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A simple procedure for the assessment of hydropeaking flow alterations applied to several European streams

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Abstract Release of water from storage hydropower plants generates rapid flow and stage fluctuations (hydropeaking) in the receiving water bodies at a variety of sub-daily time-scales. In this paper we present an approach to quantify such variations, which is easy to apply, requires stream flow data at a readily available resolution, and allows for the comparison of hydropeaking flow alteration amongst several gauged stations. Hydropeaking flow alteration is quantified by adopting a rigorous statistical approach and using two indicators related to flow magnitude and rate of change. We utilised a comprehensive stream-flow dataset of 105 gauging stations from Italy, Switzerland and Norway to develop our method. Firstly, we used a GIS approach to objectively assign the stations to one of two groups: gauges with an upstream water release from hydropower plants (peaked group) and without upstream releases (unpeaked group). Secondly, we used the datasets of the unpeaked group to calculate one threshold for each of the two indicators. Thresholds defined three different classes: absent or low pressure, medium, and high pressure, and all stations were classified according to these pressure levels. Thirdly, we showed that the thresholds can change,

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depending on the country dataset, the year chosen for the analysis, the number of gauging stations, and the temporal resolution of the dataset, but the outcome of the classification remains the same. Hence, the classification method we propose can be considered very robust since it is almost insensitive to the hydropeaking thresholds variability. Therefore, the method is broadly applicable to procedures for the evaluation of flow regime alterations and classification of river hydromorphological quality, and may help to guide river restoration actions.

Keywords regulated rivers · subdaily flow regime alterations · hydrological indicators · thresholds

1 Introduction

Flow variability is recognized as a key driver to sustain the biodiversity and the functionality of river ecosystems. This variability acts over a large spectrum of temporal scales ranging from hours to seasons, and is important for maintaining hydraulic complexity, sediment transport, hyporheic exchanges, floodplain connections and habitat structure and complexity (Poff et al 1997; Poff and Zimmerman 2010). A major role is played by sub-daily variations that may induce heavy hydro-morphological alterations in a water course. These short-time scale variations can result from natural events such as rapid snowmelt and rainfall events, or from human activities such as water releases from storage hydropower plants. The magnitude of natural events results in diel variations in flow of about 10% of the daily mean flow (Lundquist and Cayan 2002; Shuster et al 2008), while anthropogenic water releases can cause much more severe variations (Zolezzi et al 2009). The occurrence of natural events is limited to a few days (precipitations) or months (snowmelt) during the year, while anthropogenic releases can repeat each day of the year. The present work focuses on hydropeaking, the rapid variations of the flow regime induced by power production from hydroelectric plants at the sub-daily scale. Hydropeaking has several known effects on the river biota: it causes alteration of abundance and faunal composition of fish, benthic and hyporheic communities (Bruno et al 2009, 2010; Jones 2013; Tuhtan et al 2012; Young et al 2011), increases fish and invertebrate stranding (Scruton et al 2003) and reduces nearshore-riparian habitats (Fette et al 2007). Because of its relevance, quantification of sub-daily alterations is becoming increasingly important in legislation at a regional, national and international level, as, for instance, in relation to the Water Framework Directive (European Parliament, Council of the European Union 2000), in the Swiss Water Protection Act (FOEN 2011), in the implementation of Italian national methodology for hydromorphological assessment of rivers (Rinaldi et al 2013) and in the Norwegian regulations on the renewal of hydropower licensing (Anonymous 2012).

Hydrological alterations are usually quantified using daily discharge data (Richter et al 1996), thus ignoring sub-daily variations, and few methods adopt flow data at the higher resolution necessary for the quantification of hydropeaking-induced alterations (Meile et al 2011; Zimmerman and Letcher 2010; Bevelhimer et al 2014; Sauterleute and Charmasson 2014). For instance, Meile et al (2011) proposed a set of three indicators and performed an analysis on different gauging stations along the

Upper Rhone river. The authors used these indicators to define regulated and unregulated water courses. Zimmerman and Letcher (2010) developed a predictive method based on four ”flashiness indices” that can be computed from hourly discharge data, and applied it to 30 gauging stations in the Connecticut River basin (USA) to compare the potential impacts of different types of dam operations. Recently, Sauterleute and Charmasson (2014) proposed an assessment tool based on eighteen hydropeaking parameters, grouped by magnitude, time and frequency. Their analysis provides detailed information that can be particularly useful for the assessment of hydrological impacts and potential mitigation measures in relation to hydropeaking. Bevelhimer et al (2014) divided a set of streams into three different groups: without alterations, with peaking and run of the river hydropower plants and compared the respective flow regimes using different indicators that quantify magnitude, variation, frequency and rate of change of flow events at sub-daily (hourly) and daily scales. The indicators proposed by Meile et al (2011) and by Sauterleute and Charmasson (2014) can potentially be used to compare different levels of hydropeaking pressure among different streams but in both cases their application was limited to only one water course. Moreover, their methodology might not be broadly applicable, as the method proposed by Meile et al (2011) requires long-term data of the same river watershed, which may not always be available. The large number of parameters adopted in the methodology of Sauterleute and Charmasson (2014) does not permit straightforward comparison among streams. The method proposed by Zimmerman and Letcher (2010) focuses on a single watershed and requires detailed data collection of the basin in order to assess the hydrological alterations induced by a different set of dam operations. The method proposed by Bevelhimer et al (2014) aims to compare different streams but requires the calculation of a large set of indicators. Thus, a new easy-to-use methodology based on few indicators, calculated from a temporally short, but spatially distributed data is needed to classify the ”hydropeaking pressure” that we define here as the physical alteration of flow regime due to hydropeaking. In particular, we select two largely independent hydrological variables to measure pressure of hydropeaking, discharge magnitude and rate of change (Richter et al 1996; Meile et al 2011; Sauterleute and Charmasson 2014). The classification of hydropeaking pressure resulting from the application of the proposed methodology is purely hydrological and has no direct significance for the assessment of the effects on river ecology.

The use of thresholds differs from the most commonly used methods (e.g. Richter et al 1996; Sauterleute and Charmasson 2014) which usually compare before-after impacts data series. Most of the large storage hydropower plants were built around the mid-point of the past century in all three investigated countries, and discharge data at sub-daily resolution are available only for much more recent times. Therefore, we could not use a classical pre- and post-regulation comparison for each gauged station. Instead, our approach uses a space-for-time proxy to allow detecting hydrological alterations even if historical data are not available. Specifically, we sought to develop a methodology to classify levels of ”hydropeaking pressure” with the following requirements: i) it is easily implementable by using the smallest possible number of indicators, which are based on short time datasets that are commonly available at sub-daily sampling resolution; ii) it allows comparison among different gauged stations in the same area; iii) it distinguishes between types of hydropeaking pressure; iv) it is statistically robust. The methodology can effectively be used as a first screening to prioritize sites for the implementation of river restoration. Such sites would, however, need further investigation of the biotic effects of the same hydropeaking pressure which can vary from reach to reach, depending on a variety of local and non-local factors, such as channel morphology, bed sediment composition, water quality, presence of other hydro-morphological stressors (Valentin et al 1996; Bunt et al 1999; Hauer et al 2013).

