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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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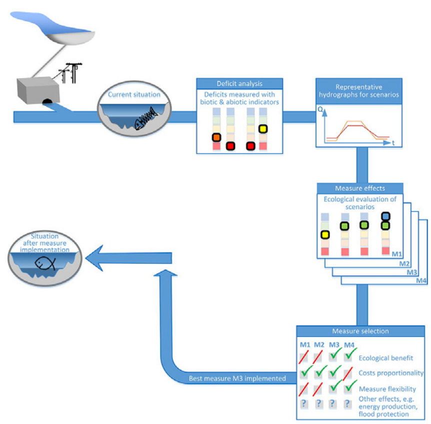
HIGHLIGHTS

- 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

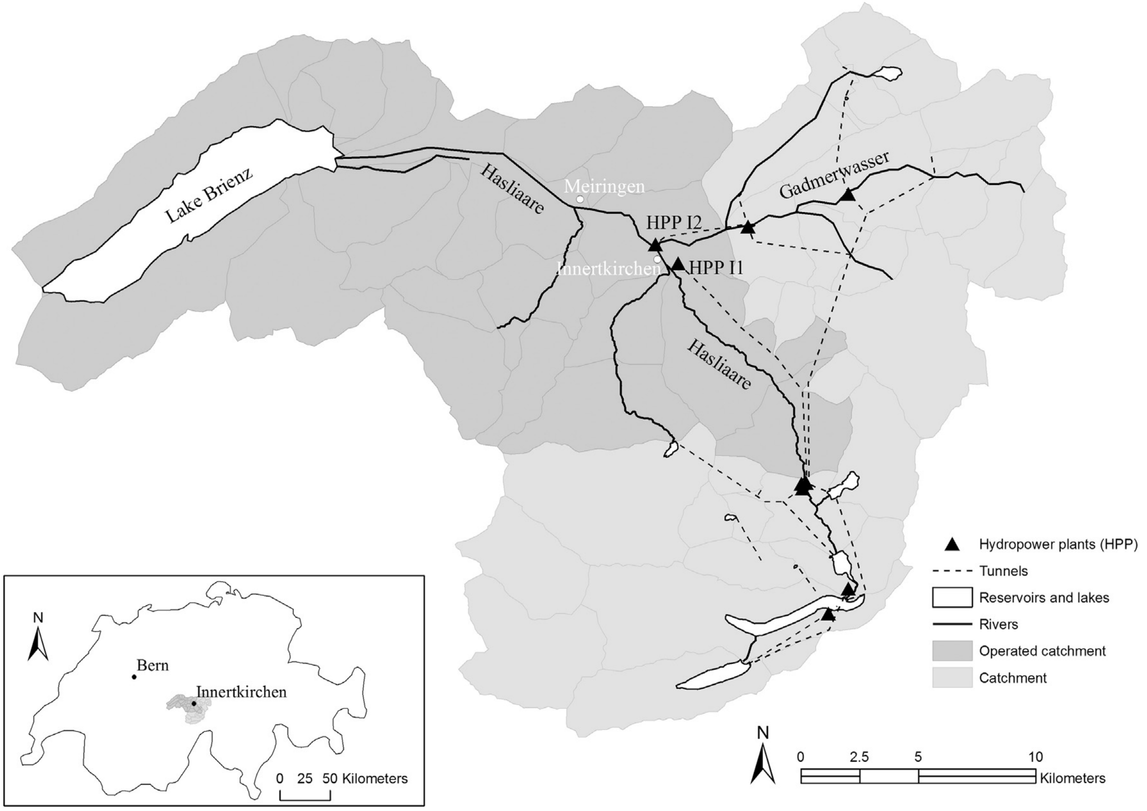

Fig. 1. Overview map of the Hasliaare catchment and the current layout of the KWO hydropower scheme. HPP I1: hydropower plant Innertkirchen I; HPP I2: hydropower plant Innertkirchen II.

Meiringen; (iv) a straight channelized 11.5 km long and 20 m wide reach between Meiringen and Lake Brienz. The median grain size of these reaches was 13 cm. Based on physical and 2D hydrodynamic models (HYDRO_AS-2D, Tolossa et al., 2009), the threshold discharge for bed movement was estimated at 150 m^3/s. Because of the special hydraulic and morphological characteristics as well as the relatively short length and pronounced shading, the Aare gorge was not considered further in the hydropeaking evaluation. Additional information on the catchment area, hydropower scheme, river morphology, and runoff/hydropeaking practice can be found in Bieri (2012), Schweizer et al. (2013a), Bieri et al. (2014), and Person et al. (2014).

2.2. Legal framework and general working phases for hydropeaking mitigation in Switzerland

With the revision of the Swiss Water Protection Act (WPA) and the Swiss Water Protection Ordinance (WPO), which came into force in 2011, a legal basis was created to enforce the reduction of adverse ecological impacts from hydropeaking. This is to be achieved by means of appropriate structural or operational mitigation measures (Moog, 1993; Person et al., 2014; Bruder et al., 2016), which have to be implemented by hydropower plant owners by 2030.

In Switzerland, mitigation of hydropeaking and its adverse effects on riverine-ecosystems is divided into four main phases (Fig. 3). Firstly, by the end of 2014, the cantons, which usually hold the water-use rights, completed their strategic planning; this included the identification of hydropower plants causing hydropeaking and thereby potentially harming aquatic organisms and their habitats, and thus subject to mandatory mitigation measures. In the second phase, cantonal authorities set out mitigation measures for hydropeaking remediation, and required hydropower plant owners to evaluate various types of potential mitigation measures (study of future scenarios), to implement cantonal plans, and select the most appropriate measure. Thirdly, owners are required to implement the best mitigation measures, for which they receive financial support (from a fund fed by an electricity consumption surcharge of 0.1 cent/kWh). Finally, in the fourth phase, owners must verify the effectiveness of the measures taken (i.e. comparison of pre-mitigation and post-mitigation scenarios).

Because of the planned upgrade in their production scheme, KWO started their hydropeaking evaluation before the revision of the WPA, and thus before the official time schedule for hydropeaking mitigation.

Fig. 2. The three study reaches of the hydropeaking section of the Hasliaare. A: channelized reach with artificial groynes in Innertkirchen; B: reach with alternating gravel-bars in Meringen; C: straight channelized reach downstream of Meiringen. Arrows indicate the direction of flow.

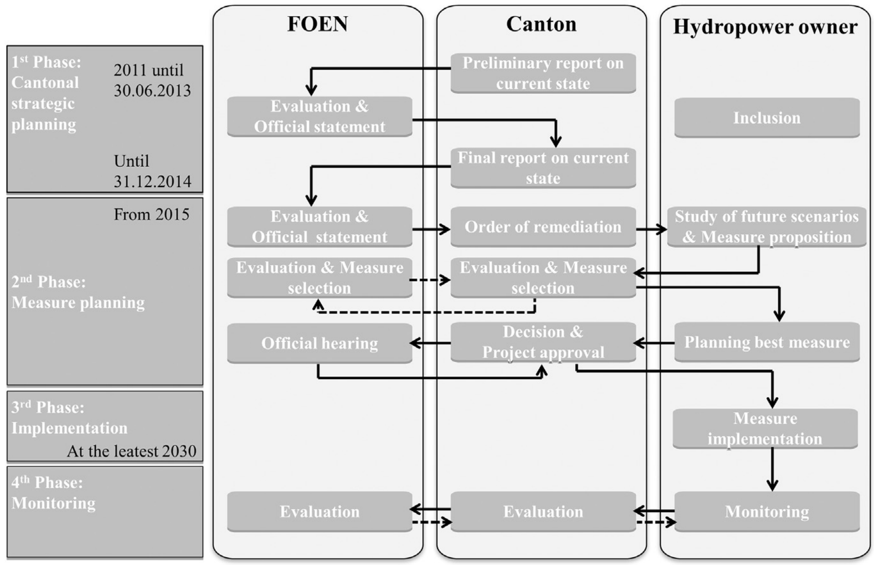

Fig. 3. Simplified overview of the four working phases for hydropeaking mitigation in Switzerland. FOEN: Swiss Federal Office for the Environment; solid arrow: mandatory; dashed arrow: if necessary.

