Spawning-to-nursery functional habitat connectivity modelling for river restoration planning and assessment

Modélisation de la connectivité fonctionnelle des habitats de frai à nurserie pour la planification et l'évaluation de la restauration des rivières

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RÉSUMÉ

La modélisation de la qualité de l'habitat est couramment utilisée pour planifier et évaluer les améliorations des habitats aquatiques, mais elle ne prend pas en compte leur connectivité.

Cette étude combine une modélisation microscopique des habitats et un modèle de dérive larvaire pour évaluer la connectivité fonctionnelle entre les habitats de frai et de nurserie de quatre espèces de poissons rhéophiles et lithophiles dans une section de la rivière Inn inférieure (Bavière, Allemagne) impactée par l'hydroélectricité. Deux chenaux sont comparés: un chenal de contournement naturel et le chenal principal rectifié, tous deux ayant subi des mesures de réhabilitation des habitats.

Les résultats montrent que la morphologie des chenaux influence fortement la connectivité. Le chenal de contournement, plus étroit et sinueux, permet une meilleure utilisation des habitats, tandis que la dérive limitée dans le chenal principal restreint l'accès à 33% des habitats. Des configurations alternatives testées pourraient améliorer la connectivité à 95,3%, soulignant l'importance d'intégrer cette dimension dans la planification des restaurations.

ABSTRACT

Habitat suitability modeling is widely used to plan and assess in-stream habitat enhancements. However, it only addresses the spatial distribution of habitats but not their connectivity.

This study integrates micro-scale habitat modeling and a larval drift model to assess functional connectivity between spawning and nursery habitats for four rheophilic and lithophilic fish species in a hydropower-impacted section of the lower Inn River (Bavaria, Germany). It compares two channels with differing sizes and morphologies: a recently constructed nature-like bypass channel and the straightened main river channel, which underwent habitat rehabilitation measures. The study aims to (1) map spawning and nursery habitats, (2) quantify their connectivity, and (3) optimize it by testing alternative habitat rehabilitation measures.

Results show that channel morphology strongly influences habitat availability and connectivity. In the bypass channel, narrower width and higher sinuosity enable full use of habitats, while limited larval drift in the wider main channel restricts accessibility to the left riverbank, making only 33% of nursery habitat usable. However, functional connectivity in the main channel could reach 95.3% with habitat spatial configurations tested in two alternative restoration scenarios, emphasizing the need to consider functional connectivity in habitat assessments and restoration planning.

KEYWORDS

River restoration; habitat modeling; larval drift; functional connectivity; spawning

1. INTRODUCTION

In recent decades, in-stream habitat models have become common for river restoration planning and assessment. These models link physical reach characteristics (hydraulics, sediment, cover) to species and life-stage preferences using statistical approaches, enabling the estimation of species distributions and biological responses to hydro-morphological features. However, functional habitat connectivity, especially for early life stages, is rarely addressed. Functional connectivity accounts for habitat quality, spatial arrangement, and accessibility of essential habitats for aquatic organisms, depending on swimming ability, dispersal behavior, and energy costs.

Fast flow preferring (rheophilic) and gravel spawning (lithophilic) species, such as salmonids and some cyprinids, depend on a variety of habitats during their life cycle: gravel bars in swift currents for spawning, shallow littoral zones for nursing, and deeper, faster areas as they grow. These habitats, with distinct hydraulic features, must be accessible when needed, especially during key developmental stages. During spawning eggs are deposited in gravel banks, and after incubation, larvae emerge and drift downstream to nursery habitats (Lechner et al., 2016). Numerical drift models can be used to directly estimate larval drift paths and hence functional connectivity between spawning and nursery habitats. They incorporate passive and active drift components (McDonald & Nelson, 2020) and probabilistically describe spatio-temporal drift characteristics, such as destination, retention, and entrainment rates.

In this study, we integrate spatially explicit micro-scale habitat modeling and a larval drift model to evaluate functional connectivity between spawning and nursery habitats for four rheophilic and lithophilic fish species (grayling, nase, barbel, and chub) in two reaches of the Lower Inn River (Bavaria, SE Germany): a newly constructed nature-like bypass channel; and the straightened main channel, comprised between two hydropower plants (HPP), which recently underwent habitat rehabilitation. The study aims to (1) map spatio-temporal availability of spawning and nursery habitats, (2) quantify their functional connectivity, and (3) optimize connectivity by testing alternative habitat rehabilitation measures.

