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An approach to simulate interstitial processes in river beds to meet biological requirements

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ABSTRACT: The quality of the hyporheic interstitial is described by multifaceted interstitial processes ranging from biological and chemical to physical and morphological processes. Regarding the ecological quality of the hyporheic zone, the dissolved oxygen concentration plays an important role in defining habitat conditions for aquatic indicator species. The oxygen supply rate for hyporheos depends on the gravel matrix of the river bed, the available pore space, deposition of fines into the gravel matrix but also on the oxygen respiration of sediments, organic material and microorganisms. The objective is to use highly sophisticated morphological models to simulate the dynamic processes affecting the gravel matrix and the changing interstitial conditions. As this is not sufficient to describe the ecological quality of the hyporheic zone in terms of habitat preferences, the results have to be linked to additional parameters like temperature, intragravel flow, organic matter, consolidation or permeability to meet biological requirements in terms of the oxygen supply rate. Therefore it is planned to apply a multivariate fuzzy-logical approach giving an imprecise range of dissolved oxygen as response for a certain combination of interstitial describing parameters and is compared to habitat demands of indicator species. As not all occurring interstitial processes can be considered due to their complexity and more than one parameter is decisive in determining the ecological quality of the interstitial, warranting the application of the fuzzy-logical approach. Thus the consideration of both biological and morphological factors can be considered.

Keywords: Hyporheic Interstitial, 3D-Sediment-Transport, Physical Habitat, Sediment Analyses

1 INTRODUCTION

1.1 *Background*

The hyporheic zone was recognized as an ecologically independent compartment between ground and running waters in a series of scientific studies starting about half a century ago (Schwoerbel, 1961, Borchardt & Pusch, 2009). Recently, the relevance of the hyporheic interstitial increased steadily and is often a focus for restoration measures. Generally the hyporheic interstitial is the dynamic and distinguishable interface between surface waters and groundwater (Dahm et al., 2006). A more biological definition is given by Brunke et al. 2007 who states the hyporheic zone is an active ecotone between surface water and groundwater with dynamic boundaries including all organisms, the so-called “hyporheos”. From a more engineering and hydrological point of view it is difficult to find a definition in literature. A geomorphologist may consider the river bed as multiple sediment-layers (Ferreira et al. 2006) with different grain size distributions and dynamic processes like sediment-transport, erosion/sedimentation, infiltration of fine sediments into the gravel-mixture. A hydrologist on the other hand may look at the amount of exchanged water and turnover rates assuming a more or less stable river bed. The morphology of the riverbed and the adjacent interstices are important factors for defining the hyporheic zone in four dimensions: vertically, laterally, longitudinally and over time (Ward, 1989). In each of them the hyporheic interstitial shows hydrological, chemical, biogeochemical and morphological processes and gradients. In this paper the morphodyanamic processes in the interstitial influencing the quality of the hyporheic zone for the reproduction of gravel-spawning fish are given focus.

According to the European Water Framework Directive (2004) the provision of spawning grounds for target fish species should be considered as one of the major aims in successful river restoration. But successful spawning is only one part of reproductive success. The interstitial time period of eggs, embryos, and larvae up to the emerging fry is relatively long and can last up to 6 months (Merz et al., 2004). The length of time between egg deposition and emergence depends on species redd location and numerous physical parameters (DeVries, 1997). The timing of spawning, egg burial depth and embryo development are tied to the dynamic hydrologic regime of a river, including disturbances such as streambed scour (Montgomery et al., 1999). According to Schiemer et al. (2003) the early life stages are particularly significant because in these life-stages fish have the highest mortality rates not only due to starvation and predation of larvae but also due to physical factors like non-optimal temperatures, oxygen deficit and dispersal of eggs. As said by Hübner (2003) & Neumann et al. (2006) different development stages give different sensitive response to interstitial quality.