2 Methods

2.1 Flow data selection

We used discharge data from 105 gauging stations located in Italy, Switzerland and Norway (Table 1), collected from public rivers monitoring agencies. Based on available GIS information, and/or the analysis of the streamflow time series, we identified two different groups of gauges: the first group is characterized by the presence of an upstream water release from a storage hydropower plant (peaked stations) and the second one without any release (unpeaked stations). The first dataset was based on 28 gauges (16 peaked and 12 unpeaked) in the NE part of Italy (Trentino region, see Fig. 1 a). These stations are well-distributed on the entire regional area. We used a 1-year dataset (2012) at a resolution of 15 minutes. The second dataset included flow data from 36 gauging stations located in Switzerland, 18 of such stations are peaked and 18 unpeaked (see Fig. 1 b). The dataset is 6 years long (2007-2012) with a resolution of 15 minutes. Finally, the third dataset is from Norway (see Fig. 1 c), where we considered 14 peaked and 27 unpeaked gauges. The dataset is 6 years long (2007-2012) and the data resolution is 1 hour. Stream gauges were chosen in order to cover different river types: glacial, snow-fed, rain-fed, lake outlet, regulated rivers not affected by hydropeaking. The size of equivalent yearly datasets was calculated by multiplying the available number of years by the number of gauging stations, for a total of 490 data series, with 282 unpeaked and 208 peaked equivalent yearly datasets. The main characteristics of the datasets and of the climate of each country are presented in Table 1, and the list of the stations used for the analysis is given in Tables 2, 3, 4.

[Fig. 1 about here.]

[Table 1 about here.]

2.2 Indicators

As a starting point we considered two of the three indicators proposed by Meile et al (2011) and we conveniently modified them in order to provide a single indicator for an easy classification of the data series. Namely, the first indicator, $HP1$, is a dimensionless measure of the magnitude of hydropeaking and is defined as follows:

$$HP1_i = \frac{Q_{max,i} - Q_{min,i}}{Q_{mean,i}}, i \in [1,365]; \quad (1)$$

$$HP1 = median(HP1_i) \,. \quad (2)$$

where subscript $_i$ denotes the day of the year. $HP1$ is defined as the annual median of daily values of $HP1_i$, calculated as the difference between the maximum and the minimum discharge value ($Q_{max,i}$ and $Q_{min,i}$, respectively) over the i^{-th} day, normalized by the discharge daily mean value ($Q_{mean,i}$).

The second indicator, $HP2$, measures the temporal rate of discharge changes and is defined as follows:

$$(HP2_k)_i = \left(\frac{\Delta Q_k}{\Delta t_k}\right)_i = \left(\frac{Q_k - Q_{k-1}}{t_k - t_{k-1}}\right)_i, i \in [1,365] \quad (3)$$

$$HP2_i = P_{90}|\,(HP2_k)_i\,|; \quad (4)$$

$$HP2 = median(HP2_i). \quad (5)$$

where Q_k refers to each available discharge datum (e.g. $[1 \leq k \leq 24]$ for data sampled every 60 minutes). $HP2$ is computed as the annual median of daily values of $HP2_i$, which is the 90^{th} percentile (P_{90}) of the discretized time derivative of the instantaneous stream-flow series. $HP2$ is a dimensional parameter and it is expressed in $m^3 s^{-1} h^{-1}$. The ninetieth percentile P_{90} was arbitrarily chosen as a measure of the daily rate of change because it is a conservative estimation of the cutoff value for extreme high flow events and allows exclusion of possible error measurements. We used the absolute value of P_{90}, this taking into account ramping rates of the hydrographs in both directions, i.e. the increasing and falling limb. Finally, we used annual median values to characterize each gauged station with a distinctive yearly value for both indicators. The median value is used, for instance, as the measure of central tendency for the non-parametric approach for the hydrological alteration parameters of IHA7 (Richter et al 1996).

2.3 Hydropeaking thresholds and hydropeaking pressure classes

For the quantification of the hydropeaking pressure we identified a threshold for each indicator: TR_{HP1} and TR_{HP2}. The thresholds are calculated from the 282 unpeaked datasets using a non-parametric method (Tukey 1977), in order to avoid a priori assumptions on normality in data distribution. The values of the two thresholds correspond to the values of the two estimators which separate the outliers from the rest of the unpeaked distribution.

The chosen outlier estimators which correspond to the thresholds' values are:

$$TR_{HP1} = P_{75}\left(HP1_i^{unp}\right) + 1.5(P_{75} - P_{25})\left(HP1_i^{unp}\right), \quad (6)$$

$$TR_{HP2} = P_{75}\left(HP2_i^{unp}\right) + 1.5(P_{75} - P_{25})\left(HP2_i^{unp}\right), \quad (7)$$

where $HP1_i^{unp}$ and $HP2_i^{unp}$ are the daily values of the two indicators for unpeaked stream gauges and P_{75} and P_{25} are the 75^{th} and the 25^{th} percentile of the distribution, respectively.

Once the thresholds (6) and (7) are identified, the following conditional rules are applied to each station to identify three different classes of hydropeaking pressure:

1. **Class 1**: *Absent or low pressure.* $HP1 < TR_{HP1}$ and $HP2 < TR_{HP2}$. The gauged station is statistically similar to an unpeaked gauged station.
2. **Class 2a**: *Medium pressure.* $HP1 > TR_{HP1}$ and $HP2 < TR_{HP2}$. $HP1$ indicator is above threshold and the gauged station is an outlier in hydropeaking magnitude compared to unpeaked group.
3. **Class 2b**: *Medium pressure.* $HP2 > TR_{HP2}$ and $HP1 < TR_{HP1}$. $HP2$ indicator is above threshold and the gauged station is an outlier in temporal rate of discharge variations compared to unpeaked group.
4. **Class 3**: *High pressure.* $HP1 > TR_{HP1}$ and $HP2 > TR_{HP2}$. Both indicators are above thresholds.

[Table 2 about here.]

[Table 3 about here.]

[Table 4 about here.]

2.4 Statistical and sensitivity analysis

Preliminary χ^2 goodness-of-fit tests were run on each equivalent yearly data series (each gauged station for each year, for a total of 490 data series) to check for normality of data; the tests were not significant for only 48 of 490 data series, thus allowing rejection of the null hypothesis of normal distribution of discharge data and supports the choice of non-parametric estimators used in this analysis.
The non-parametric thresholds defined by equations (6) and (7) can vary based on several factors, such as the climate of the investigated regions (i.e. southern or northern Alpine region or the Scandinavian Alps, in our case), the length of the considered $HP1_i^{unp}$ and $HP2_i^{unp}$ records (i.e single or multiple years), the breakdown time of the original dataset (data analysed at 15 or 60 minutes), and the number of stations used to compute them. If the hydropeaking thresholds change (eq. (6) and (7)), the same peaked gauged station may fall within different pressure classes, therefore we performed a set of analysis to assess the robustness of the method, and the sensitivity of the hydropeaking thresholds to the choice of reference unpeaked stream gauges. To achieve this goal, thresholds calculation from the unpeaked group data was performed by building four different sub-datasets according to the following criteria, which correspond to the most relevant sources of variability in calculating the thresholds:

1. **Choice of country/geographical area**: thresholds were calculated by separating the dataset by different countries (Italy, Switzerland and Norway). Multi-year datasets were available for every gauged station of Switzerland and Norway, and each year of record was considered as a different dataset;

2. **Choice of year**: thresholds were calculated for each year for all unpeaked stream gauges, when multiple years were available, for a total of 12 different threshold values for each indicator;
3. **Choice of number of stations required for the calculation**: thresholds calculation was repeated on an increasing number of stations extracted from the entire unpeaked dataset with a random sampling technique to avoid bias (random sampling without replacement). The random extraction was performed 1000 times from 2 to 275 stream gauges ($n-1$), thresholds were calculated for each extraction and a mean value of each threshold was eventually calculated over all the extracted thresholds;
4. **Choice of streamflow data time resolution**: thresholds were calculated from data with a resolution of 15 minutes and 60 minutes. Data acquired every 15 minutes were available only for the Italian and Swiss datasets. When data were collected at 15 minute intervals, we selected a subset of data corresponding to the hourly measurements (one out of four consecutive measurements).

