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# Modelling fish habitat dynamics in hydropeaking rivers considering different morphology and habitat requirements

## Current state, needs for improvement, and guidelines for application

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# Summary

Habitat suitability modelling is currently the only methodology capable of providing quantitative estimates of the ecological effects of hydropeaking mitigation. Two aspects have remained understudied in research on the effects of hydropeaking and respective mitigation measures: the impact of the river morphology on habitat availability and persistence, and the effect of natural variability in the biological input data on model outcomes.

The present interdisciplinary study aimed at i) analysing the availability and variability of habitat suitability data determined across different study systems for two fish species, ii) quantifying the impact of variability in fish habitat suitability data on the outcome of habitat suitability modelling for three different morphologies under three different flows, and iii) determining the hydraulic and ecological effects of instream structures.

The available habitat suitability data was inconsistent. We observed a pronounced variability in the suitability curves across studies, also within an age class of the same species. Our results highlight the importance of the interaction between morphology and flow: The near-natural reach provided the largest amount of suitable area (SA) for both species and the channelized reach the smallest. This pattern was consistent across the three different flows. Datasets from the same study tended to agree in which river cells had the highest suitability.

It was shown that habitat quality and availability is much higher in a morphologically heterogeneous near-natural reach compared to a moderately and heavily modified one. Furthermore, the area of habitats with a low sensitivity against flow fluctuations was significantly higher in the heterogeneous reach. No general relationship between certain types of gravel bars and impact on habitats could be found. However, a permanently wetted side channel was identified as most advantageous morphological feature to mitigate hydropeaking impacts.

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# 1. Background

River managers and scientists are increasingly asked to quantitatively forecast the environmental outcome of planned management measures such as morphological rehabilitation, hydropeaking mitigation or the re-establishment of fish passage at dams. Such forecasting aims i) at increasing the efficiency of management measures by identifying the optimal compromise between economic costs and environmental benefits, and ii) at providing baseline or "before-" data for success evaluation once the measure is implemented. In some countries, such as Switzerland, environmental forecasts are becoming a recommended prerequisite for federal funding for hydropeaking mitigation. In other words, results from environmental forecasts play an increasingly crucial role in the decision-making process, and standardized protocols which generate robust and reliable data are required (Palmer et al. 2005, Parasiewicz et al. 2013).

Habitat suitability modelling is a common methodology of providing environmental forecasts in decision making for river management, particularly when planning hydrological measures such as environmental flows or hydropeaking mitigation. A variety of models are used (Bovee et al. 1998, Hauer et al. 2009, Jorde et al. 2000, Parasiewicz and Dunbar 2001). The models link the hydro-morphologic conditions in a river with the habitat requirements of selected animal and plant species. The degree of consensus is used as a measure of habitat suitability ranging usually between 0 (unsuitable) and 1 (perfectly suitable).

Traditionally, hydro-morphologic conditions are considered by a set of abiotic parameters, such as water depth, flow velocity and substrate, i.e. parameters that can be measured or modelled and that are expected to integrally reflect anthropogenic impact on hydro-morphological conditions (Stalnaker et al. 1995). Habitat suitability for animal and plant species is usually derived from either field and lab data, or from literature review and expert judgement. Transferability of habitat suitability data is often assumed across space (e.g. using data that originate from rivers other than the study systems), through time (e.g. applying seasonal data for year-round forecasts), and/or across study designs (by combining data gathered with different methods). However, the assumption of transferability neglects that habitat suitability is driven by a myriad of factors, both biotic and abiotic that operate across multiple spatio-temporal scales. For instance, river reaches differ in habitat diversity, depending on the climate, topography and geology of the catchment (Frissell et al 1986). Species respond to different habitats with local adaptations (Blanquart et al. 2013, Kawecki and Ebert 2004), which often occur across fine spatio-temporal scales (Richardson et al. 2014). Habitat suitability has been shown to vary on a seasonal to diurnal scale (Mäki-Petäys et al. 1997), depending on the life-cycle of the species and the prevailing hydrologic conditions (e.g. floods; Holm et al. 2001). Biotic interactions, such as competition or predation, can also influence habitat use and therewith the determination of habitat suitability (Harby et al. 2004). Differences in habitat suitability can have strong impacts on the outcome of habitat suitability models (Holm et al. 2001). Despite these potential influences, it has also been found that habitat suitability data were transferable between rivers and that particularly for young fish habitat requirements related to flow velocity were comparable across rivers (Nykänen and Huusko, 2011, Teresa and Cassati 2013).

Apart from the biological input data, river morphology must also be carefully considered when forecasting hydropeaking mitigation measures. To date, hydrologic and hydraulic conditions have been the main factors used for planning mitigation measures, whereas the role of river morphology has been largely neglected (Person 2013). This is problematic, given that river morphology drives the effects of hydropeaking in two ways. First, river morphology directly affects the hydrologic dynamics, e.g. by attenuating peak flows due to roughness (Meile 2007). Second, river morphology shapes the diversity of aquatic habitats and their spatial configuration (Ward et al. 2002), with refuge habitats for adverse conditions (e.g. peak flows) existing in direct proximity to other suitable habitats. The few available studies indicate that in reaches of poor morphology, even complete (hydrologic) mitigation of hydropeaking does not result in a substantial improvement of ecosystem functioning (Schneider & Noack 2009). This result is mainly due to the absence of key habitats in such rivers. In other words, a global definition of hydraulic and hydrologic thresholds such as maximum peaking ratio or dewatering rates does not account for the complexity of the problem as the same threshold can have significantly different outcomes when applied to morphologically different river reaches (IRKA 2011).

# 2. Goals of the project and structure of the report

As described earlier, two aspects have remained understudied in research on the effects of hydropeaking and respective mitigation measures: the impact of the river morphology on habitat availability and hydropeaking mitigation, and the natural variability in the habitat requirements of fish in space and time. With this interdisciplinary study, we tackled three objectives. First, we analysed the availability and variability of habitat suitability data determined across different study systems for two fish species, brown trout (*Salmo trutta*) and grayling (*Thymallus thymallus*). Second, we quantified the impact of variability in fish habitat suitability data on the outcome of habitat suitability modelling under nine different hydro-morphological scenarios in river reaches affected by hydropeaking (i.e. three morphologies under three different flows). Third, the model results were used to determine the hydraulic and ecological effects of instream structures.

We hypothesized (i) that the availability of habitat suitability data is biased towards traditionally well-studied conditions (low to medium flows, spring to autumn months) whereas habitat suitability at high flows or during winter months has been understudied (Weber et al. 2013), (ii) that variability in habitat suitability within species and age classes results in highly variable model outcomes regarding the location and area of suitable habitat, (iii) that the area of suitable habitat for young fish of both species is highest under low flow in reaches of near-natural morphology (Hauer et al. 2012), and (iv) that suitable habitats are more stable in near-natural reaches than in channelized reaches under fluctuating flows.

Our investigation aims to provide recommendations for the informed use of available habitat suitability data and thereby maximise the effectiveness of habitat suitability models for decision-making in river management.

The present report is structured into two parts followed by a general conclusion. In part 1, data availability and model outcomes under nine different hydro-morphological conditions are presented. In part 2, the impact of river morphology on hydropeaking effects is discussed, with a special focus on instream structures for hydropeaking mitigation.

# 3. Part 1: Data availability and model outcomes

## 3.1. Methods

### 3.1.1. Literature search and availability of habitat suitability data

A systematic search of relevant books and the peer-reviewed literature via the Web of Science database (Institute for Scientific Information; Thomson Reuters Corp.) was used to identify studies for inclusion in our analysis. We restricted our search to two fish species that are common in European rivers affected by hydropeaking: brown trout (*Salmo trutta*) and grayling (*Thymallus thymallus*). The following terms were considered for literature search: microhabitat, habitat, preference, selection, modelling, preference curves and suitability. Additionally we asked experts in the field for unpublished data (grey literature). For the sake of comparability we focused on studies defining habitat suitability as the ratio of used habitat to available habitat (category III habitat suitability criteria according to Bovee 1986; specific approach by Bovee 1982; Baltz 1990).

All collected data was organized in a Microsoft Access database containing the following variables: name of the authors, title of the study and year of publishing, country, name of the river, name and coordinates of the sampling reach, biogeographic region [alpine, atlantic, boreal, continental, mediterranean; European Environmental Agency 2002], morphological state [artificial, near natural], flow regime [glacial, groundwater fed, nival, pluvial, pluvio-nival, nivo-glacial; Weingartner and Aschwanden 1992], hydrological state [near-natural, hydro-peaking, residual flow, other impacts], mean annual flow [m3/s], mean water temperature [°C], stocking history [stocking, no stocking], season of sampling [spring, summer, autumn, winter], daytime, year of sampling, flow and temperature during the sampling, flow velocity [m/s], depth, width and length of the sampled river reach [all in m], species, age class [redd, 0+ (young of the year fish), 1+ (fish between one and two years), adults (> 2 years)], body length [mm], sample size, sampling method, fish density, community composition [sympatry, allopatry] and the habitat suitability based on used and available habitat for the parameters substrate, flow velocity, water depth and cover. Where multiple habitat suitability data were available within a study, e.g. stemming from different seasons, they were handled as separate entries in the database (hereafter called datasets).

Habitat suitability data were reported as suitability curves. These curves were either based on raw data and contained usually multiple peaks (multimodal curve), or the raw data had been smoothed resulting in a unimodal curve. Our comparisons are based on smoothed curves, meaning that, if literature data was reported in an unsmoothed, multimodal curve, one of the co-authors (MS) applied a smoothing. The smoothing was performed in order to overcome discontinuities in suitability curves usually caused by small number of samples or unbalanced availability of certain habitat conditions in natural environments.

### 3.1.2. Habitat suitability modelling

Habitat suitability modelling was performed with the GIS version of the CASiMiR habitat simulation software (IRKA 2011; Jorde et al. 2000) using a mesh with cell sizes varying as a function of the topographical heterogeneity (e.g. ~130’000 cells for the near-natural reach $M_{nat}$, see below). Each cell was described by a single value for water depth, flow velocity and substrate. We focused our analyses on two metrics, SA and SI: SA is the area of suitable habitat (Person 2013) and is based on SI, the suitability index for each individual cell. SI is calculated as the geometrical mean suitability out of the suitability values for the parameters flow velocity, water depth and substrate (Person 2013)

$$SI_i(Q) = \sqrt[3]{S\big(H_i(Q)\big) * S\big(U_i(Q)\big) * S\big(S_i(Q)\big)}$$

where:

$SI_i(Q)$ describes the suitability index in cell i for flow $Q$

$S(H_i(Q))$: suitability value for depth $H_i$ for flow $Q$

$S(U_i(Q))$: suitability value for flow velocity $U_i$ for flow $Q$

$S(S_i(Q))$: suitability value for the substrate $S_i$ for flow $Q$

SI calculation was done with the smoothed data for all datasets in the database. For SA calculation, the total area of all cells with an SI >0.5 was determined (Person 2013).

We modelled SI and SA in three reaches of different morphology of the Alpine Rhine River, an 8th order river in Eastern Switzerland (Figure 1): a 1'184 m long heavily channelized reach near Koblach ($M_{chan}$), a 1'045 m long, moderately channelized reach with alternating gravel bars near Buchs ($M_{alt}$) and a 1'585 m long near-natural reach with braided morphology near Mastrils ($M_{nat}$). A two-dimensional hydraulic model was available for all three reaches from earlier studies (IRKA 2011). Three different flows within the range of reach-specific hydropeaking hydrographs were used (IRKA 2011), representing reach-specific off-peak flow, $Q_{off}$ (27, 65 and 106 $m^3/s$ for $M_{nat}$, $M_{alt}$ and $M_{chan}$, respectively), medium flow, $Q_{med}$ (110, 130 and 196 $m^3/s$) and peak flow, $Q_{peak}$ (188, 190 and 285 $m^3/s$).

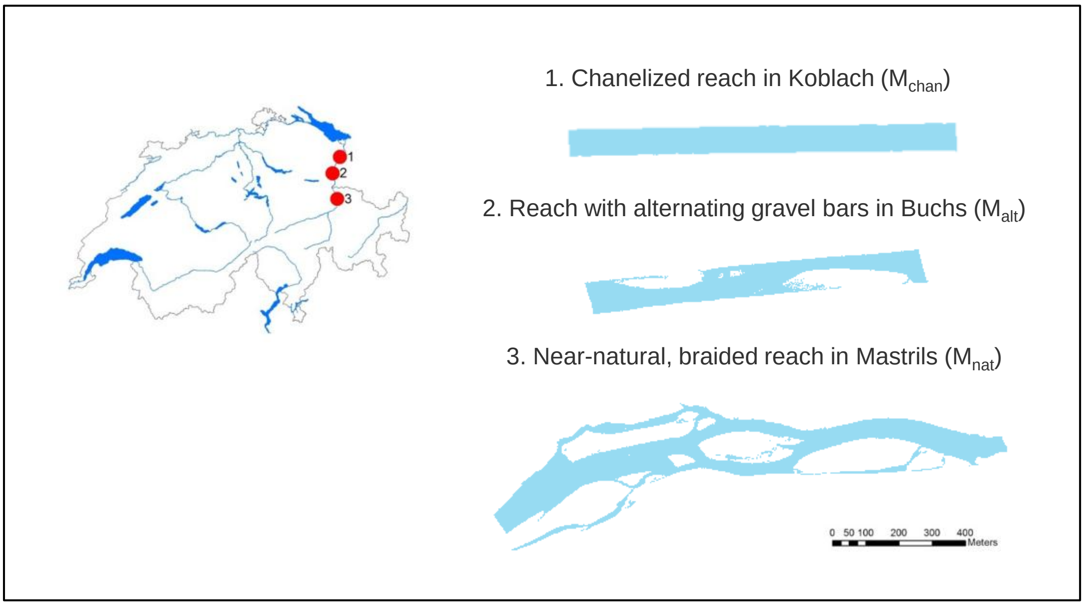



**Figure 1** **Location and wetted area (at $Q_{med}$) of the three study reaches with different morphology. Flow direction is from left to right.**

By transferring habitat suitability data from one river ("source river") to the other ("modelled river"), model outcomes can be influenced by the fact that suitable habitat conditions in the source river are lacking in the modelled river. In order to control for this, we modelled SI and SA for a "virtual river" (Figure 2) with cells covering all combinations of the three parameters depth, flow velocity and substrate.

