



**TiRiLab Report No. 5**

## **Assessing impacts of changes in minimum flow releases on aquatic habitat and sediment mobility in the Maggia River**

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## Summary

In the framework of the TiRiLab (Ticino Rivers Lab) a 8.3 km long braided river reach at the Maggia River is investigated. The canton of Ticino is interested, whether their increased environmental flows lead to an improvement in sediment mobility and aquatic habitat. To meet the canton's interests, steady state 2D hydrodynamic simulations are performed with the help of BASEMENT.

The analysis of incipient motion is carried out by three different methods. On the one hand there is the approach according to *Meyer-Peter and Müller [1948]* and on the other hand there are the methods according to *Egiazaroff [1965]* and *Parker [1990]*, which additionally take the hiding effect of grains into account. Among the three methods, the approach according to *Meyer-Peter and Müller [1948]* predicts the largest area in motion for small characteristic grain sizes and large discharges. For the characteristic grain size  $d_{10}$ , which has a diameter of 1.2 cm, and a discharge of  $9.68 \text{ m}^3/\text{s}$  the area in motion amounts to 25 % of the total inundated area. Whereas for *Meyer-Peter and Müller [1948]* at least some of the characteristic grain sizes are in motion for a discharge lower than  $2.77 \text{ m}^3/\text{s}$ , the other two approaches show no susceptibility for incipient motion. Even for larger discharges the area in motion accounts for less than 1 % of the total inundated area. Although the three methods lead to totally different results, they all agree on the fact, that at the current flow releases (2019) barely no sediment motion occurs within the investigated river reach.

In this project work aquatic habitat modelling is performed in the traditional way and by taking invertebrates as a food source for fish into account. For the traditional physical habitat modelling the depth-averaged flow velocity and the water depth from BASEMENT are used to assign them a suitability index depending on the indicator species' preferences for it. Thereby, brown trout (juvenile, adult and spawning), bullhead (juvenile and adult), *Baetis alpinus*, *Centroptilum luteolum* and *Allogamus auricollis* serve as indicator species. The integrated habitat quality assessment is done by means of Weighted Usable Area (WUA) and Habitat Suitability Index (HSI). In comparison to the previous minimum flow releases the newly increased summer month discharges lead to a large improvement in habitat quality for spawning brown trout, *Baetis alpinus* and *Allogamus auricollis*. Over all discharges the percentual changes in HSI are on average 45 %, 117 % and 37 %, respectively. The habitat quality of adult brown trout, however, remains uninfluenced by the new minimum flow releases. *Centroptilum luteolum* (−30 %), juvenile brown trout (−31 %) and juvenile/adult bullhead (−29 % and −18 %, respectively) are negatively impacted by an increase in environmental flows.

By complementing the habitat model with the biotic component food, it becomes visible, that the traditional physical habitat modelling is more in favour of low discharges as it comes to the comparison of the previous and actual minimum flow releases. The percentual change in HSI for juvenile brown trout is increased to −19 %, whereas for adult brown trout the increase in minimum flows is even more beneficial than in the case of the traditional habitat modelling (from −3 % to 21 %). Although brown trout benefit from higher discharges, the habitat quality of juvenile/adult bullhead slightly decreases in comparison to the previous flow releases (from −29 % and −18 % to −30 % and −21 %, respectively).

In summary, this project work emphasises, that at low flow conditions not the physical habitat availability is limiting the fish population size, but the total energy flux resulting from the consumption of invertebrates. Frequency-based habitat suitability curves are known to overestimate habitat quality at low flows.

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## 1. Introduction

The strive of humans to satisfy their increasing demand for freshwater has always been in direct competition with the needs of a healthy aquatic and riparian ecosystem. That is why the non-sustainable allocation of freshwater to traditional water uses such as irrigation, water supply, industry, navigation and hydropower has led to a decline in aquatic biodiversity, which is far greater than the one experienced in most terrestrial ecosystems. (Dudgeon et al. [2006])

In rivers vital ecological processes such as spawning of fish and dispersal/recruitment of seedlings have evolved in response to the natural variability in water and sediment transport and thus depend on the flow regime's key attributes (magnitude, frequency, duration, timing and rate of change). By diverting water for hydropower generation the hydro- and morphodynamics of a river gets altered, which inevitably leads to changes in habitat availability and quality. (Dudgeon et al. [2006]) Several studies deliver clear evidence for artificial flow regulations having the ability to change the composition/diversity and abundance of aquatic and riparian species. For instance *Bloesch et al. [2005]* have shown, that fish and benthic species have changed from lotic to lentic within a meandering reach of the Rhine River due to the residual flow imposed by the hydropower plant Rheinau. An other study conducted by *Schölzel and Peter [2017]* in the residual flow impacted Maggia River has revealed, that water temperatures during summer months are too high to sustain a healthy brown trout population. As shallow waters are heated up more than deeper ones, they suggested to increase minimum flows.

Driven by the need to preserve the functioning and the services of the aquatic and riparian ecosystem as well as Article 80 ff. of the Swiss Waters Protection Act, which calls for restoration measures once a river has significantly been affected by water withdrawals (GSchG [1991]), the canton of Ticino has increased its minimum flows in the Maggia River. And that is why the canton of Ticino is interested, whether its newly proposed minimum flow regulation leads to ecologically sound changes in aquatic habitat and sediment mobility compared to the latest one imposed in 1982 ( $1.2 \text{ m}^3/\text{s}$  and  $1.8 \text{ m}^3/\text{s}$  during winter and summer months, respectively) (HyMoCARES [2017]).

In order to meet the canton's interests, this project work has the purpose to run 2D hydrodynamic simulations for the proposed environmental flows with the software BASEMENT. The comparison of the actual and previous minimum flow regulations is carried out by means of physical habitat modelling and different approaches accounting for incipient sediment motion. The following section provides a brief overview of the structure of this project work.

