Application of indicators of alteration to characterize dam-induced changes in the regime of Portuguese rivers

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Introduction

The natural temporal variability of the stream-flows in the mainland Portugal results into summer water scarcity and into unpredictability of the flow regime from year to year. Consequently, many dams have been built for flood control, energy production and water storage to satisfy the urban, industrial and agricultural water requirements. However, dam-induced changes in the flow regime of rivers have important effects on the structure, composition, diversity and functioning of aquatic and riparian communities (e.g. fish, macroinvertebrates, vegetation) [1] and alter the physical components of fluvial systems (e.g. geomorphology, bank stability, substrate). Despite the increasing concern about these effects, few studies have documented the hydrological alterations of the natural flow regime induced by dams in Portugal and their associated ecological impacts. The quantification of the flow alterations is essential to understand the type and magnitude of their ecological impacts and to sustainably manage a river.

This study aims to characterize and quantify the changes in the flow regime resulting from river damming by using hydrological parameters which are ecologically meaningful.

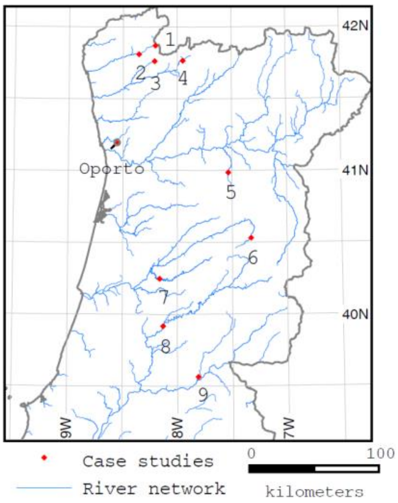

Figure 1. Case studies: (1) Alto Lindoso, (2) Touvedo, (3) Vilarinho das Furnas, (4) Paradela, (5) Vilar, (6) Caldeirão, (7) Fronhas, (8) Cabril and (9) Pracana.

Case studies, flow data and methods

We selected nine river reaches affected by an upstream hydropower dams (Figure 1) where daily flow series were available. Case study number 2 corresponds to a run-of-river; meanwhile the remaining cases have reservoirs. In cases number 3, 4, 6 and 7 water is transferred to neighbouring watersheds, and in cases number 1, 2, 5, 8 and 9 it is delivered to the same river where the dam is located, either relatively near the dams (cases number 1, 2, 8 and 9) or far downstream (case number 5).

Assessing the flow regime alteration caused by dams can be approached from many viewpoints, each one with different inherent complexities and limitations. Once daily flow data are available, one of the most direct and widely utilized procedures consists of a comparison between "natural" and "regulated" flow regimes by means of a set of statistical indicators with ecological interest: Indicators of Hydrological Alteration (IHA), as proposed by Richter in 1996 [2]. In the present study, the nine selected sites (river-dams) have relatively long daily series of flow upstream (inflows to the dam) and downstream from the dam (outflows from the dam); we considered the inflows as "natural" and the outflows as "regulated". We calculated 33 indicators of hydrological alteration by applying the software IHAv7 [3], and then organized them into groups according to the different intrinsic characteristic of the flow regime which they represent (adapted from [2]) : 1 – magnitude of monthly water conditions; 2 – magnitude and duration of annual extreme water conditions; 3 – timing of annual extreme water conditions; 4 – frequency and duration of high/low pulses; and 5 – rate and frequency of water condition changes. The intrinsic characteristics of the flow regime represented by the 33 IHA and their allocation into the five groups considered are shown in Table I.

