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# Estimating Stranding Risk due to Hydropeaking for Juvenile European Grayling Considering River Morphology

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## Abstract

Extreme, short-duration fluctuations caused by storage hydropower plant discharges or 'hydropeaking' occur when hydropower is used to cover the peak electrical loading conditions of a power network. The overall effects of hydropeaking can result in serious disturbances to the hydrologic regime, river morphology and the ecological condition of a river. In this study a transient, fuzzy logic based two-dimensional fish habitat model was used to investigate the stranding risk to juvenile European grayling (*Thymallus thymallus*) corresponding to different river morphologies. The stranding risk was simulated using two 24 hour discharge hydrographs in two alpine gravel bed river reaches. Both reaches were in close proximity to the hydropower plant outlet and were chosen due to their starkly contrasting morphological features. Spatially distributed stranding risk was determined based on a multi-step procedure which took into account the stationary habitat suitability, critical dewatering rates and flow depths. Although the number of reaches used in the investigation was limited in scope, clear distinctions with respect to the stranding risk were found. The reach with wider, flatter cross sections had a larger amount of stranding risk areas as compared to the reach with a steeply incised channel form. Stranding risk was found to be related to a specific set of changes in the discharge than to a particular rate of change or magnitude of the flow fluctuations. The temporal distribution of stranding risk was found to be almost identical for both reaches.


Keywords: *hydropeaking, fuzzy-logic, fish habitat model, river morphology, European grayling*

## 1. Introduction

Rivers are integral parts of the valleys that they drain. Large catchment areas can be viewed as ecosystems with both natural and cultural interactions (Hynes, 1975; Stanford *et al*., 1996). In European alpine communities, hydropower has become a locally available resource with growing transboundary value due to the increasing demand of renewable energy in the European energy sector. However, hydropower operations can result in significant disturbances to the flow regime, negatively impact water quality, and are often a major cause of fish habitat loss due to morphological degradation. Rapid fluctuations in the daily discharge regime downstream of peak power producing hydropower facilities are particularly pronounced due to the large difference between the early morning base and the afternoon/evening peak flow rates. The hydropeaking phenomenon is persistent, having been documented in the European Alps since the late 1930s (Meile *et al.,* 2010). Determination of the magnitude and severity of such effects has already been investigated in several studies, where BUWAL (2003) and more recently Bain (2007) provide a thorough review of these works. Fish and macrozoobenthos are especially well suited for use as biological indicators for the impact assessment of hydropower operations due to their positions in the trophic chain. For all organisms in the alpine river, persistence comes at the cost of participation (Tuhtan, 2011). In this work we chose to focus the analysis on the European Grayling, as it represents an endangered population in many alpine river ecosystems (Persat, 1996), and thus the effects of hydropeaking on this species are of particular interest. Juvenile fish drift during the rising limb of the hydropeaking wave and can be stranded during the receding limb, and are one of the most commonly investigated indicators of river ecological health. In addition to the modification of the flow regime, changes to river morphology caused by hydropeaking play a central roll in determining a river's ecological state. The highly heterogeneous nature of instream structures (gravel banks, islands, woody debris, etc.) often aids in reducing the negative effects of hydropeaking, but can also exacerbate conditions. As an example, the formation of shallow pools due to changing flow conditions can provide refuge for juvenile fish during the rising limb of the hydrograph, reducing drift, but can also lead to fish stranding after the wave has passed.

Contemporary fish habitat models are built on the assumption

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of stationary relations between physical and biological parameters, and are thus not able to account for unsteady habitat conditions due to drift or stranding during hydropeaking events. In order to study the potential effects of hydropeaking on a reach scale, it is necessary to implement a new type of instationary fish habitat model. Furthermore, most studies on the effects of hydropeaking have focused on the analysis of the discharge hydrographs under the assumption that absolute changes in the hydrograph, such as the ramping rate and magnitude of change of the flow fluctuations should serve as suitable indicators for the effect of hydropeaking on river ecosystems (Limnex, 2004; VAW and LCH, 2006). If such coarse criteria are to be used in the estimation of hydropeaking effects on the reach scale, the use of the proposed three indicator approach developed by Meile *et al*. (2010) is recommended. In this work we first introduce an instationary expert knowledge based habitat model suitable for studying rivers impacted by hydropeaking. Two alpine reaches with starkly contrasting morphologies are then compared under varying flow conditions to illustrate the insights gained by applying such a model.

