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Evaluation of mitigation measures to reduce hydropeaking impacts on river ecosystems – a case study from the Swiss Alps

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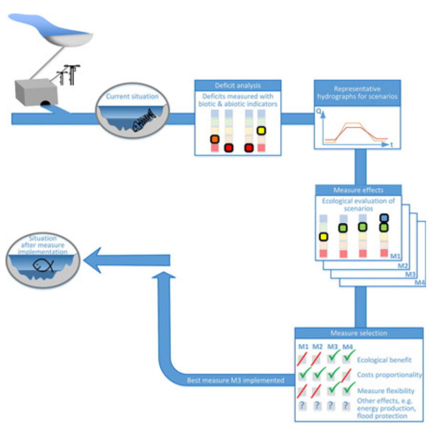
HIGHLIGHTS

- We propose a procedure for the evaluation of hydropeaking impacts and measures.
- Evaluation should be based on representative hydrographs and ecological indicators.
- Mitigation measures should be evaluated with key stakeholders.

GRAPHICAL ABSTRACT



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ABSTRACT

New Swiss legislation obligates hydropower plant owners to reduce detrimental impacts on rivers ecosystems caused by hydropeaking. We used a case study in the Swiss Alps (hydropower company Kraftwerke Oberhasli AG) to develop an efficient and successful procedure for the ecological evaluation of such impacts, and to predict the effects of possible mitigation measures. We evaluated the following scenarios using 12 biotic and abiotic indicators: the pre-mitigation scenario (i.e. current state), the future scenario with increased turbine capacity but without mitigation measures, and future scenarios with increased turbine capacity and four alternative mitigation measures. The evaluation was based on representative hydrographs and quantitative or qualitative prediction of the indicators. Despite uncertainties in the ecological responses and the future operation mode of the hydropower plant, the procedure allowed the most appropriate mitigation measure to be identified. This measure combines a basin and a cavern at a total retention volume of 80,000 m^3, allowing for substantial dampening in the flow falling and ramping rates and in turn considerable reduction in stranding risk for juvenile trout and in macroinvertebrate drift. In general, this retention volume had the greatest predicted ecological benefit and can also, to some extent, compensate for possible modifications in the hydropower operation regime in the future, e.g. due to climate change, changes in the energy market, and changes in river morphology. Furthermore, it also allows for more specific seasonal regulations of retention volume during ecologically sensitive periods

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(e.g. fish spawning seasons). Overall experience gained from our case study is expected to support other hydropeaking mitigation projects.

1. Introduction

Hydropower is an important renewable energy source accounting for 16.3% (without electricity generation from pumped storage) of the world electricity generation (IEA, 2015). Worldwide, China has by far the largest installed capacity (194 GW) and production (920 TWh, ca. 24% of the world total) whereas in Europe, Norway is the first and France the second highest producer of hydropower energy at 129 TWh and 76 TWh, respectively (IEA, 2015). Switzerland is also currently among the largest hydroelectricity producers in the European Alps with 604 hydropower plants greater than 300 kW and an average national annual production of approximately 36 TWh/a (SFOE, 2015). This corresponds to approximately 56% of the country's total electricity supply, and is comparable with the ca. 69% supplied by hydropower in Austria (E-Control, 2015). Around 52% of this electricity is produced by high-head storage power schemes in which water is retained in reservoirs and then fed through turbines to generate electricity on demand during peak consumption periods (SFOE, 2015); in Austria the amount is ca. 34% (E-Control, 2015).

Storage power plants offer numerous advantages over other types of power plants, such as excellent efficiency, rapid response to grid demand, carryover of electricity production from summer to winter, and provision of grid stability by supplementing erratic power production from solar and wind power plants. Furthermore, due to the expected future increase in energy demand and the planned staggered ban of nuclear power in Switzerland, supplementary electricity production by hydropower will probably grow in the coming years (SFOE, 2012). However, storage power plants alter the natural flow regime, mainly because of intermittent production due to reservoir operations reacting to energy demand, and thereby cause severe daily and sub-daily fluctuations in discharge and water levels, so-called hydropeaking (Moog, 1993; Zimmerman et al., 2010; Charmasson and Zinke, 2011; Meile et al., 2011).

