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## **An indicator to characterize hydrological alteration due to hydropeaking**

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# **An indicator to characterize hydrological alteration due to hydropeaking**

## Abstract

Hydropeaking by hydroelectric facilities generates sudden changes in river flows and can affect the composition, abundance and structure of fish and invertebrate populations over long distances. To assess the level of hydrological alteration, as a factor of risk of biological impacts, a synthetic indicator was developed. Based on the analysis of 97 hydrometric stations and 1 575 years of unaltered flow data, rates of change in flow were calculated. Formulas representing the fastest natural variations, depending on the mean stream flow, the type of variation (increase or decrease) and the range of variation were established. Based on the analysis of 80 hydrometric stations and 491 years of flow data affected by hydropeaking, a method was developed to identify hydropeaks, essentially defined as variations with a rate of change greater than the maximum natural value computed using the formulas. A synthetic indicator differentiating five levels of hydrological alteration was developed using linear discriminant analysis based on five parameters characterizing hydropeaking regimes. Examples show that this indicator is sensitive to changes in the management of hydroelectric facilities and provides information on the spatial and temporal evolutions in hydropeaking regimes, including the progressive attenuation during downstream propagation.

Keywords: Hydropeaking, Hydrological alteration, Indicator, Rate of change

## **Introduction**

The different components of flow regime, i.e. intensity, frequency, duration, timing and rate of change, are important determinants in the functioning of aquatic ecosystems (Richter *et al.*, 1996, 1997; Poff *et al.*, 1997; Bunn and Arthington, 2002).

Hydropeaking operation results in short-term changes in river flows occurring downstream of hydroelectric facilities, due to the turning on and off of turbines, a consequence of varying electricity generation and fluctuation in demand in the electricity market (Moog, 1993; Sauterleute and Charmasson, 2014). This leads to displacement of water volumes on various time scales (daily, weekly or even seasonally depending on the storage capacity of the facilities) and is likely to affect several components of stream hydrology. Hydropower is currently being developed in view of increasing renewable energies and reducing CO<sub>2</sub> emissions (Zarlf *et al.*, 2015). In addition, the development of wind and photovoltaic sources, which are intermittent and random sources of production, increases the need for other flexible sources, such as hydropeaking, to compensate for imbalances in production (Berga, 2016; Ashraf *et al.*, 2018; Schleiss, 2019).

Since the 1980s, the ecological impacts of hydropeaking have been the subject of much research, reviewed notably by Cushman (1985), Moog (1993), Valentin (1997), Baumann and Klaus (2003), Murchie *et al.* (2008), Hauer *et al.* (2017), Bejarano *et al.* (2017) and Hayes *et al.* (2019). Concerning fish populations, impacts often lead to a reduction in species richness and biomass, and a change in age structure, notably as a result of (1) failure of spawning due to dewatering or entrainment of roe, (2) mortalities of fry or even juveniles and adults due to trapping-stranding in areas rapidly dewatered or disconnected during the decrease in flow, (3) downstream entrainment and fry mortalities by forced drift during flow increases, and (4) slower growth.

In ecological impact studies, characterization of hydropeaks is often limited to the collection of basic information about powerplants, i.e. the minimum and maximum turbine throughput, which determines the amplitude of the variations. Studies more rarely relate biological impact with the actual hydrological parameters of the hydropeaks (frequency of peaks, base flows, maximum flows, amplitudes and rates of change) and their consequences on hydromorphological parameters and habitats. However, understanding these impacts and defining effective mitigation measures can be achieved only through detailed characterization of the hydromorphological alterations and then by looking for causal relationships with the observed biological effects (Zimmerman *et al.*, 2010; Bevelhimer *et al.*, 2015). In addition, the European Water Framework Directive (2000/60/CE) stipulates that a review of the impacts of human activity on the status of surface water should be undertaken every six years, with an estimation and identification of the impacts of significant water-flow regulation, including water transfer and diversion, on overall flow characteristics and water balances (article 5 and annex II). Therefore, whether for ecological impact studies or monitoring programs, a method for detailed characterization of hydropeaks and objective quantification of hydrological alteration are needed.

Among existing methods and indicators to assess alterations of flow regime, the IHA-RVA (Richter *et al.*, 1996, 1997, 1998; Shiau and Wu, 2004; Mathews and Richter, 2007; The Nature Conservancy, 2009; Gao *et al.*, 2009), DHRAM (Black *et al.*, 2000, 2005), HIP (Olden and Poff, 2003; Henriksen, 2006) and IAHRIS (Martinez *et al.*, 2008; Martinez Santa-Maria and Fernandez Yuste, 2010) methods do not enable proper characterization of hydropeaking alterations given that they are based on the examination of daily flow records, while the typical time-scale of hydropeaks is of the order of a few hours. Since the 2000s, numerous studies have been carried out to

characterize sub-daily flow variations and quantify the alterations due to hydropeaking (Baker *et al.*, 2004; Zolezzi *et al.*, 2009; Zimmerman *et al.*, 2010; Meile *et al.*, 2011; Zolezzi *et al.*, 2011; Sauterleute and Charmanson, 2014; Bevelhimer *et al.*, 2015; Carolli *et al.*, 2015; Alonso *et al.*, 2017; Bejarano *et al.*, 2017; Perez Ciria *et al.*, 2019). However, the basic approach of most of these methods is to measure, on each site, the differences between the influenced hydrology and the natural hydrology measured either upstream or prior to the construction of hydroelectric facilities (Zolezzi *et al.*, 2009; Zimmerman *et al.*, 2010; Meile *et al.*, 2011; Bevelhimer *et al.*, 2015; Alonso *et al.*, 2017; Bejarano *et al.*, 2017; Perez Ciria *et al.*, 2019). This restricts their applicability due to the scarcity of old data and of hydrometric stations on rivers with natural hydrology nowadays, as noted by Carolli *et al.* (2015) in Italy, Switzerland and Norway and also observed in France. With the exception of the methods proposed by Carolli *et al.* (2015) and Bejarano *et al.* (2017), other methods propose numerous metrics to describe hydrologic alterations, but no indicator capable of synthesizing the level of alteration into a unique score or rank, as expected for large-scale monitoring programs. The methods proposed by Zolezzi *et al.* (2011) and Sauterleute and Charmanson (2014) are the only ones that aim to precisely detect and characterize each hydropeak in hydrograph data, given that this information is essential in analyzing the consequences of flow variations for hydromorphological parameters and habitat conditions, and in establishing links with biological monitoring. These two methods involve selecting criteria on a case-by-case basis by the operator and do not distinguish between natural hydrological events and hydropeaks. This distinction is not useful where hydrology is fully controlled by the hydropower management system (e.g. immediately downstream of dams with high storage capacity), but becomes important

where there is a mix between natural and influenced regimes (e.g. downstream of dams with low storage capacity or far downstream of dams).

Based on the analysis of a large amount of hydrological data on French rivers, this paper presents a method to achieve the following objectives:

- (1) detect hydropeaks by distinguishing them from natural events, without the need for a separate natural reference site
- (2) provide a detailed characterization of each peak,
- (3) provide an indicator that synthesizes the level of hydrological alteration caused by hydropeaking, in terms of the risks of biological impact,
- (4) provide an indicator sensitive to spatial and temporal changes in the management of hydroelectric facilities and to the progressive attenuation of hydropeaks during downstream propagation,
- (5) provide an indicator with a simple, automatic procedure that can be transferred to stakeholders and requiring only easily accessible information, and that can be used for time-series data with constant or variable time steps (with sufficiently short time steps to correctly characterize hydropeaks) and on various time scales (whole years or shorter periods).

### **Characterization of natural rates of change**

The development of the proposed method first required the characterization of rates of change of natural flows, in order to establish a general criterion for distinguishing natural events and hydropeaks.



## ***Method***

### *Data set*

The hydrological dataset was compiled in 2009 from the HYDRO databank (<http://www.hydro.eaufrance.fr/>) and EDF (hydroelectric company). Natural hydrology data were collected on rivers that are or could be affected by hydropeaking:

- from hydrometric stations located upstream of hydroelectric facilities and offering recent data, or located downstream, but with data prior to the construction of the facility,
- and from hydrometric stations located on water courses close to those affected by hydropeaking (tributaries) with similar hydrologic regimes.

A total of 97 hydrometric stations were selected, located primarily in mountain regions (Alps, Pyrenees, Massif Central, Jura, Vosges, Corsica; Figure 1). The natural or minimally altered hydrology was conditional on the absence of a dam with significant storage capacity upstream and was validated by a detailed visual examination of each hydrograph. Mean Flows (MF) at the hydrometric stations varied between approximately 1 and 189 m<sup>3</sup>/s (mean 20.5 m<sup>3</sup>/s, median 8.2 m<sup>3</sup>/s). A minimum of 10 and an average of 16 years of flow data were analyzed for each station, for a total of 1 575 years. Data with different time steps were used. The data extracted from the HYDRO databank were either variable time-step flows (QTVAR 5%<sup>1</sup>) or average daily flows (QMJ). The data from EDF were hourly flows (QH). Short time-step data (QTVAR 5% or QH) enabled an accurate assessment of rates of change. The use of

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<sup>1</sup> QTVAR 5%: data with variable time steps, composed of flow-date couples set up to maintain a maximum deviation of 5% of flow with respect to all registered flow-date couples. Consequently, the time step can vary between 1 minute and several hours.

average daily flows may have led to underestimating the rates of change of variations occurring in less than a few days. However, this was the only type of data available for the period prior to the construction of some hydroelectric facilities. Information on selected hydrometric stations with unaltered flow data are provided in the supplementary material (Table S1).