The IHAv7 software allows different types of analysis, namely, i) single period or pre- and post-impact comparison analysis; and ii) parametric or non-parametric analysis. The procedure applied to the nine case studies considered the "natural" regime (inflows) and the "regulated" regime (outflows) as two independent single periods, the indicators of hydrological alteration being computed separately to each one. Afterwards, a non-parametric analysis, based on medians rather than on averages, was adopted in order to account for the skewed nature of the empirical distributions. So, to summarize the values of IHA obtained for each year within the period under analysis, the median of the annual IHA was considered. It is worth mentioning that the software IHAv7 "fills the record gaps" by linear interpolations when daily flows are not available. To avoid an excessive number of gaps, only continuous years each one with more than 300 daily flow records were used in the analysis, as specified in Table II.

Table I. Indicators of hydrologic alteration, IHA, for one year of daily records (adapted from [2]).

IHA group	Flow regime characteristics	Hydrologic indicators, IHAi	
1. Magnitude of monthly water conditions	Magnitude/Timing	IHA1	January median daily flow
		IHA2	February median daily flow
		IHA3	March median daily flow
		IHA4	April median daily flow
		IHA5	May median daily flow
		IHA6	June median daily flow
		IHA7	July median daily flow
		IHA8	August median daily flow
		IHA9	September median daily flow
		IHA10	October median daily flow
		IHA11	November median daily flow
		IHA12	December median daily flow
2. Magnitude and duration of annual extreme water conditions	Magnitude/Duration	IHA13	Annual minima of 1-day
		IHA14	Annual minima of 3-consecutive days means
		IHA15	Annual minima of 7- consecutive days means
		IHA16	Annual minima of 30- consecutive days means
		IHA17	Annual minima of 90- consecutive days means
		IHA18	Annual maxima of 1-day
		IHA19	Annual maxima of 3- consecutive days means
		IHA20	Annual maxima of 7- consecutive days means
		IHA21	Annual maxima of 30- consecutive days means
		IHA22	Annual maxima of 90- consecutive days means
		IHA23	Number of zero-flow days
		IHA24	Base flow index
3. Timing of annual extreme water conditions	Timing	IHA25	Julian date 1-day minimum
		IHA26	Julian date 1-day maximum
4. Frequency and duration of high/low pulses	Magnitude/Frequency/ /Duration	IHA27	Number of low pulses
		IHA28	Median duration of low pulses (days)
		IHA29	Number of high pulses
		IHA30	Median duration of high pulses (days)
5. Rate and frequency of water condition changes	Frequency/Rate of change	IHA31	Rise rates
		IHA32	Fall rates
		IHA33	Number of hydrologic reversals

The comparison between the values of the IHA for the "natural" and for the "regulated" river conditions can be performed in many different ways. One of them is based on the ratio of alteration, RA, defined by eq. (1):

$$RA = \frac{(IHA)_{natural}}{(IHA)_{modified}} \qquad (1)$$

However, either among the different case studies for certain IHA or among the different IHAs for a concrete case study, the ratios given by eq. (1) may differ several orders of magnitude depending on the relative values of the numerators and denominators and making such ratios difficult to compare.

Whenever we are only interested in the fraction (between 0 and 1) of the magnitude of hydrologic alteration, we use a modified ratio of alteration, defined as:

$$mRA = \begin{cases} \min\left\{\frac{(IHA)_{natural}}{(IHA)_{modified}}, \frac{(IHA)_{modified}}{(IHA)_{natural}}\right\} & \text{if } (IHA)_{natural} \neq 0 \\ 0 & \text{if } (IHA)_{natural} = 0 \end{cases} \quad (2)$$

Values of RA and of mRA were only computed when $(IHA)_{modified}$ was different from zero. A value of mRA close to zero means a large amount of hydrological alteration, while a value close to one, occurs when IHA for the "natural" and for the "regulated" river are not very different. Note that when $(IHA)_{natural} = 0$ the ratio of alteration is zero, even for possibly small values of $(IHA)_{modified}$, highlighting a very grievous alteration.

Table II – Periods adopted in the analysis. For a year with gaps, the number of days with records is specified. Orange coloured cells represent the years used for the analysis (over 300 flow records registered per year); -- means no records available.

