Environmental flows and the mitigation of hydrological alteration downstream from dams: The Spanish case

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Abstract

Dams and reservoirs cause significant alteration in natural flow patterns of rivers throughout the world. As a response, many countries have established environmental flows (e-flows) to reduce hydrological alteration and mitigate ecosystem degradation. This paper assesses hydrological changes downstream from dams in 22 rivers in Spain, 12 of them located in northern wetter regions (Duero and Ebro basins) and the remaining 10 in southern drier regions (Guadalquivir and Júcar basins). First we compared pre-dam and post-dam instream flow patterns, and then we considered a third period starting with the implementation of e-flows. We quantified changes in mean annual flows, monthly flows, and magnitude and timing of extreme flows (1-day maximum, 95th percentile, 1-day minimum and 5th percentile). The analysis aimed at: i) characterizing hydrological alterations in regulated rivers in four river basins in Spain, with a special focus on differences across regions; and (ii) assessing the capacity of the implemented e-flows to mitigate flow regime alteration downstream of the dams. All the studied rivers displayed significant changes in magnitude and timing of flows after the dam construction. A quite homogenous trend was observed in the drier basins, where mean annual flows and annual extreme flows decreased significantly. The wetter basins showed no uniform tendency in mean annual flows, while 1-day maximum and 95th percentile flow values decreased. In contrast to drier basins, 1-day minimum and 5th percentile flow values increased markedly. In most cases, the natural Mediterranean annual hydrograph was inverted, with the high-flow period occurring during the low precipitation months (summer) and the low-flow period during the wet season. After e-flows implementation, these patterns of hydrological alteration remained almost unchanged, pointing to a limited capacity of current e-flows to mitigate the hydrological impacts downstream from dams.

Keywords: Environmental flows; hydrological assessment, flow alteration; dams; Spain

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1. Introduction

Flow regimes support many fundamental ecological processes and functions required for sustaining healthy rivers. Anthropic activities such as dam construction or water diversion have caused significant alteration of natural flow patterns (Döll et al., 2009; Nilsson et al., 2005), threatening the ecological integrity of freshwater ecosystems (Dudgeon et al., 2006; Richter et al., 2003). In the early 1980s, the abundant scientific evidence about the alteration of natural flow regimes prompted the development and implementation of environmental flows (e-flows) (e.g., Bovee, 1982). Since then, different methodologies and approaches to define e-flows have emerged (see Linnansaari et al., 2013; Ramos et al., 2018; Tharme, 2003) and many countries have included e-flows in their water legislation (e.g. Acreman & Ferguson, 2010; Chen et al., 2020; Harwood et al., 2017, 2018; Ramos et al., 2018) to improve hydrological conditions of altered freshwater ecosystems.

Despite current advances in the legal and scientific definition of e-flows (Davies et al., 2014) their actual implementation faces socio-economic and technical constraints (Harwood et al., 2017, 2018; Mezger et al., 2019). Some of the challenges of their implementation at a global scale are: (a) lack of political will and stakeholders' support; (b) insufficient technical and economic resources devoted to e-flows implementation; (c) poor understanding of socio-economic costs and benefits of e-flows; and (d) scarcity of hydrological data to define e-flows adequately (Harwood et al., 2017; Moore, 2004).

In Spain, rivers are intensively regulated by over 1200 large dams (MITECO, 2018a). Their construction contributed significantly to the socioeconomic development experienced by the country during the second half of the 20th century. However, freshwater ecosystems in Spanish rivers are significantly affected by dam-related flow-regime alterations (Caiola et al., 2014; González del Tánago, 2016; 2012; Grindlay et al., 2011; Lorenzo-Lacruz et al., 2012). In order to meet the requirement of the European Union (EU) Water Framework Directive (WFD) to archive good status of all waters by 2027 at the latest, there is an urgent need to reduce the hydrological alteration in regulated rivers where different authors have reported important hydromorphological changes (e.g., González del Tánago et al., 2015; Lobera et al., 2015; Magdaleno & Fernández, 2011; Ollero, 2010), the impairment of riparian vegetation (e.g., Belmar et al., 2013; Garófano-Gómez et al., 2011; González et al., 2010), the loss of taxonomic richness of macroinvertebrate communities (e.g., Navarro-Llácer et al., 2010), the increase of invasive non-native fish species (e.g., Caiola et al., 2014), and a shift in the flux of materials and energy (e.g., Aristi et al., 2014).

Since 2001 the Spanish legislation requires the establishment of e-flows as part of the elaboration of the River Basin Management Plans (RBMPs) (Ley 10/2001, 2001; RDL 1/2001, 2001). In 2008 the definition of e-flows was adjusted to the requirements of the WFD, which represented an important milestone in the environmental management of Spanish rivers. The official guidelines for the elaboration of the RBMPs define e-flows as the flows that are able to *"maintain the functionality and structure of aquatic and associated terrestrial ecosystems, and contribute to achieve the good ecological or potential status of water bodies"* (Orden ARM/2656/2008). These guidelines require River Basin Authorities to define e-flows according to the annual variation of four variables: minimum flows, maximum flows, rates of change and channel maintenance discharges (i.e., bank-full discharges).

The implementation of e-flows in Spanish rivers started in 2013, and is not exempt of shortcomings. These include: (a) minimum flows are established in 73% of the river water bodies, whereas the rest of the variables, i.e., maximum flows, change gates and bank-full discharges have been defined in less than 8% of the river water bodies; (b) the intra-annual variability of the implemented e-flows represents only 7% of the natural variability; (c) compliance with e-flows is monitored in only 11% of the river water bodies where they have been defined; and (d) relationships between e-flow implementation and ecological response are not being assessed (Mezger et al., 2019).

Although the period since the start of e-flows implementation in Spain is still relatively short, it seems relevant to analyze the hydrological changes that they have generated in the instream flow regimes. Since RBMPs are assessed and revised according to six-year planning cycle (2009-2014; 2015-2021; 2022-2027), the early appraisal of the effect of e-flows implementation on circulating flows can provide valuable information for the upcoming revision of the RBMPs.

At present, there is a solid literature on the effects of flow regulation by damming in Spanish rivers. Several authors have analyzed the hydrologic alteration caused by dams, quantifying the effects of reservoirs in magnitude and timing of flows. Batalla et al. (2004) quantified these effects in the Ebro basin, finding an average reduction of 30% in the magnitude of frequent floods (i.e., return periods of 2 and 10 years), and the inversion of seasonal patterns of monthly flows below reservoirs devoted to irrigation. Piqué et al. (2016) characterized ten highly regulated basins in the south of France and north-east of Spain based on several indicators of hydrological alteration. A general reduction of magnitude and frequency of floods was observed after dam construction, being especially sharp for episodes with low-return periods. Vicente-Serrano et al. (2017a) studied the influence of dams in the Segre river, one of the main tributaries of the Ebro river, and found patterns of changes in monthly flows similar to those previously reported by Batalla et al. (2004). Within the same river, Vicente-Serrano et al. (2017b) observed a marked decrease in the frequency of floods exceeding the 95th percentile although no change was reported for the most extraordinary events (i.e., >99.5th percentile). More recently, Peñas & Barquín (2019) have sought general patterns of hydrological alteration caused by dams at a country level. They have identified seven distinct types of altered flow regimes, with major effects of dams associated with the modification of the intra-annual variability of daily flow, the magnitude of seasonal maximum and minimum flows and the patterns of high flow events. Finally, García de Jalón et al. (2019) have analyzed the variability of regulated flows in the Ebro, Duero and Tajo basins. These authors propose an approach to assess the natural variability of the flow regime and cluster the studied rivers according to their flow variability before and after dam construction. Their results show the influence of flow regulation producing strong changes in the seasonality of the flow regime, with artificially increased flows (i.e., high-flow impacts) during summer and artificially decreased flows (i.e., low-flow impacts) during autumn and winter in all the studied rivers.

Although all these studies give a valuable insight into the magnitude and characteristics of hydrological alteration of Spanish rivers, each of them used a different approach and addressed different objectives. Additionally, most of these studies focus on rivers located in the northeast and in central Spain, particularly in the Ebro basin. Starting from these efforts, this study aims at providing a more homogeneous and broader comparative analysis of hydrological alteration in Spanish rivers, including river basins in the east and south of Spain that have not been considered in previous works. We have used the Indicators of Hydrological Alteration initially proposed by Richter et al. (1996) to allow comparison with existing studies in other regions (e.g., Hu et al., 2008; Magilligan & Nislow, 2005; McManamay et al., 2012; Yang et al., 2012). Additionally, we have complemented the traditional pre-dam/post-dam approach with the analysis of a third period with established e-flows, which has not been considered before in Spain.

In this context, the main objectives of our study are: i) to characterize the hydrological alteration downstream from dams in four river basins in Spain, with a special focus on differences across regions (i.e., northern wetter regions vs. sourther drier regions); and (ii) to assess to what extent the implemented e-flows mitigate flow regime alterations downstream of the dams. Thus, we aim at testing two hypotheses:

- **H.1.** The hydrological regime of regulated rivers has experimented significant changes after dam construction.
- **H.2.** The implementation of e-flows has implied a decrease in the hydrological alteration downstream from dams.

2. Methods

2.1 Study area

The study area includes 22 rivers located in the Duero (6), Ebro (6), Guadalquivir (5) and Júcar (5) river basins (Fig. 1). Duero and Guadalquivir rivers flow into the Atlantic Ocean, while Ebro and Júcar rivers flow into the Mediterranean Sea. In natural conditions, all the rivers in these basins present a Mediterranean flow regime pattern, which implies two alternate periods: a high-flow period during the wet season (i.e., autumn and winter) and a low-flow period during the dry season (i.e., late spring, summer). Most of the rivers in the Duero (e.g., Esla, Luna, Porma) and Ebro (e.g., Aragón, Cinca, Ebro) basins have their sources in high altitude mountains with snow influence (i.e., Cantabric Mountains, Pyrenees) and are located in relatively wet regions, whereas all the rivers from Guadalquivir and Júcar basins are born at lower altitudes and cross warmer and drier regions (see Hernández-Pacheco, 1955; Masachs, 1948). Table 1 shows some of the main characteristics of the studied basins, reflecting the geographical gradient of precipitation, evapotranspiration and runoff from the northern wetter regions (i.e., Ebro, Duero) to the southern drier regions (i.e., Guadalquivir, Júcar) of the Iberian Peninsula.

Table 1. Main characteristics of the studied river basins. Data sources: P (Precipitation), PET (Potential Evapotranspiration) and mean runoff coefficient data calculated for the period 1940-1996 (CEDEX, 2000). Runoff amounts calculated for the period 1940-2012 (MITECO, 2018b).

Basin	**Drainage Area (km^2)**	**Mean Annual P (mm)**	**Mean annual PET (mm)**	**Mean Runoff Coefficient (%)**	**Mean Annual Runoff (Hm^3/yr)**	**Mean Specific Runoff (Hm^3/km^2 yr)**
Duero[a]	78,886	625	759	28	12,777	0.16
Ebro	85,634	682	792	31	14,623	0.17
Guadalquivir	57,196	591	991	23	7,092	0.12
Júcar	42,737	504	881	16	3,111	0.07

