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Hydraulic and Sedimentological Assessment of Salmonid Spawning Habitats in River Sections influenced by Small Hydropower Operations

Composed by

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Danksagung

Do not think that what is hard for you to master is humanly impossible; and if it is humanly possible, consider it to be within your reach.

- Marcus Aurelius

In vorderster Instanz gilt mein Dank meinem Betreuer DI Dr. Christoph Hauer, welcher mein ureigenes Interesse an der Natur und ihren Abläufen in einer für mich noch nicht da gewesenen Weise wecken konnte und der mir im Laufe des Werdeganges dieser Arbeit stets zuverlässig mit Rat und Tat beiseite stand, sodass sich jede auftretende Hürde letztlich mühelos meistern ließ.

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Kurzfassung

Österreichweit sind Salmonidenflüsse von einem hohen Regulierungsgrad durch die Kleinwasserkraft betroffen. Es wird bisher davon ausgegangen, dass sich die hydromorphologischen und sedimentologischen Veränderungen, welche sich an Gewässerabschnitten flussauf und flussab von Kraftwerkswehren feststellen lassen, potentiell nachteilig auf die Eignung betroffener Abschnitte als Laichhabitate von Salmonidenfischen auswirken. Es liegen jedoch nur wenige wissenschaftliche Arbeiten vor, die diese Thematik aufgreifen.

Im Sinne der Erreichung des guten ökologischen Zustands bzw. Potentials, welcher/s von Seiten der Europäischen Wasserrahmenrichtlinie (2000/60/EG) für alle Oberflächengewässer eines Mitgliedsstaates vorgegeben wird, bieten detaillierte Freilandbeobachtungen an betroffenen Gewässerabschnitten, ergänzt durch Laboruntersuchungen, eine wichtige Grundlage, um bestehende Wissenslücken betreffend möglicher negativer als auch eventueller positiver Auswirkungen der Kleinwasserkraftnutzung auf Salmonidenlaichhabitate zu füllen und daraus Optimierungsvorschläge für zukünftige Wasserbauvorhaben abzuleiten.

Vorliegende Masterarbeit, als Kompendium eingereicht und im Englischen verfasst, thematisiert die sedimentologische und hydraulische Bewertung von Salmonidenlaichplätzen im Einflussbereich von Kleinwasserkraftwerken.

Die Arbeit organisiert sich in zwei Abschnitte. Abschnitt 1 bietet eine Literaturübersicht zum Thema Laichhabitatwahl und –qualität bei Salmonidenfischen in Fließgewässern. In diesem Abschnitt wird zunächst auf die abiotischen (hydraulischen, sedimentologischen, geomorphologischen) Anforderungen des Laichhabitates eingegangen. Im darauf folgenden Teil wird der derzeitige Entwicklungsstand der österreichischen Wasserkraft beschrieben, sowie die potentiell negativen ökologischen Auswirkungen des Wasserkraftbaues auf Salmonidenlaichhabitate dargelegt.

Abschnitt 2 gliedert sich in zwei Fallstudien, verfasst als Wissenschaftsartikel, sowie einer daran anschließenden zusammenführenden Diskussion der Ergebnisse beider Artikel.
Artikel 1 (Letter to Esex; einzureichen für die Zeitschrift *Earth Surface Processes and Landforms*) fasst die Ergebnisse eines Laborexperiments zusammen, in welchem der Interstitialdurchfluss durch Bachforellen-Laichnester in einem hydraulischen Strömungskanal untersucht wurde. Hierbei wurde zunächst eine Methode zur Visualisierung des Interstitialdurchflusses entwickelt, um daraufhin den Interstitialdurchfluss bei zunehmender Grobsand-Infiltration der Laichnester zu messen.
Artikel 2 (Short communication paper, einzureichen für die Zeitschrift *Limnologica*) präsentiert die Ergebnisse einer Freilandbegehung zweier geologisch unterschiedlicher Salmonidenflüsse (Gr. Mühl, Oberösterreich; Gr. Erlauf, Niederösterreich). Ziel dieser Untersuchung war es, unterschiedliche kraftwerksbeeinflusste Flussabschnitte auf das Vorkommen von Salmonidenlaichplätzen hin zu untersuchen und diese abiotisch zu charakterisieren.

Abstract

Salmonid rivers in Austria show a high degree of regulation as a result of the nationwide development of small hydropower plants (SHPs). Along with this development, hydromorphological and sedimentological alterations seen in river sections affected by hydropower operations are assumed to cause limitations in the availability and quality of the spawning habitat in salmonid fishes. However, to date, studies related to the suitability of hydropower influenced river sections for spawning salmonids are still rare.

In accordance with the attainment of the good ecological status/potential, which is set out in the European Waterframework Directive (2000/60/EG) as a requirement to the surface water bodies of all member states, detailed field assessments at hydropower influenced river sections, supported by laboratory investigations, are needed to fill existing knowledge gaps about the possible negative/positive ecological effects of small hydropower operations on the spawning habitat of salmonid fishes. As an overall aim, these newly derived findings should be used for developing ecological standards in current and future water engineering projects.

This master thesis, written as a compendium, deals with the hydraulic and sedimentological assessment of salmonid spawning habitats in hydropower influenced river sections.

This thesis, written in English, consists of two sub-sections. Section 1 presents a literature review about the selection and abiotic quality criteria of the spawning habitat in riverine salmonid fishes. In this section, hydraulic, sedimentologic and geomorphologic requirements for the spawning habitat in salmonids are reviewed. Consequently, potential negative ecological affects of hydropower operations on the quality and availability of the salmonid spawning habitat in rivers are summarized.

Section 2 consists of two case studies composed as research articles, including a closing synthesis of the findings obtained with regard to management implications.
Article 1 (Letter to Esex, to be submitted for the journal *Earth Surface Processes and Landforms*) summarizes the findings obtained from a laboratory experiment dealing on the assessment of the intergravel flow through artificial brown trout spawning redds in a flume experiment. A method was conceived to visualize the intergravel flow in order to measure the intergravel flow at successive coarse sand infiltration of the spawning redds.
Article 2 (Short communication paper, to be submitted for the journal *Limnologica*) presents the results obtained from a field investigation at two geologically distinct study rivers (Gr. Mühl, Upper Austria; Gr. Erlauf, Lower Austria). The aim of this investigation was to analyze different sections of hydropower development regarding spawning redd abundances and abiotic spawning redd characteristics.

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Section 1 – Literature review

Sections 1.1-1.3 are intended to synthesize the current understanding about the abiotic requirements of the spawning habitat as one important life cycle element in the ecology of salmonid fishes. Examples and species-specific information in this section are presented for resident brown trout (*Salmo trutta f. fario*). In a concluding section (1.4), the role of hydropower in Austria and potential ecological impacts of hydropower related river regulations on salmonid spawning habitats are reviewed.

1.1. Habitat complexity as a key requirement in the salmonid life cycle

The term habitat[1] is defined as the range of physical and chemical factors that affect an animal (Armstrong *et al.*, 2003). In natural riverine ecosystems, habitats are arranged as patches along the river channel which are created and structured by hydrological, geomorphological and biological driving forces (Frissel *et al.*, 1986. Townsend, 1989). In natural rivers, the dynamic interplay between these driving forces results in the continued turn-over and re-arrangement of habitat patches, whereby the proportions of the different habitats remain stable over the long term (Ward *et al.*, 2002, Stanford *et al.*, 2005). In the spatially heterogeneous ecosystems of natural streams, the highly dynamic role of the habitat is the defining element in the viability of riverine fish communities (Townsend, 1989; Jungwirth *et al.*, 2000, Fausch *et al.*, 2002; Ward *et al.*, 2002). Hence, for successful long term development of fish populations, it must be ensured that the full spectrum of required habitats is provided to the fish during its entire life cycle (Armstrong *et al*., 2003; Kemp, 2011).

Notably, many rivers worldwide have undergone reductions in habitat heterogeneity following century-long human activities in the catchment such as channel configurations and altered landuse (Allan, 1995; Maddock, 1999; Hendry *et al.*, 2003). On the level of the catchment, important anthropogenic environmental interferences include modified flow- and sediment regimes, increased water pollution, erosion and deposition of fine sediment, bed incision from

[1] In aquatic sciences, the term habitat is commonly subdivided into macrohabitat, mesohabitat and microhabitat. While macrohabitat refers to the entire space in which an animal lives (e.g. stream reaches, subcatchments), the term mesohabitat comprises the daily range of an animal (e.g. stretches within a reach), and the term microhabitat is used to describe small spaces within a mesohabitat with relatively homogenous flow velocity, depth, and substrate type (scales of 10^{-1} metres) (Frissel, 1986; Allan, 1995; Heggenes & Salveit., 1990).

river regulation and river fragmentation (Maitland, 1995; Poff *et al*., 1997, Kondolf *et al*., 1997, Jungwirth *et al*., 2003). These impacts and their combinative effects are believed to be the main cause of the substantial retreat of freshwater fish populations from running waters throughout Europe (Jungwirth *et al*., 2003; Schinegger *et al*., 2012).

Behind this background, the recent river restoration literature points out the need to plan fish habitat rehabilitation in modified river catchments systematically, with an emphasis on the re-establishment of the physical processes responsible for the maintenance of dynamic habitat heterogeneity in rivers (Palmer et al., 2005; Wohl *et al*., 2005; Kondolf *et al*., 2006; Beechie *et al*., 2010; Thomas, 2014).

With regard to freshwater habitat rehabilitation, a comprehensive body of literature exists for salmonid fishes, which are not only a commercially and culturally important fish group, but also are highly selective in their habitat use at different life stages (Heggenes, 1996; Heggenes *et al*., 2002; Armstrong *et al*., 2003; Klemetsen *et al*., 2003; Jonsson & Jonsson, 2011). The complementary habitat-to-life stage association observed in this fish family is believed to be one of the key causes for the susceptibility of salmonids to the destruction of habitat heterogeneity in rivers and is one of the main reasons reasons for the rapid declines of salmonids from rivers worldwide (Jonsson & Jonsson, 2011).

In salmonids, habitats are size and age-structured. The following habitat types are critical to the life history of all salmonid fishes (Armstrong *et al*., 2003; Hendry *et al*. 2003, Newson *et al*., 2012; Fig. 1):

- Good-quality spawning habitat for redd creation, egg incubation and early development of incubated eggs. Good spawning habitat encompasses adequate amounts of substrate used for redd creation, sufficient flow depth and water velocity, low fine sediment content of the redd substratum, a thermal regime promoting the development of incubated eggs, and the chance of emerging successfully into nursery areas.
- Good-quality nursery and rearing habitat for the proliferation of food, flow and thermal regimes sufficient to sustain growth with space to accommodate competition and sufficient cover to avoid predation.
- Free access to and from the sea for migrating smolts and adults (anadromous salmonids)
- Proximity between critical habitats that are within the distances of movement of individual life stages.

- Refugia at all stages to permit survival during disturbance such as floods, drought, pollution, thermal maxima and predation.

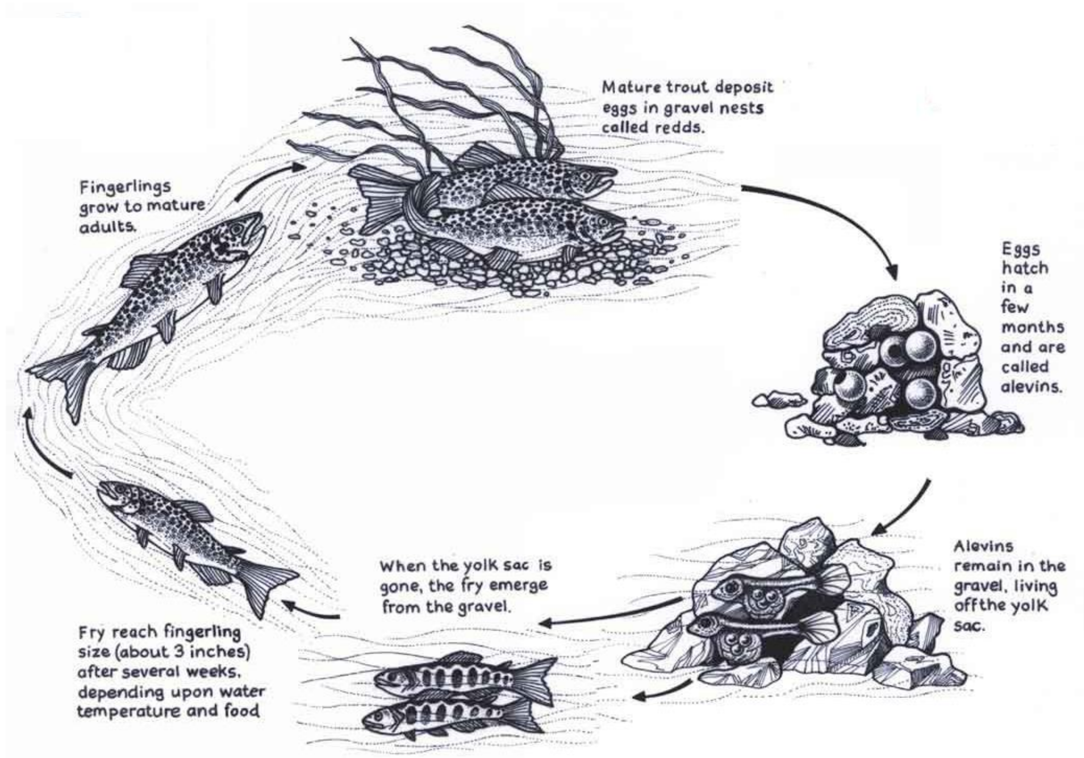

Fig. 1: Simplified illlustration of the salmonid life cycle. (Source: http://pixgood.com/trout-life-cycle.html)

All habitats need to be available in a sufficient volume to guarantee the successful development of salmonid populations (Newson *et al*., 2012). The in situ distribution and abundances of salmonids in each habitat are controlled by depth, current, substrate, and cover (Heggenes & Saltveit, 1990; Heggenes *et al*., 1996; Armstrong *et al*., 2003). The interplay of these four abiotic variables creates the variety of meso- and microhabitat structures typical for each defining habitat[2].Of similar importance to the survival of a salmonid life stage in a respective habitat is the sufficient supply of food and oxygen, as well as the prevalence of a hospitable temperature regime (Elliott, 1994; Armstrong *et al*., 2003).

The use of different habitats in salmonids relates to the desired maximization of energy intake, the balancing of foraging opportunities, behavioural costs and shelter at a given life stage (Jenkins & Keeley 2010).

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[2] For example, a typical salmonid spawning habitat may be characterized by a shallow waterdepth, swift flow velocities and gravel substrate of a certain diameter range.

1.2. The spawning habitat and its selection in salmonids

The spawning habitat is the template for the first fish life stage, which in case of salmonids begins with the incubation of fertilized eggs in the river bed and ends with the emergence of the yolk-sac larvae from the spawning habitat into the nursery habitat.

Much different than in other fish families, where eggs are laid on the ground of the river bed (*Extrastitional spawners*; Balon, 1975; Fig. 2 right), salmonids incubate their eggs up to 30 centimeters (Crisp *et al*., 1989) into the substratum of the riverbed (*Intrastitional spawners*; Balon, 1975; Fig. 2 left).

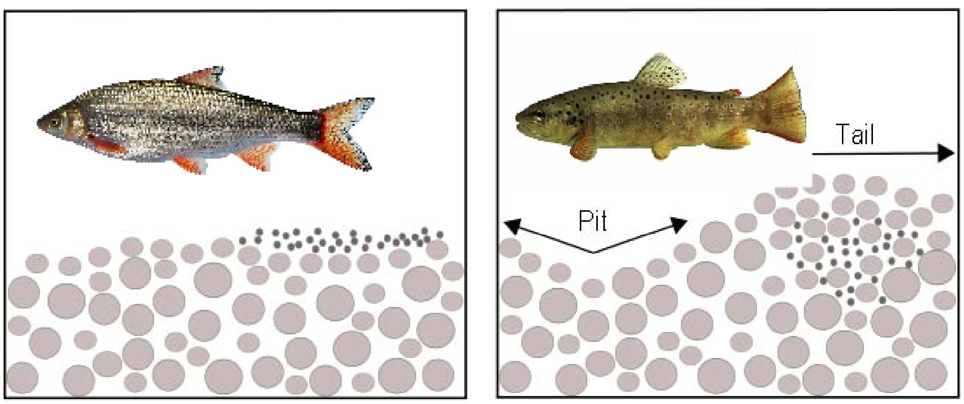

Fig. 2: Schematic illustration of the spawning behaviour of extrastitial spawners (left panel) and intrastitial spawners (right panel). Redrawn and modified from Pulg (2009)

The main ecological advantages of incubating the fertilized eggs into the substratum are believed to be the protection of the vulnerable offspring from being washed off, the protection from physical disruption and the protection from predation during the incubation time (Jonsson & Jonsson, 2011).

For each spawning event, one or several nests is/are created by the female. In salmonid ecology, a fish nest is called a redd. By definition, a redd is the contiguous area of distributed gravel containing the nest(s) of one female (Crisp & Carling 1989, Fig. 3, Fig. 4).

In the field, redds can be identified as distinct bright, oval-shaped patches of gravel on the river bed (Fig. 4). The change in colour results from the active turnover of spawning gravel by the female. Although numerous white patches may appear on the riverbed in areas with brown trout spawning activities, most of these gravel-turnovers are only a product of exploratory cutting by the female and are no true redds. At closer inspection of a true redd, one can recognize an anterior semi-sperical depression referred to as the pit, as well as an elongated, elevated tail region adjacent to the pit which consists of agglomerated spawning gravel.

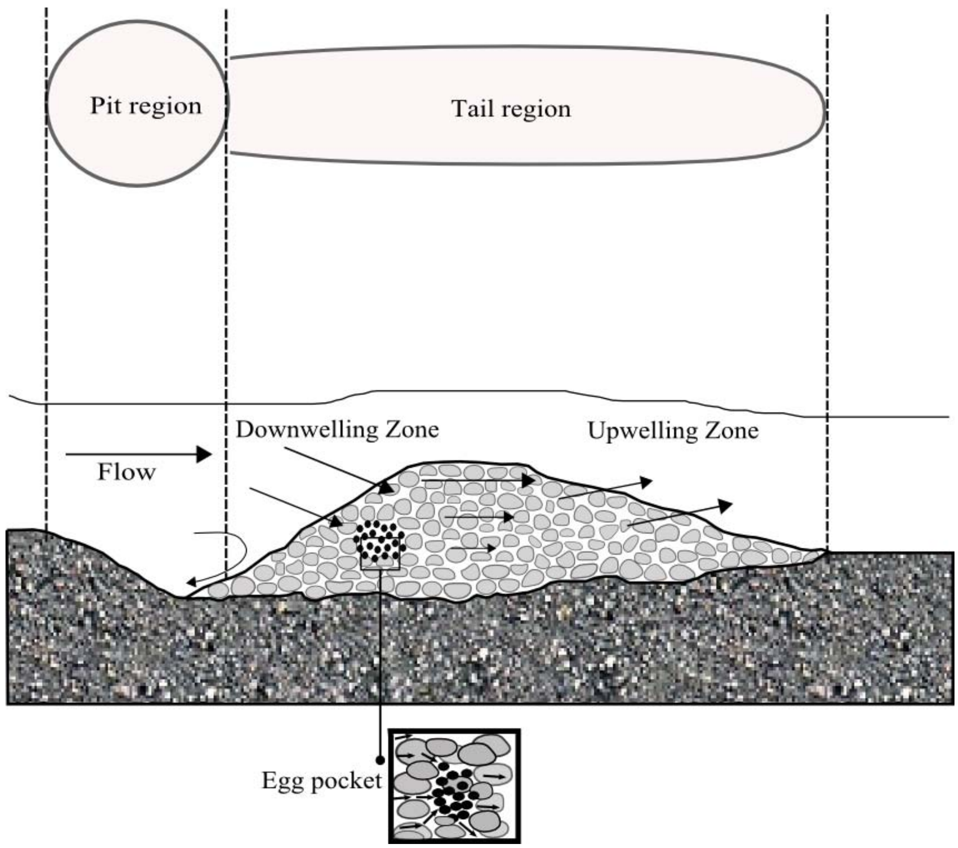

Fig. 3: Planimetric view (above) and cross sectional illustration (below) of a typical salmonid spawning redd. Arrows indicate the flow paths of water outside and inside the redd. Modified from Greig *et al*. (2007a).

The density of redds in streams depends on the amount of stream area usable for spawning, the number and size of spawning fishes, structural cover in the closer distance to the redds, and behavioural aspects during the spawning time (Bjornn & Reiser, 1991).

Fig. 4: Brown trout spawning redds from two Upper Austrian rivers, the Gr. Mühl river (left picture) and the Alm river (right picture)

The size of spawning redds and their position along the riverbed is not arbitrary, but dependent on fish size. The larger the body size of spawning salmonids, the larger are normally the redd dimensions (Crisp & Carling, 1989). Faster flowing channel sections can be potentially used by larger spawners while smaller individuals may be limited to low flowing areas (e.g. areas close to the river bank). According to Crisp (1993) the area of the redd is typically 3.5 times the body length of the female on the long axis and 0.3 to 0.6 times the body length of the female on the short axis. The average area of brown trout redds (*Salmo trutta f. fario*) is about 0.5 m^2 (Bjornn & Reiser, 1991). In this thesis, axial brown trout redd lengths obtained from the Gr. Mühl river (Upper Austria) fell between 0.95 m and 1.96 m and had areas (calculated via an ellipsoid formula) between 0.24 m^2 and 0.84 m^2, respectively.

The selection of spawning habitats of salmonids at a certain locality in the river is the result of interacting abiotic controls acting at multiple geographic scales. Based on the hierarchical stream habitat classification scheme of Frissel *et al*. (1986), Beechie *et al*. (2008) adapted a hierarchical concept of salmonid spawning habitat selection. In this concept, salmonid spawning habitat selection is governed by controls on the continental ($>10^6$ km^2), regional (10^4 km^2-10^5 km^2), watershed (10^2 km^2-10^3 km^2) and reach (10^{-2} km^2-$10^{-1}$$km^2$) scale. In this order, the predominant environmental controls are 1) latitude, topography, climate; 2) elevation, topography, geology; 3) channel slope, channel morphology, channel geology; and 4) local abiotic variables such as stream temperature, channel hydraulics and spawning substrate size (Fig. 5)

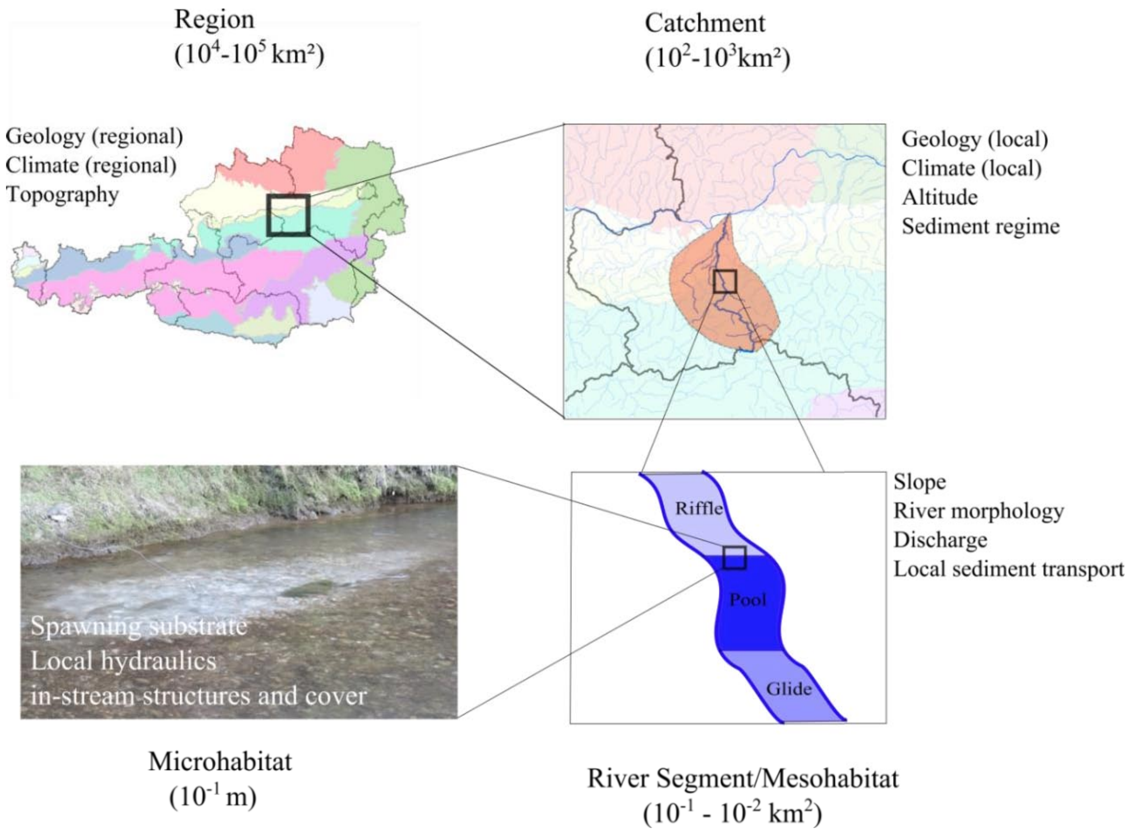

Fig. 5: Spatial hierarchy of spawning habitat selection. Drawn using information from Beechie *et al*. (2008)

On the mesohabitat level, salmonids prioritize riverbed zones for spawning where downwelling (Stuart 1953) or oxygen-rich groundwater seepage (Hansen, 1974) occur. Similarly, the presence of structural elements and habitat heterogeneity on the meso-/microhabitat level affects brown trout spawning habitat selection in several positive ways (Wheaton *et al*., 2004). For instance, woody material in stream channels provides cover and creates deep pools which may be sought after by females as welcome resting areas prior to and during spawning (Bjornn & Reiser, 1991; Nika *et al*., 2011; Jonsson & Jonsson, 2011). Another advantage of structured riverbeds comes into effect with the settling of spawning gravel in shear zones behind roughness elements (e.g. logs and boulder clusters; Buffington & Montgomery, 1999; Kemp, 2011; Buffington *et al*., 2004, Wheaton *et al*., 2004). The strong affinity of brown trout to structures on the riverbed during the spawning site selection was well confirmed in a study of Witzel & MacCrimmon (1983) who, in studying streams in southeastern Ontario, found that 84% of brown trout redds were located within 1.5 m of instream structures.

1.3. Microhabitat scale abiotic quality requirements in salmonid redds

The three microhabitat variables considered most important in the selection of spawning habitats in salmonids are flow velocity, water depth and substrate (Armstrong *et al*., 2003, Jonsson & Jonsson, 2011).

As for depth, water must be deeper than the body depth of the female to enable redd digging and avoid stranding of adult fish (Crisp *et al*., 1989). Water velocity must be low enough for mating brown trout to hold position, but high enough to dispatch excavated substrate downstream (Beechie *et al*., 2008). Water depths of less than 6 cm and water velocities lower than 12 cm.s^{-1} are avoided by spawning brown trout (Grost *et al*., 1990). In general, salmonids prefer swift flowing, shallow riffle areas in tributaries or main arms of streams with substrates of suitable diameter for the construction of their redds. Flow velocities of around 0.4 m.s^{-1} and water depths of about 0.3 m are assumed to offer favorable conditions for spawning brown trout (Jungwirth *et al*., 2003). However, grand deviations in both of the two parameters are reported in many studies dealing with redd characteristics of brown trout (e.g. Louhi *et al*., 2008). This indicates a certain degree of environmental flexibility in the spawning habitat selection of brown trout. Especially in the light of man made channel configurations,where hydraulic and morphologic characteristics are permanently altered, adaptiveness to depth and flow velocity in the redd site selection may be the only way for succesful reproduction. For example, in an Upper Austrian plane bed river, the Gr. Mühl River, which is naturally limited in spawning gravel, Hauer *et al*. (2011) found water depth ranges of 0.77-0.92 meters for brown trout and grayling in the backwater of a weir. In this thesis, average water depths of brown trout and rainbow trout spawning redds in hydropower influenced river sections of two study rivers (Gr. Mühl, Upper Austria; Gr. Erlauf, Lower Austria) were also greatest upstream of weirs (1.1 m at the Gr. Mühl river, 0.98 m at the Gr. Erlauf river).

Substrate, as the third important microhabitat variable influencing spawning habitat selection in salmonids, is considered the true limiting factor for the suitability and availability of spawning habitats (Kondolf & Wolman, 1993). Because the body size of the female sets an upper size limit to particle diameters usable as spawning substrate (Bjornn & Reiser, 1991; Kondolf & Wolman, 1993), only a fraction of the natural gravel size distribution in the river can be utilized for spawning. Consequently, the relationship between the natural sediment supply from the catchment and the transport rate of the river channel play the most fundamental role for the local deposition of spawning gravel in a river (Montgomery & Buffington, 1997).