Case study	Flow conditions	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
1	Natural	--	--	--	22	54	156	269	326	301	333	347	352	354	333	330	304	356	360	256
	Modified	--	--	--	--	54	156	270	329	303	335	347	350	344	333	330	304	356	360	256
2	Natural										333	339	347	346	341	328	335	352	358	256
	Modified	--	--	--	--	56	156	269	328	300	335	339	347	346	341	328	335	357	359	256
3	Natural	--	--	--	--	--	--	--	--	--	--									--
	Modified	--	--	--	--	--	--	--	--	--	--									--
4	Natural	--	--	--	--	--	--	--	--	--	--									--
	Modified	--	--	--	--	--	--	--	--	--	--									--
5	Natural	--	--	--	--	--	--	--	--	--	--									--
	Modified	--	--	--	--	--	--	--	--	--	--									--
6	Natural	--	--	--	--	--	--	--	--	--	--									--
	Modified	--	--	--	--	--	--	--	--	--	--									--
7	Natural	--	--	--	99	269	177	279	328	321	333	332	348	339	342	325	335	351	357	256
	Modified	--	--	--	53	273	177	289	334	323	336	334	348	340	342	325	335	356	358	256
8	Natural	--	--	--	--	--	--	--	--	--	--									--
	Modified	--	--	--	--	--	--	--	--	--	--									--
9	Natural	--	--	--	--	--	--	--	--	--	--									--
	Modified	--	--	--	--	--	--	--	--	--	--									--

Results and discussion

The ratios of alteration obtained for the nine case studies by applying the previous methodology are presented in Table III. We distinguished between: i) low alteration, when the mRA > 0,67; ii) moderate alteration, when the 0,67 > mRA > 0,33; and iii) high alteration, when mRA < 0,33. These results show that the diversion dams (cases number 3, 4, 6 and 7) cause the greatest hydrologic alterations, whereas the run-of-river dams (case number 2) cause the lowest, as expected. The remaining case studies, where water is delivered to the same river downstream from the dam (number 1, 5, 8 and 9), suffered from moderate hydrologic alterations.

To synthetize the results from Table III, the average values of each IHA group were computed, as presented in Table IV. The average values express the global alteration of the specific regime characteristics within each group and confirm the results from Table III.

Conclusions

A methodology based on very efficient software was applied to ascertain the alterations of the flow regime resulting from the operation of selected Portuguese hydropower dams by using several hydrologic indicators. Different types of dams regarding the storage capacity, the water transfer between watersheds and the location of the powerhouse outlet, were analysed. Our results confirm that the storage dams, especially those transferring water among different watersheds, induce the most severe hydrologic changes. Results also show the run-of-river dams as the less hydrologically impacting. We would expect that the ecological impacts deriving from these hydrological changes were of similar degree.

However, conclusions should be taken with caution given the low sample of case studies. A post-analysis to identify the best indicators which represent the type and magnitude of hydrologic alteration could be interesting.

Table III. Ratios of alteration (mRA) for each case study.