### *Analysis*

Increasing and decreasing rates of change of flow were assessed over eight variation ranges between 5% and 400% of MF, delimited by 9 flow thresholds expressed in percentage of MF (5%, 10%, 15%, 25%, 50%, 100%, 200%, 300% and 400%). Variations beyond 400% of MF were not taken into account because the maximum turbine capacities of almost all hydroelectric facilities in France do not exceed 400% of MF (Lauters, 1995). The analysis consisted in detecting crossings of flow thresholds. When two thresholds were crossed consecutively (upward or downward), this indicated that a change occurred over one of the defined ranges (Figure 2). In this case, the data on the variation range, the dates of the threshold crossings and the rate of change were extracted. Rates of change over low flow ranges (5%-10%, 10%-15% and 15%-25% of MF) were not assessed on some water courses where flows did not decrease naturally below these values. A rate of change was extracted regardless of whether the variation was strictly continuous or included phases of flow stability or of trend reversal. In this latter case, the calculated rates of change underestimated the effective instantaneous rates of change. However, the definition of eight variation ranges, with narrower amplitudes for low flows, limited the occurrence of underestimates. It was decided not to consider only strictly continuous flow variations because, with short time-step flow data, the variations frequently show phases of flow

stability or of trend reversal between two consecutive values, especially during slow decreases in flow.

### ***Results***

Figure 3 shows the characteristic values of the rate-of-change distribution for three hydrometric stations and illustrates the following findings:

- for a given hydrometric station and range of variation, rates of change of flow increases are higher than those of flow decreases,
- for a given hydrometric station, rates of change of increasing and decreasing flow are lower over low flow ranges than over high flow ranges,
- locations with higher MF had lower rates of change for both increasing and decreasing flows.

All results on rate-of-change statistics for increases and decreases in flow, for each variation range and each hydrometric station are provided in the supplementary material (Table S2).

### ***Formulas representing the fastest natural variations***

Results on natural rates of change have been used to establish formulas representing the fastest natural variations and then to detect variations with higher rates of change within flow data affected by hydropeaking. The fastest natural increase and decrease in flow were reconstructed between 15% and 400% of MF, based on the hydrometric stations showing the highest 90<sup>th</sup> percentile of rates of change, for each of the eight variation ranges and as a function of the MF of the water course (Figure 4; see

Courret, 2010 for detailed information). Decreases in flow were reproduced by an exponential function:

$$Q = 4 * e^{-dt^{0.75}} \text{ where} \quad (1)$$

$$d = \frac{1}{(8.266 \cdot 10^{-5} * MF^3 - 1.046 \cdot 10^{-2} * MF^2 + 0.576 * MF + 2.262)} \text{ for } 1 \leq MF < 50 \text{ m}^3/\text{s}$$

$$d = 6.560 \cdot 10^{-2} \text{ for } MF \geq 50 \text{ m}^3/\text{s}$$

Where Q is the flow in % of MF and t the time in hours.

Similarly, increases in flow were reproduced by an exponential function:

$$Q = 4 * e^{-it^{1.15}} \text{ where} \quad (2)$$

$$i = \frac{1}{(2.574 \cdot 10^{-5} * MF^3 + 3.394 \cdot 10^{-3} * MF^2 + 3.710 \cdot 10^{-2} * MF + 0.422)} \text{ for } 1 \leq MF < 50 \text{ m}^3/\text{s}$$

$$i = 7.153 \cdot 10^{-2} \text{ for } MF \geq 50 \text{ m}^3/\text{s}$$

For a given variation time t ( $t \geq 0$ ), equation (1) produces the flow value reached during a decrease starting from 400% of MF, and equation (2) produces the flow value from which an increase up to 400% of MF starts. The duration of any increase or decrease in flow, below 400% of MF, can be determined by the difference between the times corresponding to the start and end flows. These two equations can be extrapolated to flows of less than 15% of MF in that the corresponding rates of change are of the same order of magnitude as the highest values of the 90<sup>th</sup> percentile observed over the low flow ranges (5%-10%, 10%-15%).

## **Selection and characterization of hydropeaks**

### ***Method***

#### *Data set*

. A total of 80 hydrometric stations with variable and short time-step data (QTVAR 5%) were selected on streams downstream of hydroelectric facilities that generate hydropeaks (listed by Lauters, 1995). These hydrometric stations were located primarily in mountain regions (Figure 1). Mean Flows (MF) of the stations varied between approximately 1.2 and 384 m<sup>3</sup>/s (mean 50.9 m<sup>3</sup>/s, median 27.0 m<sup>3</sup>/s). Except in four hydrometric stations where the influence of hydropeaking was noticeable during only one or two years of data, a minimum of three and a median of seven years of flow data were analyzed for each station, for a total of 491 years. Information on selected hydrometric stations is provided in the supplementary material (Table S3).

#### *Step 1. Reconstitution of flow variations*

In short time-step data, flow variations are usually described by several successive measurements (Figure 5). A first step consists in identifying the flow increases and decreases by (1) determining a rate-of-change threshold value between two measurements beyond which the flow is considered to vary, and (2) aggregating the consecutive variations (Figure 5). The threshold value should be low enough to correctly detect the starts and ends of variations showing rates of change generally lower than the "core" of variations, in order to capture most of their amplitude. However, the threshold value should not be too low so as not to include phases with very slow changes, before and after the variations, which do not significantly contribute to their amplitude and, if included, would lower the rates of change. This issue arises in particular in determining the end of flow decreases. The rate-of-change threshold value

was set by examining two metrics, separately for flow increases and decreases, for rate-of-change threshold values between 0.1% and 10% of MF/h, for each hydrometric station affected by hydropeaking (Figure 6).

- The cumulative amplitude of detected variations divided by the sum of the amplitudes between each pair of measurements (Cum-Ampl in %).
- The average rate of change of detected variations, determined by dividing their cumulative amplitude by their cumulative duration (Av-Roc in % of MF/h).

A threshold value of  $\pm 1\%$  of MF/h, for flow increases and decreases respectively, was chosen as a good trade-off between capturing most of the amplitude of variations and obtaining representative rates of change.

#### *Step 2. Selection of hydropeak increases and decreases*

Among the identified flow increases and decreases, the second step consists in selecting the ones corresponding to hydropeaks. This selection is based on three criteria:

- a rate of change higher than the value computed by equation (1) for flow decreases and equation (2) for flow increases, depending on the start and end flows of variations and on the stream MF,
- an amplitude  $\geq 10\%$  of MF and a ratio [amplitude / base flow]  $\geq 20\%$ . This double condition was set to avoid the selection of small variations caused by irregularities of the station sensors, and those *a priori* of little consequence for the hydromorphological parameters,
- a maximum flow less than a definitive cut-off value set by the operator for each hydrometric station (see Table S3 in the supplementary material). This third condition was set to avoid the selection of variations that clearly exceed the

maximum turbine capacities of upstream hydroelectric facilities and is intended as a back-up for the first two criteria. The cut-off value is at most equal to 400% of MF, given the scope of equations (1) and (2). In addition to the knowledge of the maximum turbine capacities, a detailed visual examination of the hydrographs may be useful to set the cut-off value.

### *Step 3. Concatenation of consecutive hydropeaks*

In short time-step data, hydropeaks may be interrupted by short phases of flow stability between two measurements, of real or artificial origin. This interrupts the reconstitution of variations during the first step. This may be the case at hydrometric stations located near hydroelectric facilities, with step changes between successive operating levels of a turbine or between different turbines. This may lead to an overestimation of the number of hydropeaks and could skew the statistics on their parameters (base flows, maximum flows, amplitude, rates of change, etc.). Therefore, among the selected hydropeaks, a third step consists in concatenating consecutive hydropeaks that can be considered part of a single variation. The concatenation of two successive flow increases is carried out only if the following three conditions are met:

- the base flow of the second increase is not less than the maximum flow of the first increase, minus 10% of the MF,
- the maximum flow of the second increase is more than 10% higher than the maximum flow of the first increase,
- the global rate of change between the base flow of the first increase and the maximum flow of the second increase exceeds the value computed by equation (2).

Similarly, the concatenation of two successive flow decreases is carried out only if the

following three conditions are met:

- the maximum flow of the second decrease is not greater than the base flow of the first decrease, plus 10% of the MF,
- the base flow of the second decrease is greater than 10% less than the base flow of the first decrease,
- the global rate of change between the maximum flow of the first decrease and the base flow of the second decrease exceeds the value computed by equation (1).

### *Characterization of hydropeaks*

Each flow increase and decrease identified as a hydropeak is registered and characterized by its base and maximum flows, and its start and end dates. Then, its amplitude, duration of variation and mean rate of change are calculated, as well as several ratios, namely [amplitude / base flow], [maximum flow / base flow] and [rate of change / maximal natural rate of change] (Figure 7). Each annual hydropeaking regime is characterized by 114 parameters, namely the number of increases and decreases and eight statistical values (minimum, mean, maximum, 10<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup> and 90<sup>th</sup> percentiles) of each of the seven descriptors (base flow, maximum flow, amplitude, rates of change, ratios [maximum flow / base flow], [amplitude / base flow] and [rate of change / maximum natural rate of change]) for both increases and decreases.

### ***Results***

The method developed to select hydropeaks was first tested on the natural hydrology dataset (97 hydrometric stations and 1575 years) to verify that the criteria avoided the selection of natural increases or decreases (distinguishing hydropeaks from natural events being one of the objectives). The cumulative number of selected flow



increases and decreases was zero for approximately half of the years, less than four for approximately 90% of the years and less than 14 for 99% of the years. The maximum number was 20. Consequently, the hydrology of a station is considered to be affected by hydropeaking when the cumulative number of selected flow increases and decreases is greater than 20 per year.

Globally, the cumulative numbers of hydropeak increases and decreases vary from a few dozen to more than 3000, with a median value of 295 (Figure 8). The 10<sup>th</sup> percentile values of base flows can be very low, close to the minimum values specified in licenses (2.5% of MF before 2014 in France, 5% of MF since), or conversely can exceed 70% of MF. The 90<sup>th</sup> percentile values of amplitudes vary from approximately 20% to 260% of MF, with a median value of 73%. Similarly, the 90<sup>th</sup> percentile values of rates of change of decreases are less than 11% of MF/h for approximately 25% of years, but also exceed 38% of MF/h for another 25% of years. These results highlight the large variability in the characteristics of hydropeaking regimes due to the diversity of hydrological regimes (glacial, nival, pluvial) in dammed rivers in France, the characteristics of hydroelectric facilities (type of facility, storage capacity, turbine characteristics), licence specifications (minimum flow, possible limitations on maximum flow or on rates of change, etc.), other possible water uses (support of summer low flows, minimum water level of reservoirs for recreational activities, etc.) and distances between the hydroelectric facility (the source of hydropeaks) and the hydrometric station. Two types of hydroelectric facility can be distinguished.

