geographically consistent, reflecting the principal physiographic and climatic units of the country. CI has been shown as an index that perfectly describes the temporal behaviour of the river discharge. Furthermore, the application of the CI demonstrates its discriminatory capacity according to river type and it has been proven to be a new method for the interpretation of the distribution of flow throughout the year.

Keywords: river discharge, concentration index, Spain, spatial-temporal behaviour

Resumen

La distribución de frecuencia de caudal diario se aproxima a una distribución exponencial negativa, lo que refleja la presencia de pequeño totales diarios, poco significativos. Las curvas exponenciales positivas, que grafican los porcentajes acumulados de días con caudales contra el porcentaje acumulado de caudal en el año hidrológico, pueden evaluarse a través del Índice de Concentración (CI). Cuanto mayor sea el valor, mayor será la concentración de los caudales medios diarios de los ríos. El índice de concentración se ha aplicado como prueba inicial a un número determinado de estaciones en España. La distribución espacio-temporal del CI para las estaciones seleccionadas es geográficamente consistente, reflejando las principales unidades fisiográficas y climáticas del país. CI se ha mostrado como un índice que describe perfectamente el comportamiento temporal del caudal del río.

Además, la aplicación de CI demuestra su capacidad discriminatoria según el tipo de río, y también se erige como un nuevo método para la interpretación de la distribución del caudal a lo largo del año.

Palabras clave: caudal fluvial, índice de concentración, España, comportamiento espacio-temporal

1. Introduction

The factors involved in the hydrological behaviour of a river are extremely varied and closely related. Therefore, it is often difficult to draw the line between cause and effect. It is necessary to differentiate between natural and anthropic control factors. The former are generally constituted by precipitation, base flow, vegetation and land uses (which are also anthropic) and relief (topographical). Anthropic factors are also altered because they intervene directly in the hydrological functioning of the river, altering its natural regime by modifying its seasonal variability or by extraction (for water supply, for example).

The idea of analysing river discharge as a phenomenon that is concentrated in time is based on the negative exponential distribution of daily precipitation, that is to say that there are many days with low levels of precipitation and few with elevated quantities (Martín-Vide, 2004). The fine temporal structure of precipitation, for example, at a daily resolution, is vitally important, not only for studying climatic factors such as intensity and torrential rainfalls (dry periods and drought, etc.), but also in relation to factors such as the soil and ecosystems (erosion, desertification, etc.), the management of water resources, floods and flash flooding, the design of drainage systems, the availability and safety of transport systems, urban planning, among others. Extreme rainfall events on a daily scale are characterised by durations limited to a small number of days. However, they account for a high percentage of monthly, seasonal and annual precipitation (Brooks & Carruthers, 1953; Jolliffe & Hope, 1998; Easterling *et al.*, 2000; Martín-Vide, 2004; Alexander *et al.*, 2006; Monjo, 2016, Royé *et al.*, 2017).

This paper describes the first application of the Concentration Index (CI) (Martín-Vide, 2004) to river discharge. We studied several Spanish river gauging stations. The specific objectives of the study are: (i) to identify methodological challenges in the application of CI on flow data instead of precipitation data; (ii) to analyse what the application of the CI contributes to the interpretation of flow data; and (iii) to draw some initial conclusions in the form of weaknesses, strengths and future perspectives of CI on flow data.

2. Data and methodology

2.1. Data

The methodological trial has been applied on 10 gauging stations in the northern half of the Iberian Peninsula (Figure 1). The stations are distributed in four basins and are representative of varied hydrological environments. 40% of the stations are located in a Mediterranean climate, 40% Atlantic (Euro-Siberian region) and 20% mountain. 60% of the stations belong to the Ebro Hydrographic Confederation, 20% to the Galicia-Costa Hydrographic Confederation and 10% to the Miño-Sil and Cantábrico Occidental Hydrographic Confederations, respectively (Table I). The watershed dimensions of each station range from a maximum of 712 km^2 (Eo River) to a minimum of 47 km^2 (Veral River).

