LINKING HABITAT AND POPULATION MODELS TO DETERMINE THE EFFECT OF HYDROPEAKING ON SALMON POPULATIONS

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ABSTRACT
Hydropeaking induces flow alterations in rivers caused by hydropower plants. Water is released or held back depending on the power demand and hence changes the flow regime of rivers. To assess the ecological impact of such management strategies ecological models can be used. Models for ecological systems can be based on various approaches and as such focus on different system aspects. Whereas engineering science uses habitat models to simulate the suitability of the abiotic environment for supporting the biota under investigation, biological science focuses more on processes occurring within the biotic life-cycle (such as birth, mortality and migration). The intention of ecosystem modelling is similar in both cases, so a more complete coupling of these approaches may provide a better understanding and predictive ability of system dynamics. In this paper we present the integrating of the habitat simulation model CASiMiR and the population model IB-salmon for predicting the effect of hydropeaking on Atlantic salmon populations as executed within the Norwegian EnviPEAK project funded by CEDREN (Centre for Environmental Design of Renewable Energy; Environmental impacts of hydropeaking). The habitat simulation model CASiMiR is used to predict the stranding risk of salmon individuals in different age classes resulting from rapid changes in flow rates. This involves three major steps. Firstly, suitable habitats are identified by assessing hydro-morphological parameters using a knowledge-based multivariate fuzzy-logic rule set (defined from expert opinion). Secondly, the rate of change in water depth based on flow rates and its influence on stranding risk is assessed. Thirdly, hydraulically isolated areas that have the potential for fish stranding and thus are high risk areas during downramping are determined by combining the preceded steps, and the final stranding risk is estimated. Stranding risk from this model is then included as a mortality function in the population model IB-salmon. This model is a spatially-explicit individual based model (spatial step = 50 m, time-step = one week) designed for simulating Atlantic salmon population abundance within rivers using heuristic-based functions derived from the literature and field studies conducted by the Norwegian Institute for Nature Research (NINA).

1 INTRODUCTION

The shift towards usage and production of renewable energy increases stress on aquatic ecological systems. Given that wind power is subject to fluctuations in the potential for electricity generation and currently no efficient storage technology except pump storage plants exists, hydropower is increasingly used to produce electricity flexibly on demand (peak production). Hence disturbances in the flow regimes of rivers occur. Rapid fluctuations in discharge downstream of such hydropower plants are common and result in interferences of the ecological system in the river.

Several studies investigate the effects and provide recommendations on ecologically tolerable operational procedures based, among others, on ramping rates and discharge ratios (Freeman et al. 2001; Halleraker et al. 2003; Saltveit et al. 2001). Nevertheless the response of aquatic ecosystems to flow alterations is a question of not just one or two peaking events but, rather, repeated events over decades, and the "predictions of biological responses to hydropeaking still remain tenuous" (Meile, Boillat, and Schleiss 2011; see also Murchie et al. 2008).

Hydraulic-habitat models can be used to assess the dangers of flow fluctuations to aquatic organisms based on ecologically tolerable values and physical parameters, whereas population dynamics models simulate short- and long-term demographic changes of a population with respect to biological factors. A combination of both model types could therefore improve the understanding of long-term effects of hydropeaking on different life-stages of organisms and their abundance.

In the context of the project EnviPEAK (environmental impacts of hydropeaking) the Norwegian Center for Environmental Design of Renewable Energy (CEDREN) addresses morphological and ecological issues concerned with hydropeaking on large temporal and/or spatial scales. This paper presents the concept proposed within EnviPEAK to link the population model IB-salmon and the habitat simulation model CASiMiR to predict the effects of hydropeaking on Atlantic salmon populations within the next few decades. As a first step a short overview of the two different model categories will be given, to clarify that an integration of both is reasonable. Afterwards the models used – IB-salmon and CASiMiR – and the linkage concept is introduced. Further implications and problems arising with an integration of both models and remaining questions are addressed in a discussion and outlook.

1.1 Modelling aquatic ecological systems

Historically two different views on aquatic ecological systems exist. Biologists mainly consider biotic parameters to model systems, while the engineers' view on aquatic systems mainly considers hydraulic and stream characteristics. Consequently two main categories of models are to be distinguished that can also be identified by literature review (Frank et al. 2011): population ecology and population distribution (suitability based models).