## 2. Principles of Aquatic Habitat Modeling

To quantify and predict the impacts on ecology, aquatic habitat simulation tools have established a firm role in water resources management studies. The first available physical habitat model was PHABSIM (Bovee, 1982; Milhous *et al.*, 1989) as a component of the Instream Flow Increment Methodology (IFIM) (Bovee, 1982; Stalnaker, 1995) and was developed in North America in the 1970s. In the 1980s physical habitat models became an important tool for river management (Bockelmann *et al.*, 2004) and are currently applied worldwide in sustainable management of rivers and are currently the focus of ongoing debate and research. Today a variety of models have been developed encompassing nearly all types of aquatic organisms, here we focus on the use of physical habitat models. Comprehensive reviews of other habitat modeling techniques can be found in the literature (e.g., Rosenfeld *et al.*, 2003; Harby *et al.*, 2004; Ahmadi-Nedushan *et al.*, 2006; Conallin *et al.*, 2010).

Physical habitat models use biophysical relationships that represent the core in predictive aquatic habitat modeling as they aim to assess how environmental factors control the distribution of species and communities (Conallin *et al.*, 2010). Although many studies have assessed the biotic response of altered environmental conditions, there is still a clear need of quantifying specific species-environmental relationships (Guisan and Zimmermann, 2000). Physical habitat models allow for this quantification as they predict habitat quality in relation to the physical attributes of the environment and its changes. Following Jowett (1997), we define the physical habitat as the species' surroundings, featuring local physical, chemical and biological factors as the basis of life for instream biota. From a practical point of view, water resources managers need models which are able to quantify the disturbance level of ecosystems compared to a given reference state. When choosing modeling approaches to simulate aquatic habitats, water management professionals must compromise between model accuracy, politics, economic cost, scale, and data requirements.

The classical approach of quantifying habitat consists of estimating habitat indices regarding an optimum range of abiotic conditions of the selected indicator species (Hardy, 1998; Leclerc *et al.*, 2003). Based on the similarity of existing conditions and preferred conditions of aquatic organisms, a comparison yields a habitat quality level assigned to the location under consideration. This location could be a point, a cell within a regular or irregular grid, a volume, a transect, or an entire reach. The most common index to describe biological response is the Habitat Suitability Index (HSI) ranging from 0 (completely unsuitable) to 1 (ideally suitable). The biological response can be then expressed through a large variety of mathematical formulations such as presence/absence, abundance, or density. Linkages between biotic and abiotic factors can also be modelled using a wide variety of approaches. They are most frequently classified using univariate methods assuming independence between habitat variables, but multivariate approaches do also exist. Multivariate approaches have the advantage of being able to account for the dependency and correlation structure of habitat variables (Ahmadi-Nedushan *et al.*, 2006). Based on the HSI-values, the Weighted Usable Area (WUA) or the Hydraulic Habitat Index (HHS) (Stalnaker *et al.*, 1995; Jorde, 1996) of a species can then be estimated as a function of the flow regime (Gore and Nestler, 1988):

$$WUA = \sum_{i=1}^{n} A_i \cdot HSI_i = f(Q) \tag{1}$$

$$HHS = \frac{1}{A_{total}} \sum_{i=1}^{n} A_i \cdot HSI_i = f(Q) \tag{2}$$

where $A$ is the area of model element $i$, $n$ is the total number of elements, $HSI$ is the value (0-1) of the habitat suitability index of element $i$, and $Q$ is the flow rate.

In the case that all elements have optimal habitat suitability (HSI=1), the WUA is equal to the wetted area. Characteristically the WUA increases monotonically up to an optimum and then decreases with increasing discharge as the habitat variables become out of sync with the preferred ranges of the target species. The HHS divides the WUA by the wetted area leading to an index ranging from 0 to 1. The HHS thus eliminates the influence of the wetted area and enables a direct comparison between study-sites having different spatial scales.

Here we investigate the effects of the discharge hydrograph on the distribution of habitat suitability and stranding risk areas in order to link changes in flow to habitat conditions directly. The classical approach for habitat modeling was advanced to a multi-step fish habitat modeling procedure tailored to the investigation of stranding risk by Schneider and Noack (2009) using the juvenile European grayling as the indicator species. Two investigation reaches were chosen directly downstream of a hydropower outlet channel, and both the base habitat suitability and a stranding risk assessment were carried out using two 24 hour discharge hydrographs from April 2009.

## 3. Model Description

### 3.1 Hydraulic Model

In this work the hydraulic model of choice was Sedimentation and River Hydraulics 2D (SRH-2D), a two dimensional finite volume model developed by the US Bureau of Reclamation (USBR). The model solves the two dimensional depth averaged diffusive and dynamic wave equations under both steady and unsteady flow conditions. Sub-, super-, and trans-critical flows can be solved (Lai, 2006). Additionally, SRH-2D allows for unstructured hybrid meshes. The advantage of using a mix of element types is that the same numerical solver can be used for a variety of mesh topologies: orthogonal or nonorthogonal structured quadrilateral meshes, unstructured triangular meshes, or hybrid meshes with mixed element shapes (Lai, 2010). The model outputs are the temporal varying water surface elevation, bed elevation, water depth, bed shear stress and Froude number. SRH-2D is suitable for applications in which two dimensional and highly unsteady effects such as those occurring in the varial zone during hydropeaking conditions are important (Tolossa *et al*., 2009).

