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Spatio-temporal effects of river regulation on habitat quality for Atlantic salmon fry

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ABSTRACT

Many upland rivers in the Northern Hemisphere contain important habitat for Atlantic salmon (*Salmo salar* L.). Owing to their sensitivity to environmental change, salmon are often used as bio-indicators. In Scotland, rivers containing potentially suitable habitat for salmon fry are often also regulated for hydropower. Regulated flow regimes can differ substantially spatially and temporally. Thus, where river management may be needed to maintain, restore, and protect their ecological functioning, this needs to be based on evidence of such spatio-temporal effects. This study investigated the effects of different types of river regulation on the hydraulic characteristics of downstream river reaches and the inferred consequences for salmon fry using hydraulic habitat quality models. The study focussed on the River Lyon (390 km^2), a tributary of the Tay (4587 km^2), Scotland, UK. Hydraulic habitat variability was assessed for three reach-scale sites with contrasting flow regimes characterised by (a) releases from hydropower generation, (b) compensation flow and (c) partly re-naturalised flow conditions. For each site, high resolution Digital Terrain Models (DTMs) were developed from bathymetric surveys and 2D hydraulic models were used to assess hydraulic characteristics. Discharge time series were used to simulate hydraulic conditions for regulated and simulated natural flows. Depth and velocity data were extracted from the hydraulic models and used to infer habitat quality using a habitat model developed for Atlantic salmon fry in similar-sized Scottish rivers. Results showed the effects of regulation can vary substantially within reaches and between seasons. Comparison to natural flow regimes suggested that flow alteration has a variable influence on habitat quality depending on the type of regulation and time of year. This work has improved understanding of the effects of regulation on biophysical processes and may also be useful for managing trade-offs between management, restoration, and societal benefits.

1. Introduction

Regulation of rivers is evident at a global scale. Around 48% of the world's river volume is moderately to severely regulated, fragmented, or both, this figure could rise to 93% by 2030 (Grill et al., 2015). A major cause of this change is the proposed construction of large dams in coming decades (Grill et al., 2015; Zarfl et al., 2014). The effects of regulation on flow regime can differ substantially depending on the activity or water user e.g., water supply, hydropower, flood defence, or a combination of these (Acreman and Dunbar, 2004). It is intuitive that the timing of operation (i.e., seasonality, diel patterns), as well as the type of use (e.g., hydropower generation – a major driver for new schemes, compensation release, inter- or intra-basin water transfers) and location of regulation infrastructure (e.g., headwaters, tributaries, close to river mouth) all have a potential bearing on the effects it can have on the functioning of ecosystems.

For many fish species some degree of migration or dispersal is an integral part of their life-history, and for salmonid species the spatial and temporal scales of these migrations vary substantially between different life-stages (McCormick et al., 1998). Consequently, dams and weirs have a bi-directional (cumulative) effect on longitudinal connectivity (e.g., Buddendorf et al., 2017; McKay et al., 2013; Norrgård et al., 2013; Schick and Lindley, 2007). However, in-channel structures like dams and weirs also affect the downstream hydraulic and hydrological conditions by altering the natural flow regime with potential consequences for habitat quality (Gibbins et al., 2001; Poff et al., 1997; Richter et al., 1997). The effects of flow regulation can occur at local scales (habitat/reach scale) immediately downstream of a dam or weir,

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but they can also be propagated downstream where their impacts on hydraulic habitat can vary spatially depending on channel morphology (Petts and Thoms, 1987; Postel and Richter, 2003). Numerous studies have investigated the effects of flow regulation on lotic ecosystems (e.g., Bain et al., 1988; Cowx et al., 2012; Freeman et al., 2001; Pringle et al., 2000; Tockner et al., 2011). It has long been hypothesised that changes in flow variability are instrumental in reducing the diversity and stability of such ecosystems (Dudgeon et al., 2006; Poff et al., 1997). For salmonids in particular, the potential importance of river flow and the effects of regulation on different life-stages have been studied extensively (Armstrong and Nislow, 2012; Bendall et al., 2012; Dunbar et al., 2012; Enders et al., 2009; Gibbins and Acornley, 2000; Gibbins et al., 2001; Malcolm et al., 2012; Milner et al., 2012; Nislow and Armstrong, 2012; Puffer et al., 2015; Scruton et al., 2008; Warren et al., 2015).

In recognition of the importance of flow variability (Acreman and Dunbar, 2004; Arthington et al., 2006; Carlisle et al., 2010; Poff and Schmidt, 2016; Razurel et al., 2016; Renöfält et al., 2010), environmental regulation increasingly incorporates a certain degree of natural variation to protect the integrity and functioning of lotic ecosystems. For example, in the UK this is done using the building block approach as described in UKTAG (2013). Nevertheless, there remains considerable debate as to the most appropriate approaches for classifying hydrological alteration and how such assessments should be included in impact assessment and river management (Macnaughton et al., 2017; Penas et al., 2016).

The lack of pre-regulation data is often a major impediment to assessing and understanding the effects of flow regulation on in-stream ecology (Macnaughton et al., 2017). Consequently, it is necessary to develop assessment techniques that allow the spatio-temporal effects of river regulation to be assessed in the absence of baseline data. Such techniques should ideally be broadly applicable and preferably transferable between river systems.

