Hydropower operations in groundwater-influenced rivers: implications for Atlantic salmon (*Salmo salar*) early-life stages development and survival

Abstract

During their early-life stages (egg maturation, hatching, alevin development), between late autumn and early spring, young Atlantic salmon are exposed to surface-groundwater interactions in the hyporheic zone and may depend on influx of sub-surface water during periods of regulated low discharge for survival. Two recent studies, one in a seasonally regulated river and one in a river exposed to hydropeaking, displayed unexpectedly high survival of eggs in surface de-watered areas because of the influx of oxygen-rich sub-surface water. Field observations of newly-hatched alevins in these two rivers showed them to be more sensitive (i.e. suffered higher mortality from) to surface de-watering than were eggs. Exposure to dry conditions in drawdown areas was highlighted as the main cause for alevin mortality. Therefore, shorter periods of surface de-watering in the river with hydropeaking resulted in higher alevin survival compared to the seasonally-regulated river when still permanently drained after egg hatching. Greater consideration should be given to all early life-history stages when implementing discharge release strategies, and the extent of groundwater influence and the potential for flexible hydropower operations should be taken into account.

Keywords: hydropower regulation, hydropeaking, sub-surface water influx, egg survival, hatching success, alevin survival

Introduction

Atlantic salmon (*Salmo salar*) spawn in the autumn by burying their eggs in river gravels, with egg development during winter and hatching in spring. After hatching, alevins remain in the gravel until they have absorbed their yolk sac and then emerge from the substratum, ready for external feeding (Mills 1989; de Gaudemar *et al.* 2000). In regulated rivers, changes in discharge regime, which may leave salmon redds exposed to dry and even freezing conditions during winter, can affect egg and embryo survival (Skoglund *et al.* 2012; Harnish *et al.* 2014). Even if the embryo and alevin stages of Atlantic salmon are well protected in the gravel, then they have no opportunity to evade malign abiotic factors such as reduced discharge induced by river regulation. For optimal survival in regulated rivers, discharge release operations should take into account not only man-made changes in the hydrological regime, but also the influence of sub-surface water on spawning areas (Casas-Mulet *et al.* 2014, 2015a, 2015b).

Desiccation of salmonid redds is of great concern in water resource management (Malcolm *et al.* 2012). If spawning occurs at high flows, then these areas may be de-watered as a result of hydropower operations (McMichael *et al*. 2005; Harnish *et al.* 2014), and physical and chemical conditions in the redds may then be altered (Neitzel & Becker 1985; Young *et al*. 2011). However, because of complex interactions between surface and groundwater and intra-gravel physical and chemical processes, the consequences of de-watering for eggs and alevins are not easily predicted (Malcolm *et al.* 2012). When moist salmonid eggs can survive de-watering for weeks (Saltveit & Brabrand 2013; Casas-Mulet *et al.* 2015a, b), but newly-hatched alevins are more vulnerable and may die 4–10 hours after de-watering (Becker & Neitzel 1985; Becker *et al*. 1982, 1983; Neitzel & Becker 1985; Reiser and White 1983).

The influence of hydropower regulation type and the importance of groundwater and interstitial water for the survival of eggs have been discussed previously regarding two Norwegian rivers: the Lundesokna, which is subjected to hydropeaking (Casas-Mulet *et al.* 2015a), and the Suldalslågen, which is subjected to permanent winter drawdown (Casas-Mulet *et al.* 2015b). In both rivers, egg survival has been unexpectedly higher in the zone subject to discharge fluctuations compared with the permanently wet area, with a mean survival of 89% and >99% in the River Lundesokna, and 72% and 95% in the River Suldalslågen. Sub-surface water influxes have the potential to reduce egg mortality during de-watering events. However, little is still known regarding the consequences of discharge regulation on egg hatching and the alevin stage. Based on field observations of hatching success and alevin survival in the two above mentioned rivers, the aim of the present study was to assess the importance of adapting hydropower operations and taking into account the effect of sub-surface water on salmon populations during their early life stages within the substratum. For this, research that integrates knowledge of ecology and environmental processes is required, so the present study considers key factors for evaluating different discharge scenarios to develop a technically feasible operation strategy that could support hatching success and alevin survival.

