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Effects of river morphology, hydraulic gradients, and sediment deposition on water exchange and oxygen dynamics in salmonid redds

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HIGHLIGHTS

- Hyporheic exchange and oxygen are crucial for survival in redd and highly variable.
- Oxygen and water exchange are affected by fine sediment, C_{org} and redd morphology.
- Artificial steps in canalized river are positive in high flow section, and negative in low flow section.
- Measurement of crucial parameters in artificial redd was successful.
- Considerable work investment is needed for these measurements.

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ABSTRACT

Fine sediment decreasing gravel permeability and oxygen supply to incubating salmonid embryos, is often considered the main contributing factor for the observed decline of salmonid populations. However, oxygen supply to salmonid embryos also depends on hydraulic conditions driving water flow through the redd. A more generalized perspective is needed to better understand the constraints on successful salmonid incubation in the many heavily modified fluvial ecosystems of the Northern Hemisphere. The effects of hydraulic gradients, riverbed and redd morphology as well as fine sediment deposition on dissolved oxygen (DO) and water exchange was studied in 18 artificial redds at three sites along a modified river. Fifty percent of the redds in the two downstream sites were lost during high flow events, while redd loss at the upstream site was substantially lower (8%). This pattern was likely related to increasing flood heights from up- to downstream. Specific water infiltration rates (q) and DO were highly dynamic and driven on multiple temporal and spatial scales. Temporally, the high permeability of the redd gravel and the typical pit–tail structure of the new built redds, leading to high DO, disappeared within a month, when fine sediment had infiltrated and the redd structure was leveled. On the scale of hours to days, DO concentrations and q increased during high flows, but decreased during the falling limb of the water level, most likely related to exfiltration of oxygen depleted groundwater or hyporheic water. DO concentrations also decreased under prolonged base flow conditions, when increased infiltration of silt and clay particles clogged the riverbed and reduced q. Spatially, artificial log steps affected fine sediment infiltration, q and interstitial DO in the redds. The results demonstrate that multiple factors have to be considered for successful river management in salmonid streams, including riverbed structure and local and regional hydrogeological conditions.

1. Introduction

Native salmonid populations are declining in numerous countries around the world, including populations of brown trout *Salmo trutta* in Switzerland (Burkhardt-Holm and Scheurer, 2007), Atlantic salmon *Salmo salar* in the United Kingdom (Youngson et al., 2002) and coho salmon *Oncorhynchus kisutch* in North America (Brown et al., 1994). Habitat degradation is considered a major threat for native salmonids (e.g., Brown et al., 1994; Burkhardt-Holm and Scheurer, 2007; Gilvear et al., 2002; Hicks et al., 1991). In this regard, fine sediment (<2 mm) deposition has been argued as the single contributing factor (e.g., Jensen et al., 2009 and studies cited therein). Deposited fine sediment

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can decrease redd gravel permeability and interstitial flow (e.g., Brunke, 1999; Schälchli, 1995), which, in turn, hinders oxygen supply to incubating salmonid embryos, thereby affecting their survival (S. Greig et al., 2007; Greig et al., 2005; Heywood and Walling, 2007). However, the oxygen supply to incubating salmonids embryos depends on several further factors such as the relative contribution of oxygenated river water infiltration and exfiltration of oxygen depleted groundwater or interstitial water in the redd (Malcolm et al., 2006, 2009) or the oxygen demand of organic material (S.M. Greig et al., 2007). Although these factors vary extensively both temporally and spatially (Brunke and Gonser, 1997; S.M. Greig et al., 2007; Malcolm et al., 2006), only a few studies have resolved these processes on appropriate temporal and spatial scales.

Modeling approaches on the redd scale indicate that hyporheic velocities and dissolved oxygen (DO) concentrations within the egg pocket are enhanced due to the spawning activity, leading to reduced fine sediment and thus higher hydraulic conductivity (Tonina and Buffington, 2009; Zimmermann and Lapointe, 2005). Redd scale hyporheic exchange, measured on a centimeter to meter scale, can also be induced by the pit–tail structure of salmonid redds (Fig. 1A, Tonina and Buffington, 2009). This initial structure cannot, however, be expected to remain intact during high flow events (Ottaway et al., 1981). Hence hydraulic conditions on the redd scale likely change during the incubation season. Moreover, recent research clearly indicates the need for a multi-scale approach when investigating the dynamics of abiotic conditions in salmonid redds (Baxter and Hauer, 2000; Zimmermann and Lapointe, 2005): the local scale covers a single redd with an applied data grid resolution down to single centimeters (Fig. 1A). The intermediate scale covers the wider redd surrounding area of the riverbed including the relevant neighboring riverbed steps (Fig. 1B). The chosen data grid for this intermediate scale is in the range of meters. The regional scale considers a larger section of the river with a length and width of tenths of meters up to several kilometers (Fig. 1C). Hydraulic processes driven at all these scales can be expected to affect water exchange in a particular redd, and hence oxygen supply to the incubating embryos (Baxter and Hauer, 2000; Malcolm et al., 2008).