[a] referred to the Spanish part of the basin

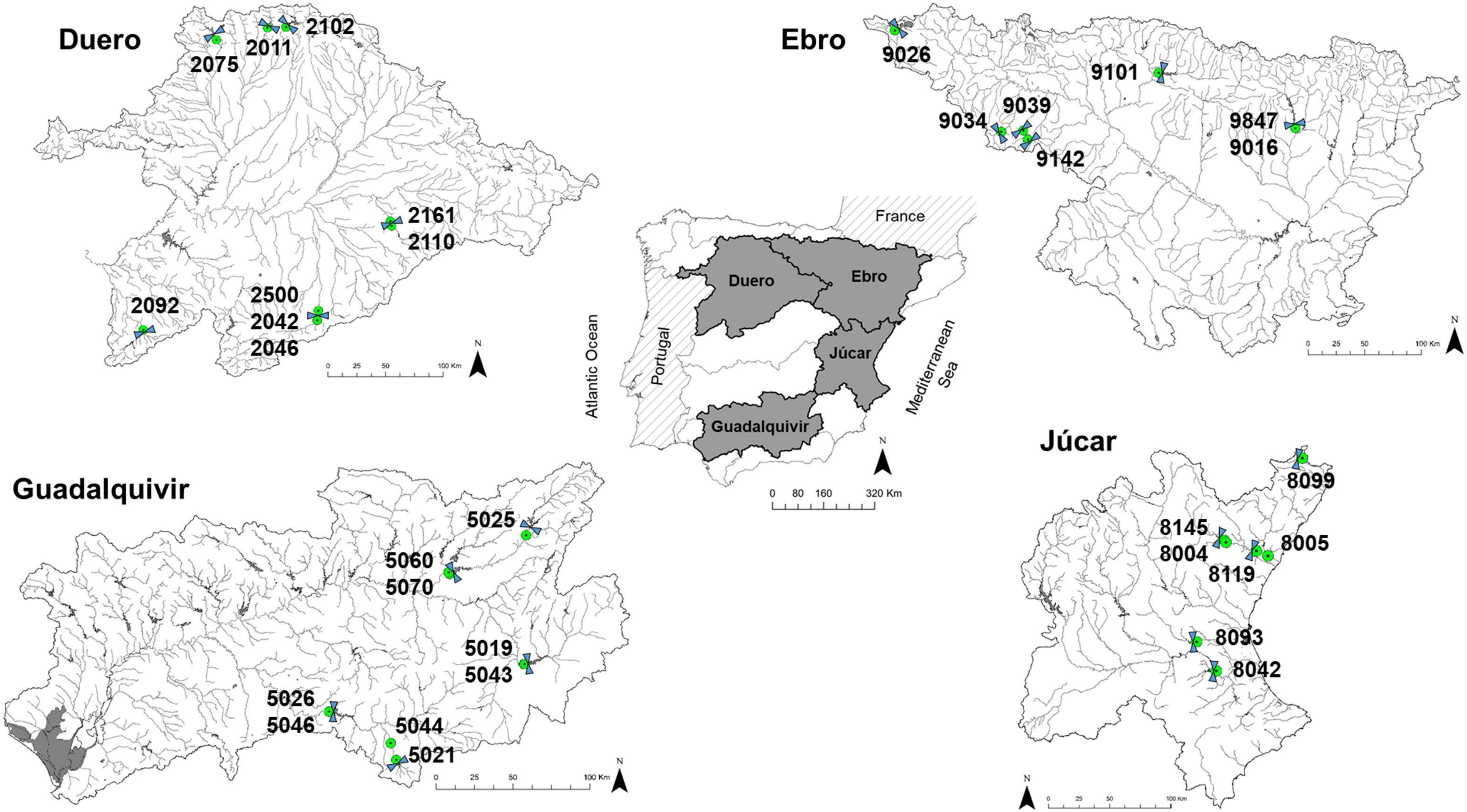


Fig. 1 Studied river basins and location of the studied dams (triangles) and gauging stations (circles) (see Table 2 for identification gauging station by numerical code).

2.2 Dataset, periods of analysis and assessment of hydrological alteration

Fig. 2 shows the steps followed in the analysis. They are described in detail below.

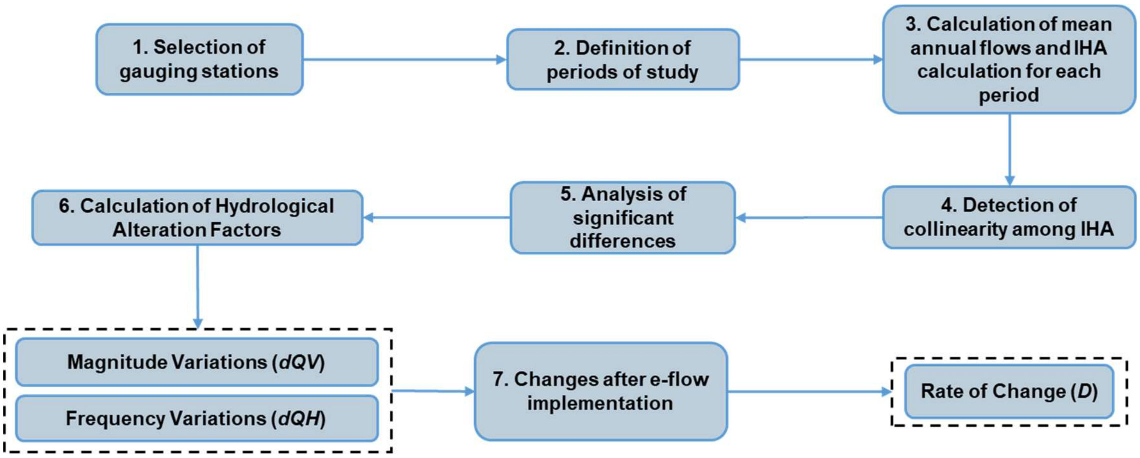


Fig. 2. Flowchart: Steps followed in the analysis. Dashed boxes represent the outputs of the methodology.

1. Selection of gauging stations

The selection of the gauging stations for our analysis was based on three criteria:

a. The gauging stations should be located in a river stretch located closely downstream of a large dam (sensu ICLD, 2011).

b. The gauging stations should correspond to river segments where at least one of the four variables of e-flows had been defined (i.e., minimum flow, maximum flow, change rate or high flow).

c. A minimum of 15 years of daily flow records should be available prior and after dam construction. The gauging station should have daily data also for the period after the establishment of e-flows in 2013.

The application of these criteria to the existing 774 gauging stations in the Duero, Ebro, Guadalquivir and Júcar basins led to the selection of 32 gauging stations in 22 rivers. The need to use more than one gauging station to characterize the hydrological regime in some rivers responds to: (i) the replacement of gauging stations operational prior to dam construction by others embedded in the dam or located immediately below it; (ii) the use of gauging stations just upstream of the dam to characterize the hydrological conditions of the river prior to flow regulation. Table 2 summarizes the location of the gauging stations, the main reservoir characteristics, the mean annual runoff, the periods of data and the variables of e-flows implemented downstream from the dam.

Table 2. Main characteristics of the studied rivers and hydrological data. Note: Impoundment ratio (IR) = storage capacity/mean annual runoff (in those rivers with more than one dam upstream, IR was calculated considering the accumulated storage capacity). Variables of the e-flows: MIN: Minimum flow at monthly scale; MAX: Maximum flow at monthly scale; CR: Change rates; HF: High flows for channel maintenance. (+) Data for e-flow period corresponds to the interval 2013-2019 for all studied rivers.

Basin	**River**	**Gauging Station**[a]	**Mean annual Runoff (Hm^3)**[b]	**Reservoir (storage capacity in Hm^3)**[c]	**Impoundment Ratio (IR)**	**Year of dam construction**[c]	**Main use of regulated water**[c]	**Data period (+)**		**Variables of e-flows**[c]
								Pre-dam	**Post-dam**	
Duero	Adaja	2046 2042 2500	105	Castro de las Cogotas (59)	0.56	1994	Irrigation	1969-1993	1996-2012	MIN; CR; HF
	Águeda	2092	244	Águeda (22)	0.54[d]	1932	Irrigation	1917-1931	1944-1995	MIN; CR; HF
	Duratón	2110 2161	120	Las Vencías (5)	0.14[d]	1928	Hydropower	1912-1927	1987-2012	MIN; CR; HF
	Esla	2102	740	Riaño (641)	0.87	1987	Irrigation	1965-1986	1991-2012	MIN; CR; HF
	Luna	2075	423	Barrios de Luna (308)	0.73	1952	Irrigation	1912-1932	1969-2012	MIN; CR; HF
	Porma	2011	334	Porma (318)	0.95	1969	Irrigation	1943-1966	1971-2012	MIN; CR; HF
Ebro	Albercos	9039	12	Ortigosa (33)	2.75	1962	Domestic supply	1943-1961	1964-2012	MIN
	Aragón	9101	1069	Yesa (447)	0.42	1959	Irrigation	1943-1958	1971-2012	MIN
	Cinca	9016 9847	1061	El Grado (400)	0.78[d]	1969	Irrigation	1913-1932	1971-2012	MIN
	Ebro	9026	352	Ebro (541)	1.54	1945	Irrigation	1915-1932	1947-2012	MIN
	Lumbreras	9142	62	Pajares (35)	0.56	1994	Irrigation	1951-1993	1995-2012	MIN
	Najerilla	9034	124	Mansilla (68)	0.55	1960	Irrigation	1943-1959	1963-2012	MIN
Guadalquivir	Cacín	5044 5021	84	Bermejales (103)	1.23	1958	Irrigation	1943-1957	1965-2012	MIN
	Genil	5046 5026	701	Iznájar (981)	1.74[d]	1968	Irrigation	1943-1962	1975-2012	MIN
	Guadalimar	5060 5070	398	Giribaile (475)	1.79[d]	1995	Irrigation	1950-1967	1998-2012	MIN
	Guadalmena	5025	397	Guadalmena (346)	0.87	1969	Irrigation	1943-1966	1993-2012	MIN;MAX
	Guadiana Menor	5019 5043	208	Negratín (567)	3.71[d]	1984	Irrigation	1943-1977	1986-2012	MIN;MAX
Júcar	Cenia	8099	28	Ulldecona (11)	0.39	1967	Irrigation	1951-1966	1971-2012	MIN;MAX
	Magro	8093	25	Forata (37)	1.48	1969	Irrigation	1943-1963	1971-2012	MIN;MAX
	Mijares	8004 8145	228	Arenós (137)	0.60	1980	Irrigation	1943-1964	1986-2012	MIN;MAX
	Mijares	8005 8119	275	Sichar (49)	0.68[d]	1960	Irrigation	1913-1932	1969-2012	MIN;MAX
	Júcar	8042	1740	Tous (379)	1.22[d]	1995	Irrigation	1913-1932	1997-2012	MIN

[a] Code number shown in Fig.1. [b] Mean annual runoff corresponds to the pre-dam period. [c] Data obtained from the corresponding basin authorities (www.chduero.es, www.chebro.es, www.chj.es, www.chguadalquivir.es) (for minimum e-flow values see Appendix A, Table A.1). [d] Rivers where IR was calculated using accumulated storage capacity.

2. *Definition of periods of study*

We defined three periods of analysis: (1) pre-dam period: before dam construction; (2) post-dam period: after the construction of the dam and before the start of e-flows implementation; and (3) e-flow period, i.e., 2013 to 2019. We used daily flows, which for the pre-dam and post-dam periods were available at: http://ceh-flumen64.cedex.es/anuarioaforos/afo/estaf-codigo.asp. Data for the e-flow period were obtained from the corresponding river basin authorities.

3. *Calculation of mean annual flows and IHA for each period*

We used the Indicators of Hydrological Alteration (IHA, Richter et al., 1996) to characterize the flow regime in the three studied periods. We calculated 24 IHA indicators, 12 corresponding to monthly flows, 10 corresponding to magnitude and duration of extreme values and 2 relative to timing of annual extreme flows (see Appendix A, Table A.2-A.7). Additionally, we analyzed the mean annual flow for each period in order to detect significant changes at a broader time-resolution across periods.

4. *Detection of collinearity among IHA*

Due to the potential high redundancy of hydrologic indices (Olden and Poff, 2003) and in order to reduce the number of studied variables, we tested collinearity across the 24 IHA within each basin. We used the Iterative Variance Inflation Factor (IVIF) based on Booth et al. (1994) and an IVIF>10 as a threshold that indicates high collinearity between variables (Hair et al., 2014). Based on this collinearity analysis (see Appendix A, Table A.8) we retained 16 IHA for our analysis (i.e., magnitude of monthly flows (12), magnitude of 1-day max, magnitude of 1-day min, date of 1-day max and date of 1-day min).

5. *Analysis of significant differences*

In order to detect the largest IHA differences between periods, we used the non-parametric Kruskall-Wallis test. This test assesses the hypothesis that the median of the parameter in each period is similar. If p-value<0.05, this hypothesis can be rejected with a 95% confidence level. The test was performed for two time frames:

   a. Pre-dam vs. post-dam, in order to detect significant changes in the IHA after the dam construction.
   b. Post-dam vs. e-flow, to detect whether the implementation of e-flows has brought about significant changes in the circulating flows.

6. *Calculation of Hydrologic Alteration Factors*

The hydrologic alteration was assessed using two factors. The first one (dQV) (Gillespie et al., 2015; Hu et al., 2008; Poff & Zimmerman, 2010; Richter et al., 1997; Yang et al., 2012), evaluates the deviation of the magnitude of the IHA medians in each period and is calculated as:

$$dQV_{pre-dam/post-dam} = \frac{Q_{post-dam} - Q_{pre-dam}}{Q_{pre-dam}} \times 100\ (\%) \tag{1}$$

$$dQV_{post-dam/e-f} = \frac{Q_{e-flo} - Q_{post-dam}}{Q_{post-dam}} \times 100\ (\%) \tag{2}$$

The second hydrological factor (dQH), based on the "Histogram Matching Approach" (HMA), is designed to detect changes in the frequency distribution of values within each variable. This method focuses on the idea that two hydrological regimes can be compared through the frequency histograms of each of their IHA parameters (Shiau and Wu, 2008). Thus, the hydrological alteration can be evaluated based on the degree of dissimilarity between the two histograms.

Firstly, we calculated the optimal number of classes of each histogram as:

$$n_c = \frac{r \cdot n^{1/3}}{2 \cdot r_{iq}} \tag{3}$$

where n_c is the number of classes; r is the difference between maximum and minimum values of the data series; n is the total number of data and r_{iq} is the difference between third and first quartile values.

