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Sensitivity of aquatic habitat modeling to hydrodynamic calibration.

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Abstract

Fish habitats and reproduction can be significantly altered downstream of hydroelectric power plants operated by hydropeaking and resulting in rapid and frequent changes in river hydrodynamic conditions. To mitigate the impacts, it is necessary to maintain the habitat quality through operational measures. The microhabitat method, coupling 1D or 2D hydraulic simulations to biological models, is a useful tool to assess the evolution of hydromorphological parameters and fish habitats and define these mitigation measures. Calibration of the hydraulic model must be carried out carefully because the model must accurately reproduce hydraulic conditions from low to high flows. The objective is therefore to evaluate the sensitivity of the habitat value as a function of the type of calibration and the friction law for shallow habitats. The analysis is performed

by estimating the uncertainty in fish habitat values resulting from Strickler's law or Nikuradse's law. The study is carried out on a river in the French Pyrenees based on the modeling of 2 stations with different cross-sectional shapes, one with progressive overflow and the other without these phenomena. Thanks to field measurements at low and high flowrates, the calibration process showed that the friction coefficient can be multiplied by 2. Two dimensionnal simulations give similar results to those obtained with 1D when the flow remains unidirectional but differ for areas with high overflows. Calibration and models can lead to different conclusions regarding the estimation of habitat modifications due to hydropeaking operation and the definition of base flow and maximum turbine discharge.

KEYWORDS

aquatic habitat; shallow water; friction calibration; sensitivity analysis

1. Introduction

Peaking operation of hydroelectric facilities can strongly alter river hydrology, resulting in displacement of water volumes on various time scales (daily, weekly or even seasonally depending on the storage capacity of the facilities) and also rapid and frequent changes in river flow downstream of power plants (Alonso et al. 2017; Bejarano et al. 2017; Carolli et al. 2015; Sauterleute et al. 2014; Zimmerman et al. 2010). These variations in flow have direct impacts on hydrodynamic conditions and consequently on aquatic habitat and fauna. Concerning fish, hydropeaking impacts often lead to a reduction in species richness and biomass, and a change in age structure, notably as a result of (1) failure of spawning due to dewatering or entrainment of roe, (2) mortalities of fry or even juveniles and adults due to trapping-stranding in areas rapidly dewatered or disconnected during the decrease in flow, (3) downstream entrainment and fry mortalities by forced drift during flow increases, and (4) slower growth (Baumann et al. 2003; Bejarano et al. 2017; Cushman 1985; Hauer et al. 2017; Hayes et al. 2019; Moog 1993; Murchie et al. 2008).

To mitigate these potential impacts, it is necessary to maintain the habitat quality through (1) structural measures such as morphological works (shelters addition, banks

reshaping, ...) and (2) operational measures such as minimum base flow between hydropeaks, maximum turbine discharge and maximum ramping rates during increases and decreases in flow (Barillier et al. 2021; Bruder et al. 2016). The microhabitat method is a useful and widely used tool for assessing changes in hydromorphological parameters and fish habitat in relation to river flow, and defining these mitigation measures (Gibbins et al. 2000; Hallereker et al. 2007; Lamouroux and Capra 2002; Lamouroux et al. 2018; Habersack et al. 2014; Noack et al. 2013). Its principle is the coupling of hydraulic modelling to compute hydromorphological parameters (water level, wetted area, water depth and velocity) and biological models reflecting preferences of aquatic organism regarding these parameters (Dunbar et al. 2012; Melcher et al. 2018). Among modelling approaches, numerical simulation is an effective tool to compute the hydraulic variables with the advantage to describe their spatial variability and to be valid for a wide range of flowrate (Jowett and Duncan 2012; Crowder and Diplas 2000). The modelling approach can be combined with expert opinion to better delineate and quantify meso-scale fish habitat (Wegscheider et al. 2021). The accuracy and uncertainty concerning the computed hydraulic quantities depend on the type of modelling chosen, but also on the data available (bathymetry, water profile survey, etc.). For reasons of cost and duration of studies, simple 1D modelling requiring less input data and computations times are still used in some case studies, even if 2D modelling is potentially more powerful. On the other hand, it is generally possible to estimate a priori the uncertainty in the computed hydraulic variables. However, the uncertainty on the results concerning the habitat of aquatic organisms is much more delicate to appreciate, as small variations of water depth and velocity can result in important modifications of the habitat quality, in particular for the young life-stages of fish appreciating shallow areas (Benjankar et al. 2015; Kopecki et al. 2017). As these life-stages belong to the most heavily affected by hydropeaking, it is vitally important to accurately model their habitat from low to high river flows, to define relevant mitigation measures. Kopecki et al. (2017) emphasize the importance of a relevant friction law to get confident hydraulics results. The aim of this paper is to estimate the capabilities of different types of modelling (1D/2D) and friction laws to properly calculate habitat variation for 3 life-stages of brown trout (*Salmo trutta*), over a wide