In Western Europe and North America many rivers with viable salmonid populations are heavily modified, i.e., channelized and with lateral stabilizations and artificial steps introduced for slope reduction (Brookes, 1988; Gilvear et al., 2002; Wohl, 2006). In channelized rivers, the lack of geomorphic features can substantially reduce hyporheic exchange (Malcolm et al., 2010), whereas hydraulic gradients related to artificial steps can markedly increase hyporheic exchange (Endreny et al., 2011). Artificial steps generate predictable flow-paths, with increased river water downwelling above steps and upwelling of hyporheic water below steps (Fig. 1B, e.g., Gooseff et al., 2006; Huber et al., 2013; Kasahara and Hill, 2006). Accordingly, artificial steps can increase hyporheic exchange in modified rivers (Kasahara and Hill, 2006; Sawyer et al., 2011) and could thereby also affect water exchange and oxygen supply in salmonid redds. Despite this, the effects of artificial steps on abiotic conditions in salmonid redds have, to our knowledge, not been investigated. This knowledge would provide important input for process-based river management in the many heavily modified salmonid streams of the Northern Hemisphere (e.g., Gilvear et al., 2002; Newson et al., 2012).

To this end, the current study evaluates the relative contribution of fine sediment, hydraulic gradients, river morphology, and regional geomorphology to specific water infiltration and oxygen dynamics in artificial brown trout redds in the Enziwigger, a heavily modified headwater river of the Swiss Plateau in the Canton of Lucerne. The Enziwigger also maintains a viable brown trout population (Schager et al., 2007).

The objective of this study was to provide a detailed investigation of the factors affecting the abiotic redd environment in a heavily modified river including I) an investigation of fine sediment deposition, hydraulic conditions (i.e., specific infiltration q, vertical and horizontal hydraulic gradients, and water level) and their effects on oxygen dynamics in the redds, II) an assessment of the morphological change of the riverbed and of the characteristic pit and tail structure of the redds and III) a comparison of the measured data with the results of a groundwater flow model, which was set up for one of the three experimental sites (cf. Huber et al., 2013). This model predicts zones of increased downwelling river water above steps, of hyporheic water upwelling

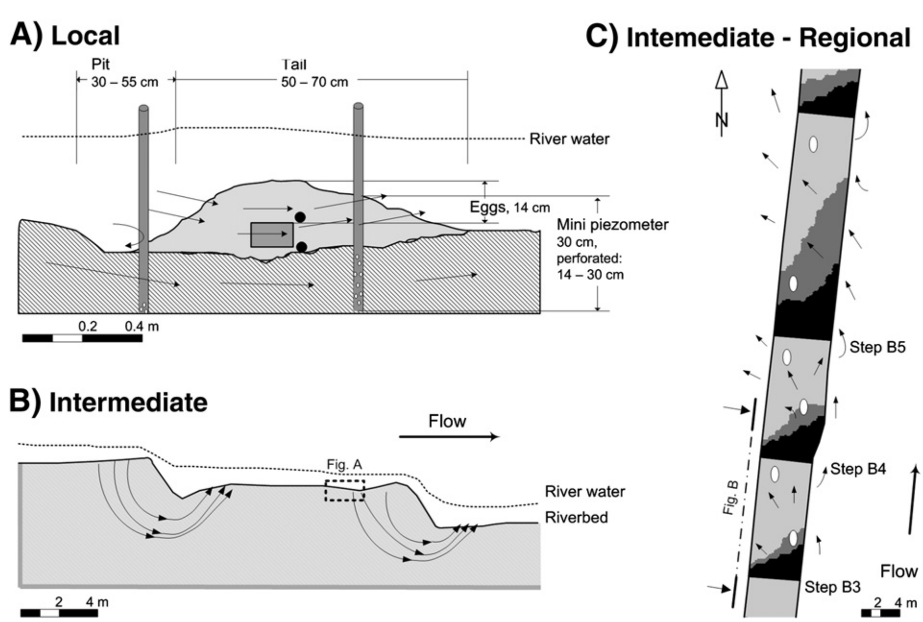

Fig. 1. Schematic view of (A) longitudinal section of an artificial redd (modified after Greig et al., 2007b) including the location of the mini-piezometers, the egg pockets (square) and temperature probes (bullet points) with the local scale flow pattern, (B) the hyporheic flow on an intermediate scale induced by riverbed steps according to the model calculations of Huber et al. (2013), and (C) the intermediate and regional scale water exchange processes (top view). Modeled river–groundwater exchange zones from Huber et al. (2013). Black: only exfiltration, gray: exfiltration and infiltration, light gray: only infiltration. Arrows indicate the main direction of the interstitial and groundwater flow, ovals represent the positions of the redds (for naming see Fig. 2).