### 3.2 Fish Habitat Model

Fuzzy-set theory was first developed by Zadeh (1965) and characterizes complex systems through imprecise, fuzzy state transitions. Contrary to Boolean logic, fuzzy-logic allows a system to obtain intermediary states, e.g., a state can be described as being both partially A and B simultaneously. In ecological modeling these intermediary states are very important as transitions in ecology are not crisp but gradual (Salski, 2002; Cadenasso *et al.* 2003). Classical aquatic habitat modeling techniques include crisp boundaries between two parameter ranges. For example, if the limit of the variable *low velocity* is set to 0.3 m/s, then a value of 0.29 m/s is considered *low*, while 0.31 m/s becomes *medium*. This crisp assumption does not fit into the ecological boundary theory as defined by Strayer *et al.* (2003) where the boundaries should be defined as gradients. Fuzzy-logic has proven to be an excellent modeling technique for ecological gradients as the overlapping fuzzy-set theory reflects these gradual transitions between pre-defined classes (van Broekhoven *et al.*, 2006; Mouton, 2008). Another drawback in classical or statistical modeling approaches is the inability to incorporate ecosystem behavior information in the form of expert knowledge (Austin, 2002) which is readily available at many sites for which it may be difficult to obtain field measurements. Other advantages of fuzzy-logic modeling are that they allow for the implementation of qualitative data in numerical processing (Ahmadi-Nedushan *et al.*, 2008), they consider multivariate effects without assuming independence of input variables, they have the ability to consider numerous combinations of habitat variables, and the models are directly interpretable (not a black box). All of these attributes allow for a sound basis for collaboration between scientists, river management professionals and political decision-makers (Casillas *et al.*, 2003).

The habitat model CASiMiR (Computer Aided Simulation Model for Instream Flow Requirements) was developed in the early 1990s at the Institute of Hydraulic Engineering at the University of Stuttgart (Jorde, 1996). Its principal purpose was the investigation of fish and invertebrate habitats as they change with river discharge. Since its inception the modeling platform has expanded to include long-term fish habitat changes in floodplain channels in the Netherlands (Kerle *et al.*, 2002), the effects of dam operation on physical habitat conditions in Chile (Garcia *et al.*, 2010) and on sturgeon habitats in a Chinese river (Yi *et al.*, 2010).

Contrary to other fish habitat models, CASiMiR applies a knowledge-based multivariate fuzzy-logical approach to link physical parameters with biological habitat requirements (Schneider, 2001). Knowledge-based rules are applied connecting physical habitat parameters to fish habitat requirements through the use of conventional linguistic terminology such as “high”, “medium” or “low”. Case-specific input parameters often occur when modeling biological systems and can be easily integrated directly into the fuzzy logic method. The standard CASiMiR model output is the habitat suitability prediction ranging from 0-1. Results vary depending on the flow rate and corresponding changes to the other input parameters. However this approach is not sufficient to determine the potential effects of hydropeaking. In order to incorporate the effects of hydropeaking on fish habitats, the hydropeaking model was set up using Matlab’s Fuzzy Logic Toolbox.

### 3.3 Hydropeaking Model

To investigate high downramping rates and varying morphological features on fish stranding a multi-step fuzzy rule-based approach has been implemented. The method includes unsteady flow conditions and the resulting change of habitat parameters over time. The first step involves retrieving the results of the base habitat suitability from the standard fish habitat model. The quality and spatial distribution of the habitats are assessed across the whole range of flow rates of the hydropeaking. This step is

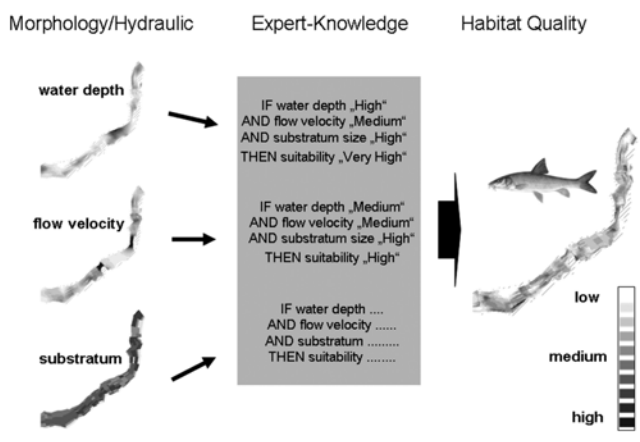


Fig. 1. Graphical Representation of the CASiMiR Modeling Concept (after Schneider 2001)

Table 1. Critical Downramping Rates for Juvenile Fish

| Rate in m/h | Rate in m/10 min | Rate in m/min | Source |
|---|---|---|---|
| 0.18 | 0.030 | 0.0030 | Halleraker *et al.* 2003 |
| 0.12 | 0.020 | 0.0020 | Saltveit *et al.* 2001 |
| 0.20 | 0.033 | 0.0033 | Meile *et al.* 2005 |

key since it is necessary to first determine the locations of a reach for which the habitat is suitable for juvenile fish. The parameters used in the basic habitat suitability are the temporal varying water depth, flow velocity, and the dominant substrate.