range of river flow, for typical reaches of rivers affected by hydropeaking in French Pyrenees mountain, with steep slopes (around 1%) and mainly composed of gravels, pebbles and blocks. In particular, we will focus on the sensitivity of the results to the friction law calibration procedure (at low, intermediate or high flow, linear interpolation or physical model), which is tricky due to the small ratio between water depth and roughness diameter, in the river bed at low water level and on the banks during overflows.

2. Material and method

The study focus on the Vicdessos River flowing in the French Pyrenees Mountains whose hydrological regime is strongly influenced by storage and withdrawals for hydroelectric production. The river section under study is usually bypassed by the Sabart hydroelectric facilities, but has been affected by hydropeaking for several years, during maintenance work of this plant. The mean natural flow (MF) of the river is $7 \text{ m}^3/\text{s}$. Hydropeaks coming from the Auzat power plant located upstream can potentially vary between a minimum flow set at $1.6 \text{ m}^3/\text{s}$ (22.8% of MF) and a maximum turbine flow estimated at $16 \text{ m}^3/\text{s}$ (2.28 times the MF; ratio of 10 between base and maximum flows).



Figure 1. Photographs of the two selected station: station 1 (a) and station 2 (b).

The two stations named Station 1 ($42^{\circ}46'32.31''\text{N}$, $1^{\circ}30'41.33''\text{E}$) and Station 2 ($42^{\circ}46'40.95''\text{N}$, $1^{\circ}31'28.29''\text{E}$) are chosen because they are typical of the flow patterns in the area. It can be seen that the hydromorphology of Stations 1 and 2 is very different (Figure 1). At the first station, the main channel is almost trapezoidal and the wetted

width increases steadily with increasing water depth. The grain size distribution is homogeneous over the bed and banks. At the second station, some banks of large blocks are likely to be submerged with a moderate flow. An average slope of 0.01 is measured for both stations. The topography of the stations is extracted from a previous study carried out by Ducos (2016). For the present study, we use the topography incorporated in the two triangular grids shown in Figure 2. To refine and improve these grids, a large number of measurement points are made in the area with large emerging blocks (Crowder and Diplas 2000). Since the goal of our work is to evaluate the model independently of the measurement quality, the 1D model is constructed using the topography of the 2D meshes. The cross-sections are separated by 10 m and interpolated with a distance of 2 m.

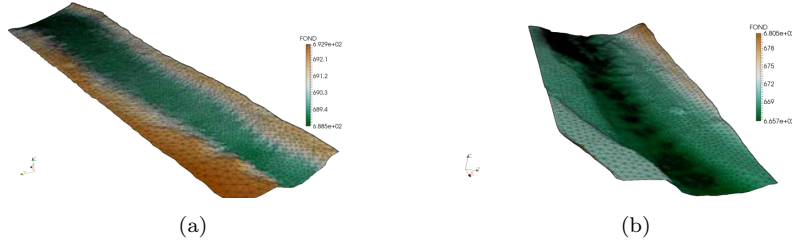


Figure 2. Mesh size for shallow water simulations of station 1 (a) and station 2 (b).