2.3. Hydropeaking evaluation

To evaluate the impacts of hydropeaking caused by KWO and the mitigation measures being considered, current hydropeaking impacts as well as further possible impacts caused by the planned increase in turbine capacity at Innertkirchen I by 25 m^3/s were considered. For this reason, a group composed of representatives of the Swiss Federal Office for the Environment (FOEN), the cantonal authorities of Bern, and the KWO defined three distinct scenarios to be evaluated by the respective four-step workflow (Fig. 4). The three scenarios were (i) the pre-mitigation scenario (i.e. current state; SI), (ii) a future scenario with increased turbine capacity but without mitigation measures (SII), and (iii) a future scenario with increased turbine capacity and a set of possible mitigation measures (SIII).

In the first step, representative hydrographs of each scenario were developed by measured flow series and hydrodynamic models to generate the distribution of hydraulic conditions for each input discharge (Fig. 4). Second, certain statistical values of the hydrographs were defined based on percentiles of the generated flow series (peak and base flow, ramping and falling rates). Third, these values were used as input for the ecological evaluation of the different scenarios, based on 12 biotic and abiotic indicators. Fourth, the most appropriate mitigation measure was selected considering the ecological benefits and the cost as well as other criteria and stakeholders interests.

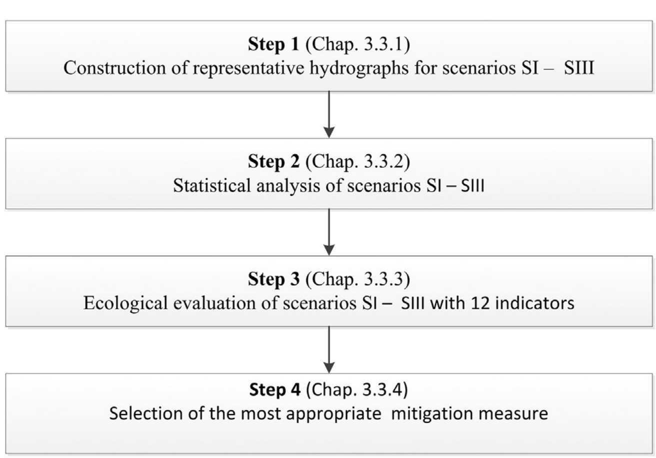

Fig. 4. Four-step workflow for hydropeaking evaluation in the Hasliaare. SI: pre-mitigation scenario; SII: future scenario with increased turbine capacity but without mitigation measures; SIII: future scenario with increased turbine capacity and a set of possible mitigation measures.

2.3.1. Step 1: construction of representative hydrographs

The largest deviation from the natural flow regime and the strongest hydropeaking effects in the Hasliaare occur in winter due to generally low natural runoff. Moreover, the winter months represent an important period for many ecological processes such as trout spawning and the life histories of many macroinvertebrate (Person et al., 2014).

In the last few years, the energy market in Europe has become exposed to higher volatility due to increased production capacity of new renewables, mainly solar and wind power. Storage hydropower plants are able to provide grid regulation, so-called ancillary services. The energy supplier is compensated for providing a particular capacity, which might be requested at given time or not. Thus, KWO recently changed the operational regime of some plants to provide ancillary services to the grid. As a consequence, the turbines of Innertkirchen I often operate with a reduced capacity, allowing for a rapid increase or decrease in electricity production as soon as requested by the grid. Analysis of the flow data series before and after the implementation of the ancillary services showed a decreasing tendency towards hydropeaking.

Instead of generating artificial operation scenarios for KWO, which would introduce several uncertainties given the assumptions made (Bieri, 2012), and because of the considerations described above, the representative hydrograph for the pre-mitigation scenario SI corresponds to the flow series measured. We considered 15-minute data series of turbine releases at Innertkirchen I and II plus the runoff from the non-operated catchment of the four winter periods between mid-November and mid-March from 2009 to 2012 (Bieri et al., 2014).

Several techniques were considered to simulate the future operation of KWO, and including market models which consider climate change and electricity price forecasts, statistical measures, etc. The parties involved agreed that the production data from 2009 – 2012 should be used to develop the future operation of the hydropower plant (with increased turbine capacity). In respect of the hydropower plant Innertkirchen I, an increased turbine capacity of 25 m^3/s was considered in scenario SII by a stepwise increase in observed turbine discharge series from 2009 to 2012 (Table 1). When the total discharge of Innertkirchen I and II was >54 m^3/s, representing around 75% of the current total capacity, the maximum increase of 25 m^3/s was added. However, it is noteworthy that the current maximal turbine capacity of 70 m^3/s was never reached between 2005 and 2012, and that turbine discharge was always below 60 m^3/s. For turbine discharge <34 m^3/s (ca. 50% of the current total capacity), no additional release was considered and between 34 and 54 m^3/s proportional addition was applied (Table 1).

An earlier socio-economic evaluation showed that retention volumes (i.e. basins and caverns) were the only structural measures that could mitigate hydropeaking impacts with a realistic cost-to-benefit ratio (Person et al., 2014). For instance, direct diversion of turbinated water into Lake Brienz was excluded because of extensive cost. Furthermore, operational measures directly at the hydropower plant (e.g. a decrease in peak flow, or a reduction in ramping and falling rates) were also discarded a priori because in Switzerland they can only be imposed by the relevant authority if chosen by the hydropower owner over structural measures. This reflects a political decision taken during the revision of the WPA, which aims to minimize the negative consequences of operational measures, such as reduced flexibility of production and lowered supply of renewable energies. Because of limited land availability and restrictions due to flood protection, the volume available for retention basins in Innertkirchen was restricted to ca. 20,000 m^3, with additional volume available only by building a cavern. Consequently, retention volumes of the following sizes were considered to be technically and economically realistic and thus further evaluated: 50,000 m^3, 60,000 m^3, 80,000 m^3 and 100,000 m^3 corresponding to scenarios SIIIa to SIIId. The representative hydrograph constructed for scenario II was used as input to simulate operation of the four possible retention volumes (for details see Bieri et al., 2014), resulting in representative hydrographs of future scenarios SIIIa to SIIId, and reflecting the effect of increased turbine capacity combined with the mitigation measures. Optimization of mitigation operation was undertaken considering characteristic statistical values described in Section 2.3.2.

Finally, the generated representative hydrograph of each scenario (SI, SII, SIIIa – SIIId) was assessed by a 2D hydrodynamic model (HYDRO_AS-2D, Tolossa et al., 2009) for each of the three morphologically distinct reaches of the hydropeaking section as attenuation of peak flow occurs along the river course. The model considered river bathymetry measured by combining a tachymeter terrestrial system with a GPS echo sounder (final grid size 0.5 m), calibrated by turbine peak flow events (Person et al., 2014). The model simulated the distribution of flow depths and velocities in the reaches, generating a distribution of hydraulic conditions for each generated input discharge.

2.3.2. Step 2: statistical analysis of the different scenarios

Once the representative hydrographs had been constructed, statistical parameters were calculated. Because of natural flow dynamics and a certain resilience of aquatic organisms to extreme events, statistical analysis was based on percentiles of the generated flow series. The 95% and 100% percentiles of peak and base flow as well of the ramping and falling rates (based on daily maximum and minimum values respectively) were defined for all scenarios. The resulting hydrological parameters (95% and 100% percentiles of peak and base flow, ramping and falling rates) and hydraulic conditions (i.e. distribution of flow depths and velocities) were then used to characterize and compare the hydropeaking events of each scenario, and as input for the ecological evaluation of the different scenarios.