The second step considers the rate of the water level decrease over time, or downramping rate. Studies have shown that the range of tolerable downramping rates range from 0.12-0.20 m/h (Halleraker *et al.*, 2003; Saltveit *et al.*, 2001; Baumann and Meile, 2004). These rates are then used as input for the superposition of highly suitable areas from step one with the ramping rates to define areas of high potential stranding risk.

In addition to the critical stranding rate, a minimum water depth for the juvenile fish of 0.2 m in conjunction with the basic habitat suitability served as the base criterion for the second model step. As long as juvenile fish are able to follow the decreasing water level, the rapid flow reduction and separation of wetted areas may not pose a problem. We focus on using established values for the critical ramping rates because it was not possible to locate stranded fish in the investigation reach due to the long-term effects of hydropeaking activity.

The final model step finds locations in which at the beginning of the time step have high HSI values, but which is subject to a high downramping rate and exhibits the minimum water depth criteria. Thus the most dangerous conditions for juvenile fish are assumed to be found when a rapid water surface reduction occurs in areas with a shallow flow depth in regions having suitable habitat conditions. The model considers such conditions as those areas having the highest risk. In this work we focus entirely on the dynamics of these stranding risk areas.

## 4. Application

### 4.1 Site Description

Both investigation reaches were on the river Inn at the Swiss-Austrian border. Both reaches were downstream of the hydropower plant outlet channel, in the river Inn at Martina (Reach 1 – directly downstream, Reach 2 – at a distance of 2.5 km). Reach 1 is a deeply incised natural gorge, with steep side slopes and a rocky bed, with some gravel and small stones. Reach 2 is more generally representative of the Inn in the Alpine region, with wide, flat cross sections and a rough, rocky bed. Fig. 3 provides a visualization of the digital terrain models of both reaches.

The investigation sites are similar in length but differ significantly in river bed width and morphological characteristics. Reach 1 is a natural narrow canyon 16 m wide, while Reach 2 has a width of 56 m. Moreover the slope in Reach 1 is almost three times as steep as Reach 2. The substrate characteristics are similar, where the dominant substrate in both sites is relatively coarse at 12-20 cm, common for alpine river reaches. With increasing discharge, the wetted area of Reach 1 remains relatively constant due to the steep banks whereas the water depth and flow velocity increase much more rapidly. Reach 2 is characterized by several morphological features absent in Reach 1 such as gravel bars, has areas with both flat and steep banks, and a moderate slope.

### 4.2 Model Set Up

#### 4.2.1 Hydraulic Model Parameters

The computational meshes were constructed using quadrilaterals having approximately equal side lengths, with an average element size of 1.2 $m^2$ for Reach 1, and 1.75 $m^2$ for Reach 2. The models were calibrated using field measured water surface ele-

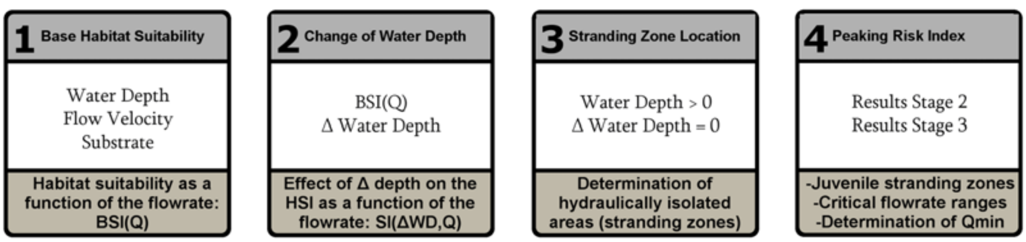


Fig. 2. Illustration of the Multistage Hydropeaking Modeling Approach Developed by Schneider and Noack (2009)

Table 2. Investigation Reach Information

| Investigation Reach | Reach Length (m) | Bed Width (m) | Bed Slope (m/m) | Substrate Composition |
|---|---|---|---|---|
| 1 | 170 | 16 | 0.015 | 80% stones 12-20 cm<br>10% small stones 6-12 cm<br>5% large gravel 2-6 cm<br>5% sand, small gravel |
| 2 | 188 | 56 | 0.006 | 90% stones 12-20 cm<br>5% small stones 6-12 cm<br>5% rocks > 20cm |