Given to the relatively long time-period in the hyporheic interstitial during the reproduction process the incubation time reacts highly sensitive to changes in the hyporheic interstitial quality induced by morphodynamic processes. River dynamic processes like the alteration of flow, sediment transport, hyporheic exchange processes or other seasonal events lead to mobilization of channel-bed sediment and provide a renewal of substrate conditions. Additionally, they can also impact one or more fish life stages and may destroy a whole generation. Intrusion of fines, armoring and embeddedness contribute to decreased substrate permeability in the hyporheic interstitial harming the development of early life stages in different ways. Possible effects are the emergence of fry from the redd may be inhibited, and a reduction of the dissolved oxygen content, or the transport of metabolic waste. Therefore it is necessary to understand the spatial and temporal variations of vertical exchange processes in the hyporheic zone (Saenger & Zanke, 2006).

Given to the complexity of processes in the hyporheic zone an interdisciplinary multivariate fuzzy-logical approach will be developed to combine different results of a high-resolution sediment-transport model (3D) to an ecological interstitial quality regarding the physical habitat preferences in the incubation phase of brown trout. As the reproduction success depends significantly on the available dissolved oxygen (DO) in the interstitial - this might be a suitable indicator for the ecological quality of the hyporheic zone.

1.2 *Study Site*

After the installation of two reservoirs used for hydropower production on the River Spöl (Engadin, Switzerland) in 1970, changes in the flow regime have affected river morphology, the sediment structure and food resources for aquatic organisms. The regulated flow regime with a nearly constant discharge of 1 m³/s leads to the absence of floods which initiate sediment-transport and prohibits natural river dynamic behavior, a general feature of many regulated rivers (Stanford & Ward, 1996). Flushing flows are increasingly being used for the rehabilitation of regulated rivers, especially with respect to fisheries (Rood et al., 2003). At the River Spöl a flood program was developed following a number of earlier studies of individual flushing flows with the aim of providing the most proper conditions for reproductive success of brown trout.

After the flushing at the Livigno reservoir in 1990, Jäger et al. (1991) reported the changes in sediment compositions, channel morphodynamics and in riparian vegetation. These studies show that the riverbed was totally altered by floods with peak discharges around 70–90 m³/s. Mürle (2000) then investigated the morphology and habitat structure of the river due to the reduced flow regime from Punt dal Gall to Punt Periv before the beginning of the present controlled flood regime.

Fig. 1 provides an overview of the River Spöl and the selected study site with a total length of approximately 350 m

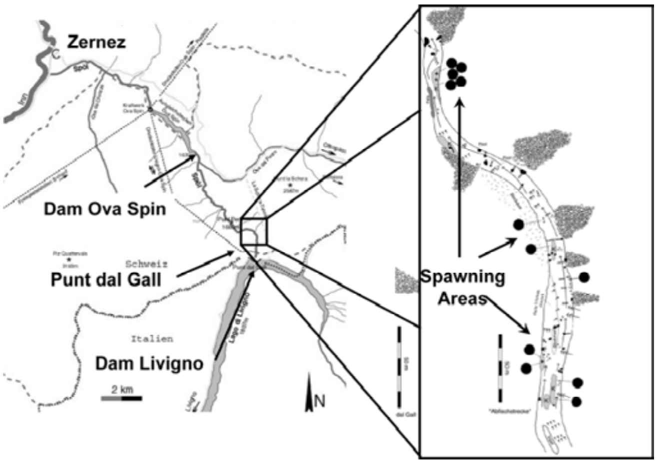

Figure 1. Map of the study area of the River Spöl, showing morphological features and several mapped spawning areas

The only fish species that lives and reproduces in the Spöl is the brown trout (*Salmo trutta fario*). The trout population in the River Spöl between the Livigno and Ova Spin reservoirs is isolated by reservoir dams and discharge gauging stations. The status of the trout population has been evaluated several times since 1990 by electro-fishing (Rey & Gerster, 1991), and more recently (2000 –

2010) the changes of habitat distribution and the status of brown trout populations are and will be investigated by Ortlepp & Mürle (2010).

2 MATERIAL AND METHODS

2.1 *Monitoring Program*

To get an idea and a sufficient database to describe the quality of the interstitial a three-year-monitoring-plan was developed covering both abiotic and biotic monitoring. Therefore in the beginning of December 2009 a total of 9 artificial spawning redds were constructed whereby all of them are located near natural spawning redds. In each artificial redd numerous abiotic and biotic measurements are carried out.