Population ecology models focus on the development of organisms in terms of demographic or genetic structures. They are used to predict abundance and growth rates or diversity of populations. The main model parameters are of biological nature and consist e.g. of fecundity, mortality, migration or age structure (Frank et al. 2011).

Population distribution models describe habitat characteristics or a possible spatial distribution of a population in a river. Therefore a relationship (preference curve) between abundance observations and measured variables (hydrological, morphological or hydraulic) is constructed to simulate the suitability of an environment to a specific organism. Generally the two approaches do not exclude each other, and some attempts have been made to integrate both model categories to simulate the physical-biological interface considering both approaches on different scales (Harby et al. (2004); IFIM combined with SALMOD, ORCM, MODYPOP, ASRAM further developed).

Mechanistic ecological population dynamics models

The models used in this paper belong to subgroups of either approach. IB-salmon is a mechanistic ecological population dynamics model. Those type of models range from group-based models (GBMs), where the population is binned into age and/or size classes and the class characteristics are modelled (e.g. Korman et al., 1994), to individual-based models (IBMs), where the characteristics of each individual organism are modelled (Gurney et al. 2008) from which population dynamics emerge from the interaction among individuals (Schank 2001). IBMs allow the incorporation of individual variation in behavioural and physiological characteristics (Hayes et al. 2009), and avoid the simplification and mathematical derivation required for GBMs (Schank 2001).

When modelling diadromous fishes (which use both freshwater and marine habitats), usually only part of the life-cycle is simulated. For example, (Gurney et al. 2008) use an IBM to examine the freshwater stage of Atlantic salmon (*Salmo salar* L.) (growth, survival and smolting); Rand et al. 1997 apply an IBM (NerkaSim) to simulate the marine life history of Pacific salmon. Few studies utilize IBMs to simulate both the freshwater and the marine phases. Fewer still use a spatially explicit approach (i.e. incorporating heterogeneity in the river habitat) when simulating population dynamics.

Multivariate fuzzy hydraulic habitat models

The habitat model CASiMiR on the other side belongs to the group of hydraulic habitat models that calculate suitability based on fuzzy logic. Usually hydraulic habitat models use physical-biota relationships (preference curves), which are derived by the abundance of the respective organism and the particular physical characteristics at the same locations (Frank et al. 2011; Harby et al. 2004). With the means of hydraulic models the physical variables (water depth, flow velocity, etc.) of an investigation area can be calculated. Univariate methods consider the habitat suitability as a function for each independent variable (Harby et al. 2004) while multivariate models take into account multilateral interactions to assess habitat suitability (Harby et al. 2005; Mouton et al. 2007). Hydraulic habitat models can therefore assess the potential availability of an organism's habitat based on the physical variables (Mouton et al. 2007). Consequently the models have been used to evaluate river restorations, minimum flow regulation assessments and hydropeaking events with each being based on different indicator species. Schneider (2001) applies fuzzy logic to hydraulic habitat modelling to compensate for the disadvantages of preference curves and the common multivariate approaches (see also Adriaenssens et al. 2004; Ahmadi-Nedushan et al. 2006).

2 METHODOLOGY

2.1 Population model IB-salmon

IB-salmon is a spatially-explicit individual-based model (IBM) designed for simulating Atlantic salmon population dynamics. Life-stages in both freshwater and marine habitats are modelled. In the freshwater habitat, stages are spawning adult, eggs, juveniles (fry and parr) and smolts (individuals that have become large enough to migrate to sea). In the marine habitat, stages are post-smolt (individuals that have just arrived at sea) and sea resident (individuals at sea that have not yet returned to freshwater for spawning). The model is run with a time-step interval of one week. The freshwater habitat (typically a river) is divided into a sequence of sections of 50 m length; the marine habitat is spatially integrated, reflecting the relative lack of knowledge on migration patterns within the marine environment. Processes affecting salmon (growth, smoltification timing, fecundity, mortality, location, migration) are modelled using heuristic functions developed from empirical studies at NINA and those present in the literature.

Egg deposition is calculated as a function of body mass of the adult salmon (Jonsson et al. 2001). Swim-up date of hatched eggs is calculated as a function of degree-days using the Andel-Crisp model (Crisp 1988). Recruitment from swim-up to fry is then estimated using an asymptotic exponential function. Parr growth in body size is calculated using a Ratkowsky-type model (Ratkowsky et al. 1983).