Table 1
Stepwise increase in maximum discharge, representing the future scenario with increased turbine capacity (SII). *Detailed considerations for the construction and selection of representative discharge conditions and representative hydrographs are described in Schweizer et al. (2013b).*

Current total turbine discharge (m^3/s)	Stepwise increase (m^3/s) for scenario SII
<34	+0
34–39	+5
39–44	+10
44–49	+15
49–54	+20
>54	+25

2.3.3. Step 3: ecological evaluation of the different scenarios

The ecological evaluation of the different scenarios was based on 12 biotic and abiotic indicators proposed by the FOEN (Baumann et al., 2012) and included hydraulic habitat modelling and expert judgments as well as comparison with published studies and with a reference river (River Lütschine: similar catchment size, morphology and glaciation as the Hasliaare, but negligible hydropower influence). The value of each individual indicator was linked to a range of five ecological-quality classes: (i) very good, (ii) good, (iii) moderate, (iv) unsatisfactory, and (v) poor, these being comparable to the classes in the assessment guidelines of the European Water Framework Directive (WFD, 2000). Evaluation of each indicator was first performed separately for the three different hydropeaking reaches, and then worst-case aggregated over the entire hydropeaking section, except for the indicator 'longitudinal zonation of macroinvertebrates' (M3; Table 1 in Schweizer et al., 2013c). All indicators are described in detail in Baumann et al. (2012; available in German, French and Italian) and a short description, including the possible methodological adjustment applied in our case study, is given below. Moreover, the four indicators 'fish stranding' (F2), 'macroinvertebrate biomass' (M1), 'diversity of sensitive macroinvertebrate taxa' (M4), and 'water temperature' (T1) were selected as the most representative for our case study, the evaluation method being described in detail in the Supplementary material.

Five indicators in Baumann et al. (2012) consider possible hydropeaking effects on fish. The indicator 'fish community structure' (F1) was evaluated considering species composition and dominance relationships, population structure and density of target species as well as deformities and anomalies of fishes caught by electrofishing (Schager and Peter, 2004). Each criterion was evaluated with a malus point system where the number of points increases with each difference to the situation expected under natural conditions. This indicator was categorized into five ecological quality-classes given using different point ranges. The indicator 'fish stranding' (F2) was evaluated considering the variation in the wetted area during a hydropeaking event (%) and the flow falling rate (cm/min) computed from hydraulic models as well as from the number of stranded fish directly observed during field surveys (#/100 m). In our case study, the effect of the percentage of wetted area and of the flow falling rate on stranding risk was computed using the ecohydraulic habitat model CASiMiR (a fuzzy logic-based model; Garcia et al., 2011). Baumann et al. (2012) categorized this indicator into three (rather than five) ecological quality-classes given by the different value ranges of each criterion (Table S1 Supplementary material). Because the evaluation of the three reaches using these three criteria was quite diverse, the experts decided to use five ecological quality-classes for this indicator for the aggregated evaluation of the entire hydropeaking section (Schweizer et al., 2013c). The indicator 'fish spawning grounds' (F3) was evaluated considering the area with sufficient water depth (>20 cm) at natural low flow and at base flow, the area with stable substrate at peak flow, and the area with appropriate grain size for spawning. In our case study, the areas were computed for the situations with and without the hydropower plant using CASiMiR. This indicator was categorized into five ecological quality-classes given by the amount of suitable area with hydropeaking compared to the area without hydropeaking. In Baumann et al. (2012), the indicator 'fish reproduction' (F4) is evaluated by considering the number of juvenile brown trout caught by electrofishing and calculated as catch per unit effort (CPUE) if sampled in spring or as abundance (#/ha) if sampled in summer/autumn. This indicator is then categorized into five ecological quality-classes given by different CPUE or abundance ranges. The abundance ranges are further grouped into three different Swiss ecoregions, the Alps, the foothills of the Alps, and the midland/ Jura. In our case study, the 0+ fish were caught in May from 2009 to 2011 and the summer abundances for the ecoregion Alps was calculated. The indicator 'fish productivity' (F5) was evaluated by considering the theoretical productivity of the river section calculated as annual fish biomass per hectare (JHE; Vuille, 1997). The formula to calculate the JHE includes macroinvertebrate biomass (g/m^2) corrected for each community composition, a water temperature coefficient, a habitat coefficient for morphological variability estimated using the river width, flow depth and velocity, grain size, etc. and the typical fish region calculated from the river width and slope (Huet, 1949). This indicator was categorized into five ecological quality-classes given by different JHE (kg/ha) ranges and further grouped using three different altitude ranges for watercourses <500 m a.s.l., 500–1000 m a.s.l., and >1000 m a.s.l. In our case study, the expected values for the JHE proposed in Baumann et al. (2012) were reduced by ca. 50% in consideration of local conditions in the Hasliaare such as the high percentage of glacial water (Schweizer et al., 2013c) and comparison with the reference river.

Four indicators in Baumann et al. (2012) consider possible hydropeaking effects on macroinvertebrates. Macroinvertebrates are semi-quantitatively collected in typical habitats by 'kick netting' (25 × 25 cm, 1 mm mesh), taxa are then sorted, counted and identified to the family or species level and finally used for the evaluation of all four indicators. The indicator 'macroinvertebrate biomass' (M1) was evaluated by considering the altitude-dependent biomass of macroinvertebrates, which was calculated using the formula described by Jungwirth et al. (1980): $BM = 1/(0.000261 \times (A - 0.032))$, where BM = macroinvertebrate biomass as fresh weight in g/m^2, and A = height above sea level in meters. This indicator was categorized into five ecological quality-classes given by various ranges of the difference (in %) between the nominal biomass value (defined by the biomass-altitude relationship) and the measured biomass (Table S2 Supplementary material). The indicator 'macroinvertebrate diversity' (M2) was evaluated considering the macroinvertebrate community structure based on species diversity and target taxa at family level calculated as IBCH index (Stucki, 2010), a Swiss adaptation of the French 'Indice biologique global normalisé' (AFNOR, 1992). This indicator was categorized into five ecological quality-classes using different ranges of the IBCH value. The indicator 'longitudinal zonation of macroinvertebrates' (M3) was evaluated by considering the longitudinal zonation (from Eukrenal to Hypopotamal) of macroinvertebrate taxa identified at species level and calculated as longitudinal zonation index (Moog & Ofenböck, 2003); this was then categorized into five ecological quality-classes using different ranges of the difference (in points) between the value determined with the longitudinal zonation index and the nominal value of the 'fish biocoenotic region' (calculated using river width, slope and temperature). In our case study, instead of taking the 'biocoenotic region' as the nominal value, the species composition of the reference river was used to evaluate whether hydropeaking had an influence on the longitudinal zonation patterns of macroinvertebrates (*sensus* Céréghino et al., 2002). The indicator 'diversity of sensitive macroinvertebrate taxa' (M4) was evaluated considering the number of macroinvertebrate families belonging to the Ephemeroptera (mayfly), Plecoptera (stonefly) and Trichoptera (caddysfly). These macroinvertebrates, commonly called EPT, are considered to be more sensitive to different water impairments than other aquatic macroinvertebrates. This indicator was categorized into five ecological quality-classes using different ranges in the number of EPT-families (Table S3 Supplementary material).