Abiotic Monitoring:
Next to the artificial spawning redds sediment samples were taken in two different sediment layers. The upper layer (UL) consists of the first 10 cm while the lower layer (LL) is between 10 - 20 cm. To determine grain size characteristics the sediment samples were dry sieved using following sieve sizes in mm (63, 31.5, 16, 8, 5, 2, 0.63, 0.2, 0.063, 0.002). The dry sediment masses ranged from 18.72 kg to 9.12 kg. These masses achieve bulk sampling criteria according the German norm DIN 18123. For all samples the weighting of the single fractions did not differ more than 1 % from the total dry weight.

Additionally, the dissolved oxygen (DO) content was measured next to the artificial redds using optodes in two different sediment depths (10 cm, 20 cm) which is similar to the natural depth of buried eggs. In total 12 DO-probes were installed using a modified version of the standpipe technique developed by Niepagenkempner et al. (2002). The interstitial water is sucked through a tube in a metal standpipe into a measuring cylinder where the optode is located. It is important that the whole instrument is water- and airtight, so that no air and surface water can get into the measuring cylinder. To measure the absolute content of DO the interstitial water temperature is measured simultaneously.

To generate a digital terrain model (DTM) of the study site cross-section were measured using a total station. For the river reach of 350 m approximately 4000 topographical points were measured to generate the DTM. For hydrodynamic calculations and calibration purposes more than 100 water levels were measured over a known discharge hydrograph.

To run the sediment-transport-model additional sediment analyses were taken using photosieving (Graham et al. 2005). Photosieving is a new method to get grain size distribution through digital imaging and autocorrelation analyses. The method aims to achieve satisfactory characterization of grain sizes while simultaneously reducing the time effort in field and laboratory. Over the whole study site totally 18 photo samples were taken with additional calibration images of certain grain sizes. The analyses are still in progress.

To calibrate the vertical hydraulic gradient of the 3D-sediment-transport-model vertical velocity profiles were measured near the artificial redds using an Acoustic Doppler Velocimeter (ADV).

As temperature is one major parameter that controls the timing of the development stages during incubation it is recorded continuously using temperature-logger giving values in 15min intervals.

Discharges and hydrographs are provided by the Federal Office for the Environment (FOEN) in Switzerland as operator of the nearest gauging station Punt dal Gall (Fig. 1).

So far two field campaigns were absolved including one artificial flood (September 2009) with a peak flow of 40 m³/s.

Table 1 gives an overview of the measured abiotic data before and after the flood.

Table 1. Overview of measured abiotic data before and after the flood in September 2009

Parameters	before	after
Hydrographs	x	x
Topography	x	x
Dissolved Oxygen	-	x
Sediment Samples	x	x
Photosieving	x	x
Velocity Gradients	-	x
Temperature	x	x

According to the measured bed level changes as well as the changes in sediment conditions the sediment-transport model will be calibrated to ensure high quality of model results.

While the temperature and discharges are measured continuously the DO, photosieving, and velocity gradients are measured monthly. All parameters (including the topography) are directly measured before and after each artificial flood.

Furthermore it is planned to use the freezecore technique to gain undisturbed sediment samples of the riverbed composition.

Biotic Monitoring:
To estimate the effect of changed environmental conditions on survival rates from egg fertilization to fry emergency of brown trout fine mesh screen cylindrical capsules were buried in each artificial redd. The technique of inserting egg capsules in

the substratum was firstly developed by Scrivener (1988) but it proved to be unsatisfactory, because of the size of capsules and insertion tube, which had to be hammered down through the gravel and thus disturbed the riverbed. Therefore a modified design of the miniaturized capsules of Dumas (2006) was constructed. The capsules were filled with 10 eggs separated by small gravels to avoid fungal contamination by dead eggs. The incubation capsules are 9 cm long and 0.9 cm in diameter cylindrical tubes made out of 1.4 mm mesh stainless steel netting (Fig. 2, left) able to retain hatched fry. The two ends of the cylinder were sealed by a plastic stopper equipped with approx. 60 cm long nylon lines. In each artificial redd 3 capsules were buried to examine the survival rate at intermediate stages of egg development (e.g. hatching).