- Facilities where water is turbined at the foot of the reservoir, or nearby downstream. The river hydrology is then fully controlled by the management of the facility, except during floods that cause the dam to spill (Figure 9a1).

Minimum base flows of hydropeaks are equal to the minimum flow delivered at

the dam and operating levels of turbines appear clearly (Figure 9a2). Such facilities, often organized in series, have been developed in low and mid-altitude mountain regions of France, for instance on the Dordogne, Maronne, Sioule, Loire, Lot and Truyère Rivers in the Massif Central. These facilities generally operate with medium-sized heads.

- Facilities operating with high heads, the water coming from one or several reservoirs located far away and at high altitude. Drainage basins between water drawoffs and powerplants can be large. Hydropeaks occur in addition to more or less reconstituted hydrological regimes (Figure 9b1). The characteristics of hydropeaks are diverse, with base flows that can be high (Figure 9b2). Such facilities have been developed essentially in the Pyrenees and Alps, i.e. in high-altitude mountain regions.

During downstream propagation, in the absence of hydroelectric facilities on the river stretch, rates of change tend to fall whereas base flows and amplitudes (in % of MF) tend to rise due to inputs from tributaries. Consequently, the numbers of selected hydropeaks decline either because their rates of change become less than the natural maximum value computed by equation (1) or (2), or because their amplitudes become less than 10% of the MF or 20% of their base flow, as illustrated by the example of the Garonne river in 2010 (Figure 10). Between the Saint-Béat and Saint-Gaudens hydrometric stations located 45.4 kilometres apart, the cumulative number of selected increases and decreases declined from 2868 to 1004. Concerning decreases, the 25<sup>th</sup> percentile of base flows rose from 39% to 53% of MF, the 75<sup>th</sup> percentile of amplitudes declined from 68% to 43% of MF and the 75<sup>th</sup> percentile of rates of changes declined from 56% to 21% of MF/h. Given that maximum natural rates of change of increases are higher than those of decreases (Figure 4), the method tends to select more decreases

than increases (Figure 9b1 and Figure 10a). This occurs particularly at hydrometric stations located far downstream from hydroelectric facilities where rates of changes are attenuated.

## **Development of a synthetic indicator of hydrologic alteration due to hydropeaking**

### ***Method***

An indicator was proposed differentiating between 5 levels of alteration, namely (1) noticeable, (2) moderate, (3) medium, (4) severe and (5) very severe. The definition of the indicator was based on the parameters characterizing hydropeaking regimes on an annual time scale (calendar year) for the 80 hydrometric stations and 491 years of affected flow data.

In order to calibrate an automatic procedure, the level of hydrological disturbance for each year was first assessed by the three authors of the study. A ranking by expertise was preferred to statistical methods of ascending or descending ranking of the data, which did not enable grouping of hydropeaking regimes identified as the most severe due to high numbers of hydropeaks, very low base flows and/or very high amplitudes and rates of change. The ranking by the authors was based on a review of the annual hydrograph and two plots displaying the number, base flows, amplitudes and rates of change of hydropeak increases and decreases respectively (as in Figure 9). The assessment of the hydrological alteration level was based on knowledge on the biological impacts of hydropeaking regimes (the higher the number of hydropeaks, the higher their amplitudes, rates of change and maximum flows, and the lower their base flows, the higher the risk of biological impacts) (Cushman, 1985; Moog, 1993; Valentin, 1997; Baumann and Klauss, 2003; Murchie *et al.*, 2008; Hauer *et al.*, 2017; Bejarano *et al.*, 2017; and Hayes *et al.*, 2019).

Linear discriminant analysis was then fitted to the ranking by expertise (Statgraphics plus 5.0 software) by selecting a limited number of uncorrelated parameters among the 114 characterizing hydropeaking regimes (all parameters were divided by the stream MF; except the number of hydropeaks). The selection of the parameters was conducted iteratively, considering (1) that these parameters should take into account changes in all the characteristics of hydropeaking regimes (number of hydropeaks, base flows, maximum flows, amplitudes and rates of change) and (2) that the biological impacts are essentially caused by the most severe hydropeaks. In the end, five parameters were selected for the discriminant analysis:

- the cumulative number of hydropeak increases and decreases per year (N),
- the 10<sup>th</sup> percentile of base flows of decreases (DQbase10),
- the 90<sup>th</sup> percentile of amplitudes of decreases (DAmpli90),
- the 90<sup>th</sup> percentile of rates of change of decreases (DRoC90),
- the 90<sup>th</sup> percentile of rates of change of increases (IRoC90).

The selection of the 10<sup>th</sup> percentile of base flows and the 90<sup>th</sup> percentile of amplitudes and rates of change targeted the most severe hydropeaks to assess the level of disturbance, while avoiding minimum and maximum values resulting from only one event. Concerning base flows and amplitudes, only parameters describing the decreases were taken into account, because those describing the increases were highly correlated with them. Parameters relating to maximum flows were not taken into account because they were redundant with those relating to base flows and amplitudes. Concerning rates of change, two parameters describing decreases and increases respectively were selected to account for changes in the two types of variation that can be uncorrelated (e.g. falls in rates of change of decreases to reduce the stranding and trapping of fish, without

modifying rates of change of increases). When the number of increases is less than 10, the value of IRoc90 is set to zero, given that the rates of change of increases have little influence on the level of hydrological alteration. Reclassification performance by the discriminant analysis has been improved with transformation formulas producing narrower and similar ranges of values for the different selected parameters (Table 1). Discriminant analysis produces a function for each class in the form of a linear combination of parameters. Each year is assigned to the class whose function produces the maximum score. All information about the functions is included in the Excel file “Hydropeaking-Indicator-2020-06” supplied in the supplementary material.

### ***Results***

When fitted for the entire dataset, the linear discriminant analysis correctly assigned 427 of the 491 years, i.e. almost 87% (Table 2). The years differently assigned were all positioned in classes just above or just below the class set in the ranking by expertise. Reclassification performance was also tested by successively removing each of the 80 hydrometric stations from the calibration data set and examining the results for the station (leave-one-out cross-validation). Under these conditions, the linear discriminant analysis correctly assigned 414 of the 491 years, i.e. 84.3% (Table 3). Once again, the years differently assigned were all positioned in classes just above or just below the class set in the ranking by expertise. Finally, among the 491 years, 91, 126, 122, 88 and 64 years were assigned to classes 1 to 5 respectively (Table 2).

From one alteration class to the next, the changes in the values of the parameters selected for the linear discriminant analysis complied, on the whole, with the objective (Figure 11 a-e), i.e. from Class 1 to Class 5, the number of hydropeaks, amplitudes and rates of change increased, base flows decreased. However, on examining the parameters independently from each other, the distribution of values of a given parameter may be

similar for two classes. Generally speaking, the scores of the linear discriminant analysis increased from Class 1 to Class 5 (Figure 11f). There was virtually no overlapping of value ranges between Classes 1 and 2. Between Classes 2 and 3, 3 and 4, and 4 and 5, there was some overlapping for approximately 25% of the values. The classification can be refined by dividing Classes 2, 3 and 4 into two subclasses each (2-, 2+, 3-, 3+, 4-, 4+), depending on whether the second highest score produced by the analysis was for the higher or lower class. The indicator was developed using annual data for hydropeaking management (calendar year). However, the indicator can be used for shorter (seasons, biological periods, etc.) or longer (several years) periods. For the linear discriminant analysis, it is sufficient to calculate the equivalent annual number of hydropeaks. No modifications are required for the four other parameters.

Concerning the example of the Garonne River in 2010 (Figure 10), the level of hydrological alteration was Class 5 at the Saint-Béat hydrometric station due notably to a high number of hydropeaks, and then Class 4+ at Chaum station and 4- at Saint-Gaudens station, i.e. the progressive attenuation of the hydropeaks downstream is detected by the indicator. The Lot River at Entraygues hydrometric station in 2010 (Figure 9a1 and a2) is another example of very severe alteration (Class 5), with fewer hydropeaks than on the Garonne River, but with low base flows and high amplitudes. The Aude River at Belvianes hydrometric station in 2010 (Figure 9b1 and b2) is an example of a medium alteration (Class 3).

Figure 12 shows the data for the indicator from the Argentat hydrometric station on the Dordogne River from 1997 to 2019, for the period from 15 March to 15 June. That period corresponds to the emergence and the first few weeks of life for salmonid alevins, a time when they are particularly sensitive to hydropeaking. Following

observations on the biological impacts of hydropeaking, efforts to mitigate the effects were progressively implemented starting in 2004 (Anonymous, 2012, 2019).

During the pre-intervention period (1997 to 2003), the cumulative number of hydropeak increases and decreases varied between 25 and almost 110 depending on the year, minimum base flows were less than 20% of MF, the 75th percentile of amplitudes were above 100% of MF most years and the 75th percentile of rates of change of decreases in flow were above 20% of MF/h most years, with maximum values above 40% of MF/h (except 1997). Consequently, according to the indicator, the level of hydrological alteration was Class 3 or Class 4, depending on the year (with a score of approximately 300 to 400).

Starting in 2004, the minimum base flows were increased above 30% of MF and the rates of change of decreases in flow were reduced, with the maximum values falling below 40% of MF/h (except in 2007 and 2013) and the 75th percentile falling below 20% of MF/h (except in 2013, a situation caused by a single hydropeak). Starting in 2005, the amplitudes were reduced for the first time, the 75th percentile falling below 90% of MF. A second reduction in the amplitude of hydropeaks occurred in 2008, with the maximum values falling below 120% of MF. Consequently, from 2004 to 2010, the level of hydrological alteration fell to Class 3 or Class 2, with the score falling to below 300 starting in 2005 (the year 2008 was exceptional with abundant flows in the spring).

Starting in 2011, the cumulative numbers of hydropeak increases and decreases were sharply reduced to less than ten, compared to an average of 50 from 1997 to 2000, the minimum base flows were increased to greater than 60% of MF (50% in 2019), and a third reduction in the amplitude of hydropeaks occurred with the maximum values falling below 50% of MF (except in 2011) and the 75th percentile falling below 45% of MF. The alteration level fell to Class 1 (with a score between 90 and 150).

