ydrological and thermal effects of hydropeaking on early life stages of salmonids: a modelling approach for implementing mitigation strategies

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Abstract

Alterations in hydrological and thermal regimes can potentially affect salmonid early life stages development and survival. The dewatering of salmon sawning redds due to hydropeaking can lead to mortality in early life stages, with higher impact on the alevins as they have lower tolerance to dewatering than the eggs. Flow-related mitigations measures can reduce early life stage mortality. We present a set of modelling tools to assess impacts and mitigation options to minimise the risk of mortality in early life stages in hydropeaking rivers. We successfully modelled long-term hydrological and thermal alterations and consequences for development rates. We estimated the risk of early life stages mortality and assessed the cost-effectiveness of implementing three release-related mitigation options. The economic cost of mitigation was low and ranged between 0.7% and 2.6% of the annual hydropower production. Options reducing the flow during spawning (B and C) in addition to only release minimum flows during development (A) were considered more effective for egg and alevin survival. Options B and C were however constraint by water availability in the system for certain years, and therefore only option A was always feasible. The set of modelling tools used in this study were satisfactory and their applications can be useful especially in systems where little field data is available. Targeted measures built on well-informed modelling tools can be tested on their effectiveness to mitigate dewatering effects *vs.* the hydropower system capacity to release or conserve water for power production. Environmental flow releases targeting specific ecological objectives can provide better cost-effective options than conventional operational rules complying with general legislation.

Keywords

Hydropeaking, Atlantic salmon, water temperature modelling, early life stages development and survival, mitigation measures, hydropower production modelling

1. Introduction

Atlantic salmon (*Salmo salar, L*) usually spawns in the autumn by burying their eggs in river gravels. The eggs hatch in spring when a certain number of degree days has been reached. After hatching, the alevins stay in the gravels until having absorbed their yolk-sac and then emerge from the substratum, ready for external feeding. These early life stages are highly dependent on the physico-chemical characteristics of the surrounding hyporheic water, with redds usually constructed in groundwater upwelling areas [*Hansen*, 1975; *Baxter and McPhail*, 1999; *Garrett et al.*, 1998; *Saltveit and Brabrand*, 2013].

In hydropeaking rivers, changes in the hydrological and thermal regimes may influence the survival and development of salmonid early life stages [*Casas-Mulet et al.*, 2014b; *Casas-Mulet et al.*, 2016; *Harnish et al.*, 2014]. Impacts in the flow regime may leave salmon redds exposed to dewatered conditions [*Young et al.*, 2011], inducing a limiting factor for the management of sustainable salmon populations [*Malcolm et al.*, 2012; *McMichael et al.*, 2005]. Even if early life stages are well protected in the gravel, dewatering conditions in the redds will impact both egg and alevin survival [*Becker et al.*, 1983; *Neitzel and Becker*, 1985]. The effects of hydropeaking on river water temperatures can also be significant [*Zolezzi et al.*, 2011]. Hydrological alterations are known to significantly impact the natural thermal regime in rivers [*Webb et al.,* 2008; *Olden and Naiman* 2010], with major effects to aquatic organisms [*McCullough,* 1999; *McCullough et al.*, 2009]. Thermal alterations can cause possible bottleneck in salmonid populations by advancing or delaying the development in early stages, promoting negative effects such earlier emergence from the redds or shorten the growth season [*Einum and Fleming,* 2000; *Fisk II et al.*, 2013].

The effects of redd dewatering to salmonid early life stages survival are well understood and differ between egg and alevin phases [*Becker and Neitzel*, 1985; *Becker et al.*, 1982; *Becker et al.*, 1983; *Neitzel and Becker*, 1985]. They are particularly relevant in hydropeaking rivers, where dewatering events occur very frequently [*Casas-Mulet et al.*, 2014b; *Casas-Mulet et al.*, 2015b; *Harnish et al.*, 2014]. Eggs are more tolerant and able to survive dewatering events for weeks if they remain moist and not subjected to extreme temperatures or predation [*Casas-Mulet et al.*, 2014b; *Reiser and White*, 1983]. Conversely, after hatching, alevins are dependent on gills for respiration and mortality increases significantly in relatively brief dewatering events (within 1 to 3 hours), if no surface water covers the redds [*Becker et al.*, 1982; *Becker et al.*, 1983].

In order to effectively implement mitigation measures in regulated rivers, environmental flows releases mimicquing the natural hydrological and thermal regime are the optimal solution to mitigate impacts to ecosystems [*Arthington et al.,* 2010; *Olden and Naiman* 2010; *Poff and Zimmerman,* 2010]. Suggested mitigation options for early life stages in regulated rivers include the active use of release-related strategies below dams. They aim at either discourage salmon from spawning in habitats potentially subject to dewatering [*McMullin and Graham*, 1981; *Connor and Pflug*, 2004], provide minimum discharges during critical conditions for eggs and alevins [*Fisk II et al.*, 2013; *Harnish et al.*, 2014; *McMichael et al.*, 2005], or reduce the difference between spawning and incubation discharge [*Stober and Tyler*, 1982]. In addition, recent studies on two Norwegian rivers emphasized the importance of considering groundwater upwelling and intragravel water quality when devising mitigation measures for early life stages survival [*Casas-Mulet et al.*, 2014b; *Casas-Mulet et al.*, 2016; *Saltveit and Brabrand*, 2013]. To our knowledge, integrated studies understanding the combined effect of hydrological and thermal alterations of hydropeaking on early life stages are currently inexistent. Such studies are key to select relevant mitigations strategies for the survival of eggs and alevins during early life development, a bottleneck for salmonid populations [*Enders et al.,* 2007].