Then, the statistical distance between the two histograms is defined as:

$$dH\ (H, K) = \sqrt{(|h-k|)^T A(|h-k|)} \tag{4}$$

where $h = (h_1, h_2, \ldots, h_{nc})^T$ y $k = (k_1, k_2, \ldots, k_{nc})^T$ are the transposed matrices (*T*) of the frequency vectors of the histograms H and K and $|h - k|$ is the distance vector. $A = [a_{ij}]$ is the similarity matrix where a_{ij} is the similarity between classes i y j, calculated as:

$$a_{ij} = \left(1 - \frac{d_{ij}}{d_{max}}\right) \tag{5}$$

in which $d_{ij} = |V_i - V_j|$ being V_i y V_j the mean values of classes i y j; $d_{max} = |V_1 - V_{nc}|$ where V_1 y V_{nc} are the mean values of the first and last classes respectively. Finally, the degree of dissimilarity between the frequency histograms of each IHA was calculated as:

$$dQH_{pre-dam/post\ dam} = \frac{dH_{pre-dam/post-dam}}{\max(dH_{pre-dam/post-dam})} \times 100\ (\%) \tag{6}$$

$$dQH_{post-dam/e-flo} = \frac{dH_{post-dam/e-flow}}{\max(dH_{post-dam/e-flow})} \times 100\ (\%) \tag{7}$$

in which $\max(dH)$ is defined as:

$$\max(dH) = \sqrt{2 + 2\left(1 - \frac{1}{n_c - 1}\right)} \tag{8}$$

7. *Changes in IHA after e-flows implementation*

In order to know to what extent the implementation of e-flows mitigates the effects of the dam (i.e. yielding a flow regime close to the one of the pre-dam period), we used the "ratio of change" (D) (Yang et al., 2016). This indicator was calculated as follows:

$$D = \left|\frac{Q_{e-flow} - Q_{pre-dam}}{Q_{post-dam} - Q_{pre-dam}}\right| \tag{9}$$

where $Q_{pre-dam}, Q_{post-dam}$ y Q_{e-flow} are the median values of each IHA for each period. If $D \approx 1$, the implementation of e-flows has not implied changes. If $0 < D < 1$, the median value of the IHA has reduced its distance to the pre-dam period, meaning that the hydrological alteration has been reduced after e-flows implementation. Finally, values of $D > 1$ imply that the distance to pre-dam period has increased during the e-flow period.

Additional analysis

Since the use of magnitude of 1-day min and 1-day max could be not enough to characterize changes in the magnitude of extreme flows, we complemented the IHA analysis with the study of changes in percentiles 5th and 95th (see Appendix A, Table A.9).

3. Results

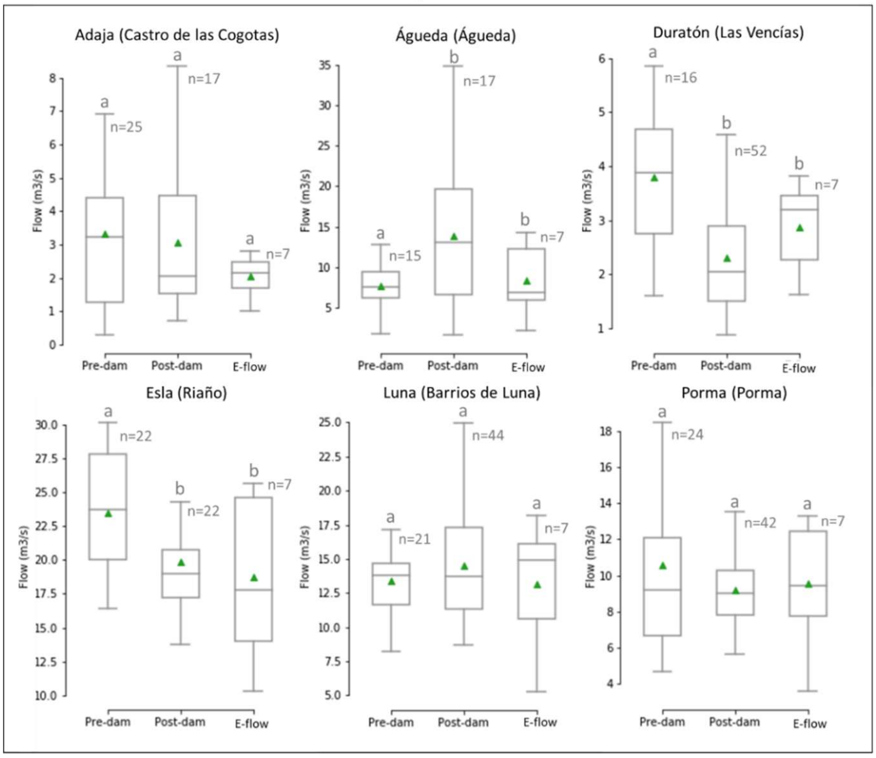
3.1 Changes in mean annual flows

The average of the mean annual flows and their range of variability has evolved across the three periods (i.e., pre-dam, post-dam and e-flow) (see average mean annual flows in each period in Fig. 3 and changes between periods in Appendix A, Table A.10). The pre-dam/post-dam comparison reveals different patterns of changes between wetter basins (i.e., Duero and Ebro) (Fig. 3 a, b) on one side, and drier basins (i.e., Guadalquivir and Júcar) (Fig. 3 c, d) on the other side. A general trend of significant decreases in the average of the mean annual flows after dam construction was observed in the drier basins. These reductions were especially sharp in the Guadalmena River (-85%) (Guadalquivir basin), and in the Mijares-Sichar (-77%) and Júcar (-75%) rivers (Júcar basin). On the contrary, no general trend was identified in the case of the Duero and Ebro basins, where the decrease resulted to be statistically significant in only 4 out of 12 rivers.

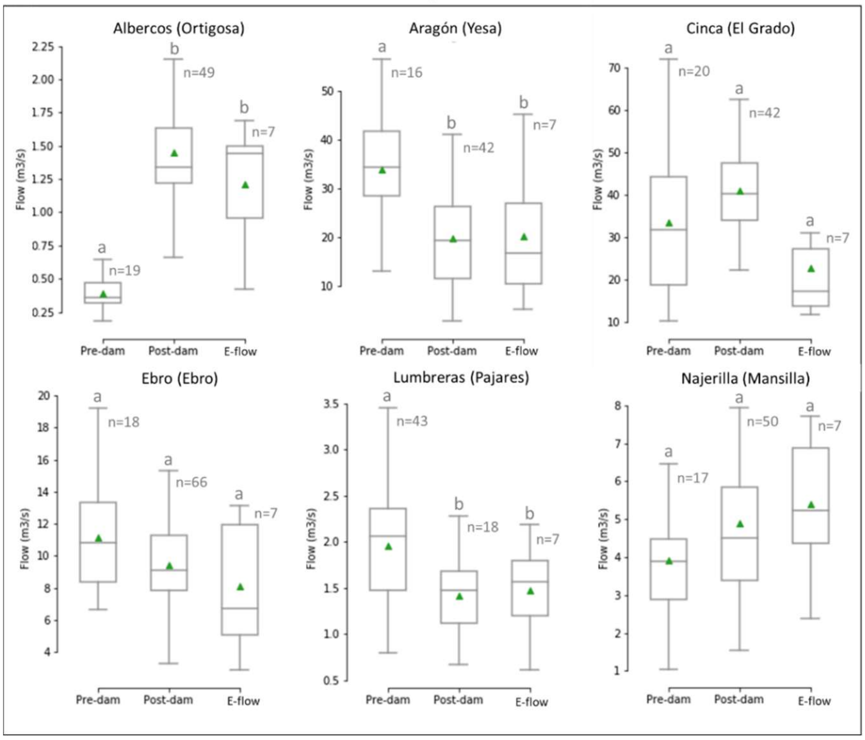
Increases in the average of mean annual flow between the post-dam and the e-flow periods resulted to be significant only in the Mijares-Sichar river (Júcar basin). In the rest of the rivers, the implementation of e-flows has not significantly affected the post-dam average of mean annual flow. However, during the e-flow period a decrease in the average mean annual flow was observed in 14 out of the 22 studied rivers.

Regarding the interannual variability of the mean annual flow, no clear pattern of change across the three periods was identified in the Duero and Ebro basins. On the contrary, in Guadalquivir and Júcar basins, river impoundment corresponded to a marked interannual homogenization of average annual flow, which has not been reversed by the implementation of e-flows.

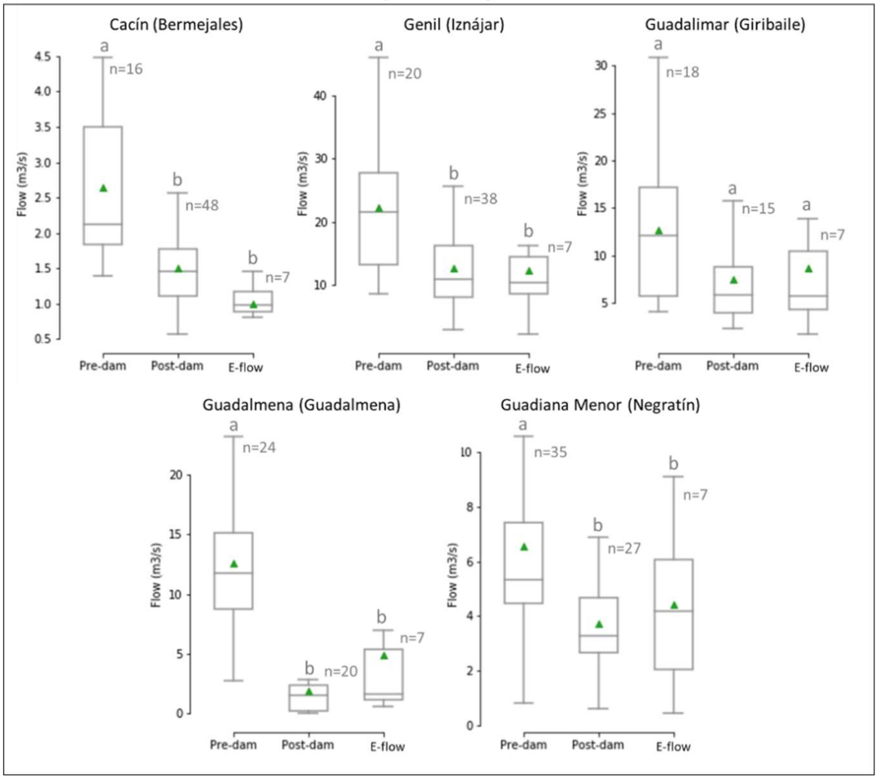
a) Duero



b) Ebro



c) Guadalquivir



d) Júcar

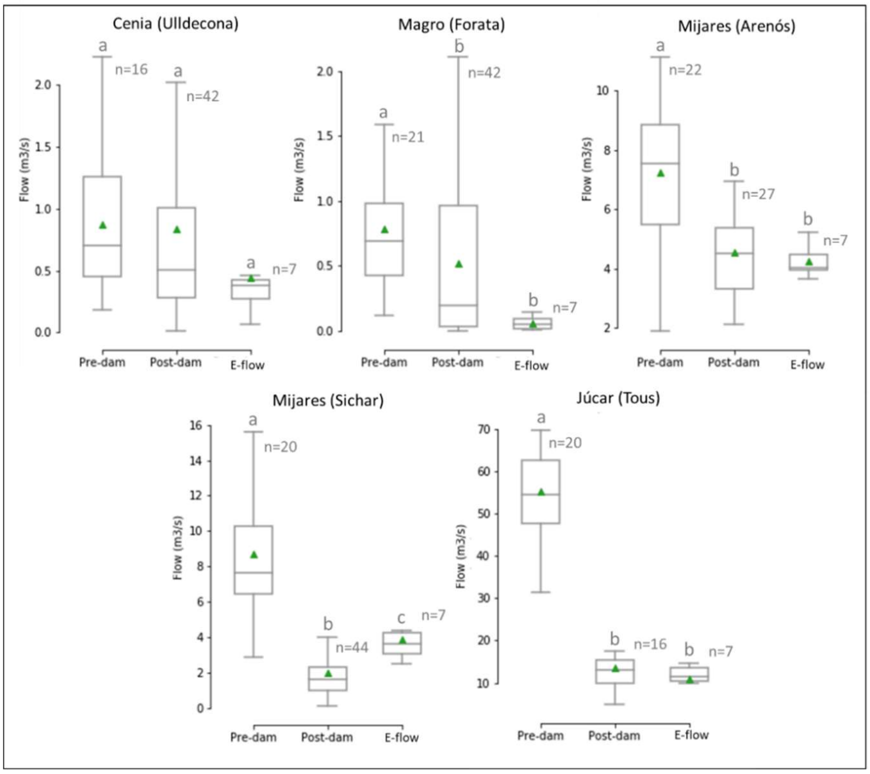


Fig. 3. Mean annual flow values of the three periods in the studied rivers. Letter “n” indicates the number of years of each period. Triangles indicate the average of the mean annual flow for each period. Same letter above means no significant differences between periods.