To solve the Saint Venant equation, we performed simulations by 1D and 2D methods with the geometry described above. For the 1D calculation, the HEC-RAS software is used in steady state. The bed friction can be described either by a constant Manning coefficient n , or by k which represents a size of roughness in the so-called "Nikuradse" model. To obtain a transverse velocity distribution, the cross-section is divided into 19 intervals corresponding to a length of about 1-2 m (station 1) and 3 m (station 2). Details of the method can be found in the HEC-RAS reference manual (Hydrologic Engineering Center 2016). The 2D calculations are performed with the TELEMAC 2D software based on the finite element method (Figure 2) (Hervouet 2007). A turbulence model ($k - \epsilon$ model) is used to better describe the velocity field near the emerging blocks (Tran et al. 2016). The time step is 0.1 second and the mesh size varies between 0.2 and 3 m. It is refined near large blocks. The simulation lasts 3000 seconds and for each calculation it is verified that the steady-state solution

is obtained. For both types of modelling, the boundary conditions are identical: a downstream rating curve and a constant flow upstream. The rating curves are obtained from the water depth measurements used for calibration (see following section).

3. Calibration of hydraulic models

Water levels were measured along the longitudinal profiles of the 1.6 and 16 m³/s flows, verified by gauging with an acoustic Doppler profiler. Measurements were taken on the left and right banks if a transverse variation is observed, which explains the distribution of measurements in Fig. 3. The coefficient of friction was determined using 1D simulations. A uniform value is assumed and the same coefficient is used for the 1D and 2D models. Nevertheless, in the 2D model additional energy dissipation is calculated by a turbulence model which implies a slightly higher water depth in 2D than in 1D for the same Manning coefficient. The difference is of the order of 3 to 4 centimetres (maximum of 10 cm).

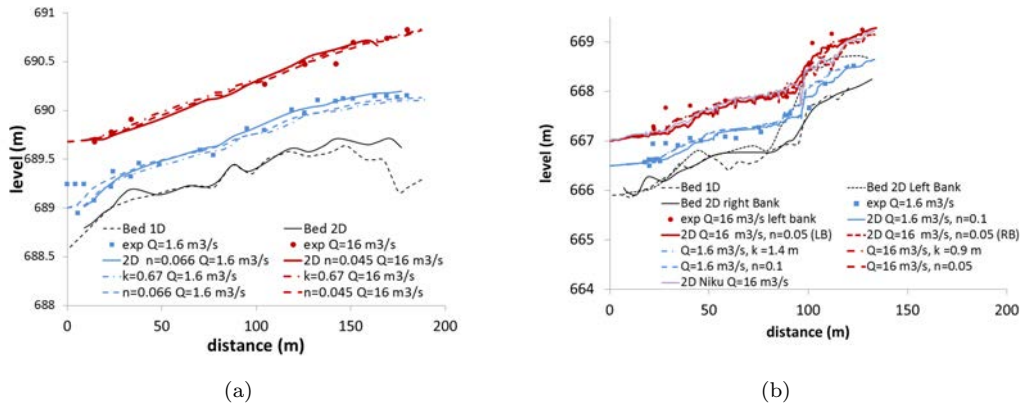


Figure 3. Longitudinal measured and calculated water profiles for station 1 (a) and station 2 (b). Simulations are 1D except if 2D is precised.

At station 1, Tables 1, 2 and Figure 3 shows that Manning coefficients of 0.066 m^{-1/3}s and 0.045 m^{-1/3}s allows the water levels to be reproduced for river flows of 1.6 and 16 m³/s respectively with a Root Mean Square error lower than few centimeters. The 1D and 2D models give very similar results because the channel is almost straight and without overflow. The flow is therefore unidirectional, the friction coefficient being spatially constant and independent of the water depth at a given discharge, equations

1D and 2D are identical (except for the turbulence model) as explained in Jowett and Duncan (2012). For station 2, Manning coefficients of $0.05 \text{ m}^{-1/3}\text{s}$ (high flow) and $0.1 \text{ m}^{-1/3}\text{s}$ (low flow) can calibrate the 2D model. For this station, it is necessary to consider the left and right sides of the channel in the upstream section separately. A difference between the 1D model and the 2D model is noticeable. In the upstream part, the 1D assumption of a uniform cross-sectional water level can easily explain the difference because the 2D model provides a water level difference of up to 15 cm between the 2 banks. This remarks explains larger RMSE observed at $16 \text{ m}^3/\text{s}$. To improve the 1D model, a spatialized calibration could have been performed, but as explained previously, we prefer to consider a general case, i.e. a uniform coefficient for the 1D and 2D models.