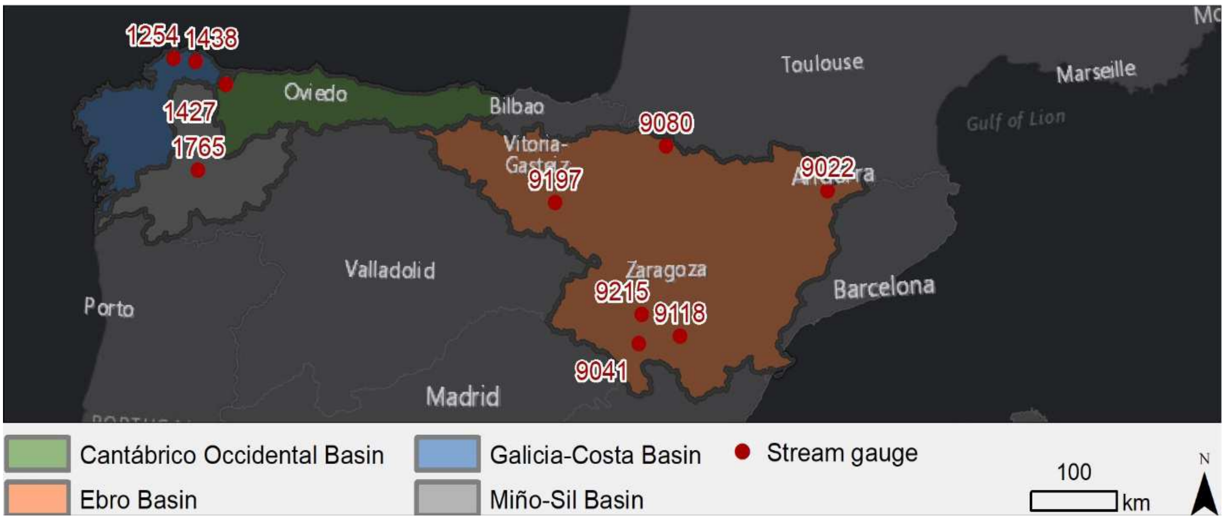

Figure 1 - Study area and stream gauges employed for the application of CI. Table I shows the characteristics of each gauging station described on the map by an ID number.

The estimation of CI was compared with five explanatory variables of the hydrological behaviour of a river, namely: precipitation, travel time, mean flow, specific flow (relation of the average flow with the size of the watershed) and size of the watershed. Each of these variables was calculated for the 10 gauging stations described, with data from 1994 to 2015 (Table I).

Table I - Gauging stations and hydrological variables used in the study. ID (official identification number), A (watershed, km^2), Q (mean discharge, m^3·s^{-1}), Qs (specific discharge, l/s/km^2), TT (travel time, hour/s), Atl (Atlantic Region), Med (Mediterranean Region), Mou (Mountain Region).

ID	**River**	**Gauging Station**	**A**	**Q**	**Q$_s$**	**TT**	**Region**
1765	Cabe	Rivas Altas	353	5.69	16.12	6.01	Atl
1254	Mera	Santa María de Mera	102	4.69	46.00	5.52	Atl
1427	Eo	San Tirso de Abres	712	19.47	27.34	15.28	Atl
1438	Landro	Chavín	198	6.78	34.22	6.01	Atl
9041	Pancrudo	Navarrete del Río	364	0.20	0.54	7.96	Med
9215	Huerva	Cerveruela	315	0.58	1.84	3.62	Med
9118	Martín	Oliete	670	1.19	1.77	10.65	Med
9197	Leza	Leza	283	1.52	5.37	6.87	Med
9022	Valira	Seu de Urgel	559	9.87	17.65	4.75	Mou
9080	Veral	Zuriza	47	1.80	38.38	1.30	Mou

The travel time variable indicates the time needed for a drop of water to go from the area furthest from the basin to the point of sampling (stream gauge) following the surface hydrographical network. This variable includes slope and distance through the channel in its formulation. Témez's equation (1978, 1991) has been used for its calculation because it is the formula used in the Spanish national scope. Témez's equation is defined as (Equation 1):

$TT = 0.3 \cdot ({}^{L}/_{S^{1/4}})^{0.76}$, Eq. 1

where,

TT: travel time (hour/s)

L: main channel length (km)

S: slope. This is equal to H / L (m/m), where H is the difference in altitude (m) between the maximum and minimum levels of the watershed.

