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A graphical approach to characterize sub-daily flow regimes and evaluate its alterations due to hydropeaking

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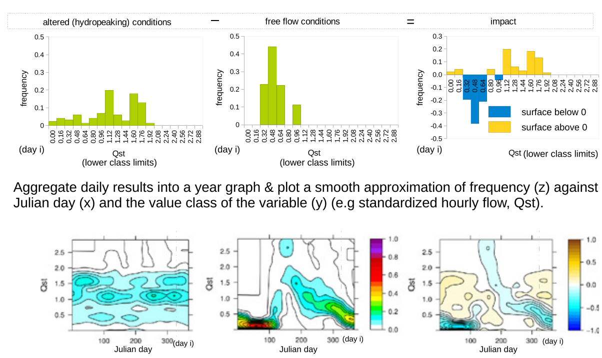
HIGHLIGHTS

- A graphic method for characterizing flow regime at short time intervals is proposed.
- Presented graphical display allows sensitive metrics visual identification.
- Hydropeaking alteration can be assessed without *a priori* subjective assumptions
- This method evaluates hydropeaking impact by comparison with reference flow conditions.

GRAPHICAL ABSTRACT



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ABSTRACT

Most flow regime characterizations focus on long time scale flow patterns, which are not precise enough to capture key components of short-term flow fluctuations. Recent proposed methods describing sub-daily flow fluctuations are focused on limited components of the flow regime being unable to fully represent it, or on the identification of peaking events based on subjectively defined thresholds, being unsuitable for evaluations of short-term flow regime alterations through comparisons between regulated and free-flowing rivers. This study aims to launch an innovative approach based on the visual display of quantitative information to address the challenge of the short-term hydrologic characterization and evaluation of alteration resulting from hydropeaking. We propose a graphical method to represent a discrete set of ecologically relevant indices that characterize and evaluate the alteration of sub-daily flow regimes. The frequency of occurrence of classified values of a descriptive hydrological variable is represented in a map-like graph where longitude, latitude and altitude represent the Julian day, the value of the variable and the frequency of occurrence, respectively. Subsequently, we tested the method on several rivers, both free-flowing and subjected to hydropower production. The advantages of our approach compared to other analytical methods are: (i) it displays a great amount of information without oversimplification; (ii) it takes into account changes in the intensity, timing and frequency of the sub-daily flows, without needing a priori defined thresholds to identify hydropeaking events; and (iii) it supports the Water Framework Directive goal. Specifically, results from applications of our graphical method agree with Sauterleute and Charmasson (2014) analytical method.

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1. Introduction

Hydropower is considered a clean, flexible, and renewable energy source, and the demand for hydropower is likely to increase as fossil fuels are phased out (e.g., by 40% until 2020 in Europe; Renöfält et al., 2010). In northern countries, climate change models predict future hydrographs to match power demands better, increasing the potential for producing more electricity (European Greenpower Marketing, 2006). Additionally, in certain regions such as Europe, hydropower is also being favored by legislation (e.g., the Renewable Energy Directive [RES; 2009/28/EC]) and the recently deregulated energy market. However, the global benefits of hydropower are accompanied by significant local impacts and environmental losses. Flow regime alteration constitutes a major impact from hydropower dam operation on fluvial ecosystems (Bunn and Arthington, 2002; Poff et al., 1997).

The deregulation and variable pricing in the electrical energy market gives hydroelectric producers an economic incentive to respond to rapidly changing electrical demands (Morrison and Smokorowski, 2000). Consequently, more hydropower installations are producing electricity using hydropeaking. Hydropeaking refers to rising or falling discharges caused either by the turning on or off of hydro-turbines to generate electricity according to variations in the market demand, often on daily or hourly time scales (Moog, 1993). As a result, downstream (Ibarra et al., 2015) and upstream river hydrology (e.g. Vollset et al., 2016) is altered due to rapid, frequent and significant fluctuations in discharge, which result also in unnatural changes in hydraulic parameters such as water level, flow velocity and bed shear stress, in water quality such as turbidity and temperature, and in river morphology. Although river flows vary on multiple temporal scales, from minutes to decades (Poff et al., 1997), it is the assessment of short-term changes in river flow (e.g., sub-daily flow variation) that is important for understanding the effects of hydropower generation dams on riparian and aquatic species and communities through hydropeaking (Meile et al. 2011; Zimmerman et al., 2010).