In 2018 and 2019, the cumulative number of hydropeak increases and decreases dropped to three or fewer, so that the number of equivalent annual hydropeaks dropped to below 20. As a result, the Dordogne River at Argentat is no longer considered to be particularly affected by hydropeaking over the period from 15 March to 15 June (Class 0).

## **Discussion**

The overall objective of the study was to provide a synthetic indicator of the hydrological alteration, in terms of the risks of biological impact, caused by hydropeaking, sensitive to spatial and temporal changes in the management of hydroelectric facilities.

A method to detect hydropeaks in hydrograph data was developed by analysing 491 years of data from 80 hydrometric stations on rivers affected by hydropeaking. This method simply requires the MF data of the river, an element of information that is easily obtainable, and the maximum turbine capacities of the upstream hydroelectric facilities in order to set the maximum flow for the analysis. Hydropeak increases and decreases are defined as variations with a rate of change greater than the maximum natural values, with in addition conditions concerning the amplitude and the maximum flow of the variations designed to systematically exclude any minor variations due to imprecise sensor operation or those with theoretically minor hydromorphological consequences, as well as floods exceeding the maximum turbine throughput of the hydroelectric facilities. Based on the analysis of 97 hydrometric stations and 1 575 years of unaltered flow data, the results concerning the rates of change for increases and decreases in natural flows were used to produce a general reference for the maximum rates of change of natural flows (equation (1) and (2)). This eliminates the need for a reference of natural hydrology for each case study, a factor that limits the applicability of most



methods currently available (Zolezzi *et al.*, 2009; Zimmerman *et al.*, 2010; Meile *et al.*, 2011; Bevelhimer *et al.*, 2015; Alonso *et al.*, 2017; Bejarano *et al.*, 2017; Perez Ciria *et al.*, 2019). The method adopts a conservative approach concerning the selection of hydropeaks, in that equations (1) and (2) were developed using the highest values of the 90<sup>th</sup> percentile of rates of change for each of the flow variation ranges between 5% and 400% of MF. The proposed selection method for hydropeaks has a number of points in common with that proposed by Sauterleute and Charmanson (2014). However, the method presented here does not call on the operator to set the value of the rate-of-change criterion and it includes the amplitude and maximum flow conditions. Method applicability in terms of the size of rivers and flow ranges is determined by equations (1) and (2), i.e. the method may be used for water courses with a MF greater than 1 m<sup>3</sup>/s and for flow variations up to 400% of MF. These criteria cover virtually all water courses affected by hydropeaking in France (Lauters, 1995), meaning that they do not represent a limit to the use of the method. The method provides a detailed description of each selected hydropeak increase and decrease (114 parameters). These data can be used in case studies on the ecological impacts of hydropeaks, e.g. via analysis of the consequences for the hydromorphological parameters of rivers and for habitats, and efforts to determine the links between hydropeaking and the observed biological effects.

An indicator was developed to provide a synthetic view of the degree of hydrological alterations caused by hydropeaking, organised in five classes. The linear discriminant analysis was fitted to an initial ranking established by the three authors of this study on the basis of their expert knowledge on the ecological impacts of hydropeaking. The five parameters selected for the discriminant analysis (cumulative number of hydropeak increases and decreases per year, 10<sup>th</sup> percentile of base flows of the decreases, 90<sup>th</sup> percentile of amplitudes of the decreases, 90<sup>th</sup> percentile of rates of

change of the decreases, 90<sup>th</sup> percentile of rates of change of the increases) are capable of taking into account the various characteristics and potential changes in hydropeaking regimes. These parameters are sufficient to produce reclassification results deemed satisfactory (84.3% of events correctly ranked [leave-one-out cross-validation] and no difference greater than one class). The classification can be refined by dividing classes 2, 3 and 4 into two subclasses each (2-, 2+, 3-, 3+, 4-, 4+). Changes in the maximum score produced by the discriminant analysis may also be of value in determining the effects of changes in the management of hydroelectric facilities that do not necessarily result in a change in class. The examples of method implementation demonstrate that the indicator is in fact sensitive to changes in the management of hydroelectric facilities and can provide information on temporal and spatial changes in hydropeaking regimes. In as much as the changes in the parameters characterizing the hydropeaks in the various alteration classes are consistent with the knowledge on the ecological impacts of hydropeaking (Figure 11), the hydrological indicator may be seen as indicative of the risks of biological impacts (but not directly an indicator of biological impacts because the vulnerability of habitat and species is not taken into account).

The procedure used to detect hydropeaks in hydrograph data, the production of tables presenting the characteristics of each hydropeak increase or decrease and the calculation of the indicator itself are all fully automated using a Visual Basic macro command in Excel. On a standard PC, the processing time for an annual series of flow data can vary from a few seconds to three or four minutes depending on the number of hydropeaks. Given that Excel is widely used software, the hydropeaking indicator can easily be made available to stakeholders. Flow data series with constant or variable time steps may be used. The Excel file and a user manual are supplied in the supplementary material. The indicator has already been used for several years by the Adour-Garonne

and the Rhône-Mediterranean-Corsica Water Agencies, the two regions in France most affected by hydropeaking. Results were included in the reviews of the impact of human activity on the status of surface water required by the European Water Framework Directive (2000/60/EC) and taken into account in the definition of the programmes of measures by helping to identify the most affected reaches (Baran 2018; Anonymous 2020).

The method to detect hydropeaks in hydrograph data and the development of the indicator required a number of arbitrary decisions by the authors, notably concerning the setting of threshold values for the hydropeak detection criteria, the ranking of hydrological alteration levels based on expert knowledge and the choice of the parameters used in the discriminant analysis. These decisions were justified whenever possible, but also depended on a degree of subjectivity on the part of the authors and are, consequently, debatable. However, decisions of this type are unavoidable and those made in developing this method are similar to those made in developing other existing hydrological indicators and methods (Carolli *et al.*, 2015; Bejarano *et al.*, 2017). One debatable aspect of this method is the ranking of the hydrological alteration levels for the 491 years in terms of the risk of biological impacts and based on the expert knowledge of the authors. Combining the data on the various parameters describing hydropeaking regimes in order to produce a single alteration class made it necessary to assign weights to the different parameters. A ranking based on expert knowledge was preferred, rather than statistical methods ranking the data in increasing or decreasing order, because it was not possible, using the latter, to group the various hydropeaking regimes thought to produce the greatest hydrological alterations for different reasons, namely high numbers of hydropeaks, very low base flows and/or amplitudes, and very high rates of change. The ranking based on expert knowledge was also selected because

it was impossible to obtain a consistent and sufficiently large data set on the ecological impacts of hydropeaking regimes and to which the indicator could be directly fitted. The small number of people who established the method (i.e., the authors) constitutes a limitation of this work. A next step could be to re-evaluate the method and possibly recalibrate it based on trials with a larger number of users.

With respect to the indicators developed by Carolli *et al.* (2015) and Bejarano *et al.* (2017), the indicator presented here has two main differences, namely (1) a step to analyse flow variations in order to differentiate between hydropeaks and natural events (sufficiently attenuated hydropeaks may reacquire the characteristics of natural events) and (2) explicit inclusion of the number of hydropeaks, which can be a decisive factor for biological impacts.

The proposed indicator nonetheless has a number of limits and it may, in the future, be improved, expanded and/or used in conjunction with other methods. Currently, selection of variations deemed to be hydropeaks is based essentially on the rate of change when it exceeds the maximum natural value calculated by equations (1) and (2), respectively for decreases and increases, and as a function of the river MF and of the variation range of the flow in question. The two equations were developed for France as a whole. One potential improvement would be to regionalize or contextualize the selection criterion for rates of change, following the lead of a number of existing studies on other hydrological parameters, for example Sanborn and Bledsoe (2006) and Snelder *et al.* (2009).

The link between the levels of hydrological alteration due to hydropeaking and the resulting biological impacts depends on the morphology of the river, the species in question and the correspondence between the different phases in their life cycle and the hydropeaking regime. Following recommendations by Stewardson and Gippel (2003)

and Poff *et al.* (2010), the indicator could be expanded to include information on the river hydromorphology, for example the relations between flow and wetted area, as well as between flow and water levels. This information could be acquired from measurements in the field or from large-scale modelling. The amplitudes of each hydropeak increase or decrease could be translated into changes in wetted area. The flow rates of change ( $\text{m}^3/\text{s}/\text{h}$ ) could be translated into water-level rates of change ( $\text{cm}/\text{h}$ ). This information could improve the selection of hydropeaks and the interpretation of their severity, drawing for example on the classifications proposed by Tonolla *et al.* (2017). Such development has been undertaken in the Rhône-Mediterranean-Corsica territory in view of prioritizing actions on the restoration of the status of water bodies (Baran 2018).

Finally, the indicator assesses the level of hydrological alteration exclusively on the basis of the hydropeak characteristics. Other aspects of hydrological alteration caused by hydroelectric facilities are not taken into account, notably changes in the frequency and timing of flows (flood-control measures, displacement of water volumes on a seasonal basis, worsening or support of low-flow conditions, etc.). It would be worthwhile to couple the proposed indicator with existing methods, such as IHA-RVA, DHRAM, HIP and IAHRIS (see the bibliographical references in the introduction), in order to develop an indicator capable of providing information on all aspects of the hydrological alterations caused by hydroelectric facilities. Thermopeaking can also be an issue to consider (Zolezzi *et al.* 2011; Vanzo *et al.* 2016).

In the future, it is vitally important to pursue analysis addressing both the detailed characterization of hydropeaking regimes and their biological impacts in order to check the relevance of the indicator and, where possible, improve it. That will require long data series on the status of fish and invertebrate communities, with more or less

severe hydropeaking regimes. Interesting relationships would appear to exist between the recruitment of salmonid alevins and the severity of hydropeaking regimes during the period of their emergence and their first few weeks of life on several rivers, for example on the Lez River (Baran *et al.* 2012), the Dordogne River and the Maronne River. This work still needs to be pursued.