Reflecting the Master Thesis of *Skourtis [2018]*, this study further develops the computational mesh of the investigated braided river reach (for a detailed description of the reach see chapter 2). With the help of the BASEmesh plugin in QGIS a fictitious trapezoidal channel is added in the upstreams, in order to avoid the upstream boundary condition having an influence on the hydrodynamics within the river reach of interest. In a next step, the hydrodynamics of the different minimum flows is assessed in terms of its relevance to cause morphological changes. Therefor, incipient motion (with/without hiding) for several characteristic grain sizes is investigated throughout the studied river reach considering the shear stress applied on the river bed. Furthermore, habitat quality is assessed for the fish species brown trout (*Salmo trutta*) and bullhead (*Cottus gobio*) as well as for the benthic invertebrates comprising mayfly (*Baetis alpinus* and *Centropilum luteolum*) and caddisfly (*Allogamus auricollis*). Whereas traditional physical habitat modelling most

often does not consider biotic factors, this study additionally includes invertebrates as a food source for fish. Which role food plays during low flow conditions is evaluated according to the integrated habitat quality expressed as Weighted Usable Area (WUA) and Habitat Suitability Index (HSI).

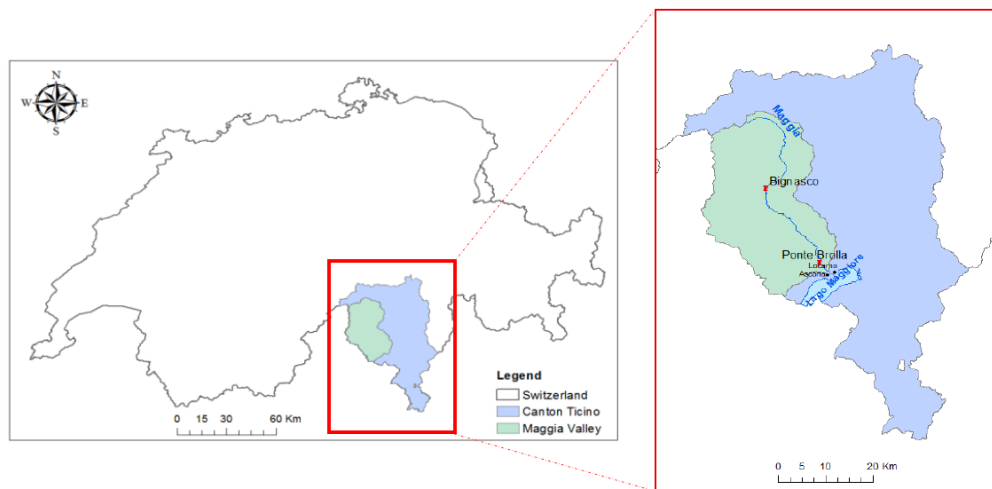


## 2. Study area

This chapter introduces the investigated Maggia River reach for which the canton of Ticino is interested in its habitat quality and sediment mobility. Apart from describing the geological, hydrological and morphological characteristics of the river reach a historical background on artificial interventions governing the river system is given. Additionally, the indicator species used for habitat quality assessment and the data providing the basis for hydrodynamic simulations with BASEMENT are presented here.

### 2.1. River reach characteristics

The Maggia River, located in the South of Switzerland (canton of Ticino), drains the Maggia Valley catchment with a total surface area of  $592 \text{ km}^2$  before it reaches Lake Maggiore (see figure 1). The alpine catchment, mainly consistent of gneiss and granite, is governed by a pluvio-nival flow regime. Under natural conditions these flows vary between less than  $1 \text{ m}^3/\text{s}$  and  $647 \text{ m}^3/\text{s}$  (peak discharge measured at station Bignasco, Ponte nuovo with return period  $\text{HQ}_{50}$  (UFAM [2019])). Large floods having the capacity to transport a lot of sediments (mainly gravel and sand see chapter 2.4) led to the braided nature of the investigated river reach, which is characterized by alternate gravel bars and vegetated islands. The river reach, which spans from Riveo to Maggia, has an approximate length of 8.3 km and an average bed slope of 8 ‰. Its floodplain is of national importance with the aim to maintain a relatively pristine river reach and thus a natural dynamics of riparian vegetation. (Ruf [2007])



**Figure 1:** The relatively pristine Maggia River reach lays within the Maggia Valley (green). It is about 8.3 km long (between settlements Riveo and Maggia) and has an average bed slope of 8 ‰. The river reach is characterized by its braided nature. (HyMoCARES [2017])

### 2.2. Hydropower operations

The hydropower-operator OFIMA (Officine idroelettriche della Maggia SA) has established an interwoven hydropower-network in the Maggia catchment consisting of 8 artificial reservoirs and 35 water intakes, that all together feed 6 hydropower-plants. First

dam construction activities in the 1950s were followed by non-sustainable operation rules, which led to the drying out of a 4 km long river reach between the settlements Visletto and Someo. In response groundwater tables have dropped to a critical level, at which the delivery of enough water for drinking water supply and vegetation growth was not ensured. To fight these negative environmental externalities, the canton of Ticino has increased its environmental flows time by time. (Ruf [2007])

Even though a constant environmental flow is assured since 1982 ( $1.2 \text{ m}^3/\text{s}$  in the winter months and  $1.8 \text{ m}^3/\text{s}$  in the summer months see table 1), the interannual variability of the streamflow is significantly reduced. The distinct spring-summer snowmelt peak discharges as well as the low magnitude, high frequency floods are captured by the reservoirs. Moreover, tributaries are completely diverted by the water intake stations from Bignasco on downwards, thus no lateral connectivity is given. (Ruf [2007]) Nevertheless, the canton of Ticino has recently launched new minimum flow regulations to maintain ecological integrity (see table 1). The increase of the summer month discharges is intended to give the river back some natural flow variability.

**Table 1:** The previous (since 1982) and the current (since 2018) minimum flow regulations are shown. Discharges of the months not listed are  $1.2 \text{ m}^3/\text{s}$  for both periods. The comparison of habitat quality and sediment mobility within the study reach is based on these minimum flows.