The use of specific discharge, such as a hydrological variable accompanying mean discharge, is justified in that its value is related to the size of the watershed, making it possible to establish real comparisons between basins of different rivers.

For the analysis of possible connections to other variables, for each gauging station we extracted the nearest precipitation point of the high-resolution daily gridded precipitation dataset for Spain, 1950-2012, (Serrano-Notivoli *et al.*, 2017).

2.2- Concentration Index

The method applied to analyse the daily concentration of river discharge is the Concentration Index, which was introduced by Martin-Vide (2004) for the study of daily precipitation. This index is based on the negative exponential distribution of daily precipitation, that is to say that there are many days with low quantities of precipitation and few with elevated quantities. This characteristic can also be observed in the number of days with more discharge than normal. Accordingly, in a similar way to the procedure for calculating the CI in the case of daily precipitation, the following steps are carried out: The first step in calculating the CI is to classify daily precipitation in classes of 1 mm, beginning with [0.1-0.9] followed by [1.0-1.9], [2.0-2.9], etc., up to the class that encompasses the highest value of daily precipitation recorded. In the case of river discharge, the number of days is counted in cardinal numbers (1, 2, 3, etc.). In order to include smaller rivers with an outflow of less than 1 m^3/s, the number was multiplied by 10; in this way the daily discharge properties are preserved.

Then, the relative cumulative frequencies of days with river discharge (expressed as percentages of the total number of days X_j) and the corresponding accumulated quantities (also expressed as a percentage of the total amount of river discharge recorded, Y_j) are identified and defined according to Equations 2 and 3:

$$X_j = 100 \cdot \frac{\sum_{i=1}^{j} n_i}{\sum_{j=1}^{N} n_j} \text{ , Eq. 2}$$

$$Y_j = 100 \cdot \frac{\sum_{i=1}^{j} D_i}{\sum_{j=1}^{N} D_j} \text{ , Eq. 3}$$

where, n_i and D_i are the number of days and the amount of river discharge yielded respectively for each class *i*, and *N* is the total number of non-zero categories. In the second step, it is assumed that X_j and Y_j are described by a positive exponential relationship, also known as a standardised precipitation curve (Jolliffe, 1996). Specifically, the exponential curve of Equation 4 is that suggested by Riehl (1949) and Olascoaga (1950):

$$Y = aX \cdot e^{bX}\text{, Eq. 4}$$

where, *a* and *b* are constants which can be estimated using the method of least squares. Finally, the CI is defined by Equation 5:

$$CI = \frac{5000 - A}{5000}\text{, Eq. 5}$$

where, *A* is the area bounded by the exponential curve and the line *Y = 0*, which can be calculated via the definite integral of the exponential curve (Eq. 4) among the values between 0 and 100 (Figure 2). It should be noted that the CI is the area between the line *Y* = *X* and the exponential curve, divided by the area of the triangle in which it is inserted. The value of the CI oscillates between 0 and 1 and represents the percentage (expressed as a decimal) of the area between the line *Y* = *X* and the exponential curve relative to the area of the triangle. The higher the CI, the farther the exponential curve from line *Y* = *X*, which means that a few days account for an elevated weight fraction of the total river discharge.

In this pilot study, to apply the CI to river discharge, the mean daily values of the gauge stations were used. In addition, the CI was calculated for each station on an annual scale and climatically for the whole time series. It is important to mention that the annual scale is refers to the hydrological year, October to September.

In order to explain possible relationships between the CI and explanatory variables of the hydrological behaviour we used the Pearson correlation coefficient (r) with a 95% level of significance. The statistical analyses, calculations and illustration of the results were carried out in the R (3.3) statistical environment (R Core Development Team, 2017).

