Modelling of environmental flow options for optimal Atlantic salmon (*Salmo salar*) embryo survival during hydropeaking

Abstract

Recent findings on causes of Atlantic salmon embryo mortality during winter in a hydropeaked river suggest that long duration drawdowns during very cold periods are the most likely cause of mortality in the ramping zone areas. This paper presents a framework in which thresholds for optimal embryo survival at the micro-scale are linked to physical habitat requirements at the meso-scale and integrated into alternative hydropower operations at the catchment scale. The connections within this framework are executed with a one-dimensional hydraulic model at the meso-scale and a hydropower simulation program at the catchment scale. The economic costs and feasibility of several alternative options for hydropeaking operation that would comply with ecological requirements for the optimal survival of embryos were evaluated. This paper presents a method to assess a wide range of alternative hydropower options that consider key factors to mitigate the conflicting process requirements of ecological targets, technical feasibility, and economics. Targeted alternative environmental flow releases to meet specific ecological objectives are often more effective than general operational rules to comply with legislation. The development of well-informed and targeted mitigation strategies is important for future environmental hydropower management.

Key words: Atlantic salmon; embryo survival, hydropeaking management, modelling tools, upscaling

Introduction

Hydropeaking in regulated rivers is predicted to be more frequent in the near future given the increasing demand for renewable energy in Europe. Norway, through its hydropower systems, has >50% of the total European water storage potential with possibilities for increase (Catrinu-Renström and Knudsen, 2011), providing opportunties for balancing the energy load with other renewables such as wind power. Load balancing using hydropower implies more frequent fluctuations of water levels in rivers due to hydropeaking operations.

Atlantic salmon (*Salmo salar*) spawns typically in the autumn by depositing their eggs in redds in the river bed gravels (de Gaudemar *et al.*, 2000, Mills, 1989). The most restrictive niche of all Atlantic salmon life stages is egg and embryo development, which occurs during winter (Cunjak *et al.*, 1998, Cunjak and Therrien, 1998). Although survival rates of embryo and alevins in natural conditions can be very high (Elliott, 1984) mainly due to the protection offered in the gravels, eggs have no capacity to move from malign abiotic factors. This makes their survival dependent on subsurface and surface water exchange (Schmidt and Hahn, 2012), hyporheic water quality, water delivery rate, temperature and gravel composition and the complex interaction between these (Gibbins *et al.*, 2008, Malcolm *et al.*, 2008, Malcolm *et al.*, 2003).

River regulation may reduce the amount and quality of suitable spawning habitat, which is a prime necessity for recruitment and population sustainability. In particular, the dewatering of salmonid redds is of great concern for water resource management in regulated rivers (Malcolm *et al.*, 2012). If spawning occurs during high flows, nest sites may be dewatered as a result of hydropeaking operations (McMichael *et al.*, 2005; Vollset *et al.*, unpublished data) or when water levels are not maintained (Bauersfeld, 1978; Skoglund *et al.*, 2012). Eggs of fall-spawners can freeze and die in cold areas during low flow periods in late winter under natural conditions, in regulated rivers with large annual variations, or in rivers subject to hydropeaking if flow is reduced after spawning (Skoglund *et al.*, 2012). The extent of egg mortality due to freezing in regulated rivers can be influenced by subsurface water inputs in the catchment (Saltveit and Brabrand, 2013), but the exposure to dry and frost conditions will remain a main driver for the survival of Atlantic salmon eggs in rivers with long drawdowns due to hydropeaking regulations (Casas-Mulet *et al.*, submitted).

Harby *et al.* (2001) introduces some general advice on best-practices for environmental management of Norwegian power plants with hydropeaking operations, but more emphasis is needed to develop targeted mitigation strategies on an individual-case basis, particularly for salmonid populations. Some examples of research-based targeted mitigation measures for salmonids are presented in the literature for regulated rivers (Fjeldstad *et al.*, 2014, Gibbins and Acornley, 2000). However, for the environmental management of hydropeaking further research is needed to fully understand the issues on an individual-case basis in order to develop targeted mitigation strategies at the catchment scale.

With detailed investigations of small-scale physical and biological processes, and a good understanding of the links with processes operating at larger scales, it is possible to reflect how management decisions at larger scales can affect such small-scale processes. In order to transfer the information from small to large scales, spatial upscaling methods are needed, to overcome the validity problems that micro-scale habitat analysis might carry (Borsányi, 2005).