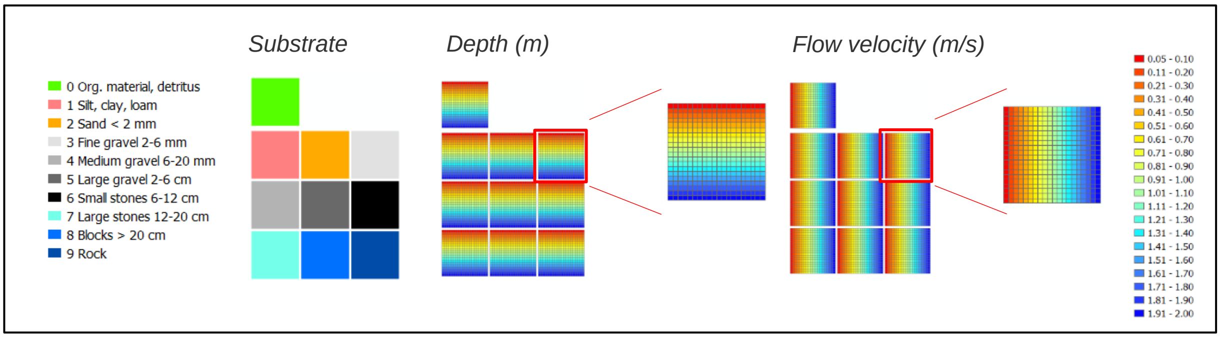



**Figure 2** **Virtual river containing all possible combinations of the three parameters substrate, depth and flow velocity. Total number of cells = 10 x 20 x 20 = 4000.**

### 3.1.3. Comparison of model outcomes under different hydro-morphological scenarios

Model outcomes for the different datasets were compared at two different spatial scales – the reach level (for SA) and the cell level (for SI).

#### *3.1.3.1. Reach-level comparison*

The impact of river morphology and flow on SA was analyzed by means of a two-factor ANOVA with repeated measures (IBM SPSS Statistics 20.0.0, 2011). As introduced earlier, both factors contained three factor levels representing morphological integrity ($M_{nat}$, $M_{alt}$, $M_{chan}$) and flow conditions ($Q_{off}$, $Q_{med}$, $Q_{peak}$), respectively. In order to account for a potential effect of the input data, the datasets were included as repeats. Given that the wetted area varied among the study reaches, SA was standardized to SA [$m^2$] / river length [m]. The standardized values were $\log_{10}$ transformed in order to achieve normal distribution for statistical analysis.

#### *3.1.3.2. Cell-level comparison*

The similarity among datasets of SI values in each cell of the study reaches was visualized using a dendrogram based on Euclidean distance. This is the distance between each pair of datasets across multidimensional space, where the suitability index SI of each cell in the river reach provides the value for each dimensional axis (i.e. there are as many dimensional axes as cells). The dendrogram was generated using hierarchical cluster analysis based on a hierarchical agglomerative algorithm with group-average linkage in the multivariate statistics package PRIMER 6 (PRIMER-E 2008). The analysis was conducted for the virtual river and for the near-natural reach $M_{nat}$ at medium flow ($Q_{med}$).

## **3.2. Results**

### 3.2.1. Data availability

#### *3.2.1.1. Database*

We selected 24 studies, published in peer-reviewed journals or as grey literature between 1989 and 2014, for use in our study (Table 1). 13 studies presented habitat suitability data for trout, 9 studies for grayling, and 2 studies considered both species. From the studies we extracted 105 datasets; 72 for trout and 33 for grayling.

**Table 1: List of studies and datasets, arranged by species and year of publication**

| ***Salmo trutta*** | | | ***Thymallus thymallus*** | | |
|---|---|---|---|---|---|
| Author | Year | Number datasets | Author | Year | Number datasets |
| Belaud et al. | 1989 | 15 | Bullock et al. | 1991 | 4 |
| Bullock et al. | 1991 | 4 | Sempeski et al. | 1995a | 3 |
| Rincón et al. | 1993 | 4 | Sempeski et al. | 1995b | 2 |
| Mäki-Petäys et al. | 1997 | 9 | Guthruf | 1996 | 1 |
| Cortes et al. | 1999 | 4 | Mallet et al. | 2000 | 6 |
| Schneider | 2000 | 1 | Müller et al. | 2002 | 2 |
| Vismara et al. | 2001 | 2 | Nykänen et al. | 2002 | 1 |
| Heggenes | 2002 | 1 | Nykänen et al. | 2003 | 3 |
| Ayllón et al. | 2009 | 6 | Vehanen et al. | 2003 | 2 |
| Gortázar et al. | 2012 | 1 | Nykänen et al. | 2004 | 3 |
| Ayllón et al. | 2013 | 11 | Schneider et al. | In Prep. | 6 |
| Person et al. | 2013a | 2 | | | |
| Person et al. | 2013b | 3 | | | |
| Stakenas et al. | 2013 | 3 | | | |
| Schneider et al. | In Prep. | 6 | | | |
| **Total** | **15** | **72** | | **11** | **33** |

The majority of datasets (51%; 37 datasets) for brown trout were produced in Spain and France, and in France and Finland for grayling (58%; 19 datasets; Figure 3a), respectively. Accordingly, most datasets for trout came from the atlantic region (42%) followed by the alpine and mediterranean regions, whereas the continental region was most represented for grayling (33%; Figure 3b). The datasets were generated in 21 rivers (data not shown). 11 datasets for brown trout were based on observations in multiple rivers and for 20 datasets, river name was not mentioned. Most datasets (78%) described three parameters to characterize habitat suitability (flow velocity, depth and substrate), whereas 13% of studies described four parameters (flow velocity, depth, substrate and cover) and 8% considered only two (flow velocity and depth; Figure 3c). Adult trout and 0+ grayling were species age-classes best represented among the available datasets (31% and 33% of the datasets respectively). Three brown trout studies combined suitability curves across multiple age classes (0+ - adult and 1+ - adult; Figure 3d).

We categorized the time of the sampling into the four seasons spring, summer, autumn, winter, and combinations thereof for sampling over multiple seasons. Datasets for both species covered all seasons, but winter was underrepresented for grayling (0 datasets for winter and 2 for autumn/winter). For a considerable number of datasets, sampling season was not mentioned (10% for trout and 21% for grayling; Figure 3e). Most of the sampling for brown trout was done by electrofishing (68%) whereas most datasets for the grayling were based on expert knowledge (30%; Figure 3f). The composition of the fish community inhabiting the study reach was mentioned for 51 datasets (49%). The brown trout occurred mainly, and the grayling exclusively, in sympatry with other species (Figure 3g). The morphological and hydrological state of the river was not described in many datasets (54% and 33%, respectively), particularly for studies focussing on trout (Figure 3h and i). If the hydro-morphological state was reported, most datasets for brown trout fell in the near-natural category. The datasets for grayling also came mostly from rivers with near-natural morphology, but with impacted hydrology. Most datasets from brown trout were developed in rivers with widths between 5m and 15m (36%) and the grayling datasets in rivers wider than 25m (30%; Figure 3j).

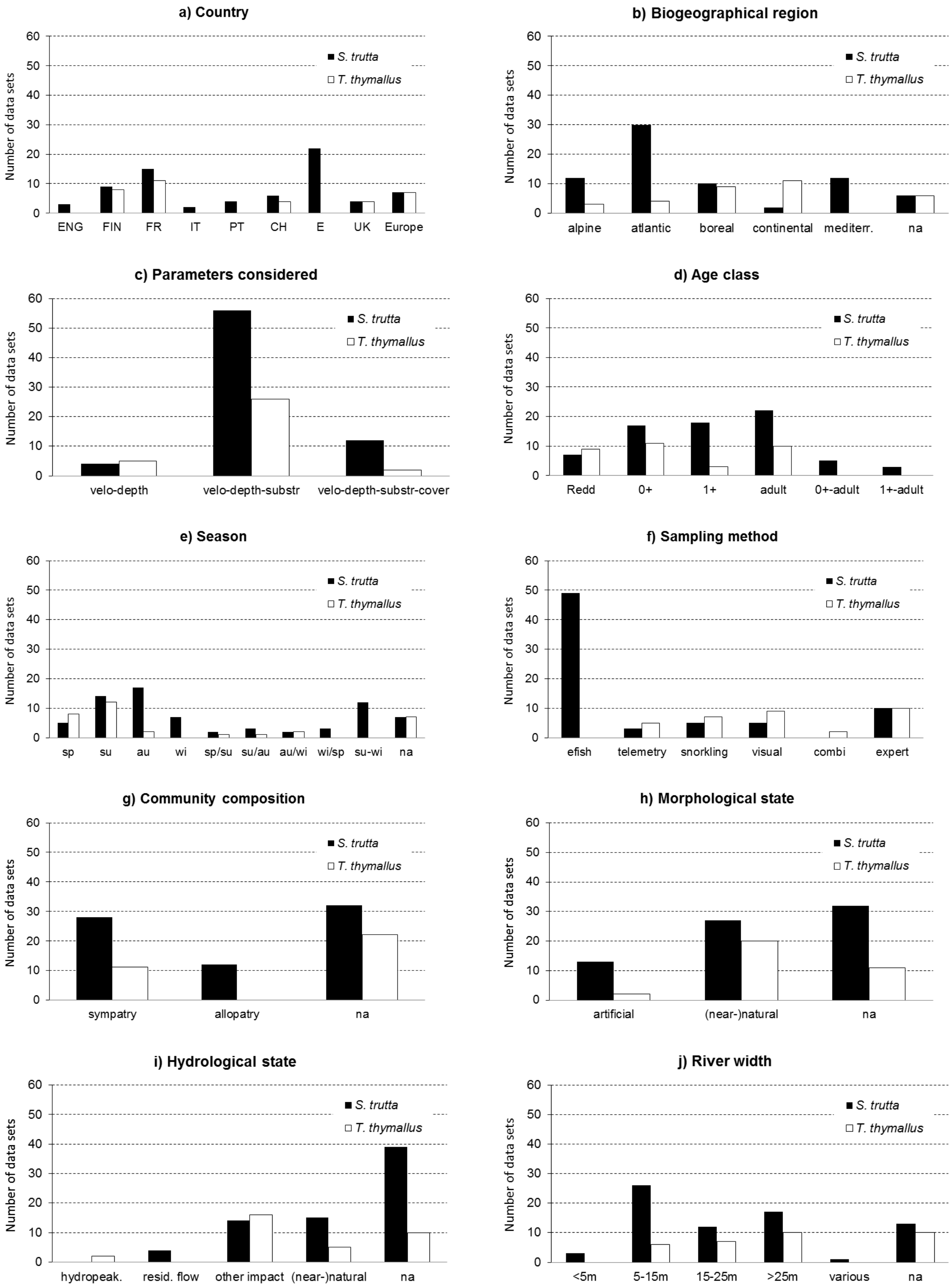



**Figure 3** Data availability (n = 105 datasets): a) country of origin; b) biogeographical region; c) parameters considered for habitat suitability; d) age class; e) season of sampling; f) sampling method; g) community composition; h) morphological state; i) hydrological state; j) river width.

### *3.2.1.2. Suitability curves*

The un-smoothed suitability curves for the three parameters water depth, substrate and flow velocity are shown for different age classes of trout in Figure 4 and grayling in Figure 5, respectively. For both species and all the three parameters there was pronounced variability among studies. For trout, agreement among studies was highest for depth and lowest for substrate. Within the parameter depth, variability was smallest in 0+ trout. For grayling, no pattern could be observed regarding the variability between or within parameters.

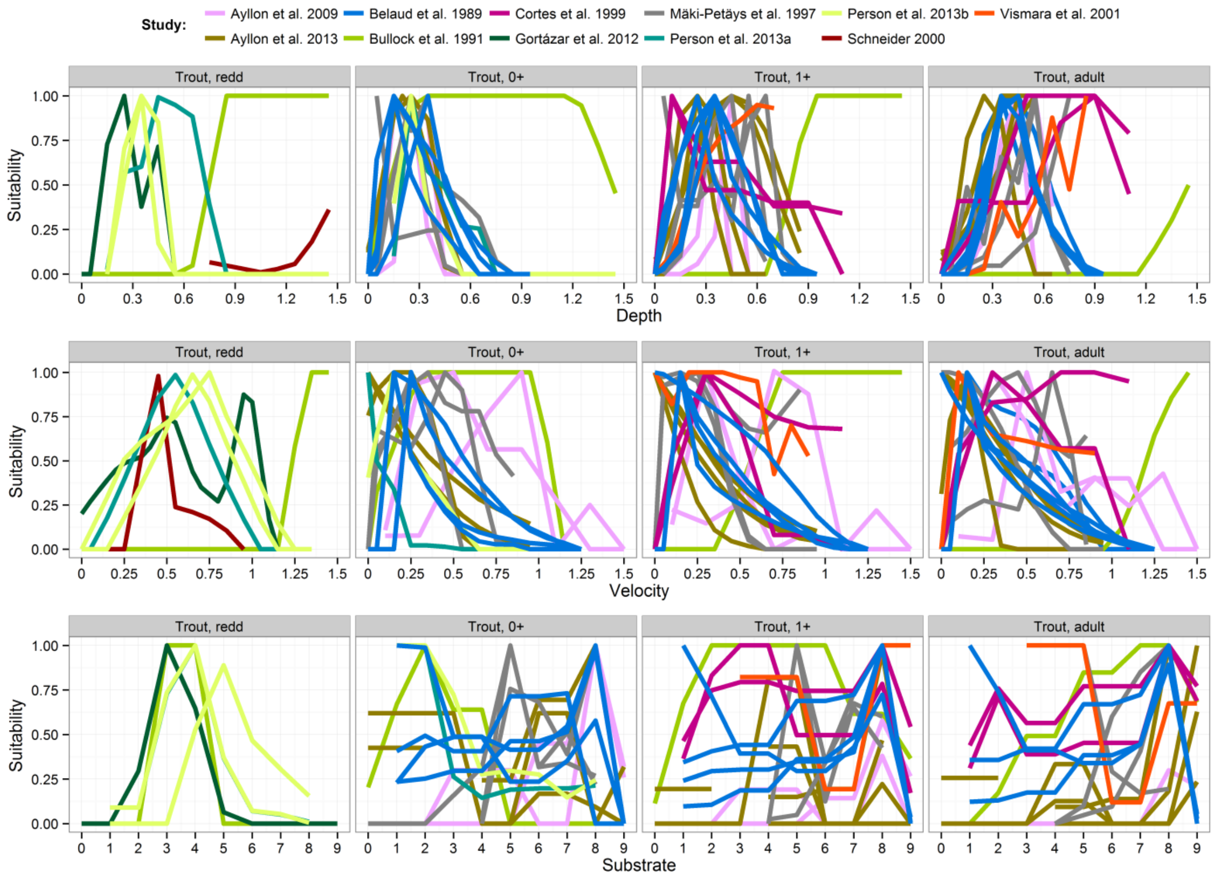



**Figure 4** **Suitability curves for different age classes of the trout for the three parameters depth (in m; first row), flow velocity (in m/s; second row) and substrate (10 grain-size classes; third row). Codes refer to the following substrate classes: 0 = organic material, detritus; 1 = clay, silt; 2 = sand (0.06-2 mm); 3 = fine gravel (2-6 mm); 4 = gravel (6-20 mm); 5 = cobbles (2-6 cm); 6 = pebbles (6 - 12 cm); 7 = boulders (12 - 20 cm); 8 = large boulders (> 20 cm), 9 = bedrock. Studies in which suitability curves were defined across multiple age classes are not shown.**