The majority of research to date has focused on flow variability at the daily, seasonal and longer time scales, and despite the numerous existing hydrologic indices (see review by Olden and Poff, 2003), most characterizations of flow regimes, quantitative measures of their alterations, and tools and software available today for calculations are based on daily-averaged flow records (e.g. Richter et al., 1996, 1997; Clausen and Biggs, 2000; Baker et al., 2004; Gao et al., 2009; Carlisle et al., 2010; Fitzhugh and Vogel, 2011) which are not precise enough to capture key components of sub-daily flow fluctuation (Zolezzi et al., 2009; Zimmerman et al., 2010). Day-to-day and within-day water additions or losses in free-flowing rivers are ultimately caused by variations in rates of precipitation, evapotranspiration, infiltration and snowmelt, and by watershed characteristics (Lundquist and Cayan, 2002; Archer and Newson, 2002). These variations are small compared to the variability at annual time scales, but they have been shown also key for fish (see for example Saltveit et al., 2001) and macroinvertebrate (see for example Cereghino and Lavandier, 1998).

Few indices have been very recently proposed to describe the sub-daily flow fluctuation. Most of them focus on certain components of the flow regime, hence being unable to fully represent it (Meile et al., 2011; Haas et al., 2014; Chen et al., 2015), and only some of them have already been used for the evaluation of sub-daily flow alterations (Zimmerman et al., 2010; Carolli et al., 2015). Sauterleute and Charmasson (2014), Bevelhimer et al. (2015) and Bejarano et al. (2016) developed a more thorough suite of indices quantifying the magnitude, the frequency and rapidity of flow changes during the day. Additionally, Sauterleute and Charmasson's indices provide information on the timing of the flow fluctuations and, together with those proposed by Bejarano et al. (2016), are the only indices which were applied to both discharge and water level. Differently to Bejarano et al. (2016) who focused on within-day hourly flow and level patterns, Sauterleute and Charmasson's methodology involves the identification of peaking events based on subjectively defined thresholds for the rate of change, making it unsuitable for evaluations of short-term flow regime alterations through comparisons between regulated and free-flowing rivers due to the unlikelihood of such peaking events in the latter.

Overall, traditionally devised hydrologic indices are analytic solutions to the problem of quantitatively describing the flow regime at different time scales. In order to properly characterize within-day hydrologic variation, there are a bunch of several key aspects of a within-day hydrograph which need to be quantitatively accounted (e.g., up to 62 hydrologic indices proposed by Bejarano et al., 2016), in the same way as up to 32 biologically relevant hydrologic parameters into five major groups (i.e., magnitude, timing, frequency, duration, and rate of change) are necessary to characterize intra-annual hydrologic variation (Richter et al., 1996). As many graphs (at least) as number of computed indices and usually large tables are commonly required to describe, explore, and summarize these sets of numbers. Consequently, the interpretation as a whole of such amount of information translated into numerical data is complex. Therefore, it is surprising that abstract, non-representational pictures haven't been used yet in the field of hydrologic characterization to help interpretations (but see for example White et al., 2005). At their best, graphics are instruments for reasoning about quantitative information (Onwuegbuzie and Dickinson, 2008). Furthermore, of all methods for analyzing and communicating large numerical information, well-designed data graphics are usually the most accurate and efficient, the simplest, and at the same time the most powerful (Tufte, 2001).

Research on short-time scale flow regimes is still needed to devise a comprehensive, non-redundant suite of sub-daily flow metrics that adequately characterize within-day flow regime and evaluate its alteration, and which provides useful and easily understandable information for an environmental management of a hydropower plant (e.g., identifying environmental flow targets, prioritizing river restoration or dam reoperation efforts and contributing information for relicensing hydropower dams). Our main goal in this study relies on the powerful ability of humans to understand spatial information (Wainer, 1992). We aim to launch an innovative approach based on the visual display of quantitative information to address the challenge of the short-term hydrologic characterization and evaluation of alteration. We first propose a graphical method to represent a discrete set of ecologically relevant indices that characterize and evaluate the alteration of sub-daily flow regimes. In this approach the frequency of occurrence of classified values of a descriptive hydrological variable (e.g. hourly flow, amplitude, rate of change, …) throughout the year is represented in a map-like graph where longitude, latitude and altitude represent the Julian day, the value of the variable and the frequency of occurrence, respectively. A large number of hourly hydrographs can be represented by means of this type of graphs. Subsequently we test the method on several rivers, both free-flowing and subjected to hydropower production. Finally, we evaluate the advantages of our approach by comparing to other analytical methods.

2. Methods

2.1. Graphical approach description

Our graphical framework involves the representation of the values of variables that characterize relevant aspects of the short-term flow regime by describing its frequency during several years of observed values of such variable throughout the year. We propose a visual display of the frequency distribution of occurrence of all values of a descriptive variable along the year by means of a map-like graph where longitude (x axis) is the Julian day, latitude (y axis) is the value of the descriptive variable and altitude (z axis) is the frequency of a given value of the variable at a given day of the year. In order to build this graph, we first calculate the frequency distribution of a given variable at a given day (Fig. 1 [a], [b], [c]), and then plot together all the daily frequency distributions along the year (Fig. 1 [d], [e], [f]).