Period	Month of the year					
	April	May	June	July	August	September
previous [ $\text{m}^3/\text{s}$ ]	1.2	1.2	1.2	1.8	1.8	1.8
current [ $\text{m}^3/\text{s}$ ]	2.77	7.23	9.68	9.68	6.53	4.33

### 2.3. Indicator species

The indicator species used for aquatic habitat modelling can be seen in figure 2. A fish ecological survey conducted in 2015/2016 by *Peter and Schölzel [2017]* has revealed, that brown trout and bullhead are among the most common fish species in the Maggia River.

**Brown trout** are often found within the trout zone (Forellenregion), which is characterized by fast flowing waters being rich in oxygen and low in water temperature (optimal temperatures range from 12 to 17 °C). Structural variabilities such as boulders, woody debris, undercut banks or overhanging vegetation serve as refuge places, be it as protection from predators or just as a means to keep swimming costs low. For the habitat modelling part three life stages are considered to be important, these include juvenile, adult and spawning brown trout. Brown trout are known to be sedentary. They defend their territories against fellow species and other invaders through aggressive behaviour. Thereby, adult, stronger individuals, which prefer deep and slow flowing pools, displace juvenile, weaker ones into places that contain less favorable conditions. These shallow water zones, however, offer protection from being eaten by adult brown trout. Daily activities like foraging take place within a distinct range, which is called homing range. Homing is defined as the return of a brown trout to its formerly used focal point, from where it initiates its activities. (Bachman [1984]) While juvenile brown trout are observed to be sit-and-wait, drift feeders, adult ones are mobile-search, drift and piscivorous feeders (Regal [1992]). Thus, homing ranges for juvenile brown trout are reported to be shorter than for their older follow species (Regal [1992], Harcup et al. [1983], Young [1994]). Benthic, emerging and terrestrial invertebrates as well as small fish such as bullhead are part of the brown

trout's diet (Regal [1992]). As it comes to the spawning in the months October till January brown trout move several hundred meters to lay their eggs in redds made up of gravel. (Seifert and Kölbing [2005])

**Bullhead** is a representative species of the trout zone as well. In contrast to brown trout, the bullhead is a weak swimmer as it has no swim bladder. As long as there are structural elements available, bullhead are able to cope with a broad range of flow velocities. During daytime it hides itself under coarse gravel in order to avoid being eaten by a predator (cryptic behaviour). Observations have shown, that bullhead are rather resident species, not least because of their limited mobility (Knaepkens et al. [2004]). Their food is mainly composed of benthic invertebrates and adult individuals even prey on small fish and brown trout eggs. Spawning takes place between February and June, whereby the male bullhead prepare the redds and protect their eggs against invaders. (Seifert and Kölbing [2005], Junker [2010]) Habitat quality assessment is carried out for juvenile and adult bullhead.

The benthic invertebrates *Baetis alpinus*, *Centroptilum luteolum* and *Allogamus auricollis* are stream residents of the Maggia River according to the fauna database of SZKF (Swiss Center of Cartography of the Fauna) (CSCF [2018]).

**Baetis alpinus** is a mayfly species and prefers fast flowing waters as they can be found in alpine regions. It is characterized by a flat body which minimizes drag forces (rheotaxis) and its strong extremities allow an active adhesion to the river bed substrate (Schnauder et al. [2010]). In the interstices of the gravel beds the mayfly feeds on algae and detritus. Once in drift, the excellent swimmer is able to reach the river bottom through abdominal contractions. (Sander [1961])

**Centroptilum luteolum** requires streamflow conditions, that are completely different from the ones preferred by *Baetis alpinus*. The mayfly is dependent on low flow velocities and that is why it resides near river banks and along lake shorelines. *Centroptilum luteolum* belongs to the feeding group collector, which gathers fine particulate organic matter (FPOM) from the river bed. (RiverFly [2019])

**Allogamus auricollis** is able to withstand higher flow velocities due to an increase in body weight by wearing a case made out of sand grains (Schnauder et al. [2010]). It attaches its case on gravel and stretches out its setaceous legs, which are formed to a catching basket, to filter-feed on organic material. As flows are becoming larger this caddisfly species is known to bury itself deep into the sediments to avoid drift. (Graf et al. [1992])



(a) Brown trout *Salmo trutta*  
(picture: Wildlife/W. Poelzer, NDR [2015])



(b) Bullhead *Cottus gobio*  
(picture: H. Hillewaert, Ryser [2014])



(c) Mayfly *Baetis alpinus*  
(picture: W. Graf, Graf [2019])



(d) Mayfly *Centroptilum luteolum*  
(picture: D. Nicholls, Nicholls [2015])



(e) Caddisfly *Allogamus auricollis*  
(picture: S. Werner, HYDRA [2011])

**Figure 2:** These indicator species, which are living within the investigated Maggia river reach, are used for habitat modelling. Shown are two stream-dwelling fish species and three benthic invertebrates.

## 2.4. Data

The basis for all 2D hydrodynamic simulations with BASEMENT is the computational mesh number 3 generated by Skourtis [2018]. As LIDAR wavelengths are not able to penetrate the water surface, the digital terrain model (DTM swissALTI<sup>3D</sup> 2012) had to be corrected by a spatially variable water depth. Therefore, the natural logarithm of the ratio between the green and the red band was computed from orthoimages (SWISSIMAGE 25 cm 2012) and a corresponding water depth was assigned based on the comparison between the DTM and cross-sectional data acquired by BAFU in 2015. (Skourtis [2018])

In total six line-sample probes of the river bed substrate are available within the investigated Maggia River reach (acquired by Wolfgang [2003] and Sturzenegger [2005]). The grain size distributions (GSD) are determined according to Fehr [1987]. The procedure comprises the conversion of the line-samples based on frequency into volume-samples based on weight. Since grain sizes smaller than  $< 1$  cm are not measured with this sampling method, the GSD has to be corrected for the percentage of fines. The percentage of fines is chosen to be 0.1 instead of 0.25 as proposed by Fehr [1987]. The reason for this lies in the fact, that the river bed of the study reach is characterized by a pronounced armour layer consisting of nearly no sand (Ruf [2007]). To better account for the coarse nature of the armour layer Rickenmann [2014] suggested to use 0.1. The distribution of the percentage of fines is assumed to follow the Fuller-curve. For a detailed description of the calculation steps please refer to the script of Bezzola [2017]. The GSD and the characteristic grain sizes can be seen in figure A.6 and table A.4 in the appendix A.