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Parameter	Range of values			Transformed parameter	Range of values		
	Min	Mean	Max		Min	Mean	Max
<b>N</b>	21	467	3659	<b>Log(N)</b>	1.32	2.47	3.56
<b>DQbase10</b>	0.02	0.243	0.77	<b>Log(1+10/DQbase10)</b>	2.70	1.68	1.15
<b>DAmpli90</b>	0.218	0.838	2.58	<b>Log(1+10*DAmpli90)</b>	0.50	0.93	1.43
<b>DRoc90</b>	0.029	0.329	6.801	<b>Log(1+5*DRoc90+IRoc90)</b>	0.06	0.43	1.63
<b>IRoc90</b>	0	0.736	21.22				

Table 1. Range of values of parameters selected in the discriminant analysis, transformation formulas and new ranges of values obtained. N: cumulative number of hydropeak increases and decreases per year; DQbase10: 10th percentile of base flows of decreases; DAmpli90: 90th percentile of amplitudes of decreases; DRoC90: 90th percentile of rates of change of decreases; IRoC90: 90th percentile of rates of change of increases.

Ranking by authors' expertise		Ranking by the linear discriminant analysis Number of years in each class				
Class	Number of years	1	2	3	4	5
1	90	83	7			
		92.2%	7.8%			
2	132	8	112	12		
		6.1%	84.8%	9.1%		
3	120		7	101	12	
			5.8%	84.2%	10.0%	
4	80			9	69	2
				11.3%	86.3%	2.5%
5	69				7	62
					10.1%	89.9%
<b>Total number of years in each class</b>						
		91	126	122	88	64
<b>Correct reclassification rate :</b>						<b>87.0%</b>

Table 2. Comparison between the ranking by author's expertise and the ranking by the linear discriminant analysis fitted for the entire dataset.

Ranking by authors' expertise		Ranking by the linear discriminant analysis Number of years in each class				
Class	Number of years	1	2	3	4	5
1	90	83	7			
		92.2%	7.8%			
2	132	9	111	12		
		6.8%	84.1%	9.1%		
3	120		9	100	11	
			7.5%	83.3%	9.2%	
4	80			14	62	4
				17.5%	77.5%	5.0%
5	69				11	58
					15.9%	84.1%
<b>Total number of years in each class</b>						
		92	127	126	84	62
<b>Correct reclassification rate :</b>						<b>84.3%</b>

Table 3. Comparison between the ranking by author's expertise and the ranking by the linear discriminant analysis fitted by successively removing each of the hydrometric stations from the calibration data set (leave-one-out cross-validation).

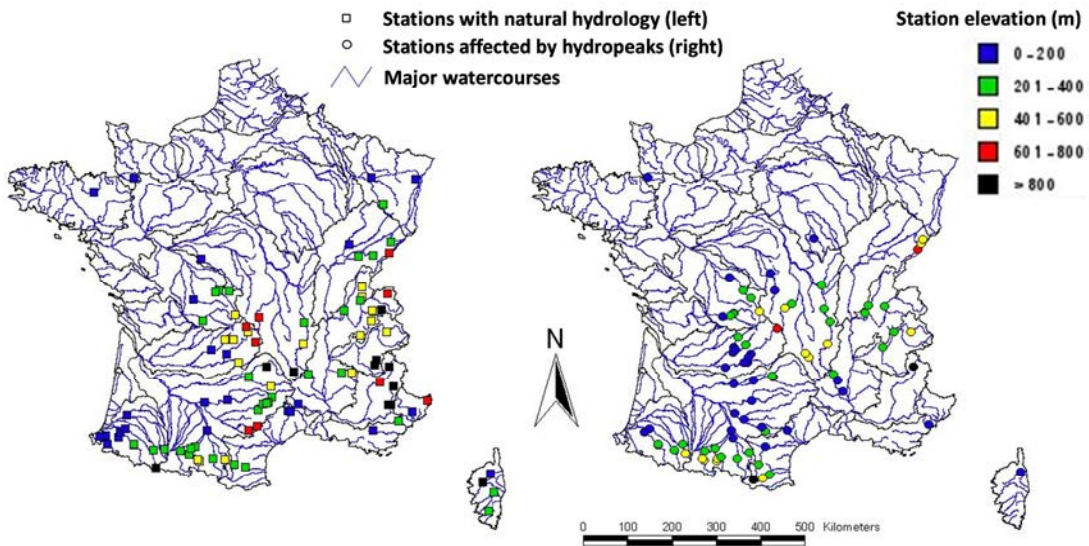


Figure 1. Location of selected hydrometric stations with natural hydrology (left) and affected by hydropeaks (right) in France.

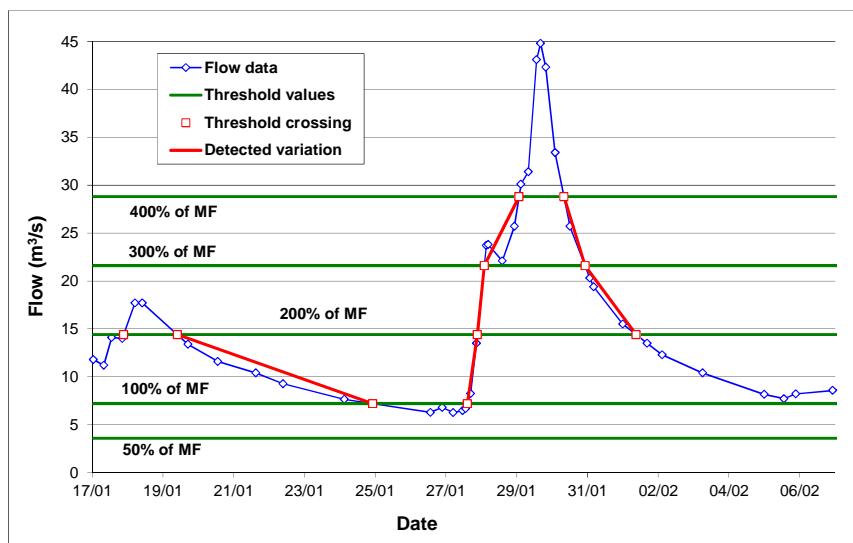


Figure 2. Illustration of the method for detecting flow variations between thresholds.

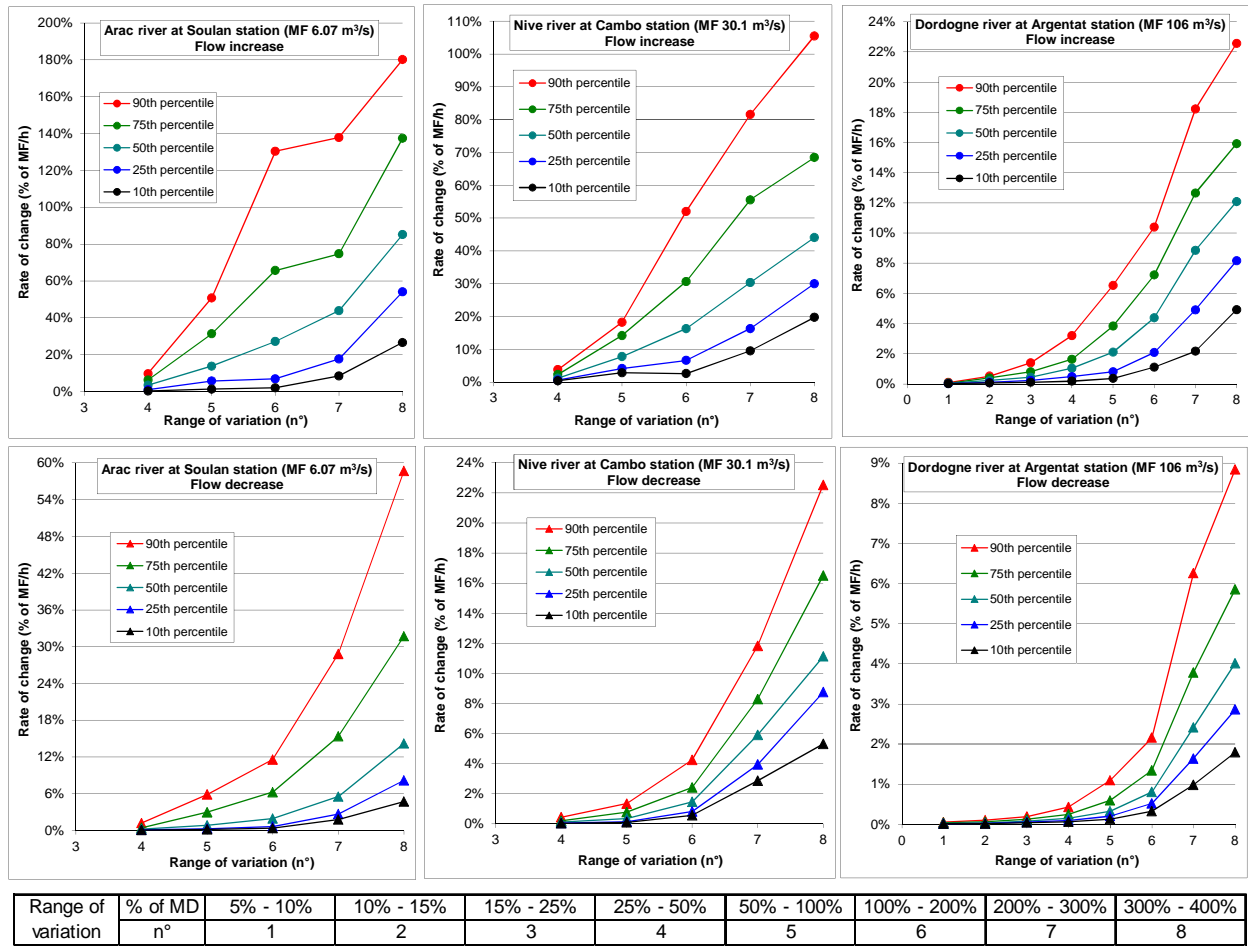


Figure 3. Characteristic values of rate-of-change distribution (in % of MF/h) for 3 hydrometric stations, according to the range of variation, for increases (top) and decreases (bottom) in flow.