Hydropower operational strategies at the catchment scale are a major influence on what occurs at the meso and micro-scales. Therefore, ecological and physical processes occurring at the smaller scales should be considered when making managerial decisions at the catchment scale. Studies at the micro-scale enable an accurate and detailed representation of ecological processes. The connections between hydraulic processes, geomorphology and river ecology have been studied in recent years (Maddock, 1999, Padmore, 1998, Petts *et al.*, 2006). Several studies have proven relevant links between physical habitat and ecology at the meso-scale (Kemp *et al.*, 1999, Moir and Pasternack, 2008, Padmore, 1997, Parasiewicz, 2007), suggesting the meso-scale to be an adequate dimension to study relevant ecological processes and a feasible scale for river management decisions (Newson and Newson, 2000).

The challenges rely on integrating different scales as a first step to link research findings with hydropower operation alternatives at the catchment scale for hydropeaking environmental impact assessment. A decision support tool that is able to evaluate ecological needs and to calculate power production in different peaking scenarios is needed for large-scale management decisions. By linking the findings at the micro-scale with meso and macro-scale processes, the resulting system should be a tool to assess the cost of production while also fulfilling ecological requirements. In order to establish real links between findings at the micro-scale to the hydropower simulation level, connections have to be done through modelling tools. The use of predictive modeling tools and their validation will be important to understand processes and to assess future changes in the regulation of the hydro systems, and they will be key to define when, where and how hydropower plants can use peaking operations without causing ecological damage.

This paper presents a framework in which research on Atlantic salmon egg survival at the small scale and links to physical habitat at the meso-scale are integrated to assess alternative environmental flow options to reduce egg mortality. The connections in this framework are executed by combining hydraulicand hydropower operation models with egg survival data for a spawning site. This paper presents a tool to assess the integration of hydropower operation at the catchment scale to mitigate and/or avoid potential impacts on small-scale fish recruitment processes in the river.

The main objective is to assess the possibilities of alternative hydropower operations for the significant improvement of egg survival potential using data from the Lundesokna river as a test case. Several scenarios will be assessed according to duration, volume of extra water release, and their economic cost. In addition, the strategy presented could be seen as a general methodology for assessing how changes in hydropower operation might influence in-stream processes.

Materials and methods

Study site

The Lundesokna hydropower system in central Norway (Figure 1) covers a total catchment area of 395 km^2 with an average annual runoff of 381 Mm^{3}y^{-1}. It comprises the whole Lundesokna catchment (264 km^2, 41.2 km river length and 247 Mm^3 average annual runoff) and part of the Burusjøen (16.8 km^2) and Holta (114.4 km^2) catchments, which are connected via three main transfers. The Lundesokna hydropower system consists of three reservoirs (Håen, Samsjøen and Holtsjøen) with a combined 145 Mm^3 in water volume, and three power plants (Sokna, Håen and Sama) with a total installed capacity of 61 MW and average annual production of 278 GWh. Sokna power plant operates according to market price fluctuations occurring daily and weekly and to available water in reservoirs. This results in the lower 2.5

km of the Lundesokna river being subject to regular and abrupt flow fluctuations with a typical flow range varying from 0.3 m^3s^{-1} (no power production) to 20 m^3s^{-1} (full production).

Sokna power plant has an optimal intake capacity of 20 m^3s^{-1} and the minimum production flow is 8 m^3s^{-1}, below of which the system might experience poor efficiency and cavitation problems (Viggo Finset, pers.comm.). There are no compulsory minimum flow requirements in the Lundesokna river, but a voluntary release of 0.3 m^3s^{-1} through a manually operated gate occurs between May and September when needed for the operation of the hatchery in the catchment. The study focuses on Lundesokna below the Sokna power plant outlet.

Durations of critical periods

Environmental requirements for the optimal survival of Atlantic salmon embryos were established from the findings in, where survival rates were lower in the ramping zone (76%) compared to the permanently wet areas (99%). Exposure to dry conditions due to production stops combined with air temperatures below 0 ^{o}C was the main factor explaining egg mortality. The maximum duration exposure to dry and freezing conditions with no egg mortality was about three hours. Highest survival rates (>86%) showed maximum durations of production stops with air temperatures below zero up to six hours. Some of Casas-Mulet, *et al.* (submitted) findings recommended to minimize the duration of hydropower production stops during extremely cold air temperatures in hydropeaking rivers.