Methods

Study sites

The two rivers used in the experimental field studies, the Lundesokna and the Suldalslågen, support natural salmon populations and are located in central and south-west Norway, respectively. The River Lundesokna is a tributary to the River Gaula, the largest river in central Norway, and listed among the top five Norwegian Atlantic salmon angling rivers. Its lowermost power plant, the Sokna, operates on a regime that varies according daily and weekly market price *vs.* available water in the reservoirs. Hydropeaking in the Lundesokna, therefore, results in periodically abrupt discharge fluctuations that can change from ≈ 20 to 0.45 m^3s^{-1} in < 20 min, with a drop in water level of > 0.6 m. The River Suldalslågen, known for its large-sized salmon, is a seasonally regulated water course. Because of water transfers, its instream discharge is reduced throughout the year, ranging between ≈ 12–65 m^3s^{-1}, depending on the time of the year and purpose (smolt migration, angling or flushing). A stable minimum discharge of 12 m^3s^{-1} is released between 15 December and 1 May from the dam at Suldalsvatn. The areas affected by discharge reductions (hydropeaking in the Lundesokna and permanent discharge reduction during winter in the Suldalslågen) are termed the drawdown zone in both rivers.

The experimental sites in both the Lundesokna (Fig. 1a) and the Suldalslågen (Fig. 1b) were the same as selected in previous studies on egg survival (Casas-Mulet *et al.* 2015a, 2015b) and each was a large gravel bar located 500–700 m below a dam. The study sites were selected because of their suitability for addressing the objectives of the present and previous studies (within a broader research programme), and in terms of their substratum and water quality for the construction of redds by indigenous salmon populations, rather than as locations known to support high salmon spawning activity.

Experimental design

The experimental set-up and procedure for data collection were also similar to those described in Casas-Mulet *et al.* (2015a, 2015b). Cylindrical boxes (24 cm high and 6.2cm diameter) comprising eight stacked, perforated compartments (Malcolm *et al.* 2004, 2009) were placed in the riverbed in two types of location in both rivers: permanently-wetted areas (used as a reference), and drawdown zones. Eleven boxes were used in the River Lundesokna and eight in the Suldalslågen (Fig. 1). Atlantic salmon eggs were acquired from local hatcheries at the same time as those used in the studies by Casas-Mulet *et al.* (2015a, 2015b). The eggs, fertilised one week earlier, were introduced into the second and seventh compartments from the top of the cylindrical boxes, 30 eggs per compartment in the River Lundesokna and 50 in the River Suldalslågen. The boxes were then buried so that the egg compartments were situated at ≈ 0.1 and 0.3 m below ground level. Six VEMCO® (Lundesokna) and five HOBO® (Suldalsågen) temperature loggers were attached to the top and bottom compartments of representative boxes in each river. Water pressure transducers were installed in piezometers in the bed to measure water levels in each pair of cylindrical boxes (Fig. 1). In addition, air pressure and temperature loggers were installed at both field locations.

The total number of eggs used in the study was 518 and 641 in the rivers Suldalslågen and Lundesokna, respectively, with 178 and 179 of these being in the reference wetted areas, respectively. Based on field observations, egg hatching started 11 March 2012 in Lundesokna. In the Suldalslågen, hatching started on 18 April 2012 according to field observations and estimates based on temperatures in 2008, 2009 and 2011 (Crisp 1981; Saltveit & Brabrand 2013). Boxes were inspected on day 22 in the Lundesokna and on day 36 in the Suldalslågen after the onset of hatching, which was in agreement with the timing and duration of natural egg development and hatching in the study areas. After removing the cylindrical boxes from the substratum, the total number of hatched *vs.* non-hatched eggs and live *vs.* dead alevins were visually identified and counted for each of the egg compartments.

Results

During the study period, the discharge in the River Lundesokna was severely reduced in twelve occasions due to breaks in hydropeaking production (Fig. 2a) – these were irregular and resulted in different combinations of reduced water level and duration: at the start of the observation period, the breaks were more frequent, and were lower and longer; towards the end, they were less frequent, shorter and more intensive. Starting in late March 2012, the spring flood coincided with higher air temperatures and almost no production stops (Fig. 2a). In the River Suldalslågen, a stable winter low discharge of ≈ 12 m^3s^{-1} was maintained. Two temporary peaks in discharge were released for smolt migration on 1 and 15 May. After the latter peak, high discharges were continuously released until the end of the study period (Fig. 2b). Statistically significant differences in water temperatures were found between both rivers (Fig. 3) in surface ($P < 0.001$, 4.2 and 1 ^{o}C, respectively) and in sub-surface waters ($P < 0.001$, 0.8 and 3.9 ^{o}C and 2 and 3.9 ^{o}C, respectively). In the River Lundesokna, water temperatures were lower (mean = 1 ^{o}C) and less variable in comparison to sub-surface water temperatures (mean = 2^{o}C in the bottom compartments). Between the compartments located in the substratum, the top ones showed higher variability and were colder than the bottom ones (Fig. 3). Water temperatures in the River Suldalslågen were the highest (mean = 4.9 ^{o}C), compared to temperatures found in the top and bottom egg compartments located in the substratum (means = 4.2 and 3.9 ^{o}C, respectively).