3.2 Changes in monthly flows

3.2.1 Changes in magnitude (dQV)

Nearly all the studied rivers have experienced significant changes in the magnitude of monthly flows after dam construction (Fig. 4). Across the wetter basins, in the majority of the studied rivers in the Duero and Ebro basins, a significant decrease of monthly flows was observed during the wet season (i.e., November to May), as well as an increase - even greater than 100% - in the magnitude of flows during the dry season (i.e., June to September). Regarding the drier basins, this pattern of seasonal alteration was found also in the Guadalquivir basin, where the observed reductions during the wet months were even higher (between -80% and -100%). In the Júcar basin, a maintained decrease in magnitude of monthly flows was recorded along the whole year in nearly all the studied rivers.

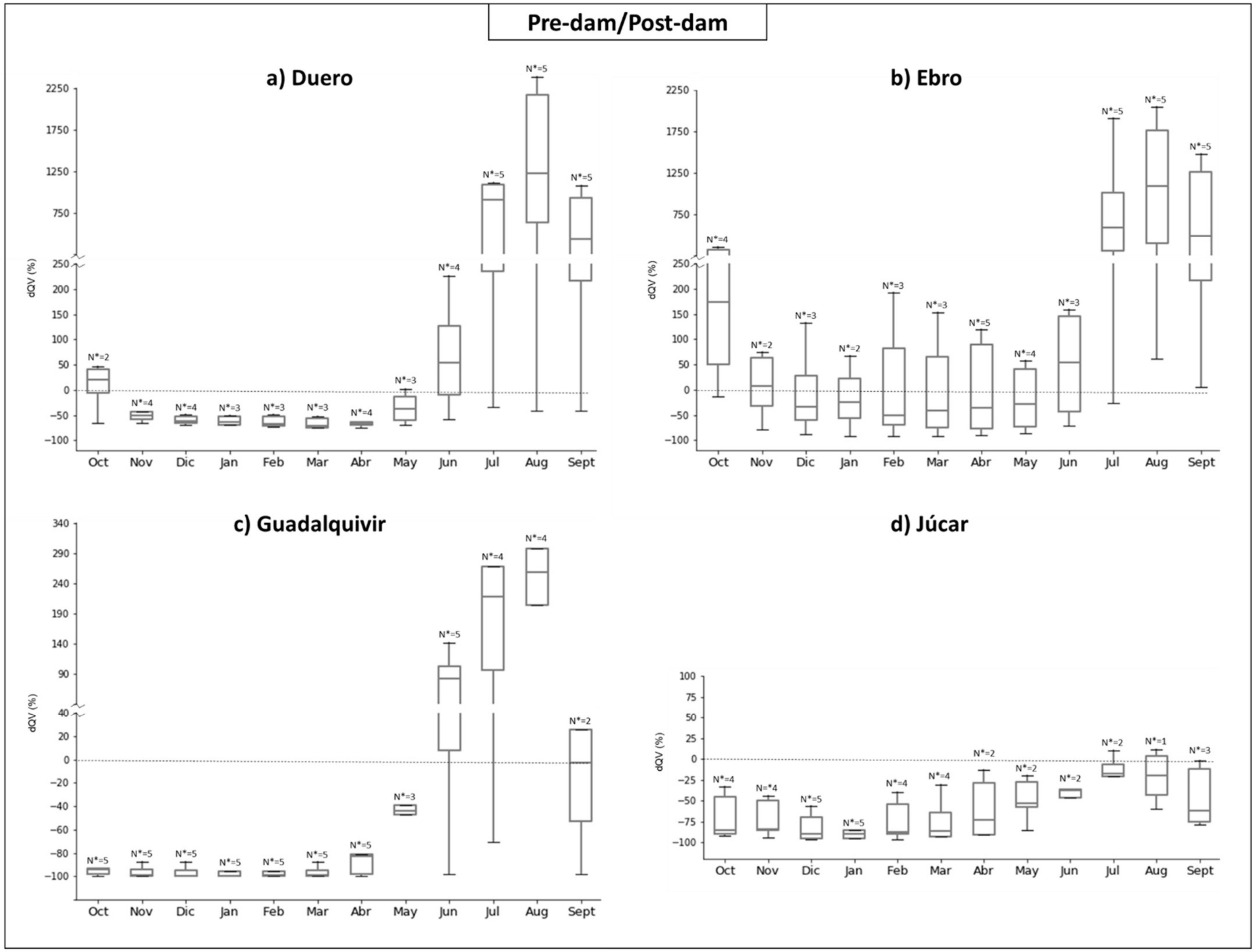


Fig. 4. Degree of variation (*dQV*) of monthly flows after dam operation in the studied basins (pre-dam/post-dam). Box-plots represent median and percentile values of *dQV* in the studied rivers within each basin. Number above box-plots indicate the number of rivers where changes in mean monthly flows were statistically significant.

In most of the studied rivers, the implementation of e-flows did not bring about significant changes in relation to the previous post-dam period (Fig. 5). However, some differences can be detected across basins: in the e-flow period the monthly flows during the wetter season tend to be slightly higher in the Guadalquivir and Júcar basins (i.e., drier basins), while these flows maintained their decreasing trend in the Duero and Ebro basins (i.e., wetter basins) (see numerical values of dQV in Appendix A, Table A.11).

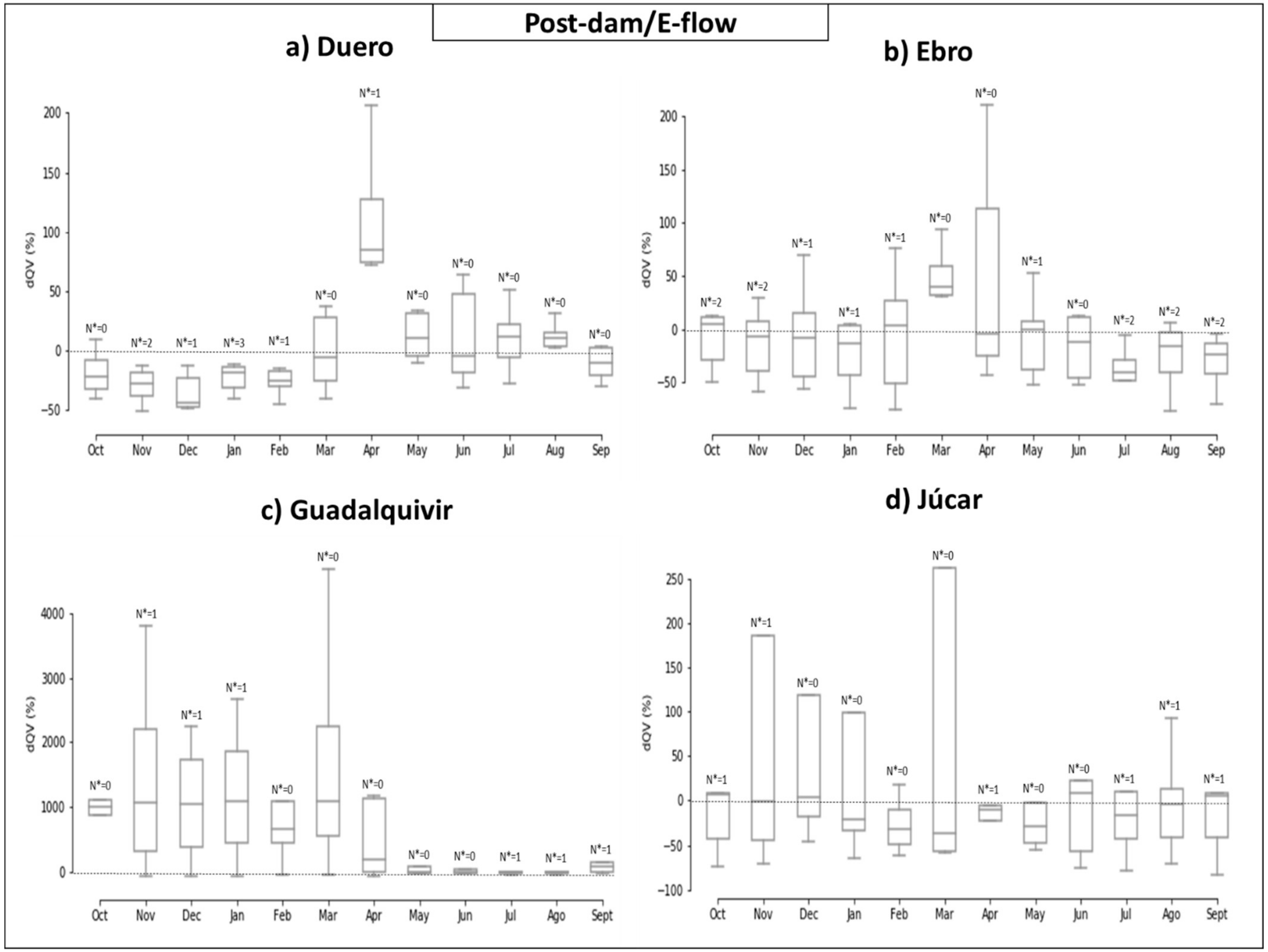


Fig. 5. Degree of variation (*dQV*) of monthly flows after e-flows implementation in the studied basins (Post-dam/E-flow). Box-plots represent median and percentile values of *dQV* in the studied rivers within each basin. Number above box-plots indicate the number of rivers where changes in mean monthly flows were statistically significant.

3.2.2 Changes in frequency histograms (dQH)

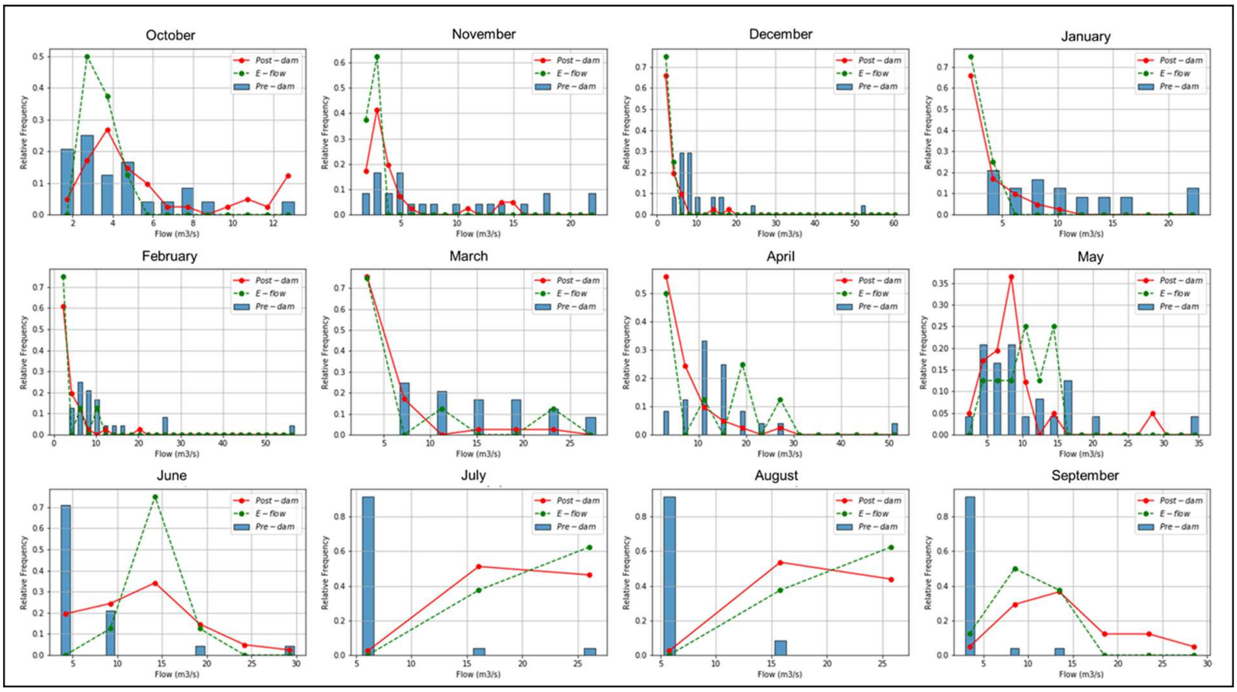
The analysis of frequency histograms (see Appendix B, Fig. B.1-B.22) reveals instream monthly flow changes in many of the studied rivers, with different patterns within the ensemble of rivers belonging to the wetter basins (Duero and Ebro) on one side, and the drier basins (Guadalquivir and Júcar) on the other side. Figure 6 shows the frequency histograms of each period in two rivers, Porma (Fig. 6a) and Genil (Fig. 6b), as representative examples of each ensemble of basins.