Using the Manning coefficients obtained during calibration, an equivalent roughness is identified from the mean water level for each flow. The conversion between n to k is provided by the integration of logarithmic boundary layer with the Nikuradse's assumption (Nikuradse 1933; Hydrologic Engineering Center 2016):

$$n = \frac{R^{1/6}}{18 \log_{10} \left[12.2 \frac{R}{k} \right]} \quad (1)$$

where R is the hydraulic radius. This law is available in both HEC-RAS and TELEMAC. The calculation of the water surface profile with the k values identified (table 2) shows that this law is also relevant for the calibration. It has also been noticed that for station 1, the 2 manning coefficients (low and high flow) lead to the same roughness size value. However it can be noticed that the k parameter is much larger than the real grain size observed on the field. This discrepancy comes from the fact that the Nikuradse law is established for bed sand rivers and not for steep rivers with coarse substrate. Cassan et al. (2019) have shown that a specific friction law allows obtaining law parameter similar to the characteristic grain size of the bed. Unfortunately, this kind of law are not yet implemented in hydrodynamic modelling software. Calibration at station 1 shows that Nikuradse's law allows to better reproduce the friction as a function of the flow rate since only one parameter is required. This behaviour is

	station 1 Q=1.6 m ³ /s	station 1 Q=16 m ³ /s	station 2 Q=1.6 m ³ /s	station 2 Q=16 m ³ /s
1D with n	0.02	0.02	0.03	0.02
1D with k	0.07	0.03	0.013	0.13
2D	0.004	0.03	0.09	0.19

Table 1. RMSE (m) between experimental and modeled water surface profile.

	station 1 Q=1.6 m ³ /s	station 1 Q=16 m ³ /s	station 2 Q=1.6 m ³ /s	station 2 Q=16 m ³ /s
n [m ^{-1/3} s]	0.066	0.045	0.100	0.050
k [m]	0.67	0.66	1.40	0.87

Table 2. Manning coefficients n (m^{1/3}/s) and equivalent roughness height k (m) calibrated at the 2 stations and for each flow rate.

due to the fact that there is no overflow and that the river bed has a homogeneous structure. For station 2, a single roughness size does not allow calibrating the model. The fact that the grain size distribution is very heterogeneous between the banks and the bed can explain the variation of 2 k -values as a function of the flow rate. Consequently, a possible strategy to simulate intermediate flows between 1.6 and 16 m³/s would be to linearly interpolate the Manning coefficient between low and high flow value. This simple method is relevant with respect to fieldwork constraints (only 2 required discharges) and it is an intermediate solution between manning constant value and computation based on Nikurdase’s laws. However, in most cases, it could be difficult to obtain calibration data for the maximum flow. In the results section, we will therefore evaluate the sensitivity of the fish habitat assessment for the different calibration strategies: 1- or 2-point calibration, 1D vs 2D, Manning interpolation vs Nikurdase’s laws.

4. Fish Habitat Modelling Methodology

The micro-habitat method requires a quantification of the adequacy of hydraulic parameters for each fish species and life stage or activity (biological model). Here, three life stages (adult, juvenile and fry) of brown trout (*Salmo trutta*) are considered as it is the main species inhabiting the Vicdessos River. The suitability curves express the preference for velocity (S_v) and water depth (S_h) (Figure 4). They can vary from 0 to 1, with 1 representing the most favourable hydraulic conditions. Although the

substrate play a significant role for habitat, it is not considered due to lack of detailed description on studied stations. Moreover, it is assumed that the substrate influence is identical for all the friction laws and calibration methods. The selected biological models are extracted from Souchon et al. (1989). Then, a weighted usable area (WUA) is defined by the following formula :

$$WUA = \sum_i a_i S_v S_h \quad (2)$$

Where a_i is the area of unit cells with homogeneous hydraulic conditions. The previous formula is given in discrete terms because the simulation results are rasterized with square cells of a_i ($dx \times dx$, with dx is the side length). To compare two different stations, the WUA is divided by the station length to provide an equivalent value for a river length of 1 meter. Thanks to the hydraulic model, the velocity field can be extrapolated and then the WUA can be calculated for a flow range between 0.1 and 16 m³/s.