Parr experience density-independent and density-dependent mortality each week. Density-independent mortality removes a proportion of the stock biomass each week. Density-dependent mortality function occurs because each river section can only support a given stock biomass (g m^{-2}) defined by a carrying capacity. Biomass exceeding this carrying capacity is forced out of the section into the section immediately downstream with migrating parr experiencing a pre-specified mortality rate representing the cost of migration. The stock biomass for any given section is dependent on parr abundance, individual parr bodymass, and the wetted area of that section. The probability of a parr developing into a smolt, and subsequently migrating to sea, is estimated as a function of length. The lower part of Figure 1 displays a structure of IB-salmon with its mechanistic relationships.

2.2 Stranding model CASiMiR

Standard CASiMiR is a multivariate fuzzy logic hydraulic habitat model. The interface between biological habitat requirements and hydro-morphological parameters is modelled by a fuzzy logic rule set (Schneider 2001). In contrary to Boolean theory, elements in fuzzy logic can belong to several sets varying in a degree between zero and one (de Macedo Mourelle and Nedjah 2005). As a consequence fuzzy logic is well suited to transfer expert knowledge and imprecise information of habitat preferences to a multivariate rule set. Expressions as “if water depth is ‘high’ and flow velocity is ‘medium’ and … then the habitat suitability is ‘high’” can be processed with sharp hydraulic inputs and result in a habitat suitability index between zero and one with one being the most suitable habitat (Ahmadi-Nedushan et al. 2006; Mouton et al. 2007; Schneider 2001).

The CASiMiR stranding model developed by Schneider and Noack (2009) applies the same principles to flow alterations as during hydropeaking events. It involves four-steps displayed in the upper section of Figure 1. Firstly, on the assumption that the imminent threat emanates from high ramping rates at the most favoured location, the suitable habitats are identified during each discharge time step. For that purpose the standard fuzzy rule sets for the species (and age groups) habitat requirements are necessary. The second step assesses the stranding risk due to the drawdown of discharge. Based on the habitat suitability of step one, a critical flow depth and the rate of water depth reduction, a stranding risk is derived. Possible hydraulic isolations of ponds or river parts impose another threat to fish. Thus a third step determines such separated areas of the main water body after a flow reduction (potential stranding zones). As the preceded steps result in independent risk zones a combination of all displays the final stranding risk as a stranding risk index (SRI, range from 0 to 1). The highest stranding risk (SRI 1) is defined by areas in which a rapid water depth reduction is combined with shallow flow conditions and a separation from the river’s main water body.

The standard CASiMiR and its stranding model can be operated on various life stages of organisms with multiple input parameters, if adequate fuzzy rule sets can be defined.

2.3 Linking the stranding and population models

To address the question of hydropeaking effects on Atlantic salmon populations, both models are linked. While IB-salmon simulates the long-term population dynamics, CASiMiR is used to determine the short-term stranding risk of the fish in different life stages. The linkage in general is based on the assumption that a stranding probability equals its stranding mortality rate. Although literature suggests that stranded fish do not necessarily die (Saltveit et al. 2001) the conservative equivalence of stranding and mortality is a reasonable assumption. As IB-salmon itself uses several stochastic functions (e.g. mortality experienced by post-smolts) an additional mortality rate can be integrated with little further modification in programming. The different variables are read into IB-salmon via arrays. They compromise the stranding mortality rate according to IB-salmon’s time-step of one week and the respective river section number depending on IB-salmon’s spatial resolution. However, some more general adjustments need to be taken into account.

Firstly, typical hydropeaking curves are a matter of a few hours, in which the area of potential stranding risk varies according to flow rate, flow ratios (maximum to minimum) and down-ramping rates. Hence the stranding model CASiMiR works in relatively short temporal resolutions of 10 to 15 minutes for the duration of a hydropeaking curve. Therefore, to implement the stranding risk into IB-salmon which operates on weekly time-steps, several hydropeaking events need to be considered in combination. With respect to simulation times and because of the similarity of daily hydrographs, the stranding risk is calculated with CASiMiR for a single day only. Assuming the daily stranding probabilities are independent and the Atlantic salmon is not conditioned by subsequent peaking events, the weekly stranding probability is the product of the individual events not occurring.