In order to translate such recommendations into practical management measures, both the three and six hour maximum cessation of hydropower production in combination with air temperatures below zero were considered as potential duration thresholds to establish alternative management options for hydropower production that would be compatible with optimal embryo survival, using the Lundesokna river as an example.

Minimum flow thresholds

The upper boundary of potentially suitable spawning areas in the Lundesokna river was estimated at 30.6 m through field observations in a representative transect in the study area in Casas-Mulet *et al.* (submitted). Such elevation was used as a threshold to establish minimum flows needs, assuming that water at this elevation would cover 100% of the potential spawning grounds (based on field observation on substrate suitability) in the ramping zone.

In order to translate the obtained water elevations to discharge in the river, hydraulic simulations had been carried out for the whole Lundesokna river length with the aid of the one-dimensional hydraulic simulation model HEC-RAS (US Army Corps of Engineers, 2012). More details on the field data collection, model set-up and calibration are described in (Casas-Mulet *et al.*, 2014). The resulting minimum discharge at which 100% of the eggs were covered by water was3.5 m^3s^{-1}. Minimum production flow of 8 m^3s^{-1} (minim turbine capacity) was also modelled in HEC-RAS and considered as the minimum flow threshold for some of the options for alternative hydropeaking management. In addition, the increase of wet area due to such additional flow increases (3.5 and 8 m^3s^{-1}) was calculated at the transect level.

Options for alternative hydropeaking management

Based on the above information, several options for additional water release were established according to: (i) type of additional water release (bypass or production); (ii) intervals of additional water release (permanently, every 3 hours or every 6 hours) and (iii) duration of the release (non-stop, 2 hours or 1 hour). Such alternative hydropower management options were to be implemented during critical periods with low flows (mainly due to production stops) coinciding with air temperatures below 0 ^{o}C. They ranged fromapermanent minimum bypass release of 3.5 m^3s^{-1} (options 1) or the minimum possible production flow of 8 m^3s^{-1} (options 2) to an alternated or flexible minimum bypass release or production conditional to air temperature (options 3 and 4). All options are illustrated in Figure 2 and summarized in Table 1.

Critical periods were first identified from available data for the hydrological years (1 September to 31 August) 2002-2003 to 2012-2013. Hourly air temperature was combined with hourly production and spill data from Sokna power plant to identify the critical periods with flows below 3.5 m^3s^{-1}. Hourly air temperature data (2002-2013) was obtained from the nearby Voll climatic station and it was used to identify periods with air temperature below 0 ^{o}C. A correction factor to estimate the actual temperature in the field site during the studied period (2002-2013) was applied to the data from Voll. The correction factor was obtained by comparison of air temperature data obtained from the field site during the period December 2011 to May 2013 with data from Voll. All data was obtained from Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Meteorological Institute.

Simulation of additional water volume used

The additional water required for additional bypass or production release in each of the options was calculated by adding up the hourly additional release for each of the periods (2002-2003 to 2012-2013).

An assessment on whether the hydropower system was able to handle the additional volume of water needed for each of the options was carried out by using the nMAG hydropower simulation program (Killingveit & Sælthun, 1995). A model of the river Lundesokna hydropower production system was established. It involved a total of 11 modules consisting of the described reservoirs, power plants, interbasin transfers and control points (Figure 3). The simulation used a reservoir guide curve for all reservoirs assuming they start at 70% of the volume on 1 January, emptied on 1 May, filled up again to 90% on 1 July and kept at that level until 1 October, then gradually decreased back to 70% on 31 December. Model inputs consisted of existing runoff data from the nearby Hugdal catchment, with similar physical characteristics to Lundesokna. Runoff data were obtained from the period 1986 to 2013. Calibration was based on historical production data and reservoir water levels for the same periods. All data were obtained from The Norwegian Water Resources and Energy Directorate (NVE) and TrønderEnergi.

The capacity of the hydropower system to provide the additional water needed for each of the designed options was assessed by comparing it to the nMAG simulated maximum volume of water available in the reservoirs for each of the simulated years.