The robustness of the method was assessed by applying a pairwise Mann-Whitney U, to test if each of the resulting sub-datasets was extracted from the same original population of data. If the test is not significant, each sub-dataset is extracted from the same population of unpeaked gauged stations. Mann-Whitney is the non-parametric ranking alternative of the Student t test. The following step consisted of calculating the thresholds using all the sub-datasets for each of the four criteria (i.e. 6 sub-datasets for the ”Year” criterion), and applying the pairwise Mann-Whitney U test to assess whether the resulting thresholds correspond to the same class distribution for all datasets. Classes were iteratively calculated using all possible combinations of hydropeaking thresholds for each sub-dataset (e.g Italian, or Swiss, or Norwegian unpeaked stations) and a Mann-Whitney test comparing each pair of classes within each subset was applied. For instance, six thresholds (three for each indicator) were calculated for different countries. Classes for each station were recalculated three times using the six different thresholds (three class values for each station). If the test is not significant, the classification of the stations does not significantly differ between each possible pair of thresholds within each sub-dataset.

2.5 Validation of the procedure

We have validated our method through the two following procedures.

First we have randomly chosen an additional control dataset within a comprehensive list of Swiss hydrometric stations for which thirty year long streamflow data series at sub-daily time resolution are available. The random extraction selected six Swiss gauged stations with 30 year-long streamflow records for a total of 180 data series, which we did not label *a priori* as peaked or unpeaked. We then run the analysis using the thresholds calculated on the entire dataset to compute the classification. This ”blind” classification exercise resulted in attributing to each of the 180 yearly datasets one of the four different classes of hydropeaking alteration. Only afterwards we have *a posteriori* verified whether each of the chosen six control stations are found

downstream of intermittent hydropower releases from storage hydropower plants, labelling them as ”peaked” or ”unpeaked”. The final step of the validation has been to assess whether (i) yearly datasets, predicted by our method to have either moderate (classes 2a, 2b) or high hydropeaking pressure/alteration, belong to *a posteriori* identified ”peaked” gauged stations; and whether (ii) yearly datasets belonging to *a posteriori* identified unpeaked stations group in class 1 (absent or low alteration). The outcome of such validation procedure for the proposed method has been considered satisfactory on the basis of the correspondence between the method predictions and the *a posteriori* assessment of the peaked and unpeaked stations.
The second procedure used to validate our method applies to five peaked gauged stations located in Switzerland, for which an idealized natural flow regime reconstruction has been carried out by Jordan (2007), by means of an hydrological model that has been used to reconstruct the hourly streamflow time series corresponding to year 1993 in the absence of regulation provided by hydropower plants. These stations are: Rhone River at Branson, Saltina River at Brig, Rhone River at Sion and Port-du-Scèx and Vispa River at Visp.

3 Results

This analysis is conducted considering a total of 490 discharge equivalent yearly data series as defined at the end of Section 2.1, corresponding to one year of data for each of the 105 examined gauging stations (see Table 1) and for the entire length of the database (6 years or 1 year).

3.1 Peaked vs unpeaked stations: cumulative distributions of hydropeaking indicators

[Fig. 2 about here.]

The cumulative distributions of the two indicators $HP1_i$ and $HP2_i$ are shown in Figures 2 and 3, respectively, for a selected subset of representative unpeaked and peaked stations: we selected the datasets with the highest and lowest median values of the two indicators, plus three datasets of random choice. The peaked stations show a higher degree of variability and larger median values and interquartile range for both indicators. The median value of $HP1$ for the entire dataset of unpeaked stations (282 data series) is 0.17 and the daily values $HP1_i$ are generally well-distributed around the median with interquartile distance equal to 0.26. Rare events (e.g. extreme summer storms, intense snow and ice-melting) are included in the higher 99^{th} percentile (P_{99}) which equals to 2.33 with a maximum value of 15.00. The median value of $HP1_i$ for the peaked group is 0.46 and the interquartile distance 0.69, suggesting a greater inter- and intra- stations variability for this group. Extreme values for the peaked group are higher with a P_{99} of 3.52 and a maximum value of 24.

[Fig. 3 about here.]

For the second indicator $HP2$ the differences between the two groups is more evident. In fact, the entire dataset of unpeaked stations has a median value of 0.17 $m^3s^{-1}h^{-1}$ and an interquartile range of 0.48 $m^3s^{-1}h^{-1}$ while the peaked group has a median value of 3.48 $m^3s^{-1}h^{-1}$ and an interquartile range of 9.74 $m^3s^{-1}h^{-1}$. Differences in extreme $HP2_i$ values between the two groups are qualitatively analogous to those detected in the case of $HP1_i$, with P_{99} of 8.69 and 39.53 $m^3s^{-1}h^{-1}$ and maximum values of 166 $m^3s^{-1}h^{-1}$ and 366 $m^3s^{-1}h^{-1}$ for the unpeaked and peaked group, respectively.

3.2 Class of hydropeaking alteration for the examined stations

Figure 4 shows the distribution of the stations in the dataset in the $HP1$ and $HP2$ indicators space. Each panel refers to stations in a different country (a: Italy, b: Switzerland, c: Norway) and is divided into four classes of hydropeaking alteration (or pressure, Section 2.3) by the corresponding thresholds computed with reference to the unpeaked group of stations for that country. For each of the three different countries all the stations in the unpeaked group, except one, are below the hydropeaking thresholds TR_{HP1} and TR_{HP2} (class 1). Only one of the peaked stations falls in class 2a, i.e., river reaches characterized by high magnitude of hydropeaking (high $HP1$) and small values of the flow rate of change (small $HP2$) are very rare in the analysed dataset. For the peaked group of the Italian dataset (Fig. 4a and Table 2), 43% of the gauged stations belong to class 3, 45% to class 2b, and 6.2% to class 1. Twenty-six percent of the Swiss peaked stations (Fig. 4b and Table 3) falls in the high pressure class (class 3) while 49% falls in the moderate pressure class 2b, and 25% in the low pressure class. Finally, the peaked Norwegian rivers (Fig. 4c and Table 4) are characterized by 11% of the dataset belonging to class 3, 69% to class 2b, and 20% to class 1.

[Fig. 4 about here.]

The global distribution of the entire dataset is summarized in Figure 5. Thresholds are calculated over the entire unpeaked dataset (282 data series). Ninety-eight percent of unpeaked stations belong to pressure class 1, 1% to class 2a and 1% to class 2b. Eighteen percent of peaked stations belong to class 1, 0.5% to class 2a, 56.5% to class 2b and 25% to class 3.

[Fig. 5 about here.]

3.3 Hydropeaking thresholds variability

We analysed how the hydropeaking thresholds TR_{HP1} and TR_{HP2} change depending on the sources of variability previously described in Section 2.4. The results for the first three sources of variability (choice of country, year and number of reaches) are summarized in Table 5. TR_{HP1} ranges between 0.96 and 1.14 and TR_{HP2} from 1.18 to 1.66 for the Swiss stations among all the years while TR_{HP1} ranges between 0.56 and 0.66 and TR_{HP2} from 1.10 to 1.59 for the Norwegian stations. Mann-Whitney tests pinpointed significant differences among the distributions of $HP1_i$ in the unpeaked group for the three countries ($p < 0.001$). In particular, the $HP1_i$ values for the Swiss stations were highly variable. The Mann-Whitney tests highlighted significant differences in $HP1_i$ and $HP2_i$ distributions ($p < 0.05$) between each pair of geographical areas.

[Table 5 about here.]