### 3. Methods

Within this chapter the working procedure is shown, which is necessary to extend the computational mesh generated by *Skourtis [2018]* (termed as initial computational mesh) at the upstream boundary. After choosing the appropriate settings and parameters to solve the shallow water equations in BASEMENT, the outputs of the steady state 2D hydrodynamic simulations are used to investigate incipient motion and habitat quality. A conceptual model is introduced here, which takes benthic invertebrates as a food resource for brown trout and bullhead into account.

#### 3.1. Generation of the fictitious channel with the BASEmesh plugin

The initial computational mesh shows two branches on the upstream boundary over which discharge gets distributed (see figure B.7). In order for this allocation of water not to be biased by the choice of the upstream boundary condition, a fictitious channel is added.

First of all, the quality mesh of a 1 km long channel is created with the help of the BASEmesh plugin in QGIS. The boundary and the breaklines are arranged in such a way, that the first 500 m of the channel are intended to be trapezoidal (bottom width 173 m) and the remaining part takes the shape of the most upstream cross-section of the initial computational mesh (width 216 m). Area points are defined to set the maximum area constraint to  $50 \text{ m}^2$  and the minimum triangle angle to  $28^\circ$ . In accordance with the initial computational mesh two material indices are chosen to separate gravel areas from vegetation areas. In a second step, the elevation mesh is generated by densifying the vertices of the boundary/breaklines and turning them into elevation points. By considering an average slope of 8 ‰ the values of the elevation points are calculated based on the ones belonging to the most upstream cross-section of the initial mesh. Additionally, it is required to triangulate the elevation points with the mesh generator 'TRIANGLE'. This allows the topographic information of the elevation mesh to be interpolated on the quality mesh. Finally, the fictitious channel is added to the initial computational mesh and to grant the internal validity of the mesh, the element ID-numbers have to be renumbered with the tool 'Renumber mesh'. (Vetsch et al. [2018]) The final mesh (2dm-file) and its specifications can be seen in figure B.7 and table B.5.

#### 3.2. 2D hydrodynamic simulations with BASEMENT

The 2dm-file generated in section 3.1 serves as an input for BASEMENT. Nonetheless, important settings and parameters have to be defined, before letting water run through the computational mesh. The roughness coefficients (Strickler-coefficient  $k_{St}$ ) of the gravel and the vegetation are chosen to be  $29 \text{ m}^{1/3}/\text{s}$  and  $20 \text{ m}^{1/3}/\text{s}$ , respectively. These  $k_{St}$ -values were determined in a calibration process by *Skourtis [2018]*, where the output of a series of hydrodynamic simulations was used to match the rating curve (hq-relation) of a nearby measuring station (*Skourtis [2018]*). By applying equation 14 with the characteristic diameter  $d_{90}$  of the coarse armoured layer (compare table A.4), the Strickler-coefficient yields  $26 \text{ m}^{1/3}/\text{s}$ . This value underlines validity of the calibrated gravel roughness coefficient. Furthermore, the calibration has shown, that the  $k_{St}$ -value of vegetation is not a sensitive parameter as it comes to the output of the hydrodynamic simulations (*Skourtis [2018]*).

The upstream boundary condition is given by a hydrograph, which is defined for each minimum flow as a constant discharge supplied to the braided river reach (compare table 1).

A hq-relation is chosen to be the downstream boundary condition. In order to reach steady state hydrodynamic conditions, total run time is set to 96 h. Thereby, simulations start from dry river bed conditions. For an overview of the settings and parameters consult table B.6 in the appendix B.2. The following sections clarify how the element centered outputs of the simulations like water depth, flow velocity and bed shear stress are used to get an estimate about incipient motion and habitat quality.

### 3.3. Sediment mobility

In his early works *Shields [1936]* has defined a dimensionless shear stress parameter, which is derived from the balance between 'hydrodynamical forces' leading to the destabilization of a grain and 'resisting forces' holding the grain in position (see equation 1). If the Shields parameter for a specific grain size exceeds a critical threshold (dimensionless critical shear stress  $\theta_c$ ), the grain is in motion. (Bezzola [2017])

$$\theta = \frac{\tau}{g(\rho_s - \rho_w)d_s} \quad (1)$$

with

$\theta$	Shields parameter [-]
$\tau$	bed shear stress from simulation output [ $N/m^2$ ]
$g$	acceleration of gravity [ $m/s^2$ ]
$\rho_s$	sediment density 2600 $kg/m^3$ [ $kg/m^3$ ]
$\rho_w$	water density 1000 $kg/m^3$ [ $kg/m^3$ ]
$d_s$	grain size of grain size class s [m]

As the calculation of incipient motion is associated with a certain degree of uncertainty, different approaches are taken into consideration in this work. These methods differ in the extent to which they define  $\theta_c$ . Whereas the approach according to *Meyer-Peter and Müller [1948]* assumes a constant dimensionless critical shear stress of  $\theta_c = 0.047$  (uniform grain size), *Egiazaroff [1965]* and *Parker [1990]* also take the 'hiding effect' into account. In sediment mixtures coarser grains are harder to move than finer ones due to the mass effect, however, the hiding effect postulates, that coarser grains are moved more easily than the finer ones as coarser grains protrude more into the current. Thus, 'true' mobility happens to lay between equal mobility (equal threshold) and full mobility (grain independence). (Siviglia [2018]) Equation 2 and 3 show the correction of the dimensionless critical shear stress by a hiding function  $\xi_s$  according to *Egiazaroff [1965]*.