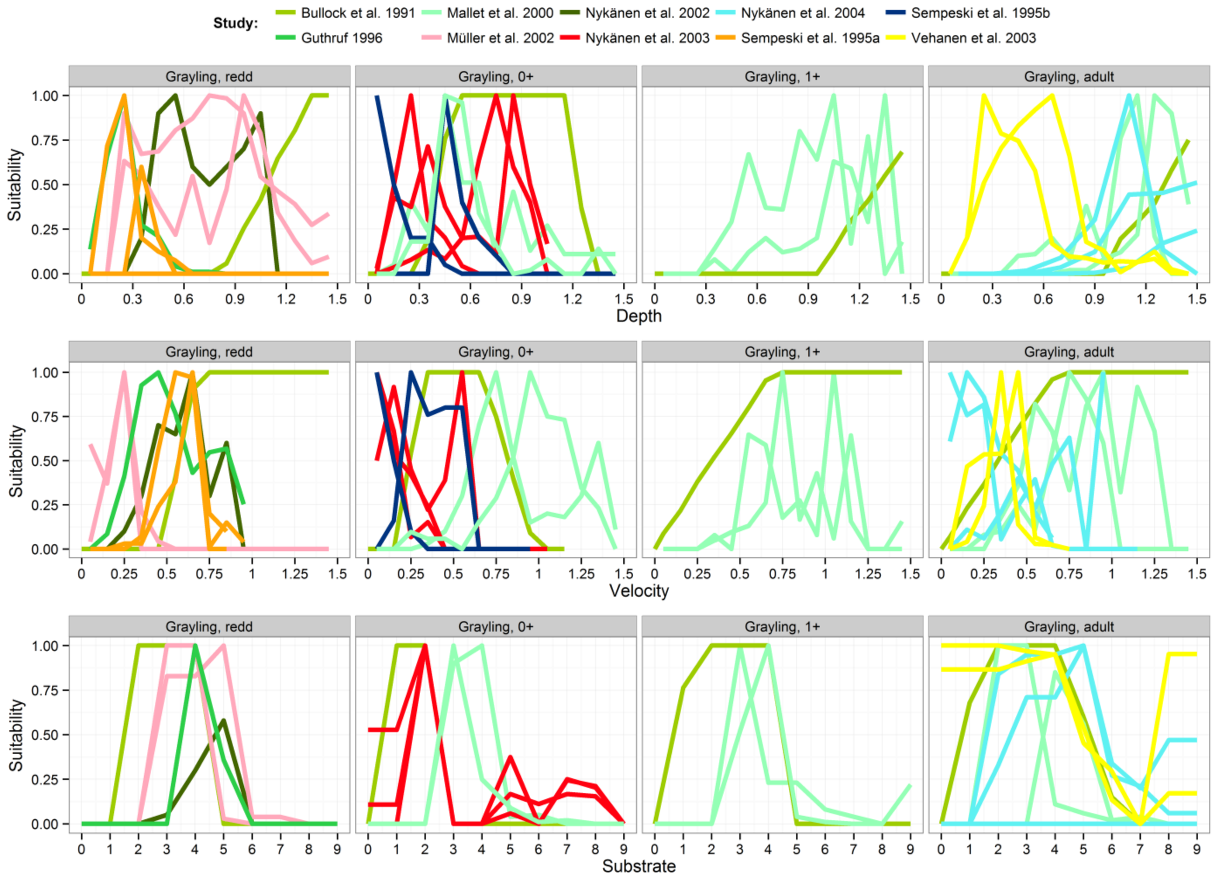



**Figure 5 Suitability curves for different age classes of the grayling for the three parameters depth (in m; first row), flow velocity (in m/s; second row) and substrate (10 grain-size classes; third row). For substrate classes see Figure 4. Studies in which suitability curves were defined across multiple age classes are not shown.**

### 3.2.2. Hydro-morphological conditions in the three reaches and under changing flows

Wetted area at all three flow levels was lowest in $M_{alt}$ (6044 – 7997 $m^2$/ 100m river length at $Q_{off}$ and $Q_{peak}$, respectively) and highest in $M_{nat}$ (8091 – 11845 $m^2$/ 100m). Increase in wetted area with increasing flow was most pronounced in $M_{nat}$ (+ 46 %), much lower in $M_{alt}$ (+ 32 %) and negligible in $M_{chan}$ (+ 4 %).

Shallow areas (< 20 cm depth) were largely missing in $M_{chan}$ at all three flows, but accounted for 11-21 % and 11-39 % of the wetted area at $M_{alt}$ and $M_{nat}$ ($Q_{off}$-$Q_{peak}$; Figure 6). Mean depth increased in all three reaches with increasing flow (62 – 133 %), but most substantial increase was observed in $M_{nat}$ (0.4 m - 0.9 m).

Flow velocity in the channelized reach $M_{chan}$ showed a unimodal distribution, with the mean increasing from 1.2 m/s at $Q_{off}$ to 1.75 m/s at $Q_{peak}$. In contrast, flow velocities in $M_{alt}$ were evenly distributed at all three flows, and the mean only slightly increased from 1.06 m/s at $Q_{off}$ to 1.3 m/s at $Q_{peak}$. In $M_{nat}$, a shift from low-medium to high velocities could be observed, with the range of velocities staying wide.

At all three flow levels, substrate in $M_{chan}$ was highly dominated by pebbles, with a minor increase in the area of boulder substrate at $Q_{peak}$ (+ 4 %). Substrate composition remained heterogeneous in both $M_{alt}$ and $M_{nat}$ with increasing flow and ranged from silt-clay to boulders with a dominance of small cobbles.

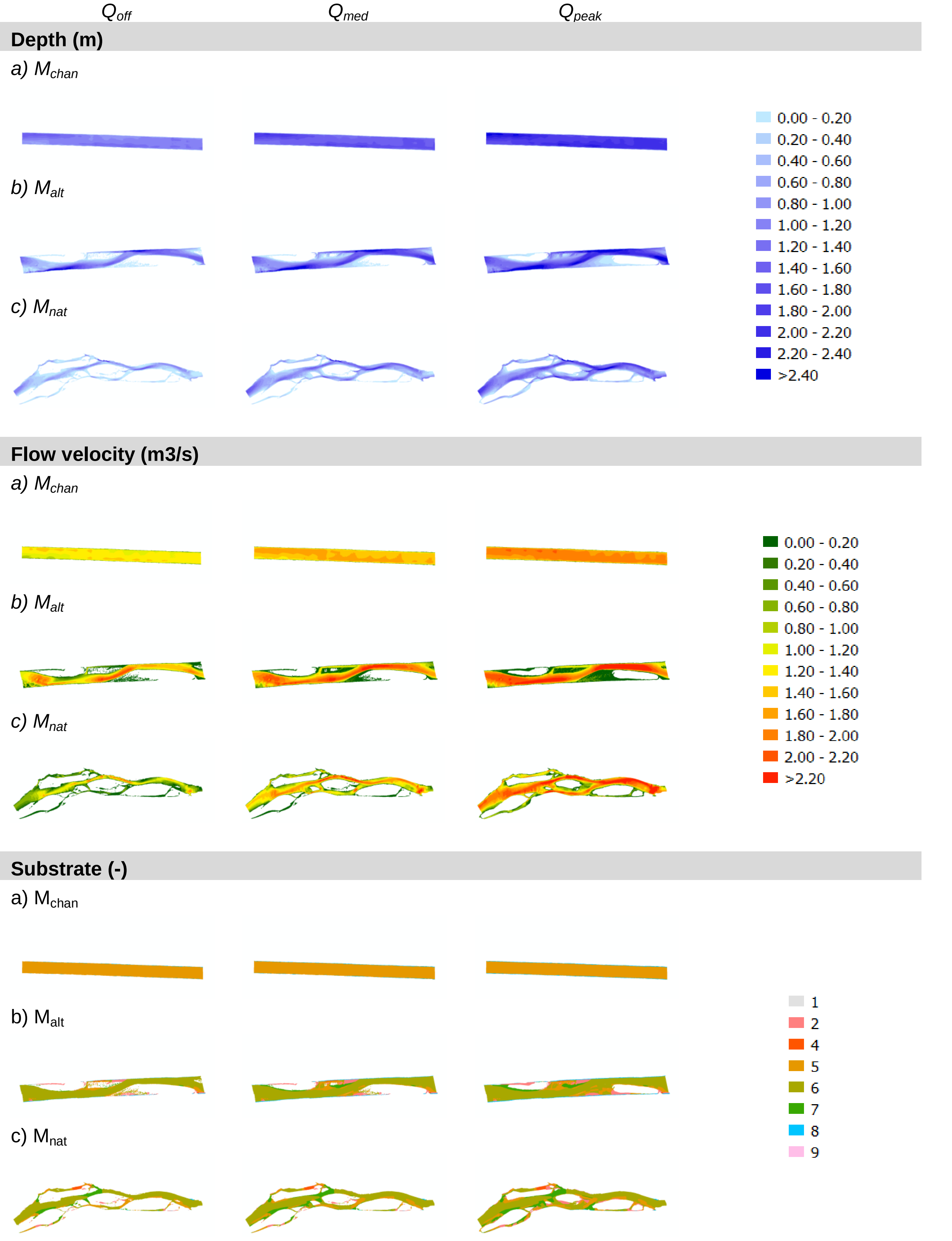



**Figure 6** **Changes in the three parameters depth, flow velocity and substrate with increasing flow under the three different morphologies. For the codes for the substrate classes see Figure 4.**

### 3.2.3. Comparison of model outcomes under different hydro-morphological conditions

*3.2.3.1. Reach level*

Suitable area (SA), averaged across all datasets, was largest in the natural river reach ($M_{nat}$) under low flow ($Q_{off}$), and smallest in the channelized reach ($M_{chan}$) with peak flow ($Q_{peak}$). Several datasets estimated an SA of zero (i.e. no suitable habitat; SI in all cells < 0.5) in $M_{chan}$ and $M_{alt}$. Variation of SA across datasets was generally high and highest in $M_{nat}$ under $Q_{off}$.

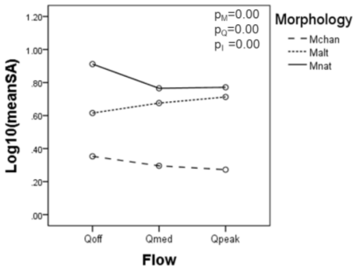
The Kolmogorov-Smirnov test for normality indicated that the $\log_{10}$-transformed SA values did not deviate significantly from normal for $M_{alt}$ under $Q_{off}$ (D=0.63, p>0.20), $M_{alt}$ under $Q_{med}$ (D=0.76, p=0.16), $M_{nat}$ under $Q_{med}$ (D=0.07, p>0.20), and $M_{nat}$ under $Q_{peak}$ (D=0.086, p=0.06). The remaining factor combinations showed a significantly non-normal distribution (p<0.05).

The two way ANOVA across all datasets (Figure 7a) showed that SA was significantly influenced by reach morphology, flow and the interaction of the two (p<0.01). Independent of the flow, the natural reach $M_{nat}$ offered the largest SA and the channelized reach $M_{chan}$, the smallest. The largest SA in these two morphologies occurred under $Q_{off}$, and decreased with increasing flow. The opposite trajectory was seen in the $M_{alt}$ where the amount of SA correlated with an increase in flow.

When the data were split by species (Figure 7b and c), we observed a more consistent pattern. $M_{nat}$ offered the largest SA for both species, $M_{chan}$ the smallest and the SA for $M_{alt}$ lay in between. Overall, SA was considerably lower for the grayling. For both species, SA varied significantly with river morphology. In contrast, flow significantly influenced the SA only for trout. The interaction between morphology and flow was again significant for both species.

Figure 7d and e show the SA for redds of brown trout and grayling, respectively. SA did not increase with flow in $M_{alt}$. In the near-natural river reach $M_{nat}$, however, SA got larger with increasing flow, but only for the brown trout was this difference significant.

We could not run the analysis for the grayling 1+ age class due to the small number of datasets (n=3). For the other juvenile age classes, i.e. for 0+ for both species and 1+ for brown trout, the SA was highest in $M_{nat}$ (figures 7f to h). There, SA decreased with increasing flow, but increased in $M_{alt}$. However, whereas the effect of morphology had a significant effect in both species and age classes, the effect of flow was just significant for 0+ trout. These patterns did not change considerably for the adult trout (Figure 7i). For the adult grayling (Figure 7j) the amount of SA was smaller compared to adult trout, and under off-peak flow SA in $M_{chan}$ equaled SA in $M_{nat}$. Accordingly, there was no significant effect in morphology for the grayling, but also not for flow. In contrast, the effect of morphology on the SA was still significant for the adult brown trout.