Three indicators in Baumann et al. (2012) considered possible hydropeaking effects on abiotic processes. In Baumann et al. (2012), the indicator interstitial 'substrate clogging' (S1) is evaluated by considering the concentration of suspended sediments (mg/l dry matter) during peak flow in winter. This indicator is then categorized into five ecological quality-classes using different ranges of suspended sediments concentrations and further grouped by varying morphological aspects of the hydropeaking reaches (e.g. straight channel, alternating gravel bars, braided). In our case study, interstitial substrate clogging was not evaluated with the concentration of suspended sediments as proposed by Baumann et al. (2012) but qualitatively (external surface aspect) and quantitatively (survival rate of fish eggs buried in the river bed) evaluated with field surveys and comparison with the reference river. The indicator 'minimal discharge' (D1) was determined by considering the remaining discharge at base flow conditions compared to minimum residual flow defined in the WPA (Art. 31–33). Baumann et al. (2012) categorized this indicator into two (rather than five) ecological quality-classes, that is 'good' if the residual flow after the hydropower release is respected, and 'poor' if not. The indicator 'water temperature' (T1) was evaluated by considering short-term thermal alterations due to hydropeaking (i.e. thermopeaking; e.g. Carolli et al., 2012) of the receiving watercourse. Baumann et al. (2012) propose to compute thermal alterations from river temperature time series recorded over five years, with a temporal resolution of 10–15 min. The following parameters are then calculated: (i) rate of temperature change (°C/h), (ii) temperature amplitude (°C), (iii) reference temperature amplitude typical for the target river type (°C), and (iv) number of daily temperature peaks. The rate of temperature change is the main criterion for the evaluation of this indicator and corresponds to a representative maximum rate of temperature change during the transition from base to peak flow and vice versa. For our case study, only the gauging station Brienzwiler collected temperature data over five years (2007–2011) and in 10-minute resolution but this station is located ca. 12 km away from the turbine release, and it is only representative of the straight channelized hydropeaking reach (Fig. 2). For the other two upstream reaches, only data collected over one year (2020–2011) in the field by temperature loggers and with a temporal resolution of one hour were available (Person et al., 2014). Nevertheless, the indicator T1 could be semi-quantitatively evaluated for the other two reaches by analogy with the channelized reach and parallel temperature measurements in the reference river (gauging station Gsteig, 10 minute temporal resolution, years 2007–2011). Au suggested by Baumann et al. (2012), this indicator was categorized into five ecological quality-classes using different ranges of the rate of temperature change corrected by the other three factors (Table S5 Supplementary material).

For the deficit-analysis of the pre-mitigation scenario (SI), the 12 indicators were assessed by an interdisciplinary team of aquatic ecologists and hydromorphologists, based on data from measurements and/or samples obtained directly in the river. Only the two indicators F2, and F3 required hydraulic modelling for their evaluation and thus the use of key hydrological parameters (i.e. base and peak flow, ramping and falling rates) extracted from the representative hydrograph of the pre-mitigations scenario (SI). On the other hand, evaluation of the future scenarios (SII, SIIIa–SIIId) always required the use of representative hydrographs to predict the intensity of impacts based on the indicators. For instance, the indicators F4, M1, and M2 can readily be assessed from samples or measurements in the river for the evaluation of current ecological conditions. However, because such indicators are influenced by various environmental and anthropogenic factors, they are almost impossible to predict quantitatively for future scenarios (Bruder et al., 2016). Thus, only four indicators could be predicted quantitatively for future scenarios (F2, F3, D1, T1), whereas the eight others were predicted qualitatively by analogy (i.e. based on published studies) and expert opinion.

Despite being aware of these limitations, we chose the indicator set proposed by Baumann et al. (2012) for two main reasons. First, time constraints for the extension of the KWO production scheme required the use of available methodology to evaluate the effects of increased turbine capacity (and respective mitigation measures) on ecological conditions in the Hasliaare. Second, this project served as a case study for the FOEN to evaluate use of this indicator set to assess the pre-mitigation scenario, to gain information on conceptual and methodological limitations of these indicators to predict future scenarios (Bruder et al., 2016), and finally to support the development of a new FOEN guideline on mitigation measures (see Section 4).

2.3.4. Step 4: selection of the most appropriate mitigation measure

In addition to the hydrological-hydraulic (hydrographs) and ecological (biotic and abiotic indicators) evaluation of realistic and feasible mitigation measures, other criteria such as the proportionality of the costs (i.e. cost-to-benefit ratio) had to be considered in the final selection of the most appropriate measure. The interest in flood protection, the technical requirements and restrictions of the hydropower plant and of hydropeaking reaches (e.g. geomorphological restrictions, minimum amount of water for the operation of turbines, possible production losses or loss of flexibility) as well as the interests of other social and political stakeholders (e.g. the community, landowners, environmental organizations, the agricultural sector, fishermen) had also to be considered into the final evaluation.

In the case of the KWO, the entire evaluation process and the final selection of the most appropriate measure was the result of intense exchanges between hydromorphologists and ecologists, regional, cantonal and federal authorities, and different NGOs and organizations. This procedure was necessary to achieve a final consensus on the most efficient mitigation measure to be implemented.

3. Results and discussion

3.1. Representative hydrographs

All the scenarios included a minimal base flow of 3.1 m^3/s in all reaches (Fig. 5; Table 2) as the residual flow in the Hasliaare had been set to this value, which is around 0.6 m^3/s higher than the natural minimal flow, in an independent cantonal agreement. The future scenario with increased turbine capacity but without mitigation measures (SII) led to a slight increase in peak flow compared to the pre-mitigation scenario (SI). However, the retention volumes considered (SIIIa–SIIId) were too small for a significant reduction in peak flow or for an increase in base flow (Fig. 5; Table 2). Instead, these mitigation measures mainly addressed a reduction in the rates of flow change.

In scenario SI, the 95% percentile of the flow ramping rate in the upstream reach was 1.36 $m^3/s \cdot min^{-1}$; this was predicted to increase to 1.43 $m^3/s \cdot min^{-1}$ in the future scenario SII, and to gradually decrease with increasing retention volume of the mitigation measures (SIIIa–SIIId) (Fig. 5; Table 2). A reduction in the flow ramping rate was expected to decrease the drift of macroinvertebrates and fish (Bruno et al., 2009, 2010; Schmutz et al., 2013; Miller and Judson, 2014). Furthermore, a reduction in flow falling rate is especially crucial for minimizing the stranding risk of fish and macroinvertebrates (Young et al., 2011; Schmutz et al., 2013). Based on field assessments, fish stranding in the Hasliaare can only occur under low flow conditions, i.e. below 8.1 m^3/s, when the river bed is not completely inundated and fish may become trapped in potholes (Schweizer et al., 2013c). Under such flow conditions, the 95% percentile of the falling rate in the upstream reach remained the same (-0.7 $m^3/s \cdot min^{-1}$) for scenario SI and the future scenario SII. A reduction in flow falling rate in this reach to -0.14 $m^3/s \cdot min^{-1}$ was possible with all mitigation measures (Table 2). Flow falling and ramping rates decreased from reach 1 to reach 3 with increasing distance to the turbine outflow because of bed roughness (especially in the Aare gorge), retention effects, and tributary inflows along the hydropeaking section.

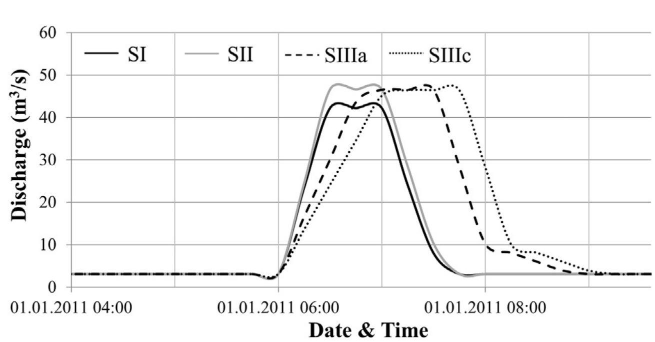

Fig. 5. Example of representative hydrographs (based on 95% percentile) for four different scenarios in the hydropeaking reach "artificial groynes" (see Fig. 2): SI: pre-mitigation scenario; SII: future scenario without mitigation measures; SIIIa and SIIIc: future scenarios with two different mitigation measures (a: 50,000 m^3; c: 80,000 m^3). *Details of hydrograph generation can be found in Bieri et al. (2014).*

Table 2
Hydrological parameters (95% percentile) calculated from the characteristic flow conditions of the three morphologically distinct reaches of the Hasliaare. SI: pre-mitigation scenario; SII: future scenario without mitigation measures; SIIIa–d: future scenarios with different mitigation measures (a: 50,000 m^3; b: 60,000 m^3; c: 80,000 m^3; d: 100,000 m^3). Reach R1: 'artificial groynes'; R2: 'alternating gravel-bars'; R3: 'straight channelized' (see Fig. 2). Q_{min}: base flow; Q_{max}: peak flow; $\Delta Q_{ramping}$: flow ramping rate; $\Delta Q_{falling}$: flow falling rate. *For details see Bieri et al. (2014).*

Scenario	Q_{min} (m^3/s)	Q_{max} (m^3/s)			$\Delta Q_{ramping}$ ($m^3/s \cdot min^{-1}$)			$\Delta Q_{falling}$[a] ($m^3/s \cdot min^{-1}$)		
	R1, R2, R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
SI	3.1	42.2	44.8	45.4	1.36	0.86	0.76	−0.70	−0.37	−0.20
SII	3.1	46.6	48.5	49.1	1.43	0.90	0.80	−0.70	−0.37	−0.20
SIIIa	3.1	46.5	48.0	48.6	0.90	0.57	0.50	−0.14	−0.07	−0.04
SIIIb	3.1	46.5	48.0	48.6	0.80	0.50	0.45	−0.14	−0.07	−0.04
SIIIc	3.1	46.4	47.9	48.5	0.70	0.44	0.39	−0.14	−0.07	−0.04
SIIId	3.1	46.2	47.0	48.3	0.52	0.33	0.29	−0.14	−0.07	−0.04

[a] Calculations of this hydrological parameter were based on discharges below 8.1 m^3/s (see text).