In most rivers from Duero and Ebro basins (see example in Fig. 6a), pre-dam monthly flows (solid columns in blue) during the wet season (i.e., October to May) were characterized by a quite broad range of values and relatively frequent large flows. During the summer (June to September), the range of flow values was much narrower, with the highest frequency usually corresponding to the smaller flows. After impoundment (solid red line), the range of flow variability during the wet season decreased and lower flow values were more frequent, while the frequency of higher flows sharply decreased. In contrast, during summer months, post-dam frequency histograms showed an increase in flow variability, which generally implied a decrease in the frequencies of low flows and an increase of high flows. Similar pattern of changes can be observed during the e-flow period (dashed green line): the range of flow variability gets even smaller than in the post-dam period and in several rivers more intense flow reductions occurred during the wet season.

In rivers from Guadalquivir and Júcar basins (see example in Fig. 6b) this pattern of changes is exacerbated. After impoundment, the natural range of flow variability during the wet season has decreased sharply and the frequency of the lower flows has grown at the expense of the frequency of the high-flow values. During the dry season the opposite occurred, with a decrease in the frequency of the lower values and an increase in the frequency of intermediate or high-flow values. Histograms after e-flow implementation showed similar trends, thus maintaining the changes occurred after dam construction.

Although the reversal of seasonality patterns have been detected in rivers belonging to the four basins, the two ensemble of basins exhibited differences between wet and dry periods. Using January and August as examples of wet and dry months respectively, we observe that post-dam changes in frequency histograms in the wet season were especially important in drier basins: mean values of *dQH* in Guadalquivir and Júcar basins are 69% and 65% respectively, while they are 51% and 36% in Duero and Ebro basins. In contrast, *dQH* values in the dry season indicate higher alteration in the wetter basins (mean *dQH* value was 73% in Duero and 63% in Ebro basins) than in the drier ones (56% and 25% in Guadalquivir and Júcar basins) (See numerical values of dQH in Appendix A, Table A.12).

a) Porma river (Duero basin)



b) Genil river (Guadalquivir basin)

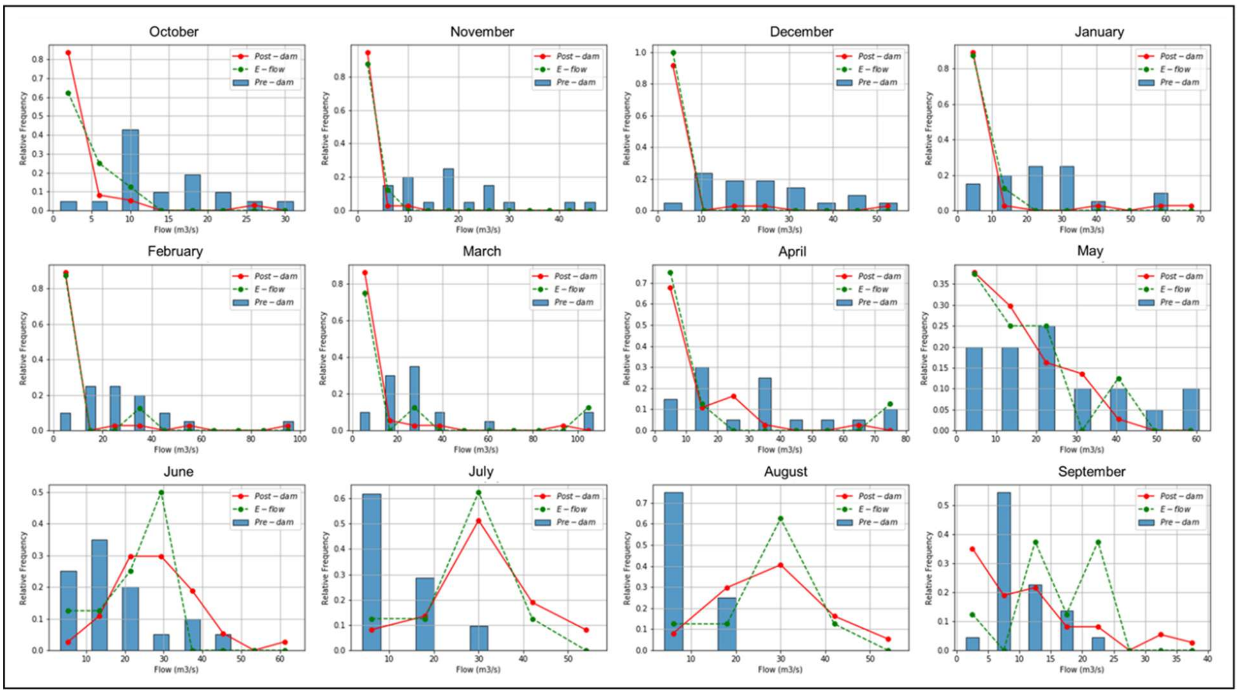


Fig. 6. Frequency histograms of monthly flows of the (a) Porma river (Duero basin) and (b) Genil river (Guadalquivir basin) during the three studied periods

3.*2.3 Ratio of change (D)*

Fig. 7 shows the *D* values in the studied basins. As explained in the Methodology section, this value expresses to what extent the e-flows implementation has reduced the distance to pre-dam conditions. In most of the cases, *D* median values are very close to 1 (horizontal line) for all the months. This suggests that, in general, e-flows did not mitigate the post-dam hydrological alteration. As a matter of fact, while in the Guadalquivir basin the implementation of e-flows seems to slightly reduce alteration (i.e., *D* values are smaller than 1 throughout the year), in the rest of the basins, especially in the Duero basin, the hydrological alteration seems to intensify in certain months during the e-flow period (see Fig. 7 and numerical values of *D* in Appendix A, Table A.15).

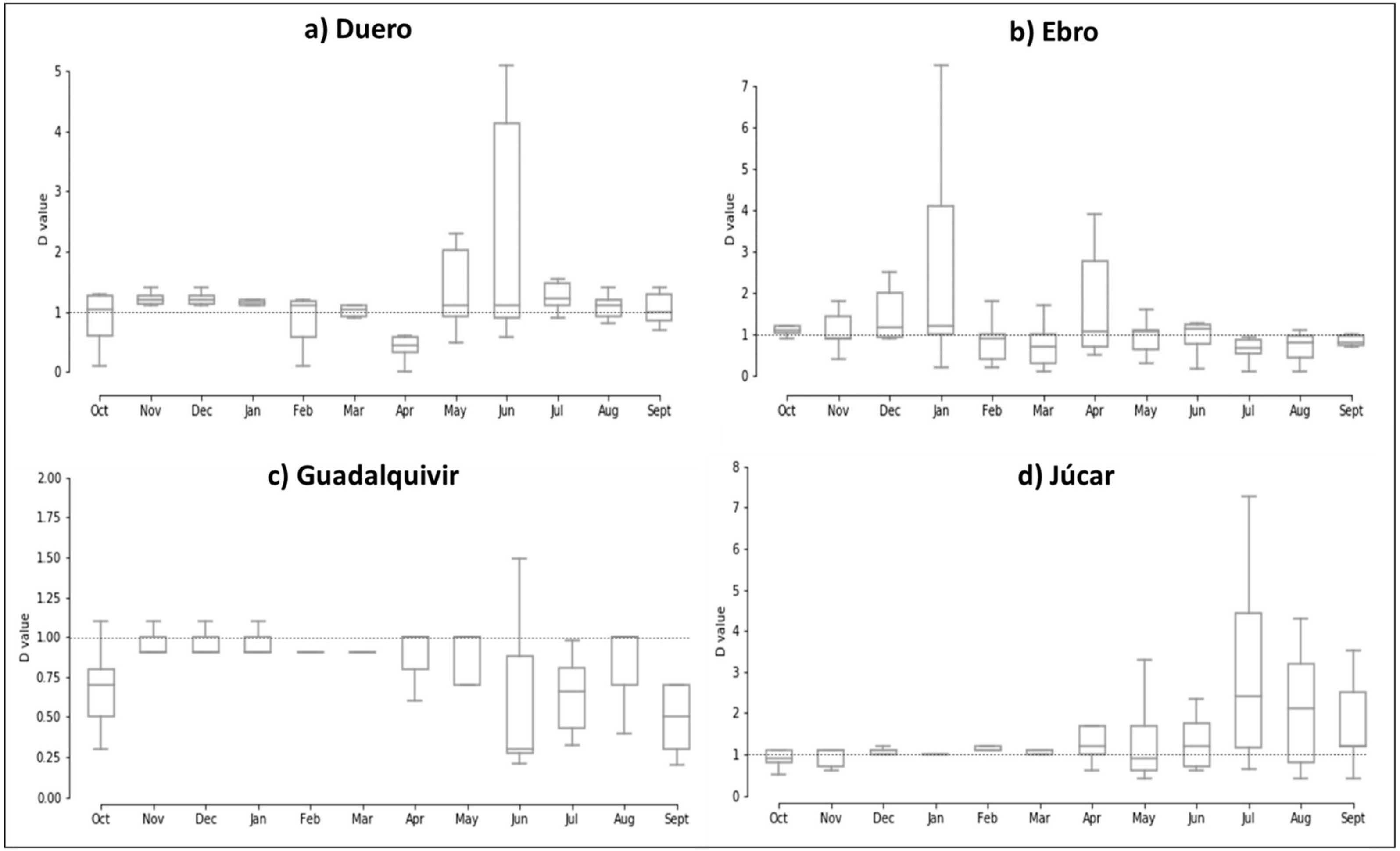


Fig. 7. Ratio of change (D values) in magnitude of monthly flows. Horizontal line (i.e., D=1) means no change. D values above the horizontal line imply an increase of hydrological alteration whereas D values under horizontal line imply a decrease in hydrological alteration after e-flow implementation

3.3 Changes in extreme flows

3.3.1 Changes in magnitude (dQV)

Nearly all the studied rivers experienced significant changes of extreme flows after impoundment (see numerical values of *dQV* in Appendix A, Table A.13). 1-day maximum flow decreased significantly in most of the studied rivers, being this trend particularly marked in the Guadalquivir and Júcar basins (where the mean reductions were -76% and -80% respectively) (Fig. 8). On the contrary, 1-day minimum flows recorded significant increases in the wetter basins (mean increase of 384% and 144% in Duero and Ebro basins) but significant reductions in the drier ones (mean reduction of -92% and -80% for Guadalquivir and Jucar basins respectively) (Fig. 8).

The analysis of percentiles confirmed similar trends to those exhibited by 1-day maximum and 1-day minimum flow, although displaying less marked changes. After impoundment, percentile 95th flow values in all the studied rivers decreased more slightly than the 1-day maximum flow, in terms of both the magnitude and the number of rivers where changes were significant (mean reduction of 95th percentile: Guadalquivir, -38%; Júcar -54%; Duero -30%; Ebro -22%). 5th percentile of flows increased in the Duero and Ebro basins, with mean values of 205% and 115%, respectively, whereas it showed reductions of -89% and -75% in Guadalquivir and Júcar basins, respectively.