2. MATERIALS AND METHODS

2.1 Study area and target species

The study site comprises the 12.7 km long Inn River impoundment downstream of the HPP Ering-Frauenstein and upstream of HPP Egglfing-Obernberg (Fig. 1, a). Between 2017 and 2019, two restoration measures were implemented, aimed at improving connectivity and habitat conditions for spawning and juveniles: a 2.6 km long nature-like bypass channel constructed around the Ering-Frauenstein HPP (Fig. 1, c) and an island side-channel system created downstream of it (Fig. 1, d).

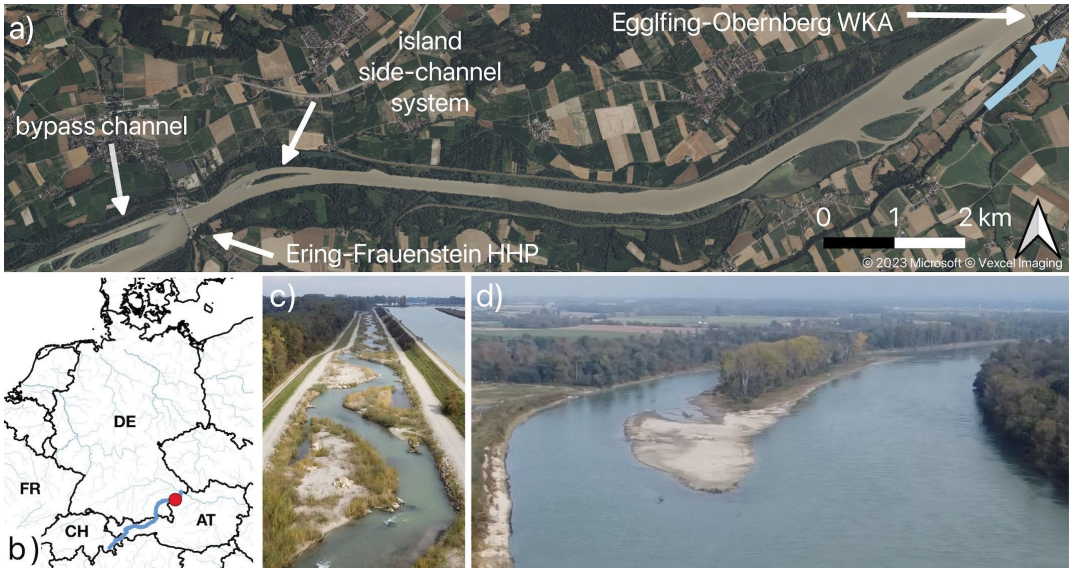

Fig. 1: Study area in SE Germany (b): main channel (a); and rehabilitation sites bypass channel (c) and island side-channel system (d).

2.2 Functional connectivity model

Functional habitat connectivity is assessed using an integrated approach combining micro-scale habitat modelling and larval drift modelling (Farò & Wolter, 2024).

Habitat suitability for spawning and larval nursery was assessed using a micro-habitat model based on 2D hydraulic modeling. Habitat suitability criteria were compiled from literature data for water depth, flow velocity and substrate. A bioenergetic approach is used to estimate likely spawning and nursing bioperiods based on river temperature and spawning, egg incubation, and larval growth for each modelled species.

Larval drift is modelled using a Lagrangian particle tracking model (McDonald and Nelson, 2020). The drift includes passive and active drift components. The passive drift combines advection by the flow with dispersion formulated as a random walk. To describe the active swim component of the modelled larvae, the following simplified assumptions were made: (i) No active swimming is considered at velocities higher than 10 cm/s; (2) Cyprinid larvae (nase, barbel, chub) are assumed to drift close to the water surface, while grayling larvae are assumed to drift closer to the river bottom.

2.2 Habitat and functional connectivity scenarios

Habitat and functional connectivity scenarios were run for the nature-like bypass and main channels. Discharges in the bypass channel ranged from 2 to 8 m^3/s, and from 486 to 1195 m^3/s in the main channel.

For the main channel, functional connectivity was assessed for three different habitat rehabilitation scenarios: (A) the current conditions, comprising a bypass-channel and the island-side channel system on the left-hand side; (B) an alternative bypass channel on the right-hand side; and (C) an alternative bypass channel on the right-hand side and the current island-side channel system on the left-hand side.

3. RESULTS

Differences in habitat sizes and distribution can be observed between the bypass channel and the side channel. In the bypass channel suitable spawning patches for all species are small but distributed across the whole channel, with small nursery habitat patches found along the banks and in backwater areas. In the main channel, large patches on the upstream edge of the island provide spawning habitats, while nurseries are prominently found in the island system upstream of the Egglfing-Obernberg HPP, in the restored side channel and around the island, and to a lesser extent along the left and right banks of the main channel.