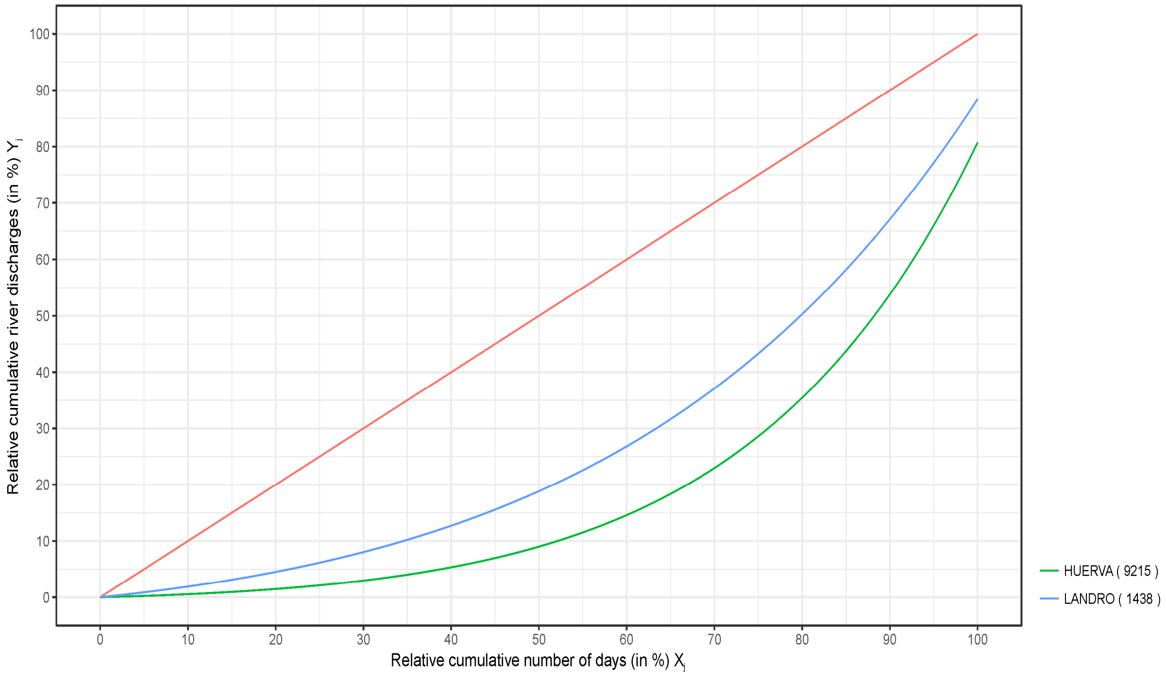

Figure 2 – Examples of CI of river discharge (1995-2015).

3. Results and discussion

The CI values for the 10 gauging stations studied have a maximum value of 0.63 (Huerva River) and a minimum of 0.46 (Landro River) (Figure 3) for the whole study period, which is ~25% less than the second over the total of the first. In general, it can be said that the five highest CI values are associated with Mediterranean-type stations and the five lowest with Atlantic-type stations. The two mountain-type stations are part of one of these two groups, just as each of them hosts a station of the other group. The division of the graph of Figure 3 into two groups supposes that, in the first, a few days of high flow have more repercussion in the total volume reached and vice versa, for the second group, the weight per day is less concentrated in a few.

The temporal distribution of CI values for each gauging station between the years 1994 and 2015 (Figure 4) shows a very similar behaviour for the Atlantic stations of Mera, Eo and Landro. However, the Cabe station is partially separated from this Atlantic group. The mountain station of Valira shows a behaviour which is totally different from the rest of the stations. The Mediterranean stations and Veral station have a behaviour which exhibits no apparent common pattern.