IHA Group	IHAi	Case studies								
		1	2	3	4	5	6	7	8	9
1. Magnitude of monthly water conditions	IHA1	0,856	0,936	0,046	0,000	0,861	0,000	0,291	0,949	0,624
	IHA2	0,939	0,914	0,072	0,000	0,630	0,000	0,123	0,764	0,740
	IHA3	0,723	0,826	0,086	0,000	0,511	0,000	0,127	0,941	0,679
	IHA4	0,855	0,932	0,093	0,000	0,511	0,000	0,000	0,760	0,925
	IHA5	0,998	0,645	0,146	0,000	0,656	0,000	0,000	0,657	0,141
	IHA6	0,957	0,739	0,305	0,048	0,153	0,000	0,000	0,526	0,000
	IHA7	0,758	0,836	0,395	0,307	0,041	0,000	0,000	0,150	0,000
	IHA8	0,636	0,814	0,509	0,843	0,079	0,000	0,000	0,101	0,000
	IHA9	0,388	0,714	0,700	0,741	0,061	0,000	0,000	0,197	0,000
	IHA10	0,632	0,602	0,117	0,000	0,080	0,000	0,000	0,386	0,351
	IHA11	0,957	0,763	0,097	0,000	0,959	0,000	0,000	0,802	0,790
	IHA12	0,899	0,702	0,079	0,000	0,900	0,000	0,000	1,000	0,547
2. Magnitude and duration of annual extreme water conditions	IHA13	0,000	0,000	0,048	-	0,000	0,000	0,000	-	-
	IHA14	0,000	0,000	0,256	-	0,000	0,000	0,000	0,000	-
	IHA15	0,270	0,109	0,343	0,000	0,000	0,000	0,000	0,743	-
	IHA16	0,886	0,602	0,859	0,000	0,833	0,000	0,000	0,325	0,875
	IHA17	0,735	0,716	0,379	0,000	0,433	0,000	0,000	0,313	0,142
	IHA18	0,753	0,869	0,062	0,088	0,401	0,212	0,433	0,843	0,719
	IHA19	0,826	0,998	0,045	0,115	0,421	0,135	0,608	0,812	0,866
	IHA20	0,812	0,981	0,034	0,131	0,532	0,072	0,618	0,786	0,901
	IHA21	0,851	0,910	0,033	0,065	0,756	0,030	0,452	0,906	0,999
	IHA22	0,885	0,965	0,042	0,067	0,774	0,016	0,354	0,891	0,994
	IHA23	0,013	0,023	0,583	0,188	0,038	0,023	0,008	0,279	0,510
	IHA24	0,275	0,115	0,022	0,000	0,000	0,000	0,000	0,303	
3. Timing of annual extreme water conditions	IHA25	0,208	0,309	0,280	0,010	0,173	0,005	0,033	0,448	0,083
	IHA26	0,803	0,841	0,437	0,591	0,936	0,423	0,674	0,579	0,790
4. Frequency and duration of high/low pulses	IHA27	0,616	0,965	0,032	0,000	0,000	0,000	0,000	0,891	-
	IHA28	0,923	0,714	0,056	0,000	0,000	0,000	0,000	1,000	-
	IHA29	0,365	0,957	0,159	0,365	0,275	0,057	0,211	0,461	0,350
	IHA30	0,593	0,795	0,122	0,873	0,156	0,827	0,642	0,387	0,221
5. Rate and frequency of water condition changes	IHA31	0,303	0,989	0,155	0,782	0,236	0,041	0,076	0,308	0,138
	IHA32	0,336	0,993	0,094	0,531	0,276	0,056	0,178	0,367	0,193
	IHA33	0,993	0,884	0,043	0,087	0,913	0,003	0,049	0,953	0,695

Low alteration: mRA > 0,67; Moderate alteration: 0,67 > mRA > 0,33; High alteration: mRA < 0,33

Table IV. Average of the ratios of alteration (mRA) per IHA group for each case study.

IHA Group	Regime characteristics	Case studies								
		1	2	3	4	5	6	7	8	9
1. Magnitude of monthly water conditions	Magnitude/Timing	0,800	0,785	0,220	0,162	0,453	0,000	0,045	0,603	0,400
2. Magnitude and duration of annual extreme water conditions	Magnitude/Duration	0,526	0,524	0,226	0,065	0,349	0,041	0,206	0,564	0,751
3. Timing of annual extreme water conditions	Timing	0,506	0,575	0,358	0,301	0,554	0,214	0,353	0,513	0,437
4. Frequency and duration of high/low pulses	Magnitude/Frequency/Duration	0,624	0,858	0,092	0,309	0,108	0,221	0,213	0,685	0,286
5. Rate and frequency of water condition changes	Frequency/Rate of change	0,544	0,955	0,097	0,467	0,475	0,033	0,101	0,542	0,342

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