Salmonids generally use fractions of gravel and cobble as spawning substrate. In brown trout, gravel diameters in the range of 16-64 mm (pebble) are the spawning gravel diameters favoured by brown trout (Table 1). In a regulated Bavarian chalk stream, Pulg (2009) found no evidence for brown trout spawning activities on substrate with average diameters of less than 5 mm. The same seems to be true for gravels with high contents of fine sediment, which are rejected by the female during exploratory cutting (Rubin *et al*., 2004; Svensson, 2012).

Table 1: Spawning habitat characteristics of brown trout with regard to mean water velocity, water depth and particle diameters.

Mean water velocity (cm/s)	Water depth (cm)	Particle diameter (mm)	Reported parameter	Reference
24-37	12-18	-	range	Grost et al. (1990)
35-42	77-96	35.5-38.6**	range	Hauer et al. (2010)
15-80	6-82	5-128	range	Jonsson & Jonsson (2011)*
30-50	10-50	10-70	range	Jungwirth et al.(2003)*
20-55	15-45	16-64	range	Louhi et al (2008)*
30-100	10-100	8-63	range	Pulg (2009)
30-40	10-20	16-32	range	Riedel & Peter (2013)
26.7	65	39.4	mean	Shirvell & Dungey (1983)
≥24	21-64	6-76	range	Bjornn & Reiser (1991)
46.7	25.5	-	mean	Witzel & Maccrimmon (1983)

*based on review result - not available

**based on the d_m

When an adult fish selects a spawning site, it is also selecting the incubation environment. Given the long time[3] that some salmonid embryos spend in the substratum, the quality and stability of the spawning habitat during incubation time is of overriding significance to the long term population development.

Different quality aspects are of varying importance during different stages of spawning and early development (i.e. redd digging, incubation, emergence; Kondolf *et al*., 2008; Fig. 6).

[3]For example, brown trout embryos can stay up to 5 months in the substratum until hatching (Pulg, 2009)

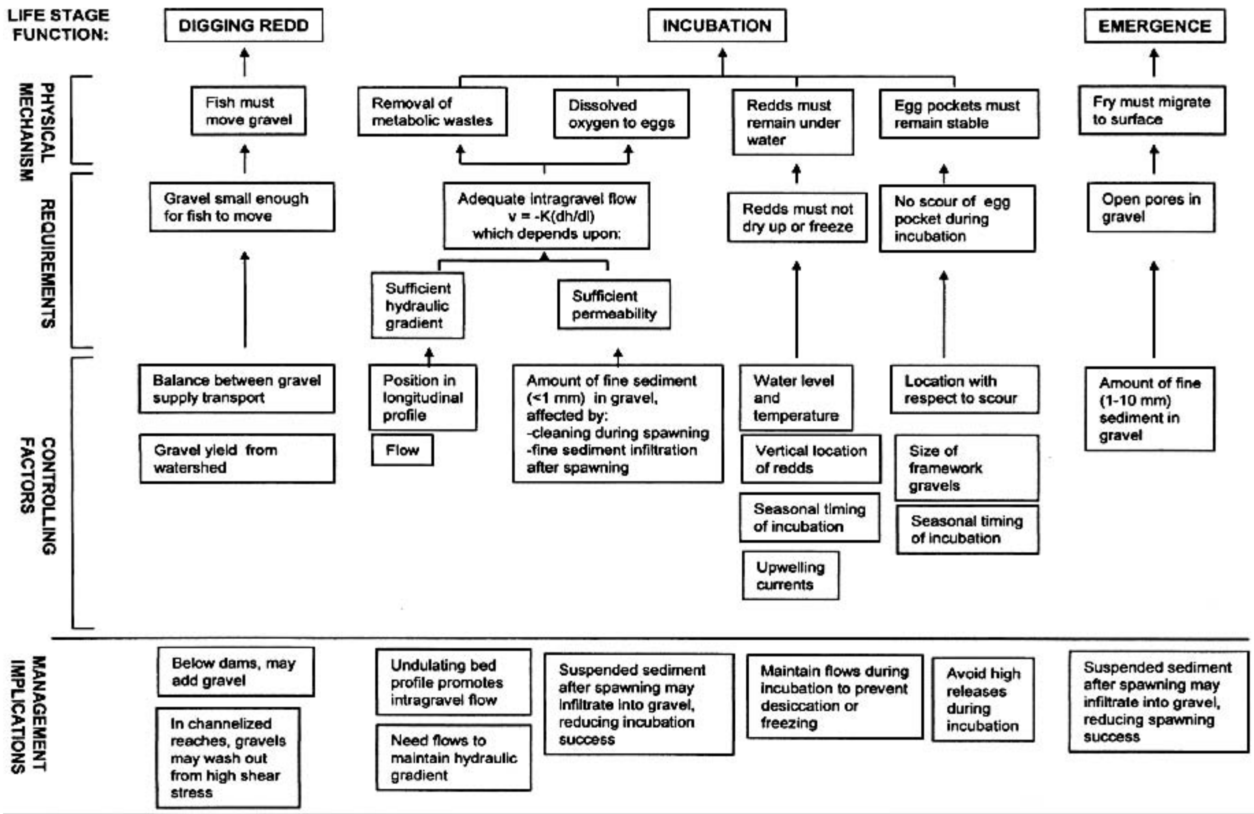

Fig. 6: Conceptual diagram synthesizing the spawning habitat requirements of salmonids for redd digging, incubation and emergence. Source: Kondolf *et al.* (2008)

The most important quality criteria for successful egg development in the substratum are (Bjornn & Reiser, 1991; Crisp *et al.*, 1993, Kondolf, 2000):

- Constant, well oxygenated intergravel waterflow
- Low fine sediment content (<15% ;Kondolf, 2000, Crisp *et al.*, 1993)
- Optimal temperature regime
- Mechanical stability of redds during the time of incubation.
- No dewatering of redds throughout the time of incubation

Constant, well oxygenated intergravel flow.

The term ‘intergravel flow’ describes the water movement through the spawning gravel (Kondolf *et al.*, 2008). The minimum dissolved oxygen requirements in developing brown trout eggs and yolk-sac larvae are higher than in older life stages, ranging from 2 mg.l^{-1} - 8 mg.l^{-1} (Kondolf,

2000). Especially in the larval stage of the incubation after hatching and shortly before emergence from the redd, the oxygen demand peaks up to 7 $mg.l^{-1}$ - 10 $mg.l^{-1}$ (Elliott, 1994).
Paramount to the survival of salmonid eggs and yolk-sac larvae in the pre-emergent phase is therefore the permanent proliferation of oxygen via intergravel flow (Chapman, 1988; Kondolf, 2000; Malcolm *et al*., 2003; Greig *et al*., 2005; Greig *et al*., 2007a; Sear *et al*., 2008; Sternecker *et al*., 2013; Schindler Wildhaber *et al*., 2014). It thus is not surprizing that salmonids selectively spawn in river segments where increased downwelling and upwelling of surface water into the riverbed occurs (e.g. Baxter & Hauer, 2000).
The flux of water through the riverbed is controlled by particle size grading, particle shape and gravel porosity (Cooper, 1965; Greig *et al*., 2007a; Kondolf, 2008).
A continuous intergravel flow in the egg environment satisfies the respiratory requirements of the eggs, and carries away toxic metabolic wastes (Crisp, 1993; Kondolf, 2000). Greig et al. (2005) demonstrated that the intergravel flow, measured as interstitial flow velocity, is a useful indicator for the embryonic survival of salmon eggs.
If intergravel flow rates within the egg environment become too restricted by reason of interstitial pore filling of fine sediment, the proliferation of oxygen into the egg pocket may be reduced to an extent where high embryo mortalities arise (Cooper, 1965; Chapman, 1988; Greig *et al*., 2005). Greig *et al*. (2007b) report a four orders of magnitude reduction in intragravel flow rates within Atlantic salmon redds as a result of fine sediment accumulation.
Salmonids have evolved at least three behavioral strategies to maintain and optimize the intergravel flow through their redds:

1) *Selection of hydraulically favorable bed topologies as redd sites*.

   Irregularities in the river bed are known to enhance the exchange processes between surface water and ground water via convective flow into (downwelling) or out of (upwelling) the streambed (=hyporheic exchange[4]; Cooper, 1965; Thibodeaux & Boyle, 1987, White, 1990; Elliott, 1991; Harvey & Bencala, 1993; Elliott & Brooks, 1997 a,b; Tonina, 2005; Tonina & Buffington, 2009a,b). Laboratory and field investigations dealing with various salmonid species have shown that spawning fishes are frequently drawn to

[4] Hyporheic exchange is a process that mixes river water with pore water by bringing surface water and solutes into the sediment (Tonina, 2005)

river channel segments with high proportions of bed irregularities (e.g. Curry & Nuakes, 1995; Geist & Dauble, 1998; Montgomery *et al.*, 1999; Baxter & Hauer, 2000) The strength of the exchange process induced by bed irregularities is dependent on the four factors streambed pressure, bed mobiliy, alluvial volume and hydraulic conductivity (Tonina & Buffington, 2009a). Bed irregularities in the form of pool-riffle-sequences are among the preferred structures used for spawning salmonids (Jonsson & Jonsson, 2011).
The preferred salmonid spawning site is described as the transition zone between the end (tail) of a pool and the start of a riffle (Crisp, 1993). This observation is explained by that pressure gradients induced by the pool-riffle-formation enhance the flow of oxygen-rich river water into the riverbed. According to Darcy's law (Darcy, 1856), the rate of groundwater flow V is the product of the hydraulic conductivity (K) and hydraulic gradient dh/dl.

$$\mathbf{V = - K \frac{dh}{dl}}$$

The negative sign in this equation indicates that the direction is opposite to the energy gradient. Because of the elevational drop in the hydraulic head from the upstream pool (low pressure zone) to the downstream riffle (high pressure zone), a hydraulic gradient is generated that induces downwelling at the tail of the pool into the riffle (Fig. 7).

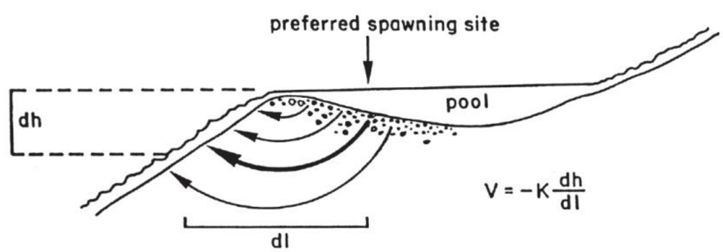

Fig. 7: Illustration of intergravel flow paths through the tail of a pool. Source: Kondolf (2000)

2) *Redd topography supporting the intergravel flow*

The typical pit-tail-topography resultant redd construction creates similar hydraulic pressure head differences as those observed in the larger-scale pool-riffle-sequences, but with an even stronger hyporheic exchange (Carling *et al.*, 2006; Tonina & Buffington, 2009b).

As flow accelerates over the tail of the redd, a recirculating shear zone forms within the pit region (Fig. 8). A negative pressure gradient over the tail forces water to be directed into the gravel matrix of the tail so that the intergravel water flow through the redd becomes accelerated in comparison to that in the surrounding bed sediment. Intergravel water exits the tail as upwelling eddies in the lee zone of the tail where a second low pressure zone forms (Fig. 8).

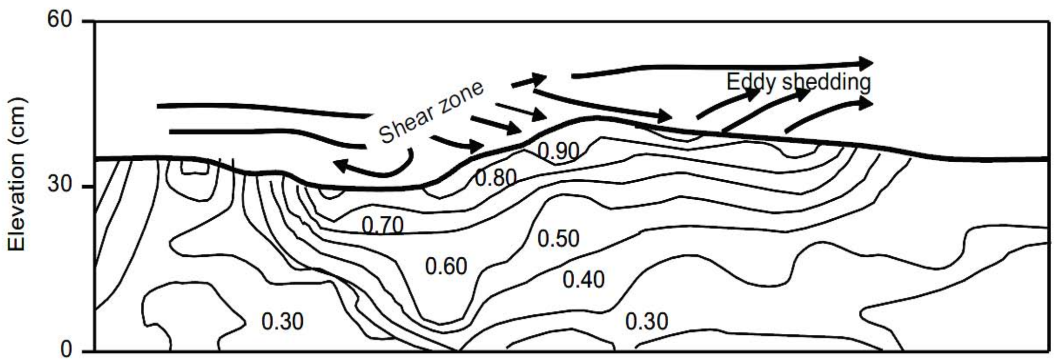

Fig. 8: Longitudinal view of pool-riffle bedform with redd and associated intergravel flow contour lines. Black arrows indicate flow paths near the redd. Source: Sear et al. (2008).

Redd-induced intergravel flow may be several times higher than the bedform-only induced intergravel flow (Sear *et al*., 2008; Tonina & Buffington, 2009b). In simulating and comparing redd topography induced to bed-form induced intergravel flow through a gravelly pool-riffle riverbed in a 3D- modelling application, Tonina & Buffington (2009b) found a three-to four times higher intergravel flow rates within the redd than in a pool-riffle sequence.

3) *Winnowing of fines from the redd during redd creation* (low fine sediment content)

The content of fines is reduced during the construction of the tail via mechanical movement and turnover of substrates (Kondolf, 2000).

Fine sediment is a particle fraction of small diameter that – when entering fish spawning habitats at excessive amounts – is known to have deleterious effects on the incubation success of salmonid eggs and pre-emergent incubated larvae (Chapman, 1988; Sear, 1993, Wood & Armitage, 1997; Sear *et al*., 2008; Kemp *et al*., 2011). Chapman (1988) classified fine sediment in the context of salmonid spawning studies as sediment particles less than 6 mm. Kondolf (2000) discusses the terminological problemacy of defining the scientific meaning of fine sediment since there is high studywise variation in the particle diameters that are reported to assess the negative impacts on incubated salmonid offspring[5]. The same author proposes a definition of fine sediment to be smaller than 1 mm in diameter. Also, to derive an approximation for the percentage of fines at which significant mortality occurs in the incubated offspring, Kondolf (2000) uses an upper threshold of 50% emergence success as cut-off value. Applying this scheme to a meta-analysis, the author comes to the conclusion that about 14 % of fines are necessary to reduce the incubated offspring by 50%. Similarly, Crisp (1993) states that a percentage of 10-15% fines (<1mm) "may lead to much lower egg survival rates".

The quantity of fines deposited and the depth to which it infuses depend on the ratio of the substrate particle diameter and the pore space, the flow conditions in the stream, and the amount of the transported fine sediment (Bjornn & Reiser, 1991). The smallest particles generally infiltrate the deepest sections of the redd (Bjornn & Reiser, 1991; Sear *et al*., 2008).

There are several (interactive) pathways how fine sediment can reduce the survival of egg embryos (Fig. 9). Besides the above mentioned oxygen limitation in response to reduced intergravel flow from interstitial pore filling, Greig *et al*. (2005) mention two further effects driving the suffocation of egg embryos. First, a coat of clay particles (< 0.063mm) covering the egg membrane inhibits oxygen diffusion by clogging the micropores of the egg membrane. Second, organic fine sediment sources in the egg pocket can drive oxygen consumption by bacterial respiation causing oxygen limitations in the egg pocket.

In intensively managed catchments, fine sand infiltration into redds is enhanced in the wintertime during storm events (Soulsby *et al*., 2001; Acornley & Sear, 1999). In their field investigation in a lowland agricultural stream, Soulsby *et al*. (2001) concluded that complete fine sand infiltration of open gravel matrices can occur within less than a week and probably even after a single storm event.

[5] In analyzing 18 studies, Kondolf (2000) finds that diameters of what has been referred to as fine sediment range from 0.83mm to as much as 9.5mm

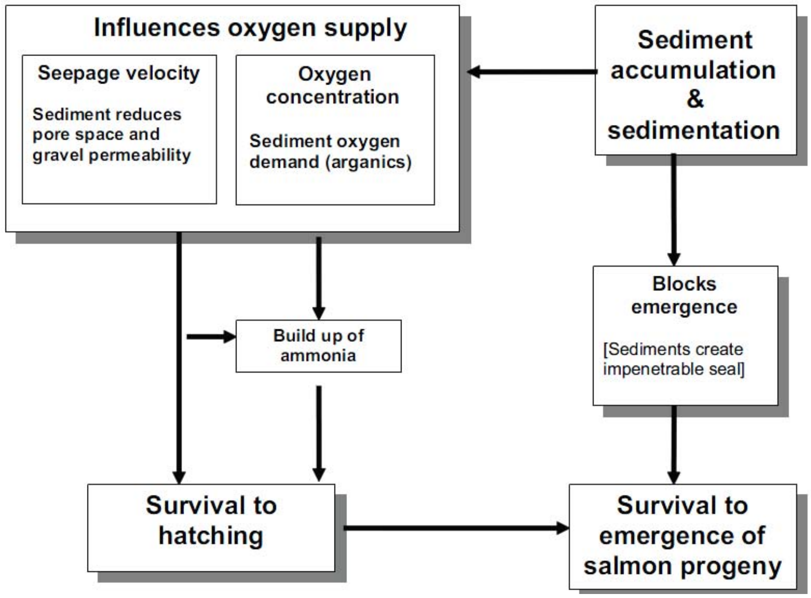

Fig. 9: Scheme conceptualizing the interactive pathways of the negative effects of fine sediment on the salmonid offspring. Source: Sear *et al*., 2008

Similar to fine sediment, high loads of coarser sandy substrate (1-2mm) on the riverbed fill up pore spaces and reduce the intergravel flow through redds (Ferreira *et al*., 2009). In this thesis, it was found that coarse sand (D_{50} = 2 mm) infiltration into the redd framework gravel of artificial brown trout redds reduces the intergravel flow up to four times compared to the non-infiltrated reference situation.

Even larger particle sizes in the range of 6-8 mm, while deemed less problematic in terms of intergravel flow permeability, can cause the emergence of upwards moving alevins to fail by the sealing of pathways leading out of the redd (Bjornn & Reiser, 1991; Kondolf, 2000; Sternecker & Geist, 2010; Sternecker *et al*. 2013).

Although spawning brown trout avoid areas of the riverbed with high fine sediment content and clean the gravel from fine sediment mechanically during the spawning activities (Kondolf, 2000; Rubin *et al*., 2004; Svensson, 2012), the amount of fine sediment within the redd framework gravel usually increases during the course of incubation (Bjornn & Reiser, 1991; Greig *et al*., 2007a; Pulg, 2007; Sternecker *et al*., 2013; Pulg *et al*., 2013).

On a natural basis, fine sediments are present in all lotic ecosystems and their transport rate varies over the year in response to fluctuations of the discharge regime, vegetation pattern, soil composition and landuse (Wood & Armitage, 1997).Therefore, erosive catchment landuse, as generated from intensified agriculture, road construction and large scale deforestation, can exacerbate the physical process of fine sediment infiltration in the spawning environments of riverine fishes (e.g. Wood & Armitage, 1997; Soulsby *et al*., 2001, Kemp *et al*., 2011). Throughout the year, regular bed mobilizing flood events are necessary to uphold high-quality spawning gravels with satisfactorily low fine sediment contents (Hauer *et al*., 2011). Hauer *et al*. (2011) proposed a concept of the effective discharge of spawning gravel, which is the discharge at which most of the spawning substrate is re-mobilized and deposited at known spawning sites.

Optimal temperature regime.

The optimal temperature for brown trout egg survival was found to lie between 8 and 10 °C (Ojanguren & Brana, 2003). Normally, more than 95% of trout eggs survive at temperatures between 0 and 10°C, but less than 50% survive at temperatures above 12°C and none survive at temperatures above 15.5°C (Crisp, 1993).
In rivers having high groundwater permeabilies, such as in chalk streams, incubated salmonid embryos find a more favorable thermal environment than in rivers with restricted groundwater supply. This is because of the higher temperature of the groundwater in comparison to the stream water temperature in the wintertime (Acornley, 1999). Also, diel temperature fluctuations are more even in redds with higher groundwater influence and become more so with increasing redd burial depth (Crisp, 1990; Acornley, 1999).

Stability of redds during the time of incubation.

Soon after they have been laid, salmonid eggs become sensitive to mechanical shock and they are readily killed thereof (Crisp, 1993). The stability of the egg environment during the incubation time is therefore a crucial premise for the reproduction success in salmonids. High-flood events in the winter can lead to bed-scour and mechanical destruction of the redds with high accompanied mortalities in developing embryos (Pulg, 2007; Unfer *et al*., 2011). Thus, times of high bed mobility in the year where the scour depth exceeds the egg burial depth have to be avoided by spawning salmonids (Montgomery et al., 1999).

There exists a trade-off between egg survival and burial depth. If eggs are located shallow in the redd, oxygen delivery may be sufficient. However, the risk of mortality linked to bed scour increases (Elliott, 1994). If eggs are buried deeper in the substratum, the likelihood of washout will be reduced and better development due to higher temperature can be expected, but oxygen then becomes limiting and can trigger asphyxia (Bjornn & Reiser, 1991; Armstrong *et al*, 2003).

No dewatering of redds throughout the time of incubation

Spawning in shallow areas of the river (e.g. glides, riffles, areas close to the river bank) is often discovered in salmonids (Crisp, 1993). This behavioural trait may be disadvantageous in times of low flow when redds in shallow waters fall dry (Bjornn & Reiser, 1991). Particularly in river sections downstream weir where water diversion takes place (e.g. for hydropower generation), the problem of dessicating salmonid spawning redds can be substantial (Bjornn & Reiser, 1991).

1.4. Hydropower in Austria and its possible impact on salmonid spawning habitats

Hydropower (syn.: Hydroelectricity) refers to the practice of generating electricity by taking advantage from the kinetic energy of flowing water (Egre & Milewski, 2002). What all hydropower installations have in common is that they employ turbines which convert the flowing water's energy into mechanical and subsequently electrical energy.

In most cases, hydropower projects are realized by regulating parts of the river with a transversal flow obstruction (dam, weir) in order to use the stored water for energy generation.

Austria looks back at a long history of hydropower development. As of 2013, hydropower production in Austria accounted for 67.2 percent of the country's total electricity production (E-Control, 2014), making it the most important energy resource of the country.

According to the classification scheme for hydropower in Austria after Habersack *et al*. (2012), the broadest classification of hydropower systems in Austria can be made in terms of bottleneck capacity. Herein, small hydropower systems (<10 MW) are set apart from large hydropower systems (>10 MW), Fig. 10. On the next classification level, large and small hydropower systems can be categorized further into the type of architecture (run-of-river, storage, pump-storage). The classification hierarchy continues with storage volume (daily, weekly or annual storage), location of powerhouse (main river, diversion, impoundment) and, finally, operation mode of power generation (run-of-river, hydropeaking, impoundment, pump-storage).

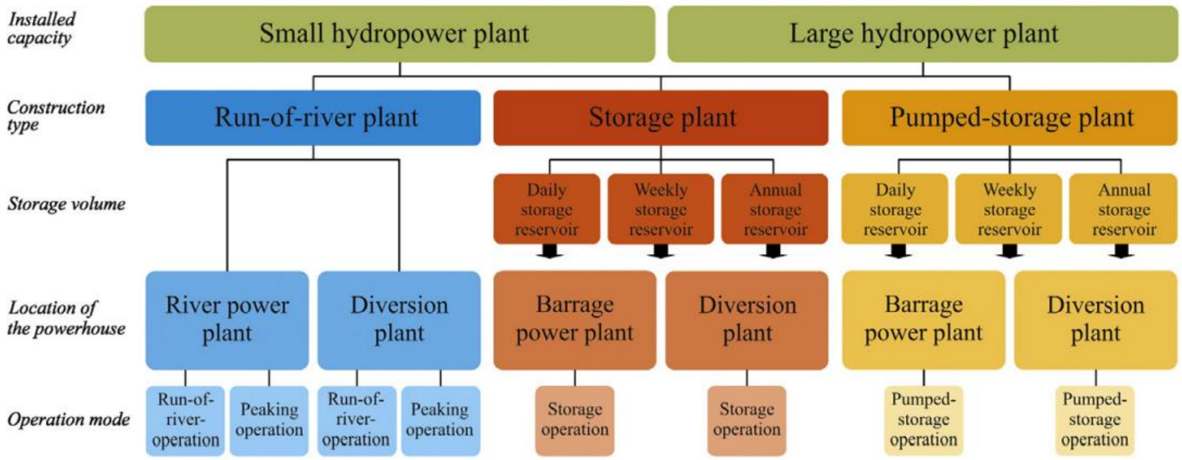

Fig. 10: Concept of hydropower classification in Austria. Source: Wagner *et al*., 2015

The total number of hydropower plants in Austria (including facilities of private use) amounts to more than 5200 of which 2882 facilities are feeding into the national energy grid (Wagner *et al*., 2015). The by far largest share of hydropower plants feeding into the national energy grid constitutes small hydropower plants (<10 MW, 96.4%). Despite the large share of small hydropower plants, most energy (86.2%) is generated by the remaining 5.6 % of large hydropower plants (> 10 MW) (Wagner *et al*., 2015).

From the small hydropower plants, 88 % belong to the diversion construction type (Habersack *et al*., 2012). Therefore, most of the regulated rivers in Austria show far from natural hydrological conditions, with alternating sequences of impoundments, residual flow areas and remaining free flowing areas in between. The two study rivers investigated in the scope of this thesis, the Gr. Mühl river (Upper Austria) and the Gr. Erlauf river (Lower Austria), are both examples of salmonid running waters with moderate to high hydropower usage along the river course. Black dots on the map (Fig. 11) represent weirs of SHPs, with the pie charts below each study river map indicating the proportion of free-flowing areas, residual flow areas and impoundment areas.

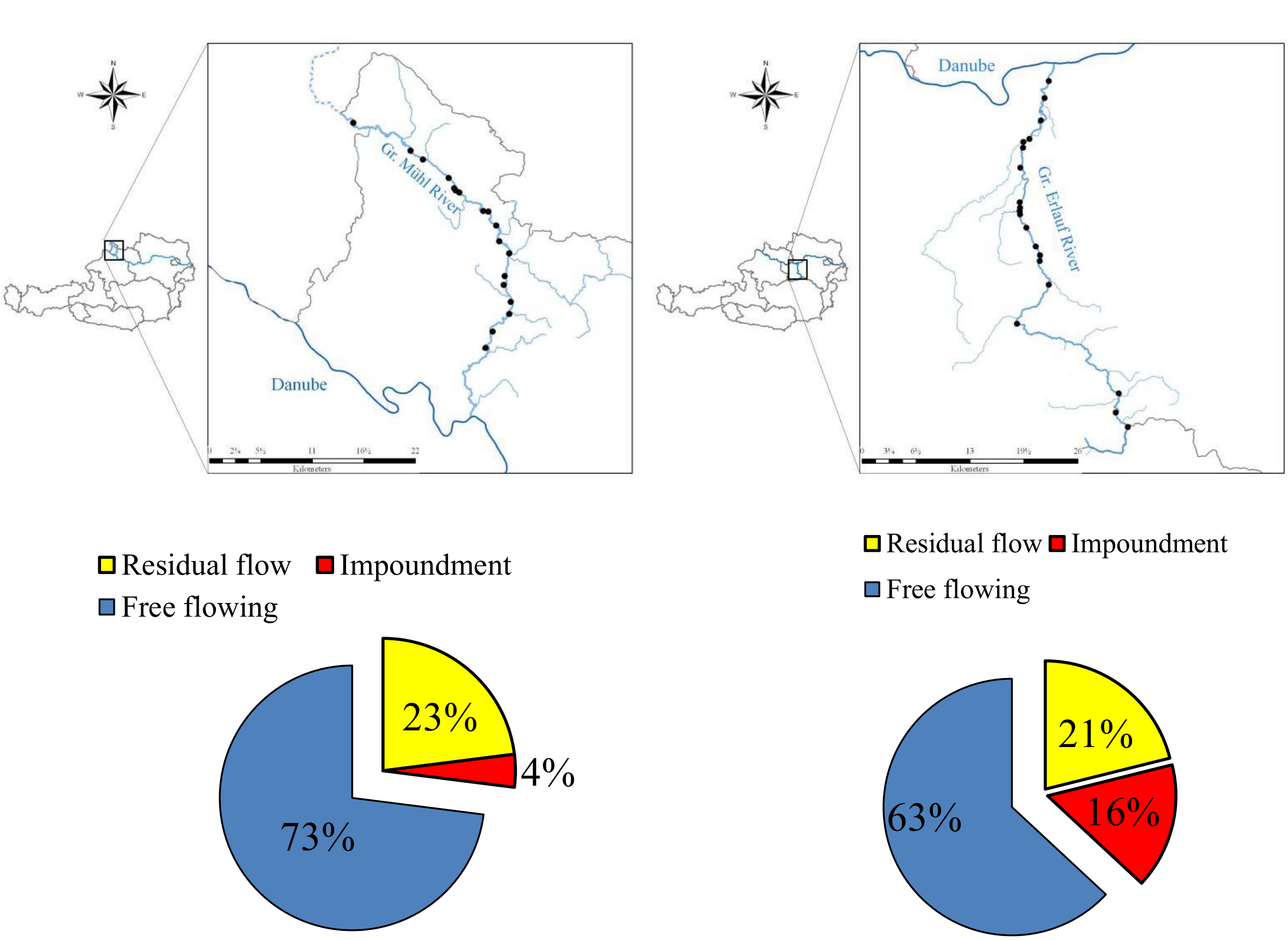

Fig. 11: Maps showing the Gr. Mühl river (top left) and the Gr. Erlauf river (top right). Filled black circles on each map represent hydropower weirs. Pie charts below each river's map show the share of free flowing, impounded and residual flow areas for each river. Map source and data source: BMLFUW.