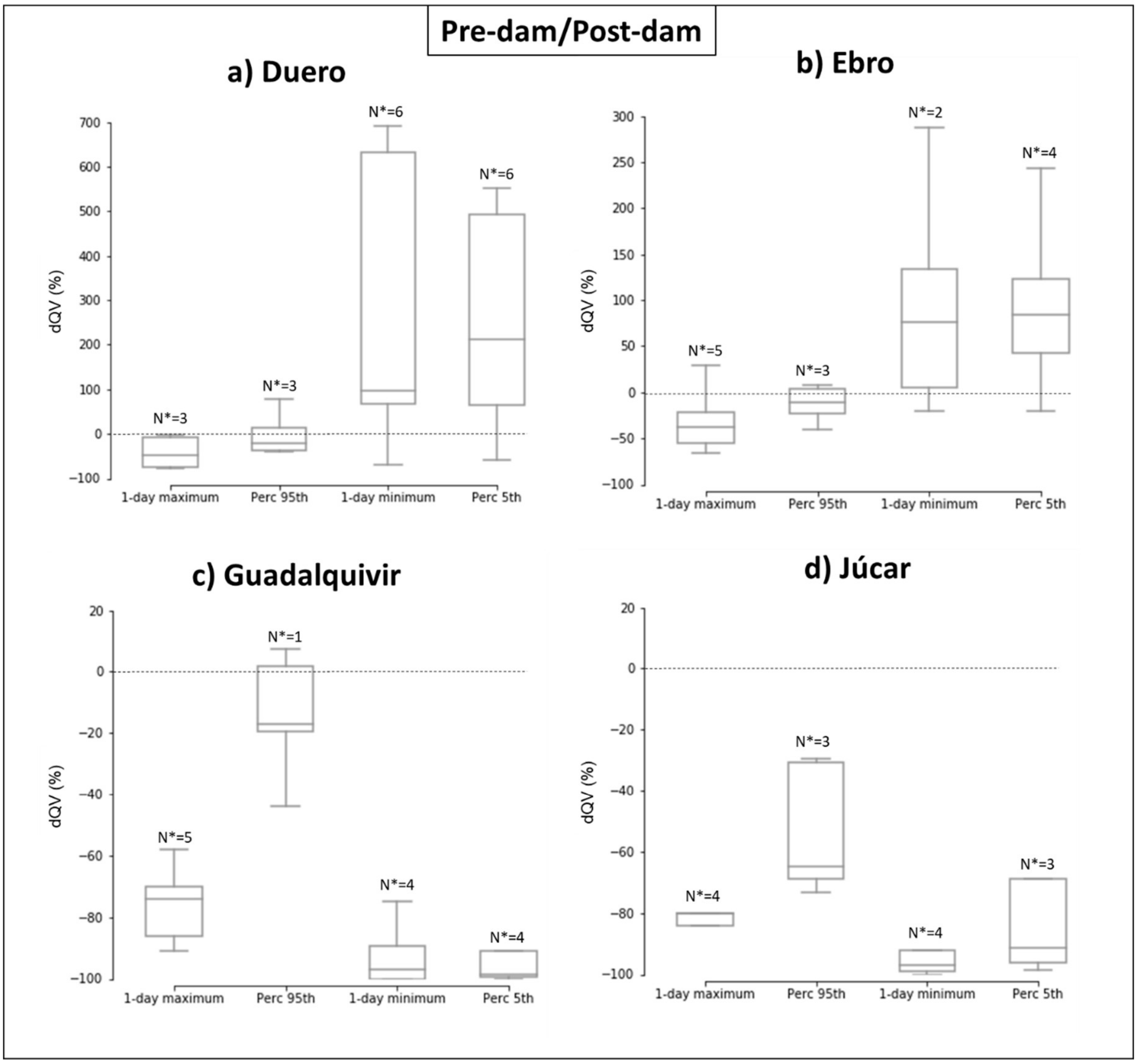


Fig. 8. Degree of variation (*dQV*) of annual extreme flows (1-day maximum flow, 95th percentile, 1-day minimum flow and 5th percentile) in the post-dam period. Box-plots represent median and percentile values of *dQV* in the studied rivers within each basin. Number above box-plots indicate the number of rivers where changes resulted significant.

Fig. 9 shows changes in annual extreme flows after e-flows implementation. In this case, changes were not statistically significant in most of the rivers. The median value of 1-day maximum flows still decreased in all basins, while the median of 1-day minimum flows increased in all basins except for the Duero. Results from percentile 95th and percentile 5th showed similar trends to those observed for 1-day maximum and 1-day minimum flows, with a remarkable increase of the 5th percentile flow value in the rivers of the Guadalquivir basin.

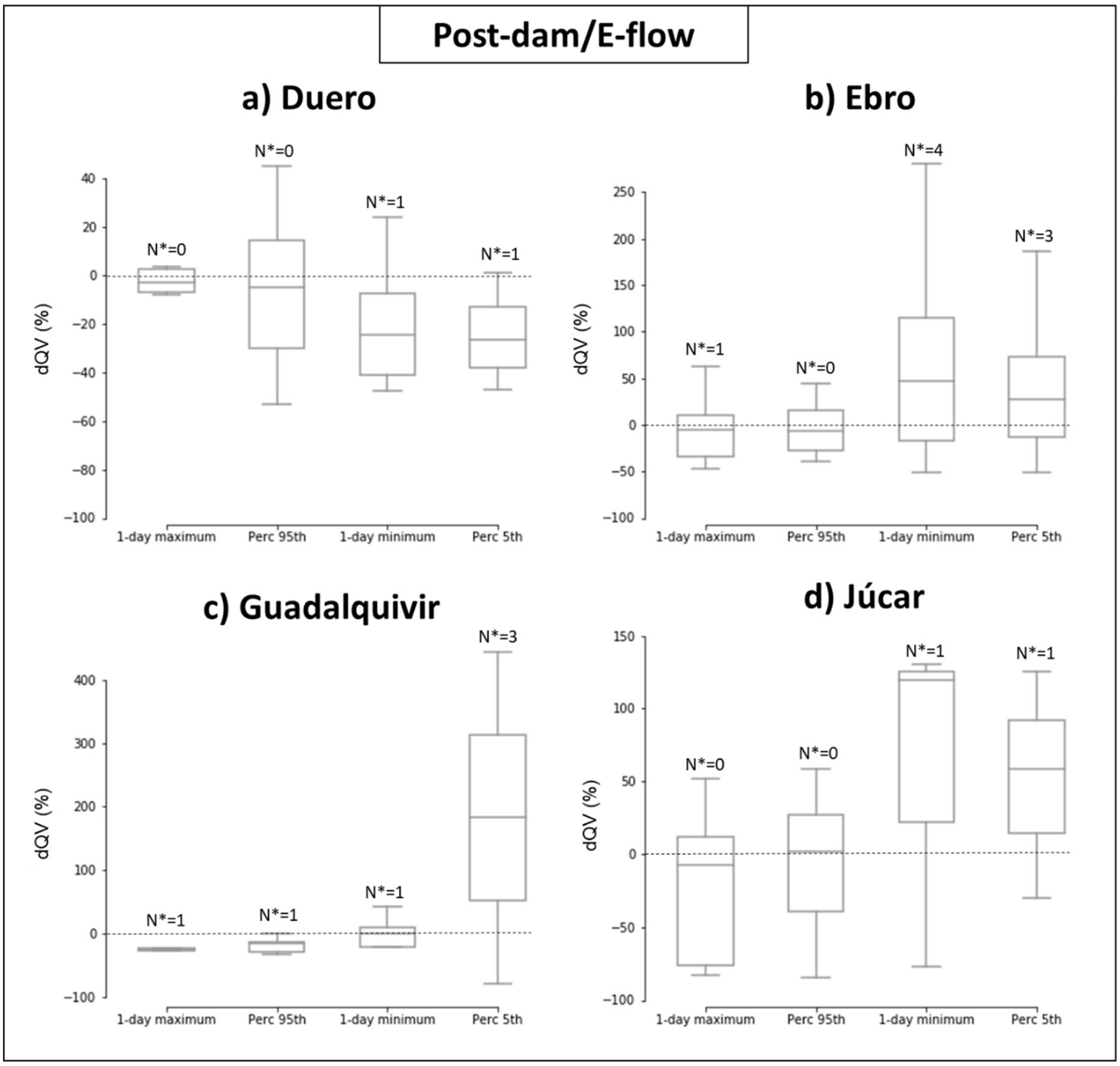


Fig. 9. Degree of variation (*dQV*) of annual extreme flows after e-flows implementation. Box-plots represent median and percentile values of *dQV* in the studied rivers within each basin. Number above box-plots indicate the number of rivers where changes in magnitude of 1-day maximum/minimum flows and percentiles 5th and 95th resulted significant.

3.3.2. Changes in frequency histograms (dQH)

The analysis of the frequency histograms of extreme flows reveals differences across basins (see Appendix B, Fig. B.23-B.30). Fig. 10 shows the frequency histograms of the Lumbreras (Ebro basin) and Júcar rivers (Júcar basin), selected as representative examples of the overall changes in wetter and drier basins respectively.

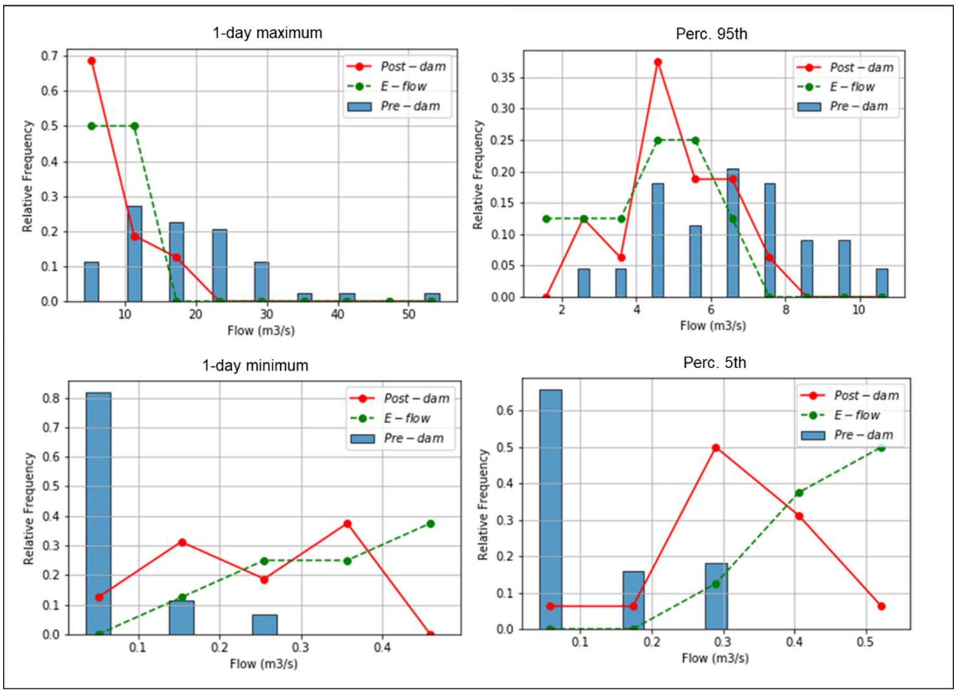
In the Lumbreras river (i.e., wetter basins), pre-dam frequency histograms (in blue, solid columns) (Fig. 10a) were characterized by a high variability of annual maximum flows (1-day maximum flow) with a relatively high frequency of intermediate values, and a relatively small variability of minimum flows (1-day minimum flow) with a high frequency of the smallest values. During the post-dam period (in red, solid line), the range of maximum flow values decreased, lower values became the most frequent and the higher ones completely disappeared. Regarding 1-day minimum flows, after dam construction the range of variability of values enlarged and the frequency of higher values increased. After the e-flows implementation (in green, dashed line), post-dam trends for both maximum and minimum flows remained unchanged or were even exacerbated.

In the Júcar river (i.e., drier basins) frequency histograms of pre-dam annual maximum flows (Fig. 10b) showed similar patterns as in the wetter ones, with a large range of flow variability. On the contrary, the range of variability of minimum flows resulted to be much broader than in the Lumbreras river, with higher frequencies of the higher values. The regulation of rivers implied a sharp increase of the frequency of the lower annual extreme values, both for the maximum and minimum flows. This trend continued or has been intensified after the implementation of the e-flows.

The analysis of hydrological alteration in terms of percentiles of flow values (both 95th and 5th percentiles) shows similar changes than those reported for 1-day maximum and minimum flows, although changes were slightly less pronounced for percentile 95th especially in rivers located in the wetter basins.

Mean values of *dQH* for 1-day maximum flow were quite similar across basins but slightly higher in the drier basins, ranging between 48% and 44% in Duero and Ebro basins and between 54% and 55% in Guadalquivir and Júcar basins. Regarding 95th percentile flows, hydrological alteration was slightly lower and there was no remarkable differences across basins (mean values of *dQH* ranged from 35% to 46% for all the studied basins). No consistent differences across basins were found either in *dQH* mean values for 1-day minimum (Duero 62%, Ebro 42%, Guadalquivir 52% and Júcar 62%) or in 5th percentile flow values (Duero 58%, Ebro 40%, Guadalquivir 67% and Júcar 58%) (See numerical values of *dQH* in Appendix A, Table A.14).

a) Lumbreras river (Ebro basin)



b) Júcar river (Júcar basin)

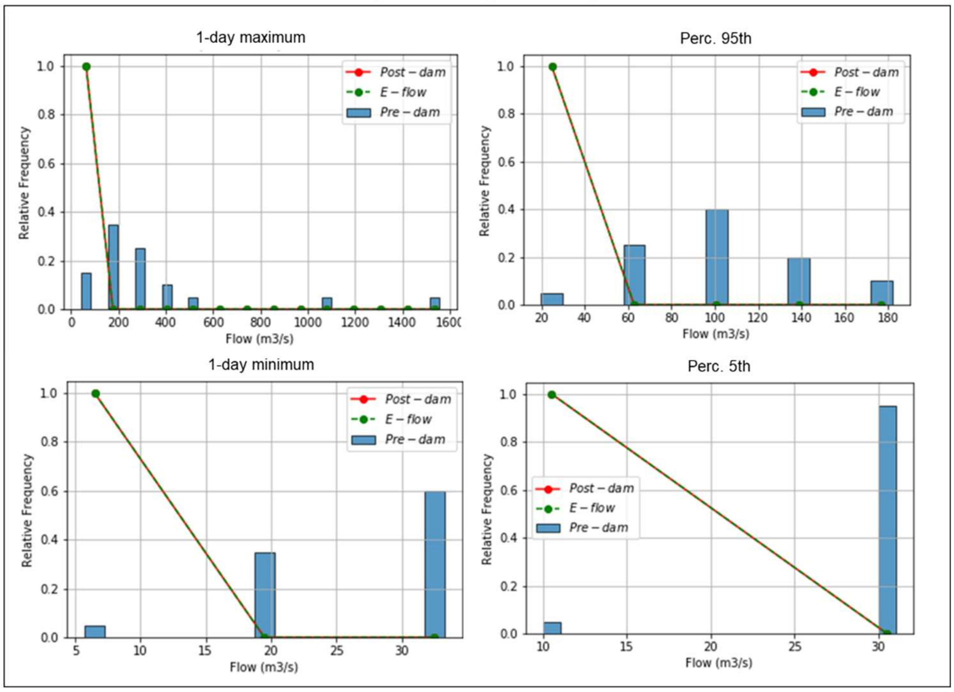


Fig. 10. Frequency histograms of annual extreme flows in a) Lumbreras river (Ebro basin) and b) Júcar river (Júcar basin).