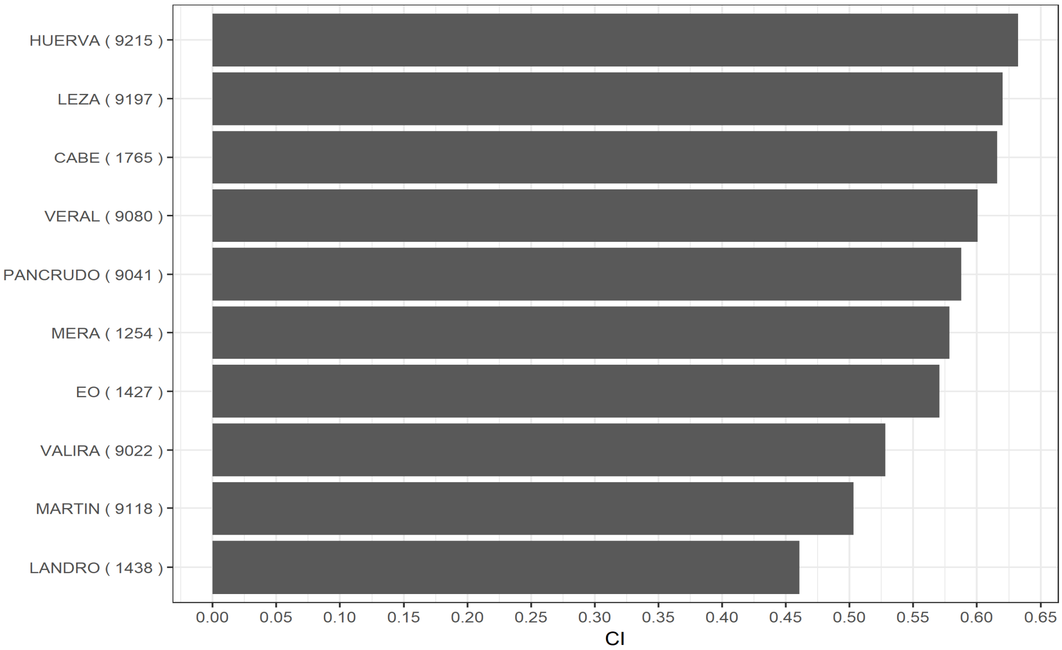

Figure 3 - CI values for each gauging station ordered from highest to lowest (see also Table I).

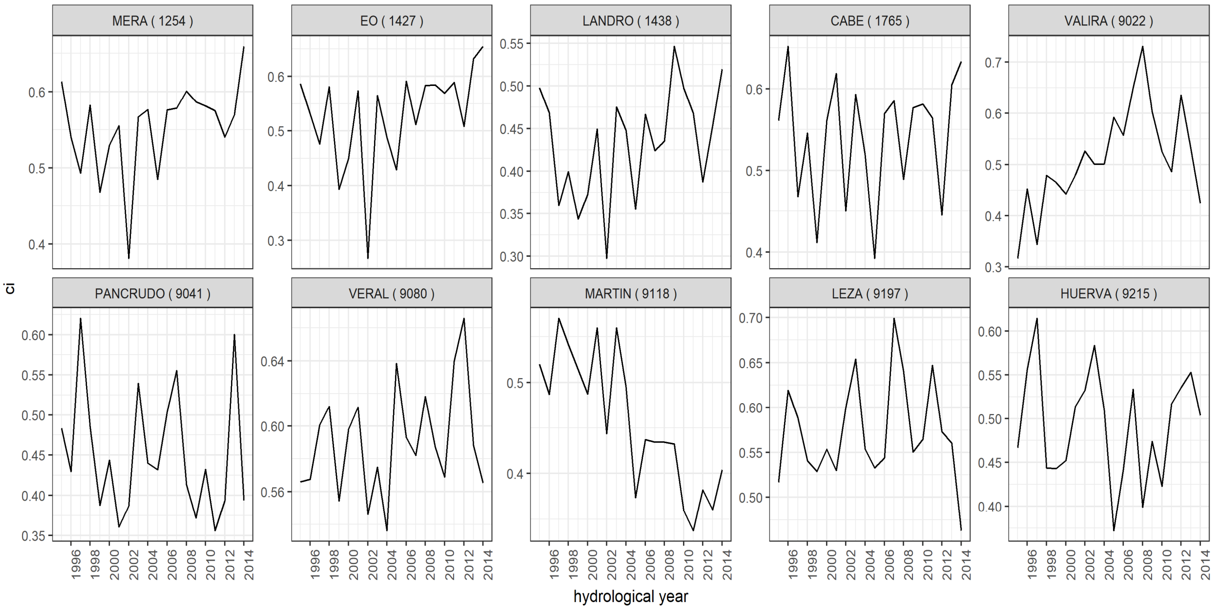

Figure 4 - Temporal distribution of CI values for each gauging station between the years 1994 and 2015.