In our case study, only the 95% and 100% percentiles of the hydrographs were considered, thus focusing mainly on quite rare but pronounced hydropeaking events. Depending on the ecological impairment, additional statistical parameters such as the median or 60% percentile were used for a more comprehensive characterization of recurrent hydropeaking events, and thus further helped experts in the ecological evaluation of mitigation measures.

3.2. Ecological evaluation

3.2.1. Evaluation of the different scenarios

For the three abiotic indicators 'substrate clogging' (S1), 'minimal discharge' (D1) and 'water temperature' (T1), a good ecological state was predicted for all the scenarios (Table 3). The concentration of suspended sediments as well as the hydraulic conditions in the river bed (e.g. shear stress), which are relevant parameters for interstitial clogging, did not differ between scenarios SII and SIII, and therefore indicator S1 was judged by the experts to be in a good ecological state for both scenarios (Table 3). D1 remained in a good ecological state because the base flow remained the same with future scenarios (Table 2).

Water temperature alteration (i.e. thermopeaking) for the future scenarios SII and SIII were predicted using the expected mixing ratio of the base flow upstream of the two hydropower plants and the future discharge released by the retention volume, as well as the respective water temperatures. Changes in T1 were minimal in respect of scenario SI, and thus this indicator remained in a good ecological state. Even if peak flow can theoretically increase by a maximum of 25 m^3/s in future scenarios, the probable increase is much smaller considering the 95% percentile (Table 3). Moreover, the indicator T1 is principally characterized by the 'rate of temperature change' and not by the temperature amplitude (Table S5 Supplementary material), which is mostly affected by differences in base and peak discharge. Therefore, also in scenarios where the retention volume was too small to compensate for peak flow and temperature amplitude, the rates of change in temperature

Table 3
Ecological evaluation of the entire hydropeaking section for the different scenarios studied in the Hasliaare using 12 ecological indicators. SI: pre-mitigation scenario; SII: future scenario without mitigation measures; SIIIa–d: future scenarios with different mitigation measures (a: 50,000 m^3; b: 60,000 m^3; c: 80,000 m^3; d: 100,000 m^3). Colours visualize the ecological class of the indicators, where blue = very good; green = good; yellow = moderate; orange = unsatisfactory; and red = poor. Evaluation of the different reaches (R1, R2, R3; Fig. 2) was worst-case aggregated for the evaluation of the entire hydropeaking section. *Detailed information on the evaluation of the different scenarios can be found in Schweizer et al. (2013c, 2013d).*

Indicator	Scenario			
	SI	SII	S IIIa/IIIb[a]	S IIIc/IIId[a]
Fish community structure (F1)	yellow	yellow	yellow	yellow
Fish stranding (F2)	yellow	yellow	green	blue
Fish spawning grounds (F3)	green	green	green	green
Fish reproduction (F4)	red	red	red	red
Fish productivity (F5)	orange	orange	yellow	yellow
Macroinvertebrate biomass (M1)	yellow	yellow	green	blue
Macroinvertebrate diversity (M2)	green	yellow	green	green
Longitudinal zonation of macroinvertebrates (M3)	blue	green	blue	blue
Diversity of sensitive macroinvertebrate taxa (M4)	green	yellow	green	green
Substrate clogging (S1)	green	green	green	green
Minimal discharge (D1)	green	green	green	green
Water temperature (T1)	green	green	green	green

[a] The scenarios SIIIa and SIIIb, as well as scenarios SIIIc and SIIId achieved the same results, and are thus presented in the same columns.

were slightly smoothed because of the reduction in ramping and falling rates (Table 2). Temperature alterations due to hydropeaking can have flow-independent impacts on aquatic organisms and, e.g. increase macroinvertebrate drift (Carolli et al., 2012; Bruno et al., 2013) or influence stranding risk (Saltveit et al., 2001; Halleraker et al., 2003). Therefore, even if minimal, a decrease in the flow rates could result in a reduction in the everyday stress of aquatic organisms due to daily short-term temperature variability.

Three macroinvertebrate indicators, ‘diversity’ (M2), ‘longitudinal zonation’ (M3) and ‘diversity of sensitive taxa’ (M4), were in a good or very good ecological state in scenario SI, but were predicted by the experts to degrade by one ecological class in the future scenario SII (Table 3). Only the macroinvertebrate indicator ‘biomass’ (M1) was in a moderate state in both scenarios SI and SII. Evaluations of the future scenarios SII and SIII were also supported by drift experiments in the Hasliaare performed in 2008 (Schweizer et al., 2013a). Because future scenarios with increased turbine capacity and mitigation measures (SIIIa–SIIId) had considerably reduced flow ramping rates (Table 2), the experts estimated lower macroinvertebrate drift and thereby a long-term recovery in their biomass. Hence, the state of indicator M1 was evaluated as good for retention volumes of 50,000 m^3 and 60,000 m^3, and as very good for the larger volumes 80,000 m^3 and 100,000 m^3 (Table 3).

The predicted decrease by one ecological class of the other three macroinvertebrate indicators (M2, M3, M4) in scenario SII was a consequence of the higher peak flow and flow ramping rates (Table 2), which increased flow velocity and hydraulic stress, and thus also the probability that sensitive taxa disappeared or were replaced by rheophilic taxa. Moreover, if sudden changes in water temperature increase as a consequence of possible higher peak flow in future conditions, further biomass reduction and community shifts may occur because of increased active behavioral drift of macroinvertebrates induced by the thermopeaking wave (Carolli et al., 2012; Bruno et al., 2013). However, hydropeaking normally induces higher drift than thermopeaking; both of them may act as separate stressors or in combination, and induce taxon-specific drift. Because of these possible effects, the indicators M2, M3 and M4 were conservatively predicted for the future scenario with mitigation measures (SIIIa–SIIId), and remained in the same ecological class as for the pre-mitigation scenario SI (Table 3).

The evaluation of fish indicators highlighted several ecological deficits in the Hasliaare. Only the indicator ‘spawning grounds’ (F3) showed a good ecological state over all scenarios (Table 3). This indicator was predicted using the parameters suitable grain size for spawning, areas with >20 cm water depth at base flow, and substrate stability at peak flow. The grain sizes in the hydropeaking section are, in general, too large (d_m = 13 cm) and not appropriate for the spawning of brown trout. For example, Armstrong et al. (2003; and references therein) reported a mean substrate size of 6.9 mm (range 8–128 mm) and Louhi et al. (2008) of 16–64 mm as most suitable for brown trout spawning. However, hydraulic models showed that appropriate substrate is lacking not due to hydropeaking, but because of river geomorphology. Moreover, spawning of brown trout in the Hasliaare was observed, and stability of spawning ground was verified with hydraulic models and field surveys. Therefore, to objectively evaluate the hydropeaking effect, an appropriate amount of suitable grain size for spawning was assumed. Water depth did not vary between the different scenarios because the base flow was the same (3 m^3/s; Table 2), and the unstable substrate area changed only slightly between the different scenarios, always remaining below 2% of the total area. Therefore, the ecological state of F3 was evaluated as good for all the scenarios (Table 3). This indicator, however, does not consider flow velocity during spawning activity, which has also been found to be an important parameter for successful spawning (Armstrong et al. (2003). For example, Louhi et al. (2008) indicated 20–55 cm/s as a favorable flow velocity range for trout spawning.