The second adjustment to be made concerns the spatial solution. As EnviPEAK objectives aim at considering hydropeaking in rivers holistically, both models need to work on large river stretches. Although neither IB-salmon nor CASiMiR have a spatial limitation, the 2D hydraulic model which is needed to compute flow characteristics for a CASiMiR application limits the investigation area due to computational time. Additionally a sufficiently performing 2D hydraulic simulation for CASiMiR requires detailed topographical and morphological river data. As the data acquisition for both models is already high, and the parameterization for IB-salmon and the development of fuzzy rule sets for CASiMiR is time consuming, it is decided to limit the additional efforts of a topographical survey to an acceptable extent. Hence characteristic river reaches are identified on the basis of topography, cross sectional profile, bank slope, morphological parameters and cover availability. On each characteristic river reach a CASiMiR stranding risk calculation is performed and results in a characteristic standing risk. IB-salmon divides the longitudinal propagation of the river in equal distances of 50 m. Depending on the sections’ physical parameters they are assigned to a characteristic reach with its characteristic stranding risk to be implemented as stranding mortality.

Generally a hydropeaking hydrograph stretches with increasing distance from its release station due to energy losses along the way. It is therefore necessary to account for this attenuation effect depending on the distance between characteristic river reaches, power station and topographical conditions. Therefore a 1D-model needs to be set up to determine whether the peaking curves at farther characteristic river reaches result in less dangerous water level reductions and flow rates.

Peaking hydrographs also vary with electricity production and hence it can be observed that discharges change during week days and holidays. However, simulating the effects of decades of hydropeaking power demand and hydropower plant management has to be anticipated. As the proposed linkage of hydraulic-habitat and population dynamics model is based on the open structure of the interface, different hydrograph scenarios can be computed. In a first step different hydrographs have to be identified. A CASiMiR stranding simulation is applied on each hydrograph and their specific stranding characteristic is determined. Finally the hydrographs can be combined in different scenarios before the weekly stranding risk is calculated. Such hydrograph combinations and scenarios not only allow for unknown future discharges, but also adaptive management approaches. These approaches consist of operational changes and adoptions during seasons when the fish population is particularly vulnerable to stranding and account for the special endangerment of fry to stranding during changes in flow or water surface fluctuations (Bell et al. 2008; Freeman et al. 2001). As a populations viability depends largely on the fishes' early life history (Schiemer, Keckeis and Kamler 2002) the effect of such measurements on fish demography can be assessed and compared.

3 DISCUSSION AND OUTLOOK

Both models have been applied to case studies on their own (IB-salmon: River Nausta, Norway, (Hedger et al., in review) CASiMiR: (Schneider and Noack 2009)) and have proved their applicability and efficacy. The two models are currently being integrated. This integration requires a more detailed knowledge on the interface of population dynamics models and hydraulic habitat models, necessitating further research for model parameterization. For example, it is an inherent part of hydraulic habitat models that fish prefer the most suitable potential habitat available. Preference curves connect the observed frequency of the fishes' use of various habitats to the availability of these habitats using physical variables (such as flow velocity or water depth), but other factors affecting population density are often not considered. The assertion that fish are most frequently observed in their most preferred habitat is valid, meaning that hydraulic models can be used to evaluate potential fish habitats throughout long river stretches. However, at a smaller scale, there are many factors which affect local population density other than habitat suitability (Railsback et al. 2003). In regards to IB-salmon, a section of ideal habitat may be unoccupied simply because it is too distant from a spawning habitat and fish have not yet migrated there. Likewise, the abundance in a river section may change temporally due to crowding-out of individuals when the section's carrying capacity is exceeded. Such patterns would not be identified using a hydraulic modelling approach. Integration of population dynamics models and hydraulic habitat models therefore requires deeper understanding and more sophisticated concepts based on the disciplines of ecology and hydraulics (Lancaster and Downes 2010; Murchie et al. 2008).

The linkage of the two models provides opportunity for additional implementation and collaboration. One example is accounting for additional parameters that can influence both model outputs. As literature shows (Halleraker et al. 2003; Saltveit et al. 2001), the danger of stranding depends not only on hydraulic parameters, but differs between day and night, summer and winter, and is especially dependent on temperature. As IB-salmon includes water temperature and is based on temporal time steps with reference to the year, both factors can be included in CASiMiR as rule parameters. Its fuzzy rule sets can be adopted to include the additional parameters of diel period, season and water temperature to simulate stranding risk on more than only hydraulic characteristics.

Acknowledgements

The concept is funded by the Norwegian Centre for Environmental Design of Renewable Energy (CEDREN) via its two projects "Environmentally Designed Operation of Regulated Rivers" (EnviDORR, IB-salmon) and "Environmental impacts of hydropeaking" (EnviPEAK, linkage of both models).