Our aim is to present a set of modelling tools for the integrated assessment of impacts and mitigation options for embryo and alevin survival in hydropeaking rivers. Using the Lundesokna river (Norway) as a case study, we addressed the following objectives:

- To model the alteration of natural thermal regimes and consequences for early life stages development,
- To estimate the combined impact of altered hydrological and thermal regimes to egg and alevin survival,
- To assess the cost-effectiveness of different release-related mitigation approaches to minimise early life stages mortality.

2. Field study in the Lundesokna River

2.1. Study sites

The River Lundesokna is a major tributary to the River Gaula (Figure 1). The Gaula is the largest unregulated river in Central Norway. It is listed among Norway's top three salmon rivers, with an average annual catch of about 34 tons over the last 15 years. The Lundesokna is subject to daily flow fluctuations as its lowermost power plant, Sokna (Figure 1), operates according to daily and weekly market demand. Three reservoirs (Håen, Samsjøen and Holtsjøen) supply 145 Mm^3 of water to the Lundesokna hydropower system (Figure 1). Hydropeaking in the Lundesokna results in periodically abrupt flow fluctuations that can change from 0.45 to 19 m^{3}s^{-1} in < 20 minutes (ramping rate ~3 cm.min^{-1}). A minimum flow of 0.3 m^{3}s^{-1} bypasses the power house, and the production discharge ranges between 8 m^{3}s^{-1} (minimum) and 18 m^3.s^{-1} (maximum). A more detailed description of the Lundesokna hydropower system is found in *Casas-Mulet et al.* [2014c].

A total of four sites in the River Lundesokna (Figure 1) were selected for this study. They were characterised for differentiated river morphologies and had been used in previous studies on fish stranding potential [*Casas-Mulet et al.*, 2015c]. Additional studies were carried out in site 2 (Figure 1), with a focus on egg and alevin development and survival [*Casas-Mulet et al.*, 2014b; 2016].

2.2. *Field data collection*

Water levels, discharges and water temperatures were collected at the four selected sites. Two piezometers containing water pressure and temperature loggers (Diver ®) were installed at each of the sites (Figure 1) to monitor surface and interstitial water. One piezometer was located permanently under water (W) and the other in the ramping zone (RZ). RZ are locations subject surface dewatering as a consequence of fluctuating flows (Figure 2). One VEMCO water temperature logger was also installed in the water column at each site. Additionally, one air pressure (for water pressure compensation) and temperature logger (Baro Diver ®) was installed at Site 2. Data was collected from March 2012 to June 2013 at 10 min-resolution.

3. Modelling tool-set

The following sub-sections describe the set of modelling tools we used to address each of the specific objectives stated above (Figure 3). They include long-term comparisons between (i) unregulated and hydropeaking scenarios to assess how hydrological and thermal alterations impact salmonid early life stages development and survival; and (ii) current and alternative hydropeaking scenarios to assess the feasibility of implementing release/related mitigation options.

3.1. *Long-term discharge and water temperature modelling*

In order to enable long-term comparison between hydropeaking and unregulated scenarios, the following modelling strategy was devised for the period 2002-2015[1]:

(i) Daily unregulated discharge

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[1] The first available regulated discharge data in Lundesokna was 2002.

No records of unregulated flows and/or water temperature exist for the Lundesokna River. Therefore, we used hourly Gaula discharge data to compute unregulated discharge in Lundesokna using a quantile regression method described by *Hailegeorgis and Alfredsen* [2016]. We used discharge data from Eggafoss gauge, in the Gaula river (Figure 1), obtained from the Norwegian Water Resources Directorate (NVE). A flow duration curve was generated for Lundesokna by a separate linear regression model for every 1% using catchment area as the variable, and a total of 26 measured catchments in the region as basis for the transfer. The unregulated time series were then created from the flow duration curve assuming that streamflow at time *t* has the same percentile for the gauged and ungauged catchment. Daily unregulated discharge were subsequently computed. For details on model fits and catchments used in the transfer, see *Hailegeorgis and Alfredsen* [2016].

(ii) Daily unregulated water temperature

We used air2stream [*Toffolon and Piccolroaz*, 2015] to estimate unregulated daily water temperature in the Lundesokna River. Air2stream makes simplifications to the basic lumped energy balance model resulting in a model only dependent on air temperature and discharge to simulate the changes in water temperature. The model was therefore well suited for Lundesokna where observed water temperature, local radiation data and river geometry upstream of the power plant outlet were missing. We calibrated air2stream using 2010-12 discharge and water temperature data from the river Gaula (Egafoss gauge, NVE) and air temperature from the Voll station near Trondheim (obtained from the Norwegian Meteorological Institute). The calibrated air2stream model (Nash-Sutcliffe Efficiency, NSE of 0.95) was then used to compute water temperature in Lundesokna based on air temperature data from Voll and modelled unregulated discharge from Lundesokna.

(iii) Hourly hydropeaking water discharge

Regulated discharges in Lundesokna downstream Sokna power plant were computed by adding the 0.3 $m^3.s^{-1}$ constant bypass release to Sokna production and spill data, available in hourly resolution from NVE.