It shows that more than one third of the Gr. Erlauf river course and close to one third of the Gr. Mühl river course are hydrologically altered by the presence of impoundments and residual flow areas (Fig.11).

The long history of man-made damming (including the worldwide development of hydropower ensuing the industrial era) and its physical and biotic changes to the upstream and downstream extent of a dammed river section are comprisively shown up in the literature (e.g. Baxter, 1977; Raymond, 1979; Ward & Stanford, 1983; Ligon *et al*., 1995; Kondolf, 1997, Poff *et al*., 1997; Jungwirth *et al*., 2003).

(Hydropower) dams alter the two most important processes of the geomorphic system in rivers – discharge and sediment transport (Poff *et al*., 1997; Grant *et al*., 2003). The resulting biophysical impacts damming brings about in river ecosystems include the following (Baxter, 1977; Poff *et al*., 1997; Jungwirth *et al*., 2003):

- Reductions in the single components of the natural flow regime (magnitude, frequency, duration, timing, rate of change) up/downstream
- Changes in the natural sediment flux and storage up/downstream
- Changes in the natural groundwater tables up/downstream
- Changes in the temperature regime up/downstream
- Loss of structural complexity in the riverbed
- Decoupling of the main river and its surrounding area (lateral connectivity)
- Riverbed incision downtream of the dam

River regulations from hydropower operations may compromise the spawning habitat of salmonids in the following ways (Crisp, 1993; Kondolf, 1997; Pulg, 2009):

- Insufficient flow velocities in impounded sections
- Spawning gravel retention in impounded sections with limited availability of spawning gravel downstream of weirs
- Gravelbed colmation from fine sediment infiltration in impounded sections
- Insufficient water depths for redd cutting and desiccation of incubated eggs in residual flow sections

Insufficient flow velocities in impounded sections are the result of backwater effects from weirs and can lead to *a priori* rejections of spawning fishes in river areas with otherwise suitable spawning conditions (presence of spawning substrate, sufficient water depths; personal observations). In addition, lower flow velocities facilitate the deposition of fine sediments, which are known to reduce the survival of embryos in redds that have already been cut (e.g. Greig *et al.*, 2005).

Spawning gravel deficiencies in river sections downstream of weirs can be caused by reduced shear stresses upstream of weirs where a partial or an entire entrapment of bedload occurs (Kondolf, 1997). Aside from this problem, the sediment-depleted water released downstream of dams (“hungry water”; *sensu* Kondolf, 1997) may lead to riverbed consolidation (=bed armoring) in downstream reaches because gravel is rarely or never moved by flood flows (Nelson *et al.*, 1987). Over the long term, the bed may coarsen to such an extent that even for larger fishes, no more redd digging is possible (Kondolf, 1997).

Gravelbed colmation can either occur as inner (clogging of interstitial pores) or outer (clogging of the surface stratum) colmation and can have abiotic (fine sediment deposition) and biotic (activities of cyanobacteria) origins (Pulg, 2009). In the case of gravelbed colmation occurring in impoundments, reduced shear stresses upstream of dams facilitate the deposition and coverage of layers of fine sediment on the riverbed, making spawning areas inaccessible for spawning fishes (Wood & Armitage, 1997). Colmation of riverbeds from fine sediments can also be possible in downstream areas of weirs (Sear, 1993), e.g. where a large bed mobilizing flow event has caused the release of waves of fine sediment captured in the impoundment for longer periods as a consequence of the flow control via the impoundment (Poff *et al.*, 1997).

Insufficient water depths in spawning grounds can have natural causes (e.g. during periods of extremely low flow in the spawning season) and can be caused (enhanced) by flow controlling measures (e.g. diversion hydropower systems where parts of the main river flow are bypassed, leaving behind dewatered residual flow sections).

References

Acornley, R. M., & Sear, D. A. (1999). Sediment transport and siltation of brown trout (Salmo trutta L.) spawning gravels in chalk streams. Hydrological Processes, 13(3), 447-458.

Acornley, R. M. (1999). Water temperatures within spawning beds in two chalk streams and implications for salmonid egg development. Hydrological Processes, 13(3), 439-446.

Allan, J. D. (1995). Stream ecology. Structure and function of running waters. Chapman and Hall, London, 1995. 388pp. ISBN 0 412 35530 2

Armstrong, J. D., Kemp, P. S., Kennedy, G. J. A., Ladle, M., & Milner, N. J. (2003). Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries Research, 62(2), 143-170.

Balon, E. K. (1975). Terminology of intervals in fish development. Journal of the Fisheries Board of Canada, 32(9), 1663-1670.

Baxter, C. V., & Hauer, F. R. (2000). Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (Salvelinus confluentus). Canadian Journal of Fisheries and Aquatic Sciences, 57(7), 1470-1481.

Baxter, R. M. (1977). Environmental effects of dams and impoundments.Annual Review of Ecology and Systematics, 255-283.

Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., ... & Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. BioScience, 60(3), 209-222.

Beechie, T., Moir, H., & PESS, G. (2008). Hierarchical physical controls on salmonid spawning location and timing. In American Fisheries Society Symposium (Vol. 65, pp. 000-000).

Bjornn, T., & Reiser, D. W. (1991). Habitat requirements of salmonids in streams. American Fisheries Society Special Publication, 19, 83-138.

Buffington, J. M., & Montgomery, D. R. (1999). Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research, 35(11), 3507-3521.

Buffington, J. M., Montgomery, D. R., & Greenberg, H. M. (2004). Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. Canadian Journal of Fisheries and Aquatic Sciences, 61(11), 2085-2096.

Carling, P. A., Whitcombe, L., Benson, I. A., Hankin, B. G., & Radecki-Pawlik, A. M. (2006). A new method to determine interstitial flow patterns in flume studies of sub-aqueous gravel bedforms such as fish nests. River Research and Applications, 22(6), 691-701.

Chapman, D. W. (1988). Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society, 117(1), 1-21.

Cooper, A. C. (1965). The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin (p. 71). New Westminster, BC: International Pacific Salmon Fisheries Commission.

Crisp, D. T. (1993). The environmental requirements of salmon and trout in fresh water. In Freshwater Forum (Vol. 3, No. 3, pp. 176-202).

Curry, R. A., & Noakes, D. L. (1995). Groundwater and the selection of spawning sites by brook trout (Salvelinus fontinalis). Canadian Journal of Fisheries and Aquatic Sciences, 52(8), 1733-1740.

Darcy, H. (1856). Les fontaines publiques de la ville de Dijon: exposition et application... Victor Dalmont.

Egré, D., & Milewski, J. C. (2002). The diversity of hydropower projects. Energy Policy, 30(14), 1225-1230.

Elliott, A. H. (1991). Transfer of solutes into and out of streambeds (Doctoral dissertation, California Institute of Technology).

Elliott, A. H., & Brooks, N. H. (1997)(a). Transfer of nonsorbing solutes to a streambed with bed forms: Laboratory experiments. Water Resources Research, 33(1), 137-151.

Elliott, A. H., & Brooks, N. H. (1997)(b). Transfer of nonsorbing solutes to a streambed with bed forms: Theory. Water Resources Research, 33(1), 123-136.

Elliott, J. M. (1994). Quantitative ecology and the brown trout. Oxford University Press, 286 pp.

Fausch, K. D., Torgersen, C. E., Baxter, C. V., & Li, H. W. (2002). Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes A Continuous View of the River is Needed to Understand How Processes Interacting among Scales Set the Context for Stream Fishes and Their Habitat. BioScience, 52(6), 483-498.

Frissell, C. A., Liss, W. J., Warren, C. E., & Hurley, M. D. (1986). A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental management, 10(2), 199-214.

Geist, D. R., & Dauble, D. D. (1998). Redd site selection and spawning habitat use by fall chinook salmon: the importance of geomorphic features in large rivers. Environmental Management, 22(5), 655-669.

Grant, G. E., Schmidt, J. C., & Lewis, S. L. (2003). A geological framework for interpreting downstream effects of dams on rivers. A peculiar river, 203-219.

Greig, S. M., Sear, D. A., & Carling, P. A. (2005). The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. Science of the Total Environment, 344(1), 241-258.

Greig, S. M., Sear, D. A., & Carling, P. A. (2007a). A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. Hydrological Processes, 21(3), 323-334.

Grost, R. T., Hubert, W. A., & Wesche, T. A. (1990). Redd site selection by brown trout in Douglas Creek, Wyoming. Journal of Freshwater Ecology, 5(3), 365-371.

Habersack, H., Wagner, B., Hauer, C., & Jäger, E. (2012). Wasserkraft in Österreich—aktueller Bestand und Decision Support System (DSS WASSERKRAFT). Österreichische Wasser-und Abfallwirtschaft, 64(5-6), 336-343.

Hansen, E. A. (1975). Some effects of groundwater on brown trout redds.Transactions of the American Fisheries Society, 104(1), 100-110.

Harvey, J. W., & Bencala, K. E. (1993). The effect of streambed topography on surface-subsurface water exchange in mountain catchments. Water Resources Research, 29(1), 89-98.

Hauer, C., Unfer, G., Tritthart, M., & Habersack, H. (2011). Effects of stream channel morphology, transport processes and effective discharge on salmonid spawning habitats. Earth Surface Processes and Landforms, 36(5), 672-685.

Heggenes, J. (1996). Habitat selection by brown trout (Salmo trutta) and young Atlantic salmon (S. salar) in streams: static and dynamic hydraulic modelling. Regulated Rivers: Research & Management, 12(2-3), 155-169.

Heggenes, J. (2002). Flexible summer habitat selection by wild, allopatric brown trout in lotic environments. Transactions of the American Fisheries Society, 131(2), 287-298.

Heggenes, J., & Saltveit, S. J. (1990). Seasonal and spatial microhabitat selection and segregation in young Atlantic salmon, Salmo salar L., and brown trout, Salmo trutta L., in a Norwegian river. Journal of Fish Biology, 36(5), 707-720.

Hendry, K., Cragg-Hine, D., O'Grady, M., Sambrook, H., & Stephen, A. (2003). Management of habitat for rehabilitation and enhancement of salmonid stocks.Fisheries Research, 62(2), 171-192.

Jenkins, A. R., & Keeley, E. R. (2010). Bioenergetic assessment of habitat quality for stream-dwelling cutthroat trout (Oncorhynchus clarkii bouvieri) with implications for climate change and nutrient supplementation. Canadian Journal of Fisheries and Aquatic Sciences, 67(2), 371-385.

Jonsson, B., & Jonsson, N. (2011). Ecology of Atlantic salmon and brown trout: habitat as a template for life histories (Vol. 33). Springer.

Jungwirth, M. (2003). Angewandte Fischökologie an Fließgewässern. Facultas-Verlag.

Jungwirth, M., Muhar, S., & Schmutz, S. (2000). Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept (pp. 85-97). Springer Netherlands.

Kemp, P. (Ed.). (2011). Salmonid fisheries: freshwater habitat management. John Wiley & Sons.

Kemp, P., Sear, D., Collins, A., Naden, P., & Jones, I. (2011). The impacts of fine sediment on riverine fish. Hydrological Processes, 25(11), 1800-1821.

Klemetsen, A., Amundsen, P. A., Dempson, J. B., Jonsson, B., Jonsson, N., O'connell, M. F., & Mortensen, E. (2003). Atlantic salmon Salmo salar L., brown trout Salmo trutta L. and Arctic charr Salvelinus alpinus (L.): a review of aspects of their life histories. Ecology of freshwater fish, 12(1), 1-59.

Kondolf, G. M. (1997). PROFILE: hungry water: effects of dams and gravel mining on river channels. Environmental management, 21(4), 533-551.

Kondolf, G. M. (2000). Assessing salmonid spawning gravel quality.Transactions of the American Fisheries Society, 129(1), 262-281.

Kondolf, G. M., & Wolman, M. G. (1993). The sizes of salmonid spawning gravels. Water Resources Research, 29(7), 2275-2285.

Kondolf, G. M., Boulton, A. J., O'Daniel, S., Poole, G. C., Rahel, F. J., Stanley, E. H., ... & Nakamura, K. (2006). Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society, 11(2), 5.

Kondolf, G. M., Williams, J. G., Horner, T. C., & Milan, D. A. V. I. D. (2008). Assessing physical quality of spawning habitat. In American fisheries society symposium (Vol. 65, pp. 000-000).

Louhi, P., Mäki-Petäys, A., & Erkinaro, J. (2008). Spawning habitat of Atlantic salmon and brown trout: general criteria and intragravel factors. River Research and Applications, 24(3), 330-339.

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

Maitland, P. S. (1995). The conservation of freshwater fish: past and present experience. Biological Conservation, 72(2), 259-270.

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.

Montgomery, D. R., Beamer, E. M., Pess, G. R., & Quinn, T. P. (1999). Channel type and salmonid spawning distribution and abundance. Canadian Journal of Fisheries and Aquatic Sciences, 56(3), 377-387.

Montgomery, D.R., and Buffington, J.M. 1997. Channel reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 109: 596–611.

Nelson, R. W., Dwyer, J. R., & Greenberg, W. E. (1987). Regulated flushing in a gravel-bed river for channel habitat maintenance: a Trinity River fisheries case study. Environmental Management, 11(4), 479-493.

Newson, M., Sear, D., & Soulsby, C. (2012). Incorporating hydromorphology in strategic approaches to managing flows for salmonids. Fisheries Management and Ecology, 19(6), 490-499.

Nika, N., Virbickas, T., & Kontautas, A. (2011). Spawning site selection and redd gravel characteristics of sea trout Salmo trutta in the lowland streams of Lithuania. Oceanological and Hydrobiological Studies, 40(1), 46-56.

Ojanguren, A. F., & Brana, F. (2003). Thermal dependence of embryonic growth and development in brown trout. Journal of fish biology, 62(3), 580-590.

Palmer, M. A., Bernhardt, E. S., Allan, J. D., Lake, P. S., Alexander, G., Brooks, S., ... & Sudduth, E. (2005). Standards for ecologically successful river restoration. Journal of applied ecology, 42(2), 208-217.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., ... & Stromberg, J. C. (1997). The natural flow regime. BioScience, 769-784.

Pulg U. 2009. Laichplaetze der Bachforelle (Salmo trutta) in der Moosach – die Bewertung ihrer Funktionsfaehigkeit, ihre Degradierung und ihre Restaurierung. Dissertation am Lehrstuhl fuer Landschaftsoekologie der Technischen Universitaet Muenchen. http://mediatum2.ub.tum.de/node? id=680304

Pulg, U., & Bayern eV, L. (2007). Die Restaurierung von Kieslaichplätzen.Landesfischereiverband Bayern eV, München. http://www.argefa.org/sites/default/files/publikationen/pdf/kislaichplatzbroschuere.pdf

Pulg, U., Barlaup, B. T., Sternecker, K., Trepl, L., & Unfer, G. (2013). Restoration of spawning habitats of brown trout (Salmo trutta) in a regulated chalk stream. River Research and Applications, 29(2), 172-182.

Riedl, C., & Peter, A. (2013). Timing of brown trout spawning in Alpine rivers with special consideration of egg burial depth. Ecology of Freshwater Fish,22(3), 384-397.

Rubin, J. F., Glimsäter, C., & Jarvi, T. (2004). Characteristics and rehabilitation of the spawning habitats of the sea trout, Salmo trutta, in Gotland (Sweden). Fisheries Management and Ecology, 11(1), 15-22.

Schindler Wildhaber, Y., Michel, C., Epting, J., Wildhaber, R. A., Huber, E., Huggenberger, P., ... & Alewell, C. (2014). Effects of river morphology, hydraulic gradients, and sediment deposition on water exchange and oxygen dynamics in salmonid redds. Science of the Total Environment, 470, 488-500.

Schinegger, R., Trautwein, C., Melcher, A., & Schmutz, S. (2012). Multiple human pressures and their spatial patterns in European running waters. Water and Environment Journal, 26(2), 261-273.

Sear, D. A. (1993). Fine sediment infiltration into gravel spawning beds within a regulated river experiencing floods: ecological implications for salmonids.Regulated Rivers: Research & Management, 8(4), 373-390.

Sear, D. A., Frostick, L. B., Rollinson, G., & Lisle, T. E. (2008). The significance and mechanics of fine-sediment infiltration and accumulation in gravel spawning beds. In American Fisheries Society Symposium (Vol. 65, pp. 000-000).

Shirvell, C. S., & Dungey, R. G. (1983). Microhabitats chosen by brown trout for feeding and spawning in rivers. Transactions of the American Fisheries Society, 112(3), 355-367.

Soulsby, C., Youngson, A. F., Moir, H. J., & Malcolm, I. A. (2001). Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. Science of the Total Environment, 265(1), 295-307.

Stanford, J. A., Lorang, M. S., & Hauer, F. R. (2005). The shifting habitat mosaic of river ecosystems. Internationale Vereinigung fur Theoretische und Angewandte Limnologie Verhandlungen, 29(1), 123-136.

Sternecker, K., & Geist, J. (2010). The effects of stream substratum composition on the emergence of salmonid fry. Ecology of Freshwater Fish,19(4), 537-544.

Sternecker, K., Cowley, D. E., & Geist, J. (2013). Factors influencing the success of salmonid egg development in river substratum. Ecology of Freshwater Fish, 22(2), 322-333.

Stuart, T. A. (1953). Water currents through permeable gravels and their significance to spawning salmonids, etc. Nature 172, 407 - 408 (29 August 1953); doi:10.1038/172407a0

Svensson, J. (2012). Spawning site selection of brown trout in habitat restored streams. http://stud.epsilon.slu.se/4289/1/Svensson_J_120612.pdf

Thibodeaux, L. J., & Boyle, J.D. (1987). Bedform-generated convective transport in bottom sediment. Nature 325: 34 l- 343.

Thomas, G. (2014). Improving restoration practice by deriving appropriate techniques from analysing the spatial organization of river networks.Limnologica-Ecology and Management of Inland Waters, 45, 50-60.

Tonina, D. (2005). Interaction between river morphology and intra-gravel flow paths within the hyporheic zone (Doctoral dissertation, University of Idaho).

Tonina, D., & Buffington, J. M. (2009a). Hyporheic exchange in mountain rivers I: Mechanics and environmental effects. Geography Compass, 3(3), 1063-1086.

Tonina, D., & Buffington, J. M. (2009b). A three-dimensional model for analyzing the effects of salmon redds on hyporheic exchange and egg pocket habitat.Canadian Journal of Fisheries and Aquatic Sciences, 66(12), 2157-2173.

Townsend, C. R. (1989). The patch dynamics concept of stream community ecology. Journal of the North American Benthological Society, 36-50.

Wagner, B., Hauer, C., Schoder, A., & Habersack, H. (2015). A review of hydropower in Austria: Past, present and future development. Renewable and Sustainable Energy Reviews, 50, 304-314.

Ward, J. V., Tockner, K., Arscott, D. B., & Claret, C. (2002). Riverine landscape diversity. Freshwater Biology, 47(4), 517-539.

Wheaton, J. M., Pasternack, G. B., & Merz, J. E. (2004). Use of habitat heterogeneity in salmonid spawning habitat rehabilitation design. In Fifth International Symposium on Ecohydraulics. Aquatic Habitats: Analysis & Restoration. Madrid (pp. 791-796).

White, D. S. (1990). Biological relationships to convective flow patterns within stream beds. Hydrobiologia, 196(2), 149-158.

Witzel, L., MacCrimmon, H., 1983. Redd-site selection by brook trout and brown trout in southwestern Ontario streams. Trans. Am. Fish. Soc. 112, 760–771.

Wohl, E., Angermeier, P. L., Bledsoe, B., Kondolf, G. M., MacDonnell, L., Merritt, D. M., ... & Tarboton, D. (2005). River restoration. Water Resources Research, 41(10).

Wood, P. J., & Armitage, P. D. (1997). Biological effects of fine sediment in the lotic environment. Environmental management, 21(2), 203-217.

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Section 2 – Research Articles

The below presented research articles are intended to be submitted for publication.

Article 1 (to be submitted as Short Communication paper for the journal *Earth Surface Processes and Landforms*) investigates the intergravel flow through artificial brown trout (*Salmo trutta f. fario*) redds under increased coarse sand infiltration in a laboratory flume experiment.

Article 2 (to be submitted as Letter to ESEX for the Journal Limnologica) deals about the spatial distribution of resident brown trout (*Salmo trutta f. fario*) and non-resident rainbow trout (*Oncorhynchus mykiss*) spawning redds in hydropower influenced river sections of two geologically distinct study rivers (Gr. Mühl river, Upper Austria; Gr. Erlauf river, Lower Austria)..

2.1. Research Article 1

PHYSICAL LABORATORY ANALYSES OF INTERGRAVEL FLOW THROUGH BROWN TROUT REDDS (*Salmo trutta f. fario*) IN RESPONSE TO COARSE SAND INFILTRATION

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Abstract

The quality of the intergravel flow within the spawning environment of salmonids and other fishes disposing their eggs into the river bed gravel matrix is an essential abiotic requirement to the survival success of incubated embryos. As one of the most prominently investigated man-made environmental impact in watersheds, the enhanced mobilization of fine sediments (<1mm) and their entry into riverine ecosystems is considered a major cause for the degradation of a variety of biological processes and habitats, including the spawning habitat of salmonid fishes. In catchments draining crystalline bedrock,

however, like the Bohemian Massif in the northern part of Austria, the excessive loading of river channels with sediments coarser and less cohesive than fines (1-10 mm) is a common observation as a consequence of altered catchment landuse. However, far less understanding exists for the mechanism and the possible implications of coarse sand infiltration on the functioning of the intergravel flow in salmonid redds. In order to investigate the intergravel flow hydraulics in response to coarse sand (D_{50} = 2 mm) infiltration through brown trout (*Salmo trutta f. fario*) spawning redds under controlled conditions, a laboratory flume experiment with three successive scenarios was conducted: (1) no infiltration, (2) segmental infiltration and (3) full section infiltration. A more than two times drop in the average intergravel flow velocity was documented from scenario 1 (5.85 $cm.s^{-1}$) to scenario 2 (2.53 $cm.s^{-1}$) and another clear reduction was seen from scenario 2 (2.53 $cm.s^{-1}$) to scenario 3 (1.61 $cm.s^{-1}$). In scenario 3, a clear shortening of the intergravel flow traveling distance was observed. Future considerations regarding the sustainable catchment management of salmonid fisheries should include programs to alleviate not only the excessive entry of fines, but, in the relevant catchments, also the entry of excessive coarse sand into the riverine ecosystem.
Keywords: *intergravel flow, coarse sand, brown trout redd, sand infiltration, clogging;*

Introduction

In riverine ecosystems, habitats are arranged as patches along the river channel which are temporally created and reshaped by hydrological, geomorphological and biological driving forces acting on a hierarchy of spatial scales (Frissel *et al.*, 1986. Townsend, 1989; Jungwirth *et al.*, 2000, Fausch *et al.*, 2002; Ward *et al.*, 2002). On the scale of the catchment, important abiotic driving forces affecting the in-stream habitat configuration include the hydrology in the catchment, channel form and sediment regime (Allan *et al.*, 1997). Within short evolutionary time spans, man-made landuse changes in river catchments have substantially altered the ways in which in-stream habitats are configured by these abiotic driving forces. As a prominent example, the accumulation of fine sediments (<1 mm) in the riverine ecosystem have to be mentioned. Beyond the natural sediment supply resultant erosive land use practices like deforestation, intensive agricultural activities, road construction and gravel mining have led to undesired negative impacts on riverine biota and their habitats (Wood & Armitage, 1997).

As with the habitats of other riverine organisms (e.g. macroinvertebrates), the quality of the spawning habitat of salmonids is notably affected by the excessive accumulation of fine sediments on the riverbed (Chapman, 1988; Sear, 1993; Wood & Armitage, 1997; Soulsby *et al.*, 2001; Sear *et al.*, 2005, 2008; Kemp *et al.*, 2011). As salmonids rely on loose gravel for both, the creation of spawning redds and the incubation of fertilized eggs (Kondolf & Wolman, 1993; Kondolf, 2000), the infiltration of spawning gravel pore spaces with fines can have a twicefold negative impact on the population dynamics of salmonids. On the one hand, the covering of potentially usable spawning grounds with fines over the year may lead to the consolidation of the surface layer and an a priori elimination of otherwise suitable spawning locations (Pulg *et al.*, 2013). On the other hand, embryos incubated within successfully constructed redds may be threatened by fine sediment accumulations within the egg environment during the incubation time (Soulsby *et al.*, 2001; Sear *et al.*, 2005; Zimmermann & Lapointe, 2005; Greig *et al.*, 2007). The major negative impact of fine sediment infiltrating the egg environment is a decline in the intergravel flow through the redds which in turn disconnects incubated embryos from the essential supply with oxygenized water (Zimmerman & Lapointe, 2005, Greig *et al.*, 2007, Sear *et al.*, 2008). In a field study, Greig *et al.* (2007) report a four orders of magnitude reduction in intragravel flow rates within Atlantic salmon redds as a result of fine sediment accumulation.

In addition to reducing the intergravel flow and limiting the oxygen availability in egg pockets, fine sediments may also cause respiratory limitations within the egg pocket by the attachment of clay particles on egg membrane pores and by creating oxygen depletions from the respiration of accumulating organic fines (Sear *et al.*, 2005). To date, literature dealing with the effects of fine sediment infiltration in salmonid spawning habitats has chiefly concentrated on sediment particles <1 mm according to the classical definition of the term 'fine sediment' after Kondolf (2000). However, far less understanding exists for the mechanism and the possible implications of coarse sand (D_{50} = 1 mm-2 mm) infiltration on the intergravel flow hydraulics in salmonid redds (but see Ferreira *et al.*, 2010).

In catchments draining crystalline lithologies as granite and gneiss, like in the rivers of the Bohemian Massif in the landscape of northern Austria (Fig. 1), the weathering of bedrock results in a bimodal grain size distribution where large sediment particles (i.e., boulders, cobbles) and small sediment particles (sands, fine gravel) dominate the substrate composition of the riverbed (Fryirs & Brierley, 2012; Hauer *et al.*, 2011; Hauer, 2014). Here, in the catchments of the Bohemian Massif (Fig. 1), the increased sediment input from finer grain fractions (1-10 mm) over the last decades was exacerbated by the regulation of tributaries and other landuse changes (e.g. afforestation leading to increased soil acidification and weathering of the bedrock) (Hauer, 2014). Moreover, recent findings have established a clear association between the surplus riverbed loading of these mobile sediment fractions and the degradation of erstwhile high quality habitats of single benthic species (e.g. the world wide threatened freshwater pearl mussel *Margaritifera margaritifera*) (Jung *et al.*, 2013; Hauer *et al.*, 2014, Scheder *et al.*, 2014) and whole benthic invertebrate communities (Leitner *et al.*, 2014).

The major aim of this work is to investigate the intergravel flow movement through artificial brown trout (*Salmo trutta f. fario*) redds in a laboratory flume experiment in response to increased levels of infiltrating coarse sand (D_{50}=2mm). This analysis includes the application of a simple yet reliable method of intergravel flow visualization and the derivation of approximated intergravel flow velocities. In order to investigate the free channel flow hydraulics parallel to the intergravel flow hydraulics in the course of the infiltration procedure, repeated flow velocity measurements were made along the channel section. An illustration of the vertical flow structure of the free channel flow under reference conditions (=no infiltration) is presented applying a 2D/3D numeric modelling approach.

Material & Methods

During a period of three weeks (26.01.2015 – 09.02.2014), a flume experiment with artificial brown trout spawning redds was carried out. A tilting laboratory hydraulic flume (Armfield S6 Tilting Flume) with transparent glass side walls and a pump-driven circulation flow was used for the experiment (Fig. 2, for technical data refer to Table 1). The channel section used for the experiment was filled with clean gravel (D_{50}=20.2mm) potentially usable for spawning by brown trout (*Salmo trutta f. fario*) (Kondolf & Wolman, 1993). With the introduced gravel, two form identical spawning redds were constructed in a sequential arrangement. Redd dimensions were taken from a field measurements obtained from the Große Mühl River (Hauer *et al.*, 2014; Unfer *et al.*, 2011). The finalized gravelbed section was divided into seven sub-sections, as illustrated in Fig. 3: Pre-section (0.4m), Pit 1(0.45m), Tail 1(0.95m), Transition zone (0.1m), Pit 2 (0.45m), Tail 2 (0.95m), and a Post-section (0.45m). A constant inflow of 12.0 l/s was set which produced near-bottom flow velocities in the range of 0.2 $m.s^{-1}$ - 0.4 $m.s^{-1}$. This flow velocity range was considered suitable in several studies for the spawning environment of brown trout in rivers (e.g. Louhi *et al.*, 2008; Hauer *et al.*, 2011).