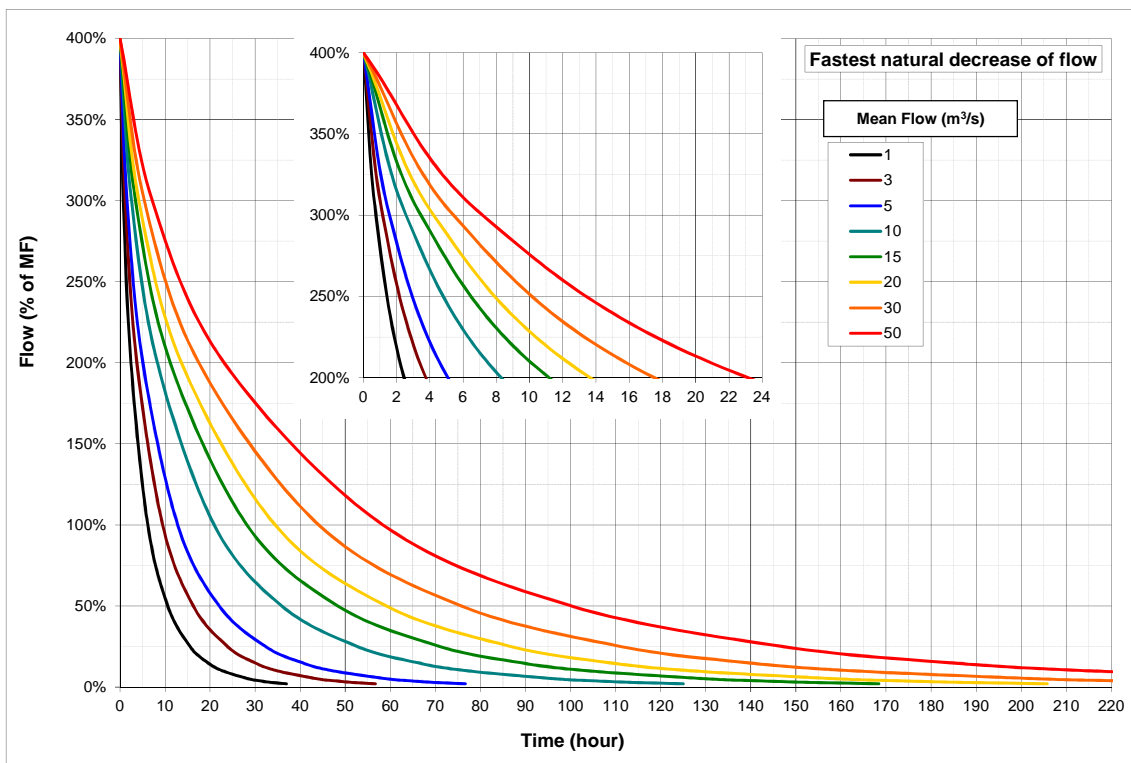
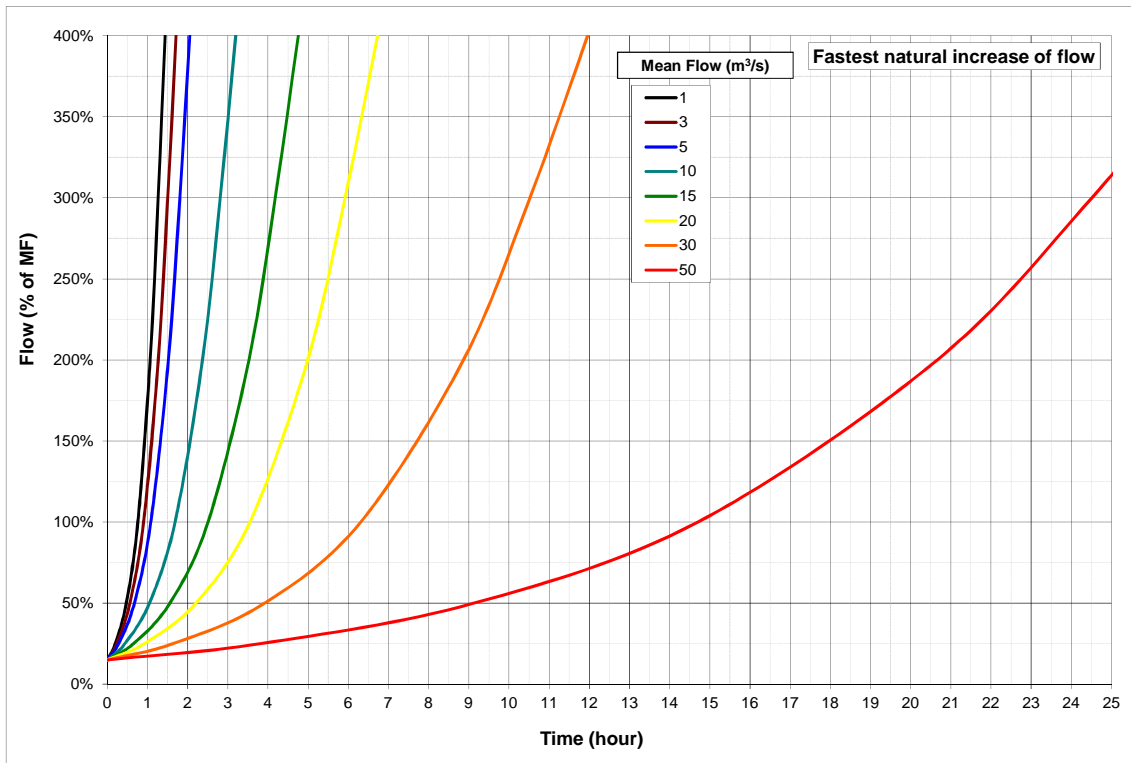


Figure 4. Fastest natural increase (top) and decrease (bottom) in flow, depending on the stream MF, using equations (2) and (1) respectively.

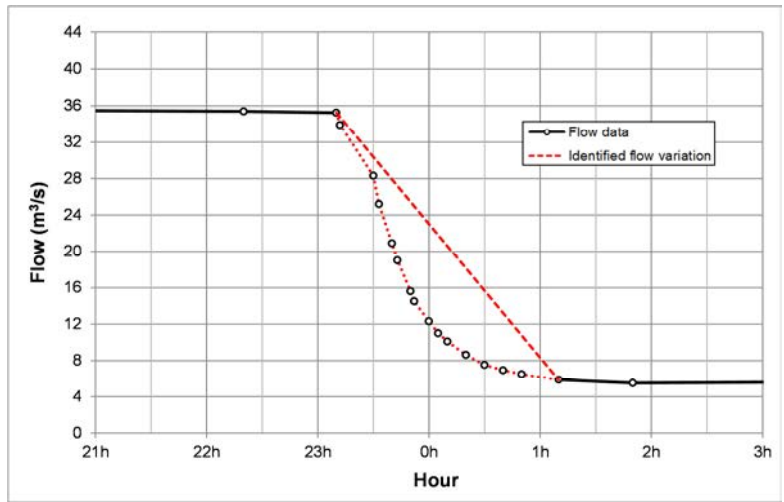


Figure 5. Illustration of the method for identifying the flow increases and decreases in variable and short time-step data. Dashed segments in flow data exceed or equal a rate of change of 1% of MF/h.

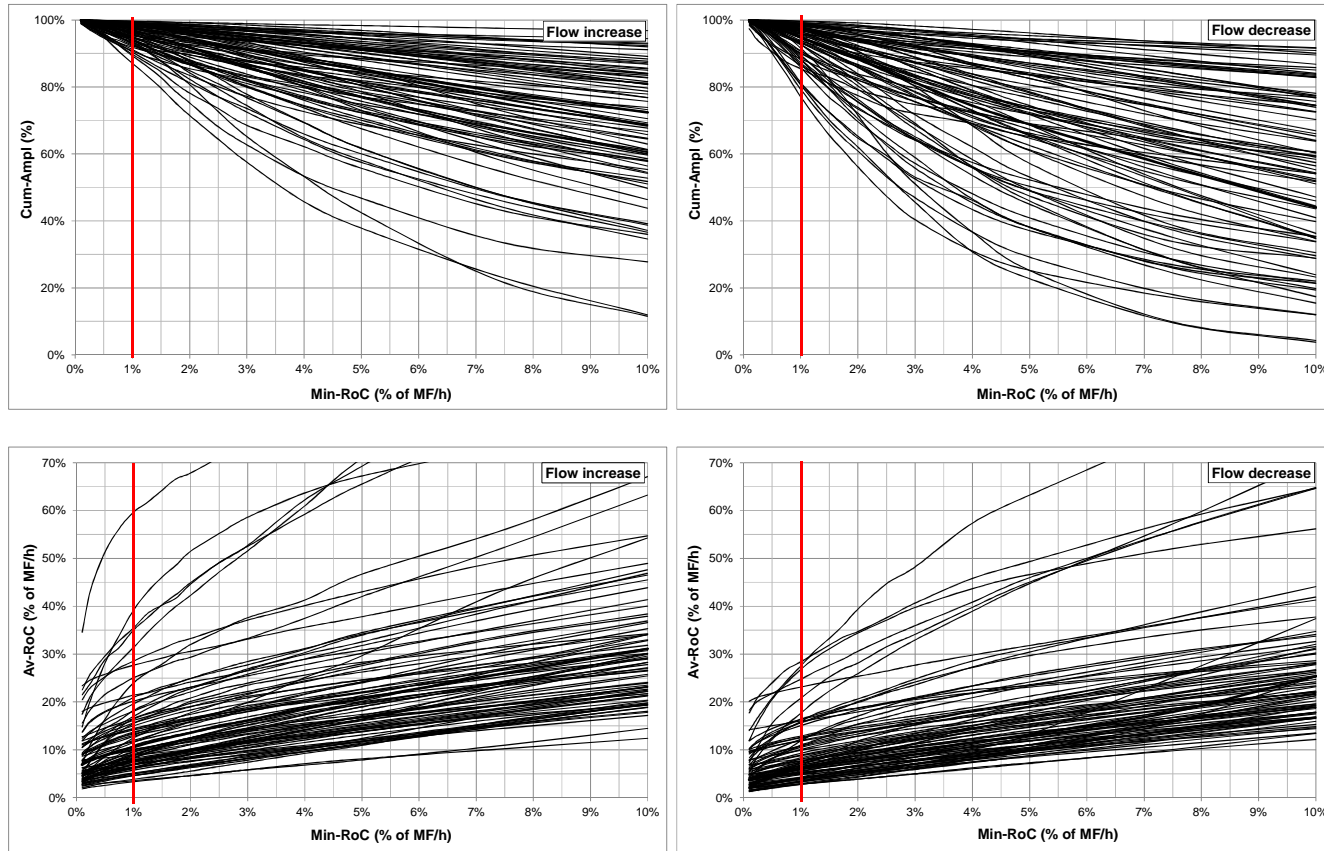


Figure 6. Cumulative amplitude of detected variations divided by the sum of the amplitudes between each pair of measurements (Cum-Ampl in %; top), and average rate of change of detected variations determined by dividing the cumulated amplitude of detected variations by their

cumulated duration (Av-RoC in % of MF/h; bottom), for the flow increases (left) and decreases (right), depending on the threshold value of the rate of change between pairs of measurements (Min-RoC in % of MF/h). Each curve corresponds to a hydrometric station.