(iv) Hourly hydropeaking water temperature

Regulated water temperature downstream Sokna power plant was calculated by applying a simple energy balance model [*Zolezzi et al.*, 2011] at an hourly time-step, with the temperature after mixing resulting in:

$$T_d = \frac{T_u Q_u + T_r Q_r}{Q_d} \qquad (1)$$

where Q is the flow and T is the water temperature for (*u*) unregulated upstream reach, (*r*) release from Sokna reservoir and (*d*) downstream reach. We applied modelled unregulated daily data at an hourly step for Q_u and T_u calculations, and used hourly hydropeaking water discharge calculations for Q_r. Based on the observed data in 2012-13, we established the following rules and relationships for T_d *and* T_r estimations:

- If production <=1 $m^3.s^{-1}$, $T_d = T_u$.
- When production was >1 $m^3.s^{-1}$,
    - T_r ~0.81, during 01.12 -28.02,
    - $T_r = 0.7 \times T_u + 0.5$ (R^2=0.7) from 1 March to 31 July,
    - $T_r = 0.9 \times T_u - 0.6$ (R^2=0.7) between 1 August and 30 November.

(v) Estimation of interstitial water temperature in the redds

We used hourly 2012-13 field data to estimate the relationship between surface and interstitial temperature in the redds though linear regressions at each site (1-4) and locations (RZ and W). We then applied these relationships to model 2002-15 daily surface water temperature data for both unregulated and hydropeaking scenarios. For unregulated scenarios, we used W data only to be applied at both locations (RZ and W), as we assumed exposure to dewatering at RZ locations was minimal.

3.2. Estimation of critical conditions for egg and alevin stages

3.2.1. Development rates estimation

We use Crisp model [*Crisp*, 1988] to estimate egg and alevin development rates and the timing of hatching and initial feeding or swim-up. The following formula was used to determine the time intervals:

$$\log D = b \log(T - \alpha) + \log a \qquad (2)$$

where D is the number of days from spawning until 50% of the eggs have developed to the next stage, T is the water temperature in the redds, and b, a and α are constants established at -2.6, 5.2 and -11, respectively, for salmonids [*Forseth and Harby*, 2014]. By using the daily average temperature in the redds (interstitial water) from the peak time of spawning (1 November), daily egg development can be estimated as a percentage (100/D). The cumulative sum of the development can then be used to estimate the timing of hatching and swim-up; when the sum of development reaches 100% and 170%, respectively. Despite no data on natural spawning timing was available for the Lundesokna River, we considered spawning period to start 1 October with a peak on 1 November. Such consideration was based on observations made in other parts of the Gaula catchment, and information provided from the local hatchery in Lundesokna.

We used hourly interstitial water temperatures at locations RZ and W to compute daily average data for input to the Crisp model. We then estimated egg and alevin development rates for long-term unregulated *vs*. hydropeaking scenarios. Observations of early life stage development were made in the Lundesokna River for the period 2011-12 [*Casas-Mulet et al.*, 2014b] and they were used as an approximate comparison to the modelled estimations.

3.3. Establishment of critical conditions

Based on previous observations in the river Lundesokna [*Casas-Mulet et al.*, 2014b, 2016] and survival thresholds form the literature, we defined a set of critical conditions that could potentially lead to salmonid early life stages mortality. We used RZ locations in site 2 as a reference and established the following:

(i) Critical conditions for eggs (pre-hatch stage) occur when discharge ≤ 0.65 $m^3.s^{-1}$ and air temperatures are below 0 ^oC for periods of ≥ 3 hours.

Casas-Mulet et al. [2014b] observed total dewatering of the redds at RZ locations when discharges were ≤ 0.65 $m^3.s^{-1}$ (Figure 4). Despite surface dewatering, the eggs were able to survive for long periods of time given moist conditions in the gravel. Mortality risk started after 3 hours of exposure to air temperatures below 0 ^oC.

(ii) Critical conditions for alevins (hatch-to-swim-up stage) mortality occur when discharge ≤ 3.5 $m^3.s^{-1}$ for periods of ≥ 3 hours.

Alevins require surface water covering the redds for survival [*Casas-Mulet et al.*, 2016]. Potential spawning areas at site 2 were totally covered in water during discharges ~3.5 $m^3.s^{-1}$ [*Casas-Mulet et al.*, 2014c; 2015b] (Figure 4). Alevins may tolerate dewatering within the first 1 hour of dewatering exposure, but significant decreased survival within 3 hours [*Becker and Neitzel*, 1985; *Becker et al.*, 1982; *Becker et al.*, 1983; *Neitzel and Becker*, 1985]. Therefore, we considered mortality risk for alevins occur after 3 hours of dewatering.

Estimated hatching and swim-up dates were combined with long-term hourly hydrological and air temperature data to determine whether eggs or alevins were in the redds and to identify critical conditions. We did the computations for both unregulated *vs.* hydropeaking scenarios.

3.4. Assessment of mitigation strategies implementation in the Lundesokna River

Table 1 provides a representative selection of flow-related mitigation options to minimise salmonid early life stages mortality in rivers subject to dewatering. *Stober and Tyler* [1982] suggested to reduce the differences between spawning and incubation flows to provide eggs and embryos with greater protection from dewatering in a river subject to frequent flow changes. A reduction in the area of river channel subjected to dewatering was also suggested by *McMullin and Graham* [1981] and *Connor and Pflug* [2004]. Altering the timing and magnitude of discharge fluctuations can minimize the adverse effects of operating hydroelectric dams on the productivity of downstream fall salmonid populations [*Fisk II et al.*, 2013; *Harnish et al.*, 2014; *McMichael et al.*, 2005].