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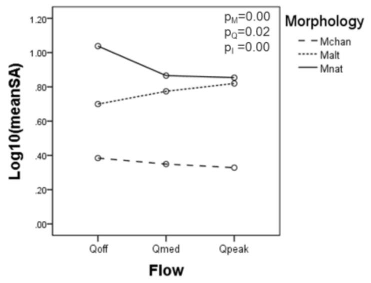


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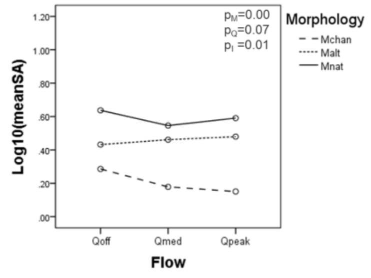


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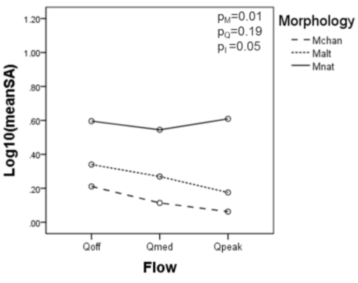


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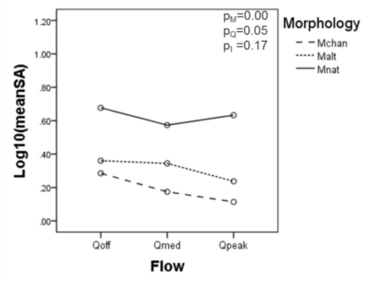


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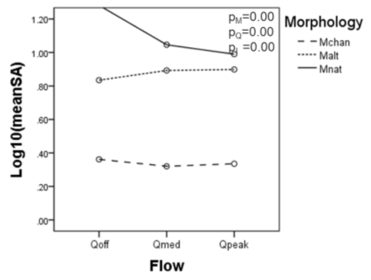


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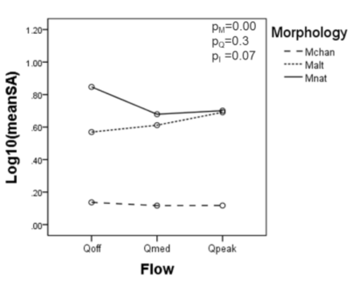


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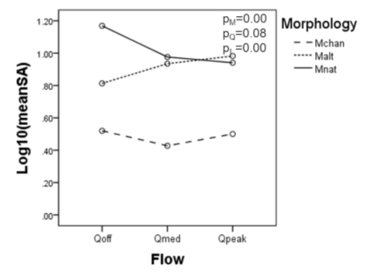


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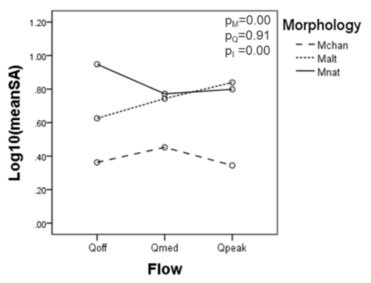


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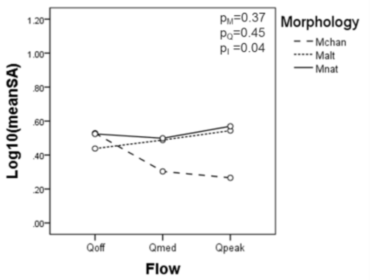


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**Figure 7 Mean SA analysed by a two-way ANOVA with repeated measures for a) all datasets; b) all brown trout datasets; c) all grayling datasets; d) brown trout redds; e) grayling redds; f) brown trout 0+; g) grayling 0+; h) brown trout 1+; i) brown trout adult; j) grayling adult. The x-axis represents the three levels of the factor flow ($Q_{off}$, $Q_{med}$, $Q_{peak}$). The y-axis shows the $log_{10}$ transformed SA for the three levels of the factor morphology ($M_{chan}$, $M_{alt}$ and $M_{nat}$). The p-values represent the effect on SA by morphology ($p_M$), flow ($p_Q$), and the interaction of the two ($p_I$).**

### *3.2.3.2. Cell-level*

The hierarchical cluster analysis for each species indicated that the datasets extracted from the same studies clustered together, independent of the age class (Figure 8 and Figure 9). For instance, all except one of the six grayling datasets from Mallet et al. 2011 were closely grouped, covering three different age classes (Figure 8a). This study effect was consistent in both the near-natural reach $M_{nat}$ under $Q_{med}$ and the virtual river.

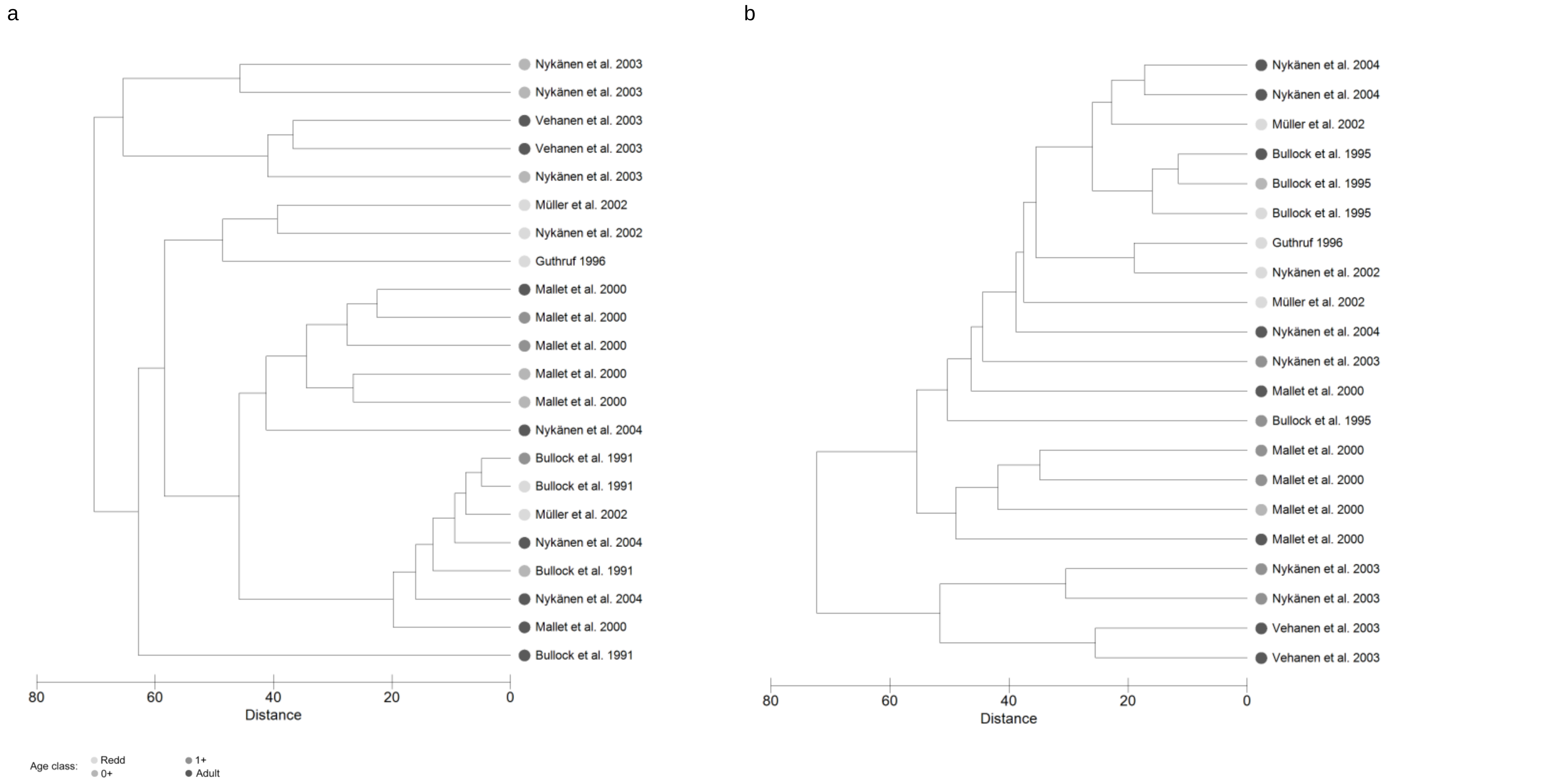



**Figure 8** **Dendrograms showing the similarity of SI-values from different studies and datasets at the cell scale for grayling for a) $M_{nat}$ and $Q_{med}$ and b) the virtual river. Each branch represents a dataset, with the age classes indicated as symbols and the study mentioned in the label. The longer the distance between nodes the larger the difference in the SI values among the cells.**

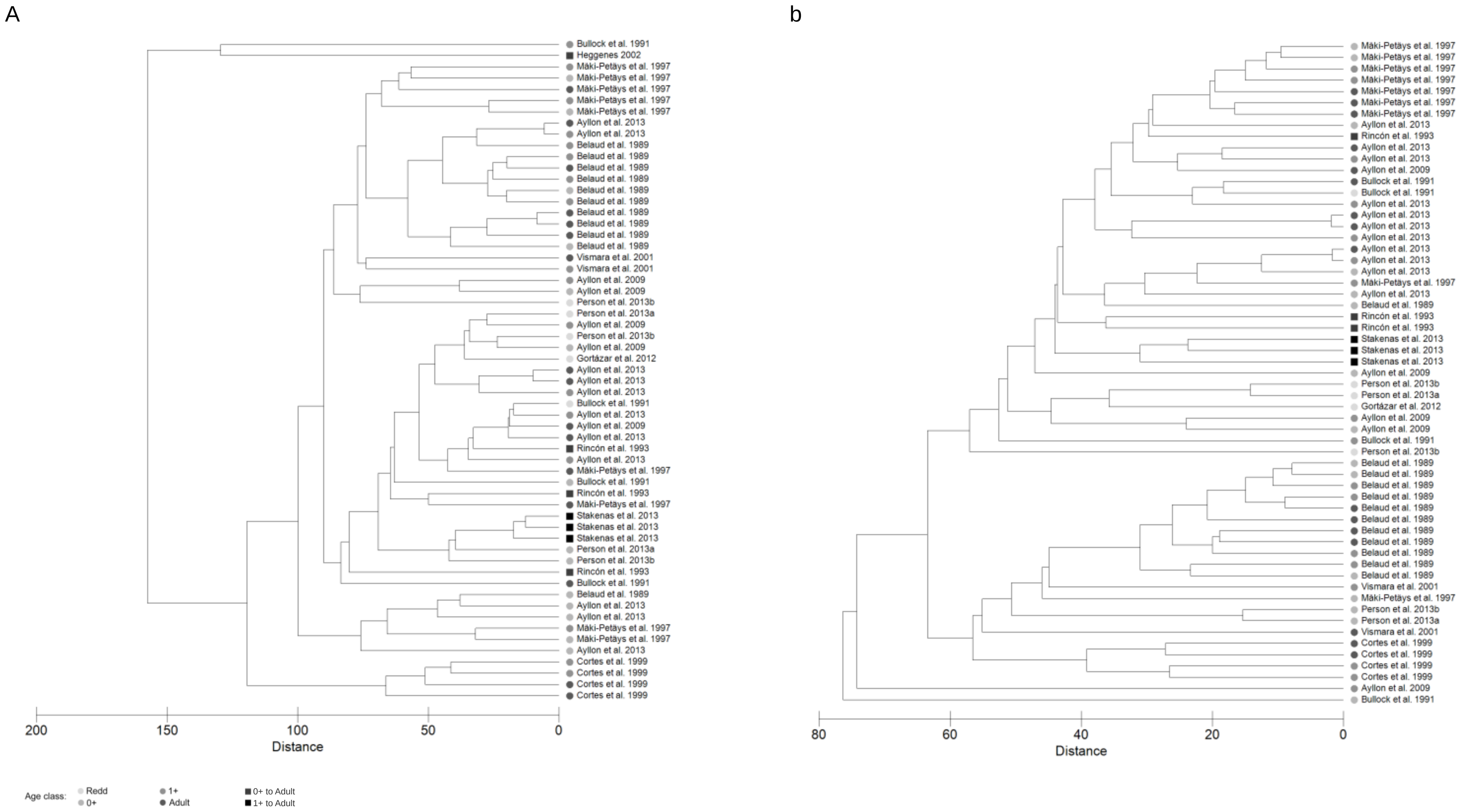



**Figure 9** **Dendrograms showing the similarity of SI-values from different studies and datasets at the cell scale for grayling for a) $M_{nat}$ and $Q_{med}$ and b) the virtual river. For further explanation of this dendrogram, see caption for Figure 8.**

## 3.3. Discussion

### 3.3.1. Availability of habitat suitability data

Habitat suitability data used in this study were originally generated for a wide variety of objectives. For instance, Sempeski and Gaudin (1995a, 1995b) described spawning and juvenile habitat for grayling, whereas Mallet et al (2000) tested the transferability of habitat suitability data between two river reaches. Nykänen and Huusko (2002) developed generalized suitability curves, and Ayllón et al. (2013) investigated how densities in different age classes affect habitat selection of 0+, 1+, and adult brown trout. However, all our studies have in common that they defined habitat suitability as the ratio between habitat use and habitat availability or based on expert knowledge (Bullock et al. 1991; Schneider et al 2015).

Overall, the available habitat suitability data is quite heterogeneous, with important information missing. Cover, for example, is considered a key parameter for habitat selection for brown trout (Heggenes and Traaen 1988). However, in most studies this parameter was not mentioned, or if so, then described in an inconsistent manner. For example, Mäki-Petäys et al. (1997) used the percent cover of instream vegetation per habitat area, whereas Vismara et al. 2001 concentrated on percent cover by boulders and overhead canopy. Ayllón et al (2013) reported cover and substrate characteristics in a combined channel index using categories such as substrate shelters, undercut banks, or a combination of vegetation and woody debris. Given these methodological inconsistencies among studies, we excluded the parameter cover from our calculations of SI and SA.

Habitat diversity is reduced in channelized or regulated rivers (Weber et al. 2009; Person 2013) thereby affecting habitat selection of fish. As a consequence, the hydro-morphological status of a reach has major consequences on the determination of habitat suitability. Surprisingly few studies provided information about the hydro-morphological status in the studied rivers. Habitat suitability data originating from small streams (<5m) were also underrepresented in the literature, despite the proven importance of low-order rivers as nursery habitats and refuges from adverse conditions, e.g. during floods (Heggenes 1989, Armstrong et al. 2003).