Additionally, traps (Fig.2, right) for emergent fry were constructed using one incubation tube with a 1.4 mm mesh and a second tube as trap connected to the incubation tube by a screwed lid. Both cylindrical tubes are identical in design (20 cm x 12 cm).

Figure 2.Exemplary egg-capsule (left) and a trap for emergent fry (right)

For each stage during the development (e.g. eyed-stage, hatching) one capsule is controlled and the survived eggs are counted. The emergent tubes will be controlled at the end of reproduction to get the total survival rate.

In the study site of River Spöl totally nine artificial redds were constructed. In each of them three capsules were buried with one trap for the emergent fry. The result of the biological monitoring is not yet finished.

2.2 *Modelling Sediment-Transport*

To simulate the morphodynamic processes induced by the artificial floods but also the changing sediment conditions during the long low flow period a three-dimensional numerical model is required that is able to simulate vertical hydraulic gradients, several sediment layers and graded sediment transport. Regarding the interstitial processes especially the grain size distributions in the different sediment layers and the vertical hydraulic gradient near the river bed are important. While during the artificial flood the bed load transport is significant for mixing sediment and bed level changes the suspended load is of major importance during the long low flow period with input of fine sediment due to snow melt and rainfall.

The applied 3D-sediment-transport model is SSIIM (Olson, 2009). SSIIM is a free CFD software and is the abbreviation for Sediment Simulation In Intakes with Multiblock option. The main strength of SSIIM is the capability of modeling sediment transport in three dimensions with moveable bed in a complex geometry. This includes multiple sediment sizes, sorting, bed and suspended load, bed forms and effects of sloping beds. The latest modules for wetting and drying in the unstructured grid further enables complex geomorphologic modeling. Given to the simulated grain size distributions several substrate indices related to DO can be calculated. Dirksmeyer (2008) has shown that the percentage of fine sediments is significantly correlated with the DO. Together with additional parameters taking the whole grain size distribution into account like the sorting coefficient or the Fredle-Index the results of SSIM provide substantial input information for the multivariate fuzzy-logical model.

SSIIM solves the Navier-Stokes equations with k-ε model on a three-dimensional non-orthogonal grid. A control volume method is used for discretization, together with the power-law scheme of the second order upwind scheme. To couple pressure the SIMPLE method is used. An implicit solver is used, producing the velocity field in the geometry and the convection-diffusion equations for different sediment sizes.

Another benefit of SSIIM is its capability to be easily adapted and implement additional code; e.g. the integration of an additional sediment-transport equation or porosity model etc.

2.3 *Multivariate fuzzy-logical Approach*

The major objective of this research is to predict the quality of the hyporheic interstitial in terms of reproduction of gravel spawning species. Therefore an interdisciplinary approach is required involving all relevant processes. The plan is to combine several results of the numerical modeling and correlate the combined effect to the measurements of DO as the most significant parameter for hyporheic quality (Ingendahl, 2001) by using the fuzzy-logical approach of CASiMiR.

Before fuzzy-modelling can be performed a parameter analyses is necessary to determine the dominating processes and parameter influencing the interstitial quality.

Fuzzy-Logic allows calculations with imprecise (fuzzy-) information. The basic elements of fuzzy-logic systems are overlapping membership-functions described by so-called fuzzy-sets. All input-parameters are described in such sets and are directly linked to the output-parameters (DO) using an inference rule system. E.g. Dirksmeyer (2008) states that a DO below 5 mg/l results in no reproduction, while between 5-7 mg/l the reproductions might be affected and above 7 mg/l would be no negative impact. This could be directly transferred into a fuzzy-set with membership-functions of “low”, “medium” and “high” DO-content.