The hydropeaking thresholds calculated using unpeaked flow data series belonging to the same year were significantly different for each pairwise comparison (Mann-Whitney, $p < 0.001$), with the exception of pairwise comparison of indicators for years 2008 vs 2012 ($p = 0.40$ for $HP1$ and $p = 0.42$ for $HP2$). The assessment of the number of data series required to correctly define $HP1$ and $HP2$ thresholds showed that a minimum of 51 data series is required. In fact, using more than 50 unpeaked data series resulted in distributions of $HP1$ and $HP2$ not significantly different from the total distribution (Mann-Whitney tests, $p > 0.14$ for all pairwise comparisons), i.e., not further depending on the number of yearly data series.
Finally we tested if the hydropeaking thresholds change for different distributions based on breakdown time, i.e. $15'$ vs $60'$. The resulting distributions were highly different with $p < 0.001$ for both indicators. It is worth mentioning that the calculated confidence intervals were very narrow (0.7482 ± 0.001 for $HP1$ and 1.2315 ± 0.002 $m^3 s^{-1} h^{-1}$ for $HP2$, global thresholds), and therefore not included in the analysis of threshold variability.

3.4 Class changes of stations with thresholds variability

As the distributions used to calculate the thresholds significantly differed within each of the main criteria used to define the reference group of unpeaked stations (i.e. choice of country, year, number of stations and data resolution), we analysed if such thresholds variability would result in changes in the classification of hydropeaking alteration of the gauged stations, i.e. we investigated if a gauged station would change its hydropeaking pressure class due to thresholds changes. The class changes of the peaked group due to thresholds variations among the three countries were not significant ($p > 0.16$). For thresholds calculated referring to different years, changes were also not significant (lowest $p = 0.18$), although the comparisons were conducted between a one-year dataset of one station with thresholds calculated within the overall unpeaked data of that same year ($p < 0.001$). When the comparison of classes was performed with a progressively increasing number of stations, changes were significant only if thresholds were defined using fewer than 10 stream gauges ($p < 0.001$). Classes calculated using different data breakdown times were not significantly different with a minimum p value of 0.24. The classification of the unpeaked stations never changed significantly for any of the four criteria, with a lowest p value of 0.36.

Table 6 summarizes the frequency of class changes associated with threshold variability due to different choice of country, years (Switzerland and Norway datasets), number of stations used for the calculation (from 2 stations up to 275) and breakdown time ($15'$ vs $60'$, Switzerland and Italy datasets) to define the reference group of unpeaked stations. The frequency of class changes measures how many times a given data series of a station belongs to the same class. It is quantified through a value in the interval (0:1), with 0 meaning that no changes between classes occur, 1 meaning that changes in classes occur for each comparison within dataset. For instance, the frequency of 0.1 recorded in peaked Italian stations (first row and first column, table 6) means that each stream gauge falls in the same class 90 % of the times, when classes were calculated using the three different country-specific thresholds values.

[Table 6 about here.]

We verified which class changes occurred more frequently in the peaked stations (see Tables 2, 3, 4, last column). The percentage of changes was always very low in peaked stations and very often equal to zero in unpeaked stations. For all the possible sources of variability (Table 6) the frequency of changes between class 1 and class 3, which is obviously the most critical for the robustness of the proposed methodology, was always zero except for one case (Norway, thresholds calculated referring to different years), still with a very low frequency (3.5%). Two Norwegian gauged stations were responsible for this change (see Table 4): Sokna River station in Melhus at the Sokna power plant (once for the six year data record), and Holm Bru station (Kafjord River, twice).

Considering the entire dataset, the most frequent changes occurred from class 2b to 3 (10.2 %), fewer changes between class 1 and 2b (4.2 %), while no changes were detected between 1 and 2a, 2a and 2b, and between 2a and 3.

3.5 Validation of the procedure

The random selection of the control dataset extracted station 2019, Aare-Brienzwiler; 2070, Emme-Emmenmatt; 2473, Rhein-Diepoldsau; 2152, Reuss-Luzern; 2372, Linth-Mollis and 2425, Kleine Emme-Littau. The control and the original dataset overlapped for eighteen yearly data series, i.e. six yearly data series for each of 2019, 2070 and 2473 stations. We computed the indicators ($HP1, HP2$) for the 180 yearly data series of the chosen six control stations and assigned classes of hydropeaking alteration using the global thresholds (see Table 5, last row). Results are reported in Figure 6. Three stations (2019, 2473, 2372) were predicted to lay always above at least one of the two thresholds for each of their thirty year long data series, therefore falling either in class 2b or in class 3 (Fig. 6). The thirty yearly data series for each station always fell within the same class, except for station 2372 that shifted between classes 2b and 3 over time (after 1998), possibly due to changes in hydropower production patterns that altered both the rate and the magnitude of hydropeaking (denoted with a lozenge in Figure 6). After the analysis, we have further verified whether or not the six control stations are actually found downstream of intermittent releases from storage hydropower plant: stations (2019, 2473, 2372) are actually located downstream from storage hydropower plant releases, and have been therefore *a posteriori* labelled as peaked, while (2070, 2152, 2425) are not, and have been therefore *a posteriori* labelled as unpeaked. Finally, comparing the outcomes of the classification predicted by our method with the *a posteriori* labelling procedure has yielded a 100 % correspondence, namely: yearly datasets having either moderate (class 2b) or high (class

3) hydropeaking alteration, belong to *a posteriori* identified ”peaked” gauged stations (i.e. 2019, 2473, 2372); and yearly datasets belonging to *a posteriori* identified unpeaked stations (i.e. 2070, 2152, 2425) group in class 1 (absent or low hydropeaking alteration).

[Fig. 6 about here.]

Results of the second validation procedure are given in Table 7. For each station two hydropeaking classes have been computed. ”Measured data” correspond to the hydropeaking pressure class for that station obtained by computing the proposed indicators for the measured streamflow time series in 2007-2012 period. ”Reconstructed data” refers to the hydropeaking class resulting after computing the indicators for the ”natural” streamflow time series that has been reconstructed through an hydrological model by Jordan (2007) in the absence of hydropower plants. It clearly emerges how the proposed procedure is capable of discriminating peaked from unpeaked sub-daily streamflow series. In particular from the analysis of measured data it emerges that three stations fall into class 2b (Branson, Rhone; Porte du Scèx, Rhone; Sion, Rhone), one in class 3 (Visp, Vispa), and one in class 1 (Brig, Saltina) calculated using global thresholds. The analysis of the reconstructed data shows that all the five stations considered fall into class 1 even using the global thresholds. The station of Brig is in class 1 for both real and simulated data.

[Table 7 about here.]

4 Discussion

Several other studies have applied indicators in different countries to analyse and quantify sub-daily flow fluctuations in regulated rivers (Meile et al 2011; Zimmerman and Letcher 2010; Sauterleute and Charmasson 2014; Bevelhimer et al 2014). In our approach, the main hydrological differences between peaked and unpeaked rivers can be captured analysing the discharge signal focusing on two indicators: the magnitude of hydropeaking and the rate of change in discharge ($HP1$ and $HP2$). The use of these two indicators allows classifying river stations based on their degree of alteration and assessing the sub-daily flow variations induced by water releases from storage hydropower plants.

The statistical analysis of class changes proposed by our method (see Table 6) shows that classes remain the same even if the geographical location, year and temporal resolution of the discharge dataset used to calculate the thresholds changes. However, some stations moved between classes when different years were analysed. Two changes of class are particularly relevant: changes between medium and high hydropeaking pressure classes, and changes between low and any of the other hydropeaking pressure classes. Changes from medium to high pressure classes can be considered less relevant than changes between low pressure and any of the others for water managers, who should prioritize actions on heavily impacted river reaches. Only a few stations (four in the Swiss dataset and one in the Norwegian dataset) slightly changed among peaked classes over time (from class 2b to 3 class). Some peaked stations were distributed near the thresholds and showed class changes between low and moderate pressure classes (1 to 2b). In this respect, the thresholds calculated on the entire dataset (Figs. 5 and 6) can be considered as *universal*, i.e. they clearly identify, for the entire dataset, the stations with high hydropeaking pressure.