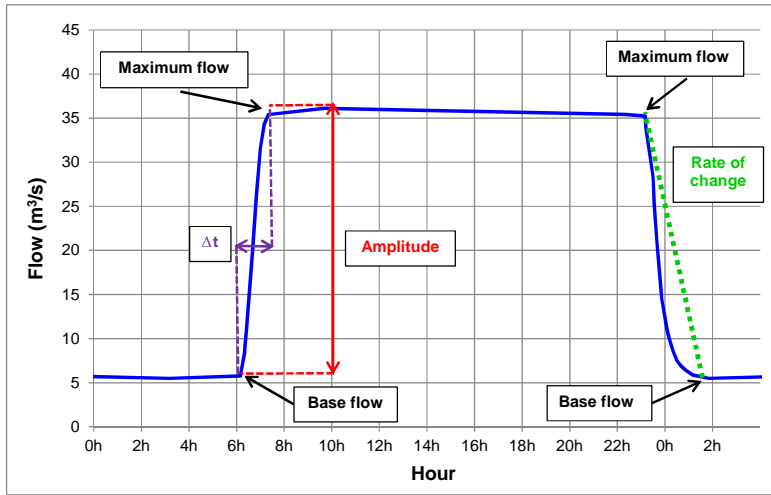


Figure 7. Characterization of hydropeak increases and decreases.

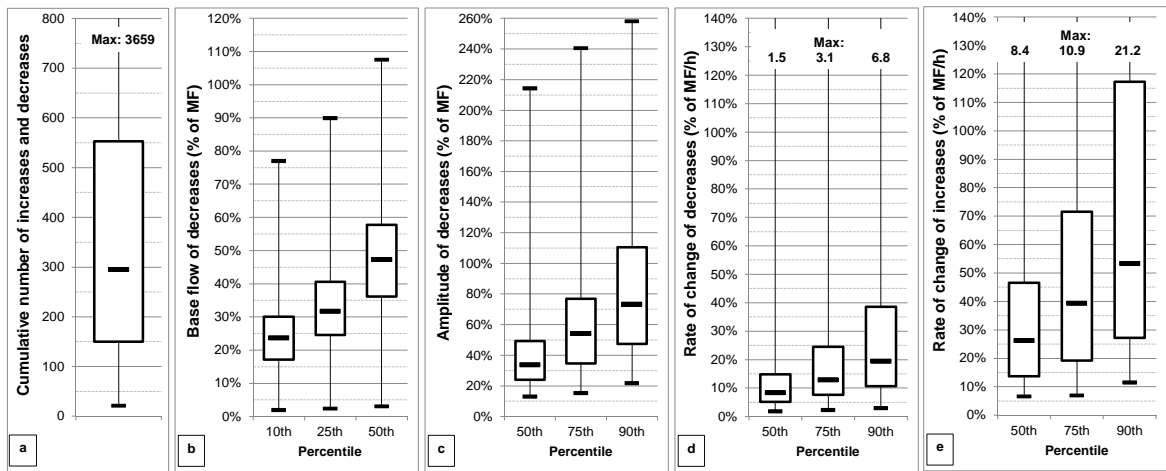


Figure 8. Box plots of (a) cumulative numbers of hydropeak increases and decreases for each of 491 years of flow data affected by hydropeaking, (b) base flows of decreases (10<sup>th</sup>, 25<sup>th</sup> and 50<sup>th</sup> percentiles), (c) amplitudes of decreases (50<sup>th</sup>, 75<sup>th</sup> and 90<sup>th</sup> percentiles), (d and e) rates of change of decreases and increases respectively (50<sup>th</sup>, 75<sup>th</sup> and 90<sup>th</sup> percentiles). Box plots show the median (dark horizontal line), 25<sup>th</sup> and 75<sup>th</sup> percentiles (edges of box), minimum and maximum values (end of vertical line).

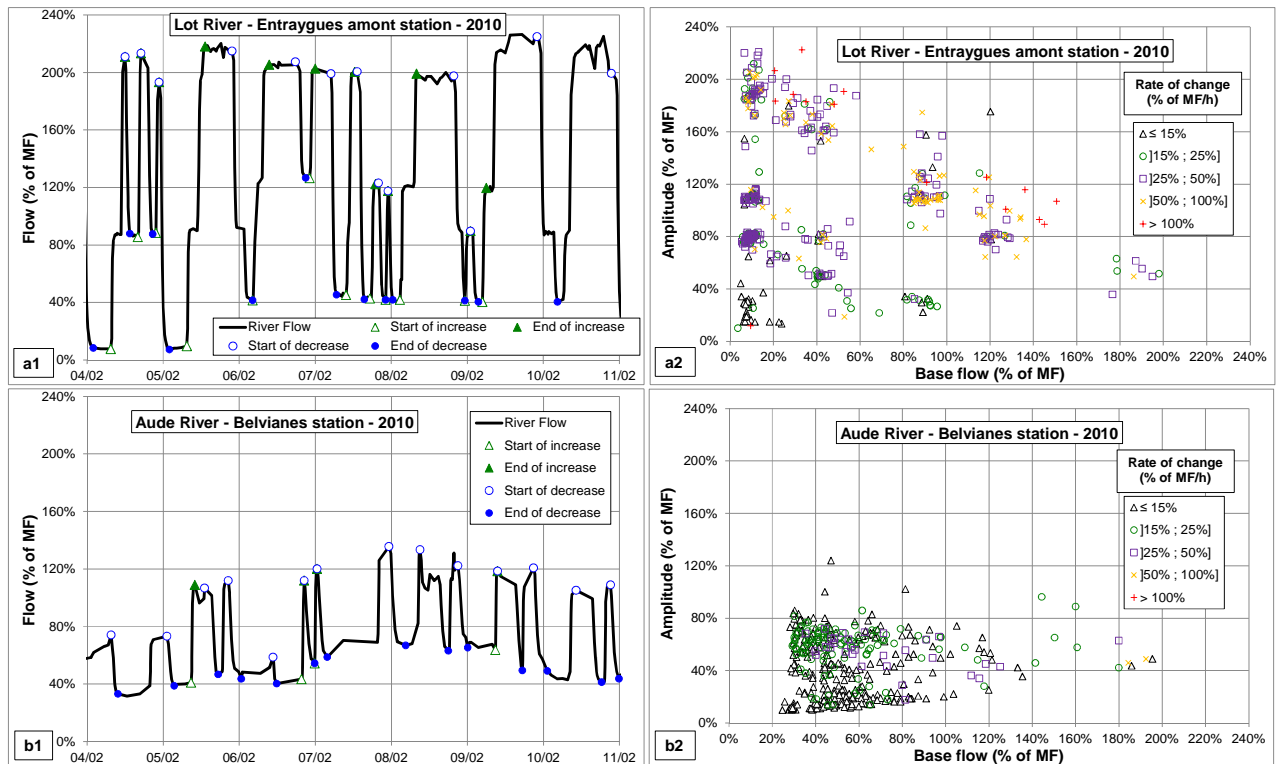


Figure 9. Illustration of hydropeaking regimes observed in 2010 on (a) the Lot River at the Entraygues Amont hydrometric station and (b) the Aude River at the Belvianes hydrometric station, with (1) excerpts of hydrograph data during the same week in February and (2) plots of selected hydropeak decreases. In the plots, each point corresponds to a decrease displayed according to its base flow (x-axis), its amplitude (y-axis) and its rate of change (different series).