In summary, a minimum flow release during critical conditions for egg and alevin stages is the dominant suggested mitigation measure (Table 1). In addition, a flow reduction during the spawning period is also suggested to constraint the spawning area that later can be watered securely when minimum flow is released during egg and alevin development. Information gained from Table 1 provided the basis to select potential release-related mitigation options in the Lundesokna River. Current limitation in the hydropower system also had to be considered. They include an absolute minimum production discharge of 8 $m^3.s^{-1}$ for environmental flow release, as no automatic bypass system is implemented Sokna power plant. *Casas-Mulet et al.* [2014c] suggested a release of 8 $m^3.s^{-1}$ for 1 hour every 3 hours to be the most cost-effective for egg survival studies. Based on the above, the following three release-related mitigation options were established:

Option A: Minimum production discharge to be released during periods with critical conditions for egg and alevins from 1 November. This option would cover most redds in water but could not ensure the total protection of redds created by early spawners (before 1 November), neither the redds spawned during high discharges (> 8 $m^3.s^{-1}$). We consider this option would reduce the risk of mortality moderately.

Option B: Minimum production discharge to be released during periods with critical conditions for egg and alevins from 1 November. In addition, a reduction in flows (maximum release of 8 $m^3.s^{-1}$) between 15 and 30 October to be applied. This option would ensure full protection for mid/late spawners but could not ensure total protection of redds by early spawners (before 15 October). We consider this option would considerably reduce the risk of mortality.

Option C: Minimum production discharge to be released during periods with critical conditions for egg and alevins from 1 November. In addition, a reduction in flows (maximum 8 $m^3.s^{-1}$) between 1 and 30 October to be applied. This option would ensure full protection for all spawners. We consider this option would significantly reduce the risk of mortality.

We modelled the implementation of each of the mitigation options using long-term hourly hydropeaking discharge data. We forced the hydropower system to release the required flow (Option A) and/or to stop/reduce the production (Options B/C) during all identified critical conditions for eggs and alevins, depending on the flow requirements for each stage.

3.5. *Feasibility and cost-effectiveness assessment*

We assessed the feasibility in terms in terms of water usage for each of the release-related mitigation options (A, B and C) by:

(i) comparing the availability of water in the hydropower system for minimum flow releases during critical conditions.

We obtained the volume of water available in the system (including the three reservoirs, Figure 1) on 1 November and 1 April through nMAG hydropower simulation program [*Killingtveit and Sælthun*, 1995]. The available volume was then compared to the volume of water needed to implement the necessary minimum release for eggs and alevin. We assessed water availability for the implementation of each option for the period 2002-15.

(ii) comparing the available storage in the reservoirs *vs*. volume of water needed to hold for flow reduction during spawning (for options B and C only).

Data on available storage in the reservoirs was obtained from subtracting nMAG modelled reservoir volumes on 1 October to the total system capacity (145 Mm^3). The total water produced in October each year was then compared to such storage capacity to assess if the system was able to store the water needed for flow reduction during spawning.

The nMAG program was validated with actual reservoir data obtained from NVE and Trønderenergi (hydropower company operating in Lundesokna), available for the period 2004-15.

(iii) calculating additional production flow needed for release during critical conditions.

The percentage of additional discharge needed for release was compared to the actual water used for production for each year. This comparison was used to estimate the relative impact of each mitigation options to long-term water usage. For options B and C, the water saved in October was discounted from the water usage to release during critical conditions (half of it during pre-hatch and half during hatch-to-swim-up).

In order to assess the economic feasibility of each option, we used long-term hourly production (MWh) data obtained from NVE, and hourly energy market price (euro/MWh) from Nord Pool[2]. We estimated annual costs and revenue, including:

(i) opportunity gains from Sokna power plant additional production during critical periods, assuming it was sold to actual market price;
(ii) opportunity gains from selling the water saved in October later on at an average annual market price. The price estimation excluded the period for which the water was saved, being 37.44 euro.MWh^{-1} for option B and 40.68 euro.MWh^{-1} for option C;
(iii) opportunity costs attached to Sokna power plant production during critical periods instead of during higher market prices assuming to be the average of all annual prices (43.56 euro.MWh^{-1});
(iv) potential costs related to additional starts and stops of the turbines (each estimated on 200 euro [*Casas-Mulet et al.*, 2014c]) during critical periods.

A final balance was calculated to assess the relative cost-effectiveness of implementing each of the options. This was then compared to the current annual revenue from Sokna power plant production.

4. Results

4.1. Discharge and water temperature modelling

Long-term discharge, surface and interstitial water temperatures were successfully modelled for unregulated *vs.* hydropeaking scenarios. Figure 5 illustrate the outcomes for the period 2012-13, for which observed hydropeaking water temperature data only was available for comparison (resulting in 0.8 R^2 via linear regression). Air2stream model validation for the year 2012-13 resulted with a NSE value of 0.88.

Whilst unregulated water temperature changes were minimal within a season, discharge and water temperatures varied greatly in hydropeaking scenarios (Figure 5). W location temperatures were

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[2] www.nordpoolspot.com

generally warmer than RZ locations and surface water during both winter and spring. Only in early summer, RZ became similar or even warmer than W locations and surface water.

4.2. Egg and alevins development rates

Long-term hydrological and thermal modelling were used to estimate hatch and swim-up dates at locations W and RZ for unregulated *vs*. hydropeaking scenarios (Table 2). Egg development rates (hatching dates) at site 2 were non-significantly ($p=0.89$) different between hydropeaking *vs.* unregulated scenarios. However, hatching was significantly ($p<0.001$) delayed (12 days, in average) at RZ locations in hydropeaking scenarios when compared to unregulated scenarios. At all sites, during hydropeaking conditions, hatching occurred significantly ($p<0.001$) earlier at locations W than in locations RZ, with up to 16 days in difference (Figure 6).

Estimated swim-up occurred significantly earlier in unregulated compared to hydropeaking scenarios at both locations RZ ($p<0.001$) and W ($p=0.012$). Average differences were 11 and 6 days, respectively. In hydropeaking scenarios, swim-up occurred 6 days (on average) earlier in W positions than in RZ locations (Figure 6).