Channel flow velocity measurements

In accordance with the three infiltration scenarios described below, detailed flow velocity measurements of the channel flow were made three times in the course of the experiment under steady state conditions. To this end, flow velocities ($m.s^{-1}$) were recorded along the centerline of the flume with a flow-velocity meter (Höntzsch µP-ASDI®) at constant longitudinal 5cm-intervals (= theoretically, 75 intervals for the entire section). In addition to the detailed monitoring bathymetric high and lows, a 10 cm-measurement interval was deemed sufficient for gravel bed regions with low flow turbulence (i.e., the planar pre- and post regions, and gravel substrate covered with a coarse sand layer.) At each measurement interval, vertical point measurements in 2 cm-intervals were made. Based on the high resolution measuring design, between N=272 (scenario 3) and N=517 (scenario 1) point measurements were made. Other analyses carried out during the experiment were water surface elevation measurements (cm) in 20 cm-intervals along the flume during each scenario and the documentation of the infiltration depth of the coarse sand into the framework gravel of the two redds.

2D/3D-numeric modeling of the free channel flow

The geometric data used for the 3D-numeric model was obtained from tape-measured height measurements of the gravelbed in 2.5 cm longitudinal intervals along the flume (N=150). From these measurements, a grid surface (321x31=9951 nodes) was created for modeling the vertical channel flow hydraulics along the two redds (Fig. 2, Fig. 3). The modeling software used for this investigation was the FaSTMECH (Flow and Sediment Transport with Morphological Evolution of Channels) river flow/riverbed variation analysis solver developed by Dr. Jonathan Nelson. FaSTMECH is a quasi-three dimensional software, also referred to as 2.5D, which means the model solves the vertically averaged equations expressing conservation of mass and momentum, and then uses that solution along with simple vertical structure functions (equation 1) and the streamlines of the vertically averaged flow solution to assign vertical structure along those streamlines (Nelson *et al.,* 2010). The vertically averaged equations of motion expressing conservation of mass and momentum in a curvilinear coordinate system can be written as follows:

$$\frac{1}{1-N}\frac{\partial}{\partial s}(<u>h)-\frac{<v>h}{(1-N)R}+\frac{\partial}{\partial n}(<v>h)=0$$

$$\frac{1}{1-N}\frac{\partial}{\partial s}(<u>^2\ h)+\frac{\partial}{\partial n}(<u><v>h)-\frac{2<u><v>h}{(1-N)R}=-\frac{gh}{1-N}\frac{\partial E}{\partial s}+$$
$$\frac{1}{\rho}\left[\frac{1}{1-N}\frac{\partial}{\partial s}+(<\tau_{ss}>h)+\frac{\partial}{\partial n}(<\tau_{ns}>h)-\frac{2<\tau_{ns}>h}{(1-N)R}\right]+$$
$$\frac{1}{\rho}\left[\frac{1}{1-N}+(\tau_{ss})_B\frac{\partial B}{\partial s}+(\tau_{ns})_B\frac{\partial B}{\partial n}-(\tau_{zs})_B\right]$$

$$\frac{1}{1-N}\frac{\partial}{\partial s}(<u><v>h)+\frac{\partial}{\partial n}(<v>^2\ h)+\frac{(<u>^2-<v>^2)h}{(1-N)R}=-\frac{gh}{1-N}\frac{\partial E}{\partial n}+$$
$$\frac{1}{\rho}\left[\frac{1}{1-N}\frac{\partial}{\partial s}+(<\tau_{ns}>h)+\frac{\partial}{\partial n}(<\tau_{nn}>h)-\frac{<\tau_{ss}-\tau_{nn}>h}{(1-N)R}\right]+$$
$$\frac{1}{\rho}\left[\frac{1}{1-N}(\tau_{ns})_B\frac{\partial B}{\partial s}+(\tau_{nn})_B\frac{\partial B}{\partial n}-(\tau_{zn})_B\right]$$

eq. 1

where < > denotes vertical averaging, u and v are the streamwise and cross-stream components of Reynolds-averaged velocity (m s^{-1}), E is the water surface elevation (m), B is the bed elevation (m), h is the local depth (m), g is the gravitational constant (6.67408×10^{-11} m^3 kg^{-1} s-^{2}), ρ is the fluid density (kg m^{-3}).

The model was calibrated comparing modeled water surface elevations with measured water surface elevations using a range of drag coefficients c_d (0.01-0.04) in test runs. A c_d of 0.017 was set which produced minimal error between modeled and measured water surface elevations. Moreover, the flow velocities have been compared along the central axis in a three-dimensional form (surface, depth-averaged and near bottom velocities. To investigate the channel hydraulics under different flow situations, three discharge scenarios were applied for the modeling runs: 12.0 l.s^{-1}, 6.0l.s^{-1}, and 3.0l.s^{-1}, respectively.

Intergravel flow analysis

The intergravel flow through the tailspills of redd 1 and redd 2 was visualized using an aqueous fluid tracer of potassium permanganate ($KMnO_4$). Based on a concentration of 1g/l, the solution takes on a deep purple color which enables visual analyses of the flow travelling through the redd framework. A syringe with a capacity of 300 ml and an opening diameter of 5 mm as shown in Fig. 4 was applied as injection device. For injections into the gravel substrate through an overlying coarse sand layer, a rubber tube (opening diameter=5mm) was fixed to the front opening of the syringe prior to injecting. Thus, the pipe's movement through the sand layer was possible without structural damage of the sand layer (Fig. 5). Approximately 100 ml of fluid tracer were injected per run.

For each redd and scenario, tracer injections were performed at the rising limb of each redd's tail at three substrate injection levels, as illustrated in Fig. 4 and Fig. 5: At 8 cm, 11 cm and 14 cm, respectively. To obtain representative measurement results (trajectory time) at each respective substrate injection level, measurements were made along three points of the cross-section: to the right (3 cm from right side wall), on the center (15 cm from both side walls) and to the left (3cm from left side wall). To reduce of measuring outliers N=3-5 measurements were made at each injection point. Then the intergravel flow velocities were calculated by timing the passed distance of the moving fluid tracer through the redd between two fixed points (point A: injection point, point B: first outflow point; Fig. 4) The necessary information was obtained from post-hoc analyses of video taped injection runs. The actual traveling distance of the fluid tracer was determined using an orthogonal line starting at the injection point and bending up vertically at the first outflow point, as shown in Fig. 4. The intergravel flow velocity ($m.s^{-1}$) for each substrate injection level was calculated as follows:

$$V_{intergravel\ flow}\ (cm.s^{-1}) = \text{Intergravel flow distance (cm)/ Passed time(s)} \qquad \text{(eq. 2)}$$

In addition to intergravel flow analyses, intergravel flow trajectories from the moving fluid tracer were documented for each substrate injection level (n = 3), redd (n = 2) and scenario (n = 3) to describe the intergravel flow pattern through brown trout redds under reference conditions as well as in response to increasing coarse sand infiltration. The intergravel flow trajectories can be assigned with the calculated intergravel flow velocities as averaged by substrate injection level resulting in lines of equal velocity (=‘isovels’). Isovels were redrawn on scaled diagrams as additional information to the free channel measurments and the intergravel flow velocity measurements.

Coarse sand infiltration scenarios

The infiltration process was initiated by the placement of coarse sand at the upstream end of the section (1 m) and increasing the channel inflow temporarily from 12 $l.s^{-1}$ to 40 $l.s^{-1}$to establish continuous sediment transport. As illustrated in Fig. 5a-c, three scenarios of coarse sand infiltration were applied:

Scenario 1: No coarse sand infilration (reference condition, Fig. 5a):

Scenario 2: Coarse sand infiltration up to the rising limb of Redd 1, no coarse sand infiltration in the remaining section of redd 2 (Fig. 5b)

Scenario 3: Coarse sand infiltration over the full channel section (Fig. 5c)

Statistical analyzes

Significance testing was applied with regard to mean intergravel flow velocity differences (1) between redd 1 and redd 2 within each scenario and (2) independently for redd 1 and redd 2 among the three scenarios. As testing procedure for (1), a Student's t-test for two independent samples was employed after checking for normal distributions using a Shapiro-Wilk normality test (Shapiro & Wilk, 1965) and checking for homogeneity of variances using a Levene's-test (Levene, 1960). In case of inhomogenous variances, a Welch test for two independent samples was applied.

As for (2), a Student's t-test for independent samples was employed after checking for homogeneity of variances as described above. Average intergravel velocities from the three substrate injection levels were pooled by redd. For each redd, a separate before-after significance testing was applied. The tested groups for each redd were *Scenario 1-Scenario 2* and *Scenario 2-Scenario 3*. For all testing procedures, a level of significance of α=0.05 was set.

Results

Channel flow velocity measurements

The results for the channel flow velocity measurements for each scenario are presented in Table 2 and depicted in Fig. 9a-c. A general observation of the flow in the reference situation (scenario 1) was a smooth homogenous flow along the Pre-Section (0-0.4 m) at a depth-averaged flow velocity of 0.23 ms^{-1} (S.D.=0.03, N=29). Sharp flow reductions were seen in pit sections (i.e., Pit 1 and Pit 2) as well as at the lee-sites of the tail sections (i.e., Tail 1 and Tail 2) whereas flow velocity accelerations and water surface drops of ~ 0.4 cm were observed along the rising limbs and crests of Tail 1 and Tail 2. While the measured flow velocities within the Pits and in the lee-sites of the tails were near to zero or zero, flow velocities were at maximum (0.39-0.40 ms^{-1}) above the redd crests of redd 1 and 2 (Fig. 9a).

In Scenario 2, the sand seal covering up redd 1 up to the rising limb of the tail (0 m-1.1 m) had a pronounced effect on the flow velocity distribution in the remaining uninfiltrated channel section (1.1 m-3.75 m) (Fig. 9b). Whereas the average flow velocity in the Pre-Section is slightly higher as in Scenario 1 (Table 2), all downstream subsections show a clear decrease in flow velocity in comparison to Scenario 1. Although flow accelerations are still seen along the rising limbs and above the crests of redd 1 and redd 2, the average flow velocity is reduced by 0.02 ms^{-1} at Tail 1 and by 0.09 ms^{-1} at Tail 2 as compared to the corresponding sections in Scenario 1.

In Scenario 3, the full sand seal along the channel section induced a clear flow acceleration along the whole channel section (Fig. 9c). As pits and falling limbs of the redds were covered with sand, no larger areas with low flow velocities were observed. Clear accelerations were measured at the protruding redd crests, with maximum flow velocities of 0.39 ms^{-1} above the crest of redd 1 and 0.45 ms^{-1} above the crest of redd 2.

2D/3D-numeric modeling of the free channel flow

In Fig. 6a-c, the 2D/3D modeling results of the free channel flow are presented. In all three discharge scenarios, the flow pattern along redd 1 and redd 2 is very similar. Flow velocity accelerations are seen over the tail crests whereas the lowest flow velocities are consistently found in the pit sections and falling limbs of tails. In Fig. 7, the longitudinal profiles of the near-bottom flow velocity (left series), depth-averaged flow velocity (middle series) and near-surface flow velocity (right series) along the centerline of the redds are presented for three modelled discharges. As can be seen in Fig. 7 (from top to bottom), increasing the modelled discharge from 6 $l.s^{-1}$ to 12$l.s^{-1}$ leads to a higher flow velocity acceleration above redd 2 compared to redd 1.

Description of the intergravel movement and intergravel flow distances

Results for the intergravel flow movement through the redds for each scenario and injection level are described below and illustrated in Fig. 9a-c. At the lowest injection level (8cm), the fluid tracer plunges slightly deeper and disperses downstream almost parallel to the channel bed for the first 20-25 cm. For the remaining distance, the tracer trajectory bends upward and its angle becomes increasingly steeper nearing the outflow point (Fig. 9a). In both redds, the outflow point is situated at the falling limb only 0.1 m downstream of the crest. As the tracer exits the tail through the outflow point, it forms a distinct plume in the free-channel flow. At the higher injection levels (11 cm and 14 cm, respectively), the tracer trajectory shortens and becomes increasingly convex (Fig. 9b+c). Outflow points are still found closely behind the redd crest or on the redd crest.

Intergravel flow velocities and coarse sand infiltration

Results for the calculated intergravel flow velocities for each scenario are shown in Fig. 8. Calculated average intergravel flow velocities were highest in scenario 1 (3.1 cms^{-1}- 8.3 cms^{-1}), followed by scenario 2 (1.6 cms^{-1}- 6.6 cms^{-1}) and scenario 3 (0.8 cms^{-1}- 3.2 cms^{-1}). Under reference conditions, there is a steady increase of the intergravel flow velocity from the lowest to the highest injection level (Fig. 8) This tendency is no longer seen in infiltrated redds with (Fig. 8).

Table 4 and Table 5 summarize the results obtained from the significance testing of the intergravel flow velocities based the within-scenario comparison between redd 1 and redd 2 for each given scenario (Table 4) and the among-scenario comparison separately for redd 1 and redd 2 (Table 5).

In scenario 1, the comparisons between the two redds show significantly different average intergravel flow velocities in in two out of three substrate injection levels. Whereas at the highest injection level, average intergravel flow velocities are significantly higher in redd 2, there were significantly lower average intergravel flow velocities in the lowest injection level (8 cm) of redd 2 (Table 4). After the infiltration of redd 1 in scenario 2, there was a highly significant decrease of the average intergravel flow velocity from 5.85 $cm.s^{-1}$ to 2.52 $cm.s^{-1}$. In redd 2, which had remained un-infiltrated in scenario 2, a significant decrease from 5.11 $cm.s^{-1}$ to 4.26 $cm.s^{-1}$ was observed. The infiltration of both redds (scenario 3), redd 2 had significantly lower intergravel flow velocities compared to redd 1 in two out of three injection levels. As for scenario 3, the complete infiltration of both redds led to highly significant declines of intergravel flow velocity from 2.52 $cm.s^{-1}$ to 1.61 $cm.s^{-1}$ in redd 1 and from 4.26 $cm.s^{-1}$ to 1.26 $cm.s^{-1}$ in redd 2.

Discussion

As with other studies dealing with the fluid dynamics within and surrounding salmonid redds (Carling *et al.*, 2006; Tonina & Buffington, 2009; Marchildon *et al.*, 2011), the measurements and modelling results obtained from this investigation confirm the presence of low pressure zones in pit regions and falling limbs of tails where the flow velocity is reduced to near-zero values, and high pressure zones forming above the tail crests where the flow is being accelerated over a certain downstream distance.

The 2D/3D numeric modelling revealed flow characteristics that are in well agreement with the results derived from the flow velocity measurements, confirming the short alteration of low velocity zones and high velocity zones at the corresponding channel segments. Applications of detailed three-dimensional models developed to analyze the hydraulics surrounding salmonid redds are rare in the literature (but see Marchildon *et al*., 2011). However, in comparison to the flow velocity measurements conducted in this study, the 3D numeric modelling approach proved to be a reliable and time-saving way to visualize realistically the hydrodynamics near the surface structure of salmonid redds. However, the model applied in this study suffers from the limitation of being limited to the redd surface, thus not taking into account intergravel flow pathways. Hence, future multi-dimensional numeric modeling applications on the hydraulics of salmonid redds should include ways to analyze surface flows and intergravel flows together, with the greater goal to study hydraulic changes in response to outer pressures on the redd (e.g. successive infiltration of redds with fine sediments).

The narrow transition of low and high pressure zones occuring over bed irregularities and permeable sediment structures such as salmonid redds leads to enhanced convective flows into the porous medium, also referred to as 'downwelling' (Cooper, 1965; Thibodeaux & Boyle, 1987, White, 1990; Elliott, 1991; Harvey & Bencala, 1993; Elliott & Brooks, 1997 a,b; Tonina, 2005; Buffington & Tonina, 2009). Intergravel flow paths documented in this study were more or less parallel to the river bed for a certain distance until bending upward towards a characteristic outflow point situated at the falling limb closely behind the redd crest. Very similar intergravel flow patterns are described in Thibodeaux & Boyle (1987) who focused on the subsurface flow through dunes of fine gravel very similar in shape to redds. The authors identified the upstream horizontal part of the intergravel flow through the porous medium of the dune as dispersion process and the upwards bending portion of the intergravel flow as fluid drag which is induced by the pressure drop starting at the dune's falling limb. The peculiar transport mechanism of the intergravel flow in salmonid redds necessary to deliver sufficient amounts of oxygen to the egg pocket is therefore directly coupled to the pit-tail-morphology.

Marchildon *et al.* (2013) stated that the intergravel flow dynamics must be related to the specific hydrodynamics occurring in the channel. This notion can be corroborated in that intergravel flow velocities assessed in this study were higher at increasing injection levels of the tail's rising limb, i.e., there was an increase of the intergravel flow velocity correspondent to the flow acceleration present at greater heights of the tail's rising limb. Highest intergravel flow velocities were found at the top injection level (14 cm) at a substrate depth of 3 cm. These observations would underline the results of Riedel & Peter (2013), who found mean burial depths of brown trout redds in Alpine rivers to be 3.8 cm. It can be argued that brown trout preferrably chooses to deposit eggs into shallow redd depths as a way to offer optimal intergravel flow conditions to the incubated embryos. However, this assumption should be treated with caution as burial depths in brown trout can vary considerably in different study rivers (Armstrong *et al*., 2003) and may be mostly governed by the size of the spawning fish (Elliott, 1994).

Using an orthogonal line as intergravel flow distance approximation, as done in this study, is likely to underestimate the actual intergravel flow velocity through the porous gravel medium. However, as this method is applied in the whole experiment, the obtained results are comparable between the different coarse sand infiltration scenarios as well as between redd 1 and redd 2.

A significantly higher intergravel flow velocity in the uppermost injection level (14 cm) was found in the downstream positioned redd (redd 2) compared to the upstream positioned redd (redd 1). This finding can be attributed to the flow acceleration over the tail of redd 1 which led to higher flow velocities in the closer upstream extent of redd 2, in turn producing measurably higher intergravel flow velocities in the upper tail portion of redd 2. The successive placement of redds within short inter-redd distances of < 1m by female brown trout from downstream to upstream has been regularly observed at the Gr. Mühl river (Hauer, pers. comm., own observations), and in other field studies (e.g. Essington *et al*., 1998; Youngson *et al*., 2011). Youngson *et al*. (2011) suggested that the observation of cutting linear redd sequences in female brown trout may yield energetic benefits and a reduced risk of body tissue damage when reworking gravels that have already been loosened by preceding spawning females. In addition to these explanations, it is suggested here that linear redd sequences could be beneficial to the survival of the incubated offspring due to modifications of the intergravel flow. As seen in this study, flow velocity accelerations over upstream located redd crests enhanced the intergravel flow velocity significantly in closely downstream positioned redds. This effect can be expected to improve the oxygen delivery into the egg pockets of downstream located redds. However, in validation of this suggestion, field investigations on brown trout redd sequences with incubated eggs, incorporating oxygen measurements, would be needed.

Under full coarse sand infiltration, intergravel flows were reduced up to four times compared to the reference situation. Accompanied with this reduction was a decline of the intergravel flow paths as seen by a farther upstream exit of the injected tracer at the redd crest. As the intergravel flow traveling distances in redd 1 had remained unchanged after infiltrating only the rising limb (scenario 2), it must be assumed that the infiltration of the tail's falling limb was responsible for the reduction of the intergravel flow traveling distance. Hence, a continuous sand seal covering up the pit- and tail structures of the redd induced a decline in the water pressure gradient along the redd to an extent where the function of the intergravel flow became disturbed.

The highest channel flow velocities and the lowest intergravel flow velocities were found in scenario 3. Also, in fully infiltrated redds, there was no more trend of an intergravel flow velocity increase at higher substrate injection levels. This finding suggests that the infiltration with coarse sand led to a complete decoupling of the intergravel flow and the channel flow.

This study has set out to identify and quantify changes of the intergravel flow hydraulics with regard to coarse sand infiltration. However, in terms of estimating the survival risk of incubated embryos within redds infiltrated by coarse sand, field assessments or channel experiments with actual egg insertions and accompanied DO measurements would be required. Although the here reported declines of the intergravel flow velocity induced by coarse sand infiltration are of less magnitude as in studies dealing with fine sediment (<1 mm) (e.g. Greig *et al.*, 2005; 2007), the infiltration of redds with coarse sand may impact salmonid populations on the long run in similar or even worse ways than fine sediments. Possible reasons for this assumption include on the one hand large catchment imputs of coarse sand as seen in the rivers of the Bohemian Massif. On the other hand, sandy sediments, because of their low cohesiveness in comparison to smaller and larger grain sizes (Hjülström, 1935), are readily transported at comparatively low flow velocities and may cover up freshly cut salmonid redds immediately even at relatively low discharges (Hauer, 2015). In addition, sand particles infiltrating the redd framework could strongly reduce the availability of dissolved oxygen in the egg pocket due to respiratory activities of microbial biofilms attaching to the grain surfaces (Hoffmann & Scoppettone, 1988). Another not to be underestimated danger to the incubated salmonid offspring emanating from the infiltration of coarser sediment particles is the blockage of connected pore spaces used for emerging fry (e.g. Sternecker & Geist, 2010).

Conclusion and outlook

This study investigated intergravel hydraulics in brown trout redds in response to increased coarse sand infiltration. A clear decoupling of the intergravel flow from the channel flow was documented after the infiltration and covering of all redd structures with coarse sand. In the catchments draining granite lithologies, such the Bohemian Massif in northern Austria, river ecosystems are threatened by the increased sediment surplus into rivers with mobile bed forms even under low flow condions, often covering up freshly cut brown trout redds completely during autumn and winter. Taking possible natural changes as well as man-made land use modifications in the catchment into account which have already degradated riverine habitats of different freshwater species, future management options are to be addressed towards minimizing the long-term entry of excessive coarse sand into the river channels of the catchments of the Bohemian Massif and related catchments worldwide. Examples for mitigating coarse sand overfeeding in catchments of concern may include the rehabilitation of regulated tributary systems to restore natural sediment dynamics; the removal of cultivated plant species that have caused increased bedrock erosion from soil acidification (e.g. pine tree monocultures) following the replacement with plant species occurring naturally in the catchment; the establishment of riparian vegetation used as sediment buffer strips along deforested river courses; or the periodic mechanical removal of sediment material from areas of increased accumulation in the river (e.g. dredging out impoundments).

In approaching the coarse sand problem with feasible mitigation measures, detailed studies on the biotic response of (spawning) habitat restoration measures are needed.

References

Allan, J., & Johnson, L. 1997. Catchment ‐ scale analysis of aquatic ecosystems. Freshwater Biology, 37(1), 107-111.

Armstrong, J. D., Kemp, P. S., Kennedy, G. J. A., Ladle, M., & Milner, N. J. (2003). Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries research, 62(2), 143-170.

Carling, P. A., Whitcombe, L., Benson, I. A., Hankin, B. G., & Radecki-Pawlik, A. M. 2006. A new method to determine interstitial flow patterns in flume studies of sub-aqueous gravel bedforms such as fish nests. River Research and Applications, 22(6), 691-701.

Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society, 117(1), 1-21.

Cooper, A. C. 1965. The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin (p. 71). New Westminster, BC: International Pacific Salmon Fisheries Commission.

Elliott, A. H. 1991. Transfer of solutes into and out of streambeds (Doctoral dissertation, California Institute of Technology).

Elliott, J. M. 1984. Numerical changes and population regulation in young migratory trout Salmo trutta in a Lake District stream, 1966-83. The Journal of Animal Ecology, 327-350.

Elliott, J. M. 1994. Quantitative ecology and the brown trout (Vol. 7). Oxford: Oxford University Press.

Essington, T. E., Sorensen, P. W. & Paron, D. G. (1998). High rate of redd superimposition by brook trout (Salvelinus fontinalis) and brown trout (Salmo trutta) in a Minnesota stream cannot be explained by habitat availability alone. Canadian Journal of Fisheries and Aquatic Sciences 55, 2310–2316. doi: 10.1139/cjfas-55-10-2310

Fausch, K. D., Torgersen, C. E., Baxter, C. V., & Li, H. W. 2002. Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes A Continuous View of the River is Needed to Understand How Processes Interacting among Scales Set the Context for Stream Fishes and Their Habitat. BioScience, 52(6), 483-498.

Ferreira, R. M., Ferreira, L. M., Ricardo, A. M., & Franca, M. J. 2010. Impacts of sand transport on flow variables and dissolved oxygen in gravel-bed streams suitable for salmonid spawning. River research and applications,26(4), 414-438.

Frissell, C. A., Liss, W. J., Warren, C. E., & Hurley, M. D. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental management, 10(2), 199-214.

Fryirs, K. A., & Brierley, G. J. 2012. Geomorphic analysis of river systems: an approach to reading the landscape. John Wiley & Sons.

Greig, S. M., Sear, D. A., & Carling, P. A. 2005. The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. Science of the Total Environment, 344(1), 241-258.

Greig, S., Sear, D., & Carling, P. 2007. A field-based assessment of oxygen supply to incubating Atlantic salmon (Salmo salar) embryos. Hydrological processes, 21(22), 3087-3100.

Harvey, J. W., & Bencala, K. E. 1993. The effect of streambed topography on surface-subsurface water exchange in mountain catchments. Water Resources Research, 29(1), 89-98.

Hassan, M. A., Petticrew, E. L., Montgomery, D. R., Gottesfeld, A. S., & Rex, J. F. 2011. Salmon as biogeomorphic agents in gravel bed rivers: the effect of fish on sediment mobility and spawning habitat. Stream Restoration in Dynamic Fluvial Systems, 337-352.

Hauer, C. 2014. Review of hydro-morphological management criteria on a river basin scale for preservation and restoration of freshwater pearl mussel habitats. Limnologica-Ecology and Management of Inland Waters.

Hauer, C., Unfer, G., Tritthart, M., & Habersack, H. 2011. Effects of stream channel morphology, transport processes and effective discharge on salmonid spawning habitats. Earth Surface Processes and Landforms, 36(5), 672-685.

Hjülström, F., 1935. The morphological activity of rivers as illustrated by river Fyris.Bulletin of Geological Institute, pp. 25.

Hoffman, R. J., & Scoppettone, G. 1988. Effect of water quality on survival of Lahontan cutthroat trout eggs in the Truckee River, west-central Nevada and eastern California. US Geological Survey water-supply paper (USA).

Jung, M., Scheder, C., Gumpinger, C., & Waringer, J. 2013. Habitat traits, population structure and host specificity of the freshwater pearl mussel Margaritifera margaritifera in the Waldaist River (Upper Austria). Biologia, 68(5), 922-931.

Jungwirth, M., Muhar, S., & Schmutz, S. 2000. Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept (pp. 85-97). Springer Netherlands.

Kemp, P. (Ed.). 2011. Salmonid fisheries: freshwater habitat management. John Wiley & Sons.

Kemp, P., Sear, D., Collins, A., Naden, P., & Jones, I. 2011. The impacts of fine sediment on riverine fish. Hydrological Processes, 25(11), 1800-1821.

Kondolf, G. M. 2000. Assessing salmonid spawning gravel quality.Transactions of the American Fisheries Society, 129(1), 262-281.

Kondolf, G. M., & Wolman, M. G. 1993. The sizes of salmonid spawning gravels. Water Resources Research, 29(7), 2275-2285.

Leitner, P., Hauer, C., Ofenböck, T., Pletterbauer, F., Schmidt-Kloiber, A., & Graf, W. 2014. Fine sediment deposition and the consequences for macroinvertebrate communities in the pearl mussel river Waldaist (Austria) considering possible impacts of long term changes in land-use and runoff.Limnologica.

Levene, H. 1960. Robust tests for equality of variances1. Contributions to probability and statistics: Essays in honor of Harold Hotelling, 2, 278-292.

Louhi, P., Mäki-Petäys, A., & Erkinaro, J. (2008). Spawning habitat of Atlantic salmon and brown trout: general criteria and intragravel factors. River Research and Applications, 24(3), 330-339.

Marchildon, M. A., Annable, W. K., Imhof, J. G., & Power, M. 2011. A high‐resolution hydrodynamic investigation of brown trout (Salmo trutta) and rainbow trout (Oncorhynchus mykiss) redds. River Research and Applications, 27(3), 345-359.

Nelson, J. M., Shimizu, Y., Takebayashi, H., & McDonald, R. R. 2010. The international river interface cooperative: public domain software for river modeling. In 2nd Joint Federal Interagency Conference, Las Vegas, June(Vol. 27).

Pulg, U., Barlaup, B. T., Sternecker, K., Trepl, L., & Unfer, G. 2013. Restoration of spawning habitats of brown trout (Salmo trutta) in a regulated chalk stream. River Research and Applications, 29(2), 172-182.

Riedl, C., & Peter, A. 2013. Timing of brown trout spawning in Alpine rivers with special consideration of egg burial depth. Ecology of Freshwater Fish,22(3), 384-397.