$$\theta_{c,s} = \xi_s \cdot \theta_{c,MPM} \quad (2)$$

with

$\theta_{c,s}$	dimensionless critical shear stress of grain size class s [-]
$\theta_{c,MPM}$	dimensionless critical shear stress according to Meyer-Peter and Müller [-]
$\xi_s$	hiding function of grain size class s [-]

$$\xi_s = \left( \frac{\log_{10} 19}{\log_{10} (19 d_s/d_m)} \right)^2 \quad (3)$$

with

$d_m$	mean diameter of sediment mixture [m]
-------	---------------------------------------

In contrast to the latter approach, *Parker [1990]* has introduced three major differences. On the one hand, the 'reduced' hiding function is formulated for the GSD of the surface (armour) material (see equation 5). Within the framework of this paper, no distinction is made between the GSD of the surface material and the one of the subsurface, since the GSD has already been corrected for the coarse nature of the armour layer (see section 2.4). On the other hand, the grain size diameter in equation 1 is referred to the mean diameter of the surface material ( $d_{m,surf}$ ) and not to the one of the fraction  $s$  ( $d_s$ ). Lastly, the Shields parameter is multiplied with the 'reduced' hiding function and not  $\theta_c$  (see equation 4). (*Parker [1990]* uses a reference dimensionless shear stress  $\theta_{ref} = 0.0386$  instead of  $\theta_c$ , which presumes, that there is already little sediment transport present) As a result the mobility of the mean diameter of the surface material gets corrected, whereas *Egiazaroff [1965]* corrects the mobility of a grain size, as if it was surrounded by uniform grain sizes with diameter  $d_s$ . (Vetsch et al. [2018], Hunziker [1995])

$$\theta_{corr,d_{m,surf}} = \xi_s \cdot \theta_{d_{m,surf}} \quad (4)$$

with

$\theta_{corr,d_{m,surf}}$  corrected Shields parameter of  $d_{m,surf}$  [-]

$$\xi_s = \left( \frac{d_{s,surf}}{d_{m,surf}} \right)^{-0.0951} \quad (5)$$

with

$d_{s,surf}$  grain size diameter of grain size class  $s$  of the surface material [m]  
 $d_{m,surf}$  mean diameter of the surface material [m]

### 3.4. Aquatic habitat modelling without food

The rising field of ecohydraulics strives to couple physical processes (physical model) with the ecological requirements of the aquatic ecosystem (biological model). Thereby, physical habitat modelling takes the advantage of the fact, that many aquatic species show clear preferences for hydraulic variables such as water depth, flow velocity, substrate and cover. Apart from these traditional variables, other abiotic factors like water temperature, dissolved oxygen content, turbidity and morphological changes are claimed to have a great impact on habitat suitability as well. In summary, many models (PHABSIM/CASiMiR) assume, that the availability of physical habitat is the limiting factor for population size and not biotic factors such as food, competition and predation. (Jorde [2018])

The aquatic habitat indexes provided in the following are not only applied to the whole river reach, but also to three subdivisions of the reach (see figure B.7). The sectional division is based on morphological aspects and assigning approximately the same length to the sections. Section one is less braided than the other two sections and is mainly constricted by topographic and infrastructural (villages) features.

#### 3.4.1. Fish habitat suitability

Frequency-based habitat suitability curves provide the link between a physical habitat variable (univariate) and a species' preference for it. In habitat modelling practices these

curves are assumed to be discharge independent. In this work the element centered simulation outputs (water depth and flow velocity) are used to assess habitat quality for brown trout and bullhead. The preference curves of the indicator fish species can be seen in figures B.8 to B.10 in the appendix B.3. Additionally, a short description is provided, from which river they have been derived.

The composite suitability index for a certain combination of water depth and flow velocity is calculated based on the geometric mean approach (see equation 6)

$$CSI = \sqrt{SI_h \cdot SI_v} \quad (6)$$

with

- $CSI$  composite suitability index for a computational cell [-]
- $SI_h$  suitability index for water depth [-]
- $SI_v$  suitability index for flow velocity [-]

For an integrated habitat quality assessment the Weighted Usable Area (WUA) and the Habitat Suitability Index (HSI) are considered (see equations 7 and 8, respectively).

$$WUA = \sum_{i=1}^n A_i \cdot CSI_i \quad (7)$$

with

- $WUA$  Weighted Usable Area [ $m^2$ ]
- $A_i$  area of computational cell i [ $m^2$ ]
- $CSI_i$  composite suitability index of cell i [-]

$$HSI = \frac{1}{\sum_{i=1}^n A_i} \sum_{i=1}^n A_i \cdot CSI_i \quad (8)$$

with

- $HSI$  Habitat Suitability Index [-]

### 3.4.2. Invertebrate habitat suitability

The preferences of macroinvertebrates for certain hydrodynamic conditions are often expressed as FST-numbers (Fließwasserstammtisch). According *Statzner and Müller [1989]* 24 hemispheres, which are equal in shape but different in density, are used to deduce near-bed hydrodynamic forces. Since a lot of measurements have to be taken in the field with this method, *Kopecki [2008]* has proposed an approach, which is solely based on the output of a hydrodynamic model and the GSD of the substrate. (Jorde [2018]) In order to see, how the water depth, the depth-averaged flow velocity and the characteristics of the substrate are combined to derive the FST-number, the reader is requested to consult the work of *Kopecki [2008]* or *Skourtis [2018]*.

Figure B.11 visualizes the contrasting FST-number preferences of the target invertebrate species. The suitability curves of *Baetis alpinus* and *Allogamus auricollis* are collected from *Mürle [2000]* and *Caballita et al. [2013]*, respectively. Since the preference curve of *Centropilum luteolum* is only found to be expressed as abundance instead of suitability index (Dittrich and Schmedtje [1995]), the curve is normalized by its maximum. This procedure is commonly done as it comes to the generation of suitability curves (Mérigoux et al. [2009]).



### 3.5. Aquatic habitat modelling with food

So far, habitat quality assessment for the indicator species brown trout and bullhead is only based on physical parameters. To extend the model by a biotic component, the three macroinvertebrates are taken into account as a food source.