Fuzzy-logic has proven to be an appropriate modelling technique to deal with these ecological gradients because the boundaries between the classes of the input variables are overlapping und thus reflects these gradual transitions (Salski, 1992, Mouton 2008)

Given the fact that multivariate approaches take interactions of physical variables into account in order to determine interstitial quality and given to the uncertainty due to the complexity of interstitial processes, a multivariate fuzzy-logical approach is an appropriate tool for simulating the quality of the hyporheic zone for reproduction of gravel-spawning fish.

3 FIRST RESULTS & OUTLOOK

The beginning of monitoring was in September 2009 with the first artificial flood. So far the collected and analyzed data are related to this single event and the changes in the sediment conditions are described below.

3.1 *Bed Level Changes*

The artificial flood with a maximum peak of 40 m^3/s induced morphodynamic processes. The sedimentation and erosion areas are visualized in Figure 3. The black areas in Figure 3 indicate erosion while the grey areas indicate deposition of sediments.

There is no distinctive trend in erosion or sedimentation. The 10% and 90 % quantiles are between -0.14 m and +0.13 m. Only in local spots and at the borders of the wetted area of the low flow period are bigger bed level changes. The mean deviation is 0.08 m that barely exceeds the uncertainties regarding the interpolation of measured topographical points. These moderate bed level changes were hardly surprising as spatial bed alterations are expected at discharges between 70 m^3/s and 90 m^3/s (Jäger, 1991).

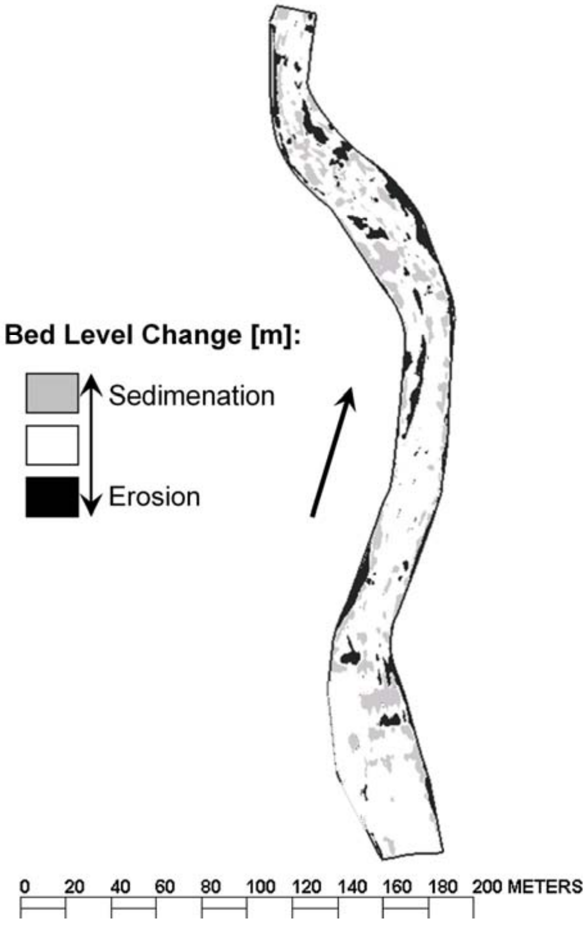

Figure 3. Measured bed level changes given to the artificial flood in September 2009

3.2 *Grain Size Analyses*

Next to the bed level changes the sorting processes and mixing of grain sizes in different sediment layers are of interest.

Figure 4 shows exemplary the results of sediment sieving of one sediment sample before and after the artificial flood (upper and lower sediment layer).

For the upper sediment layer (10 cm), Fig. 4 indicates the coarsening of the grain size distribution for the whole range of grain sizes. In the lower layer (10-20 cm) it can be seen that mainly the sediment range between 0.5 and 5 mm was mobilized due to the flood.