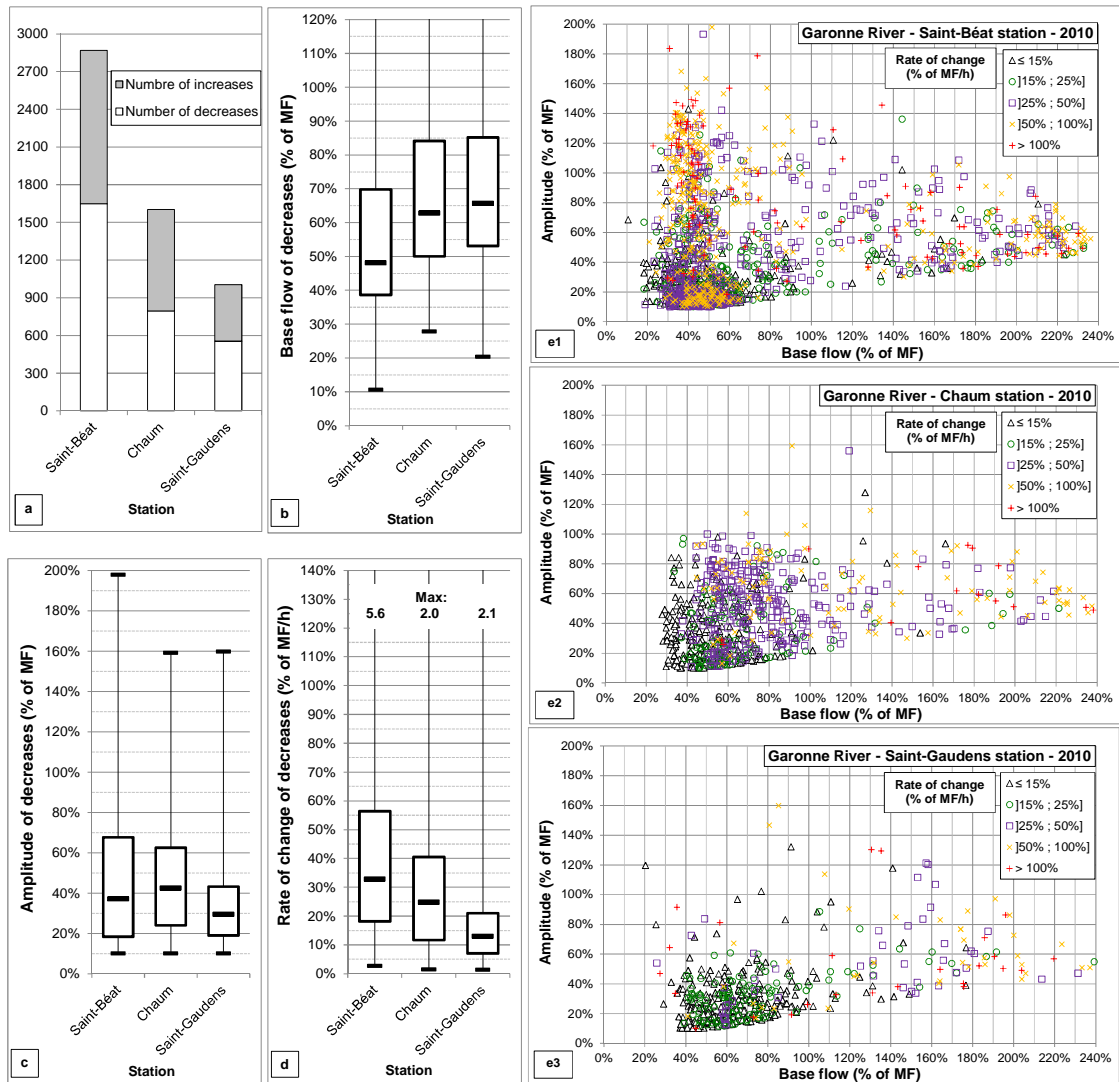


Figure 10. Characteristics of hydropeaking regimes observed on the Garonne River in 2010 at the Saint-Béat, Chaum and Saint-Gaudens hydrometric stations located 3.5, 9.8 and 48.9 km respectively downstream of the Fos-Arlos hydroelectric facility, with (a) cumulative numbers of hydropeak increases and decreases, box plots of (b) base flows, (c) amplitudes and (d) rates of change of decreases, and (e1, e2, e3) plots of selected hydropeak decreases. See Figure 9 for plot definition and Figure 8 for box-plot definition.

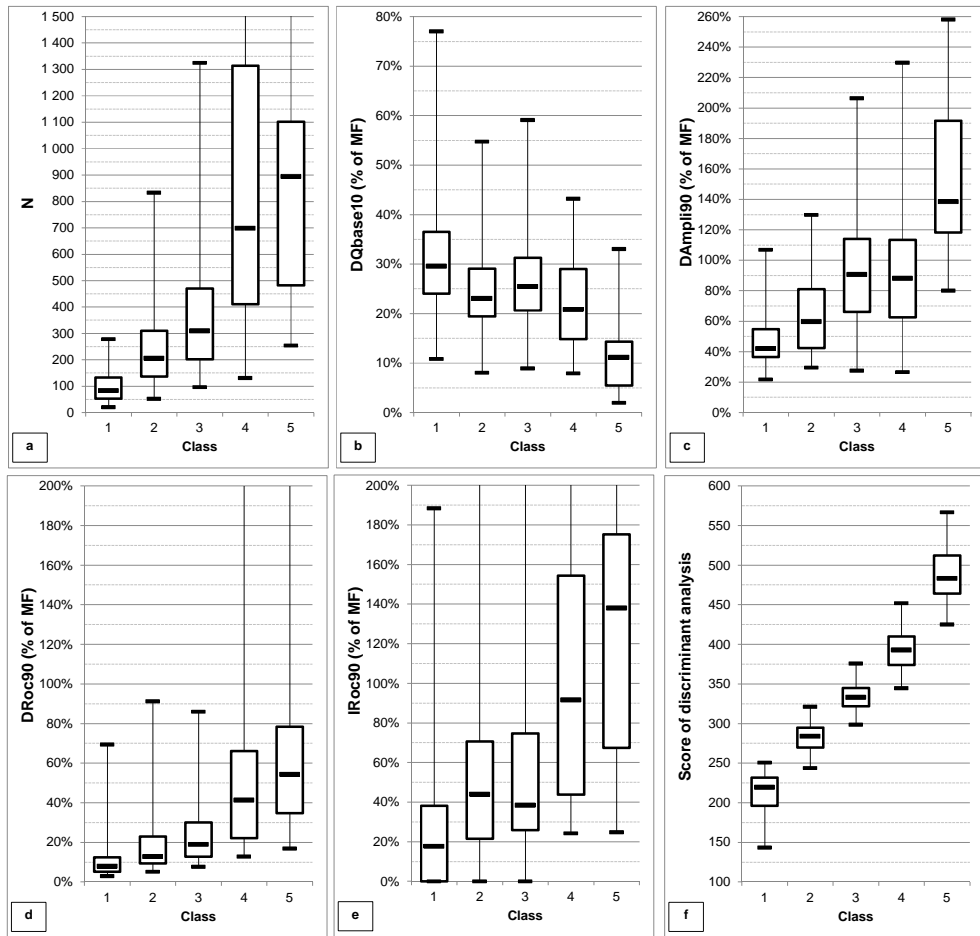


Figure 11. Box plots of the selected parameter in the discriminant analysis – (a) N, (b) DQbase10; (c) DAMpli90, (d) DRoc90, (e) IRoc90 (see text for the definitions) – and (f) box plot of the score produced by the discriminant analysis, for each class of hydrologic alteration. See Figure 8 for box-plot definition.



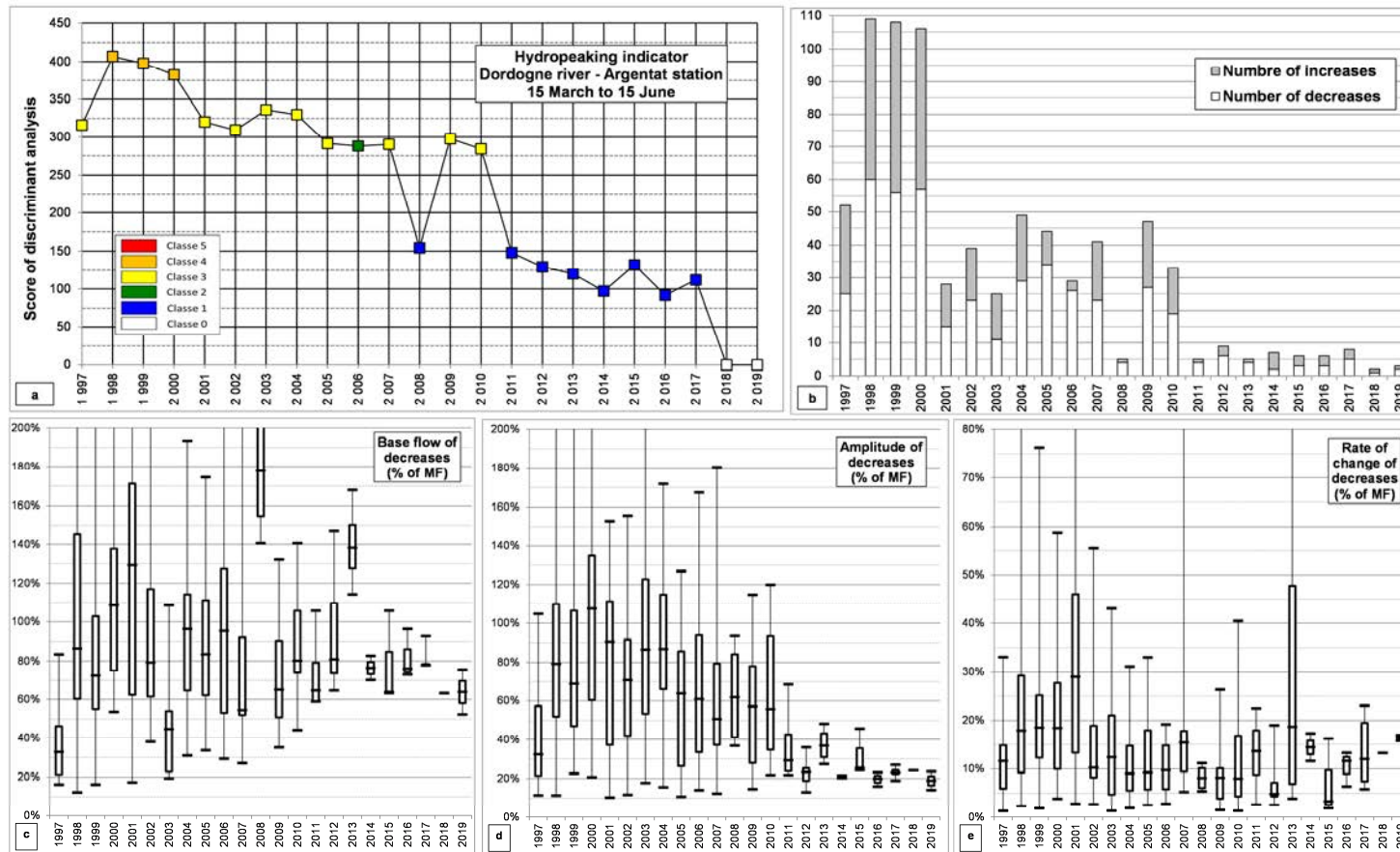


Figure 12. Dordogne River at the Argentat hydrometric station from 1997 to 2019, during the period from 15 March to 15 June. (a) Score and rank of the hydropeaking indicator. (b) Cumulative numbers of hydropeak increases and decreases. Box plots of (c) base flows, (d) amplitudes and (e) rates of change of flow decreases. See Figure 10 for box-plot definition.