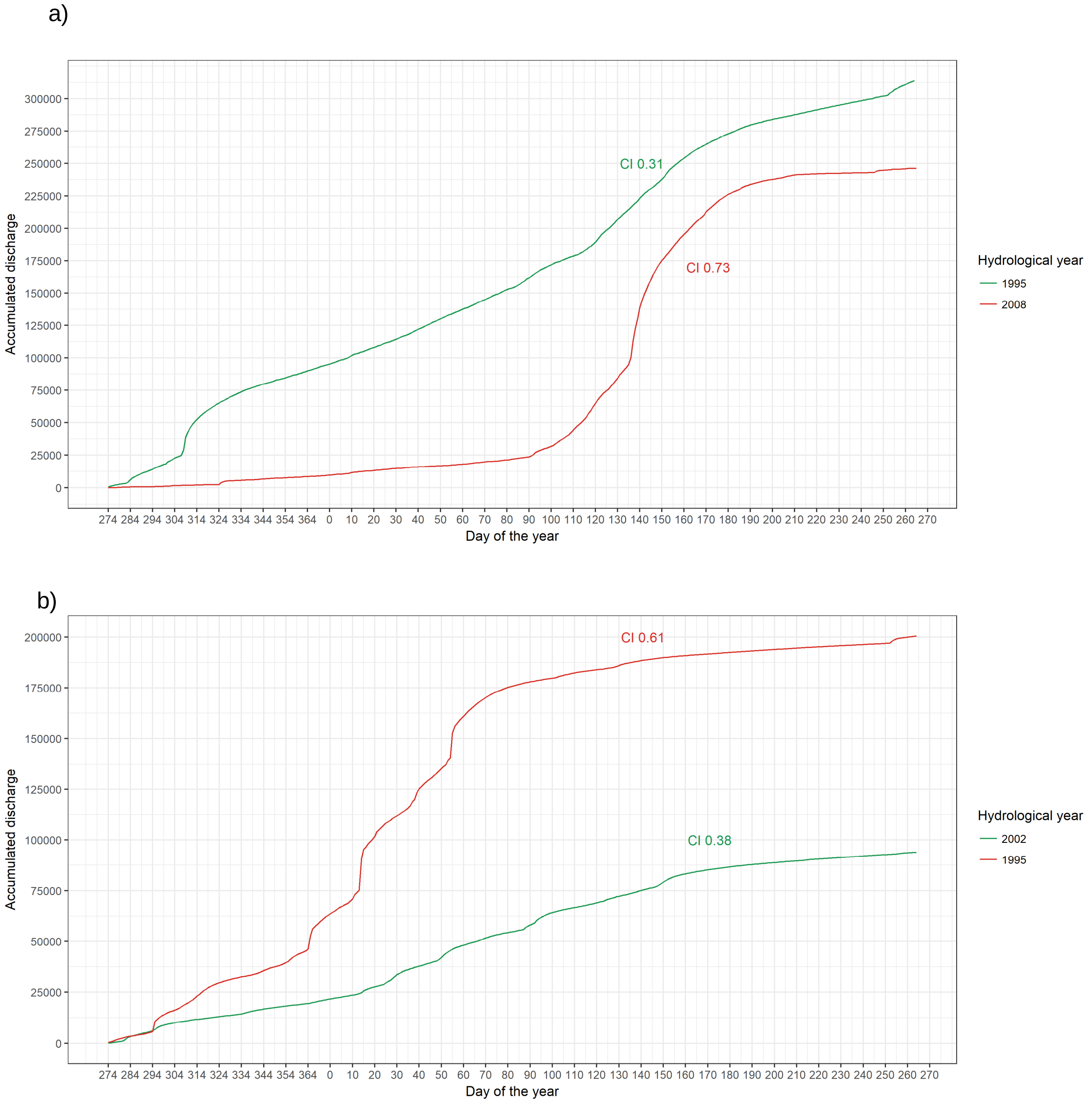

Figure 5 – Accumulated flow (m^3/s) for minimum and maximum CI in the Valira River (a) and Mera River (b).