Observations of hatching occurrences at W locations in site 2 were made on 14 April 2011 and alevins with a fully depleted yolk sack were observed on 16 June. Modelling outcomes for the same year estimated hatching and swim-up dates on 28 April and 13 June, respectively (Table 2).

4.3. Critical periods for eggs and alevins

Differences in development rates between hydropeaking and unregulated scenarios were greater at sites 1 and 2 in the period 2012-13 (Figure 7). In hydropeaking scenarios, higher frequency of critical conditions for both eggs ($\leq 0.65 m^3.s^{-1}$) and alevins ($\leq 3.5 m^3.s^{-1}$) occurred at site 2.

Table 3 illustrates that for the period 2002-15, critical conditions for early life stages occurred more frequently in hydropeaking scenarios than in unregulated conditions at site 2. In hydropeaking scenarios, critical conditions for eggs occurred every single year, with maximum durations of 8.5 days; and critical conditions for alevins occurred every year, except in 2011-12, with durations up to 7.9 days (Table 3). In unregulated scenarios, critical conditions at site 2 occurred only in two years (2002-03 and 2010-11), affecting solely egg stages. They occurred in 10 and 7 occasions, but with longer durations up to 14.5 days.

4.4. Feasibility and cost-effectiveness of mitigation options

Validation of the nMAG model showed 0.6% average differences between daily simulated and observed total reservoir volumes for the period 2004-15.

The feasibility assessment in terms of annual water usage is summarised in Table 4 for options A, B and C. Water usage and additional production were the highest in option A, as water was not hold during spawning. For all options, more changes in water usage were required in the system to minimise alevin mortality than to reduce egg mortality. Changes included increased numbers of minimum releases released for option A or increased flow reductions for options B and C.

The implementation of options B and C were not feasible in some the years as no sufficient storage capacity was available in the reservoirs on 1 October. The reservoirs were too full at that time to hold the water needed for flow reduction during spawning. Insufficient available storage (>100%, Table 4) occurred in periods 2002-05 and 2007-12 for option B. For option C, insufficient available storage only occurred in years 2004-05 and 2007-08.

The economic feasibility assessment concluded that additional costs would be incurred if any of the three options were implemented in the Lundesokna system (Table 5, Figure 8). However, implementation costs would be low compared to the annual production revenue from the Sokna power plant. They were 1.87% (option A), 0.69% (option B) and 0.7% (option C) (Figure 8). The estimated costs of implementing option A resulted from lower opportunity revenue and higher opportunity and extra start costs. The differences in costs between applying options B *vs*. C was minimal, with negligible differences in extra starts costs and slight higher opportunity costs in option B.

5. Discussion

Self-assessment of the modelling tool-set

The modelling tool-set presented in this study was overall satisfactory to assess impacts and mitigation options for embryo and alevin survival in hydropeaking rivers. This modelling tool-set can be particularly useful in hydropower systems where little field data is available. Several site-specific limitations and considerations for its transferability are described below, but overall, the set of modelling tools can be used (individually or integrally) in other hydropower systems to support the assessment of defined flow-related mitigation options.

Hydrological and thermal modelling. Hydrological and thermal modelling were satisfactory and allowed comparison between hydropeaking *vs*. unregulated scenarios. *Hailegeorgis and Alfredsen* [2016] showed that the quantile regression model provides good simulation of discharge data in the test catchments in the same region as Lundesokna. The approach to model unregulated water temperature gave satisfactorily results based on calibration and validation outcomes from Egafoss. The transferability of the model to Lundesokna could not be validated as unregulated data observations were not available (in general, pre-regulation hydrological and thermal data are rare in most catchments in Norway). However, given the proved high performance of such modelling tools in other contexts, we believe these are highly reliable for the purpose of this study.

Interstitial water temperature modelling. Modelled interstitial water temperatures provided a reliable prediction of the overall trends, but did not reflect variations in relation to surface water temperatures accurately. We recognise accurate surface *vs*. interstitial water temperature modelling is required to further advance our understanding in such important processes in the redds, particular for fine time-scale studies. However, for the purpose of this study and provided we used daily averaged data for input to the Crisp model, we considered this approach to be sufficient.

Early life stages development estimation and validation. Crisp's model application assumed all spawning occurred 1 November. Although 1 November is considered the peak date for spawning, we acknowledge this is a limitation not only because it assumes all spawning occurred in one day, but also because any potential effects of hydropeaking on spawning timing were not considered [*Vollset et al.*, 2016]. These investigations were outside the scope of this paper but should be taken into account in future research. Although modelled *vs*. observed data in 2011 was a positive validation, we prefer to not use these dates as strict reference for two reasons: (i) hatchery eggs were used for the experiments, potentially promoting earlier dates given the unnatural exposure to warm water in pre-eyed stages, and (ii) high hydrological and thermal variability due to hydropeaking occurs between years, with consequences to development.

Establishment of critical conditions for early life stages. Thresholds used to establish critical conditions for eggs and alevins were site-specific of the River Lundesokna and may not be directly translated into other river systems. Moreover, the predominance of oxygenated groundwater in Norway allowed for a very low flow threshold for eggs to survive (assuming groundwater influx would encourage egg survival). This assumption may not be feasible in other parts of the world as the effect of groundwater influx may promote embryo mortality [*Malcolm et al.*, 2009; *Soulsby et al.*, 2005].