Because the hydrological effects of hydropeaking occur much faster and more frequently than those driven by natural events, they may significantly affect aquatic habitats, organisms and riverine ecosystem processes (for a review see Young et al., 2011; Bruder et al., 2016). Common consequences include stranding (e.g. Saltveit et al., 2001; Young et al., 2011; Nagrodski et al., 2012) and drift of aquatic organisms (e.g. Bruno et al., 2009, 2010; Jones et al., 2011). Moreover, fish spawning grounds may be disturbed, for example through dewatering, and suitable shore habitats displaced or lost (Liebig et al., 1998; Saltveit et al., 2001); fine sediments are re-suspended, increasing erosion and water turbidity (Anselmetti et al., 2007; Wang et al., 2013), and water temperature is altered (Zolezzi et al., 2011; Carolli et al., 2012; Bruno et al., 2013). As a consequence, hydropeaking reduces the quality and availability of suitable habitats (Person et al., 2014), which is often manifested in reduced reproduction, survival and biodiversity.

In Switzerland, hydropeaking from 100 to120 hydropower plants with a ratio between peak and base flow ≥1.5:1 is estimated to seriously affect ca. 1000 km of watercourses (Swiss Federal Office for the Environment, 2015, unpublished). To reduce the adverse effects of hydropeaking on riverine ecosystems, hydropower plant owners must take appropriate mitigation measures by 2030 (Art. 39a and 83a Swiss Water Protection Act). Similarly, hydropeaking mitigation is included in the European Water Framework Directive (WFD, 2000), which contains similar procedures as the Swiss legislation. However, detailed knowledge of various hydropeaking effects, and, in particular, of efficient approaches to mitigate them, is still rare despite increased interest in research and management in recent decades (Moog, 1993; Parasiewicz et al., 1998; Person et al., 2014; Bruder et al., 2016; EnviPEAK, 2016). Methods to investigate hydropeaking impacts have recently been proposed, but they primarily focus on hydrological-hydraulic responses of river reaches to hydropeaking or on a limited number of ecological indicators that can be assessed using statistical or numerical modelling approaches (e.g. Bevelhimer et al., 2015; Carolli et al., 2015; Vanzo et al., 2016). Moreover, these methods consider a reduced number of theoretical measures (e.g. morphological restoration or only changes in hydrological-hydraulic parameters of the flow regime); they have not yet been developed and applied to concrete mitigation projects and specific local conditions.

The aims of our study were to examine possible methods to evaluate hydropeaking impacts, to predict the ecological benefits of possible measures to mitigate these impacts, and to define a viable procedure to select the most appropriate mitigation measure. Using a recent mitigation project as a case study, i.e. that of the hydropower company Kraftwerke Oberhasli AG (KWO), we provide a detailed and applied working example for hydropeaking mitigation. In contrast to previous methods, our overall evaluation of hydropeaking impacts is based on representative hydrographs as well as 12 abiotic and biotic indicators applied to a comparative analysis of several alternative mitigation measures and to the current state. The wealth of information and experience available as a consequence of various assessments carried out in respect of our case study provides methodological details relevant to managers and experts involved in similar hydropeaking mitigation projects. Furthermore, we have embedded the procedures exemplified by our case study in a conceptual framework for hydropeaking mitigation that is transferable to other mitigation projects (see Bruder et al., 2016).

2. Methods

2.1. Hydropower scheme and study area

The hydropower company Kraftwerke Oberhasli AG (KWO) in the Bernese Alps of Switzerland uses the energy of water from a 450 km^2 catchment (21% glaciated in 2003). This water is released into the River Hasliaare (also called upper Aare River) by the two hydropower plants Innertkirchen I and II, where it causes hydropeaking (Fig. 1). Currently, KWO is increasing the turbine capacity of Innertkirchen I from 40 to 65 m^3/s (one additional turbine), allowing for a maximum total flow release in Innertkichen of 95 m^3/s instead of the current 70 m^3/s, which will result in an additional energy gain of 70 GWh/a without supplementary water intakes.

The 16 km of river affected by hydropeaking (henceforth referred to as 'hydropeaking section') begins after the inflow of the River Gadmerwasser into the Hasliaare and ends in Lake Brienz (Fig. 1). The mean annual discharge in the hydropeaking section is ca. 35 m^3/s with natural minimal flow in winter ($Q_{347} = 2.4$ m^3/s; based on data from 1913–1921) and floods typically occurring from May to October ($HQ_2 = 190$ m^3/s), although occasional winter floods can reach 40 m^3/s. The Hasliaare is an oligotrophic alpine river with good water quality.

To reflect the morphological complexity of the Hasliaare and for an accurate evaluation of the biophysical processes occurring (see Section 2.3), the hydropeaking section downstream of the powerhouse releases was divided into four reaches according to their predominant morphological characteristics (Fig. 2): (i) a 0.7 km long and 27 m wide reach with artificial groynes in Innertkirchen; (ii) a naturally channelized 1.9 km long and <10 m wide reach in the Aare gorge; (iii) a 1.4 km long and 34 m wide reach with alternating gravel bars in