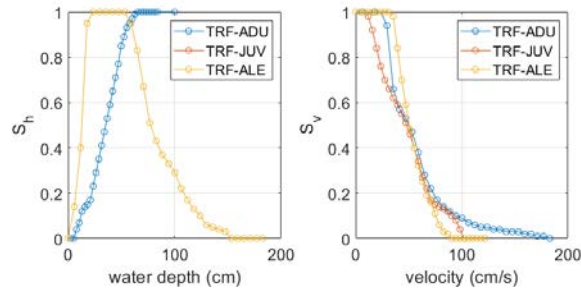


Figure 4. Preference curve for adult, juvenile and fry trout concerning the water depth (left) and velocity (right). Curves for juvenile and fry are confounded concerning the water depth.

5. Results and discussion

5.1. Sensitivity to the habitat variable interpolation method

Habitat determination requires a good description of the bank areas where velocities are generally lower. From a hydraulic point of view, the accuracy of the calculation may be reduced due to the strong influence of the bathymetry in describing the wet or dry areas. In addition, the mesh size of the 2D calculation can also influence the result

if it is too large. In our simulations, the mesh size is 1 meter close to the banks and therefore small enough to minimize the uncertainty in determining WUA . However, we first propose to focus on the sensitivity of the habitat variable to the spatialization method considering the same mesh size. The hydraulic calculation is constant but its interpolation for WUA computation can be either linear or nearest neighbour. The sensitivity of the method is evaluated on station 1 and the Nikuradse model, which is a priori the most sensitive for the calculation of low velocities along river banks.

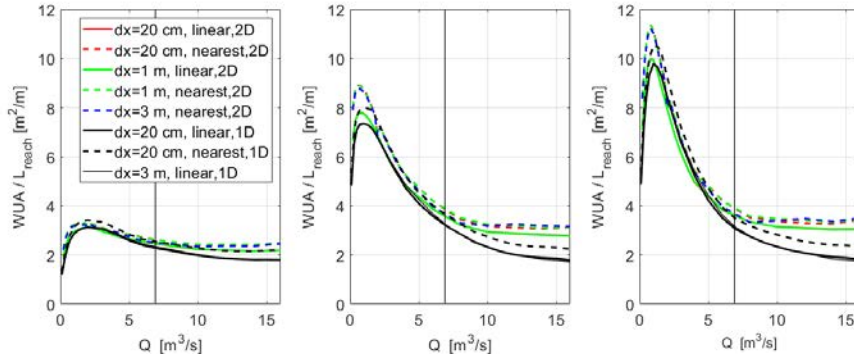


Figure 5. WUA curves for adult (left), juvenile (centre) and fry (right) stages at station 1 and Nikuradse law for different interpolation methods. The vertical line indicates the mean natural flow of the river.

Globally, the WUA curves for the 3 life stages of trout show the same trend (figure 5): from low to high flow, the WUA values first increase, reach a maximum and then decrease more or less rapidly. Flows corresponding to the maximum WUA values are generally higher for adults than for juveniles and fry. These are referred to as optimum flows. As the flow rate increases, the WUA decreases, due to the increase in water velocity and water depth over most of the station.

For the 3 stages of trout, it was observed that using the nearest neighbour (NEAR) method tends to provide larger WUA than with the linear 1D and 2D method. It is interesting to notice that unlike 1D simulations, the 2D ones provide a constant WUA when the flow rate is superior to $7 m^3/s$. Another difference is the 10 % change of the optimum flow rate, 1D model indicates a slightly higher optimum flow rate. This can be explained by the regular shape of the main channel at station 1, which leads to close hydraulic results between 1D and 2D. Similar conclusions were drawn by Papadaki et al. (2017) concerning the difference between 2D and 1D model with lateral redistribution of velocity.

Since the interpolation step consumes computational time, it is interesting to see that 3 m interpolation gives the same results as smaller interpolation meshes. Choosing an interpolation mesh smaller than the hydraulic calculation mesh does not provide any supplementary information and therefore does not improve the quality of the calculation. However improvements can occur if the resolution of the topography is smaller than that of the calculation mesh. In our case, the 2 resolutions are identical.