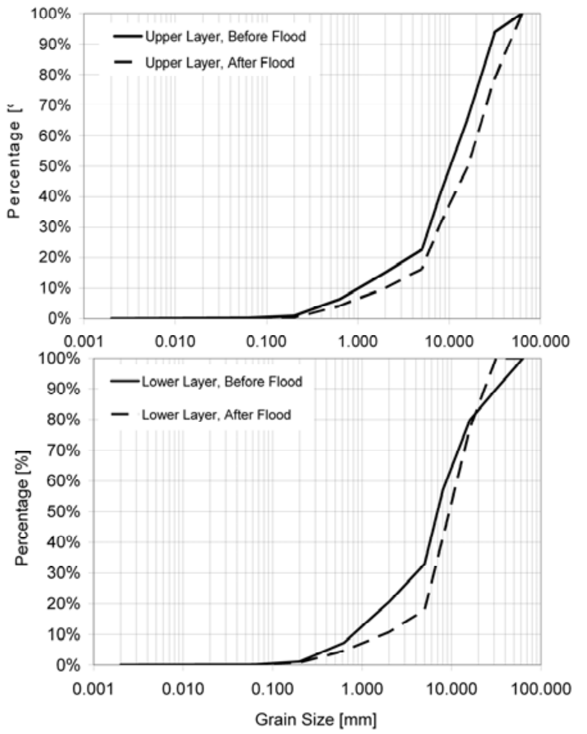

Figure 4. Sieving results before and after the artificial flood. Samples were divided in an upper layer (10 cm) and lower layer (10-20cm)

For grain sizes larger than 20 mm the distribution before the flood was coarser compared to the distribution after the flood.

Given to the sieving results of the sediment samples various sediment indices analyzing the grain size distribution were calculated.

The characteristic grain size (Meyer-Peter, Müller, 1948) is a representative grain size for a sieve curve.

$$d_{ch} = \frac{\sum_{i=1}^{n}\left(\Delta p_i \cdot d_{k,i}\right)}{100\%} \tag{1}$$

where d_{ch} = characteristic grain size, Δp_i = percentage of fraction i, $d_{k,i}$ = mean grain size of fraction i.

The sorting index (SO) (Shirazi & Seim, 1981) of a grain size distribution considers the filling of finer fractions in the interstices of coarser grains. This means, the higher the SO the lower the pore spaces of the investigated sediment layer.

$$SO = \sqrt{\frac{d_{75}}{d_{25}}} \tag{2}$$

where SO = sorting coefficient, d_{75} =g rain size for which 75% is smaller in size, d_{25} = grain size for which 25% is smaller in size.

The Fredle-Index FI was subsequently proposed as an index of gravel quality that combined a measure of central tendency (d_g=geometric mean) with a measure of dispersion (Lotspeich & Everest, 1981).

$$FI = \frac{d_g}{SO} \tag{3}$$

$$d_g = \sqrt{d_{84} \cdot d_{16}} \tag{4}$$

where FI = Fredle-Index, d_g = geometric mean, d_{84} = grain size for which 84% is smaller in size, d_{16} = grain size for which 16% is smaller in size.

The last parameter investigated is the percentage of fine sediments in the grain size distribution. The use of “percent fines” in fish biology literature is originated with a study relating incubation success to gravel size be McNeil & Ahnell in 1964. In this study fine sediments are defined as a grain size > 2mm.

In Table 2 the various analyzing methods are listed for the grain size distribution shown in Figure 4.

Table 2. Results of sediment analyses (UL=Upper Layer, LL=Lower Layer)

Substrate Index	Upper Layer		Lower Layer	
	before	after	before	after
d_{ch}	14.19	20.47	12.18	11.62
Sorting-Index [-]	1.98	2.09	2.16	1.62
Fredle-Index [-]	3.39	6.58	2.71	5.71
Percentage of Fines	15.25	10.45	20.75	10.75

The characteristic grain size d_{ch} as a representative value of a sieve curve does not provide adequate information about sediment properties to conclude about the interstitial quality but gives a first hint about present grain sizes. The importance of d_{ch} is decreasing with increasing heterogeneity of the grain size distribution. For the analyzed grain size distribution a coarsening of the upper layer can be determined while for the lower layer d_{ch} is slightly decreased.

The Sorting-Index (SO) shows for the upper layer a slightly higher value after the flood meaning less pore spaces compared to the sediment conditions before the flood. But especially the SO of the lower layer declined significantly. This may be a sign that the fine sediments are flushed out of the gravel matrix leading to a higher permeability in the lower layer.

