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Research papers

Characterizing effects of hydropower plants on sub-daily flow regimes

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ABSTRACT

A characterization of short-term changes in river flow is essential for understanding the ecological effects of hydropower plants, which operate by turning the turbines on or off to generate electricity following variations in the market demand (i.e., hydropeaking). The goal of our study was to develop an approach for characterizing the effects of hydropower plant operations on within-day flow regimes across multiple dams and rivers. For this aim we first defined ecologically meaningful metrics that provide a full representation of the flow regime at short time scales from free-flowing rivers and rivers exposed to hydropeaking. We then defined metrics that enable quantification of the deviation of the altered short-term flow regime variables from those of the unaltered state. The approach was successfully tested in two rivers in northern Sweden, one free-flowing and another regulated by cascades of hydropower plants, which were additionally classified based on their impact on short-term flows in sites of similar management. The largest differences between study sites corresponded to metrics describing sub-daily flow magnitudes such as amplitude (i.e., difference between the highest and the lowest hourly flows) and rates (i.e., rise and fall rates of hourly flows). They were closely followed by frequency-related metrics accounting for the numbers of within-day hourly flow patterns (i.e., rises, falls and periods of stability of hourly flows). In comparison, between-site differences for the duration-related metrics were smallest. In general, hydropeaking resulted in higher within-day flow amplitudes and rates and more but shorter periods of a similar hourly flow patterns per day. The impacted flow feature and the characteristics of the impact (i.e., intensity and whether the impact increases or decreases whatever is being described by the metric) varied with season. Our approach is useful for catchment management planning, defining environmental flow targets, prioritizing river restoration or dam reoperation efforts and contributing information for relicensing hydropower dams.

1. Introduction

Critical components of the flow regime such as magnitude, frequency, duration, timing and rate of change control ecological processes in river ecosystems (Poff et al., 1997), and modification of flow regimes constrains the distribution of species, their adaptive capacity, survival, dispersal and reproduction (Lytle and Poff, 2004). Each of these five flow components describes the variability over a wide range of spatial and temporal scales (Ward, 1989). Flow variability may be considered at long time scales, which are commonly controlled by inter- and intra-annual variations in climate. Year-to-year variation in flows associated to the Interdecadal Pacific Oscillation index and shifts in the El Niño Southern Oscillation phenomenon (Biggs et al., 2005), and month-to-month variation in flows associated to seasons (Bejarano et al., 2010) are examples of large time-scale flow variability. Additionally, topography and geology are usually superimposed on climate and shape intra-annual flow variation in, for example, snowmelt-fed or groundwater-fed rivers (Bejarano et al., 2010). Furthermore, flow variability may also be considered at shorter time scales, from months to hours (or smaller). Day-to-day and within-day water gains or losses are ultimately caused by varying rates of precipitation, evapotranspiration, infiltration, and snowmelt and by catchment characteristics such as drainage area, slope and land uses (Lundquist and Cayan, 2002; Archer and Newson, 2002), and can often be in the order of 10% of the mean daily flow in free-flowing rivers (Schuster et al., 2008). While these variations are small relative to the variability at annual time scales, they are still likely to be important to some stream ecosystem characteristics. Biggs et al. (2005) described how flow variation at these different temporal scales affects different ecosystem components and

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processes in rivers from New Zealand. They recognized that there may be a hierarchical relationship between time scales of flow variability and related physical processes, the effect of these physical processes on biological processes and, ultimately, the organization of ecosystem characteristics.

Rivers used for hydropower production usually show day-to-day and within-day flow variations that are considerably higher, more rapid and frequent than the ones characterizing free-flowing rivers. This is the result of turning hydro-turbines on or off to generate electricity based on variations in the market demand, so called hydropeaking (Moog, 1993), which has been recently promoted by the deregulation of the energy market. Additionally, changes in the short-term flow regimes are accompanied by changes in hydraulic parameters such as water level, flow velocity and bed shear stress, and in water quality and river morphology, and all together cause significant environmental losses in the fluvial systems. Although there are still many unknowns, studies have revealed significant effects of hydropeaking on fish, including low egg survival (Casas-Mulet et al., 2015), slow growth (Flodmark et al., 2004), reduced abundance (Korman and Campana, 2009), stranding (Saltveit et al., 2001), habitat deterioration (Vehanen et al., 2005) and changes in behavior (Robertson et al., 2004). A few studies have also pointed out heavy drift of macroinvertebrates (Carolli et al., 2012), and reductions in the occurrences of beetles (Van Looy et al., 2007) and macrophytes (Mjelde et al., 2013). Above all, hydropower is the world's leading form of renewable energy, and its demand is likely to increase globally as being a clean, flexible, and renewable energy source which does not produce greenhouse gases. Development of new hydropower plants is accelerating in Southeast Asia, Africa, and Latin America (Jager et al., 2015). In Europe, hydropower is being promoted by legislation such as the Renewable Energy Directive (RES; 2009/28/EC), which sets a legally binding national target of 20% of gross final energy consumption from renewable sources by 2020. In addition, 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). Consequently, an important challenge for river management arises which involves maximizing hydropower production with minor ecological impacts. To cope with this demand for industry and society, assessment of the short-term changes in river flow following hydropeaking and of the resulting ecological responses is key. This paper deals with such assessment.