Seasonality in fish behavior has been well studied for brown trout and many other species (Cunjak 1996), and can affect habitat suitability. Trout parr, for example, become increasingly nocturnal during winter (e.g. Heggenes and Saltveit 1990) and movement and food intake are generally reduced during the cold season (Huusko et al. 2006). Such changes in activity-levels lead to shifts in habitat use and therewith in habitat suitability. Habitat suitability for grayling during winter is particularly understudied. To our knowledge, no study has quantified habitat suitability during the night.

Determination of habitat suitability can be biased by methodological differences. Most of the presented habitat suitability data for trout were based on electrofishing surveys. Electrofishing bears the risk of confusing patterns of microhabitat use, e.g. by triggering a hiding or flight response of the fish to potentially unsuitable habitats. Prerequisites for observations by snorkeling or diving are a sufficient water depth, low turbidity and flow velocity; furthermore, observation quality is higher with fine substrates. Heggenes et al (1990) compared electrofishing, diving and surface observation of young brown trout and atlantic salmon. Diving and surface observation gave comparable results in habitats with flow velocities < 0.2m/s and fine substrate. In contrast, electrofishing was more effective in shallow riffles with higher flow velocity and larger substrate.

Resource competition, which is often density-dependent, can lead to competitive habitat displacement, and thereby to shifts in habitat use. Resource competition can be intraspecific (Alanärä et al 2001) or interspecific (Hesthagen and Heggenes 2002). Accordingly, information on fish densities and community composition are essential in order to interpret habitat suitability data. Community composition was mentioned for half of the datasets, and fish density only in a marginal number of studies.

Riverine fish have different habitat requirements throughout their life history (Jonsson and Jonsson, 2011). Studies that combine habitat suitability data across multiple age classes (Rincón et al 1993, Heggenes 2002, Stakenas et al 2013) are therefore difficult to interpret. However, such an integrative approach may also better reflect habitat requirements throughout a species' life history.

The lack of important information about the eco-hydrologic context for many of the studies made it prohibitively complex to include these additional variables in the analyses (e.g. as covariates).

### 3.3.2. Variability in the habitat suitability data

We observed a pronounced variability in the suitability curves. The variability of suitability curves within an age class of the same species was particularly remarkable. From a methodological point of view, the following two factors could affect the variability:

- *Calculation of habitat suitability*: There are at least three different approaches of describing the suitability of habitats for riverine fish (category I to III criteria according to Bovee 1986) –

    i) expert judgement,

    ii) habitat use indices (e.g. Wollebaek et al 2008; Riedl and Peter 2013) and

    iii) indices based on use-to-availability ratios (e.g. Mäki-Petäys et al. 1997; Heggenes and Dokk 2001).

  Also for category III criteria, i.e. the use-to-availability ratios, there are several methods available, such as the suitability approach, as used in this study (see also Bovee 1982; Baltz 1990), or the Jacobs Selectivity Index (Jacobs 1974), that distinguishes between selective use of habitats and habitat avoidance. In order to exclude variation due to the different approaches for calculating suitability, we concentrated our literature search exclusively on the suitability approach (Bovee 1982; Baltz 1990). The observed heterogeneity in the habitat suitability data is therefore not due to the calculation used.
- *Habitat diversity and availability in the source rivers:* Category III criteria are meant to create more general and comparable habitat suitability indices by accounting for differences in habitat availability between reaches (Bovee 1986; Harby et al. 2004). However, there are two major challenges concerning habitat availability that may influence curve calculation and therewith cause inappropriate conclusions: i) the presence of rare habitats which, if used by fish, seem to be highly suitable, thereby causing considerable alteration in the calculated suitability curves (Payne and Allen 2009), and ii) the complete absence of habitats which might, if they were present, be used by fish (Payne and Allen 2009). As discussed earlier, habitat diversity has been shown to be influenced by hydromorphological integrity (e.g. Weber et al. 2009; Person 2013), with the more natural reaches presenting a more diverse set of habitat types and a more even frequency distribution (note that this pattern can also be seen in our three study reaches with different morphologies; Figure 6). Accordingly, we would expect that the two challenges mentioned above (rarity of habitats, lack of habitats) are more probable in reaches affected by hydrologic and/or morphologic impairment. The respective information was lacking in most of our studies (Figure 3), but, several studies had been conducted in impaired reaches.
- Based on our review of the literature for the present work, it is clear we need a better understanding of the influence of the type and amount of habitat among study rivers on perceived habitat suitability. In particular, we need to quantify i) the role of rare habitats in determining the study-specific suitability curves, and ii) the similarity in habitat types and availability across studies. We will include additional analyses in the scientific article emerging from the present project (Junker et al. In Prep).

### 3.3.3. Model outcomes under different hydro-morphological conditions

#### *3.3.3.1. Reach-level comparisons*

Analyses of the channelized reach $M_{chan}$ indicated very low SA for both trout and grayling, particularly under $Q_{peak}$. This resulted in a positively skewed SA distribution, i.e. there was a high proportion of SA values close to zero and a more normal distribution at higher SA values. The $log_{10}$ transformation failed to achieve normality of the SA values for all nine factor combinations of morphology and flow. However, results of additional investigation and tests on the distribution of the untransformed raw data were in line with our ANOVA results. For the scientific article emerging from the present project (Junker et al. In Prep) we plan to run additional analyses, such as Generalized Linear Models that allow non-normally distributed response variables.

The general and most significant pattern over all datasets was that the near-natural reach $M_{nat}$ provided the largest amount of SA, $M_{chan}$ the lowest and $M_{alt}$ lay in between. This pattern was consistent across the three different flows ($Q_{off}$, $Q_{med}$, $Q_{peak}$). We assume that the pattern is mainly due to the hydro-morphological diversity of the three reaches, with $M_{nat}$ offering the most diverse set of hydro-morphological conditions and a more even distribution of habitats in contrast to the rather monotonous situation in $M_{chan}$. Habitat suitability in the datasets was also quite heterogeneous and it seems therefore obvious that the most heterogeneous reach $M_{nat}$ offered the largest amount of SA across studies.

The amount of SA changed with increasing flow differently among the three reaches. SA in $M_{nat}$ was highest under $Q_{off}$, decreased with $Q_{med}$ and stabilized still on a quite high level under $Q_{peak}$. The amount of SA in $M_{chan}$ stayed on a low level or even decreased with increasing flow. Exceptions to this pattern were observed for the 1+ and adult trout, as for these age classes highest suitability for water depth and flow velocity was achieved under $Q_{peak}$ and $Q_{med}$ respectively. $M_{alt}$ offered more SA for all age classes with increasing flow except for redds of both species. With increasing flow, water at the gravel bars got retained, but at the same time the wetted area increased. The gravel bars still provided slow flowing, shallow habitats even under $Q_{peak}$. However, gravel bars can trap juvenile fish under fast dewatering events. Such stranding is common in hydropeaking reaches (Halleraker et al 2003).

Our results highlight the importance of the interaction between morphology and flow. We therefore conclude that hydropeaking mitigation projects must, in order to be successful, consist of both hydrological and morphological measures. A hydrologically restored, but morphologically impaired river reach will still not provide a high SA (see also Person 2013). Furthermore, a wide river bed, like in $M_{nat}$, is able to buffer the strength of high flows as they prevail during hydropeaking or floods. Compared to $M_{chan}$, where the water level increased to a bankfull stage, the water in $M_{nat}$ is able to spread also in a lateral dimension, reducing flow velocity, depth and therefore bed shear stress (Hauer et al 2012, Goode et al 2013). Considerations about fish stranding and morphological structures that buffer hydropeaking effects are given in chapter 4.3.3.

### 3.3.4. Cell-level comparisons

Analysis of habitat suitability at the cell level had two objectives: First we wanted to quantify how the variability in datasets derived from different studies influenced habitat suitability at the level of the individual cell. We achieved this by testing the correlation of cell-level suitability among datasets i.e. whether datasets agreed in cell-level SI estimates within a reach. Second, we then tested whether variability in cell-level SI estimates among datasets could be explained by explanatory variables, such as study or age-class.

Based on the similarity of the SI across cells and data sets, we observed a clear study effect, i.e. the clustering could mostly be explained by the variable “study”. This result is more pronounced for trout than grayling and clearer in the virtual river than in $M_{nat}$.

In other words, the availability of all combinations of flow velocity, depth and substrate adds more strength to the study as an explanatory variable than to other variables included (e.g. age class). This is an argument to compare and transfer habitat suitability data just within rivers with similar habitat availabilities. A further argument for this can be found by focusing on clusters built by single studies. For example the data sets from Belaud et al (1989), stem from 4 different rivers, each river provides a 0+, 1+ and adult data set. These data sets do still cluster mostly according to their original river and not by age class. This is again true for the natural river reach $M_{nat}$ and the virtual river (Fig. 8a and 8b).

# 4. Part 2: River morphology and hydropeaking effects

## 4.1. Methods

For the consideration of hydropeaking effects on habitats it is important to investigate the temporal changes of the habitats. It has been found that stranding and drift of juvenile fish and the damage of spawning grounds are major effects. Based on these findings a guideline for the assessment of hydropeaking rivers has been established in Switzerland in order to define reaches with mitigation needs (level 1; Baumann et al. 2012). Main indicators to be assessed with modelling approaches are

- For stranding:
  - ratio between wetted area for peak flow and off-peak-flow,
  - water level drop velocity
- For spawning:
  - minimum depth on potential spawning grounds for off-peak flow
  - stability of substratum on potential spawning grounds

These indicators are related to fish habitats and cover purely physical parameters. Only few studies on the assessment of aquatic habitats in unsteady flow conditions are available (Bruno et al. 2009, Flodmark et al. 2006 , Garcia et al. 2011, Hunter et al. 1992, Kopecki et al. 2012, Parasiewicz et al. 1998, Saltveit et al. 2001, Schneider & Noack 2009, Scruton 2008, Shen et al.2010). The following approaches were used to investigate the effects on habitats under hydropeaking conditions.

### 4.1.1. Generalized suitability curves

For the investigation of habitats with modelling approaches it was necessary to select habitat requirement data that could be used for the comparison of different morphological reaches and features. The evaluation of the model results based on the database of habitat requirements, setup in the first project part, showed that the different datasets led to heterogeneous results. For that reason a generalized set of preference functions had to be used. These functions were created after elimination of outliers and integrating information from general fish habitat descriptions listed in guidelines for minimum flow assessment (LfU 2013) and documents setup for the fiBs method (a fish-based method to evaluate river ecological quality with the implementation of the Water Framework Directive, LAWA 2014). The goal was to setup model input data describing habitat requirements in a non-reach specific way.

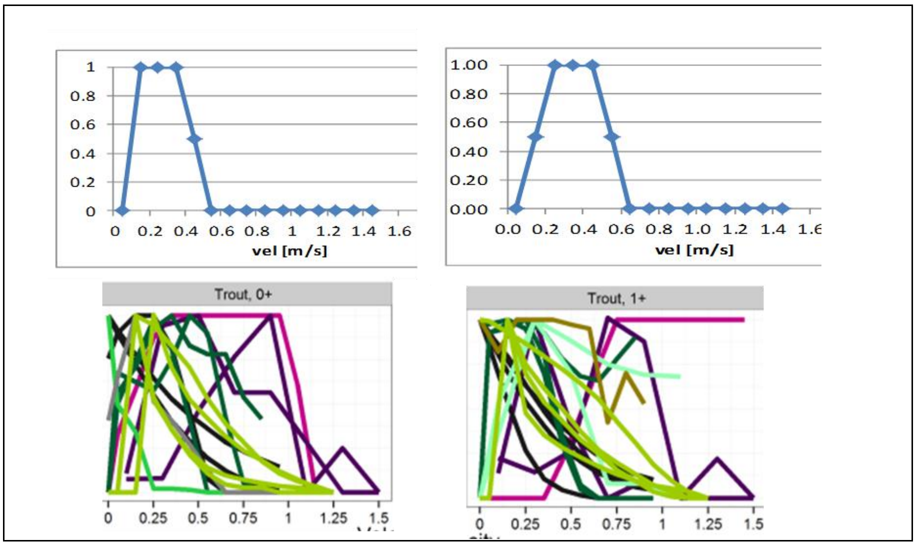



**Figure 10 Generalized suitability curves related to flow velocity for 0+ (left) and 1+ fish (right) of brown trout (top) and underlying data from the database of habitat requirements (bottom)**

The results were compared with those obtained from a fuzzy-rule based approach with fish habitat requirements specifically defined for the Alpenrhine reaches (Eberstaller et al, 2012). It was shown that the habitat suitability patterns from both simulations were very similar with a slightly higher degree of detail for the specifically developed data (example for spawning habitats in Figure 13, a and b). Based on this outcome the generalized suitability curves were considered to be suitable for the analysis of morphologic impacts.

### 4.1.2. Habitat persistence during hydropeaking

The habitat persistence approach is based on the assumption that a continuous level of suitability during the whole peaking event has to be present in habitats in order to ensure their functionality (Person 2013, Kopecki et al. 2012). This approach is particularly used for habitats for life stages that are restricted in terms of mobility such as redds and larvae. The level of habitat suitability that is not undercut during a peaking event can be found by selecting the minimum value of the habitat suitability of all time steps modelled and covering the event with a sufficient resolution.

### 4.1.3. Risk assessment

The approach used in CASiMiR-GIS for the assessment of hydropeaking impacts is based on several simulation steps (Eberstaller et al. 2012). The first step is to calculate a base suitability without considering hydropeaking effects. Base suitability is simulated in a high temporal resolution, i.e.in our study in 10 min steps for the whole hydropeaking event. For the spawning habitats the maximum value is stored as first result since the egg deposition could basically happen any time of the hydropeaking event, For the juveniles the suitability value of each time step is stored since this life stage is able to follow suitable habitats up to a certain range and speed of dislocation.

In a second step the risk level is calculated, just as habitat suitability on a scale between 0 and 1 (0 = no risk, 1 = maximum risk). For spawning areas the risk of drying out and the risk of sediment movement are considered. For juvenile fish the risk of stranding and the risk of being washed out/ drifted are most relevant. Risk is calculated for each time step. By integrating the derived values over the whole peaking event the size and risk potential of areas in the investigated river reach is found.