The robustness of the approach is confirmed by the example of the two Norway gauged stations (the Sokna power plant station on the Sokna River and the Holm bru station on the Kafjord River) which are the only gauged stations which showed extreme variability (e.g between low and high pressure classes) throughout the entire dataset. These stations were not regulated for part of the analysed period, which may explain the observed changes in class. The Sokna River station recorded periods of low peaking frequency, e.g. for a period in 2010 when the plant was shut down for maintenance, and in spring of 2012 when it ran continuously for weeks due to high inflow and large snowmelt. The Kafjord River experienced close-to-natural flood episodes especially in spring for the entire six year period, which may have been superimposed on the daily hydropeaking-induced flow regime alterations.

The thresholds derived by the application of our method are general and representative of a large set of unpeaked gauged stations. In fact, when validating the procedure, the unpeaked stations in the control dataset always grouped in class 1 of pressure classification (Fig. 6 and Table 7). Our analysis also showed that extreme class changes (from 1 to 3) are rare among peaked stations for different years, suggesting that the proposed methodology can characterize each station by using only one standard year. However, it is advisable to choose the longest available dataset in order to reduce the error rate; if a yearly dataset is chosen, it should be representative of the range of typical discharge variations, and it should be selected by technicians and practitioners with a good knowledge of the river systems.

A second outcome of our method regards the data breakdown interval at which the discharge data are measured. Previous research assessed the data breakdown time required to capture sub-daily flow variations (Zimmerman and Letcher 2010; Bevelhimer et al 2014); these authors used both hourly and daily data and concluded that hourly data are necessary. Our results are in agreement with Bevelhimer et al (2014) but as a further step we showed that a resolution lower than $60'$ is not necessary. In fact, the use of different breakdown time did not influence the indicators because class variations were not detected. Therefore, the classification is not statistically different using data at $15'$ or $60'$ breakdown time.

The methodology we proposed requires sub-daily data from unpeaked rivers to derive the thresholds to be used for the classification. From our analysis it emerges that 10 data series of one year (e.g. 10 gauged stations for 1 year from unpeaked sites) are sufficient to produce robust thresholds. However, when 10 data series of one year are not available, the global thresholds (i.e extracted from the entire dataset) defined in Table 5 may be used for the classification. In fact, the exploration of all the possible sources of variability in the dataset (e.g. geographical areas, years, etc..) showed that unpeaked and peaked stations never significantly change classes when thresholds change (Table 6). The caveat is to use data from similar climatic regions, in our case data from mountain streams and rivers. Finally, our results show that the distributions from which the hydropeaking thresholds are computed differed significantly within each source of variability (country, years, etc.), and a minimum dataset size of 50 gauged stations is required to define the thresholds. In fact, this subset was statistically representative of the entire dataset of the unpeaked stations.

5 Conclusions

The method proposed here allows classification of river stations in four different classes of hydropeaking alteration defined on the basis of an unpeaked group of reference stations. Class changes among extreme classes are rare and can be explained by the different power plant management schemes for different years. Although the application of the proposed methodology is purely hydrological and has no direct significance for the assessment of the effects on the river ecology, the proposed methodology is nonetheless particularly interesting for management. In fact, because the stations with high pressure of hydropeaking never change class for different years, our method objectively identifies the stations where restoration projects should be implemented. Moreover, the robustness of this methodology, and the relative ease of application, can potentially lead to its use in regulatory and monitoring activities. For instance, the classification of the stream ecological state as required by the EU Water Framework Directive (European Parliament, Council of the European Union 2000) introduces hydromorphology as one of the elements to be evaluated, together with water and biological quality, to obtain the evaluation and classification of the ecological status of a water body. The method proposed here could be integrated in a quantitative evaluation procedure to classify the stream hydrological quality. The ease of use assures that the method could be used by competent authorities (i.e., public agencies, river basin managers); if calibrated according to the different climatic conditions of one country, it could cover the full range of physical conditions, morphological types, degree of artificial alterations existing there.

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List of Figures

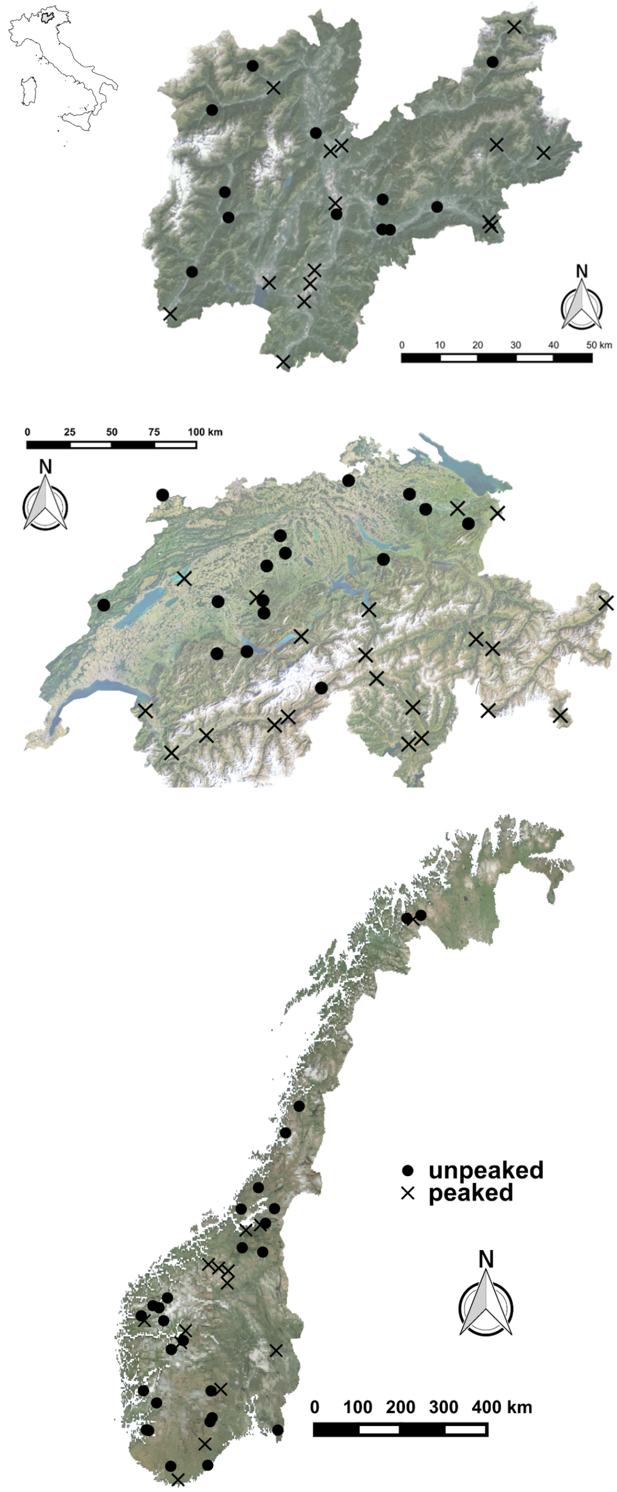

Fig. 1 Geographic distribution of the a) Italian gauging stations, b) Swiss gauging stations, and c) Norwegian gauging stations. Circles represent the unpeaked stations, and crosses the peaked stations.