To evaluate the impact of hydropeaking resulting from hydropower production on short-term (e.g., sub-daily) flow regimes, it is necessary to characterize the within-day flow regime along the river reach affected by the hydropower plant and to quantify its deviation from the unaltered state. Metrics available are scarce and do not allow a comprehensive characterization of short-term flow regimes as they do not account for all hydrological attributes of ecological importance (Zimmerman et al., 2010; Meile et al., 2011; Haas et al., 2014; Sauterleute and Charmasson, 2014; Bevelhimer et al., 2015; Carolli et al., 2015; Chen et al., 2015). In addition, most proposed metrics are not conceived to quantify the degree of alteration. Research to date has focused on flow variability at the daily, seasonal and longer time scales (see review by Olden and Poff, 2003). Most characterizations of flow regimes, quantitative measures of their alterations, and tools and software available 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., 2011; Fitzhugh and Vogel, 2011), which are not precise enough to capture key components of sub-daily flow fluctuation. Long series of instantaneous flow records (e.g., every 15, 30 or 60 min) are required from both the altered and comparable free-flowing conditions for characterization of flow regimes at such shorter time scales and for evaluating the intensity of the changes.

The fact that these pairs of flow series are commonly difficult to find might have discouraged the studies on short-term flow regimes up to date, though this situation is reverting in recent times. Thus, new methods are needed to comprehensively describe all facets of within-day flow regimes and assess their degree of deviation from the natural conditions, to identify dams that artificially modify natural sub-daily variations and river reaches that are likely to experience ecological degradation because of it. Such analyses are useful for catchment management plans, defining environmental flow targets, prioritizing river restoration or dam reoperation efforts and contributing information for relicensing hydropower dams. The goal of our study was to develop an approach for assessing the effects of hydropower dam operations on within-day flow regimes across multiple dams and rivers. For this aim we first defined ecologically meaningful metrics that provide a full representation of the short-term variation of flow in free-flowing rivers and rivers exposed to hydropeaking. We then defined metrics that enable quantification of the deviation of the characterized altered short-term flow regime from the unaltered state. We applied devised characterization and impact metrics to several study sites along a free-flowing river and a river with hydropeaking (at hydropower plant locations) and, with management facilitation purposes, we classified them according to their short-term flow regime alterations.

2. Material and methods

2.1. Study area and flow data

The study was located to the Vindel and Ume rivers in the Ume River basin in northern Sweden (Fig. 1). The Vindel River is the main tributary of the Ume River; it runs parallel to the Ume and joins it about 30 km upstream of the mouth in the Baltic Sea. Both rivers show similar characteristics. The whole Ume basin is characterized by cold-temperate climate, boreal coniferous vegetation and podzol soils. The upland vegetation consists of subalpine birch forests dominated by *Betula pubescens*, and coniferous forests dominated by *Pinus sylvestris* and *Picea abies*. The riparian vegetation includes woody species such as *Alnus incana*, *B. pubescens* and *Salix* spp., and herbs such as *Carex* spp. and *Ranunculus reptans*. The Vindel and Ume rivers have catchment areas encompassing 13,183 and 13,633 km^2, respectively, their channel lengths are 445 and 455 km, and their natural mean monthly flows (at the junction) 197 and 239 m^3/s. Whereas the flow regime of the Vindel River remains unaltered, the Ume River flow is highly impacted by a chain of hydropower plants and reservoirs which cause hydropeaking (Fig. 2). The free-flowing regime experiences a marked seasonal variation with low flows during late autumn and winter and floods during spring. Within a day, the free-flowing regime is relatively smooth and only fluctuates significantly after water additions or losses resulting from significant precipitation, evapotranspiration, infiltration and snowmelt events. In contrast, dams and reservoirs alter both the long- and short-term flow regimes of the Ume River; whereas the natural seasonality of flows is attenuated, the within-day flows fluctuate abruptly (Fig. 2). We selected three sites along the Vindel River [from upstream to downstream: Gautsträsk (U; 33 m^3/s mean annual flow), Sorsele (S; 119 m^3/s) and Granåker (K; 176 m^3/s)] and eight sites along the Ume River coinciding with dam and reservoir locations [Grundfors (G; 187 m^3/s), Rusfors (R; 213 m^3/s), Bålforsen (L; 215 m^3/s), Betsele (B; 218 m^3/s), Tuggen (T; 222 m^3/s), Bjurfors övre (O; 227 m^3/s), Bjurfors nedre (N; 232 m^3/s) and Harrsele (H; 235 m^3/s)] where 15-min and 1-h interval flows were available, respectively (Fig. 1). For the