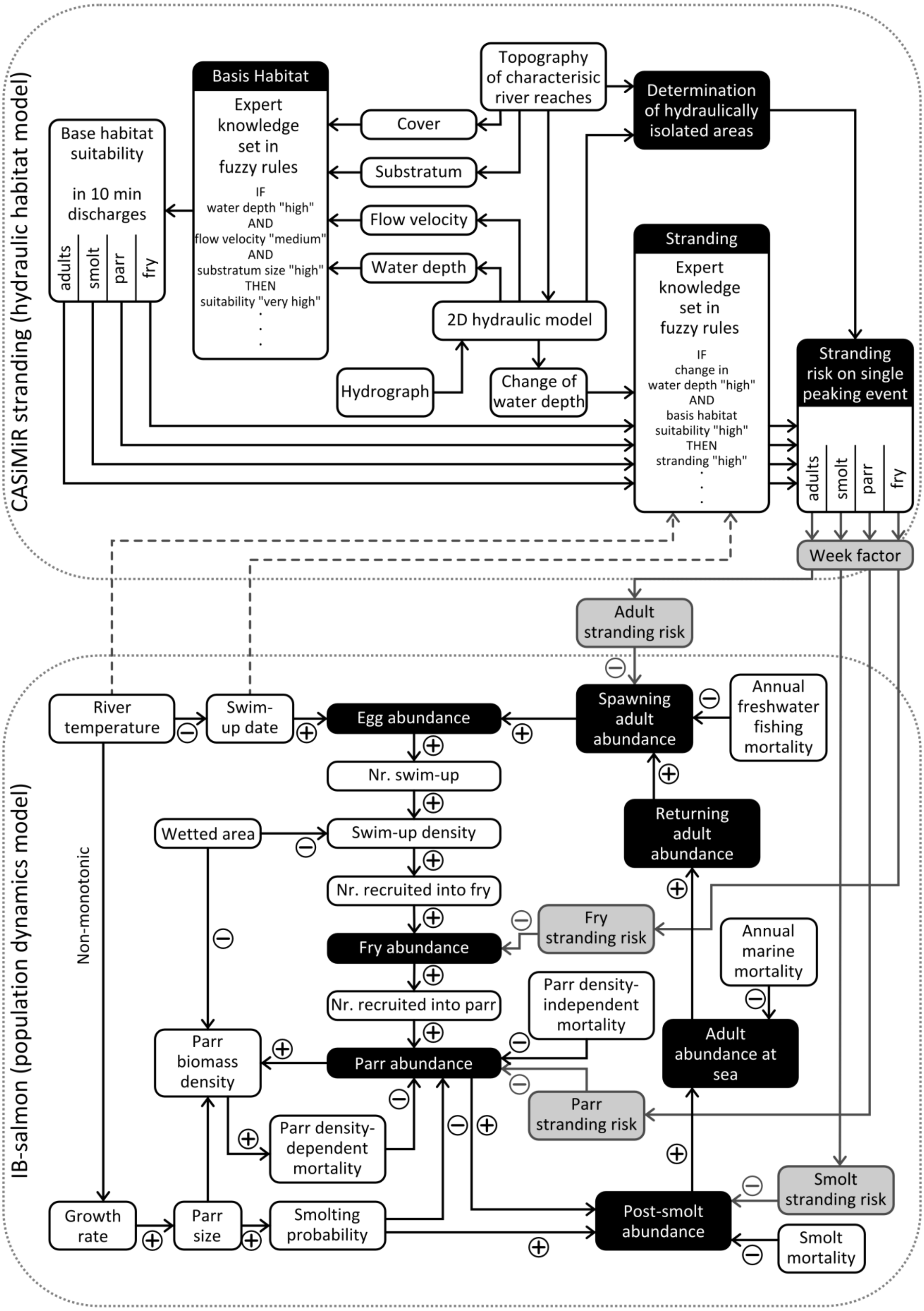

Figure 1: Mechanistic relationships of IB-salmon (lower part, taken from Hedger et al. under review), CASiMiR stranding (upper part) and the proposed linkage: Flow arrows accompanied with negative or positive sign indicate respective relationships. Linkage interfaces are shaded in grey. Dashed arrows illustrate further implementation possibilities discussed in section 3.

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