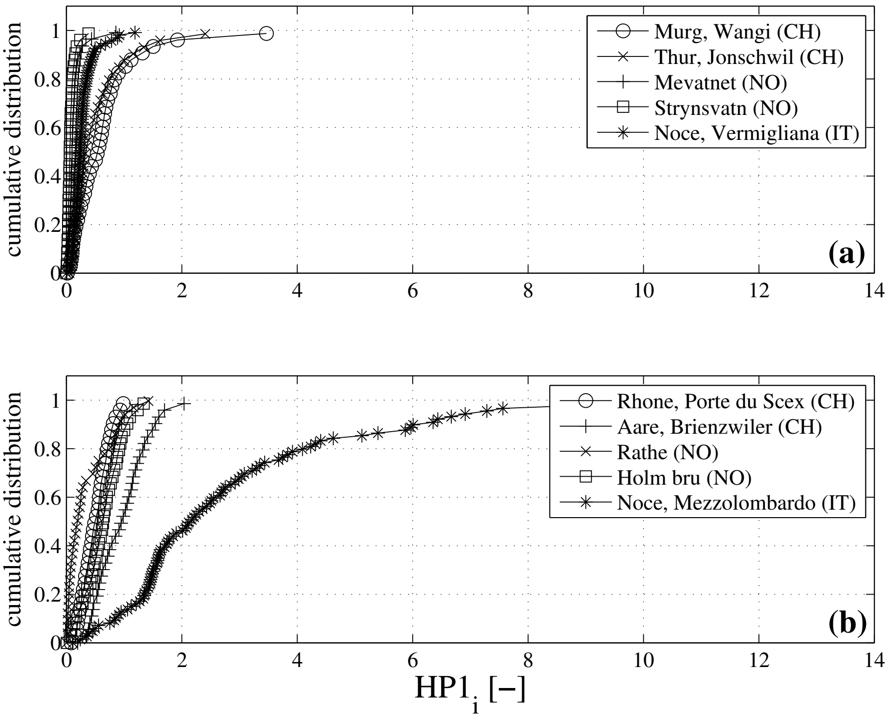

Fig. 2 Cumulative distribution of $HP1_i$ for some representative (a) unpeaked and (b) peaked gauged stations.

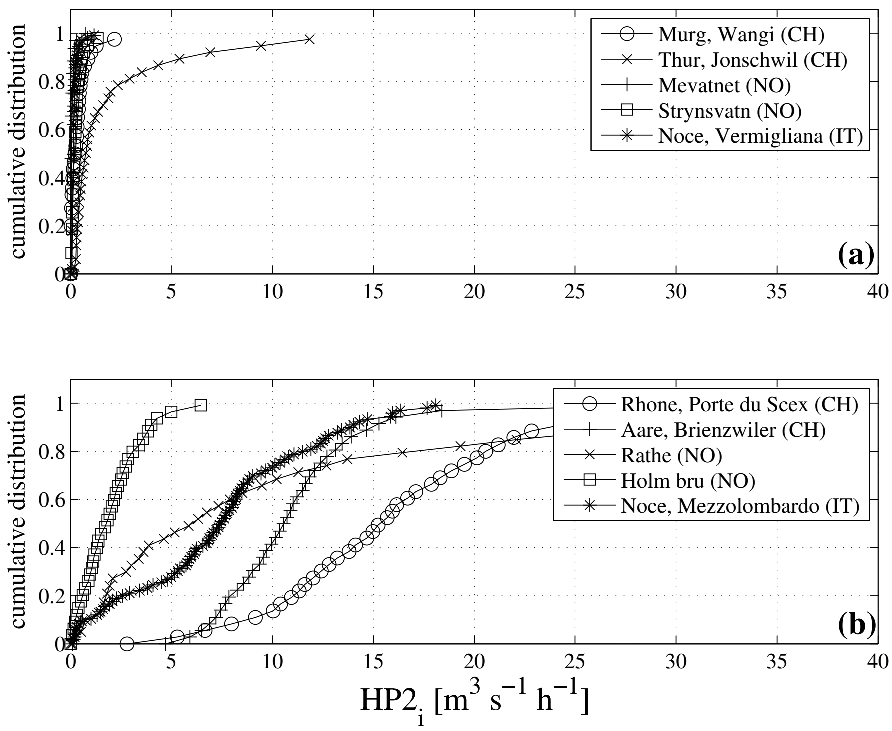

Fig. 3 Cumulative distribution of $HP2_i$ for some representative (a) unpeaked and (b) peaked gauged stations.

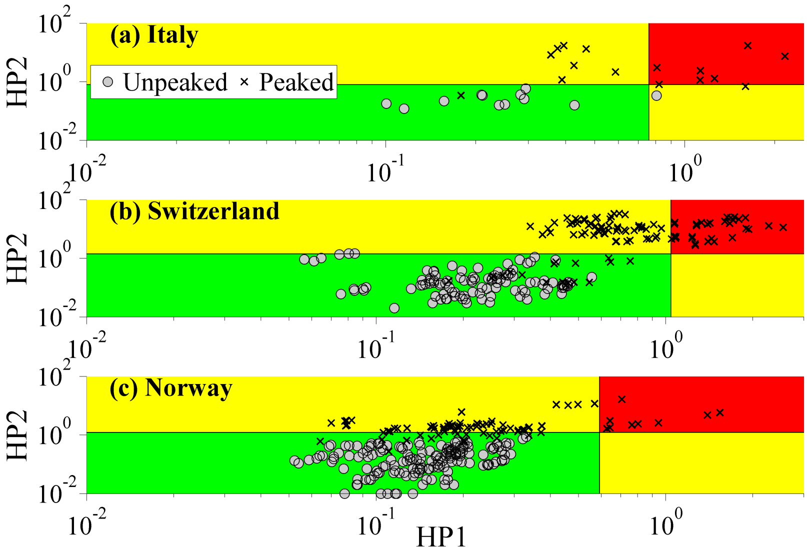

Fig. 4 Dataset distribution in classes of different pressures for Italian (panel a), Swiss (panel b) and Norwegian (panel c) data. Thresholds are calculated for each country. Different groups are denoted with cross (unpeaked) and circles (peaked). The space in the $HP1$ and $HP2$ plane is divided in 4 different regions identified by the two thresholds TR_{HP1} and TR_{HP2} which were computed for the three geographical regions considered. The four regions identify the three different classes of hydropeaking pressure: class 1 (absent or low pressure, green colour, left bottom); classes 2a and 2b (moderate pressure, yellow colour, right bottom and left top respectively) and class 3 (high pressure, red colour, right top).

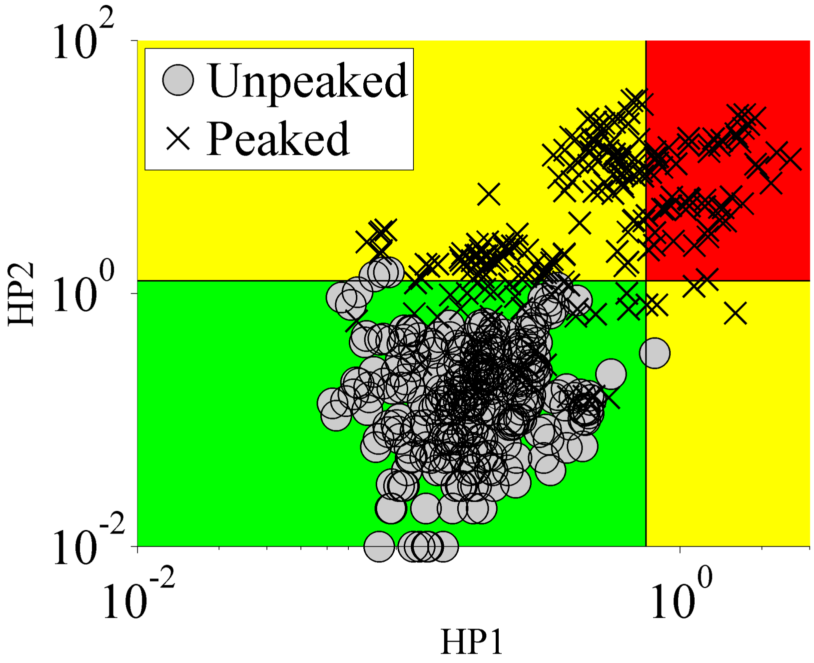

Fig. 5 Global distribution of all datasets in classes of different pressures. Thresholds calculated over the entire unpeaked dataset. Different groups are denoted with cross (unpeaked) and circles (peaked).The four regions identify the three different classes of hydropeaking pressure: class 1 (absent or low pressure, green colour, left bottom); classes 2a and 2b (moderate pressure, yellow colour, right bottom and left top respectively) and class 3 (high pressure, red colour, right top).