Scheder, C., Lerchegger, B., Flödl, P., Csar, D., Gumpinger, C., & Hauer, C. 2014. River bed stability versus clogged interstitial: Depth-dependent accumulation of substances in freshwater pearl mussel (Margaritifera margaritifera L.) habitats in Austrian streams as a function of hydromorphological parameters. Limnologica-Ecology and Management of Inland Waters.

Sear, D. A. 1993. Fine sediment infiltration into gravel spawning beds within a regulated river experiencing floods: ecological implications for salmonids.Regulated Rivers: Research & Management, 8(4), 373-390.

Sear, D. S., Frostick, L. B., Rollinson, G., & Lisle, T. E. 2008. The significance and mechanics of fine-sediment infiltration and accumulation in gravel spawning beds. In American Fisheries Society Symposium (Vol. 65, pp. 000-000).

Shapiro, S. S., & Wilk, M. B. 1965. An analysis of variance test for normality (complete samples). Biometrika, 591-611.

Soulsby, C., Youngson, A. F., Moir, H. J., & Malcolm, I. A. 2001. Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. Science of the Total Environment, 265(1), 295-307.

Sternecker, K., & Geist, J. 2010. The effects of stream substratum composition on the emergence of salmonid fry. Ecology of Freshwater Fish,19(4), 537-544.

Thibodeaux, L. J., & Boyle, J. D. 1987. Bedform-generated convective transport in bottom sediment. Nature, 325, 341-343.

Tonina, D. 2005. Interaction between river morphology and intra-gravel flow paths within the hyporheic zone (Doctoral dissertation, University of Idaho).

Tonina, D., & Buffington, J. M. 2009. A three-dimensional model for analyzing the effects of salmon redds on hyporheic exchange and egg pocket habitat. Canadian Journal of Fisheries and Aquatic Sciences, 66(12), 2157-2173.

Townsend, C. R. 1989. The patch dynamics concept of stream community ecology. Journal of the North American Benthological Society, 36-50.

Ward, J. V., Tockner, K., Arscott, D. B., & Claret, C. 2002. Riverine landscape diversity. Freshwater Biology, 47(4), 517-539.

Wood, P. J., & Armitage, P. D. 1997. Biological effects of fine sediment in the lotic environment. Environmental management, 21(2), 203-217.

Youngson, A. F., Piertney, S. B., Thorley, J. L., Malcolm, I. A., & Soulsby, C., 2011. Spatial association of nest construction by brown trout Salmo trutta.Journal of fish biology, 78(3), 713-725.

Figure captions

Figure 1. Map of Austria showing the geological formation of the Bohemian Massif (black) and the Danube river (grey)

Figure 2. Setup of the flume section used for the experiment. Dimensions are given in meters (m).

Figure 3. Cross-sectional drawing of the channel section used for the experiment. The y-axis delimits the elevation (cm) of the substrate (hatched line) and the water level (solid line). The x-axis delimits the channel stationing (m) from upstream to downstream (=left to right).

Figure 4. Illustration of the intergravel flow measurements. Red dashed lines frame the actual pathway of the $KMNO_4$-solution through the tail of the redd at the 8 cm-substrate injection level. The blue solid orthogonal line delineates the approximated intergravel flow traveling distance between the injection point (A) and the first outflow point (B) to be used for the intergravel flow calculation.

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Figure 6. Shown are the results obtained from the 3D numerical modeling for (a) 3l/s, (b) 6l/s, (c) 12l/s. The upper left inset represents the 2D-modeling result with corresponding depth-averaged flow velocities ($m.s^{-1}$). The large lower picture shows the 3D-modeling result with corresponding point flow velocities ($m.s^{-1}$).

Figure 7. Serial diagrams of the modeled longitudinal flow velocity distribution along the centerline of the flume section. Top, middle and bottom horizontal series correspond to a modeled discharge of 3 l/s, 6 l/s, and 12 l/s, respectively. Left, middle and right vertical series correspond to near-bottom, depth-averaged, and surface flow velocities, respectively.

Figure 8. Box-plot diagram of the calculated intergravel flow velocities ($cm.s^{-1}$) in the three scenarios. Panels from left to right refer to scenario 1, scenario 2 and scenario 3. Intergravel flow velocities from the three cross sectional injections (left, middle, right) were pooled for each referring injection level. One box comprises 50% of measurements at a given substrate injection level. The upper and lower "hinges" of the box correspond to the first and third quartiles (the 25th and 75th percentiles). The upper whisker extends from the hinge to the highest value that is within 1.5 *IQR (inter-quartile range, distance between the first and third quartiles). The lower whisker extends from the hinge to the lowest value within 1.5 * IQR of the hinge. Data beyond the end of the whiskers are outliers and plotted as white circles.

Figure 9. Cross-sectional diagrams of the channel experiment showing channel flow velocity characteristics and intergravel flow measurement results for (a) Scenario 1, (b) Scenario 2, (c) Scenario 3. The y-axis on the lower diagram of each scenario delimits the elevation of the water level and substrate level (cm). The corresponding x-axis refers to the stationing from upsteam (left) to downstream (right) in meters (m). Flow velocity measurements ($m.s^{-1}$) are displayed as coloured upright rectangle where a 5 cm - measurement interval along the channel corresponds to

two adjacent squares. Documented intergravel flow trajectories for each substrate injection level and their corresponding intergravel flow velocities ($cm.s^{-1}$) for the right side wall are delineated as black lines and corresponding numbers atop of the lines. The histograms shown on the top of the diagram show the flow velocity distribution at a given pit- or tail segment in 0.05 $cm.s^{-1}$ velocity classes.

Table captions

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Table 2. Channel flow velocity measurement results. Compared are the number of measurements (N), mean flow velocity ($\bar{x}$) in m.s-1, and the standard deviation around the mean flow velocity (S.D.) for each scenario.

Table 3. Measured intergravel flow traveling distances (cm) for each redd, injection level, orientation and scenario.

Table 4. T-test comparison table of the mean intergravel flow velocities $\bar{x}$ ($cm.s^{-1}$) between redd 1 and redd 2 for each scenario and injection level (8cm, 11 cm, 14 cm). $\bar{x}$= mean intergravel flow velocity, Hyp.=Alternative hypothesis (smaller or larger than…), t= t-statistics result, df= degrees of freedom, p= significance.

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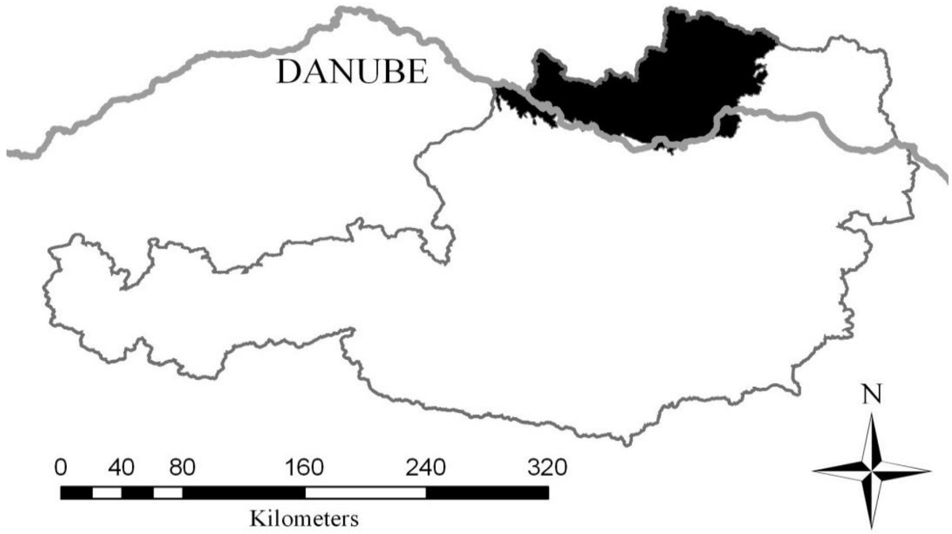

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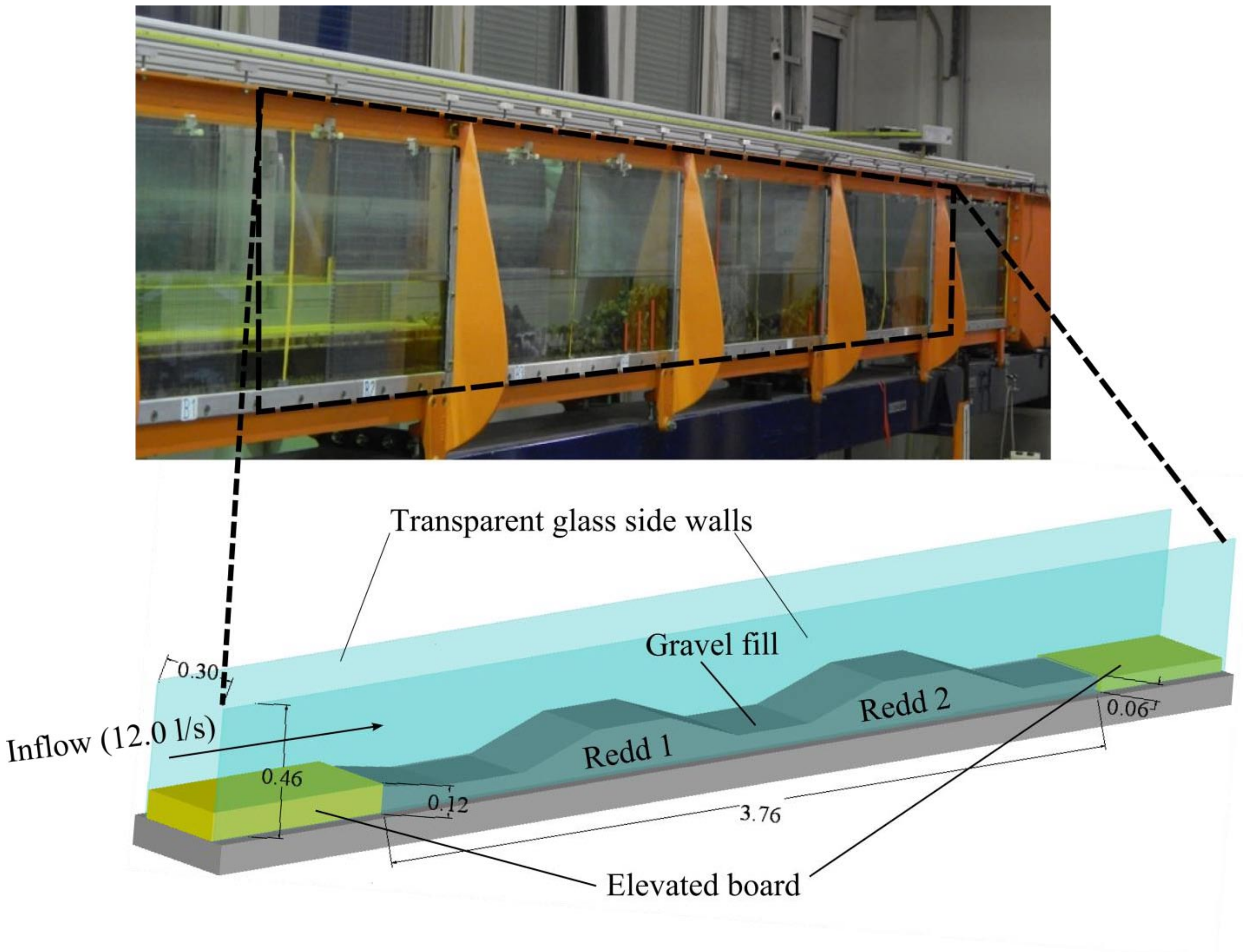

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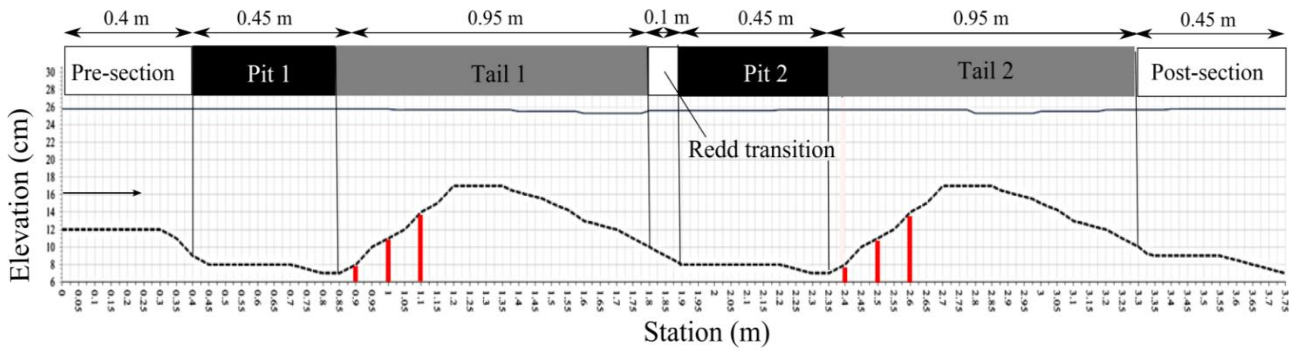

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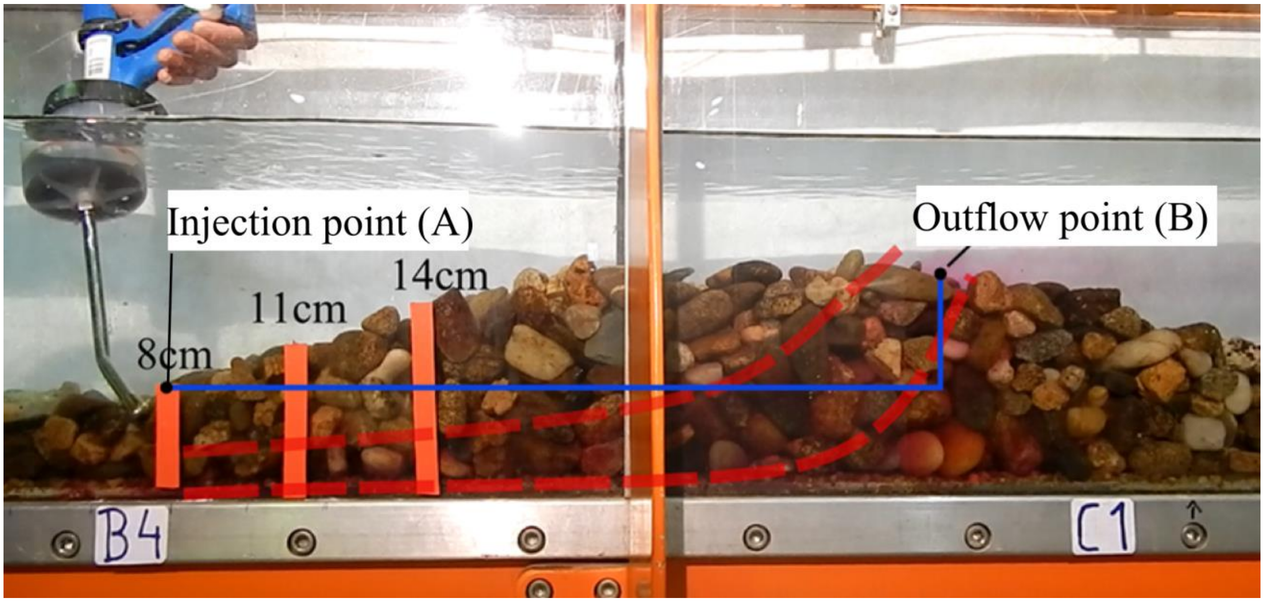

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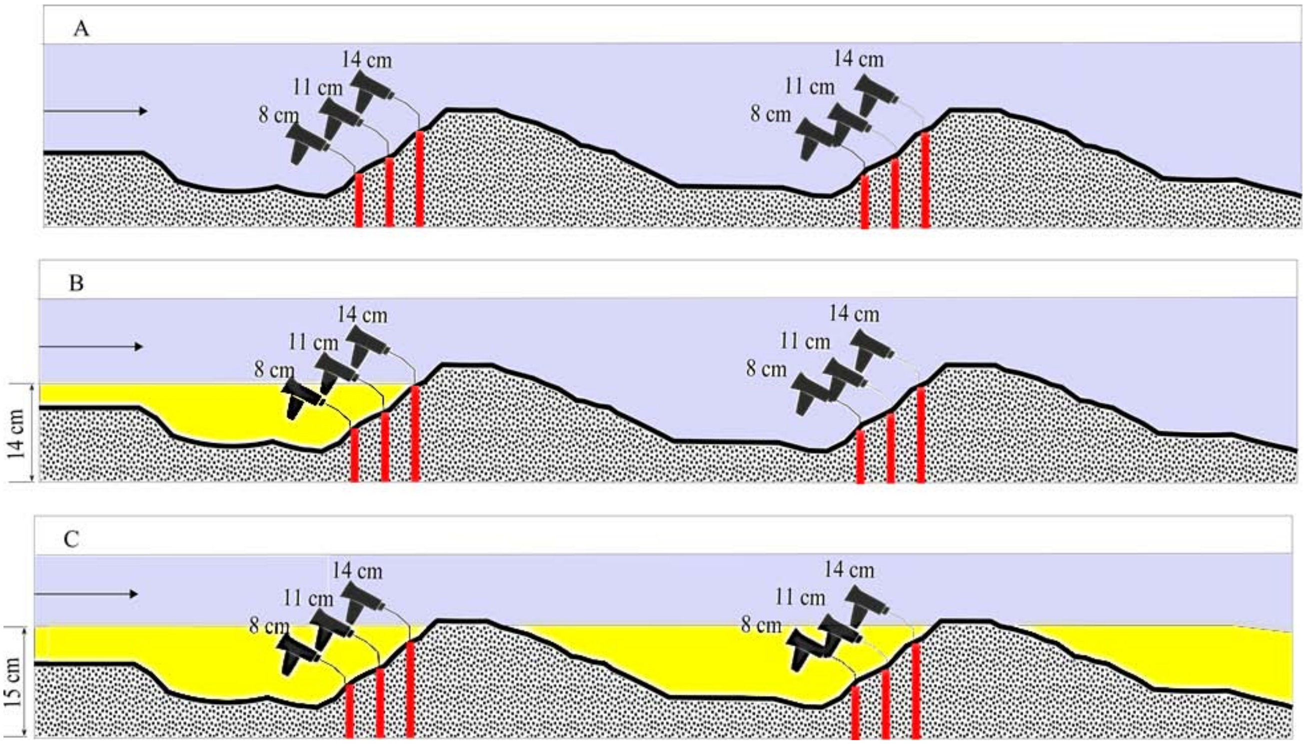

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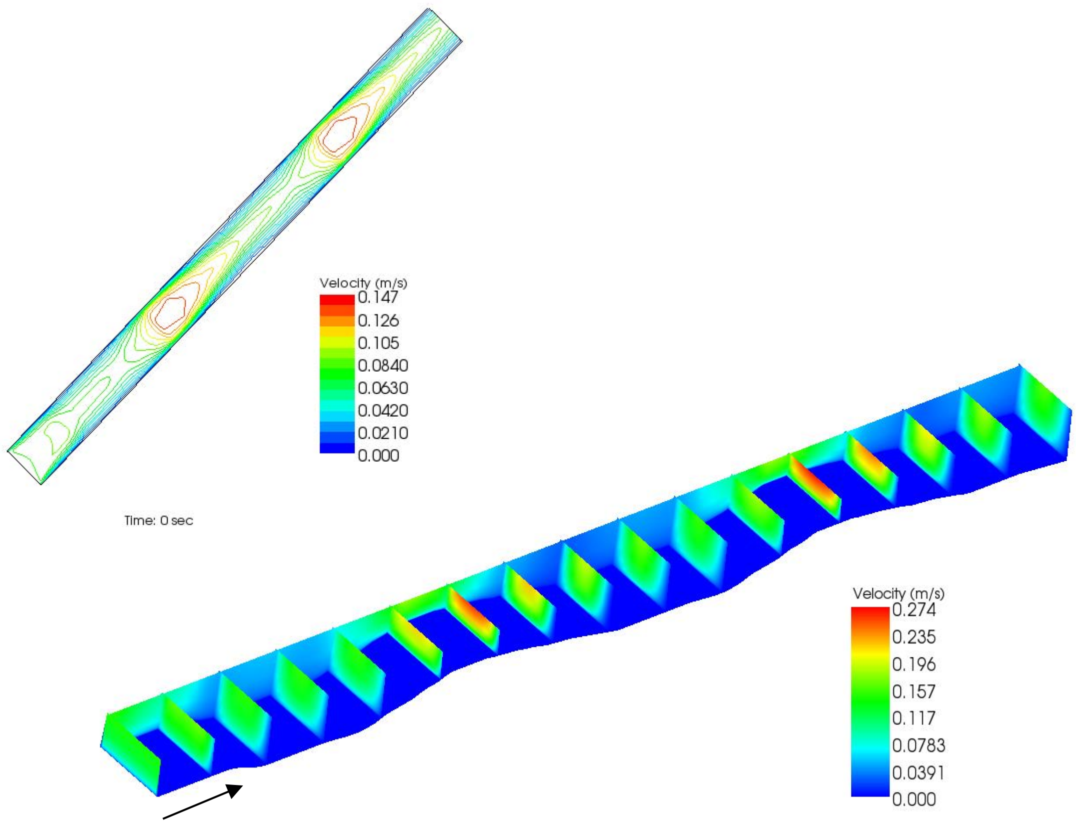
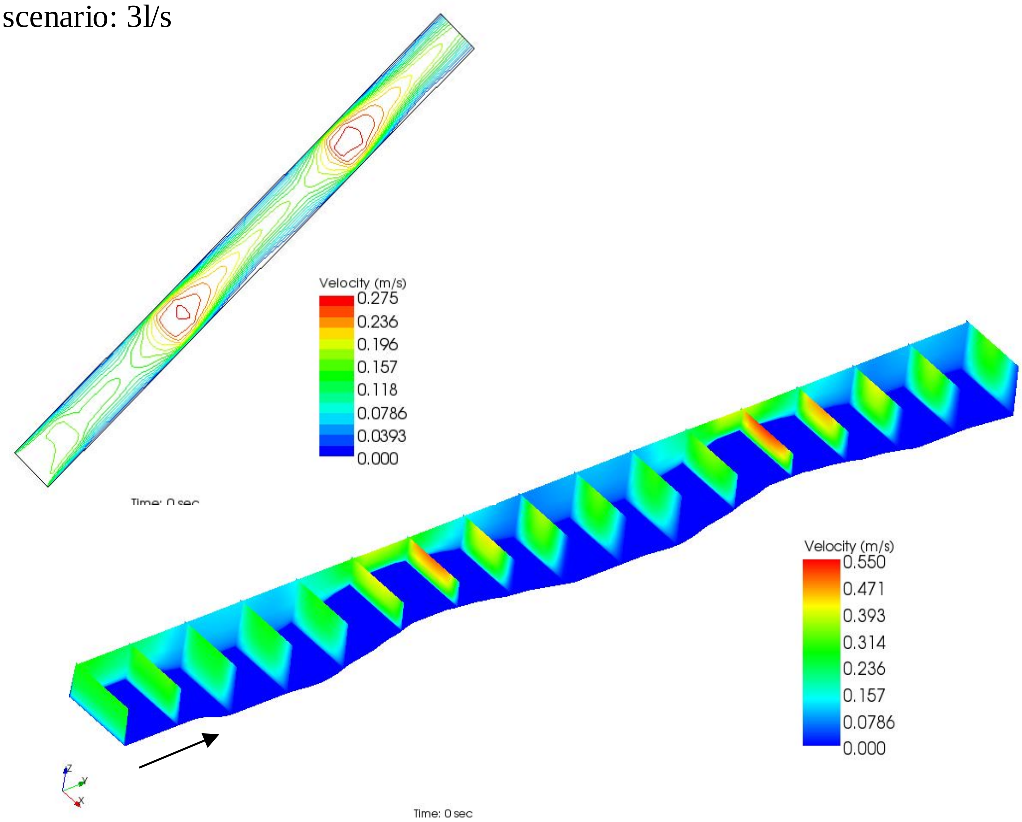
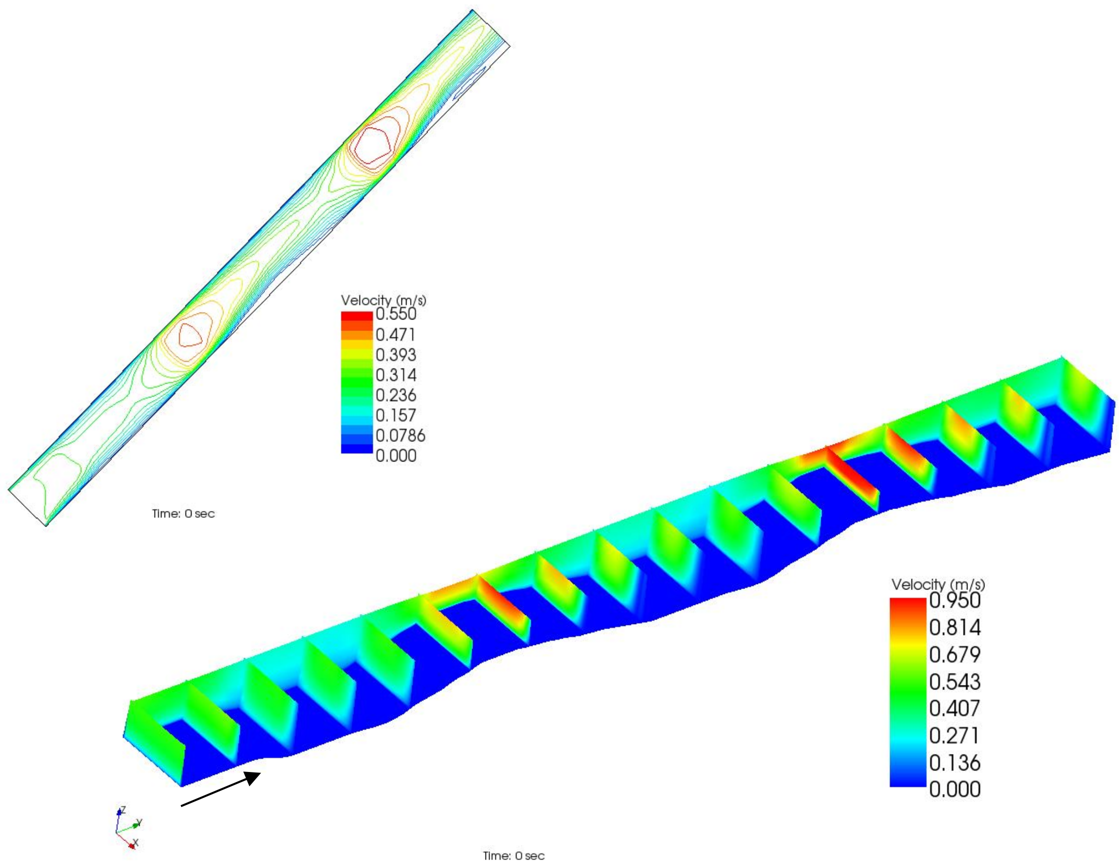


(a) Modeling scenario: 3l/s



(b) Modeling scenario: 6l/s



(c) Modeling scenario: 12l/s

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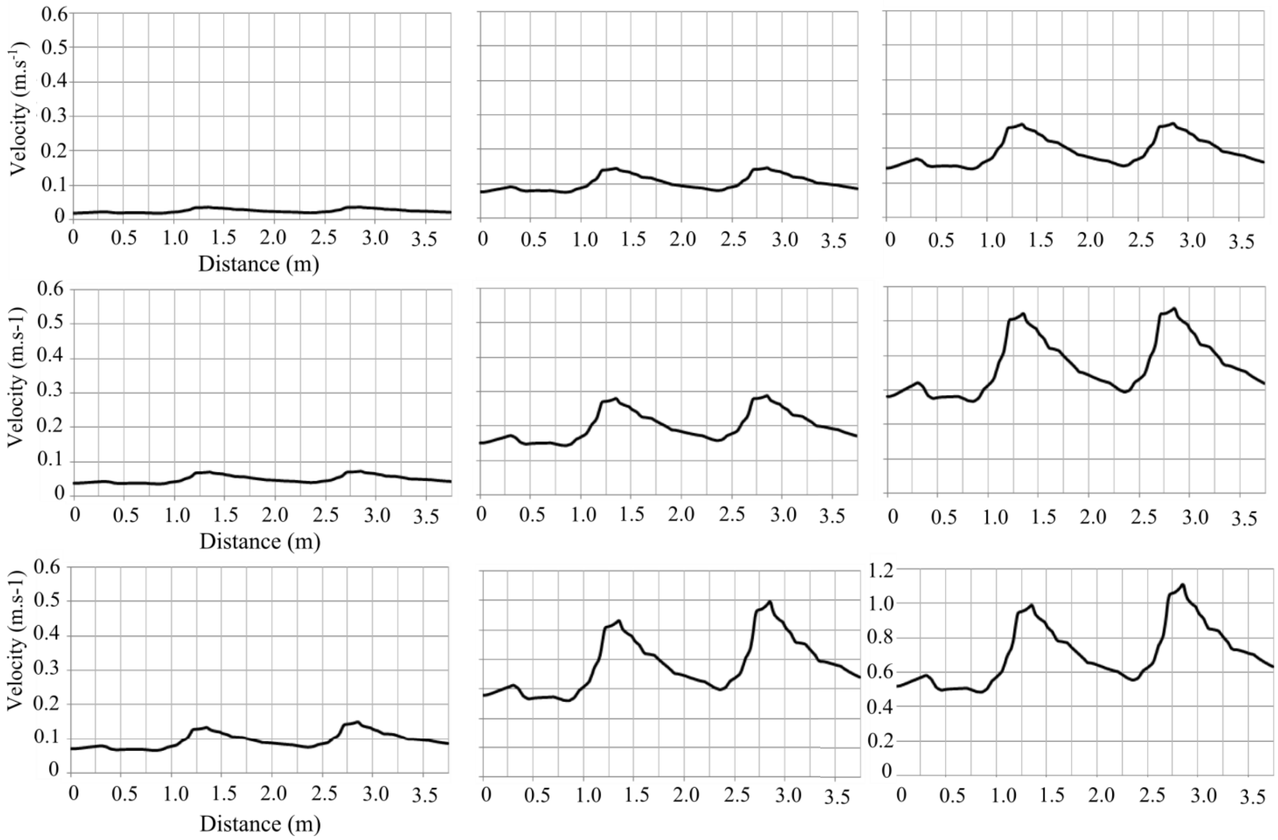