The availability of spawning habitat remains relatively constant for each species throughout their spawning periods. Nursery habitats exhibit a stronger temporal variability, being more dependent on discharge, with higher habitat areas observed at lower discharges.

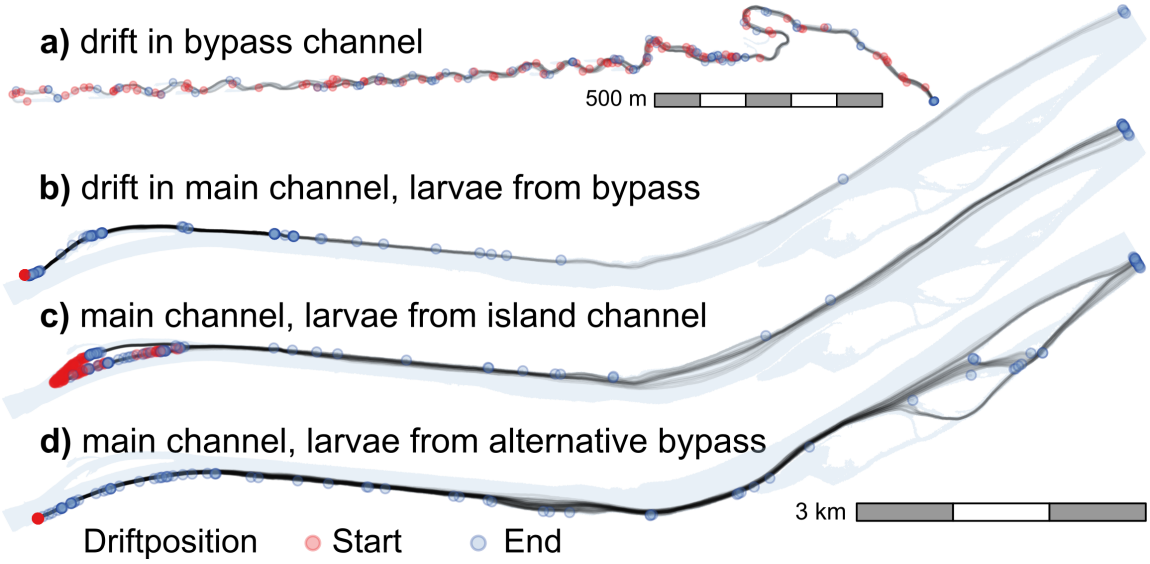

Fig. 2: Drift trajectories for grayling in modelled period Apr1, for: larvae originating and drifting in bypass channel (a); larvae originating bypass and drifting in main channel (b); and larvae originating around island and drifting in main channel (c).

Due to more distributed spawning patches, and the higher channel sinuosity, drift trajectories in the bypass

channel are shorter, with larvae reaching the left and the right banks across the whole channel (Fig. 2, a). In the main channel however, all larvae drifting out of the bypass channel, as well as larvae originating from the spawning habitats around the island, exhibit an immediate tendency to be directed towards the left bank of the side channel and do not disperse across the main channel (Fig. 2, b/c). Consequently, these larvae can only access nursery areas located on the left side of the main channel. Similarly, larvae originating from the alternative bypass channel situated opposite the current one, only reach nurseries along the right banks (Fig. 2, d).

Functional connectivity between spawning and nursery habitats in the bypass channel is 100%, since drifting larvae can reach habitats on both the left and right banks. In the main channel, functionally connected nursery habitats are 33.0% of total available habitat in scenario A, increase to 72.6% in scenario B, and are highest (95.3%) in scenario C.

4. DISCUSSION

The results of this investigation show that the availability of spawning and larval nursery habitats and their connectivity are influenced by the interplay of morphological complexity and flow. The result underline the importance of functional habitat connectivity between spawning and nursery habitats. Besides habitat quality, the spatial arrangement and accessibility needs to be considered, while otherwise usable habitat area will be heavily overestimated. While 100% functional connectivity was provided in the bypass channel, only a fraction (33%) of the available nurseries was functionally connected to the spawning habitats in the main channel.

The integrated functional habitat modelling approach presented here can also support river restoration planning by providing a tool to assess and predict functional habitat connectivity, and to optimize the spatial arrangement of newly created habitats. By testing alternative rehabilitation scenarios, functional connectivity could be increased up to 95.3%.

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