The fish indicators ‘community structure’ (F1) and ‘reproduction’ (F4) were predicted for scenarios SI and SII to be in a moderate and poor state, respectively, and could not be improved with the mitigation measures (SIIIa–SIIId) considered in our case study (Table 3). For F1, the main constraining factors were identified in the structure and density of trout populations, and for F4 in the very low abundance of juveniles (e.g. for scenario S1 between 2009 and 2011 only 33–44 juveniles per hectare were caught). These three parameters were predicted not to further deteriorate with the slight increase in peak flow and flow ramping rate in scenario SII, but also not to ameliorate with a reduction in flow ramping rate in scenario SIII (Table 2).

The risk of fish stranding (F2) was evaluated as moderate in scenario SI as well as in scenario SII (Table 3), mainly because there were no changes in base flow conditions and in flow falling rates with increased turbine capacity (Table 2). With a retention volume of 50,000 m^3 (SIIIa) it was already possible to significantly reduce the flow falling rate to a threshold value of 0.3–0.5 cm/s, which is defined as good ecological status for this indicator (Table S1 Supplementary material). Therefore, scenarios SIIIa and SIIIb were evaluated as good, one class better than scenarios SI and SII (Table 3). Scenarios SIIIc and SIIId were evaluated one class better than scenarios SIIIa and SIIIb as larger retention volumes (80,000 and 100,000 m^3 respectively) could be used to further reduce the flow falling rate (by regulation of the basin/cavern) in the case of future morphological restoration measures (e.g. widening of the river bed; see Section 3.3). Generally, slower flow falling rates are expected to provide longer response times for fish to move to appropriate refugia during hydropeaking.

The evaluations of the indicator ‘productivity’ (F5) were the same for scenarios SI and SII, but it was predicted to improve by one ecological class in the future scenarios with mitigation measures (SIIIa–SIIId) due to probable increase in macroinvertebrate biomass (indicator M1), which is a substantial part of fish diets. The monotonous morphology of the Hasliaare with no major in-stream structures limited habitat availability for juvenile fish irrespective of hydropeaking, and thus curtailed further improvement of the indicators F1, F4 and F5. In fact, hydraulic modelling showed that high-quality habitats for young-of-the-year brown trout were only available at discharges below 20 m^3/s (Person et al., 2014). However, natural mean monthly flow during the development of juvenile fish was higher (e.g. 45 m^3/s in May), and thus suitable habitats would also be limited under natural flow conditions.

3.2.2. Overall evaluation

After ecological evaluation of the indicators for all scenarios, an integrative qualitative evaluation was carried out in a workshop with experts, the cantonal and federal authorities, and KWO. This led to the following conclusions (see also Table 3):

(i) In the pre-mitigation scenario (SI), hydropeaking resulted in serious harm to aquatic organisms and habitats: five indicators were found to be in a lower-than-good ecological state.
(ii) A reduction in macroinvertebrate biomass (indicator M1), as a consequence of high drift, as well as fish stranding (indicator F2) were the most severe hydropeaking effects in the pre-mitigation scenario (SI), which suggests a need for reductions in ramping and falling flow rates.
(iii) The upgrade of the hydropower plant Innertkirchen I (SII) caused a slight degradation of the ecological situation compared to the pre-mitigation scenario (SI): three indicators (M2, M3, M4) were degraded by one ecological class.
(iv) The two mitigation measures (SIIIa and SIIIb) with the smaller retention volumes (50,000 m^3 and 60,000 m^3 respectively) were able to compensate for the increase in hydropeaking impacts due to an increase in turbine capacity, which led to a slight ecological improvement compared to the pre-mitigation scenario (SI): three indicators (F2, F5, M1) improved by one ecological class.
(v) Retention volumes of 80,000 m^3 and 100,000 m^3 (SIIIc and SIIId respectively) led to a moderate ecological improvement compared to the pre-mitigation scenario (SI): one indicator (F5) improved by one ecological class and two indicators by two ecological classes (F2, M1).
(vi) The ecological state of the indicators F1, F4 and F5 can only be further ameliorated with morphological restoration measures. Such measures are currently being discussed for the Hasliaare.

3.3. Selection of the most appropriate mitigation measure

The evaluations described above identified the most efficient mitigation measure based on current knowledge (for details, see Schweizer et al., 2013d, 2016). The cantonal and federal authorities chose the measure with a retention volume of 80,000 m^3 (SIIIc) because, together with measure SIIId, it was found to have the greatest ecological benefits. For instance, the retention volume and the operation rules of the basin have already been optimized to substantially reduce flow falling and ramping rates, which were identified as particularly detrimental in the Hasliaare, and have consequently decreased ecological impacts that are influenced by these parameters (Table 3). For example, dampening the flow falling rate is expected to reduce stranding risk of juvenile trout at low flows, and minimizing the flow ramping rate is expected to reduce macroinvertebrate drift. Moreover, this retention volume may suffice, to a certain degree, to compensate for possible future modifications in the operation mode of the hydropower plant due to climate change or changes in electricity demand as well as morphological restoration of the hydropeaking section. For example, a widening of the river bed would ameliorate the hydraulic conditions in the hydropeaking section, creating areas with low flow depth and velocity. On the one hand, as fish habitat diversity and stranding risk are strongly influenced by channel morphology (Person et al., 2014; Vanzo et al., 2016), this would improve hydro-morphological habitat conditions for fish larvae and juveniles, but on the other hand it would increase the risk of stranding because of larger dewatering areas that are only inundated during peak flows but not during base flow. The latter could again be reduced by further decreasing the flow falling rate, which is not possible with smaller retention volumes, thus providing longer response times for trout larvae (which are more sensitive to stranding than older fish stages; Schmutz et al., 2013) in April–May. A further reduction in flow falling rates would also reduce the stranding risk for flow conditions above 8.1 m^3/s; although stranding is currently not possible under these conditions, this may change in the future due to morphological restoration and thus larger areas with dewatering potholes that could act as fish traps. Theoretically, a larger retention volume could, at least during smaller peaks, operate a ‘conditioning reduction’, i.e. a rapid decrease and increase in flow prior to a planned reduction, to mitigate the increased stranding risk associated with long-wetted histories (Irvine et al., 2009). However, recent findings suggest that this effect is probably less than initially supposed, because even a short-term drop could cause high mortality due to stranding (Irvine et al., 2015). Finally, a volume of 80,000 m^3 would also allow for seasonal regulation of the retention volume, for example to reduce small flow peaks during the trout spawning season (October–December), thus prolonging periods with good spawning conditions. The smaller volumes of 50,000 m^3 and 60,000 m^3 were rejected because they did not meet the legal obligation to sufficiently mitigate the serious harm to aquatic organisms and their habitat caused by hydropeaking. The largest retention volume (100,000 m^3) was also rejected because costs were disproportionally higher compared to the 80,000 m^3 volume, as it would require a new layout of the cavern and an additional storage site for the excavated material.

The construction of the retention basins and the cavern started in spring 2013 and was completed in summer 2016. A comprehensive monitoring program over the next 10 years has been planned to evaluate the predicted ecological improvements, further optimize the regulation of the retention volume, and gain new knowledge on the efficiency of such mitigation measures.