Correlation values between the CI and the hydrological variables studied (Table I) do not reflect a clear relationship between the 10 stations. Neither is the correlation consistent as far as those belonging to the Atlantic group are concerned. The Mediterranean stations show a correlation >0.90 between the variables of area and travel time. However, the relationship has a negative sign, namely, smaller size of the basin and less travel time is linked to higher CI values and, consequently, the volume of flow it concentrates in less days, unlike what happens in larger basins.

In Figure 5, the accumulated river discharge for minimum and maximum CI values during the hydrological year shows the greater and lesser concentration of the flow in different years. For the years 1995 (Valira) and 2002 (Mera), a regular and constantly increasing river discharge can be identified. In contrast, the other years with high CI values are noteworthy due to a significant increase in the flow in late spring and winter, respectively. In the case of the Valira River, the explanation can be found in different annual precipitation amounts. In 2008, the next precipitation point shows a total of 589 mm, which is 422 mm less than in the hydrological year of 1995. Therefore, a Pearson correlation coefficient (r) of -0.62 was estimated for this river. In consequence, when the total annual precipitation is low then the CI value increases. However, the Mera River shows a positive correlation value of 0.33 and seems to be less influenced by precipitation. As the relationship is positive, the CI values increase with increasing annual precipitation. We think that to achieve a more precise explanation for the case of the Mera River, it is necessary to focus on the hydro-geological component (flow base) and how this behaves as precipitation increases.

The Pearson correlation coefficients of all the rivers analysed are shown in Table II. For the gauging stations of Valira and Veral a moderate negative relationship was found. However, the Cabe, Huerva and Martín Rivers present positive moderate coefficients. If the correlation is negative, then it means that the CI increases when the annual precipitation amount decreases, which in turn indicates a stronger concentration of river discharge in time. Especially for Valira and Veral, the relationship is clear and shows a dependence for precipitation variability. Nevertheless, there is a residual part of variability which cannot only be explained by precipitation. In this sense, it is necessary to delve into other explanatory variables: lithology, land use, slope, hydrogeology, urbanisation or water extraction, for example. The different behaviour in the pattern observed in the Martín River, part of the Mediterranean regime, is still unclear. It is possible that it is due to an extreme hydrological event in 2013. In this sense, further study will be necessary in order to understand these complex relationships and causes.

Table II – The Pearson correlation coefficient (r) between the annual CI and precipitation (p-value < 0.001).

ID	**River**	**r**
1765	Cabe	0.65
1254	Mera	0.33
1427	Eo	-0.09
1438	Landro	-0.01
9041	Pancrudo	0.40
9215	Huerva	0.55
9118	Martín	0.53
9197	Leza	0.24
9022	Valira	-0.62
9080	Veral	-0.48

The role of precipitation in small watersheds is yet to be determined, where, a priori, they have a more direct influence on the variability of the flow than in larger basins, which have a greater potential to accommodate climatic, topographic, lithological and land uses. Furthermore, a comparison with other temporal indices of watersheds which assess impacts in river systems should be undertaken in the future (Pandeya et al., 2012).

4. Conclusions

The CI has proven to be an index which perfectly describes the temporal behaviour of river discharge. Its application on the study stations has served to (i) demonstrate its discriminatory capacity regarding river types and (ii) as another method to interpret the distribution of the flow throughout the year.

The open research line of CI on river discharge will continue in the coming years. The proposed steps to be followed are aimed at: (i) increasing the network of study stations; (ii) establishing a method of selecting them; and (iii) introducing new hydrological variables to explain flow behaviour and its relationship with the CI. These future objectives will be extremely useful as a complement to other studies of the hydrological regime and fluvial ecology.

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