Hydropower production simulations. Simulated reservoir volumes and available storage through nMAG were satisfactory to assess water usage feasiblity. Similar modelling outcomes were achieved in *Casas-Mulet et al.* [2014c]. Particularly in systems where hydropower regulation data is not available, the use of hydropower simulation models such as nMAG is highly valuable to evaluate release-related options with variable system constraints. Hydropower simulators can also be helpful during decision-making to estimate the feasibility of mitigation options before implementation.

Economic feasibility assessment. We recognise limitations in estimating cost and revenues to assess cost-effectiveness of mitigation options. Changes would undoubtedly occur in the overall annual production if any of the options were to be implemented. Therefore, such calculations should be used as a relative measure only to enable comparison between options.

Thermal regime alteration and consequences for salmonid early life stages development

Changes in surface water temperatures due to hydropeaking are termed as thermopeaking [*Zolezzi et al.*, 2011], with the highest alterations during extreme dewatering events [*Casas-Mulet et al.*, 2015b]. All our findings coincide in the seasonal patterns of reduced water temperature during dewatering events in winter and an increase in spring follows the expected seasonal pattern [*Casas-Mulet et al.*, 2015b; *Vanzo*, 2015; *Zolezzi et al.*, 2011].

Both the hydrological and thermal regimes in the Lundesokna are altered by hydropeaking production with resulting delays on salmon hatching and swim-up. Altered surface water temperature from hydropeaking translate into changes on interstitial water temperatures [*Casas-Mulet et al.*, 2015b]. As a consequence, these changes may impact embryo development. However, the greatest differences were found in the ramping zone. Regular dewatering at RZ locations led to interstitial water being exposed to cold air temperature in winter, delaying development in the reds. Conversely, *Fisk II et al.* [2013] had observed dewatering events were likely to accelerate the development likely from exposure to warmer ambient temperature in non-salmonid species.

Combined impacts of thermal and hydrological alterations on salmonid early life stages survival

Hydropeaking scenarios illustrated several critical periods for both eggs and alevins survival in almost all years. Unregulated scenarios resulted in few but long-lasting critical conditions due to natural flow fluctuations. However, they only occurred in two years and solely affected egg stages. These events would not occur often, but their extended durations would most likely impact the salmonid population for that year. Flows during the hatch to swim-up period are most critical for population success [*Harnish et al.*, 2014]. Moreover, no critical low flows occurred between hatch to swim-up in unregulated scenarios, suggesting such period should be a key focus in future environmental flows management in salmonid rivers.

In hydropeaking scenarios, the consistent delay in hatching may provide some opportunities for overall survival in some years if salmonids remain longer in egg stages, given their less-demanding water needs. This assumption, however, needs to be investigated further on a specific year basis.

Cost-effectiveness of mitigation approaches

Minimum flow releases during critical conditions are a common mitigation recommendation to minimise early life stages mortality. Although it may not avoid mortality in redds laid during the highest flows, it would ensure high probability of survival in targeted areas. Additional flow reduction during spawning (options B and C) would ensure higher survival rates as it would target the avoidance of spawning in high potential mortality areas. Assuming that optimal spawning areas are distributed equally in the riverbed (see *Casas-Mulet et al.*, 2014a), this additional measure would be the most effective to minimise mortality. The sooner and longer flow reduction is implemented during spawning, the higher the probability that no fish would spawn in high mortality risk areas. In this regard, option A was the least effective to minimise mortality risk and the most expensive. However, options B and C could not always be applied due to the limited storage capacity in the reservoirs. Therefore, option A was the only feasible measure many of the years.

Understanding the feasibility in terms of water usage in hydropower systems is therefore key. Reliable information on storage and water availability in a hydropower system is needed, so realistic environmental releases can be achieved. In addition, allowing flexible operations may results in win-win situations for the overall system economics and environmental benefits, rather to stick to strict legislative rules.

6. Conclusions

In this study, we successfully applied a set of modelling tools to assess impacts and mitigation options to reduce early life stages mortality risk in hydropeaking rivers. We modelled long-term hydrological and thermal alterations to estimate development rates; we estimated the risk of early life stages mortality and assessed the cost-effectiveness and feasibility of implementing three release-related mitigation options.

The natural hydrological and thermal regimes are affected by hydropeaking, with consequences to salmon early life stages development and survival. Redd dewatering due to hydropeaking increases the mortality risk for early life stages with higher impacts to alevins given their lower tolerance to exposure. The implementation release-related mitigation options during identified critical conditions for egg and alevins can potentially reduce the risk of mortality. The costs of the three assessed mitigation options was relatively low compared to annual production revenue (A: 1.87%, B: 0.69% and C: 0.7%). Options B and C were the most effective in minimising the mortality risk. However, lack of available storage in the reservoirs some of the years limited their application. Therefore, Option A was the only option that could be feasibly implemented every year for the period 2002-15.

Targeted options built on well-informed modelling approaches can provide opportunities to mitigate effects of dewatering with optimal use of water in the hydropower system. They can be tested on efficiency, feasibility and costs through different hydropower production scenarios before implementation. Environmental flow releases targeting specific ecological objectives can provide better cost-effective options than conventional operational rules complying with general legislation. The outcomes of this research are particularly relevant for the future management of hydropeaking rivers.

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References

Arthington AH, Naimar RJ, McClain ME and Nilsson C. 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology*, 55, 1-16.

Baxter, J. S., and J. McPhail (1999), The influence of redd site selection, groundwater upwelling, and over-winter incubation temperature on survival of bull trout (Salvelinus confluentus) from egg to alevin, *Canadian Journal of Zoology*, *77*(8), 1233-1239.

Becker, C. D., and D. A. Neitzel (1985), Assessment of intragravel conditions influencing egg and alevin survival during salmonid redd dewatering, *Environmental Biology of Fishes*, *12*(1), 33-46.