In this paper it is assumed, that brown trout and bullhead forage within the homing range. Based on scientific observations, a range of 10 m is chosen to be representative for juvenile brown trout and bullhead (both life stages). Adult and spawning brown trout are shown to have larger ranges. Thus, 50 m is considered here to delimit their territories. (Regal [1992], Harcup et al. [1983], Young [1994], Knaepkens et al. [2004]) Furthermore, there is evidence, that brown trout mainly feed on drifting invertebrates, whereas bullhead are restricted to benthic invertebrates as they have no swim bladder (Elliott [1970], Seifert and Kölbing [2005]). Thus, brown trout are modelled as drift-feeders and bullhead as benthic-feeders only.

The distinction between invertebrates being in drift and those remaining in the benthic zone is made by means of catastrophic drift. It is widely known, that drift rates are positively correlated with sediment transport rates. Catastrophic drift has therefore been associated with large flood events, which have the ability to shape the river bed. However, *Gibbins et al. [2007]* have shown in their work, that the occurrence of catastrophic drift is already possible at discharges, which do not have the ability to cause morphological changes. Namely, the authors argue, that the sole mobilization of fine sediment is capable of causing the entrainment of benthic invertebrates. The reason for this lays in the fact, that once shear stress exceeds a critical threshold the sediments get shaky and in turn the invertebrates get dislodged. Based on these findings, drift is modelled with the incipient motion approach according to *Meyer-Peter and Müller [1948]* (compare chapter 3.3) To be more precisely, for each computational cell the grain size is evaluated which is in motion and together with the GSD, the corresponding fraction in motion is determined. By assuming a homogeneous distribution of invertebrates over the substrate, the fraction in motion is considered to be representative of the fraction of invertebrates being in drift. Since the suitability index is indicative of the abundance, the amount of invertebrates in drift for each cell is calculated with equation 9. Once in drift, the invertebrates are neglected from the benthic zone (see equation 10).

$$SI_{drift,i,sp} = SI_{i,sp} \cdot p_s \quad (9)$$

$$SI_{benthic,i,sp} = SI_{i,sp} \cdot (1 - p_s) \quad (10)$$

with

$SI_{drift,i,sp}$	abundance of drifting invertebrate sp in cell i [-]
$SI_{benthic,i,sp}$	abundance of benthic invertebrate sp in cell i [-]
$SI_{i,sp}$	cell suitability of invertebrate sp in cell i as calculated in the case of no food (see chapter 3.4)
$p_s$	fraction in drift

For each fish cell suitability calculated in the case without food and being above 0 (CSI > 0), the opportunity is given to improve or worsen, depending on how much food is available around the considered cell. Here, the non-conservative assumption is made, that fishes rely on the food source, which is most abundant. Therefore, the maximum of all the three invertebrate species is selected in a cell. If gut content analyses from a biologist

were available, a linear combination of the three invertebrates would be an other option. The suitability index for food (drift or benthic) is calculated by taking the mean of all the food cells over the homing range (see equation 11 and 12). Finally, the new fish composite suitability index is calculated with the geometric mean (see equation 13). The procedure of the conceptual model is visualized in figure 3.

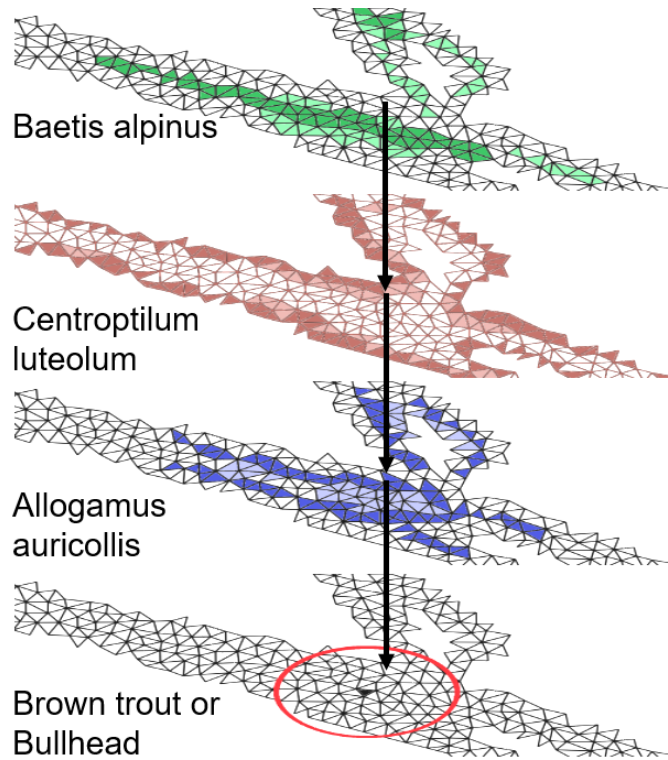
$$SI_{f,drift} = \frac{1}{R} \sum_{i=1}^R \max_{sp=1..n} (SI_{drift,i,sp}) \quad (11)$$

$$SI_{f,benthic} = \frac{1}{R} \sum_{i=1}^R \max_{sp=1..n} (SI_{benthic,i,sp}) \quad (12)$$

with

$SI_{f,drift}$	suitability index for drifting food [-]
$SI_{f,benthic}$	suitability index for benthic food [-]
$R$	number of cells within homing range [-]
$n$	number of species sp [-]

$$CSI = \sqrt[3]{SI_h \cdot SI_v \cdot SI_f} \quad (13)$$



**Figure 3:** The conceptual model shows, how the three indicator invertebrate species are taken into account as a food source.