In a third step the base suitability is reduced by the risk level between 0 and 1 and habitat suitability is calculated. This suitability can be integrated in a fourth step by selecting the minimum suitability during the whole peaking event. The result is the effective habitat suitability under peaking conditions.

### 4.1.4. Horizontal velocity approach

Although it has been mentioned as impact factor in some publications currently there are no thresholds defined for the maximum horizontal dislocation of the water edge due to hydropeaking. Instead, many studies (Salveit et al. 2001, Schneider & Noack 2009, Schmutz et al 2013) concentrate on values for a critical velocity of water level change. Nevertheless, it is assumed that for small fish the horizontal velocity of the water edge during decreasing flows is even more important since it determines the distance fish have to follow in order not to get trapped. However, it is worth to investigate this parameter in a study on hydropeaking effect in different morphologies. The horizontal velocity is derived by analysing the position of the water edge for different time steps in a hydrodynamic model.

### 4.1.5. Morphologic classification

It is assumed that the fast change of environmental conditions during hydropeaking events is a hazard for water organisms. Thus it is useful to have a look at the difference between these conditions for off-peak flow and the peak flow. Also the maximum of the water level drop rate is an indicator for the continuity of hydraulic conditions. These parameters are indicators of the stability in hydraulic conditions, which we describe with the new term “hydraulic stability”.

Another option to analyze the changes in conditions between peak flow and off-peak flow is the comparison of highly suitable habitats for both flow situations – peak and off-peak flow. This shift between the two extreme flows has also been used in the classification.

Stranding and drift impacts occur usually on gravel bars. In order to find a relation between types of gravel bars and their behavior during hydropeaking events, a categorization of gravel bars performed in Habersack et al (2013) has been used to for a comparison with the findings in the Alpenrhein reaches.

## 4.2. Results

### 4.2.1. Indicators to address hydropeaking effects

#### *4.2.1.1. Habitat suitability and habitat shift*

The results of habitat simulations in the near natural reach $M_{nat}$ and the alternating gravel bar reach $M_{alt}$, that were expected to change drastically with flow, are illustrated in the following figures.

In the $M_{nat}$ the quality and quantity of juvenile habitats is highest for $Q_{off}$ (27 m³/s). Habitats are spatially shifted with increasing flow, but several locations of medium to high quality habitats (SI > 0.4) are found close to the original position during low flow.

In contrast the reach with alternating gravel bars $M_{alt}$ provides the highest suitabilities for the high flow situation. With decreasing flow most of these habitats are lost and new suitable habitats show up, but in completely different locations at the beginning and end of the reach.

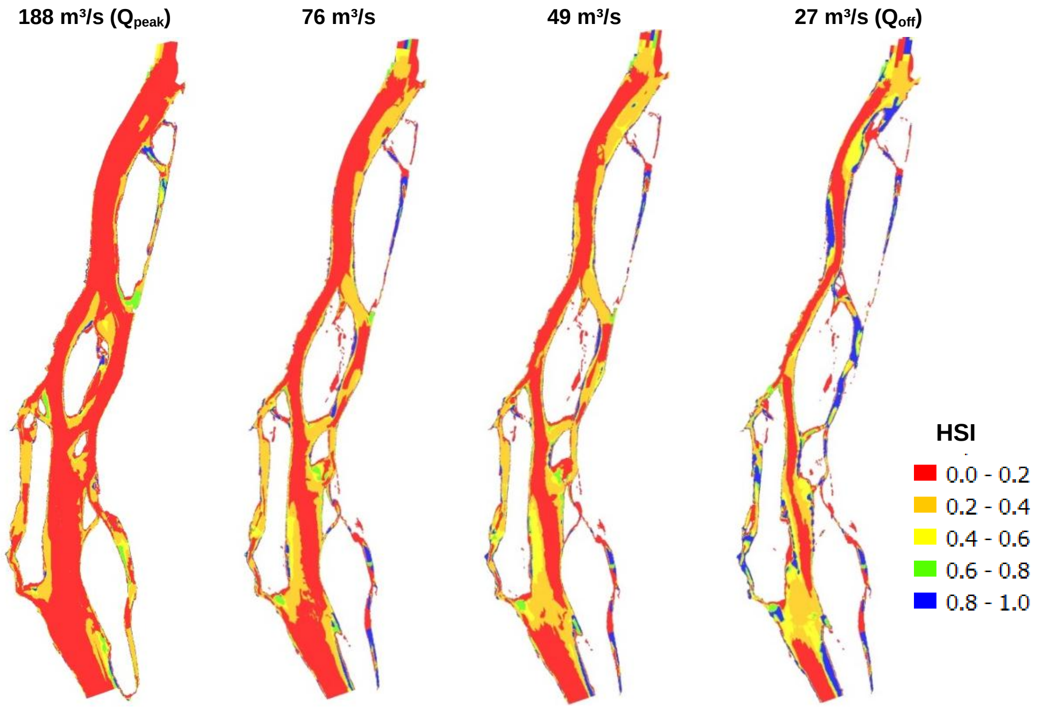



**Figure 11 Base suitability for juvenile brown trout in the near-natural reach $M_{nat}$ for different flows**

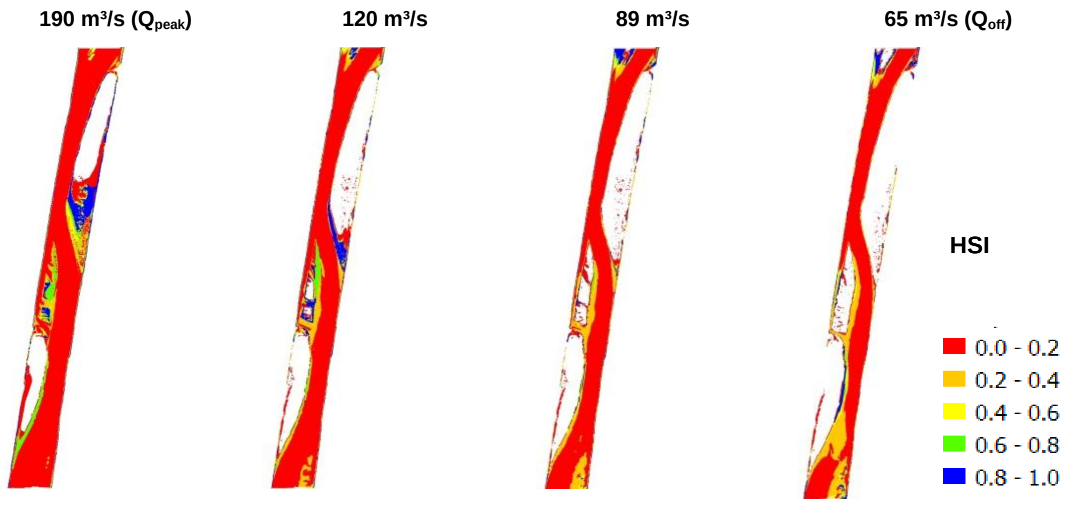



**Figure 12 Base suitability for juvenile brown trout in the reach with alternating gravel bars $M_{alt}$ for different flows**

#### 4.2.1.2. Habitat persistence during hydropeaking

The persistent spawning habitats, i.e. the minimum value of spawning suitability for the whole hydropeaking event in the near-natural reach $M_{nat}$, are shown in Figure 13. It can be seen that the amount and quality of spawning grounds in the reach is quite high for the low flow situation that is typical for the spawning period in early winter. This is true for the generalized preference curves as well as for the results derived from a fuzzy logical calculation with a dataset specifically developed for the river reach in a former study (Eberstaller et al. 2011). The maximum suitability from all time steps reflects the spawning options for brown trout during the whole hydropeaking event and is even higher. However, the minimum value for the whole hydropeaking event has to be considered to find out about the persistent habitats. Result: no spawning ground with a persistent suitability higher than 0.4 is available. In the reach with alternating gravel bar $M_{alt}$ persistent spawning areas are not available at all (suitability 0 or close to 0).

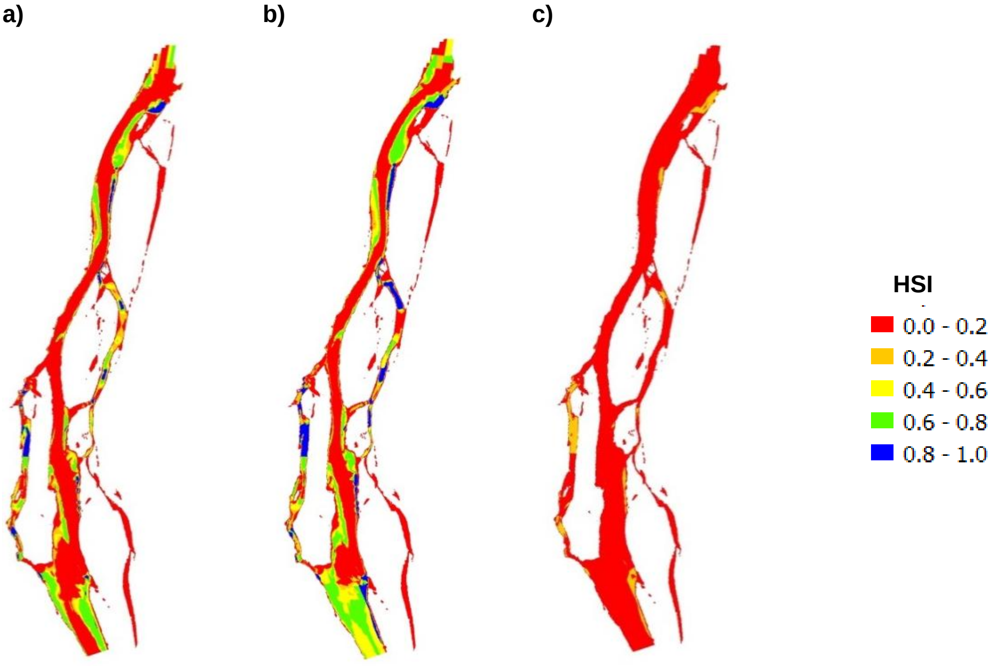



**Figure 13 Spawning habitat suitability for brown trout based on a) generalized preference curves (off-peak flow 27 m³/s); b) fuzzy sets/rules specifically developed for the Alpine Rhine (off-peak flow 27 m³/s); c) persistent habitats based on spawning activity, derived by risk assessment**

#### 4.2.1.3. Risk assessment

The risk assessment for stranding shows different patterns for the near-natural reach $M_{nat}$ and the reach with alternating gravel bars $M_{alt}$ as well (Figure 14).

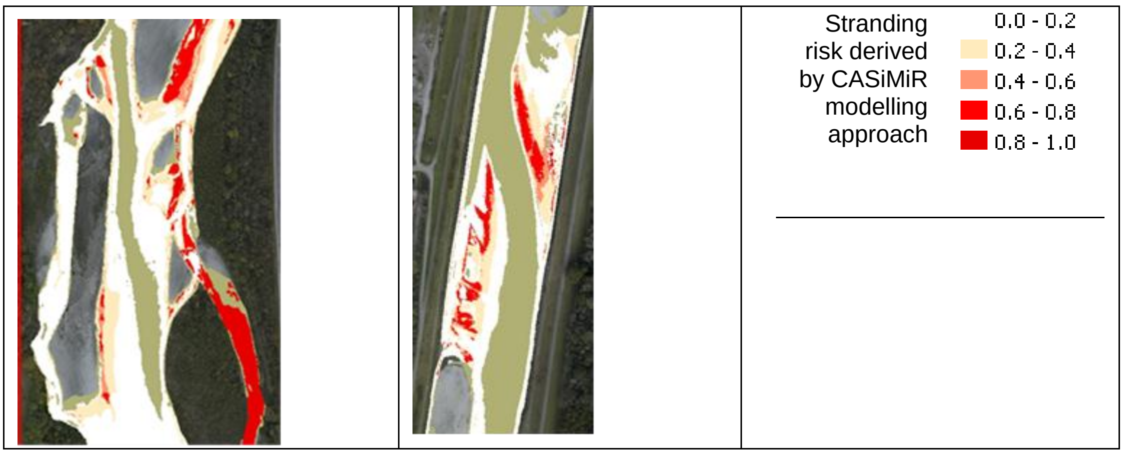


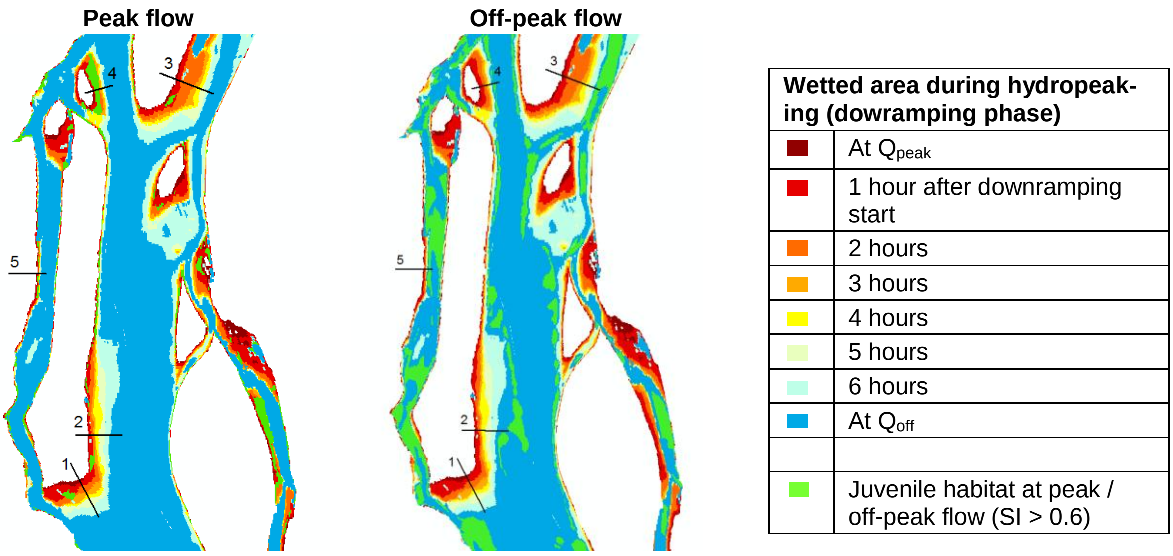

**Figure 14 Stranding risk in the near-natural reach $M_{nat}$ and the reach with alternating gravel bars $M_{alt}$**

In $M_{nat}$ it is mainly the side branches falling dry for low flow and some gravel bars close to the river bank that show high risk. However, there are also large areas with little risk of standing such as the left side channel and the left side of the gravel bar in the center. In $M_{alt}$ the highest elevations of the gravel bars within the main channel include the highest risk of stranding. The steep rip rap banks provide juvenile habitats with little stranding risk; however, the extension of these areas is limited.