Differences in hatching rates between the drawdown zones of the Suldalslågen and the Lundesokna (54 and 38%, respectively, Fig. 4a) were non-significant (P = 0.7). In the Lundesokna, differences in hatching success (Fig. 4a) between the permanently-wetted area and the drawdown zone were also non-significant ($P > 0.05$, Table 1) and showed similar variability and mean values (40 and 38%, respectively). In the Suldalslågen, significant differences in hatching rates were found between the permanently-wetted area (97%) and the drawdown zone (54%) with greater variability in the latter (Fig. 4a, Table 1). In both rivers, the top and bottom compartments located in the drawdown zone showed differences in hatching success (20 and 49% in the Lundesokna and 63 and 44% in the Suldalslågen, Fig. 4b). However, these differences were only significant (Table 1) in the River Lundesokna, where hatching success in the bottom compartments was higher (49%, Fig. 4b). No significant differences in hatching success were found between top and bottom compartments in the River Suldalslågen (Table 1).

Alevin survival (Fig. 5) was high in the permanently-wetted areas, however there were no significant ($P = 0.2$) differences between both rivers. Alevin survival rates in the drawdown zone were significantly higher in the Lundesokna ($P = 0.03$) than in the Suldalslågen. In the Lundesokna, the survival of alevins was not significantly different in the drawdown zone compared to the permanently-wetted area. In the Suldalslågen, rates were significantly ($P = 0.009$) lower in the drawdown zone than in the permanently-wetted area (Table 2, Fig. 5a). The top compartments showed significantly higher alevin survival than the bottom ones in the River Lundesokna ($P = 0.004$, Table 2), but no significant differences in the vertical distribution of alevin survival were found in the Suldalslågen ($P = 0.4$, Table 2, Fig. 5b).

Discussion

The regulated rivers Lundesokna and Suldalslågen illustrate distinct regimes in terms of hydropower operations and discharge regimes that affect surface-groundwater interactions. This has clear consequences for egg survival (Casas-Mulet *et al.* 2015a, 2015b), hatching success and alevin survival in Atlantic salmon. Hatching success in the Suldalslågen was higher than in the Lundesokna, despite the shorter duration between the start of hatching and the end of the study period. These differences may be explained by the overall higher substratum water temperatures in the Suldalslågen compared with the Lundesokna. Assuming a wet or moist environment around the egg boxes, different temperature regimes could explain the differences in hatching success between the top and bottom compartments in both rivers. Indeed, the significant differences in hatching success between the bottom and the top compartments in the Lundesokna could be explained by differences in sub-surface water temperature – with lower mean and more variable temperatures in the top compartments compared to the bottom. This is presumably due to the fluctuations in river water levels, resulting in periods of air exposure. In the Suldalslågen, higher hatching success in the top compared to the bottom compartment could be related to small difference in temperatures, with a greater influence on egg incubation after 1 May due to inundation of the cylinders.

Inter-gravel stage mortality in both rivers was found to be higher for the alevin stage than for the eggs, with time of exposure to dry conditions being a key factor for alevin survival. This agrees with the findings in the literature, which state that newly-hatched alevins are less tolerant to de-watering than are eggs (Becker *et al.* 1982, 1983; Reiser & White 1983; Becker & Neitzel 1985; Neitzel & Becker 1985). For a reach with hydropeaking in the Columbia River, U.S.A., high mortality of the inter-gravel life stages of fall Chinook salmon (*Oncorhynchus tshawytscha*) was attributed to de-watering of redds, resulting in a pronounced effect on the productivity of the salmon population (Harnish *et al.* 2014). In particular, de-watering events that occurred after hatching but prior to swim-up resulted in low egg-to-presmolt survival, whereas de-watering events that occurred prior to egg hatching had little effect on pre-smolt survival (Harnish *et al.* 2014).

Differences in alevin survival rates between the drawdown areas of both rivers clearly reflected differences in hydropower operation strategies. Alevin mortality was significantly lower in the drawdown zone of the Lundesokna than in the Suldalslågen. In the Lundesokna, shorter and more infrequent de-watering episodes due to lower hydropeaking activity resulted in a high survival as a consequence of almost permanent high discharges inundating the egg boxes during the hatching period. The high variability in survival rates in the drawdown zone of the Suldalslågen may be linked to the vertical and horizontal placement of the eggs, which could induce variable surface and sub-surface water levels. However, it can also be hypothesised that very high alevin mortality was found amongst alevins hatching before 1 May due to desiccation of the substratum before the peak release, which inundated the egg compartments. High mortality could also have occurred amongst alevins hatching between 1 and 15 May. The drop in water level between the two peaks in discharge could have desiccated the boxes. Only late-hatching salmon, i.e. after 15 May, could have survived given the stable, higher discharge that inundated the boxes.