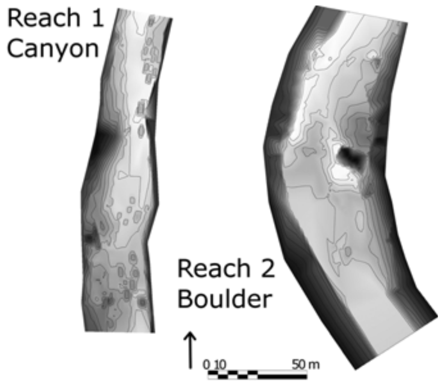


Fig. 3. Digital Terrain Models Used as the Basis of Both Investigation Reaches (The arrow indicates flow direction.)

vation data for a series of steady flow rates ranging from 5-200 $m^3/s$. Hydrographs A and B were run as individual 24 hour unsteady simulations, were model results were saved at 10 minute intervals. The upstream boundary conditions were the hydrographs A and B based on unmodified data sets obtained from the Swiss Federal Office for the Environment's (BAFU) gauging station at Martina-Pradella (ID 2067), and are shown in Fig. 4. The downstream boundary conditions were input as discharge-water surface elevation rating curves based on field data. Manning's roughness values $n$ were assumed constant over the hydrograph and ranged from 0.013-0.83 depending on surface conditions. Both models were calibrated using a limited number of water surface measurements taken during constant flow conditions. Due to the difficulty and danger of traversing the investigation reaches during hydropeaking events, it was not possible to obtain field observations of the stage-discharge relations using conventional terrestrial surveying equipment.

### 4.2.2 Fish Habitat Model Parameters

The fish habitat model used the fuzzy rules and sets taken from Schneider and Noack (2009), which were found to be in general agreement with the empirically determined preferences on the river Ain as reported by Mallet *et al.* (2000). Time variant input parameters were the water depth and flow velocity, where the substrate properties were assumed constant for each time step. The habitat suitability results were defuzzified into the HSI.

The fuzzy sets defining critical dewatering were based on Saltveit *et al*. (2001) where rates higher than 0.02 m/10 min were considered as especially dangerous. Fuzzy sets describing the critical depths were also taken from Schneider and Noack (2009).

## 4.3 Results

### 4.3.1 Reach 1 Base Habitat Suitability

The assessment of the base habitat suitability in Fig. 5 considers only values of HSI > 0.5. This was considered to be a better overall indicator than the Weighted Usable Area (WUA). The WUA describes the total area which is defined as suitable habitat by multiplying the element-wise HSI values with their individual areas. Because of the WUA's dependence on the total wetted area it is difficult to directly compare sites with different wetted areas, especially if there are large differences in morphology. Additionally, normalizing the WUA to a Hydraulic Habitat Index (HHS) would also be incorrect as the absolute values of the wetted areas are needed to compare each reach's habitat availability as a function of their specific morphological characteristics and flow rate (Jorde, 1996).

As shown in Fig. 6, for both hydrographs A and B there is a strong negative correlation between the HSI and the flow rate. For hydrograph B, it can clearly be seen that that there is little change in the HSI over the full range of flow rates (30-85 $m^3/s$). Since juvenile grayling prefer lower water depths and slower flow velocities, for flow rates greater than 10 $m^3/s$ in Reach 1 (from 6:00 to 23:00), the vast majority of suitable habitat is depleted rapidly to an almost steady flow rate invariant 250 $m^2$. Another