The persistent redd habitats obtained by risk assessment are slightly larger than those for persistent habitats considering spawning activity (Figure 13 c). This is due to the fact that in the risk approach it is not assumed that the spawning grounds must be accessible during the whole hydropeaking event (depth > 20 cm), but they just have to be protected against drying out (depth > 5 cm) after egg deposition.

### *4.2.1.4. Horizontal velocity*

The width of the areas in different colours in Figure 15 is an indicator for the velocity the waterline is moving during the downramping phase of a hydropeaking event. These areas represent the hourly change of the wetted area in the reach. It is illustrated that the shallow, flat banks of the islands in the middle of the reach provide good juvenile fish habitats for flows slightly above off-peak flow, but in the last phase of the dewatering period (after 6 hours) a drastic reduction of wetted area can be observed, indicating an elevated risk of stranding.




| Position | Bank steepness | Width of dewatered zone [m] | Velocity of horizontal water surface change (mean/max) [m/hour] |
|---|---|---|---|
| 1 | **1:100** | 42 | 6.0/10.0 |
| 2 | 1:30 | 24 | 3.4/7.0 |
| 3 | 1:30 | 38 | 5.3/15.5 |
| 4 | 1:22 | 14.3 | 2.0/4.0 |
| 5 | 1:7.3 | 4 | 0.6/1.0 |

**Figure 15 Wetted area in the near-natural reach $M_{nat}$. The progress of the waterline is indicated in hourly steps by different colours, steepness of banks, width and horizontal velocity**

The horizontal velocity does <u>not</u> relate linearly to the steepness of the banks. The gravel bank in position 1 has a very low gradient of 1:100 and the max horizontal velocity of the waterline is around 10 m/hour, whereas the gravel bank in position 3 is more than three times steeper with a gradient of 1:30; however, the maximum horizontal velocity is even as high as 15.5 m/h.

### 4.2.2. Hydraulic and morphologic classification

#### *4.2.2.1. Hydraulic stability*

Hydraulic stability has been defined by the difference of the min and max values of flow velocity, water depth and water level drop velocity during a hydropeaking event. The three parameters are shown for reach $M_{nat}$ in Figure 16.

It becomes clear that the side arms are among the areas with the smallest change. As mentioned the side arms on the right hand side face the risk to dry out during low flows. Thus it is mainly the permanently wetted side arm on the left hand side that is of particular interest. Furthermore the inlet area of the side arm, as well as some smaller areas in the backwater range of larger gravel bars, provide comparatively stable conditions with changes of less than 0.5 m in water depth, less than 0.5 m/s in flow velocity and maximum water level drop rates below 0.3 cm/min.

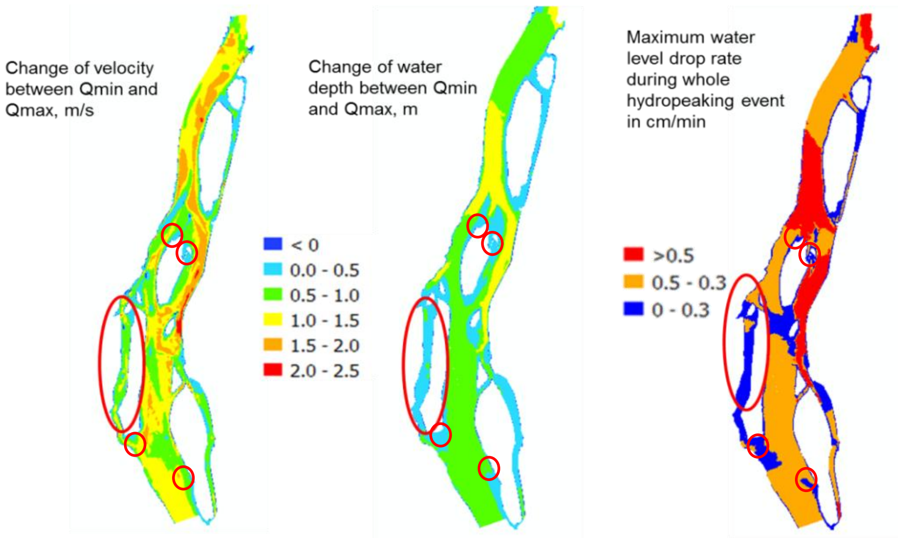



**Figure 16 Hydraulic stability defined by changes between $Q_{peak}$ and $Q_{off}$**

#### *4.2.2.2. Habitat shift $Q_{off}$-$Q_{peak}$*

The shift of highly suitable areas between peak flow and off-peak flow is shown in Figure 17.

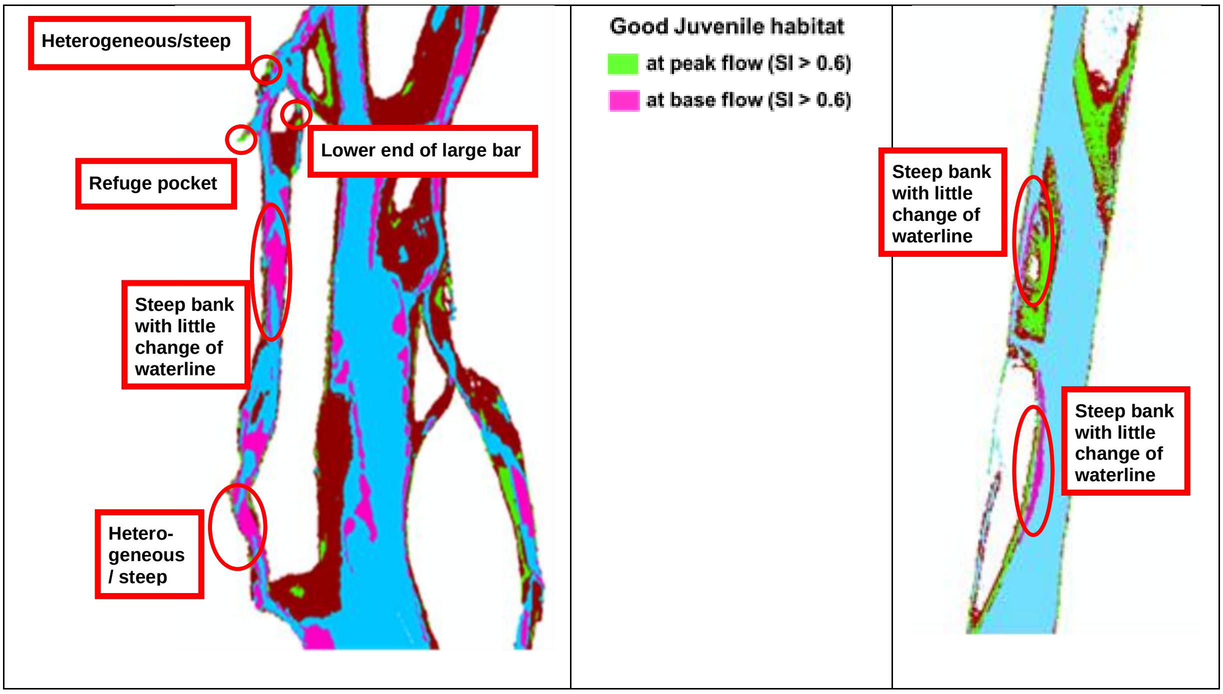



**Figure 17 Shift of suitable juvenile habitats between peak flow and off-peak flow of hydropeaking event**

Juvenile habitats with a suitability SI>0.6 are illustrated in green for the off-peak flow and magenta for the peak flow. Small distances between the two colors indicate areas with a good chance for juveniles to find persistently suitable hydraulic conditions during a peaking event. Note: the larger side arms on the right hand side in reach $M_{nat}$ show partly a small shift of habitats. This area is excluded from the considerations because it is disconnected from the main channel in the off-peak flow situation.

It is found that particularly in the left side channel of reach $M_{nat}$ there are several morphologic advantageous features with only small shift of suitable juvenile habitats. $M_{alt}$ provides two areas with small dislocation of good habitats as well. One of them is located directly in the main channel though and could be negatively affected by waves often present during hydropeaking.

### *4.2.2.3. Gravel bar types*

The categorization of gravel bars in Figure 18 is taken from Habersack et al (2013). Their study indicated that particularly point bars show a smaller sensitivity to artificial flow changes than other bar types. Point bars are characterized by their location at the inner side of curves, providing protected pockets at their lower end with steep river banks (due to cohesive materials) and a smaller width. According to Habersack et all (2013) all these properties lead to a lower stranding risk for larvae, whereas alternating gravel bars generally show a bigger change in width.

Based on our findings from the Alpine Rhine we can confirm that some of the hydraulically stable areas could be found at the lower end of large gravel bars (Figure 16). Also one of the areas with a small spatial shift of suitable juvenile habitats for different flows has been found at the lower end of a large gravel bar (Figure 17). However, these areas cannot necessarily be described as point bars, since they are neither in the inner side of a curve nor do they include cohesive materials. On the other hand the alternating gravel bars in reach $M_{alt}$ have partly a small change in width (Figure 17). Even the cited study is not consistent in characterizing the bar types. For instance is alternating gravel bar 5 smaller in width change than point bar 2 though both are located in river Ach.

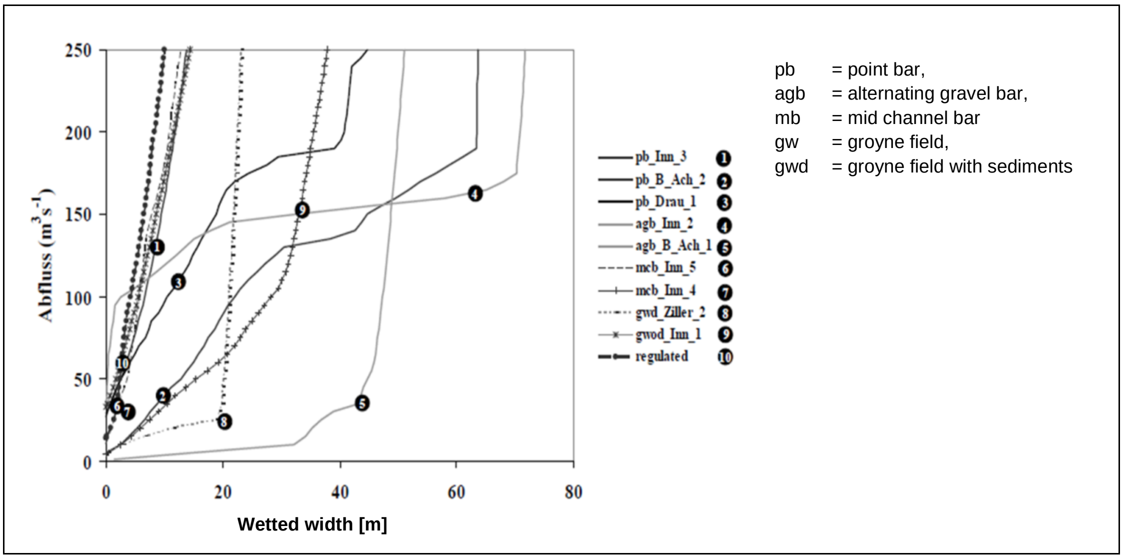



**Figure 18 Types of gravel banks, relation between wetted width and flow (after Habersack et al. 2012)**

### *4.2.2.4. Advantageous morphological features*

a) Permanently wetted side channel

One specific morphologic feature is apparently the most effective in terms of mitigating hydropeaking effects. The permanently wetted side channel in reach $M_{nat}$ provides most of the structures that are less sensitive to fast flow changes. Steep river banks are available as well as refuge pockets as special type of backwater area (see definition in next chapter) and heterogeneous river banks that provide locally small areas with good conditions for young fish. Additionally the whole side arm is hydraulically stable with less change in depth and flow velocities than other parts of the river reach. This supports also little shift of habitats at the lower end of the neighbored large gravel bar.


**Figure 19 Permanently wetted side channel in reach $M_{nat}$ with narrow in- and outlet**

b) Refuge pocket

Mitigation can also be performed in a smaller scale. One of the morphological features within the side channel described above is named refuge pocket (Figure 17). These are small backwater areas with higher water depth and steeper river bank gradient than the surrounding area. One artificially created example from a study by the authors in HyTEC flume in Lunz, Austria, is illustrated in Figure 20. It shows the comparison between a gravel bank without and with a “refuge pocket”. In the example the flow drops from 125 l/s to 25 l/s within four minutes.