Economics

An economic assessment was carried out for each of the options by calculating the revenue of additional production, the costs of additional water release and the costs of additional starts in Sokna power plant. The revenue of additional production was obtained by adding up the additional hourly production (MWh) multiplied by the real hourly energy price (euro per MWh) for each of the options. This only applied to options 2 and 4. Energy price data were obtained from TrønderEnergi in norwegian crowns (NOK) per MWh that was converted into euro per MWh according to daily exchange rates from The National Bank of Norway. A monetary cost due to additional water used was assumed on the basis that such extra use of water could have been kept and used at times with a higher hourly price. This assumption was applied to all the options irrespective of bypass release or production. Therefore, the final annual production or bypass release flow (m^3s^{-1}) used was added up, converted to production (MWh) and multiplied by a high price assumed to be a 0.99 percentile of the annual price range for the periods 2002-2003 to 2012-2013. The monetary cost of the additional turbine starts due to additional production (only options 2 and 4) in Sokna power plant was considered for each of the periods. The cost of starting the hydropower plant is at present 200 euros. Inflation values were obtained for each of the periods and applied to the present cost to obtain the actual cost for each of the simulated periods. The final economic balance for each of the designed options was compared to the actual annual revenue made for each of the periods.

A final qualitative and quantitative assessment was made for each of the options regarding (i) the likelihood to meet optimal survival of eggs, (ii) the feasibility of the hydropower system to carry out the additional production or bypass releases in terms of water usage, economically and technically, and (iii) the additional usage of the power plant. The likelihood of meeting the optimal survival for eggs was assessed as *very likely* when potential spawning areas were wet during air temperatures below zero with 100% of certainty or with safe intervals of 3 hours, and *likely* when potential spawning areas were wet during air temperatures below zero but with <100% of certainty or with intervals of 6 hours. Feasibility in terms of water usage was ranked according to the average additional percentage of water used in relation to the maximum volume of water in the system. Economic feasibility was assessed relative to the average percentage of monetary loss in comparison to the annual revenue. Technical feasibility was assessed as not feasible and feasible according to the present technical characteristics of the system. The additional usage of the power plant was ranked according to the average percentage of additional hours of production in relation to average actual production.

Results

Linking scales and models: The linking methodology

Findings from Casas-Mulet *et al.* (submitted) helped establish certain bottleneck periods for the survival of Atlantic salmon embryo in a study site in the Lundesokna river. A certain minimum water elevation (30.6 m) should be maintained during periods with air temperature below 0 °C to avoid mortality in potential spawning areas. Links between the micro and meso-scales were made by translating water elevations into minimum flows (3.5 m^3s^{-1}) through a HEC-RAS simulation. Such minimum discharge and critical conditions were then translated into several alternative hydropower operation options encompassing bypass release or production flow to be carried out at certain periods and time intervals. The method of linking scales is illustrated in Figure 4 as part of the assessment process explained below.

Modelling calibration and outputs

The nMAG simulation with the current operational strategy resulted in a total annual production of 305.1 GWh, showing a difference of <0.001 % in comparison to the actual production of the three power plants for the period 1986-2009. Average reservoir water levels differed between 0.01 and -0.41% when compared to the actual reservoir data for the studied period (Table 2).

The calibrated HEC-RAS model for the Lundesokna river provided that the increase of wet area from the minimum recorded flow (0.3 m^3s^{-1}) to the minimum bypass release (3.5 m^3s^{-1}) was 55%, while from the minimum recorded flow to the production flow (8 m^3s^{-1}) the increase was 190% at the transect level.

Water use and system availability assessment

The additional volume of water needed for each of the options and for each of the simulated years is illustrated in Figure 5. Scenarios with permanent or partially permanent production or bypass release (options1 and 2) required volumes of additional water ranging from 77.5 to 15.1 million of m^3 per year. Option 4.1 (permanent production during periods with air temperature below zero) also had a high requirement for additional water (20 mill. m^3). Those were very high in comparison to those required in options 3 and 4 (ranging from 0.7 to 7 mill. m^3).

The percentage of additional volume of water needed in comparison to the maximum water volume in the system (including Håen, Samsjøen and Holtsjøen reservoirs) for each of the simulated years is illustrated in Figure 6 for each of the bypass and production options. Option 2.1 would require between 90% and 27% of the maximum water volume in the system, showing great variability between individual years. Options with targeted releases through bypass and production (3.2.1 to 3.3.2 and 4.2.1 to 4.3.2) would require much less percentage of the total volume, varying between 9% and 0.02% of such volume, showing as well some variability between individual years.