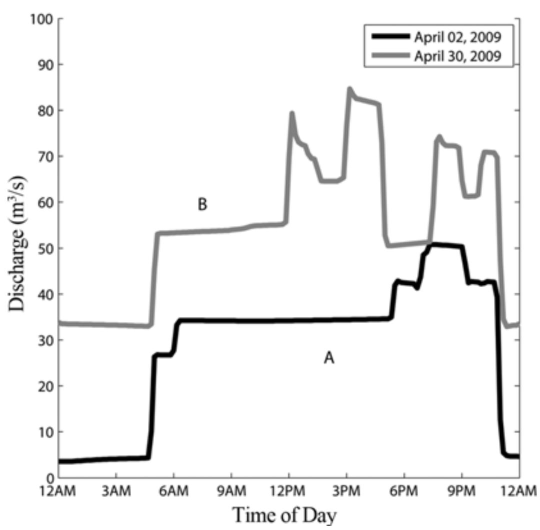


Fig. 4. Discharge Hydrographs of the Two Days Investigated at Martina

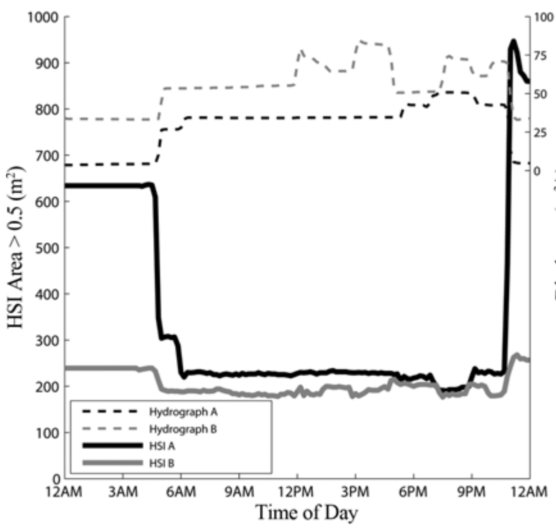


Fig. 5. Areas of HSI > 0.5 for the Hydrographs A and B in Reach 1

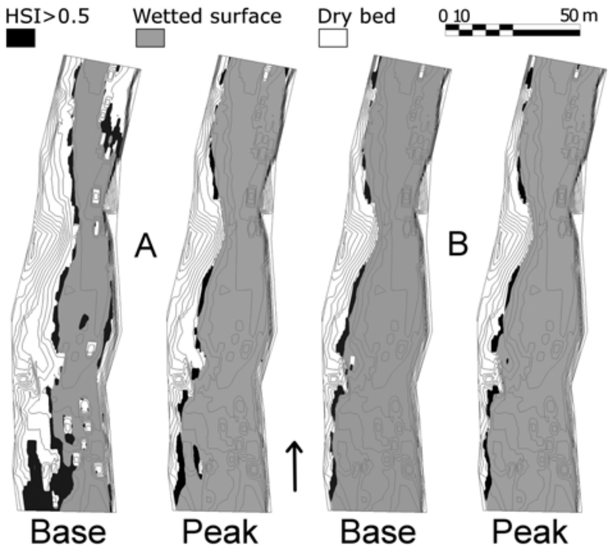


Fig. 6. Spatial Distribution of HSI and Wetted Area for the Lowest and Highest Flow Rates from Hydrographs A and B in Reach 1 (White areas are the dry bed areas, gray the wetted surface and black are areas having an HSI > 0.5. The only notable difference in the HSI distribution occurs during hydrograph A where the flow rate is the lowest.)

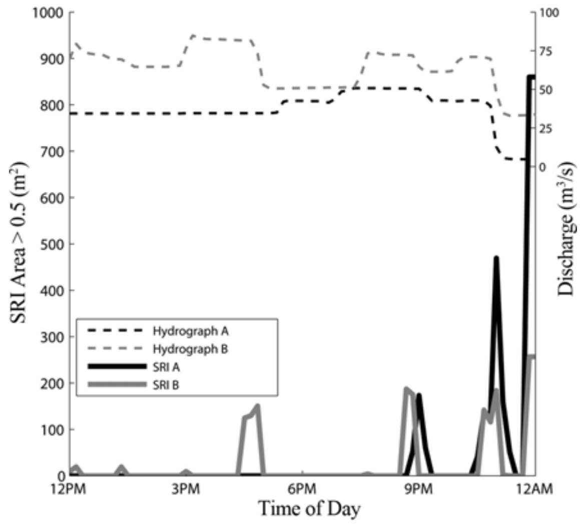


Fig. 7. SRI due to Down-ramping for Reach 1 and the Hydrographs A and B

interesting observation is the increase in available habitat during rapid dewatering. Between 23:00 and 23:30 there is a large downramping event in hydrograph A. Here it can clearly be seen that there is more suitable habitat available at higher flow rates than at the beginning of the day. This is caused by the presence of flooded areas which were not wet at the beginning of the day, but which contain favorable habitat conditions during dewatering. These areas show a slower decline than hydrograph A because of the formation of a large low flow pool at the upstream end of the reach. During hydrograph B the pool area exhibits higher flow velocities and depths, and is thus not suitable for juveniles.

### 4.3.2 Reach 1 Stranding Risk Index

Figure 7 shows the relation between simulated stranding risk index due to down-ramping and the hydrographs A and B. The spatial distribution of the stranding risk for both reaches is shown for comparison in Fig. 8 for the largest down-ramping event at 17:00. The distribution of stranding risk exhibited three curious features. First, the relative magnitudes of the SRI were found to be more strongly correlated to specific flow rates than to the magnitude of the dewatering events. Second, it can be indicated that hydrograph A, although milder in its flow fluctuations than B, provided worse conditions for juvenile grayling during the final dewatering event. The reason behind this becomes evident when comparing the HSI distribution during this time. Since the base flow of hydrograph A is much lower than B, it leads to a higher change in the wetted area. Furthermore, hydrograph B begins and ends with a base flow resulting in lower overall HSI values, thus stranding risk for is also lower simply because of the reduced overall amount of available suitable habitat. Finally, it


Fig. 8. Spatial Distribution of SRI during the Largest Down-ramping Event at 23:00 for Reaches 1 and 2 during Hydrographs A and B [White areas indicate the dry bed, gray the wetted surface and black are areas having an SRI > 0.5. Due to the differences in morphology, it can clearly be seen that the largest dewatering event of hydrograph A (With the lowest final flow rate) has a much larger area of SRI as compared to the events having higher final flow rates.]

was observed that during hydrograph B for the intervals 17:00-17:30, 21:00:-21:30 and 23:00-23:30 there were essentially equal areas with a stranding risk greater than the threshold. The spatial distribution of SRI shows the risk areas along the left bank where the juvenile stay during high flow as these are the flow-protected area. These areas are most endangered areas during down-ramping.