Becker, C. D., D. A. Neitzel, and D. H. Fickeisen (1982), Effects of dewatering on Chinook salmon redds: tolerance of four developmental phases to daily dewaterings, *Transactions of the American Fisheries Society*, *111*(5), 624-637.

Becker, C. D., D. A. Neitzel, and C. S. Abernethy (1983), Effects of dewatering on Chinook salmon redds: tolerance of four development phases to one-time dewatering, *North American Journal of Fisheries Management*, *3*(4), 373-382.

Casas-Mulet, R., K. Alfredsen, and A. García-Escudero Uribe (2014a), A cost-effective approach to predict dynamic variation of mesohabitats at the river scale in Norwegian systems, *International Journal of River Basin Management*, *12*(2), 145-159.

Casas-Mulet, R., S. J. Saltveit, and K. Alfredsen (2014b), The survival of atlantic salmon (Salmo salar) eggs during dewatering in a river subjected to hydropeaking, *River Research and Applications*.

Casas-Mulet, R., K. Alfredsen, and A. Killingtveit (2014c), Modelling of environmental flow options for optimal Atlantic salmon, Salmo salar, embryo survival during hydropeaking, *Fisheries Management and Ecology*, *21*(6), 480-490.

Casas-Mulet, R., K. Alfredsen, A. Brabrand, and S. J. Saltveit (2015a), Survival of eggs of Atlantic salmon (Salmo salar) in a drawdown zone of a regulated river influenced by groundwater, *Hydrobiologia*, *743*(1), 269-284.

Casas-Mulet, R., K. Alfredsen, B. Hamududu, and N. P. Timalsina (2015b), The effects of hydropeaking on hyporheic interactions based on field experiments., *Hydrological Processes*, *29*(6), 1370-1384.

Casas-Mulet, R., K. Alfredsen, T. Boissy, H. Sundt, and N. Ruther (2015c), Performance of a one-dimensional hydraulic model for the calculation of stranding areas in hydropeaking rivers, *River Research and Applications*, *31*(2), 143-155.

Casas-Mulet, R., K. Alfredsen, Å. Brabrand, and S. Saltveit (2016), Hydropower operations in groundwater-influenced rivers: implications for Atlantic salmon, Salmo salar, early life stage development and survival, *Fisheries Management and Ecology*.

Connor, E. J., and D. E. Pflug (2004), Changes in the distribution and density of pink, chum, and Chinook salmon spawning in the upper Skagit River in response to flow management measures, *North American Journal of Fisheries Management*, *24*(3), 835-852.

Crisp, D. T. (1988), Prediction, from temperature, of eyeing, hatching and 'swim-up'times for salmonid embryos, *Freshwater biology*, *19*(1), 41-48.

Einum, S., and I. A. Fleming (2000), Selection against late emergence and small offspring in Atlantic salmon (Salmo salar), *Evolution*, *54*(2), 628-639.

Enders E, Smokorowski K, Pennell C, Clarke K, Sellars B, Scruton D. 2007. Habitat use and fish activity of landlocked Atlantic salmon and brook charr in a newly developed habitat compensation facility. In Developments in Fish Telemetry, Almeida P, Quintella B, Costa M, Moore A (eds). Springer Netherlands; 133–142.

Fisk II, J., T. J. Kwak, R. Heise, and F. Sessions (2013), Redd dewatering effects on hatching and larval survival of the robust redhorse, *River Research and Applications*, *29*(5), 574-581.

Forseth, T., and A. Harby (2014), Handbook for environmental design in regulated salmon rivers, *NINA Special Report*, *53*, 1-90.

Garrett, J. W., D. H. Bennett, F. O. Frost, and R. F. Thurow (1998), Enhanced incubation success for kokanee spawning in groundwater upwelling sites in a small Idaho stream, *North American Journal of Fisheries Management*, *18*(4), 925-930.

Hailegeorgis, T. T., and K. Alfredsen (2016), Regional Statistical and Precipitation–Runoff Modelling for Ecological Applications: Prediction of Hourly Streamflow in Regulated Rivers and Ungauged Basins, *River Research and Applications*, n/a-n/a.

Hansen, E. A. (1975), Some effects of groundwater on brown trout redds, *Transactions of the American Fisheries Society*, *104*(1), 100-110.

Harnish, R. A., R. Sharma, G. A. McMichael, R. B. Langshaw, T. N. Pearsons, and R. Hilborn (2014), Effect of hydroelectric dam operations on the freshwater productivity of a Columbia River fall Chinook salmon population, *Canadian Journal of Fisheries and Aquatic Sciences*, *71*(4), 602-615.

Killingtveit, A., and N. R. Sælthun (1995), *Hydrology. Volume 7 in the Hydropower Development series*, 213 pp., Norwegian Institute of Technology.

Malcolm, I., C. Soulsby, A. Youngson, and D. Tetzlaff (2009), Fine scale variability of hyporheic hydrochemistry in salmon spawning gravels with contrasting groundwater-surface water interactions, *Hydrogeology Journal*, *17*(1), 161-174.

Malcolm, I., C. Gibbins, C. Soulsby, D. Tetzlaff, and H. Moir (2012), The influence of hydrology and hydraulics on salmonids between spawning and emergence: implications for the management of flows in regulated rivers, *Fisheries Management and Ecology*, *19*(6), 464-474.

McCullough DA, Bartholow JM, Jager HI, Beschta RL, Cheslak EF, Deas ML, Ebersole JL, Foott JS, Johnson SL, Marine KR. 2009. Research in thermal biology: burning questions for coldwater stream fishes. *Reviews in Fisheries Science*, 17: 90-115.