5.2. Influence of the calibration method

To study the influence of calibration methods, we first look at their impact on water surface levels and areas (Fig. 6). The 2D calculations provide larger wetted surfaces due to the slightly higher water surface profile but also due to the linear interpolation between 1D sections which does not exactly reproduce the longitudinal evolution of the bed width. It can be observed that for station 1, the evolution is monotonous with the flow, which reflects the regular shape of the cross section. On the contrary, at station 2 (Fig. 6.b), the lateral overflowing are visible by a less regular evolution for the 2D calculations. For the 2D simulations, one may wonder about the appearance of maximums due to areas with low water depth (high roughness). For these flows, a better description of the mesh size and the bathymetry in the banks seems necessary for $Q < 2 \text{ m}^3/\text{s}$.

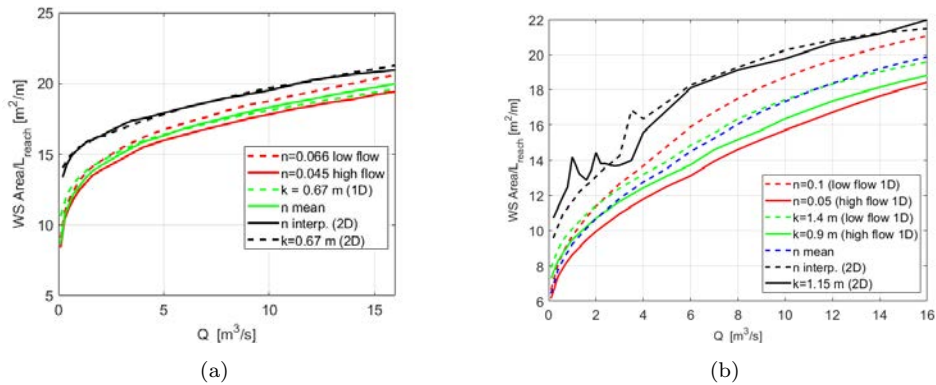


Figure 6. water surface as a function of the friction model for station 1 (a) and station 2 (b).

WUA curves are much more sensitive to the calibration procedure of hydraulic simulations than to the interpolation method. For example, at the 2 stations and at

	n low fl.(1D)	n high fl. (1D)	k (1D)	n interp (2D)	k (2D)
S1 ($1.6m^3/s$)	-3.1 / -2.4	-32 / -25	14 / 12	2.3/ 0.5	16 / 14
S1 ($16m^3/s$)	45 / 38	-6.3 / -1	0.8 / 4	-1.3 / 31	18 / 56
S1 (all Q)	20 / 18	-30 / -21	-6.7 / -1.7	-9.4 / -1.7	-0.55 / 16.5
S2 ($1.6m^3/s$)	-17 / -1.3	-44 / -31	-23 / -5.2	-8.7 / 5.7	-5.5 / 15.4
S2 ($16m^3/s$)	205 / 96	0.31 / 0.24	20.8 / 11.3	33.2 / 32.6	127 / 128
S2 (all Q)	60.3/36.9	-37.1 / -29.6	-19.9 / -14.4	7.5 / 13.6	31.2 / 54.1

Table 3. Variation of WUA (%) compared to the reference case n interp (1D) at low, high discharge and averaged for all discharge. The first number is for adult and the second for juvenile.

$Q=7 m^3/s$, the WUA differs by a factor of 2 for all stages of development, between simulations using a fixed Manning value calibrated either at low or at high flow rates (Figs. 7 and 8). These differences may lead to different conclusions on the mitigation measures for hydropeaking, including the maximum acceptable turbine flow. These results therefore emphasize the importance of measuring water levels at multiple flows to provide reliable hydrodynamic calibration for fish habitat modeling over a wide range of flows.

Since a single constant Manning value is unsatisfactory, it is possible to use either a linearly interpolation of Manning's coefficient (series "n interp" in Figures 7 and 8) or a Nikuradse-type law based on roughness height (series "k = "). At station 1, these two methods give close results (Fig. 7 and table 5.2) even if the law based on the roughness height is easier to apply (only one identical parameter whatever the flow rate) and is more physical. In Jowett and Duncan (2012), it is stated that 1D modelling is possible if the model is well calibrated. The use of Nikuradse-type law can help to achieve this relevant calibration. But at station 2, the two methods differ for the following reasons (Fig. 8).