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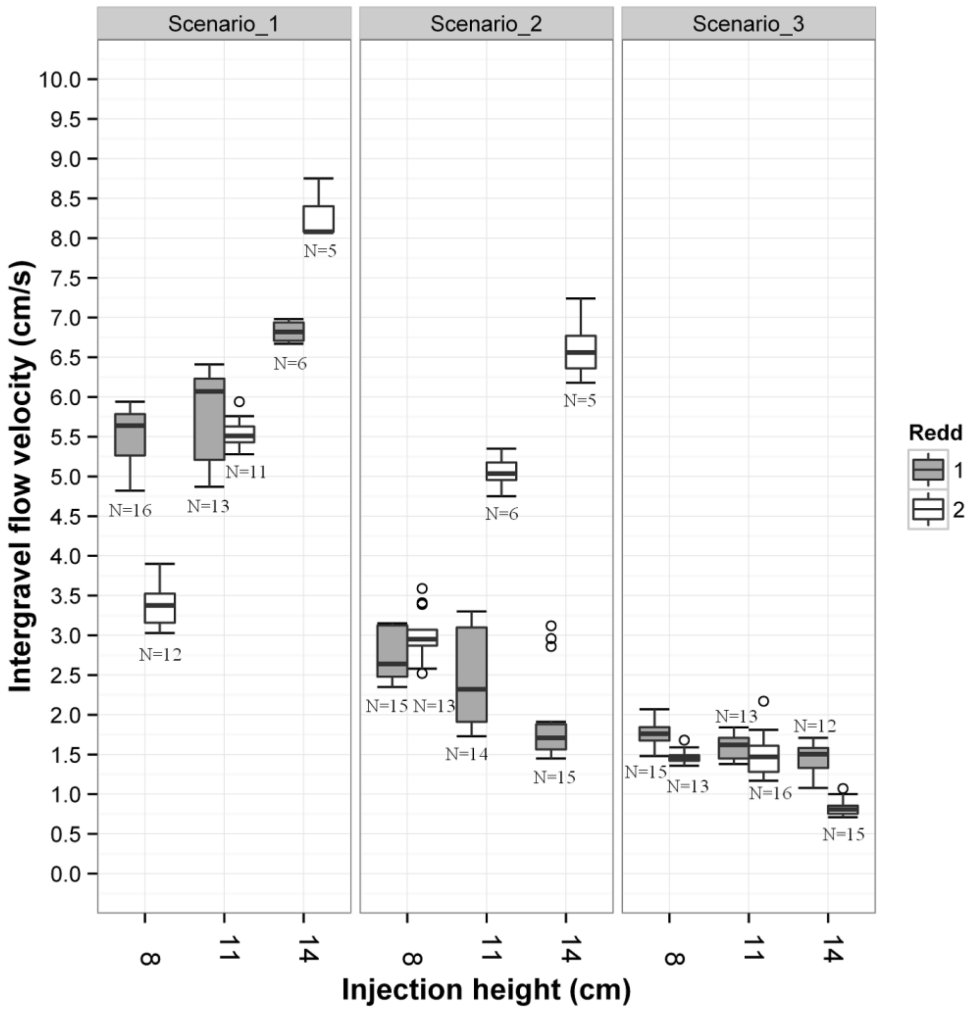

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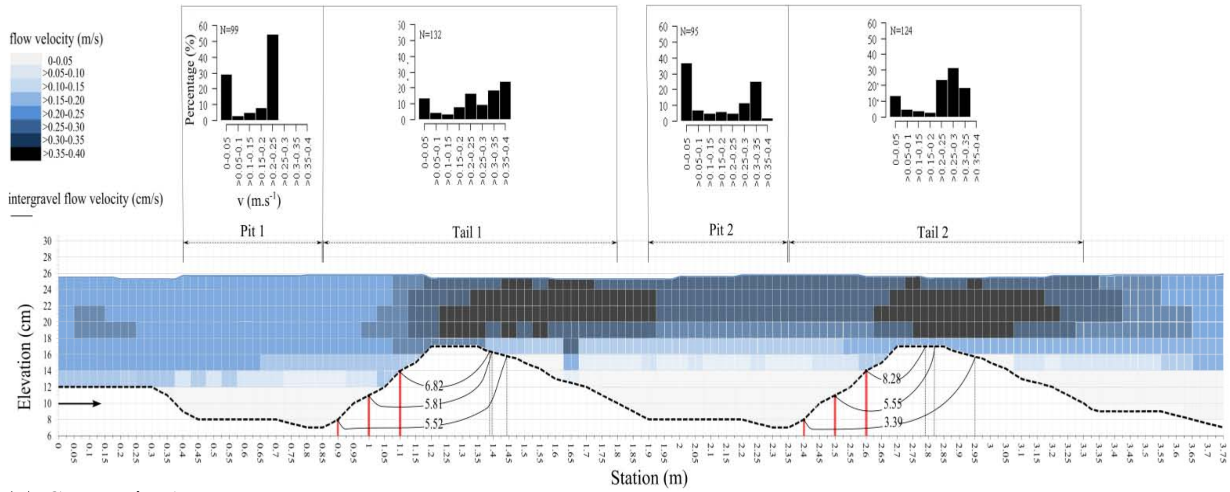
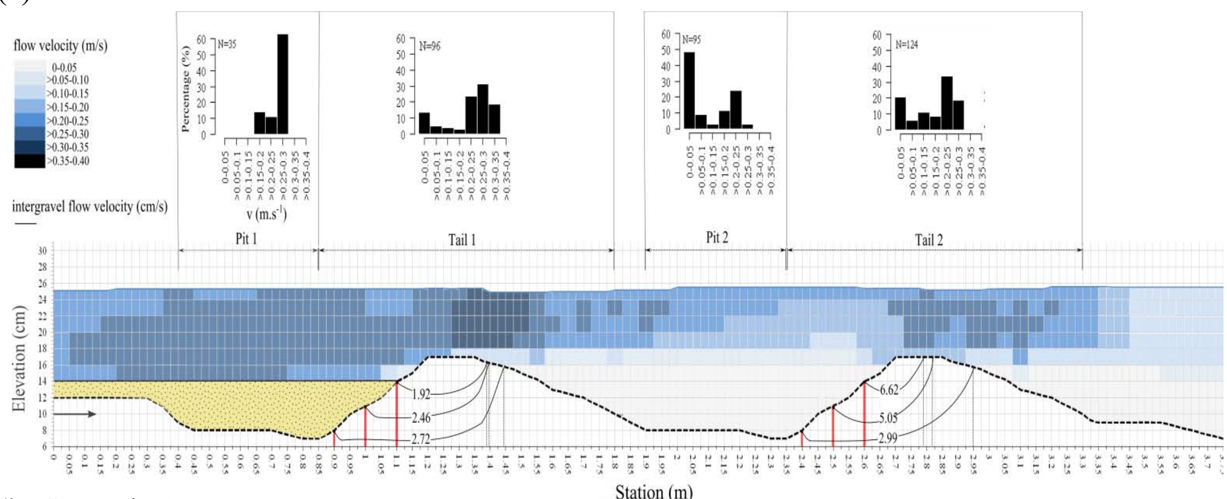
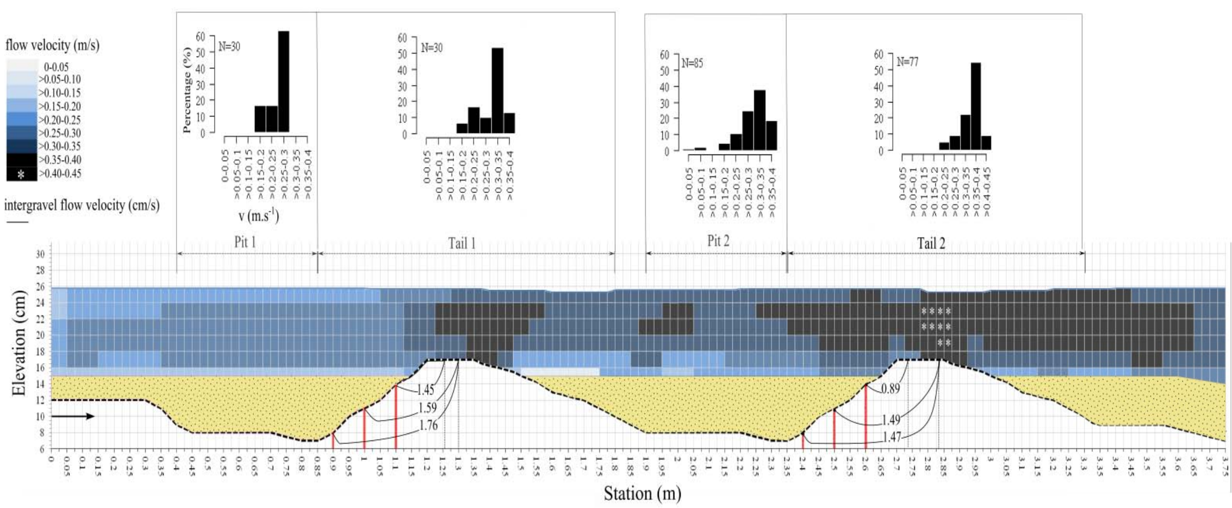


(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

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Table 1. Physical characteristics of the channel section, channel hydraulics, substrate characteristics and redd dimensions used for the experiment.

Channel section	
Total length (m)	3.75
Height (m)	0.46
Inner width (m)	0.30
Outer width (m)	0.31
Flume slope (‰)	3.00
Flume hydraulics	
Discharge (l/s)	12.00
Average flow velocity (m/s)	0.21 ± 0.13
Average water surface elevation (cm)	25.5 ± 0.21
Substrate characteristics	
Spawning gravel diameter (D_{50}, mm)	20.20
Coarse sand diameter (D_{50}, mm)	2.00
Redd dimensions	
Total redd length (m)	1.40
Pit length (m)	0.45
Tail length (m)	0.95
Average pit depth (cm) ± S.D. (cm)	4.16 ± 0.54
Average tail height (m) ± S.D. (cm)	13.20 ± ± 2.32

Table 2. Channel flow velocity measurement results. Compared are the number of measurements (N), mean flow velocity ($\bar{x}$) in m.s^{-1}, and the standard deviation around the mean flow velocity (S.D.) for each scenario.

	Scenario 1			**Scenario 2**			**Scenario 3**		
Subsection (m)	N	$\bar{x}$ (m.s^{-1})	S.D.	N	$\bar{x}$ (m.s^{-1})	S.D.	N	$\bar{x}$ (m.s^{-1})	S.D.
Pre-section (0-0.4)	29	0.23	0.03	28	0.25	0.03	24	0.24	0.02
Pit_Redd1 (0.4-0.85)	99	0.15	0.10	30	0.26	0.04	30	0.25	0.03
Tail_Redd1(0.85-1.8)	132	0.24	0.13	96	0.22	0.11	85	0.30	0.07
Pit_Redd2 (1.8-2.35)	95	0.16	0.13	95	0.10	0.10	30	0.31	0.05
Tail_Redd2 (2.35-3.3)	124	0.26	0.13	124	0.17	0.10	78	0.36	0.05
Post-section (3.3-3.75).	37	0.18	0.11	37	0.09	0.07	25	0.34	0.06
Σ/ Overall $\bar{x}$/ Mean S.D.	517	0.21	0.10	415	0.18	0.07	272	0.30	0.05

Table 3. Measured intergravel flow traveling distances (cm) for each redd, injection level, orientation and scenario.

	Redd 1			**Redd 2**		
	Scenario			**Scenario**		
Injection level	1	2	3	1	2	3
8						
Right	61.75	61.75	49	62.75	62.75	52
Middle	61.75	61.75	49	62.75	62.75	47
Left	53	53	51	55.5	55.5	49
11						
Right	44.25	44.25	36	38	38	39
Middle	42.5	42.5	34	38	38	34
Left	37	37	32	38	38	33
14						
Right	30	30	19	21	21	16
Middle	30	30	19	21	21	16
Left	30	30	21	21	21	16

Table 4. T-test comparison table of the mean intergravel flow velocities $\bar{x}$ $(cm.s^{-1})$ between redd 1 and redd 2 for each scenario and injection level (8cm, 11 cm, 14 cm). $\bar{x}$= mean intergravel flow velocity, Hyp.=Alternative hypothesis (smaller or larger than…), t= t-statistics result, df= degrees of freedom, p= significance.

Injection level	**$\bar{x}$ (Redd 1)**	**Hyp.**	**$\bar{x}$ (Redd 2)**	**t**	**df**	**p**
Scenario 1						
8	5.52	>	3.39	16.70	26	**<0.001**
11	5.81	>	5.55	1.48	22	0.08
14	6.82	<	8.27	-10.73	9	**<0.001**
Scenario 2						
8	2.72	<	2.99	-2.19	26	**0.02**
11	2.46	<	5.05	-10.38	18	**<0.001**
14	2.40	<	6.62	-22.13	18	**<0.001**
Scenario 3						
8	1.47	<	5.47	5.47	26	**<0.001**
11	1.59	<	1.50	1.16	27	0.13
14	1.45	>	0.83	11.07	25	**<0.001**

Table 5. T-test comparison table of the mean intergravel flow velocities $\bar{x}$ ($cm.s^{-1}$) between scenarios 1 and 2 and scenarios 2 and 3 for each redd. $\bar{x}$= mean intergravel flow velocity, Hyp.=Alternative hypothesis (smaller or larger than…), t= t-statistics result, df= degrees of freedom, p= significance.

Redd 1					
x (Scenario 1)	Hyp.	$\bar{x}$ (Scenario 2)	df	t	p
5.85	>	2.52	77	27.66	<**0.001**
x (Scenario 2)	Hyp.	$\bar{x}$ (Scenario 3)	df	t	p
2.53	>	1.61	62.875	12.09	<**0.001**
Redd 2					
x (Scenario 1)	Hyp.	$\bar{x}$ (Scenario 2)	df	t	p
5.11	>	4.26	50	1.79	0.04
x (Scenario 2)	Hyp.	$\bar{x}$ (Scenario 3)	df	t	p
4.26	>	1.26	24.357	9.39	<**0.001**

2.2. Research Article 2

ABIOTIC CHARACTERIZATION OF BROWN TROUT (*Salmo trutta f. fario*) AND RAINBOW TROUT (*Oncorhynchus mykiss*) SPAWNING REDDS IN AUSTRIAN RIVER SECTIONS AFFECTED BY SMALL HYDROPOWER PLANTS

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Abstract

Salmonid rivers in Austria are considerably regulated by small hydropower facilities resulting in potential declines of the spawning habitats of salmonids. To assess the restrictions and possible quality of hydropower influenced river sections for salmonid spawning beside the well studied migration aspects, redd densities of brown trout and rainbow trout were monitored in two study rivers in 2014 and 2015. Based on the monitoring results, opportunities for spawning habitat enhancement of salmonid fishes in river sections regulated by small hydropower facilities are discussed.

Introduction

The spawning habitat of fishes is considered as the most critical bottleneck factor in the success or failure of a population (Schiemer *et al.*, 2002), as fishes are most vulnerable to environmental impacts during their earliest life stages (Kamler *et al.*, 1992; Elliott, 1994). From an abiotic perspective the spawning habitat selection of salmonids is understood as the response behaviour of a spawning female which favorizes potential spawning sites according to specific hydrological, sedimentological and river-morphological characteristics (Crisp, 1993, Armstrong *et al.*, 2003). The abiotic spawning criteria considered to be most important for salmonids are sufficient water depths, favorable flow velocity ranges and the local availability of high quality (i.e., low in fine sediment) spawning gravel for redd construction (Kondolf & Wolman, 1993; Crisp, 1993; Armstrong et al., 2003). Besides these primary abiotic requirements, salmonids are known to prioritize sites for spawning that are close to bed irregularities and structural elements on the riverbed (e.g. logjams, aquatic vegetation, boulders) (Witzel & MacCrimmon, 1983). Moreover, additional benefits for salmonids spawning near instream structures may include the visual protection from predators, the provision of resting areas during the exhausting spawning procedure (e.g. pools created by deadwood or boulders), or the local accumulation of spawning gravel as a consequence of the change in the flow hydrodynamics induced by the instream structures (Bjornn & Reiser, 1991, Newson *et al.*, 2004).

However, river engineering practices that involve the damming of a river section may alter many abiotic components in riverine ecosystems, especially with regard to hydrological and sedimentological processes (e.g. Poff *et al.*, 1997). In Austria, on of the most common types of transversal obstruction is the establishment of hydropower facilities. Hydropower can be regarded the backbone of the Austrian energy market, with approximately 65.7 % of the national energy generation coming from hydropower plants (Wagner et al., 2015). More than 5200 facilities are currently in operation in the rivers of Austria: The largest share is made up of small hydropower facilities (<10 MW working capacity) dominated by diversion systems in small-to-medium sized rivers (Wagner *et al*, 2015). In numerous Austrian salmonid rivers, diversion hydropower facilities are often aggregated in chains along the main river course resulting in close sequences of impounded sections and residual flow sections. In recognition of these long-term hydrological and hydromorphological changes from hydropower operations, the spawning habitat of salmonids, and hence, the reproductive success of salmonid populations, may be compromised in the following ways (Crisp, 1993; Kondolf, 1997; Pulg, 2009):

- Insufficient flow velocities in impounded sections
- Spawning gravel retention in impounded sections with limited availability of spawning gravel downstream of weirs
- Gravelbed colmation from fine sediment infiltration in impounded sections
- Insufficient water depths for redd cutting and desiccation of incubated eggs in residual flow sections

Concerning these issues and possible impacts on spawning habitats this study investigates the spawning habitat use of native non-anadromous brown trout (*Salmo trutta f. fario*) and non-native rainbow trout (*Oncorhynchus mykiss*) in two Austrian salmonid rivers. Based on field observations the study investigates river reaches affected by small hydropower plants and their operations (residual flow sections, impounded sections, intake channels) with the aim to assess their quality (probably suitability) as spawning environments for salmonids. Moreover, emphasis is given on the abiotic parameter description of the mapped spawning redds (redd dimensions, redd position on the riverbed, water depth) and the microhabitat selection with regard to instream structures (macrophytes, boulders, deadwood, other redds). With the obtained results, opportunities (technical, ecologically oriented) for the improvement of the local spawning habitat quality of salmonids in river sections influenced by small hydropower operations are discussed.

Study reaches

Two rivers have been selected for the presented study which are different in sedimentological and morphological characteristics.

The Gr. Mühl river is a left-hand tributary of the Danube river and located in the north-eastern part of Upper Austria draining a catchment size of 559.5 km². The catchment of the Gr. Mühl river contains crystalline bedrock of the Bohemian Massif where granites and gneiss are dominant. According to Montgomery & Buffington (1997), most reaches of the Gr. Mühl river can be classified as plane-bed channel, with commonly featureless straight bedforms and a relatively high degree of bed surface armoring. In addition, the long-term weathering of granite rock results in a bi-modal river sediment composition in the catchment with high proportions of cobble and sand, and low contents of coarse gravel (20 mm-50 mm). Under these circumstances, spawning gravel and opportunities for spawning are naturally limited in the riverbeds of the Gr. Mühl river catchment (up to 90 percent unsuitable) (Hauer, 2015).

The Gr. Erlauf river is a right-hand tributary of the Danube and located in the south-eastern part of Lower Austria with a catchment size of 624.3 km^2. The Gr. Erlauf river drains parts of the Limestone Alps, where limestone sediments and cobble to gravel depositions of the tertiary ("Molasse") dominate the catchment sediment composition. The river morphology of the Gr. Erlauf river alternates between glides, pool-riffle sequences and canyon passages incised into conglomerate bedrock (Radler *et al.*, 1992). Receiving high sediment inputs of gravel, the riverbeds of the Gr. Erlauf river and its tributaries offer adequate sedimentological conditions for spawning salmonids (up to 80 percent suitable).

Both study rivers, however, are considerably impacted by small hydropower operations, with 18 small hydropower weirs located along the Austrian course of the Gr. Mühl river and 20 small hydropower weirs located along the Gr. Erlauf river. Concerning the aims of the presented study, three reaches were investigated in detail, with two reaches at the Gr. Mühl river and one reach at the Gr. Erlauf river (Table 1). Reach 1 and 2 (Gr. Mühl river) show plane-bed morphologies with cobble-dominated riverbeds. Reach 3, in contrast (Erlauf river), is classified as a gravel dominated section with alternations of pool- glide- and riffle sequences. A large (~100 m) gravel bar can be found in the upstream section of reach 3. The two studied rivers are regulated by transversal obstructions, diversion channels and rip-rap along the river banks used for flood protection. All hydropower facilities investigated are diversion systems, with intake channel lengths varying between 30 m (reach 3) and 1065 m (reach 2). A total of N=5 hydropower facilities are contained in the two study reaches of the Gr. Mühl with N=4 facilities contained in reach 1 and N=1 facility contained in reach 2 (Table 1). A total of N=2 hydropower facilities are contained in the study reach of the Gr. Erlauf river (reach 3, Table 1).

Methods

At the Gr. Mühl river, resident brown trout (*Salmo trutta f. fario*) spawning redds were recorded during December and January 2014 shortly after the end of brown trout spawning season (October-November) (3.12. 2014, 4.1.-7.1. 2015). At the Gr. Erlauf river, rainbow trout (*Oncorhynchus mykiss*) spawning redds were recorded during spawning season in March and April 2015 (29.3., 9.4., and 10.4).

Assessed spawning redd parameters included:

- Position in the river channel (GPS-coordinates, measurement of the distance of the redds from the next shore)
- Redd dimension measurements
- Presence of instream structures at the microhabitat level

For redd dimension measurements, redds were divided into their pit and tail sections. Length-, width- and water depth measurements were made at constant 20- or 30- cm intervals along the length axis of the pit and tail sections. Instream structures on the microhabitat scale were assessed analogous to Witzel & MacCrimmon (1983) by documenting structures within a distance of 1.5 m near the redds. Identified structures were:

- Boulders and large stones > 0.3 m
- Macrophytes > 0.5 m

- Deadwood > 0.5 m
- Other redds upstream/downstream

To analyze spawning redd densities in river reaches affected by hydropower operations, the affected river reaches and the anthropogenic disturbances respectively were divided into the following sub-units on investigation day one at each referring river:

1) Impounded: River sections upstream of hydropower weirs with backwater effects (reduced flow velocities) and maximum water depths of the thalweg >1 m
2) Residual flow and intake channels: River sections where a significant amount of flow was diverted upstream for hydropower use by an intake channel with a dewatered river section downstream.
3) Free-flowing: River sections with free flowing character not influenced by backwater effects of transversal obstructions (weirs) or residual flows, or river sections downstream of diversion channel inlets into the main river
4) Artificial secondary side channels close to small hydropower plants.

Results

A total of N=42 brown trout redds were documented at the two study reaches of the Gr. Mühl river (reach 1, 2) and a total of N= 43 rainbow trout spawning redds were documented at the Gr. Erlauf river (reach 3). Results of the detailed sampling of redd dimensions for the two investigated fish species are presented in Fig. 1. Brown trout redd dimensions from the Gr. Mühl river and rainbow trout from the Gr. Erlauf were similar with regard to the pit and tail measurements. A slightly higher maximum redd length (1.96 m) was found in brown trout redds of the Gr. Mühl river. In contrast, rainbow trout redds were associated with greater mean water depths, as indicated by a median of 0.48 m (N=42) in rainbow trout redds versus a median of 0.36 m (N=43) in brown trout redds (Fig. 1). Greatest water depths were found immediately upstream of weirs; with maximum mean redd depths of 1.14 m at the Gr. Mühl river and 0.92 m at the Gr. Erlauf river, respectively (Fig. 1).

Redd distances from the next shore for the two study rivers are presented in Fig. 2. Most brown trout redds were situated within less than 2 meters from the next shore (Fig. 2B). In contrast, rainbow trout redds at the Gr. Erlauf river were more evenly distributed over the riverbed in longitudinal and transversal direction, with most redds found between a distance 4 and 6 meters away from the next shore (Fig. 2A). Instream structures were found to be present near most brown trout redds (83.3 % , N=35) with up to three different types of structures near one redd. Boulders were most common (36.2%), followed by macrophytes (31.9%), other redds (27.7%) and deadwood (<1%). At the Gr. Erlauf river, only 18.6% (N=8) of rainbow trout redds were associated with a maximum of one structure type per redd. Structures near rainbow trout redds were either boulders (N=4) or other redds upstream or downstream (N=4), respectively. A comparison of the spawning redd densities (redds/100 m) for each investigation reach is presented in Fig 3.

The results of the redd density assessment in the three river reaches allows three main inferences:

1) The investigated residual flow section and highly technical intake channels had zero to near-zero redd densities
2) Impounded sections had either zero-redd densities or densities comparable to free-flowing sections, depending on the local hydraulic conditions (e.g. whether an overflow over the weir was present during the spawning season)

3) Redd densities in a small artificially built side channel (Gr. Mühl river) were at least twice as high as in the free flowing main river section due to local accumulation of suitable spawning gravel with appropriate hydraulic conditions (e.g. near bottom flow velocities)

Discussion

The investigated residual flow section (Gr. Mühl river), at a length of 565.5 m, showed to be an unsuitable spawning environment for brown trout, as only one redd at a mean water depth of 0.2 m was documented. The obvious reason for the low spawning density in the residual flow section were insufficient water depths during the spawning season. According to Crisp (1993), water depths in spawning salmonids need to exceed at least the body height of a spawning female. Hence, substantial reductions in the wetted area and a decrease in water depth below diversion weirs (as witnessed in this study) are equivalent to the loss of considerable portions of the river usable as spawning grounds even if suitable spawning gravel is found there.

A similar finding as seen in the residual flow section was found for intake channels, which were unoccupied with spawning redds in 6 out of 7 cases. A major reason for this finding is that the 6 intake channels not used by spawning fishes represented highly technical engineering solutions unsuitable as spawning environments, with uniform u-shaped concrete channels, and the absence of spawning gravel in the intake channels resulting from sediment diverting gate configurations although suitable flow velocities were partially found in the channel. As the only exception, the intake channel investigated in reach 2 (Gr. Mühl river) has to be mentioned, which was a non-concreted side channel overshadowed by riparian vegetation and fixed laterally only with fascines. Spawning, although to a minor degree downstream of the inlet, took place in this intake channel as spawning gravel could be transported through the opening gate.

In impoundment sections (upstream backwaters), brown trout/rainbow trout redds were only present when weir crests had been lowered during the spawning time so that the weir was overflown to a certain degree. This observation was made at one impoundment at the Gr. Mühl river (N=5 redds) and at the two impoundments investigated at the Gr. Erlauf river (N=2 redds, N=4 redds). The likely reason for this observation is a local increase in flow velocities induced by the overflow, producing suitable abiotic conditions for the spawning site selection in the two trout species. In addition, visual inspections indicated that riverbed colmation with fine sediment was largely reduced close to the overflown weirs. However, redds were always clustered to a narrow extent (< 15 m) upstream of the weir so that the remaining impoundments (50 m – 300 m) remained still free of redds.