The Fredle-Index (FI) increased in the upper layer indicating higher pore spaces than before the flood which is in contrast to the conclusion according to the SO. For the lower layer the FI increased crucially supporting the result of SO.

The percentage of fines shows on the one hand the higher amount of fine sediment in the lower layer and on the other the coarsening of both layers. While the percentage of fines is reduced by approx. 30% in the upper layer the fines could be halved in the lower layer.

Regarding the biological interpretation to assess the substrate indices in terms of interstitial quality or reproduction success thresholds are given by Dirksmeyer (2008). The characteristic grain size should have a minimum value of 14 mm that is only provided in the upper layer. Even after the flood the lower layer does not fulfill this criterion. For the SO of natural spawning areas he gives a range of 3 – 5. Both sediment layers of River Spöl have lower SO indicating an insufficient sediment-mixing. The minimum FI-value is 3.5 for successful reproduction. The FI-values in Tab. 2 clearly show the positive effect of the artificial flood. For both layers a significant improvement could by achieved with an increase from 3.4 to 6.6 in the upper layer and from 2.7 to 5.7 in the lower layer. Regarding the fine contents (< 2mm) Soulsby et al. 2001 give a rule of a thumb not to exceed 15 %. Both layer show a reduction of fine sediments after the flood below 15 % proving that the flood is flushing out fine sediments.

The results of the biological interpretation indicate the changing substrate conditions due to the flood. While the characteristic grain size and the sorting-coefficient is not in the optimal range for successful reproduction the flood-induced substrate changes significantly improve the Fredle-Index and reduce the contents of fine sediments. To get a overall res not a single index assessment is not sufficient and approaches considered multiple parameters are required.

4 DISCUSSION

The bed level changes give a hint where sediment dynamics highly occur. Especially the erosion depth is of importance regarding the deposited eggs in the spawning redds of brown trout. As in this study site floods only occur artificially and not during the reproduction period of brown trout this represents not a problem.

The different analyses of the grain size distributions are a first approach to investigate significance of existing analyzing methods to assess interstitial quality. So far no combined effects are considered nor are the parameter analyses about the most significant parameter finished. Furthermore, additional parameters like the porosity, permeability, turbulence or hydraulic gradients are required to consider sediment infiltration (Sear et al. 2008)

Other aspects are the sediment indices themselves:

According to Klingeman et al. (1998) the Fredle-Index can be criticized on at least three grounds. The first is that there is no physical reason to expect that a measure of d_g divided by a measure of dispersion yield a meaningful index of gravel quality. Secondly, the geometric mean is calculated using d_{16} and d_{83} and is thus influenced by the extremes of the distribution. The last aspect is the calculation of the dispersion using d_{25} and d_{75} covering only 50 percent of the whole distribution. However, the FI-values might give a fmore irst qualitative hint about the available pore space.

The percentage of fine sediments below a given size is influenced not only by the amount of fine sediment but by the other sized present as well, because it is simply a percentage of the total. E.g in many studies large grain sizes are excluded from the analysis, this artificially increases the amount of finer fractions (Kondolf & Wolman, 1993). On the other hand the amount of fine sediment could effect the permeability of gravels depending on framework grain size (Sear et al. 2008) that have to be considered via sediment infiltration.

Regarding the quality of the interstitial for the reproduction of brown trout the objective is to combine several sediment indices by the multivariate fuzzy-logical approach with the target value dissolved oxygen and not to use only one single index. Therefore also no sediment parameters are of interest. E.g. the hydraulic gradient in the surface water or the influence of groundwater or the exchange processes of these two compartments may play a major role in assessing the interstitial quality. One of the largest advantages of using fuzzy-systems is that additional parameters can be implemented easily e.g. hydraulic gradients, biological parameter or exchange coefficients like the leakage coefficient (Herbert, 1970). Furthermore fuzzy-systems dealing automatically with a certain uncertainty giving to the overlapping membership-functions in the fuzzy-sets which is necessary as not all complex interstitial processes can be implemented deterministically.

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