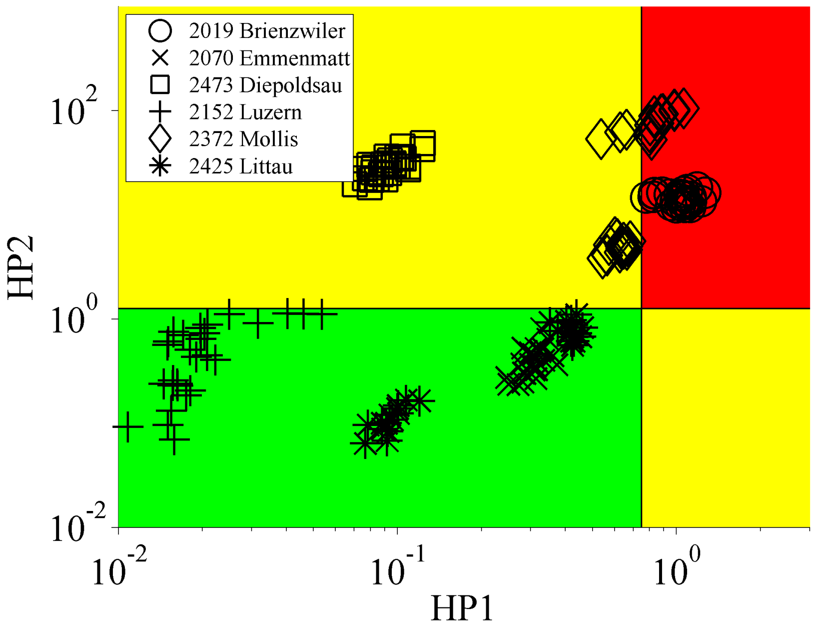

Fig. 6 Distribution of six stations used as control group. The displayed thresholds are the global thresholds. Different groups are denoted with cross (unpeaked) and circles (peaked).The four regions identify the three different classes of hydropeaking pressure: class 1 (absent or low pressure, green colour, left bottom); classes 2a and 2b (moderate pressure, yellow colour, right bottom and left top respectively) and class 3 (high pressure, red colour, right top).

List of Tables

Table 1 Summary of features of the three datasets.

	Italy (IT)	Switzerland (CH)	Norway (NO)
Total stations	28	36	41
Peaked stations	16	18	14
Unpeaked stations	12	18	27
Data breakdown time [min]	15	15	60
Length of data record (available years)	1 year (2012)	6 years (2007-2012)	6 years (2007-2012)
Size of the equivalent yearly dataset (peaked and unpeaked stations)	28	216	246
Size of the equivalent yearly dataset (peaked stations)	16	108	84
Size of the equivalent yearly dataset (unpeaked stations)	12	108	162
Latitude Limits	45°-46°30′	45°-48°	57°-71°
Longitude limits	10°-11°50′	5°-11°	5°-31°
Climate (Kottek et al 2006)	Polar tundra, snow fully humid cool summer, snow fully humid warm summer	Polar tundra, continentally fully humid cool summer, continentally fully humid warm summer	Polar tundra, snow fully humid cool summer, continentally fully humid cool summer

Table 2 Italian gauged stations grouped by the values of the hydropeaking indicators $HP1$ and $HP2$, and relative hydropeaking pressure class (calculated from a one year data record).

Watershed	Gauged station	Group	HP1	HP2	Class
Vanoi	Caoria	Peaked	1.12	1.14	2a
Avisio	Cavalese	Peaked	1.13	2.39	3
Cismon	Fiera di Primiero	Peaked	0.82	0.81	2a
Noce	Malè	Peaked	0.59	2.15	2b
Noce	Marco	Peaked	0.43	3.60	2b
Noce	Mezzolombardo	Peaked	1.62	17.25	3
Noce	Pellizzano	Peaked	0.81	3.02	3
Brenta	Ponte Filippini	Peaked	0.39	1.16	1
Adige	Ponte San Lorenzo	Peaked	0.39	17.21	2b
Chiese	Ponte Tedeschi	Peaked	2.16	7.44	3
Leno	Rovereto	Peaked	1.26	1.29	3
Adige	San Michele all' Adige	Peaked	0.36	8.25	2b
Sarca	Torbole	Peaked	0.18	0.34	1
Fersina	Trento	Peaked	1.60	0.70	2a
Adige	Villalagarina	Peaked	0.38	13.55	2b
Adige	Vo Destro	Peaked	0.47	13.19	2b
Brenta	Borgo Valsugana	Unpeaked	0.16	0.22	1
Brenta	Caldonazzo	Unpeaked	0.80	0.34	2a
Avisio	Campitello	Unpeaked	0.29	0.26	1
Fersina	Canezza	Unpeaked	0.43	0.16	1
Chiese	Cimego	Unpeaked	0.10	0.18	1
Brenta	Levico	Unpeaked	0.12	0.12	1
Sarca	Preore	Unpeaked	0.29	0.59	1
Rabbies	Rabbies	Unpeaked	0.25	0.17	1
Avisio	Soraga	Unpeaked	0.21	0.34	1
Sarca	Spiazzo	Unpeaked	0.28	0.36	1
Sporeggio	Sporeggio	Unpeaked	0.21	0.36	1
Noce	Vermigliana	Unpeaked	0.24	0.16	1

Table 3 Swiss gauged stations grouped by corresponding maximum and minimum value of hydropeaking indicators $HP1$ and $HP2$ and hydropeaking pressure class changes (calculated based on six year data record).

			HP1		HP2		
Watershed	Gauged station	Group	Min	Max	Min	Max	Class
Ticino	Bellinzona	Peaked	0.60	1.28	10.39	15.00	2b-3
Rhone	Branson	Peaked	0.39	0.64	10.17	16.60	2b
Aare	Brienzwiler	Peaked	0.68	0.97	8.44	10.57	2b-3
Saltina	Brig	Peaked	0.39	0.54	0.12	0.15	1
Rhein	Diepoldsau, Rietbrucke	Peaked	0.46	0.58	20.01	24.95	2b
Hintherrhein	Fursteanu	Peaked	0.91	1.66	14.22	18.30	3
Aare	Hagneck	Peaked	0.49	0.72	21.94	34.09	2b
Poschiavino	Le Prese	Peaked	0.41	0.75	0.66	1.00	1-2a
Inn	Martina	Peaked	1.63	1.89	20.12	25.87	3
Ticino	Polleggio, Campagna	Peaked	0.93	2.55	5.49	12.99	3
Rhone	Porte du Scèx	Peaked	0.34	0.55	12.39	16.53	2b
Ticino	Riazzino	Peaked	0.60	1.28	11.63	16.79	2b-3
Reuss	Seedorf	Peaked	0.51	0.63	6.16	9.19	2b
Rhone	Sion	Peaked	0.38	0.61	6.39	8.84	2b
Mera	Soglio	Peaked	0.18	0.32	0.17	0.34	1
Sitter	St. Gallen, Bruggen	Peaked	1.26	1.70	2.80	5.11	3
Albula	Tiefencastel	Peaked	0.67	1.23	3.74	4.87	2b-3
Vispa	Visp	Peaked	0.75	1.23	4.12	5.66	3
Reuss	Andermatt	Unpeaked	0.18	0.27	0.16	0.26	1
Sitter	Appenzell	Unpeaked	0.34	0.47	0.14	0.18	1
Aare	Bern-Schonau	Unpeaked	0.06	0.08	0.81	1.47	1-2b
Allaine	Boncourt, Frontiere	Unpeaked	0.16	0.33	0.03	0.07	1
Emme	Eggiwil, Heidbuel	Unpeaked	0.38	0.46	0.06	0.13	1
Alp	Einsiedeln	Unpeaked	0.31	0.45	0.05	0.12	1
Emme	Emmenmatt	Unpeaked	0.26	0.30	0.24	0.41	1
Kander	Hondrich	Unpeaked	0.15	0.22	0.35	0.56	1
Langeten	Huttwill, Haberenbad	Unpeaked	0.16	0.20	0.04	0.07	1
Thur	Jonschwil, Muhlau	Unpeaked	0.28	0.42	0.65	1.12	1-2b
Ilfis	Langnau	Unpeaked	0.22	0.28	0.15	0.21	1
Luthern	Nebikon	Unpeaked	0.20	0.25	0.03	0.05	1
Simme	Oberwil	Unpeaked	0.14	0.22	0.15	0.26	1
Rhone	Reckingen	Unpeaked	0.13	0.20	0.09	0.22	1
Glatt	Rheinsfelden	Unpeaked	0.08	0.09	0.06	0.10	1
Areuse	St. Sulpice	Unpeaked	0.12	0.24	0.02	0.10	1
Murg	Wangi	Unpeaked	0.22	0.56	0.07	0.23	1
Wigger	Zofingen	Unpeaked	0.14	0.18	0.10	0.14	1