## 4. Results

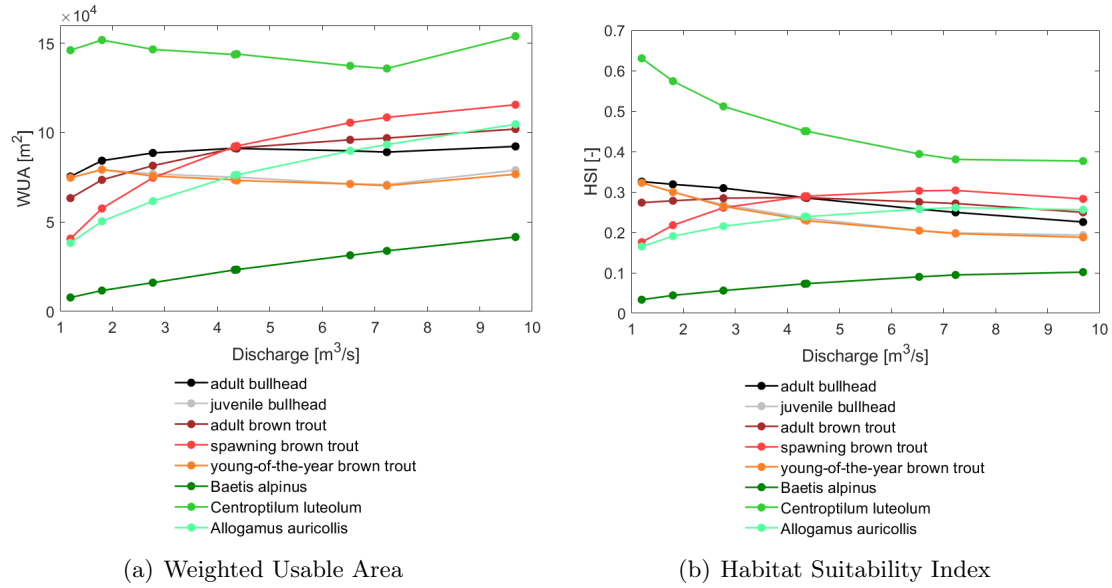
Before proceeding to the results of the incipient motion and the habitat quality assessment, it has to be mentioned, that all the calculation steps and their results can be verified with the help of the MATLAB-scripts and bmc-files provided on the attached CD.

### 4.1. Incipient motion

Tables C.7 to C.9 provided in the appendix C.1 show the extent of the river bed area in motion for different combinations of minimum flow and characteristic grain size. Among the three different methods, the *Meyer-Peter and Müller [1948]* approach leads to the largest area being moved for grain sizes smaller than  $d_{40}$ . For larger discharges ( $9.68 \text{ m}^3/\text{s}$ ) and smaller grain sizes ( $d_{10}$ ) it accounts for up to 25 % of the total inundated area. The reason for the significantly higher values lays in the fact, that in contrast to the other two methods the hiding effect is not taken into consideration. This inevitably leads to a decreasing trend of the mobilized area as grain sizes increase. Comparing the *Meyer-Peter and Müller [1948]* and the *Egiazaroff [1965]* approach, it becomes visible, that nearly the same values for the  $d_{60}$  are obtained. Since the  $d_{60}$  is approximately the same in diameter as the  $d_m$ , the hiding function yields 1 (see equation 3), hence, leading to the same results. Moreover, grains being smaller than the  $d_{60}$  are harder to move (value of hiding function  $< 1$ ), which justifies the fact, that less area is in motion for *Egiazaroff [1965]* than for *Meyer-Peter and Müller [1948]*. The opposite holds true for grains larger than the  $d_{60}$ . The approaches according to *Egiazaroff [1965]* and *Parker [1990]* agree on the fact, that there is no sediment mobilization below a discharge of  $2.77 \text{ m}^3/\text{s}$ . Even for larger discharges the area in motion accounts for less than 1 % of the total inundated area.

### 4.2. Aquatic habitat modelling without food

The Weighted Usable Area and the Habitat Suitability Index as a function of the minimum flow releases can be seen in figure 4. On the one hand, the WUA continuously increases for adult and spawning brown trout as well as for the invertebrates *Baetis alpinus* and *Allogamus auricollis* with an increase in discharge. On the other hand, an increase in minimum flow does not significantly change the WUA of the remaining species and life-stages as the curves stay fairly constant. On average the WUA of the *Centroptilum luteolum* makes up to 50 % of the total inundated area, whereas the values of the other species and life-stages (except *Baetis alpinus*) are in the range of 25 % of the total inundated area. Looking at the HSI curves, it becomes evident, that the habitat suitability of the species *Centroptilum luteolum*, juvenile/adult bullhead and juvenile brown trout decreases with an increase in discharge. The effect on adult/spawning brown trout and *Allogamus auricollis* is mixed. Namely, the habitat suitability increases first with discharge and then decreases for higher discharges. Thereby, the point of inflection indicates, that the increase in WUA of the corresponding species is an artefact of an increase in inundated area and not because of improved hydrodynamic conditions. The sole species, who's habitat suitability increases throughout the whole discharge spectrum, is the mayfly *Baetis alpinus*.



**Figure 4:** WUA and HSI in dependence of discharge for the whole river reach without food.

The HSI comparison between the previous and the current minimum flow releases of the different indicator species and their life-stages can be seen in table 2. The new flow releases lead to a habitat quality improvement for spawning brown trout, *Baetis alpinus* and *Allogamus auricollis*. On the contrary, the higher summer month discharges put the juvenile brown trout, juvenile/adult bullhead and the *Centroptilum luteolum* at a disadvantage with regard to the new hydrodynamic conditions. For adult brown trout the increased discharge in the months April, August and September gives rise to better habitat conditions. The months May, June and July are negatively impacted though.

**Table 2:** HSI comparison (relative changes) between the previous and current minimum flow releases for the whole river reach without food.