The fourth tested sub-unit was the artificial side channel investigated in reach 1 (Fig. 3A), which had twice as high brown tout redd densities (5 redds/100 m) compared to free flowing main river sections at the Gr. Mühl river. Redd densities in the side channel would have been notably higher when standardized for area, as the width of the side channel was only 4-5 meters in comparison to the main river with at the study reach (15 m – 20 m). A possible explanation for the high redd density in the artificial side channel is that a flow velocity range of 0.3 $m.s^{-1}$ – 0.5 $m.s^{-1}$ was found in most parts of the channel which can be considered optimal for spawning resident brown trout (e.g. Louhi *et al.*, 2008). Moreover, at the given flow conditions, the channel was sorting high amounts of gravel in a diameter range of 3 cm – 5 cm during high flow events which is the favoured gravel size for spawning brown trout (Louhi *et al.*, 2008) and limited by the geomorphological boundary conditions in the crystalline catchment (Hauer, 2015; Hauer *et al.*, 2011). Based on the findings of the presented study (mapping of spawning redds) it could by underlined (like it was stated in Kondolf & Wolman, 1993), that the presence of high quality spawning gravel in the river is the dictating abiotic variable in the control of salmonid populations. The formation of used small scale spawning sites may be possible, even close to hydropower facilities, when the hydraulics and the sedimentological characteristics are at a suitable stage. Moreover it could be documented that a well-structured reach with large boulders and overhanging bank vegetation (sub-unit 4 – artificial secondary sidearms) contained useful additional quality elements (e.g. visual protection) which favoured the spawning of brown trout.

In conclusion, the findings of this study have demonstrated that the operation of small diversion hydropower plants can substantially decline areas of the river potentially usable for spawning salmonids (brown trout and rainbow trout) upstream and downstream of weirs in different geomorphological regions. However, implementable ways (technical and self-forming) to improve the local salmonid spawning habitat potential near small hydropower plants exist:

- Increasing the residual flow into downstream areas where water depths are insufficient for spawning, including the duration of the spawning season and time of incubation until fry emergence
- In impounded areas, improving flow conditions for spawning salmonids by lowering the weir crest, (local) reduction in reservoir depth, or structural modification (e.g. boulder placement) in the tail of the backwater; -all of these measures should increase local flow velocities
- Compensating for lost spawning areas (e.g. after the establishment of an impoundment) by the construction of key spawning refugias, either in the form of artificial side channels upstream of impoundments, or, by (re-)designing diversion channels into more natural solutions where successful spawning can take place.

All these issues for possible mitigation however, require the availability of suitable spawning gravel at the points of interest, which can only be considered or even restored in a broader (reach to catchment scale) perspective.

References

Armstrong, J. D., Kemp, P. S., Kennedy, G. J. A., Ladle, M., & Milner, N. J., 2003. Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fisheries Research, 62(2), 143-170.

Bjornn, T., & Reiser, D. W., 1991. Habitat requirements of salmonids in streams. American Fisheries Society Special Publication, 19, 83-138.

Crisp, D. T., 1993. The environmental requirements of salmon and trout in fresh water. In Freshwater Forum (Vol. 3, No. 3, pp. 176-202).

Elliott, J. M., 1994. Quantitative ecology and the brown trout. Oxford University Press, 286 pp.

Habersack, H., Wagner, B., Hauer, C., & Jäger, E., 2012. Wasserkraft in Österreich—aktueller Bestand und Decision Support System (DSS WASSERKRAFT). Österreichische Wasser-und Abfallwirtschaft, 64(5-6), 336-343.

Hauer, C., 2015. Review of hydro-morphological management criteria on a riverbasin scale for preservationand restoration of freshwater pearl mussel habitats.Limnologica 50, 40–53.

Hauer, C; Unfer, G; Tritthart, M; Habersack, H, 2011. Effects of stream channel morphology, transport processes and effective discharge on salmonid spawning habitats. Earth Surface Processes and Landforms 36: 672-685.

Kamler, E., 1992. Early life history of fish: an energetics approach. London: Chapman & Hall, 330 pp.

Kondolf, G. M., & Wolman, M. G., 1993. The sizes of salmonid spawning gravels. Water Resources Research, 29(7), 2275-2285.

Kondolf, G. M., 1997. PROFILE: hungry water: effects of dams and gravel mining on river channels. Environmental management, 21(4), 533-551.

Louhi, P., Mäki-Petäys, A., & Erkinaro, J., 2008. Spawning habitat of Atlantic salmon and brown trout: general criteria and intragravel factors. River Research and Applications, 24(3), 330-339.

Montgomery, D. R., & Buffington, J. M., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin, 109(5), 596-611.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., ... & Stromberg, J. C., 1997. The natural flow regime. BioScience, 769-784.

Pulg, U., 2009. Laichplaetze der Bachforelle (Salmo trutta) in der Moosach – die Bewertung ihrer Funktionsfaehigkeit, ihre Degradierung und ihre Restaurierung. Dissertation am Lehrstuhl fuer Landschaftsoekologie der Technischen Universitaet Muenchen. http://mediatum2.ub.tum.de/node?id=680304

Radler, S., Pelikan, B., Bodi, K., Eberstaller, J., Gaubmann, H., Paal, W., Schön, R., Simetzberger, J., Wohlschlager, N., 1992. Fluss-Studie Erlauf. Amt der Niederösterreichischen Landesregierung.

Schiemer, F., Keckeis, H., & Kamler, E., 2002. The early life history stages of riverine fish: ecophysiological and environmental bottlenecks. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology,133(3), 439-449.

Wagner, B., Hauer, C., Schoder, A., & Habersack, H. 2015. A review of hydropower in Austria: Past, present and future development. Renewable and Sustainable Energy Reviews, 50, 304-314.

Wheaton, J. M., Pasternack, G. B., & Merz, J. E., 2004. Spawning habitat rehabilitation-I. Conceptual approach and methods. International Journal of River Basin Management, 2(1), 3-20.

Witzel, L., MacCrimmon, H., 1983. Redd-site selection by brook trout and brown trout in southwestern Ontario streams. Trans. Am. Fish. Soc. 112, 760–771.

Youngson, A. F., Piertney, S. B., Thorley, J. L., Malcolm, I. A., & Soulsby, C., 2011. Spatial association of nest construction by brown trout Salmo trutta.Journal of fish biology, 78(3), 713-725.

Figure caption

Fig. 1. Comparison of rainbow trout redds investigated at the Gr. Erlauf (left panel) and brown trout redds at the Gr. Mühl river (right panel) for the selected parameters redd length, pit length, tail length and mean redd depth.

Fig. 2. Histograms showing the distribution of distances of rainbow trout redds at the Gr. Erlauf river (A) and brown trout redds at the Gr. Mühl river (B) from the next shore.

Fig. 3. Spawning redd densities (redds/100 m) assessed for the different hydropower sections in reach 1 (A), reach 2 (B), and reach 3 (C).

Table caption

Table 1. Characteristics of the three study reaches. Reach 1 and reach 2 were investigated at the Gr. Mühl river; reach 3 was investigated at the Gr. Erlauf river.

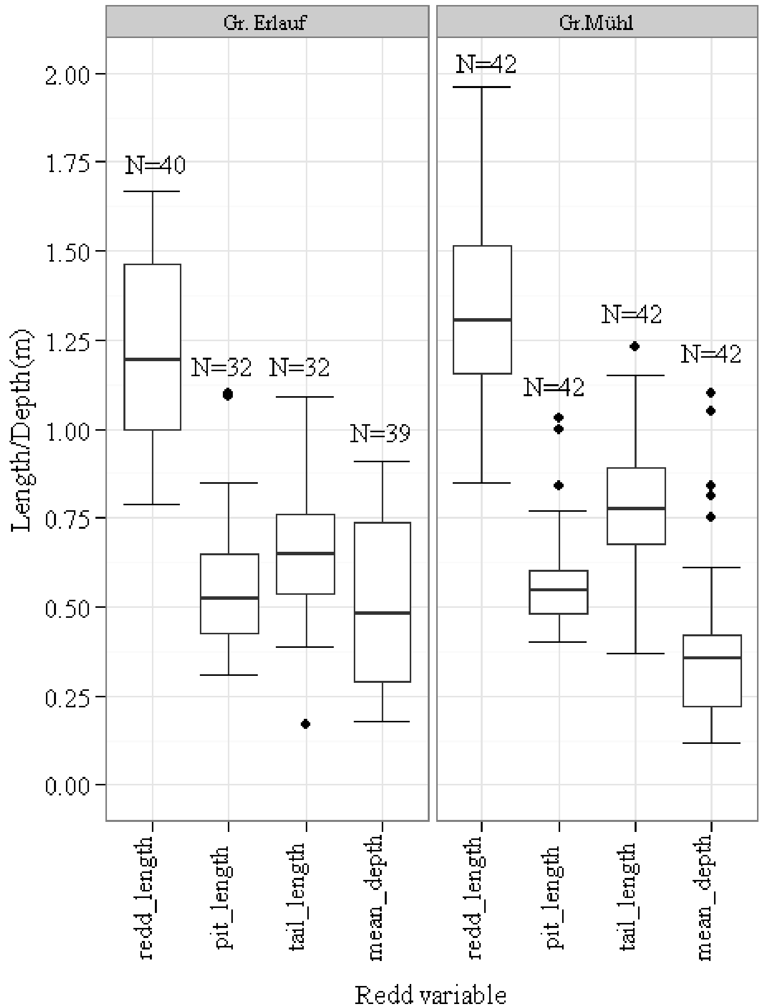


Fig. 1. Comparison of rainbow trout redds investigated at the Gr. Erlauf (left panel) and brown trout redds at the Gr. Mühl river (right panel) for the selected parameters redd length, pit length, tail length and mean redd depth.

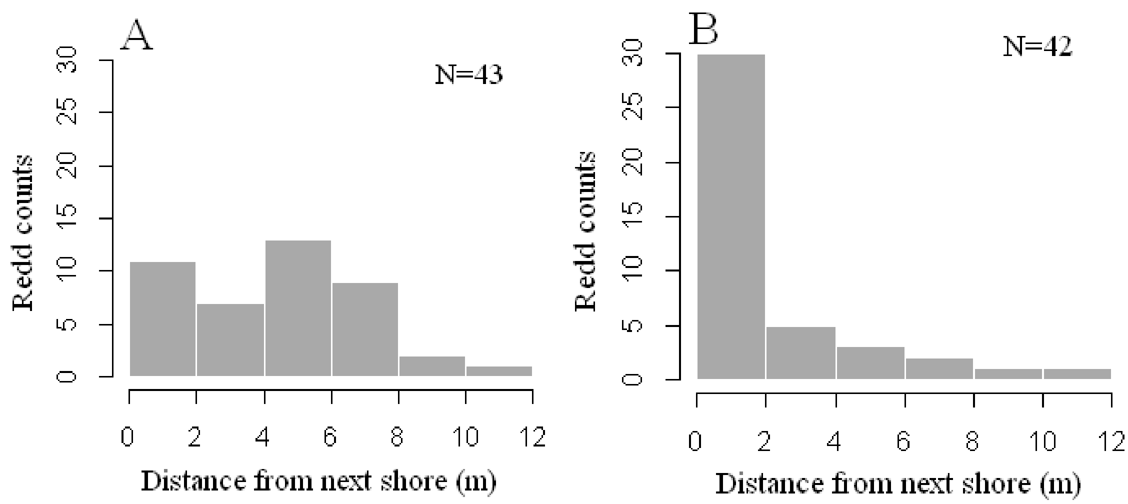


Fig. 2. Histograms showing the distribution of distances of rainbow trout redds at the Gr. Erlauf river (A) and brown trout redds at the Gr. Mühl river (B) from the next shore

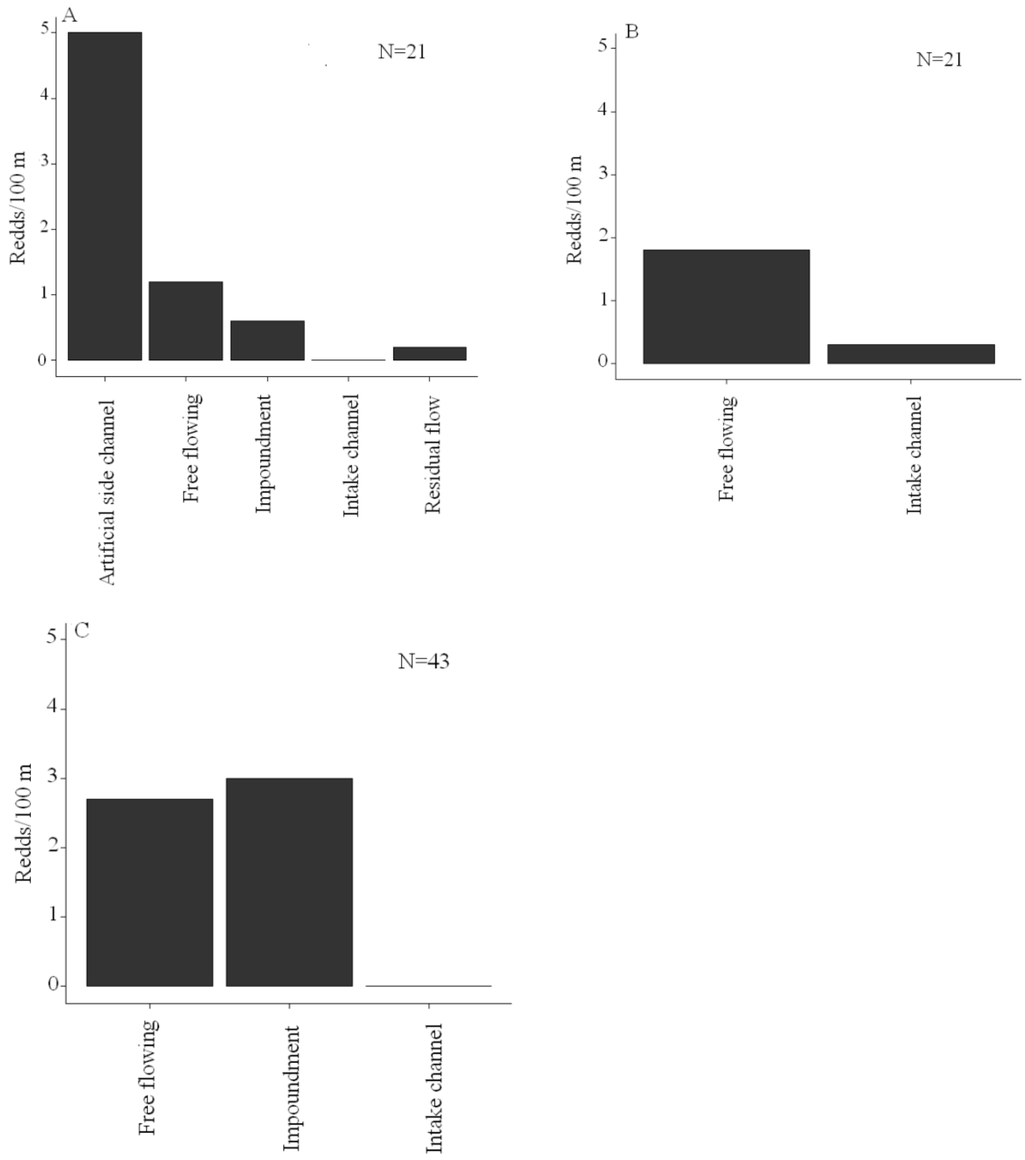


Fig. 3. Presented are the spawning redd densities (redds/100 m) assessed for the different hydropower sections in reach 1 (A), reach 2 (B), and reach 3 (C).

Table 1. Characteristics of the three study reaches. Reach 1 and reach 2 were investigated at the Gr. Mühl river; reach 3 was investigated at the Gr. Erlauf river.

	Gr Mühl river		**Gr. Erlauf river**
	Reach 1	Reach 2	Reach 3
Upstream boundary coordinates	N: 48°39'04,8" E: 13°57'01,9"	N: 48°35'23,8" E: 14°01'24,1"	N: 48°00'10,0" E: 15°09'58,3"
Elevation (m.a.sl)	545	499.6	327.2
Reach slope (‰)	4.5	3.5	4.5
Reach length (m)	2200	985	1570
Sum of free flowing sections (m)	830	985	1370
% free flowing sections	37.7	100	87.3
Sum of impounded sections (m)	804.5	0	200
% impounded sections	36.6	0	12.7
Sum of residual flow sections (m)	565.5	0	0
% residual flow sections	25.7	0	0
Sum of diversion channel lengths (m)	500	1065	50
Number of hydropower weirs/reach	4	1	2
Number of hydropower weirs/rkm	1.82	1.02	1.33

Section 3 – Conclusive Summary

On the basis of a laboratory experiment (research article 1) and field observations (research article 2), this master thesis has addressed specific research questions with respect to the hydraulic and sedimentological assessment of salmonid spawning habitats in river sections influenced by small hydropower operations.

In research article 1, it could be shown that coarse sand, which is found at increasing quantities in hydropower-regulated (e.g. impounded) river sections in the catchments of the Bohemian Massif, has an important and significant effect in reducing intergravel flows through salmonid redds when a full infiltration of the redd gravel framework occurs. Although no attempt was made in this study to relate this finding to actual negative effects of coarse sand redd infiltration on incubated embryos, earlier research work worldwide has confirmed that reduced intergravel flows can cause high mortality rates in incubated eggs and larvae. It is likely that in the catchments where the coarse sand problem is evident, the recurring burial of redds with coarse sand in the spawning season, already driven by small flow events, substantially reduces the survival rates of the salmonid offspring, making the long term survivability of self sustaining salmonid populations in (hydropower) regulated rivers without stocking practices questionable. For this reason, additional field studies in selected rivers of the Bohemian Massif on the biotic response of salmonids (and other organisms of the aquatic foodweb) to coarse sand infiltration are needed to evaluate the risks of ecological degradation and develop appropriate and effective management steps towards the reduction of coarse sand into the channels of the rivers draining the Bohemian Massif.

The results highlighted in research article 2 have shown clear deficits in the spawning habitat suitability for brown trout and rainbow trout in hydropower influenced river sections, as indicated by the large areas of impoundments, residual flow sections and intake channels that were not accepted as spawning grounds by the fishes. However, from the few observed spawning redds in some of these regulated sections, where acceptable spawning conditions could be detected, a list of management suggestions for the local enhancement of the spawning habitat quality was derived which could be useful for the adaptation of standards for the construction and operation of hydropower facilities in salmonid rivers. Atop of these measures, an ecologically oriented flow and sediment management for the creation of temporary spawning habitat conditions is suggested.

As for impoundments, a certain amount of flow is recommended to be directed over the main river weir crest during the spawning season (by lowering the weir mechanically, if possible) which creates flow velocities upstream of the weir necessary for spawning and appropriate intergravel flows. As this measure would incur productivity losses for the hydropower operator, alternatives could be developed where the donated amount of water is directed over electricity generating bypasses leading into the downstream river segment. In heavily dewatered residual flow sections downstream of weirs, donating sufficient flow over weirs or bypasses is also a step towards the local spawning habitat enhancement by creating water depths that are satisfactory for all body sizes of redd cutting fishes. However, in case of residual flow sections, the flow donation should be maintained at least upon the time of fry emergence so as to avoid the desiccation of redds containing the developing embryos. Diversion channels offer great potential as stand-alone spawning environments, given that channel hydraulics, water depths and, above all, sediment conditions are in agreement with the spawning requirements of one (several) salmonid species.

As a further option, the establishment of artificial secondary side channels specifically designed as spawning refugia, would be a worth considering measure where large hydropower regulated areas along the main river without spawning opportunities (e.g. impoundments of several hundreds of meters length) need to be compensated for lost spawning areas.

In implementing these and other options for the rehabilitation of salmonid spawning habitats in river sections affected by hydropower operations, a clear recommendation is given for equipping the restored riverbed sections with small, habitat heterogeneity creating instream elements (e.g. boulder series, deadwood, macrophytes) as it could be demonstrated in this study that most spawning redds were associated with at least one kind of instream element within less than 1.5 meters of distance.

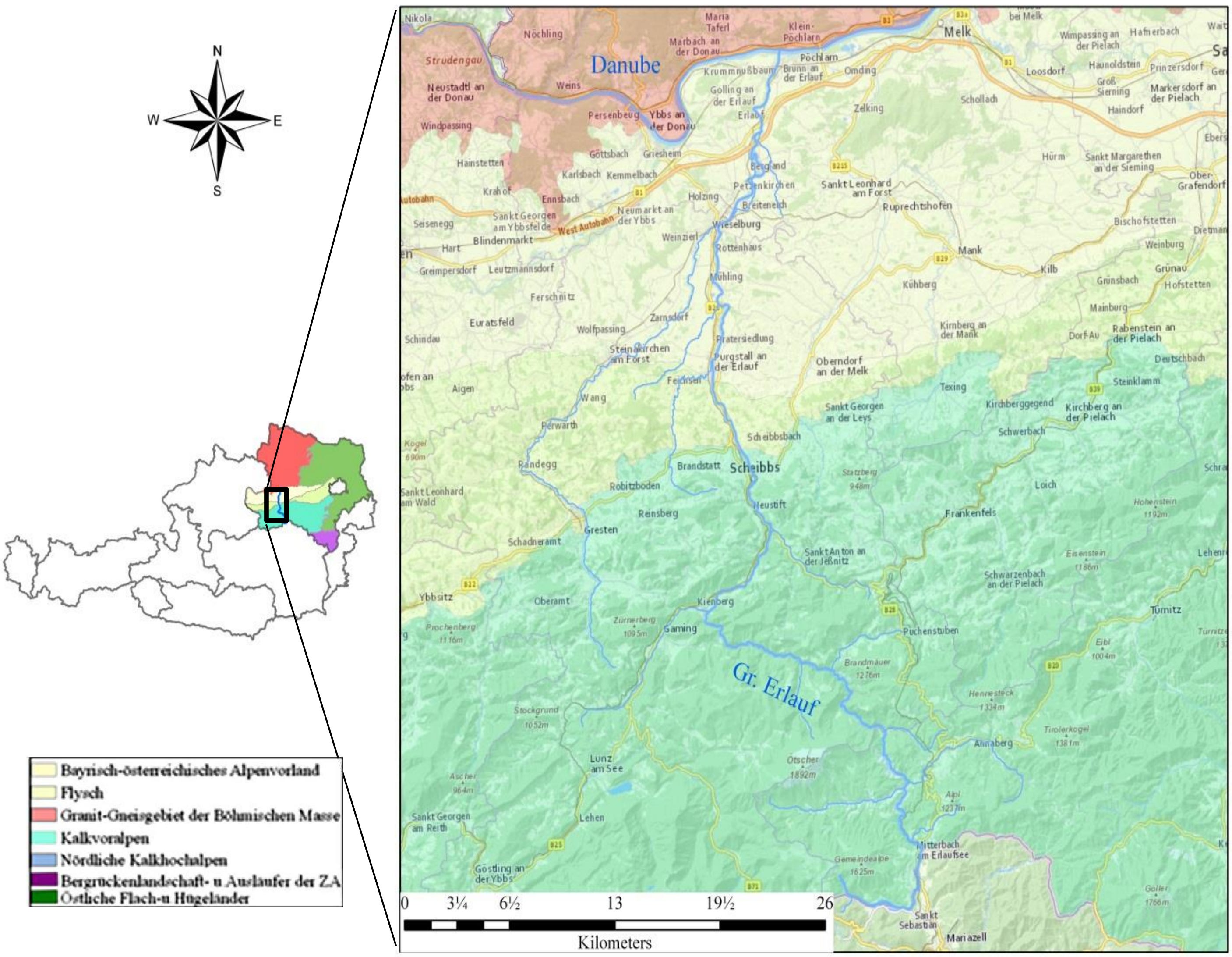
The good ecological status/potential for all surface water bodies until a provided deadline was set as priority goal for all European member states from sides of the European Water Framework Directive (2000/60/EG) in the year 2000 and was translated into the national Austrian water law in the year 2003 (WRG 1959). As one of the four important biological quality elements mentioned in the Directive, the fish fauna is of implementational relevance to the attainment of the good ecological status. As the successful completion of the early life history is the key determining factor in the population success of fishes, the preservation and restoration of the spawning habitat should be set at the baseline towards the improvement of the fish ecological status. In this regard, small hydropower facilities, which constitute the most common type of river regulation in Austria, deserve special credit in terms of future spawning habitat rehabilitation and conservation.

Appendix

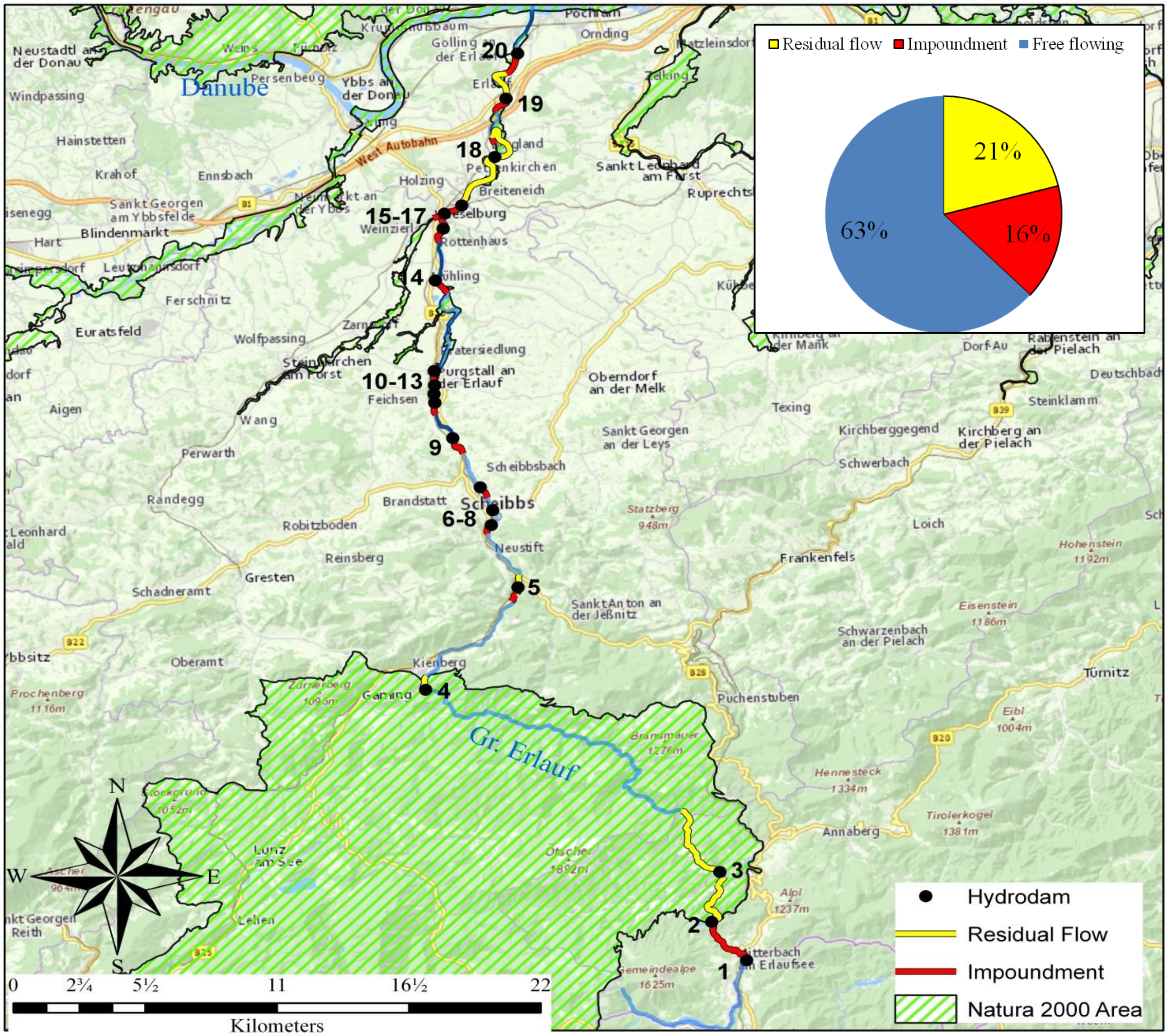
Appendix index

Appendix References:

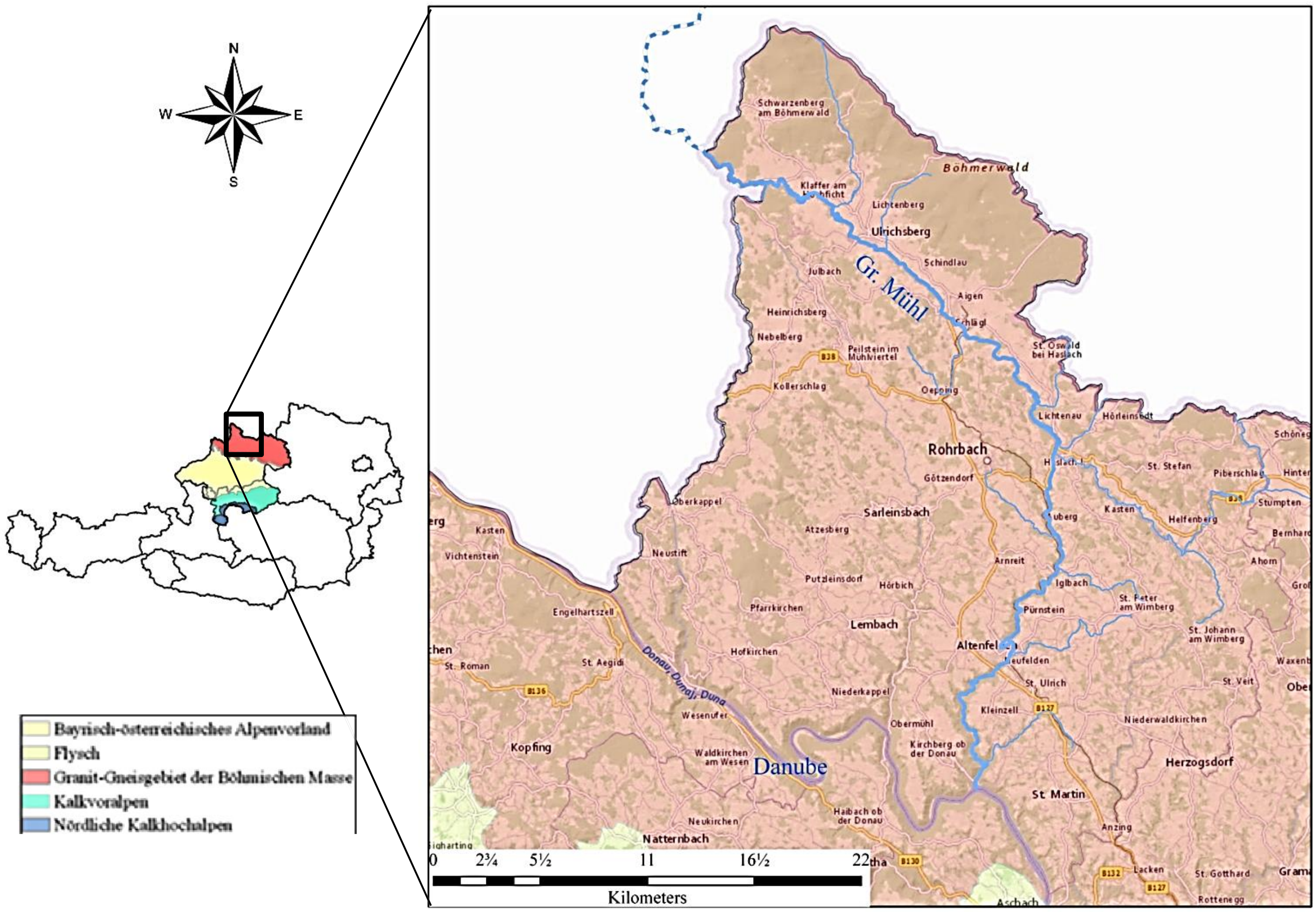
Moog, O., Schmidt-Kloiber, A., Ofenböck, T., Gerritsen, J. (2001). Aquatische Ökoregionen und Fließgewässer- Bioregionen Österreichs. Herausgegeben vom Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (BMLFUW), 106 pp. http://www.bmlfuw.gv.at/dms/lmat/wasser/wasseroesterreich/plan_gewaesser_ngp/umsetzung_wasserrahmenrichtlinie/fwbioregionen/EcoBioReg02_13-1-03/EcoBioReg02_13.1.03.pdf.