Table 4 Norwegian gauged stations grouped by corresponding maximum and minimum value of hydropeaking indicators $HP1$ and $HP2$ and hydropeaking pressure class changes (calculated based on six year data record).

			HP1		HP2		
Watershed	Gauged station	Group	Min	Max	Min	Max	Class
Numedalslagen	Bruhaug	Peaked	0.27	1.54	1.36	5.80	1-2b
Driva	Driva power plant	Peaked	0.20	0.71	6.08	16.54	2b
Driva	Driva v/Elverhøy bru	Peaked	0.14	0.22	0.97	2.56	1-2b
Tokke	Elvarheim	Peaked	0.07	0.08	2.06	3.18	1
Fortun	Fortun	Peaked	0.17	0.19	1.50	2.45	1-2b
Bardu	Fosshaug	Peaked	0.23	0.27	1.19	2.94	1-2b
Stjordalselva	Hegra bru	Peaked	0.34	0.80	0.98	2.40	1-2b
Otra	Heisel	Peaked	0.11	0.13	1.21	1.71	2b
Kafjord (Gáivuoneatnu)	Holm bru	Peaked	0.19	0.23	1.34	2.25	1-3
Mandal	Kjølemo	Peaked	0.26	0.37	1.31	2.02	2b
Nidelva	Rathe	Peaked	0.10	0.34	0.69	1.85	2b-3
Sokna	Sokna power plant	Peaked	0.15	0.17	1.25	2.07	1-3
Laerdalselvi	Stuvane	Peaked	0.15	0.34	0.75	1.75	2b
Laerdalselvi	Stuvane power plant	Peaked	0.06	0.26	0.27	0.76	2b
Storana	Ardalsvatn	Unpeaked	0.10	0.14	0.38	0.56	1
Austbygdai	Austbygdai	Unpeaked	0.16	0.25	0.12	0.33	1
Supphelleelvi	Boyumselv	Unpeaked	0.19	0.29	0.02	0.22	1
Flåmselva	Brekke	Unpeaked	0.17	0.20	0.22	0.48	1
Jolstra	Brulandsfoss	Unpeaked	0.09	0.11	0.31	0.50	1
Driva	Driva v/Risefoss	Unpeaked	0.14	0.19	0.10	0.26	1
Nidelva	Eggafoss	Unpeaked	0.17	0.20	0.13	0.28	1
Fusta	Fustvatn	Unpeaked	0.07	0.12	0.18	0.34	1
Storelva	Gloppenelv	Unpeaked	0.14	0.29	0.07	0.51	1
Helgaa	Grunnfoss	Unpeaked	0.19	0.21	0.32	0.58	1
Boelva	Hagadrag	Unpeaked	0.07	0.10	0.41	0.51	1
Forra	Høggås bru	Unpeaked	0.16	0.19	0.19	0.37	1
Nausta	Hovefoss	Unpeaked	0.19	0.33	0.13	0.88	1
Sokna	Hugdal Bru	Unpeaked	0.23	0.28	0.21	0.43	1
Aardal	Kalltveit i Årdal	Unpeaked	0.23	0.28	0.09	0.14	1
Kileai	Kilen	Unpeaked	0.14	0.18	0.02	0.03	1
Nordelva	Krinsvatn	Unpeaked	0.13	0.20	0.04	0.12	1
Aurland	Lavisbrua	Unpeaked	0.08	0.14	0.07	0.14	1
Storana	Leirberget i Årdal	Unpeaked	0.11	0.18	0.09	0.29	1
Lilleelv	Lilleelv	Unpeaked	0.08	0.13	0.01	0.01	1
Manndalselva	Manndalen Bru	Unpeaked	0.13	0.18	0.04	0.09	1
Mevatnet	Mevatnet	Unpeaked	0.09	0.10	0.02	0.05	1
Oyensaa	Øyungen	Unpeaked	0.09	0.16	0.02	0.10	1
Guddalselva	Seimfoss	Unpeaked	0.10	0.16	0.03	0.08	1
Stryn	Strynsvatn	Unpeaked	0.05	0.07	0.11	0.20	1
Reisaelva	Svartfossberget	Unpeaked	0.07	0.10	0.12	0.27	1
Lygna	Tingvatn	Unpeaked	0.10	0.14	0.06	0.16	1

Table 5 Hydropeaking threshold variability as function of: country, different years and number of gauged stations used for the computation.

	Year	TR_{HP1}	TR_{HP2}
Italy	2012	0.76	0.79
Switzerland	2007	1.10	1.61
	2008	1.00	1.33
	2009	1.09	1.42
	2010	0.97	1.36
	2011	1.14	1.18
	2012	1.01	1.66
	Mean	1.04	1.43
Norway	2007	0.61	1.36
	2008	0.56	1.10
	2009	0.59	1.16
	2010	0.56	1.59
	2011	0.66	1.59
	2012	0.57	1.27
	Mean	0.59	1.21
	N° of data series		
N° of data series for the computation	2	0.71	1.15
	5	0.73	1.17
	10	0.75	1.23
	50	0.75	1.22
	100	0.75	1.23
	150	0.75	1.23
	200	0.75	1.23
Global thresholds	282	0.75	1.26

Table 6 Frequency of class changes for different hydropeaking threshold, calculated for all the possible sub-datasets. In brackets the frequency of changes between class 1 and class 3.

	Peaked			Unpeaked		
	IT	CH	NO	IT	CH	NO
Geographical areas	0.10 (0)	0.09 (0)	0.06 (0)	0.02	0.03	0
Years	-	0.09 (0)	0.15 (0.035)	-	0	0
Breakdown time	0 (0)	0.04 (0)	-	0	0.03	-
N° of data series	0.01 (0)	0 (0)	0 (0)	0	0.01	0

Table 7 Values of the two indicators calculated on the simulated data and comparison between classes of simulated data and measured data series.

Watershed	Gauged station	Group	HP1	HP2	Class (Simulated data)	Class (Measured data)
Rhone	Porte du Scèx	Peaked	0.08	1.22	1	2b
Rhone	Branson	Peaked	0.07	1	1	2b
Rhone	Sion	Peaked	0.07	1.08	1	2b
Saltina	Brig	Peaked	0.06	0.28	1	1
Vispa	Visp	Peaked	0.09	0.18	1	3