McCullough DA. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. EPA Report, USA.

McMichael, G. A., C. L. Rakowski, B. B. James, and J. A. Lukas (2005), Estimated fall Chinook salmon survival to emergence in dewatered redds in a shallow side channel of the Columbia River, *North American Journal of Fisheries Management*, *25*(3), 876-884.

McMullin, S. L., and P. J. Graham (1981), *The impact of Hungry Horse Dam on the kokanee fishery of the Flathead River*, Montana Department of Fish, Wildlife and Parks.

Neitzel, D. A., and C. D. Becker (1985), Tolerance of eggs, embryos, and alevins of Chinook salmon to temperature changes and reduced humidity in dewatered redds, *Transactions of the American Fisheries Society*, *114*(2), 267-273.

Olden JD, Naiman RJ. 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. *Freshwater Biology*, 55: 86-107.

Poff NL and Zimmerman JK. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, 55, 194-205.

Reiser, D. W., and R. G. White (1983), Effects of complete redd dewatering on salmonid egg-hatching success and development of juveniles, *Transactions of the American Fisheries Society*, *112*(4), 532-540.

Saltveit, S. J., and Å. Brabrand (2013), Incubation, hatching and survival of eggs of Atlantic salmon (Salmo salar) in spawning redds influenced by groundwater, *Limnologica-Ecology and Management of Inland Waters*, *43*(5), 325-331.

Soulsby, C., I. Malcolm, A. Youngson, D. Tetzlaff, C. Gibbins, and D. Hannah (2005), Groundwater–surface water interactions in upland Scottish rivers: hydrological, hydrochemical and ecological implications, *Scottish Journal of Geology*, *41*(1), 39-49.

Stober, Q., and R. Tyler (1982), Rule curves for irrigation drawdown and kokanee salmon (Oncorhynchus nerka) egg to fry survival, *Fisheries Research*, *1*, 195-218.

Toffolon, M., and S. Piccolroaz (2015), A hybrid model for river water temperature as a function of air temperature and discharge, *Environmental Research Letters*, *10*(11), 114011.

Vanzo, D. (2015), Eco-hydraulic quantication of hydropeaking and thermopeaking: development of modeling and assessment tools, University of Trento.

Vollset, K., H. Skoglund, T. Wiers, and B. Barlaup (2016), Effects of hydropeaking on the spawning behaviour of Atlantic salmon Salmo salar and brown trout Salmo trutta, *Journal of fish biology*, *88*(6), 2236-2250.

Webb BW, Hannah DM, Moore RD, Brown LE, Nobilis F. 2008. Recent advances in stream and river temperature research. *Hydrological Processes*, 22: 902-918.

Young, P. S., J. J. Cech Jr, and L. C. Thompson (2011), Hydropower-related pulsed-flow impacts on stream fishes: a brief review, conceptual model, knowledge gaps, and research needs, *Reviews in Fish Biology and Fisheries*, *21*(4), 713-731.

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

Figues captions

Figure1. River Lundesokna and study sites locations.

Figure 2. Typical transect at each of the study sites and maximum and minimum discharge during regulated conditions in 2012-2013.

Figure 3. Diagram of the modelling tool-set used for the assessment of three release-related mitigation measures to minimise mortality in salmonid early life stages in the hydropeaking river Lundesokna (Norway).

Figure 4. Schematic of a representative transect in Site 2, illustrating the areas with high ($>8m^3.s^{-1}$), reduced (0.65-$8\ m^3.s^{-1}$) and very low risk ($0.3m^3.s^{-1}$) of mortality for early life stages. according to the discharge in the river at the time of spawning and whether or not mitigation measures are implemented. The thresholds of critical conditions for alevin and egg survival are also illustrated.

Figure 5. Discharge and surface water temperature for unregulated (top central) and hydropeaking (bottom central) scenarios for the period 2012-13 in the Lundesokna River. Panels above and below central graphs include surface and interstitial temperatures in the permanently wet (W, dark grey dashed lines) and the ramping zone (RZ, light grey dashed lines) locations during three days in winter (a, unregulated; c, hydropeaking) and late spring (b, unregulated; d, hydropeaking). Note that all data is modelled expect for observed discharge data for the hydropeaking scenario.

Figure 6. Average of all sites (1-4) hatching and swim-up dates at RZ (left) and W (right) redd locations during unregulated (top) and hydropeaking (bottom) scenarios for all studied year. Note vertical black lines are overall period average.

Figure 7. Illustration of egg development model (Crisp, 1985) for location RZ during unregulated (solid line) *vs.* hydropeaking (dotted line) for all sites in 2012-13. Periods with partial or total dewatering conditions are depicted in light and dark grey, respectively. Such periods are illustrated only for hydropeaking scenarios.

Figure 8. Economic assessment for each of the measures from all years' average including the economic balance of the measure (top number in bold, all costs) from the calculation of opportunity revenue and costs, and the proportion of the cost in comparison to the actual production revenue (bottom number in bold and italics, in percentage).

Tables captions

Table 1. Key literature references on mitigation measures for fish gravel stages in regulated rivers.

Table 2. Hatching and Swim-up dates at each of the locations (W and RZ) for each site (1-4) during unregulated *vs.* hydropeaking scenarios.

Table 3. Average of numbers and durations of critical periods per year occurring in Site 2, and overall period average during unregulated *vs*. hydropeaking conditions.

Table 4. Annual and all years' average of feasibility in terms of water usage for each of the implemented measures (A, B, C).

Table 5. Annual economic feasibility assessment, and average of all years, for the implementation of each measure (A, B, C).