This study aimed to investigate the spatio-temporal effects of river flow regulation on hydraulic habitat quality for juvenile Atlantic salmon (*S. salar* L.) in their first year after hatch (hereafter referred to as fry for simplicity) in the River Lyon, a major tributary to the River Tay, Scotland's largest catchment (4587 km^2). The River Lyon was selected because it is an important salmon river, and it has a relatively simple linear river network, while still being subject to different types of river regulation. Previous studies have shown substantial changes in invertebrate communities (Jackson et al., 2007), and the hydrology of the Lyon catchment (Geris et al., 2015; Soulsby et al., 2015). In addition Buddendorf et al. (2017) assessed the effects of impoundments on longitudinal connectivity. There is some limited evidence that suggests that regulation in the Lyon has brought about change (i.e., a decline) in the population of Atlantic salmon (Summers, 2000). However, there have been no previous studies of the effects of regulation on habitat quality for salmon fry. A pre-existing rainfall-runoff model to estimate natural flows (Geris et al., 2015), a discharge time series under regulated conditions, detailed bathymetric surveys, and transferable hydraulic habitat quality models for Atlantic salmon fry (Millidine et al., 2016) were used to assess the likely impacts of river regulation on habitat quality. Three sites were chosen to illustrate the effects of different common types of regulation: re-naturalised, compensation release, and hydropower generating flow conditions. The compensation release and re-naturalised sites are located increasingly downstream of a reservoir, whereas the hydropower generating site is located nearer to the headwaters of the catchment, downstream of a high-head hydropower dam (Fig. 1).

The study aimed to answer the following research questions: 1) compared to natural flow conditions, do the three common types of flow regulation have a negative impact on salmon fry habitat quality? 2) is there a change in habitat quality among seasons? 3) is temporal variability in habitat quality under regulated flow conditions lower and this is associated with a smaller variability in discharge?

2. Methods

2.1. Study site

The River Lyon is situated in the Scottish Highlands, UK (Fig. 1). The catchment area is 390 km^2, and is characterised by a steep hillslope geometry with high gradient tributary streams containing waterfalls that prevent access for Atlantic salmon (Buddendorf et al., 2017). Average precipitation is approximately 2300 mm per year. Land use in the catchment is primarily agricultural with pastures grazed by sheep throughout the year. There is some commercial forestry and there are several small settlements (with $<$ 1000 people living in the catchment).

Many of the catchment's tributaries are used for small hydropower production (typically $<$ 1 MW) of the 'run-of-river' type. In addition to these small schemes, all of which are located above natural barriers to salmon migration, the river is heavily regulated for hydropower along its main stem (Payne, 1988). Water is collected from the catchment headwaters and used to generate electricity at Lubreoch hydropower dam (Fig. 1), but water is also imported from neighbouring catchments (Geris et al., 2015). After release from Loch Lyon, water is received by the Stronuich reservoir dam, which also collects water from Loch an Daimh that has just passed through the Stronuich power station. From the Stronuich reservoir approximately 700 mm of water (in rainfall equivalent) is exported into the neighbouring Lochay catchment annually for further hydropower generation. From the Stronuich Reservoir a compensation flow is released to sustain the river Lyon downstream. The quantity of water released under base-flow conditions is augmented with freshet releases in the spring and summer periods with the aim of introducing a degree of flow variability which stimulates upstream migration by resident Atlantic salmon (*S. salar*) and Sea trout (*S. trutta*), but also to improve conditions for angling. For further details on hydropower regulation in the catchment see: Birkel et al. (2014), Geris et al. (2015), Payne (1988), and Soulsby et al. (2015).

There are multiple barriers to fish migration in the River Lyon; in addition to the Lubreoch hydropower dam and the Stronuich reservoir dam there are two significant waterfalls on the main stem of the river (Fig. 1). The Lubreoch dam is impassable for fish, whereas the Stronuich dam contains a Borland fish lift and both waterfalls are passable under high flow conditions, based on the Scottish Environmental Protection Agency (SEPA) dataset on barriers to fish migration. Other barriers that are located on tributary streams are not a focus in this study, although it is recognised that there might be potential effects on sediment budgets and food availability.

The three river reaches which are the focus of this study are all on the main stem (Fig. 1, Table 1). The first site is downstream of Lubreoch hydropower dam (henceforth referred to as the HP-site for hydropower producing flows) where the natural catchment area is 69 km^2. Under regulated conditions, the site's median wetted area is 1272 m^2 and it has a typical plane-bed morphology, characterised by a uniform bed and straight channel form. The second site is downstream of the Stronuich reservoir dam (henceforth referred to as the C-site for compensation flows). The catchment area at the C-site is 106 km^2 and under regulated conditions the median wetted area is 1829 m^2. It consists of a deeper plane-bed section, and a shallower rapid section where boulders protrude from the surface under base-flow conditions, and areas of low flow velocities. The third site is further downstream (henceforth referred to as the RN-site for re-naturalisation), where incoming tributaries have partly re-naturalised the flow regime, though the effects of regulation are still evident (Geris et al., 2015). The catchment area at the RN-site is 237 km^2 and under regulated conditions the median wetted area is 1286 m^2. The channel morphology is characterised by a deep pool section and a shallower faster flowing section. The bed is uniform with very few areas of higher roughness, but with a large depth range. Under high flow conditions the channel connects to a side channel, resulting in a small step change increase in wetted area once this threshold is reached. Additionally, riparian vegetation consists of pasture and is consistent across the sites.