4. Conclusions and outlook

The approach we illustrated with our case study allowed for an effective evaluation of different mitigation measures and selection of the most appropriate one. In contrast to previous methods (e.g. Bevelhimer et al., 2015; Carolli et al., 2015; Vanzo et al., 2016), which principally focused on hydrological-hydraulic responses of river reaches to hydropeaking or on a limited number of ecological indicators for the investigation of theoretical mitigation measures, our evaluation was based on the combined evaluation of hydrological-hydraulic conditions (representative hydrographs) as well as a comprehensive quantitative or qualitative prediction of 12 biotic and abiotic indicators, and the links between them, for three concrete scenarios (pre-mitigation, increased turbine capacity without mitigation measures, increased turbine capacity and four alternative mitigation measures). However, the ecological indicator set proposed in Baumann et al. (2012) and applied in our study was primarily developed to evaluate pre-mitigation situations (i.e. the ecological impacts caused by hydropeaking) and not to explicitly predict the ecological consequences of mitigation measures. Therefore, evaluation of the different mitigation scenarios was often possible only qualitatively but not quantitatively. To address this problem and to support hydropower plant owners, authorities and water resource managers in planning, evaluating, selecting and realizing appropriate and effective mitigation measures, a new guideline was published by the FOEN (Tonolla et al., 2016, available in German, French and Italian). This guideline is based on recent scientific findings and several case studies including the one presented here, and was developed in collaboration with national and international scientists, environmental and engineers' offices, Swiss cantonal and federal authorities, representatives of hydropower companies and NGOs. Collaboration among scientists as well as with relevant social and political stakeholders with different disciplinary backgrounds was fundamental to creating a common understanding of river ecosystems affected by hydropeaking, and thus to developing a broadly accepted approach for effective evaluation and implementation of mitigation measures.

The new guideline defines a general framework for hydropeaking evaluation and, and have also revised the indicator set proposed by

Baumann et al. (2012) by integrating recent scientific findings and practical experience as well as by proposing six indicators that are most appropriate for the prediction of hydropeaking effects and corresponding evaluation of mitigation measures. Indicator selection was based on two main criteria; firstly, the indicators needed to be specific for hydropeaking and thus not reflect other anthropogenic impacts such as poor water quality or morphological deficits (or these aspects were directly considered in the indicator); secondly, the indicators needed to be predictable for future situations at least semi-quantitatively. Such indicators can, for example, be evaluated using numerical models (e.g. habitat models for fish or macroinvertebrates), physical models (e.g. experimental channels), and hydropeaking experiments (also called discharge scenarios; Bruder et al., 2016) with direct measurements in a watercourse using representative hydrographs by directly adapting the hydropower production scheme (e.g. simulation of hydropeaking conditions by the hydropower plant while performing drift sampling). The proposed indicators are (i) stranding of larvae and 0+ fish (brown trout and grayling), (ii) suitable fish spawning grounds (brown trout, lake trout, and grayling), (iii) habitat suitability for fish (0+ and adult), (iv) habitat suitability for macroinvertebrates, (v) rate of change in water temperature, and (vi) hydrological key parameters (base and peak flow, falling and ramping rates). For details of the indicators and the proposed procedure and thresholds for evaluation in ecological-quality classes, see Tonolla et al. (2016).

We expect the applied approach presented in the KWO case study, including the future outcomes of the planned long-term monitoring, and further developed in the new FOEN guideline to support the application of Swiss and international water protection laws and, more generally, to provide useful information and necessary guidance for the evaluation of adverse hydropeaking impacts and possible mitigation measures for hydropower plants in alpine catchments. Nevertheless, more research is needed, especially to establish a standardized and reliable relationship between measurable and predictable hydrological parameters, and the status class of ecological indicators.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.09.101.

References

AFNOR, 1992. Qualité écologique des milieux aquatiques. Qualité de l'eau. Détermination de l'indice biologique global normalisé (IBGN). Norme homologuée T 90-350. Association française de normalisation.

Anselmetti, F., Bühler, R., Finger, D., Girardclos, S., Lancini, A., Rellstab, C., Sturm, M., 2007. Effects of Alpine hydropower dams on particle transport and lacustrine sedimentation. Aquat. Sci. 69, 179–189.

Armstrong, J., Kemp, P.S., Kennedy, G.J.A., Ladle, M., Milner, N.J., 2003. Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fish. Res. 62, 143–170.

Baumann, P., Kirchhofer, A., Schälchli, U., 2012. Sanierung Schwall/Sunk - Strategische Planung. Ein Modul der Vollzugshilfe Renaturierung der Gewässer. Umwelt-Vollzug 1203, Bundesamt für Umwelt, Bern.

Bevelhimer, M.S., McManamay, R.A., O'Connor, B., 2015. Characterizing sub-daily flow regimes: implications of hydrologic resolution on ecohydrology studies. River Res. Appl. 31, 867–879.

Bieri, M., 2012. Operation of Complex Hydropower Schemes and Its Impact on the Flow Regime in the Downstream River System Under Changing Scenarios PhD-Thesis 5433 EPFL, Lausanne.

Bieri, M., Müller, M., Schweizer, S., Schleiss, A.J., 2014. Flow restoration in Alpine streams affected by hydropower operations—a case study for a compensation basin. In: Schleiss, A.J., Speerli, J., Pfammater, R. (Eds.), Swiss Competences in River Engineering and Restoration. Taylor & Francis Group, London, pp. 181–190.

Bruder, A., Tonolla, D., Schweizer, S., Vollenweider, S., Langhans, S.D., Wüest, A., 2016. A conceptual framework for hydropeaking mitigation. Sci. Total Environ. http://dx.doi.org/10.1016/j.scitotenv.2016.05.032.

Bruno, M.C., Maiolini, B., Carolli, M., Silveri, L., 2009. Impact of hydropeaking on hyporheic invertebrates in an Alpine stream (Trentino, Italy). Annales de Limnologie – International Journal of Limnology 45, 157–170.

Bruno, M.C., Maiolini, B., Carolli, M., Silveri, L., 2010. Short time-scale impacts of hydropeaking on benthic invertebrates in an Alpine stream (Trentino, Italy). Limnologica 40, 281–290.

Bruno, M.C., Siviglia, A., Carolli, M., Maiolini, B., 2013. Multiple drift responses of benthic invertebrates to interacting hydropeaking and thermopeaking waves. Ecohydrology 6, 511–522.

Carolli, M., Bruno, M.C., Siviglia, A., Maiolini, B., 2012. Responses of benthic invertebrates to abrupt changes of temperature in flume simulations. River Res. Appl. 28, 678–691.

Carolli, M., Vanzo, D., Siviglia, A., Zolezzi, G., Bruno, M.C., Alfredsen, K., 2015. A simple procedure for the assessment of hydropeaking flow alterations applied to several European streams. Aquat. Sci. 77, 639–653.

Céréghino, R., Cugny, P., Lavandier, P., 2002. Influence of intermittent hydropeaking on the longitudinal zonation patterns of benthic invertebrates in a mountain stream. Int. Rev. Hydrobiol. 87, 47–60.

Charmasson, J., Zinke, P., 2011. Mitigation measures against hydropeaking effects. EnviPEAK Publications SINTEF Energy Research, Norway.

E-Control, 2015. Statistikbroschüre 2015. Energie-Control Austria, Vienna.

EnviPEAK, 2016. Effects of rapid and frequent flow changes. CEDREN: Norwegian Centre for Environmental Design of Renewable Energy http://www.cedren.no/english/Projects/EnviPEAK (Last accessed: 10.06.2016).

García, A., Jorde, K., Habit, E., Caamaño, D., Parra, O., 2011. Downstream environmental effects of dam operations: changes in habitat quality for native fish species. River Res. Appl. 27, 312–327.

Halleraker, J.H., Saltveit, S.J., Harby, A., Arnekleiv, J.V., Fjeldstad, H.P., Kohler, B., 2003. Factors influencing stranding of wild juvenile brown trout (*Salmo trutta*) during rapid and frequent flow decreases in an artificial stream. River Res. Appl. 19, 589–603.

Huet, M., 1949. Aperçu des relations entre la pente et les populations piscicoles des eaux courantes. Schweiz. Z. Hydrol. 11, 332–351.

IEA, 2015. Key world energy statistics. International Energy Agency (IEA), Paris.

Irvine, R.L., Oussoren, T., Baxter, J.S., Schmidt, D.C., 2009. The effects of flow reduction rates on fish stranding in British Columbia, Canada. River Res. Appl. 25, 405–415.