### 4.3.3 Reach 2 Base Habitat Suitability

In Fig. 9 the relation between the hydrographs A and B and the corresponding HSI are visualized for Reach 2. Comparable to Reach 1, Fig. 10 indicates that the overall amount of available suitable habitat area is larger given to the differences in morphology. Because Reach 2 has wider, smoother cross sections, it also contains more areas with low flow velocities and depths that are preferred by the juvenile grayling. Comparing the hydrographs reveals that even for a starkly different morphology, the range of flows in hydrograph A below the threshold of 5 m³/s exhibits the largest amount of suitable habitat while it sinks drastically for higher discharges (Hydrograph A). At the beginning and the end of hydrograph A the amount of available suitable habitat area are approximately equal because there are no bed form heterogeneities which cause differences in habitat availability during dewatering events. The HSI distribution during hydrograph B shows a similar invariant shape but on a higher level as compared to Reach 1.

### 4.3.4 Reach 2 Stranding Risk Index

Figure 11 provides information about the SRI for hydrograph A and B in Reach 2. The visualization of the spatial distribution of SRI for the down-ramping event at 23:00 (Hydrograph A) is also shown in Fig. 8. Comparing the SRI of Reach 2 to Reach 1 the only notable exceptions are the two dewatering events in hydrograph B around 12:00, which show lower risk areas. This difference is explained by the flatter morphology which exhibits less volatility in water depth during dewatering events. Examining the events at 17:00 and 23:00, a similar pattern of stranding risk as in Reach 1 can be found, but a significant difference in the magnitude of SRI exists due to differences in the overall amount of available habitat. The similar pattern can be mainly explained by the preference of juvenile grayling, whereas the higher SRI values stem from the flatter morphology where the drying areas increase more rapidly during down-ramping. Thus it is likely that bank slope regulates the magnitude of the stranding risk area, while the hydrograph dictates its temporal distribution. This is indicated by the sharp spike in stranding area during hydrograph B for Reach 2. Because the reach has large amounts of available suitable habitat at low flows, even extending into parts of the main channel, a rapid transition through this range caused signi-

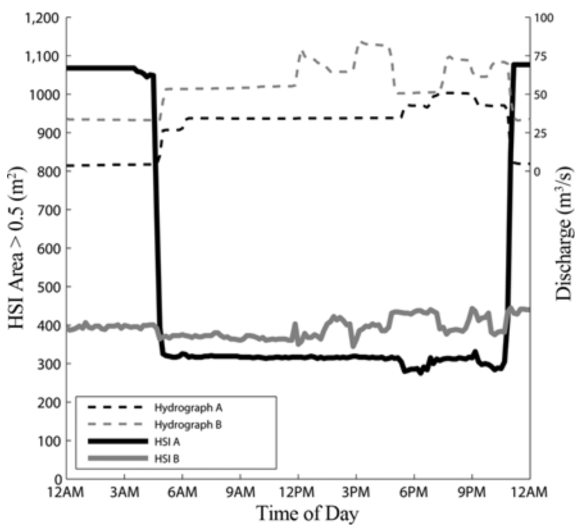


Fig. 9. Areas of HSI > 0.5 for the Hydrographs A and B in Reach 2 (As compared to Reach 1, it can be observed that it has almost twice the amount of HSI over of the range of flow rates considered.)