3.3.3 Ratio of change (D)

The ratio of change *D* (Fig. 11) indicated that the implementation of e-flows has brought about a slight decrease in the alteration of the magnitude of 1-day maximum flows in some rivers of the Duero while the alteration increased in all rivers of the other three basins. Regarding 1-day minimum flows, the *D* value showed a substantial decrease in the hydrological alteration of rivers within the Duero basin but an increase in the Ebro and Guadalquivir basins.

The analysis of percentiles revealed larger dispersion of values within basins but, in general, D values of percentiles indicated similar results to those commented above, with no consistent pattern between wetter and drier basins.

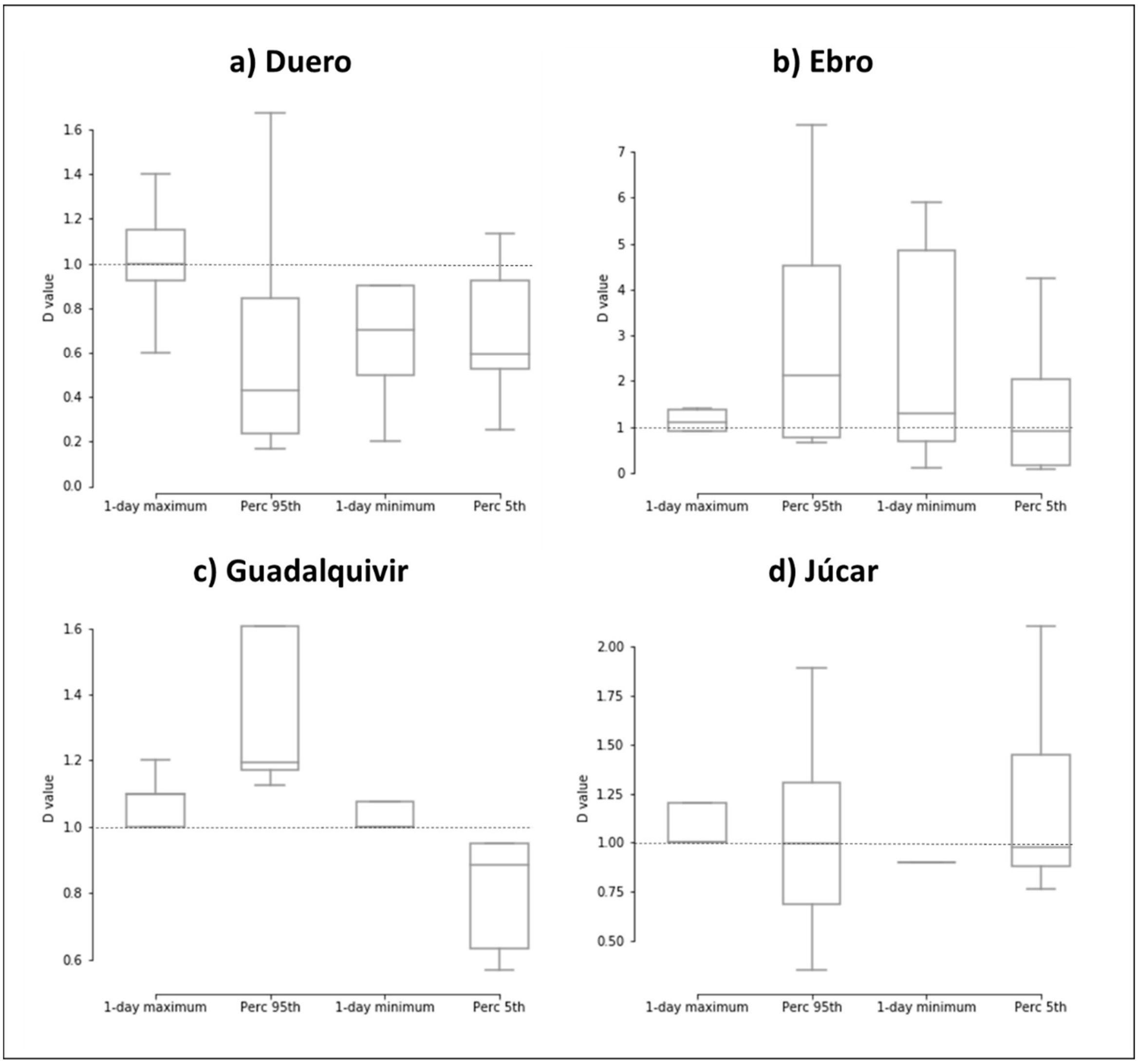
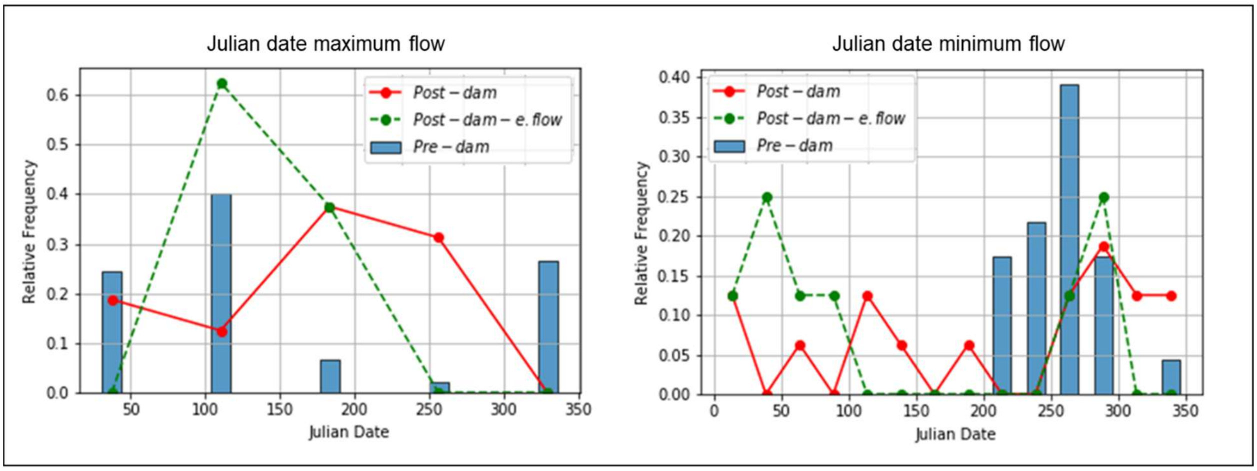


Fig. 11. Ratio of change (*D* values) in magnitude of annual extreme flows. Horizontal line (i.e., *D*=1) means no change. D values above the horizontal line imply an increase of hydrological alteration whereas D values under horizontal line imply a decrease in hydrological alteration after e-flow implementation.

3.3.4 Changes in timing of annual extreme flows

The analysis of change in magnitude and frequency of annual extreme flows was combined with the analysis of variation in the Julian day in which those annual extreme flows occur. The dates of 1-day maximum and 1-day minimum flow experienced strong variations after dam construction. In pre-dam conditions, in nearly all the rivers the 1-day maximum flow tend to occur along the wet season between December and February, while 1-day minimum flow was mostly concentrated in the dry summer months (July to September), following a typical Mediterranean climate pattern. Dam operation shifted these dates in a similar way in all the basins, reversing their natural pattern (See Appendix B, Fig. B.31-B.34). 1-day maximum flows increased their frequency during the dry months (July to September), whereas 1-day minimum flows were particularly frequent during the wet months (November to April), when reservoirs are getting filled. The implementation of e-flows has not mitigated these patterns of seasonal alteration. Fig. 12 illustrates these changes in the rivers Lumbreras (Ebro basin) (Fig. 12a) and Júcar (Júcar basin) (Fig.12b), underpinning the more pronounced effects downstream of dams in the drier basins.

a) Lumbreras river (Ebro basin)



b) Júcar river (Júcar basin)

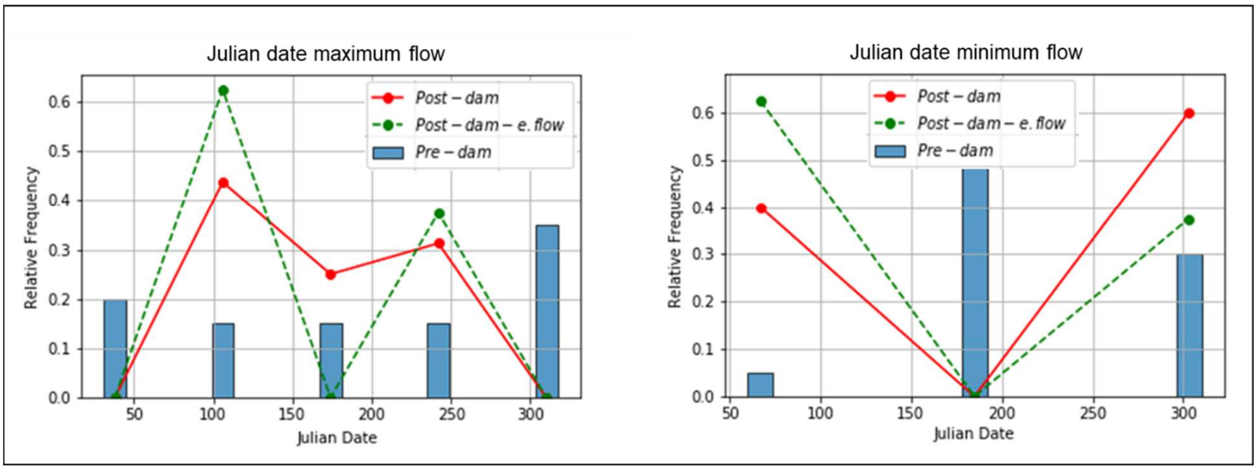


Fig. 12. Changes in frequency histograms of date of 1-day maximum and 1-day minimum flow in a) Lumbreras river (Ebro basin) and b) Júcar river (Júcar basin).

4. Discussion

This study combines the traditional comparison of pre-dam to post-dam flow patterns with the analysis of the effect of e-flows on instream flows in Spain, in order to analyze to what extent the implemented e-flows are contributing to mitigate hydrological alteration in regulated rivers. Our results reinforce findings by other authors about the decrease of maximum flows (Batalla et al., 2004; Piqué et al., 2016; Vicente-Serrano et al., 2017b) and of the inversion of the natural Mediterranean flow seasonality pattern after the impoundment of the river (García de Jalón et al., 2019; Vicente-Serrano et al., 2017a). Besides, our results highlight the differences in flow change patterns between geographical regions suggested by Radinger et al (2018), that in our case follows the climate gradient from northern basins (i.e. Duero and Ebro basins with higher natural runoff) to southern basins (i.e. Guadalquivir and Júcar basins with a lower natural runoff). Furthermore, our analysis points to the limited influence of e-flows on the mitigation of hydrological alteration in the studied rivers.

4.1 Changes in annual flows

A decrease in mean annual flows after dam construction was observed in many of studied rivers and reduction was more pronounced in the southern drier basins than in the northern wetter basins (Fig. 3). The decrease and the difference between regions is consistent with other studies addressing the evolution of annual flows in Spanish rivers (Lorenzo-Lacruz et al., 2012). Decreasing trends of mean annual flows have been observed in both regulated and non-regulated rivers throughout the Iberian Peninsula (García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2012; Martínez-Fernández et al., 2013). Therefore, although dams could exacerbate the magnitude of the trends (Lorenzo-Lacruz et al., 2012), river damming cannot be considered as the only factor driving these changes at medium or long term. Other factors at different spatial and temporal scales do play an important role explaining the changes observed in our study.

In some cases we used non-continuous data sets with different lengths. Thus, pre-dam periods could coincide with a humid series and post-dam with a dry interval. Moreover, several authors (García-Ruiz et al., 2011; López-Moreno et al., 2011; Vicente-Serrano et al., 2014) have documented decreases in accumulated precipitation and increases of mean annual temperatures in Spain during the last half of the 20th century that are likely to have affected the magnitude of instream flows (Lorenzo-Lacruz et al., 2012; Morán-tejeda et al., 2010).