For station 2, the right bank overflow is clearly detectable from $Q=6 m^3/s$, especially for juveniles and fry, inducing a WUA peak for the last method ($k=1.15$). This increase is due to the additional flooded area where the velocity is low and favourable to small fishes.

To explain the differences between the interpolated n and k computations, we can observe the velocity fields in Figure 9. With Nikuradse's law the water levels are slightly lower, but the velocities are faster in the centre of the river and lower in the shallow water areas. This phenomenon explains why the WUA is much higher with the

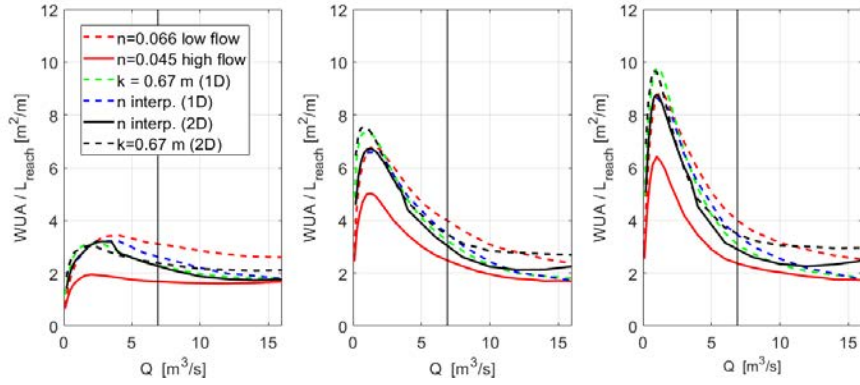


Figure 7. WUA as a function of the discharge of station 1 for different bed friction methods. the vertical line represents the annual average flow rate. left: adult, centre: juvenile, right: fry.

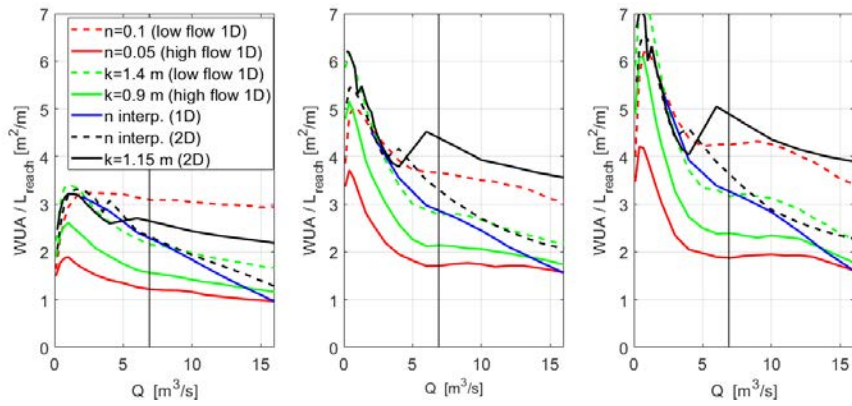


Figure 8. WUA as a function of the discharge from station 2 for different bed friction methods. the vertical line represents the mean annual flow rate left: adult, centre: juvenile, right: fry. .

Nikuradse method. A simple calibration on the water level does not allow to discriminate the most realistic friction law because it would require velocity measurements (Kondolf et al. 2000). On the other hand, one can think that the Nikuradse method based on physical considerations is more relevant. However, it is necessary to ensure that the particle size used in the model is spatially representative of that at the station. The link between roughness sizes and friction law parameters is an important issue that is currently being studied (Cassan et al. 2017; Navaratnam et al. 2018). Fabris et al. (2017) had also put forward the fact that the description of bathymetry and friction should be done at small scale, in particular to well reproduced the transition between low and high discharge.