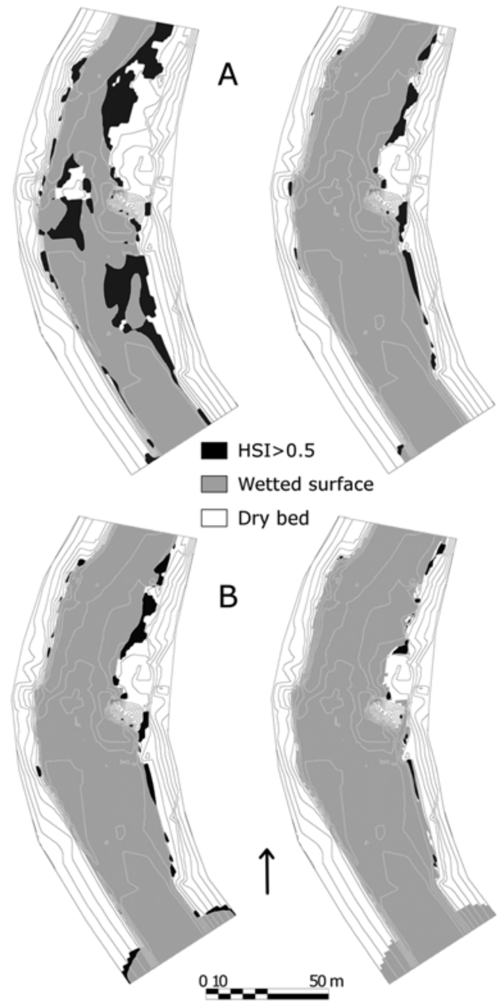


Fig. 10. Spatial Distribution of HSI and Wetted Area for the Lowest and Highest Flow Rates from Hydrographs A and B in Reach 2 [White areas are the dry bed areas, gray the wetted surface and black are areas having an HSI > 0.5. Here as well as for Reach 1, the only larger difference in the HSI distribution occurs during the lowest flow rate (Hydrograph A).]

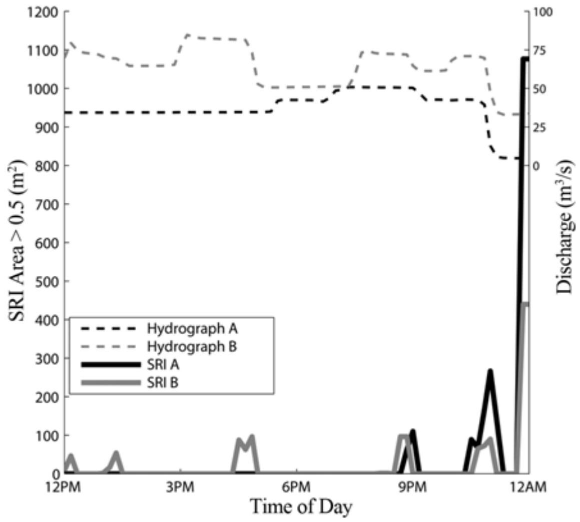


Fig. 11. SRI due to Down-ramping for Reach 2 and the Hydrographs A and B.

ficantly larger stranding risk areas than for Reach 1.

## 5. Discussion

The approach combining unsteady hydrodynamic modeling with habitat modeling can be a useful tool to identify critical discharge ranges where probability of stranding is high. Moreover the spatial distribution of SRI provides detailed information where stranding is likely and where the reach is not vulnerable to flow fluctuations. The magnitude of the stranding risk areas appears to be affected most by initial habitat suitability and morphology, where it was found that steep bank areas play a major role in terms of the magnitudes of SRI. Rivers reaches with large areas of high HSI and steep banks are probably less vulnerable to flow fluctuations than flatter and more heterogeneous ones. Another conclusion is the base flow rates seem to drive the amount of stranding risk, not the absolute change in the flow rate. Thus if hydropeaking occurs in a flow regime with high flows, then the risk of stranding can be significantly reduced. Alternately, when dewatering events begin and end around minimum flow, the risk of stranding can be reasonably expected to be higher. The base flow is therefore of major importance in when considering fish stranding.

In recent applications of the described approach in Switzerland and Austria, morphological features such as cover types and the steepness of river banks have been incorporated as additional factors influencing the stranding risk of juveniles. Water temperature and light conditions as indicators for diurnal activity of fish may also effect fish stranding as at low temperatures fish tend to stay in positions closer to the river bed and hide in the interstices within the substrate while they emerge during day when light and temperature is increasing (Scruton *et al.,* 2008). For spawning habitats the changing flow and water depth conditions during fast flow fluctuations and the stability of substratum seem to be of major importance as well. Increased embeddedness that has been observed in several studies dealing with hydropeaking effects (e.g., Schälchli *et al*., 2003) is a further effect hazarding reproduction and consequently the sustainability of fish populations.

## 6. Conclusions

Although it is difficult to make broad conclusions based on information from a specific case study, a few general remarks can be made which may prove useful in future works:

1. The magnitude of the stranding risk areas appears to be affected most by initial habitat suitability and channel side slope. Reaches where there are high amounts of HSI areas with steep side slopes are probably less vulnerable to flow fluctuations than flatter and more heterogeneous ones.
2. Initial flow rates seem to drive the amount of stranding risk, not the absolute change in the flow rate. If hydropeaking occurs in a flow regime with high flows, then the risk of stranding can be significantly reduced. Alternately, when dewatering events begin and end around minimum flow, the risk of stranding can be reasonably expected to be higher.
3. It may be possible to design practical mitigation strategies based on controlling the discharge hydrograph around key flow rates. Designing hydropeaking peak flow retention basins based on local environmental flow requirements would probably require smaller, controlled basins than previously assumed.
4. Recently promising work has been carried out indicating that in addition to modifications of the flow regime, it may be possible to design instream refugia, or fish shelters in the varial zone (Ribi *et al*., 2010). The modeling techniques in this work could therefore also be applied in the study of such structural design options in order to optimize design performance criteria before full-scale projects are constructed.

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