Apart from these changes in climatic conditions, land uses and their evolution over time may contribute to explain the observed mean annual flow decreases. Recent research found that the combination of higher atmospheric evaporative demand with the large increase in the surface of irrigated crops since 1960s are key factors explaining streamflow reduction in Spanish rivers (Vicente-Serrano et al., 2019). The increased evaporation rates from reservoirs' water surface (Piqué et al., 2016) and the existence of surface or groundwater withdrawals upstream, could explain some of the changes observed in the present study. As an example, intensive use of groundwater in the Mancha Oriental aquifer since 1980s greatly contributed to streamflow reduction in the Júcar river (Estrela et al., 2012). Moreover, other studies have linked the expansion of forest surface with reductions on water yield and streamflow during the XX century (Beguería et al., 2003; Coch and Mediero, 2016; Gallart and Llorens, 2004; López-Moreno et al., 2011; Willaarts, 2012).

During the e-flow period, mean annual flows and their inter-annual variability have maintained the observed reductions after impoundment in most of the studied rivers. The general reduction of decreasing annual runoff in Spanish rivers (García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2012; Martínez-Fernández et al., 2013) will constrain the society's capacity to cope with increasing human water demands while implementing e-flows to meet ecosystem water needs.

4.2 Changes in monthly flows

Monthly flows experienced marked reductions during winter and spring in all the studied rivers, and strong increases during summer in the all basins except Júcar (Fig. 4). In the wetter basins the most remarkable changes are the increase of flow values during the dry summer months, whereas in the drier basins they consist in a reduction in flow values during the wet colder months when reservoirs are filled. Similar changes have been reported worldwide (Döll et al., 2009), although with differences in the months when the strongest changes occur. In our study, changes following impoundment usually were more intense in December (mean reduction of -74%) and August (mean increase of 1100%), while Magilligan and Nislow (2005) detected that the strongest changes in U.S. rivers occurred in May (mean decrease of -52%) and September (mean increase of 139%). In the Huaihe river in China, these changes were stronger in February (mean decrease of -49%) and November (mean increase 138%) (Hu et al., 2008). In the rivers considered in this work, these changes represent much higher ratios than those reported in other regions. Furthermore, all the studied rivers in the Júcar basin and some of the rivers in the Guadalquivir basin show a reduction of monthly flows along the entire year since dam construction, likely due to water withdrawals to meet irrigation water demands. Our findings contribute to further document the changes occurred in flow regimes in rivers downstream from dams in the Mediterranean region, which is characterized by low natural runoff and extremely high water demands for irrigation (Vicente-Serrano et al., 2017a).

So far, the implementation of e-flows has barely produced changes in the flow regimes, although an effort to increase the instream flow values during the wet season is detected in the drier basins. The Spanish legislation (Orden ARM/2656/2008) defines the variable “minimum flow” as the minimum quantity of flow that *“should be exceeded to maintain the diversity and connectivity of aquatic habitats”*. This variable is defined monthly and has been implemented in all the studied rivers (see Table 2 and values of monthly minimum flows in Appendix A, Table A.1). In all the cases it represents a small percentage of the natural average annual flows (i.e., 21% in the Duero basin, 12% in the Ebro basin, 16% in the Guadalquivir basin and 12% in the Júcar basin) (Mezger et al., 2019), and seems to be insufficient to revert the observed strong reductions in autumn and winter flows.

On the other end of the spectrum, “maximum e-flow” quantifies the quantity of water that *“should not be exceeded in the ordinary exploitation of hydraulic infrastructure”* (Orden ARM/2656/2008). Thus, maximum e-flow should prevent situations of artificially high water discharges during summer, being defined as a single value for the drier months. This e-flow variable has been implemented only in 6 out of 22 of the studied rivers and the established thresholds appear to be too high to achieve that goal. For instance, in the Guadiana Menor river (Guadalquivir basin) the established maximum e-flow in summer is about five times the mean annual flow during the pre-dam period.

In summary, the thresholds of minimum and maximum monthly e-flows defined in the 2015-2021 RBMPs have not managed to reduce the hydrologic alteration of monthly flows downstream of dams. Most of the hydrological alteration patterns were maintained or even increased during the e-flow period. This clearly points to the need of substantially revisiting the current design of e-flows in order to mitigate the existing hydrological alteration at monthly scale and to ensure that they yield benefits for aquatic ecosystems such as the control of invasive species (Caiola et al., 2014).

4.3 Changes in annual extreme flows

Significant changes in annual extreme flows have been observed in all the studied rivers. Strong decreases in magnitude of maximum flows were found in nearly all the cases after dam construction (Fig. 8), being especially sharp in Guadalquivir and Ebro basins. These results are consistent and follow similar patterns reported by other authors. Average decreases in 1-day maximum flow of -55% (range between -20 and -80%) were reported by Magilligan & Nislow (2005) from a wide spectrum of US rivers, with a clear gradient of more intense reduction when moving from wetter to southwestern drier regions.

Accordingly, our reported decreases in 1-day maximum flow values were higher and more significant in the southern basins than in the northern basins. After the implementation of e-flows this decreasing trend did not significantly change in most of the studied basins (Fig. 9, 11). In most of the cases the analysis of percentiles 95th and 5th yielded similar results than the analysis of 1-day max and 1-day min respectively.

Changes in magnitude of minimum flows (i.e. 1-day minimum flow and 5th percentile) after dam construction exhibit marked differences across basins. In the Duero and Ebro basins their values recorded statistically significant increases, as found also by other authors (Batalla et al., 2004; Gao et al., 2012; Magilligan and Nislow, 2005; Zimmerman et al., 2018). On the contrary, minimum flows significantly decreased in the Guadalquivir and Júcar basins, as found in few other cases in the literature (Hu et al., 2008; Yang et al., 2012). The implementation of e-flows implied a small reduction of the artificially increased daily minimum flows in the Duero basin and a slight increase in the reduced minimum flows in the Júcar basin (Fig. 9).

Strong reductions of peak-flows may seriously affect sediment transport in rivers, gradually inducing channel adjustments (e.g., channel narrowing, aggradation, vegetation encroachment) and persistent river changes (González del Tánago et al., 2015; Schmidt and Wilcock, 2008). Increases in low flows may foster vegetation growth and exacerbate loss of channel mobility (e.g. Magdaleno & Fernández, 2011; Sanchis-Ibor et al., 2019). Because of their interactions with riparian vegetation and ecological consequences with the physical habitat, changes in annual extreme flows should be interpreted not only in terms of magnitude and frequency, which affect the above mentioned physical processes, but also in terms of timing of occurrence, which affects many biological processes. As an example, 1-day maximum flows occurring during summer may cause the scour of the still weakly rooted pioneer species recruitment (Politti et al., 2018), whereas 1-day minimum flow occurring during winter could prevent fish spawning and foster the expansion of invasive species (Caiola et al., 2014). Changes in magnitude and timing of extreme flows may also change the structure of riparian vegetation (Mahoney and Rood, 1998; Stromberg et al., 2010). Additionally, Fornaroli et al. (2020) have proven that the abundance of native fish species are related with the timing of minimum flow, whereas alien species are favored by lower annual minima and smaller annual maxima.

In the studied rivers, Julian days of both 1-day maximum and 1-day minimum flows differ between the pre-dam and the post -dam periods (Fig. 12). Based on this observation, it could be argued that the ecological impairment downstream from dams could be due not only to changes in flow magnitude but also to changes in their timing. Thus, our results contribute to reinforce the convenience of considering both the magnitude and the timing of extreme flows when assessing hydrological alteration by river damming, and the need of incorporating this important issue in the Spanish e-flows design, as an essential condition for ensuring integrity of river functioning (Bunn & Arthington, 2002; Poff et al., 1997).

4.4 Improving e-flows to mitigate hydrologic alteration from river damming

The intensive regulation of Spanish rivers put significant pressures on freshwater ecosystems, which underpins the importance of the establishment of e-flows to mitigate hydrological alteration (Caiola et al., 2014; Meitzen et al., 2013).

The implementation of e-flows is considered the first priority action to bend the curve of freshwater biodiversity loss at global scale (Tickner et al., 2020). This means that urgent actions should be taken to properly assess, implement and manage e-flows, based on adaptive management, knowledge transfer and social engagement (Horne et al., 2017). From the reported experience on the implementation of e-flows (Harwood et al., 2017), it emerges that e-flows should be adapted to the local context, taking into account specific water resources uses and practices. After technical studies, e-flows should be critically discussed and politically negotiated through collaborative engagement of water managers, scientists, academics and local stakeholders (Tonkin et al., 2019).

In the case of the studied rivers, our findings suggest that recovering the Mediterranean flow seasonality pattern should be one of the main priorities when revising the current RBMPs. The design of e-flows should explicitly address the need to maintain both physical processes, which are strongly influenced by the magnitude of extreme flows, and fundamental biological processes directly linked to their timing. The flows characterization carried out in this study is a necessary starting point to understand which alterations e-flows should be able to mitigate in order to contribute to the achievement of the good ecological status of rivers.

The intensive use of water resources in many regions of Spain suggests that the effectiveness of e-flows in mitigating hydrological alteration and its effects on ecosystems requires revisiting the current paradigms of water management and socioeconomic development. While it is true that changes of paradigms can be challenging, policies guiding future socioeconomic development should be oriented towards a more sustainable use of natural resources (Pahl-Wostl et al., 2013).

4.5 Caveats

Some caution is needed when interpreting the results of this study. First, we used only seven years of data (i.e. 2013-2019) to characterize hydrological changes during the e-flow period, as the systematic implementation of e-flows in Spain started in 2013. The use of such a short data series responds to the need to adjust e-flows to improve their effectiveness as soon as possible but it also implies a certain degree of uncertainty in the results. Second, the scarcity of historical data series representing hydrological regimes of “natural” (pre-dam) conditions in Spain (Baeza et al., 2018; Belmar et al., 2013) limited the length of the pre-dam period and reduced the number of gauging stations suitable for our analysis. Third, our study has characterized the hydrological alteration in relation to the existence and operation of dams. Other factors such as changes in land cover, groundwater overexploitation, water withdrawals from river intakes or changes in climatic variables could be relevant to explain changes in instream flows. Finally, our study has used flow data on a daily scale and therefore it is not able to detect short-time-scale hydrological alterations caused by e.g. hydropeaking.

5. Conclusions

We quantified the hydrological alteration in 22 regulated rivers and assessed the role of the implementation of e-flows in reducing that alteration. The studied rivers are located both in northern wetter basins (Duero and Ebro) and in southern drier basins (Guadalquivir and Júcar), in order to take into account the characteristic north-south hydrological gradient within the Iberian Peninsula.

We observed a general hydrological decline in terms of reductions of mean annual flows over the last century. Simultaneously, significant hydrologic alteration of monthly flows and their natural Mediterranean seasonality has been observed in all the studied rivers downstream of dams. Extreme flow values also indicated significant changes below dams, which affect not only the magnitude of flows but also their timing in terms of their Julian day of occurrence. These changes are compatible with the fact that the primarily use of the stored water in reservoirs is irrigation.

Our results suggest the interest of assessing hydrological alteration of the flow regime downstream from dams combining changes in magnitude with changes in the timing of flows. This is particularly important taking into account the potential ecological effects of the de-synchronized occurrence of extreme values with stages of life cycles in Mediterranean rivers. For instance, the reduction of maximum flow rates in winter greatly affects native fish communities while increasing minimum flows in summer leads to channel vegetation encroachment.

Climate and geographical contexts seem to influence the effects of dams. Rivers in the drier basins show relatively stronger reductions in monthly flows during the wet season whereas rivers in the wetter basins exhibited relatively stronger increases in monthly flows during the dry season. In both hydrological contexts, decreases in maximum flows (i.e., 1-day maximum and 95th percentile) take place after dam construction, whereas increases in minimum flows (i.e., 1-day minimum and 5th percentile) were recorded only in the wetter basins. E-flows implementation seems to have little effect in reverting these hydrological alterations, as rivers present similar flow regime patterns since dam operation started. These findings are based on the observation of trends in instream flows since the start of the implementation of the e-flows in 2013 and can contribute to the adaptive revision of their design. In the future and once more data are available, it will be interesting to explore these trends over longer time series and to assess their possible effects on the status of river ecosystems.

CRediT authorship contribution statement

Gabriel Mezger: Conceptualization, Methodology, Validation, Formal analysis, Data Curation, Investigation, Writing-Original Draft, Visualization

Marta González del Tánago: Conceptualization, Methodology, Investigation, Writing-Review and Editing, Supervision.

Lucia De Stefano: Conceptualization, Writing-Review and Editing, Supervision, Project administration, Funding acquisition

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