In general, the loss of WUA between minimum and high flow rates is reproduced regardless of the type of calibration. For Station 1, losses are about a factor of 2 (50

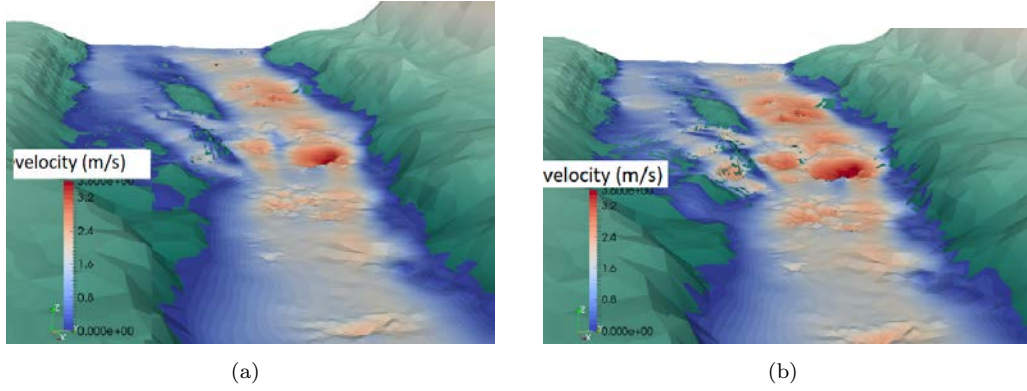


Figure 9. Velocity field $Q=16 \text{ m}^3/\text{s}$, with Manning interpolation ($n=0.05$) (a) and with Nikuradse method ($k=1.15$) (b)

%) for adults and a factor of 4 (75 %) for the other stages. An application of microhabitats may therefore suffice for a station with a trapezoidal morphology whatever the methods used (1D or 2D). The main prerequisite is to have at least 2 calibration flowrates and a variation in the friction coefficient with discharge (interpolation of Manning or Nikuradse’s law). On the other hand, as soon as significant overflow areas appear, the conclusions are less obvious. It is even possible to obtain an increase in the *WUA*. Let us note that the risk of trapping-stranding during decrease in flow and forced drift during increase in flow are not quantified by this method and then the analysis of *WUA* is not sufficient to conclude on the global impact of hydropeaking. To ensure the validity of the hydrodynamic simulation, it may be necessary to carry out velocity measurements in the interest areas. Besides these lacks in the methodology, the interest of the simulation remains because it always makes it possible to extrapolate spatially or for different flows.

The calibration method is also essential to estimate the optimum flow rate in a consistent manner. It can be seen that the *WUA* peak can vary from $Q=600 \text{ L/s}$ to $2 \text{ m}^3/\text{s}$ depending on the calibration made at high or low flow rate. This range can be considered as large with respect to the definition of a base flow between hydropeaks and its consequences on the energy production. In practice other complementary approaches (Lamouroux et al. 2018) can also contribute to set the minimum discharge.

Obviously, a low Manning coefficient (high flow calibration) tends to give lower optimum flows whatever the stage of development. Nevertheless, the sensitivity anal-

ysis provides the range of uncertainty for the optimum discharge due to hydraulic simulation. For high flows, an important result is that the decay of WUA for juveniles and especially fry towards high flows varies widely between 1D and 2D models, and between calibration types. This can lead to very different decisions concerning the maximum turbineable flow during the development periods of the trout fry. Biological models can also be a source of uncertainty but the knowledge of hydraulic limitations allow comparing several mitigation solution for a given fish species or different stations in the same ecological context (same river, species and time).

6. Conclusion

In this study, the micro-habitat method was applied using 1D and 2D hydraulic models calibrated with several methods (at low, intermediate or high flow, linear interpolation or physical friction model), corresponding to the available tools used in applied study. The simulation of habitat variables for several flows showed that the micro-habitat method can be used to identify optimal flows but also to quantify habitat losses due to an important increase in flows during hydropeaking. Concerning the uncertainty depending on the calculation methods, two types of river morphology were tested and led to two different conclusions. When the channel has a regular shape, i.e. a slight variation in mirror width as a function of water depth, the 1D model and the 2D model give very similar hydraulic results. The bed friction can be given by a friction law based on a roughness height k obtained for a single low or high flow. For braided beds or when there is overflow on the banks, the 2D model is more relevant. Manning's coefficient of friction should be calculated by interpolating two extreme flow rates. The 2D method with Nikuradse's law can be more efficient if the spatial distribution of the bed grain size is known or if velocity measurements are made.

It should be noted that the present study was carried out on small stations which allowed a fine resolution of the topography and meshes. Coarse resolutions are required for larger scale studies. The next steps will therefore be to specify the uncertainty as a function of the mesh size or resolution of the topographic data.

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