Figure 7 illustrates the percentage of additional hours of production for each of the simulated options in comparison to the actual hours of annual production. As expected, options 2.1 and 2.2, with a permanent or partially permanent production, were the options with a higher proportion of additional hours to be released (44.4% and 21.4% on average respectively). Options 4.2.1 to 4.3.2, with an alternative bypass or production of 1 hour every 6 hours, were the options with the lowest additional production hours, ranging from 10% to 1% additional production hours (see also Table 3).

Economics

Revenue from additional production and costs from additional starts in the hydropower plant did not have any effect on the economic balance made for the bypass releases options (Figure 8). The cost of bypass release was therefore related only to the potential economic loss due to volume of water used, with the higher costs found in options 1, for the permanent bypass release and the lower cost found in options 3, with the least hours of required release (3.3.2). Alternative production options accounted for some revenue due to the additional production. It was significant in comparison to the additional cost of extra starts in the power plant, but could not compensate for the loss of volume of water used that could have been used in periods with higher market prices. The final balance therefore was also an economic loss, which was greater in options 2 and was reduced progressively in options 4 as less volume of water was required. The annual balance for each of the alternative options is illustrated in Figure 9, showing the high variability in economic loss from year to year within the same option.

Table 3 summarizes the above results in ecological, economic and technical terms for the assessment of each of the options and Figure 4 illustrates a simplified decision tree including all terms of assessment and the inclusion of the linking method.

Discussion

The present study takes a multi-scale approach, from both an ecological and physical habitat point of view to a hydropower operation application. In order to establish connections between the ecological and physical processes occurring at the micro-scale and the potential hydropower operation alternatives at the macro-scale, connections were established through the use of existing modelling tools. The connection between scales was done by linking detailed findings on ecological processes at the micro-scale with the 1D hydraulic model (HEC-RAS) at the meso-scale, representing physical habitat changes, and later this was linked to the nMAG hydropower operation model at the macro-scale by assessing the additional volume of water required. Ecologically relevant findings at the micro-scale can be translated to the meso-scale with the use of HEC-RAS (water elevation and wet area changes) and that in turn provides input to the hydropower simulator nMAG. Results show this methodology is a valid way to establish links between scales and models in order to assess potential alternative hydropower operations for the management of hydropeaking rivers.

The use of modelling tools and their integration for the prediction of alternative hydropeaking management to meet environmental requirements was also illustrated in Borsányi *et al.* (2001), where links between existing programs including a one-dimensional hydraulic model and nMAG were assessed in detail for the quantification of habitat use during normal and habitat friendly hydropeaking strategies. Fjeldstad *et al.* (2014), for example used nMAG together with smolt models for the analysis of smolt migration in order to explore possible mitigation scenarios for increased smolt survival. The framework presented in the present paper can be used for any environmentally relevant findings at the micro or meso-scale and potential alternative hydropower operations at the macro-scale. Prediction of future changes in hydropower management can be done and help define when, where and how hydropower plants can use peaking operations from an environmental point of view.

The total water volume available in the Lundesokna hydropower system (from the three reservoirs) would barely allow carrying some of the alternative hydropower management options in wet years. The amount of water required in options 1 and 2 and 4.1 would make the hydropower operation unfeasible both in terms of water availability and economics. Therefore only the conditional bypass or production release in options 3 and 4 could be considered.

Technically, the mechanism used to release the additional volume of water needed (bypass or production) is an important consideration. Sokna power plant at present does not have any established system to automatically control bypass release, and 8 m^3s^{-1} is the minimum flow that the power plant is capable of producing. Therefore, currently options including production (options 2 and 4) would be the most feasible to undertake from a technical point of view.

When taking into account the amount of extra hours of production, options 2 resulted in a very high additional use of the power plant in comparison to options 4. Options 1 and 3 including bypass release, would not impose any additional production hours. This is an important factor to consider from the increased use of the turbine that might reduce its life span and impose significant additional costs in the long term.