Irvine, R.L., Thorley, J.L., Westcott, R., Schmidt, D., DeRosa, D., 2015. Why do fish strand? An analysis of ten years of flow reduction monitoring data from the Columbia and Kootenay rivers, Canada. River Res. Appl. 31, 1242–1250.

Jones, J.I., Muphy, J.F., Collins, A.L., Sear, D.A., Naden, P.S., Armitage, P.D., 2011. The impact of fine sediment on macro-invertebrates. River Res. Appl. 27, 1055–1071.

Jungwirth, M., Moog, O., Winkler, H., 1980. Vergleichende Fischbestandsaufnahmen an elf niederösterreichischen Fliessgewässerstrecken. Jubiläumsschrift der Österreichischen Fischereigesellschaft, Vienna, pp. 81–104.

Liebig, H., Lim, P., Belaud, A., 1998. Influence of basic flow and hydropeaking duration on the drift of post-emergent fry of brown trout: experiments on a semi-natural stream. Bulletin Français de la Pêche et de la Pisciculture 350–51, 337–347.

Louhi, P., Mäki-Petäys, A., Erkinaro, J., 2008. Spawning habitat of Atlantic salmon and brown trout: general criteria and intragravel factors. River Res. Appl. 24, 330–339.

Meile, T., Boillat, J.L., Schleiss, A., 2011. Hydropeaking indicators for characterization of the Upper-Rhone River in Switzerland. Aquat. Sci. 73, 171–182.

Miller, S.W., Judson, S., 2014. Responses of macroinvertebrate drift, benthic assemblages, and trout foraging to hydropeaking. Can. J. Fish. Aquat. Sci. 71, 675–687.

Moog, O., 1993. Quantification of daily peak hydropower effects on aquatic fauna and management to minimize environmental impacts. Regul. Rivers Res. Manag. 8, 5–14.

Moog, O., Ofenböck, T., 2003. Calculation of longitudinal zonation patterns. In: Moog, O. (Ed.), Fauna Aquatica Austriaca, Teil V – Ergänzungen 2003. Wasserwirtschaftskataster, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Vienna.

Nagrodski, A., Raby, G.D., Hasler, C.T., Taylor, M.K., Cooke, S.J., 2012. Fish stranding in freshwater systems: Sources, consequences, and mitigation. J. Environ. Manag. 103, 133–141.

Parasiewicz, P., Schmutz, S., Moog, O., 1998. The effect of managed hydropower peaking on the physical habitat, benthos and fish fauna in the River Bregenzerach in Austria. Fish. Manag. Ecol. 5, 403–417.

Person, E., Bieri, M., Peter, A., Schleiss, A.J., 2014. Mitigation measures for fish habitat improvement in Alpine rivers affected by hydropower operations. Ecohydrology 7, 580–599.

Saltveit, S., Halleraker, J., Arnekleiv, J., Harby, A., 2001. Field experiments on stranding in juvenile Atlantic salmon (*Salmo salar*) and Brown Trout (*Salmo trutta*) during rapid flow decreases caused by hydropeaking. Regul. Rivers Res. Manag. 17, 609–622.

Schager, E., Peter, A., 2004. Methoden zur Untersuchung und Beurteilung der Fliessgewässer –Fische Stufe F. Mitteilungen zum Gewässerschutz 44. Bundesamt für Umwelt, Bern.

Schmutz, S., Fohler, N., Friedrich, T., Fuhrmann, M., Graf, W., Greimel, F., Höller, N., Jungwirth, M., Leitner, P., Moog, O., Melcher, A., Müllner, K., Ochsenhofer, G., Salcher, G., Steidl, C., Unfer, G., Zeiringer, B., 2013. Schwallproblematik an Österreichs Fliessgewässern - Ökologische Folgen und Sanierungsmöglichkeiten. BMFLUW, Vienna.

Schweizer, S., Schmidlin, S., Tonolla, D., Büsser, P., Maire, A., Meyer, M., Monney, J., Schläppi, S., Schneider, M., Theiler, Q., Tuhtan, J., Wächter, K., 2013a. Schwall/Sunk-Sanierung in der Hasliaare – Phase 2b: Ökologische Bewertung von künftigen Zuständen. Wasser Energie Luft 105, 277–287.

Schweizer, S., Bieri, M., Tonolla, D., Monney, J., Rouge, M., Stalder, P., 2013b. Schwall/Sunk-Sanierung in der Hasliaare – Phase 2a: Konstruktion repräsentativer Abflussganglinien für künftige Zustände. Wasser Energie Luft 105, 269–276.

Schweizer, S., Schmidlin, S., Tonolla, D., Büsser, P., Meyer, M., Monney, J., Schläppi, S., Schneider, M., Tuhtan, J., Wächter, K., 2013c. Schwall/Sunk-Sanierung in der Hasliaare – Phase 1b: Ökologische Bewertung des Ist-Zustands anhand der 12 Indikatoren der aktuellen BAFU-Vollzugshilfe. Wasser Energie Luft 105, 200–207.

Schweizer, S., Schmidlin, S., Tonolla, D., Büsser, P., Meyer, M., Monney, J., Schläppi, S., Wächter, K., 2013d. Schwall/Sunk-Sanierung in der Hasliaare – Phase 1a: Gewässerökologische Bestandsaufnahme. Wasser Energie Luft 105, 191–199.

Schweizer, S., Schmidlin, S., Bieri, M., Büsser, P., Meyer, M., Monney, J., Schläppi, S., Schneider, S., Tonolla, D., Tuhtan, J., Wächter, K., 2016. Die erste Schwall-Sanierung der Schweiz: Die Hasliaare als Fallbeispiel. WasserWirtschaft 1, 10–15.

SFOE, 2012. Wasserkraftpotenzial der Schweiz. Abschätzung des Ausbaupotenzials der Wasserkraftnutzung im Rahmen der Energiestrategie 2050. Energie (SFOE), Bern, Bundesamt für.

SFOE, 2015. Stand der Wasserkraftnutzung in der Schweiz am 1. Januar 2015. Energie (SFOE), Bern, Bundesamt für.

Stucki, P., 2010. Methoden zur Untersuchung und Beurteilung der Fliessgewässer. Makrozoobenthos Stufe F. Umwelt-Vollzug 1026. Bundesamt für Umwelt, Bern.

Tolossa, H.G., Tuhtan, J., Schneider, M., Wieprecht, S., 2009. Comparison of 2D Hydrodynamic Models in River Reaches of Ecological Importance: HYDRO_AS-2D and SRH-W. 33rd IAHR World Congress. Curran Associates, Inc., Vancouver, Canada, pp. 604–611.

Tonolla, D., Chaix, O., Meile, T., Zurwerra, A., Büsser, P., Oppliger, S., Essyad, K., 2016. Schwall-Sunk – Massnahmen. Umwelt-Vollzug. Bundesamt für Umwelt, Bern.

Vanzo, D., Zolezzi, G., Siviglia, A., 2016. Ecp-hydraulic modelling of the interactions between hydropeaking and river morphology. Ecohydrolgy 9, 421–437.

Vuille, T., 1997. Ertragsvermögen der Patentgewässer im Kanton Bern. Fischereiinspektorat des Kantons Bern, Bern.

Wang, Z., Lee, J.H.W., Xu, M., 2013. Eco-hydraulics and eco-sedimentation studies in China. J. Hydraul. Res. 51, 19–32.

WFD, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Off. J. Eur. Communities, L327.

Young, P., Cech Jr., J., Thompson, L., 2011. Hydropower-related pulsed-flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs. Rev. Fish Biol. Fish. 21, 713–731.

Zimmerman, J.K.H., Letcher, B.H., Nislow, K.H., Lutz, K.A., Magilligan, F.J., 2010. Determining the effects of dams on subdaily variation in river flows at a whole-basin scale. River Res. Appl. 26, 1246–1260.

Zolezzi, G., Siviglia, A., Toffolon, M., Maiolini, B., 2011. Thermopeaking in Alpine streams: event characterization and time scales. Ecohydrology 4, 564–576.