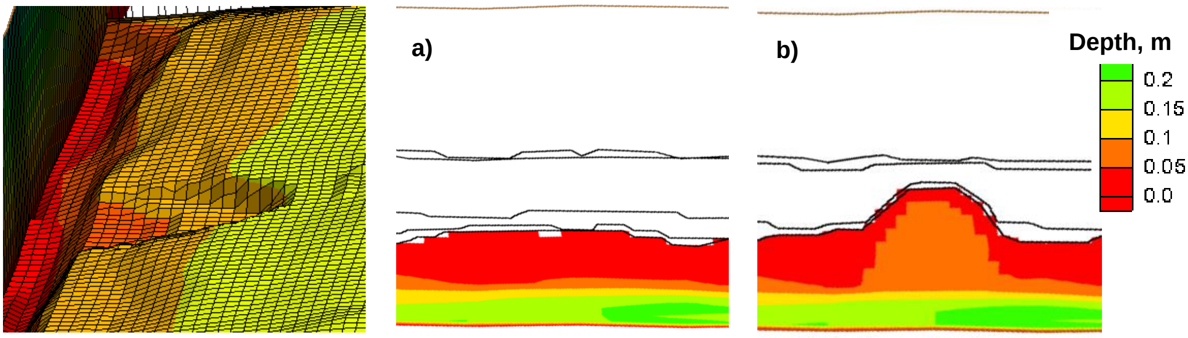



**Figure 20 3D model view of a connected refuge pocket structure on a flat bank in an artificial flume, waterlines indicating the temporal advancement of water surface (every minute) during hydropeaking: a) flat bank, b) flat bank with connected “refuge pocket”**

The evolution of the water surface for the hydropeaking event with the steady decrease of flow per time unit on the hypothetical flat bank (Figure 20 a) and on a flat bank with a permanently connected refuge pocket (Figure 20 b) is visualized through the waterline position depicted every minute of the hydraulic simulation. The spacing of lines gives a direct estimate of the horizontal velocity. For the flat bank the maximum velocity of water surface movement comprises about 1.1 m/min, locally for the bank with refuge pocket it is about 0.4 m/min, for the rest of the bank is of the same range as without structure. Despite the steady flow decrease in the laboratory test, the waterlines are not equally spaced highlighting especially dangerous time periods (lines with largest spacing) of the event for this specific geometry and specific distance to the hydropeaking source.

## 4.3. Discussion

### 4.3.1. Approaches to address the impact of morphology in hydropeaking

*Habitat shift:* The temporal change of habitats for juveniles in the near-natural reach $M_{nat}$ reflects the change that occurs under a natural flow regime. The high juvenile habitat availability for low flow is in agreement with the situation usually present after larvae emergence. However, the speed and frequency of flow changes through hydropeaking events is considerably higher than for natural events. The habitat shift is not generally small in the near-natural reach, but some elements of the natural morphology seem to give the opportunity to organisms with a low mobility to follow their preferred hydraulic habitats. The dislocation of suitable habitats in these areas is small. In contrast, the juvenile habitat development in the reach with alternating gravel bars $M_{alt}$ is very different to the conditions in $M_{nat}$. The most suitable habitats occur during the high flow situation, which is not typical for the time of emergence of the juveniles in early spring. In this period before the snow melt starts, low flows are common. In other words, the habitat dynamics in the modified morphology in $M_{alt}$ are contrary to the natural flow regime. Suitable habitats for juveniles are available only in short periods of high flow. Additionally the highly suitable habitats in the low flow situation are by a big part found in locations with a large distance from the ones in the high flow situation. Thus the probability for very young fish to reach them during fluctuating flows is low.

*Habitat persistence:* The habitat persistence approach is particularly interesting for organisms with a restricted mobility. While young fish from a certain age on are able to follow habitats changing their location with flow, redds and also many macroinvertebrates have to or prefer to stay in their original position. Even in the near-natural reach $M_{nat}$ the basically very good reproduction conditions in the low flow situation are severely reduced when regarding their persistence. However, the persistence approach as applied in Person (2013) for spawning habitat is presumably still too strict since it requires good spawning conditions over the whole hydropeaking event. After egg deposition the main hazards for redds are reduced oxygen supply and sediment movement. In other words for these periods modified suitability curves with a wider range for flow velocity and water depth could be applied. For macroinvertebrates persistence approach seems to be well suitable, but these are not considered in this study. The strong impact of morphology found in part one of the study is also shown in the habitat persistence. In the reach with alternating gravel bars $M_{alt}$ potential spawning areas, available in much smaller portions than in $M_{nat}$, disappear completely when considering their persistence.

*Horizontal velocity:* The vertical velocity of the water level change is one of the main parameters for the assessment of stranding risk in hydropeaking conditions. Values from the experiments in HyTEC flume in Lunz for Larvae of grayling (30 mm body length) and a lateral bank gradient of 1:20 (comparable to position 4 in Figure 15) indicate, that there is no stranding risk for a horizontal velocity of 2.4 m/h or less. This threshold is then transferred into a vertical velocity of 12 cm/h that has been also found as a threshold in former studies (Saltveit et al. 2001). However, the horizontal velocity related to this vertical 12 cm/h increases with decreasing steepness of the affected gravel bank. Values from Halleracker (2003) for trout indicate that there is no stranding up to a horizontal velocity of 1.6 m/h; however, the steepness of the bank is not mentioned. For gravel banks with less gradient it cannot be ruled out, that the threshold for the horizontal velocity has to be set lower. However, so far there are no thresholds defined for horizontal velocity.

In the different parts of the near natural reach $M_{nat}$ the horizontal dislocation of the waterline during different periods of an hydropeaking event is very different This can be interpreted that way that it is important to not only consider the difference of wetted area between peak and off-peak flow, but the temporal change as well. It is evident, but often not considered sufficiently that certain periods of a hydropeaking event, or in other words certain flows ranges create a particularly high risk of stranding. This risk can be significantly reduced or eliminated with comparatively low efforts as long as these flows are close to peak or off-peak flow. A slight decrease of peak or increase of off-peak flow can be sufficient. Furthermore, it is very interesting to see, that in the complex morphology of the near-natural reach $M_{nat}$ the maximum horizontal shift of the waterline in many cases is **not** linearly dependent on the steepness of the banks (see table in Figure 15). This is due to the quite different rate of change in hydraulic conditions in different parts of the reach. These conditions are much more stable in the environment of certain hydraulic features.

When analyzing the horizontal velocity it is also important to consider side arms that are disconnected from the main channel. In the $M_{nat}$ reach this is the case for the channels on the right side. Even it not drying out completely and being wetted during off-peak flow the water body is very shallow and stagnant, so young fish are endangered by predators. When water level drops further stranding risk becomes very high.

It should be noted here that the effect of drying out due to disconnection is not visible in conventional 2D models since infiltration and evaporation effects are usually not covered. These effects imply an extreme stranding risk which cannot be addressed by the horizontal velocity.

One risk effect that adds up to the horizontal velocity of the water is implied by waves that occur often during fast flow changes and cause high frequency fluctuations of the waterline. These fluctuations are specifically distinct on gravel banks directly neighbored to the main channel. Particularly one gravel bank in the reach with alternating gravel bars $M_{alt}$ that provides suitable juvenile habitats in terms of depth, flow velocity and horizontal velocity of the waterline could be heavily affected by this effect.

### 4.3.2. Morphologic classification

Based on the findings listed above we attempted to set up a classification of morphologic features and possibly characterize several of them that could mitigate the hazards for aquatic organisms under hydropeaking.

- *Hydraulic stability as* the difference of the min and max values of flow velocity, water depth and water level drop velocity for peak and off-peak flow has been found as significantly high in some areas of the near-natural reach $M_{nat}$. The parameter seems to be a suitable hydraulic indicator for the identification of areas with a high damping effect.
- *Habitat shift $Q_{off}$-$Q_{peak}$*: The hydraulic stability seems to interact advantageously with some specific morphologic features. It has been found that especially in and around the side arm several areas with little shift of good juvenile habitats between peak flow and off-peak flow are present. Generally this comparatively small dislocation of suitable habitats is also found in heterogeneous steep bank areas, at the lower end of large bars neighbored to hydraulically stable side channels. However, all these structures seem to develop their mitigating effect in conjunction with hydraulically stable river parts, such as the mentioned side channel or narrow in- and outlets of side arms.
- *Gravel bar types*: A close correlation between specific gravel bar types listed in a study by Habersack et al. (2013) and hydropeaking mitigation could not be verified. Even in the original study flow-width relations seem to depend rather on the selected river reach than on the gravel bar types. Although in the near-natural reach $M_{nat}$ some structures at the end of large gravel bars provide relatively stable habitat conditions they cannot be referred as point bars, which are according the study of Habesack et al. (2013) the most advantageous type of bars. Based on these analyses it seems to be difficult to distinguish clearly between gravel bar types and their behavior in hydropeaking conditions. Advantageous effects seem to be rather related to an interaction between hydraulic stability, larger morphologic features such as the permanently wetted channel in reach $M_{nat}$ and small scale morphologic properties such as refuge pockets as special type of backwaters or heterogeneous banks.

### 4.3.3. Advantageous structures

- *Hydraulically stable side channel*: Particularly the permanently wetted side arm on the left side of reach $M_{nat}$ provides conditions that favor organisms with a high sensitivity against fast flow changes. This is most probably due to the narrow and deep inlet and the narrow outlet. They apparently create an advantageous damping effect (Figure 19). This effect reduces the velocity of water level rise in the upramping phase but also the water level drop velocity in the downramping phase of hydropeaking events. Creating this kind of morphological feature artificially respectively supporting their development would be a most suitable way to mitigate hydropeaking effects.
- *Refuge pocket:* The hydraulic effect of a refuge pocket as one of the small scale structures in the near-natural reach $M_{nat}$ was investigated based on an existing hydrodynamic model for the HyTEC flume in Lunz, Austria. It is shown that the pocket positively affects the distance the fish should

cover at a time unit in order not to get stranded on a bank. However, the longitudinal effect zone is limited and comparable with the size of the pocket itself. In other words this kind of structure provides very local mitigation and presumably only has significant effects when installed in sufficient number.

# 5. Conclusions and outlook

At the present state of our analyses, we conclude with the points listed below. As announced earlier in the report we plan to complement the existing investigations with some in-depth analyses on specific points. These analyses might lead to minor changes in the conclusions below.

- Studies that provide suitability curves were made for various purposes. This partly explains why the studies differ in the degree of additional information provided (e.g. community composition etc.).
- It is difficult to explain the observed variability in suitability curves with the heterogeneous information provided in the studies.
- Cover is considered a key parameter for habitat selection for brown trout. However, compared to substrate where many studies follow the Wentworth scale, cover is, if at all, reported in a very inconsistent way making cross-study comparisons impossible.
- Habitat suitability data originating from reaches of impaired or unknown hydrological or morphological status should be treated with care.
- Habitat suitability data based on use-to-availability ratios have weak points (e.g. rarity or absence of habitat types) and represent a snapshot in time. It would be important to develop methods that allow for extended time periods and multiple habitat parameters to be observed as well as individual differences (e.g. acoustic methods, radiotracking).
- Both river morphology and hydrology should be considered in hydropeaking mitigation. A channelized reach does not represent the complex habitat template that aquatic organisms need throughout their life history.
- The pronounced study effect on SI on the cell level indicates that care should be taken when transferring suitability curves across rivers.
- Generalized habitat suitability curves based on a selection and smoothing of data from literature research have led to similar habitat simulation results as datasets specifically developed for the Alpine Rhine based on field sampling and expert knowledge. This encourages the assumption that defining river-type specific habitat suitability curves is feasible. To do so, an in depth analysis of collected habitat requirement data is needed (see above).
- Requirements related to the hydropeaking parameters such as horizontal waterline velocity or minimum water depth on spawning grounds are presumably rather transferable than other habitat requirement data. Available data should be further studied and possibly harmonized.
- Habitat shift has been used as suitable indicator to describe the morphological deterioration of hydropeaking reaches. This dislocation of suitable habitats is not generally lower in the near-natural reaches, but in specific areas significantly reduced compared to modified reaches.
- The approach of persistent habitats is suitable for organisms with a low mobility such as redds or certain types of macroinvertebrates (Kopecki et al 2012). It has to be extended considering the distinction of spawning activity and development of eggs.
- Purely steady-state or single flow related hydraulic considerations such as ratio of wetted area for peak and wetted area for off-peak flow are not suitable to cover unsteady hydropeaking effects.
- The horizontal velocity of the waterline is presumably more important than the vertical velocity of water level. It is not derivable from the gradient of the river bank, but depends on morphology and local hydraulic stability (see below).
- Side arms disconnected during downramping imply a major stranding risk for juveniles when drying out after disconnection. This is not covered in many hydrodynamic models (seapage and evaporation) and has to be taken into account.
- Hydraulic stability defined by changes in water depth, flow velocity and max rate of water level drop seems to be suitable to identify areas with reduced hydropeaking impacts.
- The habitat shift between peak and off-peak flow is an indicator for the distance organisms have to cover and by that for stress induced. It is an indicator for hydropeaking impact level. However, no thresholds for the shift are available yet.
- General classification of gravel bars is difficult. One type of gravel bar can behave differently in different rivers. (example alternating gravel bars, point bars)

- Most dangerous in terms of stranding risk in the investigated reaches are extended small gradient side bars. Main channel bars are less dangerous than banks of auxiliary or not permanently active channels.
- Upstream parts of islands neighbored to side channels can have advantageous hydraulic behavior in terms of decelerating the waterline regression.
- Backwater areas at the downstream end of gravel bars often have a small gradient and can increase fish stranding risk.
- Backwater at the at the downstream end gravel bars in heterogeneous areas and at the outflow of side channels can at the same time increase hydraulic stability and that way mitigate hydropeaking effects.
- Very advantageous in terms of hydropeaking mitigation are hydraulically stable and permanently wetted side channels. The stabilization effect is presumably supported by narrow in- and outlets causing a delay and diminution of unsteady flow behavior. The detailed hydraulic behavior of this kind of morphologic feature should be studied in detail.
- Connected “refuge pockets” appear to be positive for the survival of juveniles. Hydraulic studies on a laboratory example show however, that their lateral influence zone is small and comparable to the size of the structure.

# 6. Collaboration

## 6.1. National Collaboration

There were valuable synergies to the project „Wasserbau und Ökologie”, which is a joint initiative by the Swiss Federal Office for the Environment (FOEN) and the four institutions from the ETH domain Eawag, WSL, ETHZ-VAW and EPFL-LCH. The project was started in summer 2013 with a focus on sediment rehabilitation. The data on sediment preference gathered in the present project will be of interest for the research in the FOEN-project. Ch. Weber will take care of the knowledge exchange between the projects.

## 6.2. International Collaboration

Internationally, there exist a collection of research groups who are currently working on hydropeaking phenomena (e.g., University of Natural Resources and Life Sciences, Vienna; University of Trento, Italy; SINTEF, Norway). These groups are important partners for the present project and were contacted for data gathering in the first project phase and for discussion of project findings in an international expert workshop towards project end (November 2014).

In the framework of another project, Ch. Weber, Eawag, and M. Schneider, SJE, participated in an Austrian-Swiss workshop on hydropeaking mitigation in October 2013 where they discussed the present project with representatives from different institutions (university, federal offices, hydropower producers). Our initiative was very well received.

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