From an ecological point of view, an increase in wet area is likely to provide more available habitat for salmonids in early stages and can be used as a measure of reduced risk of mortality. Specifically for the purpose of this study, an increase of 55% in wet area as a result of a bypass release of 3.5 m^3s^{-1} (options 1 and 3) would be considered sufficient to ensure egg survival in the areas where spawning is more likely to occur. Equal option alternatives but with production flow to 8 m^3s^{-1} would not provide any additional benefit for the specific objective of salmon embryo survival optimization. Regardless their non-feasibility at the hydropower system level, options 1.1 and 2.1 (producing or bypassing extra water permanently) would ensure that the potential spawning areas are wet at all times, but in non-critical periods they would most likely not add any additional benefit for the optimal embryo survival. A targeted bypass release or production flow during specific periods with air temperatures below zero would be sufficient to allow optimal embryo survival. Such options would probably even be more efficient than the partial permanent release for the period 1 October to 31 March suggested in options 1.2 and 2.2. In some of the considered years, air temperatures coinciding with production stops were found to occur outside of such established period.

Economically, revenue lost in the final assessment is very similar between comparable bypass release and production options, suggesting that although production might increase some revenue, this is mainly revenue resulting from selling at low prices, which is very low in comparison of the potential loss of water volume that could had been sold at higher prices. This also indicates how the variability of the power prices is a main driver in deciding when and how much to produce and how it influences the calculation of the costs in the present study.

Overall, this paper illustrates that in certain cases, with research-based knowledge, it can be more cost-effective to employ a targeted change in production patterns aiming at a specific ecological objective than to establish a permanent release to meet general legislative rules, such as the establishment of constant or periodically constant minimum flows. Integrating knowledge of ecology and environmental processes with operational planning allows for further design of environmental flow regimes that fit the production schedule of the hydropower plant and meet ecological requirements, particularly in existing power plants.

The development of well-informed and targeted mitigation strategies is important for future environmental hydropower management. The presented method considers key factors when evaluating different hydropeaking scenarios in order to develop a technically feasible operation strategy that optimizes both economic and ecological performance. It provides a tool for setting flows for the particular case of egg survival; however the focus of this study is to provide a general methodology that is also applicable to other components of the aquatic ecosystem, and ultimately a tool that can be used in the decision-making process for the establishment of true environmental flow regimes rather than minimum flow regimes currently employed in many regulated rivers.

References

Bauersfeld K. (1978) *Stranding of juvenile salmon by flow reductions at Mayfield Dam on the Cowlitz River, 1976.* Washington State Department of Fisheries, Olympia. 36 pp.

Borsányi P. (2005) *A classification method for scaling river biotopes for assessing hydropower regulation impacts.* PhD Thesis, Norwegian University of Science and Technology, 255 pp.

Borsányi P., Killingveit Å. & Alfredsen K. (2001) A Decision Support System for Hydropower Peaking Operation. *Hydropower in the New Millennium: Proceedings of the 4th International Conference on Hydropower Development.* 20-22 June 2001. Bergen, Norway, pp. 191-196.

Casas-Mulet R., Saltveit S.J., Alfredsen K. Submitted manuscript. The survival of Atlantic salmon (*Salmo salar*) eggs during dewatering in a river subject to hydropeaking.

Casas-Mulet R., Alfredsen K., Boissy T., Sundt H. & Rüther N. (2014) Performance of a on-dimensional hdyraulic model for the calculation of stranding areas in hydropeaking rivers. *River Research and Applications*. Early view.

Catrinu-Renström M.D. & Knudsen J.K. (2011) *Perspectives on hydropower's role to balance non-regulated renewable power production in Northern Europe*. Sintef Report, Trondheim.

Cunjak R.A., Prowse T.D. & Parrish D.L. (1998) Atlantic salmon (Salmo salar) in winter: "the season of parr discontent"? *Canadian Journal of Fisheries and Aquatic Sciences* **55** (Suppl.1), 161-180.

Cunjak R.A. & Therrien J. (1998) Inter-stage survival of wild juvenile Atlantic salmon, Salmo salar L. *Fisheries Management and Ecology* **5** (3), 209-223.

De Gaudemar B., Schroder S. & Beall E. (2000) Nest Placement and Egg Distribution in Atlantic Salmon Redds. *Environmental Biology of Fishes* **57** (1), 37-47.

Elliott J.M. (1984) Numerical Changes and Population Regulation in Young Migratory Trout Salmo trutta in a Lake District Stream, 1966-83. *Journal of Animal Ecology* **53** (1), 327-350.

Fjeldstad H.P., Alfredsen K. & Boissy T. (2014) Optimising Atlantic salmon smolt survival by use of hydropower simulation modelling in a regulated river. *Fisheries Management and Ecology* **21** (1), 22-31.