Results shown in the present paper highlight the importance of developing customised stream discharge releases in regulated salmonid rivers. In addition to the moist environment required by the eggs (Casas-Mulet *et al.* 2015a, 2015b), alevins need to be continuously inundated in order to survive. Given a lack of groundwater availability, the recommended mitigation measure for hydroelectric dam operation should focus on lowering discharge rates during spawning (Harnish *et al.* 2014, Skoglund *et al.* 2012). In contrast, the presence of sub-surface influx in regulated rivers may alleviate the effects of hydropower production and allow more flexible operations during the embryo stages. However, a strong focus on maintaining higher and constant discharge rates may be required in the alevin stages to ensure their survival.

Rigid regulation regimes designed to fulfil pre-established environmental regulations may not always result in the best conditions for the survival of early salmonid life stages, as demonstrated in the case of the seasonally-regulated River Suldalslågen. In the River Lundesokna, the 2012 flow conditions were particularly favourable for alevin survival given the continuous hydropower production in spring. However, this production regime may be the exception in other years with greater power demands and/or little water availability. Moreover, rapid winter water level fluctuations due to hydropeaking may increase stranding mortality in older recruits (Saltveit *et al.* 2001).

In order to maintain a sustainable salmon population in regulated rivers, all life history stages must be taken into account when designing and implementing discharge regulation regimes. This requires evidence that integrates information on salmon biology and on environmental processes. Customised discharge regimes that resemble natural hydrological conditions have the potential to increase egg and alevin survival in salmon rivers. Such discharge regimes should be flexible and may also prove to be more cost-effective than non-flexible permanent minimum discharge releases designed to comply with rigid legislative requirements (Casas-Mulet *et al.* 2014).

The outcomes of the present study are particularly relevant to current environmental hydropower operations in Norway, as the design of stream discharge regulation does not take into account the alevin stage. In addition, hydropower facilities do not always possess the infrastructure for flexible electricity production that permits compliance with environmental needs. It is therefore relevant to consider three main factors when assessing the potential for flexible operations for stream discharge regime implementation. They include all early life-history stages, the type of hydropower regulation in place, and the extent to which groundwater influx could potentially alleviate the hydro-production effects. This knowledge needs to be integrated and used actively in the future management of regulated rivers.

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Figures

Fig. 1. Illustration of the site topography and specific position of the egg boxes in relation to groundwater and surface-water levels during low and high discharge periods in the Norwegian rivers (a.) Lundesokna and (b.) Suldalslågen.

Fig. 2. Water level fluctuations and air temperature changes during the study periods in two Norwegian rivers: (a.) the Lundesokna, which is subject to hydropeaking; and (b.) the Suldalslågen, which is seasonally-regulated.

Fig. 3. Surface river and sub-surface water temperatures distribution in the rivers Lundesokna and Suldalslågen (Norway) during the study period. Sub-surface water temperatures were measured at the top and bottom compartments of a representative box in each of the study sites (Box 1 in the River Lundesokna (see Casas-Mulet *et al*. 2015a) and Box 2D in the River Suldalslågen (see Casas-Mulet *et al*. 2015b)). Note: temperature values at the bottom of the graph are sample means.

Fig. 4. Distribution of hatching success rates (including alive and dead alevins) for: (a.) all boxes in the permanently-wetted or reference areas and in the drawdown zone (DZ); (b.) top and bottom compartments of the DZ of the rivers Lundesokna and Suldalslågen (Norway). Note: percentages shown at the top of the graphs are sample means.

Fig. 5. Distribution of alevin survival rates for: (a.) all boxes in the permanently wetted areas and in the drawdown zone (DZ); (b.) top and bottom compartments of the DZ of the rivers Lundesokna and Suldalslågen (Norway). Note: percentages shown at the top of the graphs are sample means.

Tables

Table 1. Number of hatched eggs sample size (n), mean, maximum and minimum and *P* values between same-river samples for: (a.) all boxes in the permanently-wetted or reference areas *vs.* the drawdown zone (DZ); (b.) top *vs.* bottom compartments of the DZ of the rivers Lundesokna and Suldalslågen (Norway).

Table 2. Number of surviving alevins sample size (n), mean, maximum and minimum and P values between same-river samples for: (a.) all boxes in the permanently wetted or reference areas *vs.* the drawdown zone (DZ); (b.) top *vs.* bottom compartments of the DZ of the rivers Lundesokna and Suldalslågen (Norway).