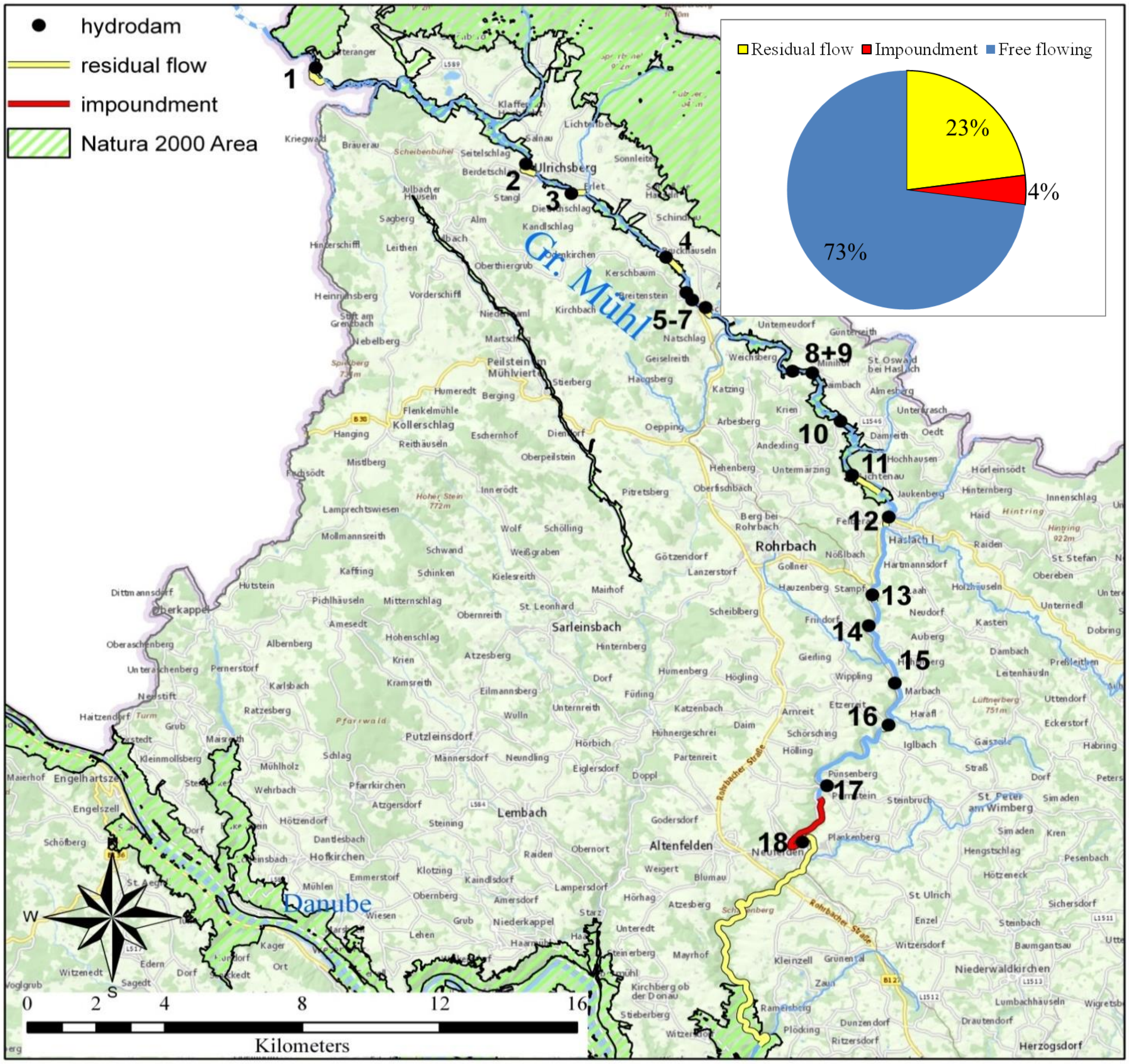
Appendix map 1: Geological formations in the Gr. Erlauf river catchment according to Moog *et al*. (2001). Source for map and data, respectively: http://www.basemap.at/, BMLFUW



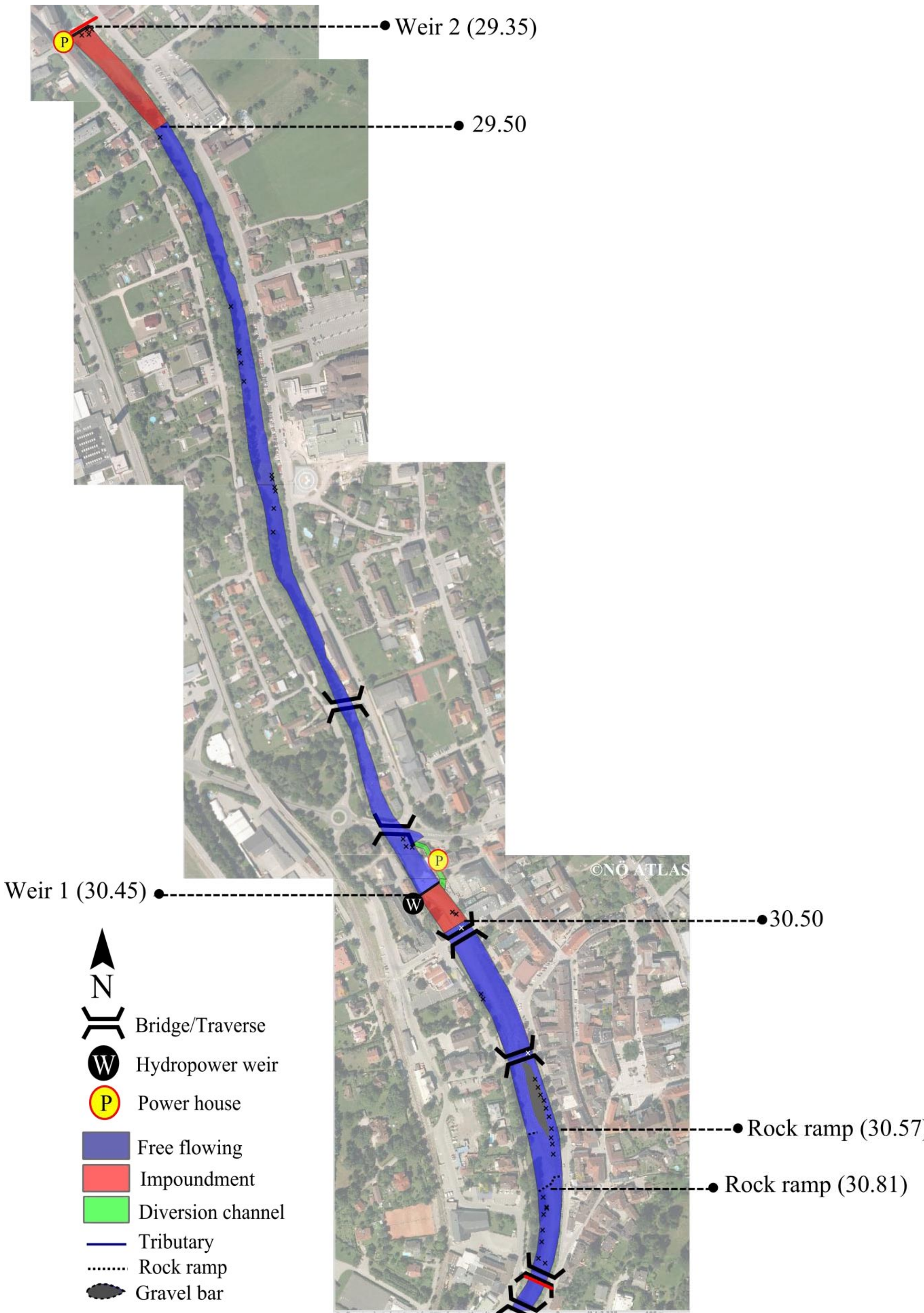
Appendix map 2: Map showing the hydropower weirs of the Gr. Erlauf river (black dots) and associated impoundment (red lline segment) and residual flow areas (yellow segment); the green hatched area refers to Natura 2000 areas. The pie diagram is representative of the shares of free flowing, impounded and residual flow areas of the study river. Source for map and data, respectively: http://www.basemap.at/, BMLFUW.



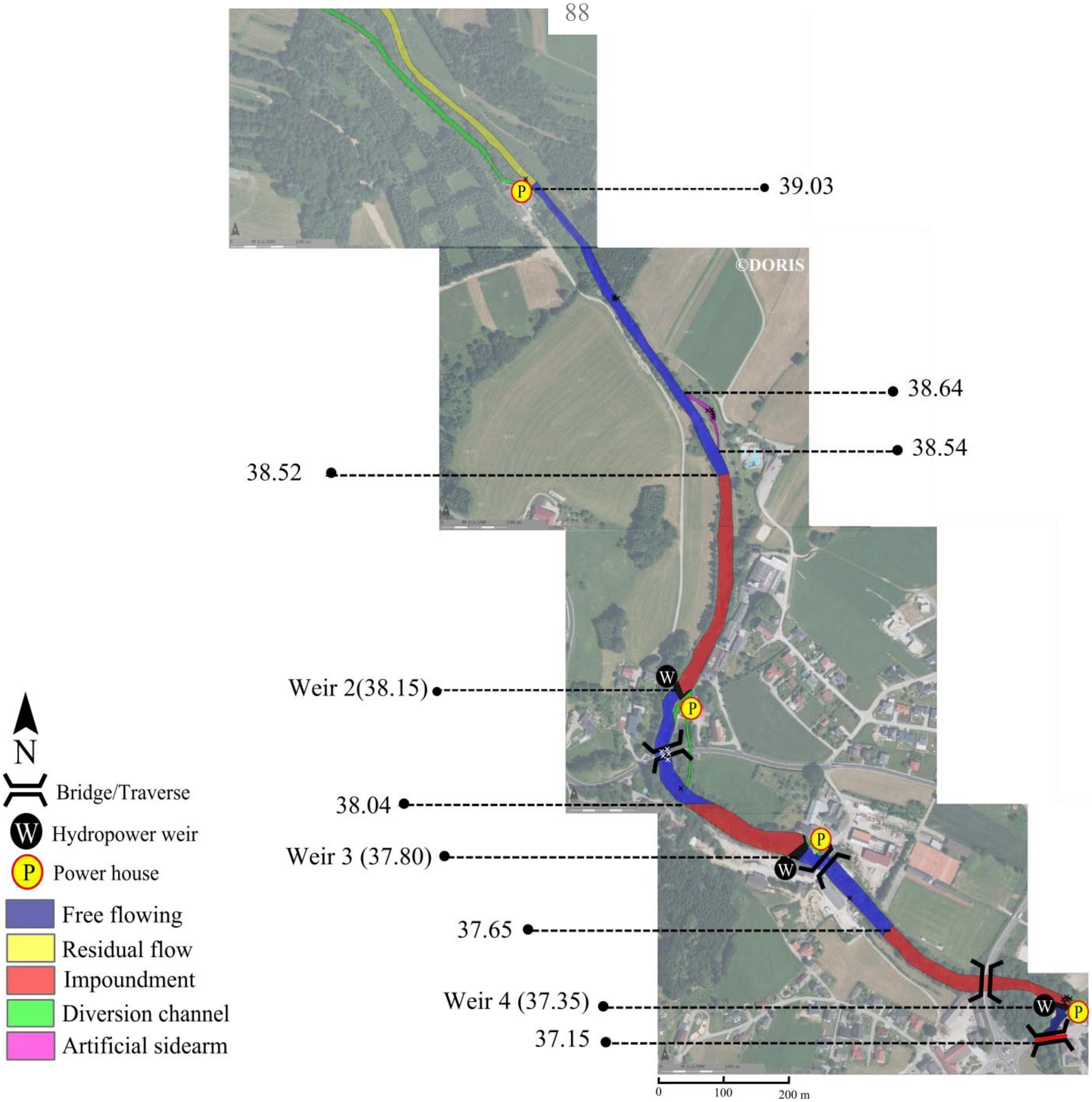
Appendix map 3: Geological formations in the Gr. Mühl river catchment according to Moog *et al*. (2001). Source for map and data, respectively: http://www.basemap.at/, BMLFUW



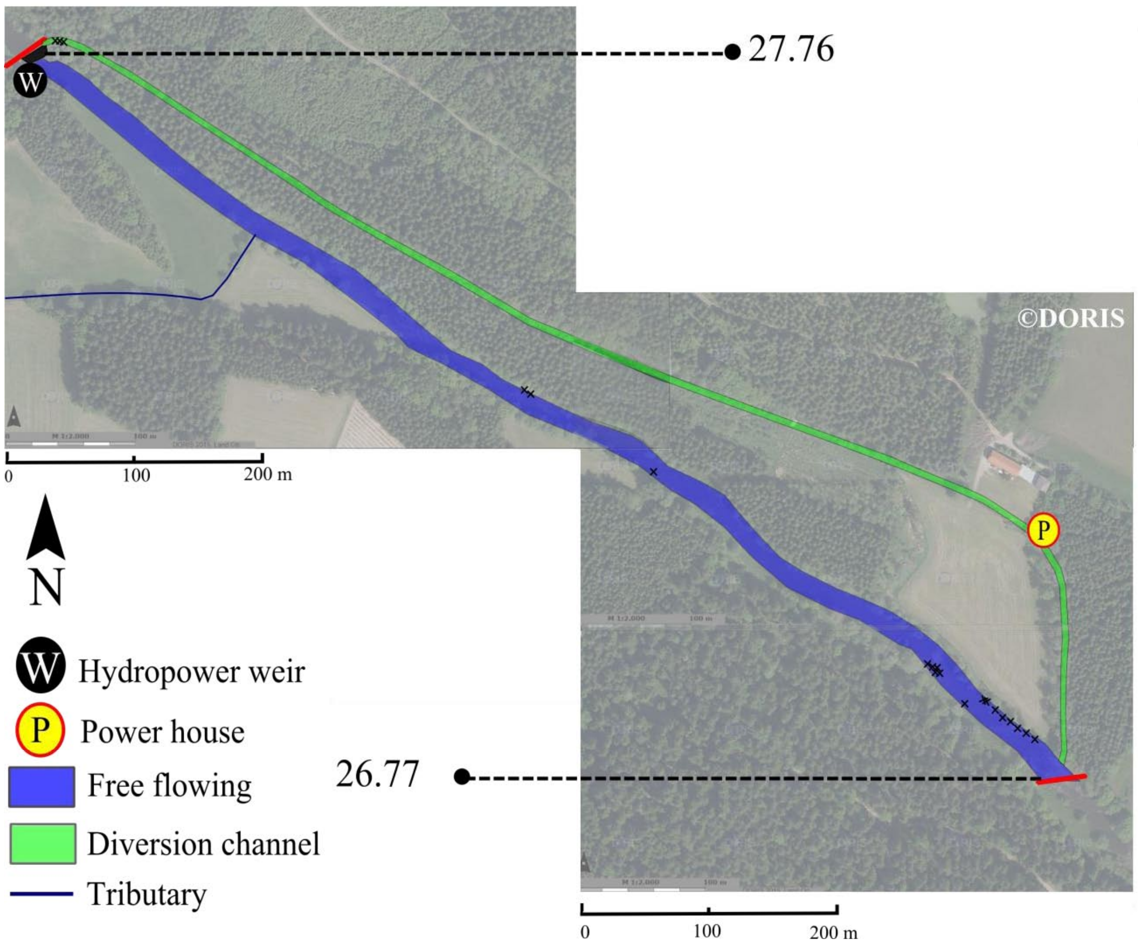
Appendix map 4: Map showing the hydropower weirs of the Gr. Mühl river (black dots) and associated impoundment (red lline segment) and residual flow areas (yellow segment); the green hatched area refers to Natura 2000 areas. The pie diagram is representative of the shares of free flowing, impounded and residual flow areas of the study river. Source for map and data, respectively: http://www.basemap.at/, BMLFUW.


Weir 2 (29.35)
29.50
Weir 1 (30.45)
30.50
©NÖ ATLAS
Rock ramp (30.57)
Rock ramp (30.81)
N
Bridge/Traverse
Hydropower weir
Power house
Free flowing
Impoundment
Diversion channel
Tributary
Rock ramp
Gravel bar
0
200 m

Appendix map 5: Study reach Scheibbs. White/black crosses mark spawning redd observationsmade during the investigation days.

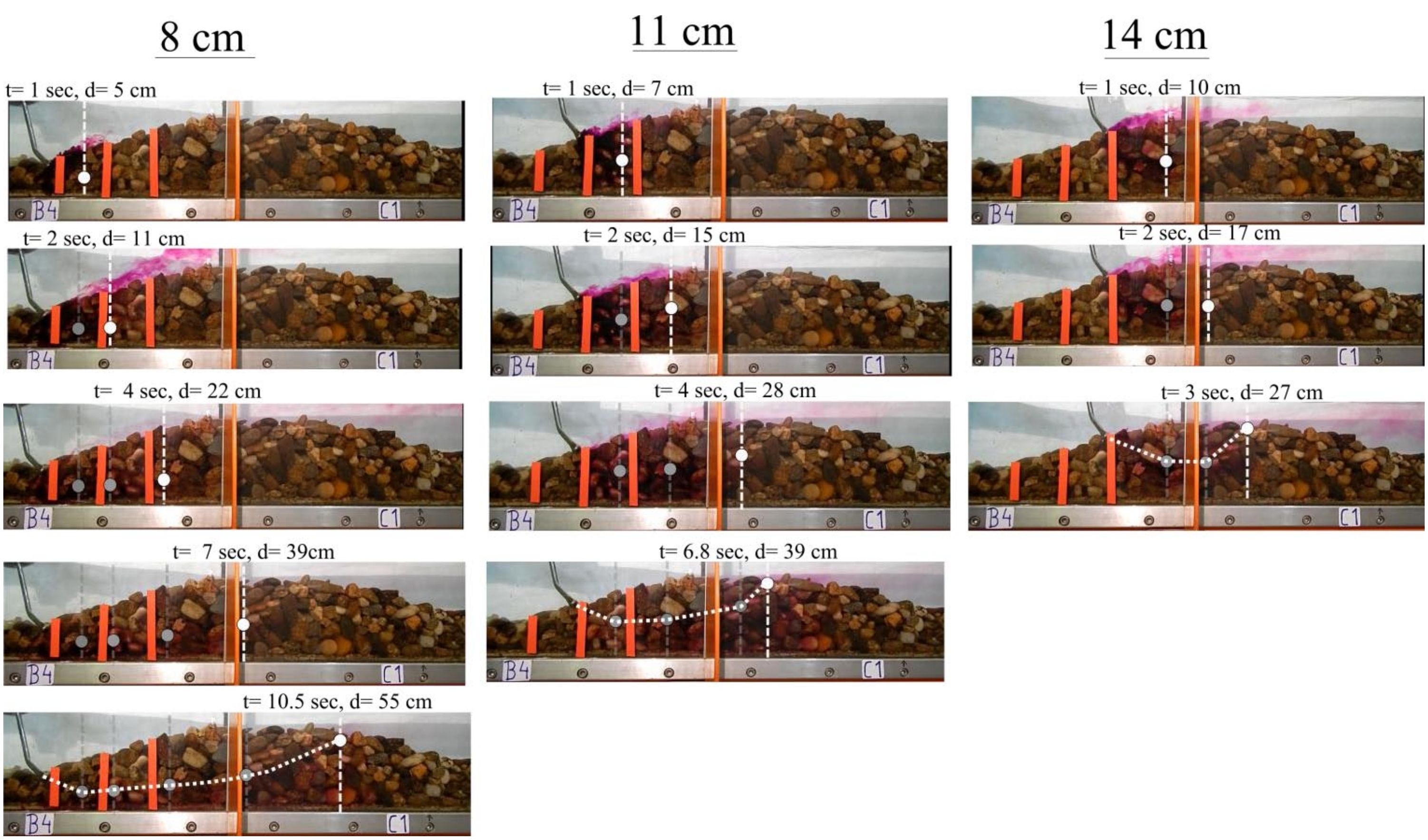


Appendix map 6: Study reach Schlägl. White/black crosses mark spawning redd observationsmade during the investigation days.



Appendix map 7: Study section Haslach. White/black crosses mark spawning redd observationsmade during the investigation days.

Appendix figure 1: Complete coarse sand infiltration into the tail of redd 1.



Appendix figure 2: Comparison of the intergravel flow trajectories through redd 1 at progressive time steps for the three substrate injection levels (8 cm: left photo series, 11 cm: middle photo series, 14 cm: right photo series). White dots and corresponding white vertical hatched lines indicate the downstream border of the moving dye tracersolutionfluid tracer at a given time step. Grey dots indicate downstream borders of the moving dye tracersolutionfluid tracer in earlier time steps.The white dotted line connects the points to illustrate the trajectory of the moving dye tracersolutionfluid tracer. t= passed time (s)

Appendix table 1: Channel flow velocity measurement results. Compared are the number of measurements (N), mean flow velocity ($\overline{x}$) in m.s^{-1}, and the standard deviation around the mean flow velocity (S.D.) for each scenario.

	Scenario 1			**Scenario 2**			**Scenario 3**		
Subsection (m)	N	$\overline{x}$ (m.s^{-1})	S.D.	N	$\overline{x}$ (m.s^{-1})	S.D.	N	$\overline{x}$ (m.s^{-1})	S.D.
Pre-section (0-0.4)	29	0.23	0.03	28	0.25	0.03	24	0.24	0.02
Pit_Redd1 (0.4-0.85)	99	0.15	0.10	30	0.26	0.04	30	0.25	0.03
Tail_Redd1(0.85-1.8)	132	0.24	0.13	96	0.22	0.11	85	0.30	0.07
Pit_Redd2 (1.8-2.35)	95	0.16	0.13	95	0.10	0.10	30	0.31	0.05
Tail_Redd2 (2.35-3.3)	124	0.26	0.13	124	0.17	0.10	78	0.36	0.05
Post-section (3.3-3.75).	37	0.18	0.11	37	0.09	0.07	25	0.34	0.06
Σ/ Overall $\overline{x}$/ Mean S.D.	517	0.21	0.10	415	0.18	0.07	272	0.30	0.05

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Appendix table 2: Selected hydropower weir characteristics of the Gr. Erlauf river. ID-Number corresponds to **Appendix map 2**. Source: http://atlas.noe.gv.at/

ID	Station (rkm)	Municipality	Facility Name	Drop height (m)	Type	Working capacity (MWh	Diversion distance (m)	passable for f
1	66.23	Mitterbach	Wehranlage Hölblinger	-	Diversion	81	30	N
2	63.65	Annaberg	Wehranlage Erlaufklaus	35	Diversion	16800	2232	N
3	60.2	Erlaufboden	WKA Erlaufboden	8.4	Diversion	14000	3800	N
4	40.6	Kienberg	Heiserwehr	6.3	Diversion	2020	600	N
5	34.8	Neubruck	WKA Neubruck	8.66	Run-of-river	5300	-	Y
6	30.25	Scheibbs	Wimmermühle	3.4	Diversion	500	70	N
7	29.32	Scheibbs	Leitnerwehr	4.15	Diversion	1100	50	N
8	28.2	Heuberg	Heubergwehr	5.5	Diversion	2000	30	N
9	25.55	Merkenstetten	Merkenstetten	2.4	Run-of-river	3684	-	N
10	23.45	Purgstall	Lagerhauswehr	4.4	Diversion	1000	20	P
11	23.07	Purgstall	Busatis	4.6	Diversion	600	20	N
12	22.8	Purgstall	Unterhumer	4.9	Diversion	1190	100	N
13	22.15	Purgstall	Schloßwehr	5.5	Diversion	2430	11	N
14	16.55	Mühling	WKA Mühling	5.7	Run-of-river	6000	-	P
15	14.87	Wieselburg	Zizala	3.7	Diversion	2078	80	N
16	12.57	Wieselburg	Bruckmühle	2.4	Diversion	1350	70	N
17	12.05	Wieselburg	Breiteneicherwehr	2.7	Diversion	5880	1870	N
18	9.52	Kendl	Hagenauerwehr	2.65	Diversion	5620	5880	N
19	5	Erlauf	WKA Plaika	6.76	Diversion	2320	3747	P
20	2.2	Brunn	WKA Neuda	4.81	Diversion	3223	2180	N

Appendix table 3: Selected hydropower weir characteristics of the Gr. Mühl river. ID-Number corresponds to **Appendix map 4** . Source: http://www.doris.at/

ID	Station (rkm)	Municipality	Facility name	Drop height (m)	Type	Diversion Distance (m	passable for fish
1	56.4	Schwarzenberg	Scheibelberger Rothmühle	1.0	Diversion	565	Y
2	45.1	Ulrichsberg	Leitner Steinmühle	1.5	Diversion	450	N
3	43.2	Ulrichsberg	E-Werksgemeinschaft Dietrichschlag E-Werk	1.5	Diversion	458	N
4	39.5	Aigen	Kern E-Werk	2.0	Diversion	661	Y
5	38.0	Aigen	Jauker Berndlmühle	2.0	Diversion	170	Y
6	37.8	Aigen	Baumgartenmühle Wöss & Eisschiel	2.5	Diversion	50	N
7	37.4	Aigen	Stift Schlägl	2.2	Diversion	77	N
8	33.1	Steineck	Kern Pfeffermühle	2.3	Diversion	77	N
9	32.5	St.Oswald	Dick Knollmühle	2.5	Diversion	116	Y
10	30.4	St.Oswald	Grundmüller-Pürmaier Furtmühle	2.5	Diversion	65	Y
11	27.8	Haslach	Grafenauer Thomas	1.5	Diversion	1080	N
12	25.7	Haslach	Furtmüller E-Werk	2.5	Diversion	270	Y
13	23.1	Haslach	Wagner Magerlmühle	2.5	Diversion	234	N
14	21.9	Auberg	Wagner Teufelmühle	2.5	Diversion	98	Y
15	19.7	Anreit	Mitheis Schönbergmühle	2.0	Diversion	80	N
16	18.2	Anreit	Wagner Iglmühle	2.5	Diversion	180	Y
17	14.4	Altenfelden	Wagner Hofmühle	2.1	Diversion	54	N
18	11.5	Altenfelden	Kraftwerk Partenstein	176.2	Storage	-	N