Gibbins C., Shellberg J., Moir H. & Soulsby C. (2008) Hydrological influences on adult salmonid migration, spawning, and embryo survival. In: Sear, D. & P. Devries (eds) *Salmon Spawning Habitat in Rivers: Physical Controls, Biological Responses and Approaches to Remediation,* American Fisheries Society.

Gibbins C.N. & Acornley R.M. (2000) Salmonid habitat modelling studies and their contribution to the development of an ecologically acceptable release policy for Kielder Reservoir, North-east England. *Regulated Rivers: Research & Management* **16** (3), 203-224.

Harby A., Alfredsen K., Fjeldstad H.P., Halleraker J.H., Arnekleiv J.V., Borsányi P., Flodmark L.E.W., Saltveit S.J., Johansen S.W., Vehanen T., Huusko A., Clarke K. & Scruton D.A. (2001) Ecological Impacts of hydro peaking in rivers. *Proceedings of the 4th International Conference on Hydropower Development*. Lisse, Netherlands.

Kemp J.L., Harper D.M. & Crosa G.A. (1999) Use of 'functional habitats' to link ecology with morphology and hydrology in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems* **9** (1),159-178.

Killingveit Å. & Sælthun N.R.(1995) Hydrology. *Volume 7 in the Hydropower Development series*. Norwegian Institute of Technology, Trondheim, 213 pp.

Maddock I. (1999) The importance of physical habitat assessment for evaluating river health. *Freshwater Biology* **41** (2), 373-391.

Malcolm I.A., Gibbins C.N., Soulsby C., Tetzlaff D. & Moir H.J. (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.

Malcolm I.A., Youngson A.F., Greig S. & Soulsby C. (2008) Hyporheic influences on spawning success. In: Sear, D. & Devries, P. (eds) *Salmon Spawning Habitat in Rivers: Physical Controls, Biological Responses and Approaches to Remediation,* American Fisheries Society.

Malcolm I.A., Youngson A.F. & Soulsby C. (2003) Survival of salmonid eggs in a degraded gravel-bed stream: effects of groundwater–surface water interactions. *River Research and Applications* **19** (4), 303-316.

McMichael G. A., Rakowski C. L., James B. B., & Lukas J. A. (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.

Mills D.H. (1989) *Ecology and Management of Atlantic Salmon.* London: Chapman & Hall.

Moir H.J. & Pasternack G.B. (2008) Relationships between mesoscale morphological units, stream hydraulics and Chinook salmon (Oncorhynchus tshawytscha) spawning habitat on the Lower Yuba River, California. *Geomorphology* **100** (3–4), 527-548.

Newson M.D. & Newson C.L. (2000) Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography* **24** (2),195-217.

Padmore C.L. (1997) Biotopes and their hydraulics: a method for defining the physical component of freshwater quality. In: Boon, P.J. & Howell, D.L. (eds) *Freshwater Quality: Defining the Indefinable.* Edinburgh, Scottish Natural Heritage.

Padmore C.L. (1998) The role of physical biotopes in determining the conservation status and flow requirements of British rivers. *Aquatic Ecosystem Health & Management* **1** (1),25-35.

Parasiewicz P. (2007) The MesoHABSIM model revisited. *River Research and Applications* **23** (8), 893-903.

Petts G., Morales Y. & Sadler J. (2006) Linking hydrology and biology to assess the water needs of river ecosystems. *Hydrological Processes* **20** (10), 2247-2251.

Saltveit S.J. & Brabrand Å. (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.

Schmidt S.I. & Hahn H.J. (2012) What is groundwater and what does this mean to fauna? – An opinion. *Limnologica - Ecology and Management of Inland Waters* **42** (1), 1-6.

Skoglund H., Barlaup B., Gabrielsen S., Lehmann G., Halvorsen G., Wiers T., Skår B., Pulg U., & Vollset K. (2012) Fiskebiologiske undersøkelser i Eidfjordvassdraget – sluttrapport for perioden 2004-2012. uniMiljø Report. 108 pp

US Army Corps of Engineers (2012) HEC-RAS. 4.1 ed.

Vollset K., Barlaup B., Skoglund H., Gabrielsen S. & Wiers T. Unpublished data. Effects of hydropeaking on the spawning behaviour of Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*).