Month		Apr.	May	Jun.	Jul.	Aug.	Sep.
Minimum flow release [ $\text{m}^3/\text{s}$ ]	Previous	1.2	1.2	1.2	1.8	1.8	1.8
	Current	2.77	7.23	9.68	9.68	6.53	4.33
Aquatic species HSI [%]	Juvenile brown trout	-18	-39	-42	-37	-32	-23
	Adult brown trout	4	-1	-9	-10	-1	3
	Spawning brown trout	48	73	61	30	39	33
	Juvenile bullhead	-17	-38	-40	-36	-32	-21
	Adult bullhead	-5	-23	-31	-29	-19	-10
	<i>Baetis a.</i>	67	182	203	130	104	65
	<i>Centroptilum l.</i>	-19	-40	-40	-34	-31	-22
	<i>Allogmus a.</i>	30	58	55	34	35	25

Figures C.12 to C.14 show the HSI curves of the sectional habitat quality assessment. In summary, it can be said, that section one (least braided) provides the most preferable hydrodynamic conditions for juvenile/spawning brown trout, juvenile/adult bullhead and *Allogamus auricollis* (for almost all discharges). Adult brown trout and *Centroptilum*

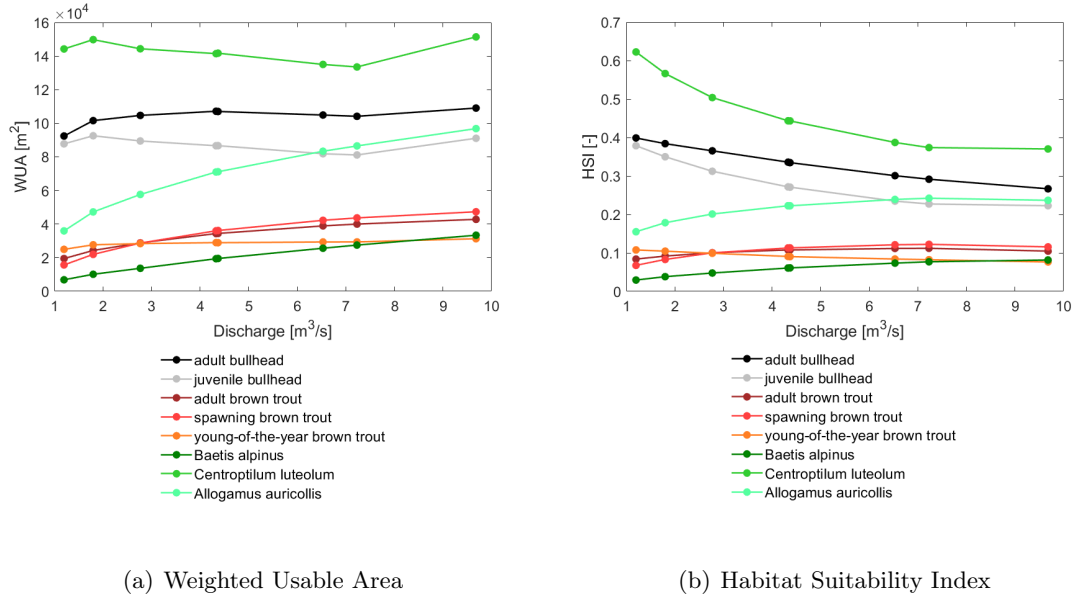
luteolum can rather be found in the braided section two. The braided section three is only favoured by *Baetis alpinus*. It has to be mentioned, that the clear assignment of a 'preference-section' has to be taken with caution, as the HSI values of the three sections often differ marginally from each other. Further, a distinct preference-section not always persist throughout the whole discharge spectrum.

The comparison between the previous and actual minimum releases for the three sections is listed in the tables C.10 to C.12. Noteworthy is the fact, that the average of the relative changes in HSI over the three sections corresponds to the value of the whole river reach in table 2. Deviations are due to rounding effects. For juvenile brown trout the new minimum flow releases lead to a decrease in habitat quality over the whole river reach. The same negative trend can be observed for all three sections as well. Thereby, section two is the least worst. Whereas the adult brown trout habitat quality is negatively impact in the months May, June and July over the whole reach by the increased discharges, section two shows even for these months more suitable hydrodynamic conditions. In section three the critical discharge of  $9.68 \text{ m}^3/\text{s}$  leads to a decrease in habitat quality of adult brown trout compared to the previous minimum flow releases. With lower discharges, however, better physical habitat conditions are reached. The habitat quality of both bullhead life-stages suffers in each section due to the increase in minimum flow releases, the least in section two for juvenile and section one for adult bullhead. As *Baetis alpinus* and *Allogamus auricollis* prefer faster flowing waters, an increase in habitat quality is recorded for all the sections by increasing the summer month discharges. On the contrary, such high discharges in each of the sections inevitably lead to a decrease in physical habitat condition of the mayfly species *Centroptilum luteolum*, which favours shallow and slow flowing waters.

### 4.3. Aquatic habitat modelling with food

Compared to the WUA curves without food, the ones with food are much lower for brown trout and all its life-stages (see figure 5). Thereby, the WUA in relation to the corresponding inundated area decreases from 25 % on average in the case of no food to 10 % in the case with food. For juvenile/adult bullhead, however, the inclusion of food leads to higher WUA values. Without food the WUA amounts to 25 % of the inundated area on average, whereas with food it is 30 %. For the invertebrates there is only a slight decrease in WUA if food is taken into account. Thus, the ratio between invertebrates being in drift and benthic invertebrates is very low. These low drift rates are the reason why the WUA curves of brown trout are that low. Furthermore, the difference between the WUA without food and with food increases with discharge for invertebrates (see figure C.15). This observation can be traced back to the way, how drift is modelled in this paper. As discharge increases and thus also shear stress, more invertebrates are in drift.

The same trends described above also apply to the HSI curves. Although, the HSI values of juvenile/adult bullhead are higher in the case with food than in the case without food, there is a larger percentual decrease in habitat quality if the comparison between previous and actual minimum flow releases is made (see table 3). That is because at low discharges less invertebrates are in drift and thus more are available for the benthic living bullhead than at higher discharges. In spite of that, drift rates at the previous minimum flow releases are so low, that an increase in discharge leads to an improvement in habitat quality of brown trout. Hence, with food the brown trout values in table 3 are better or less worse than without food.



**Figure 5:** WUA and HSI in dependence of discharge for the whole river reach with food.

**Table 3:** HSI comparison (relative changes) between the previous and current minimum flow releases for the whole river reach with/without food.

Month		Apr.	May	Jun.		Jul.	Aug.	Sep.
Minimum flow release [ $m^3/s$ ]	Previous	1.2	1.2	1.2	1.8	1.8	1.8	1.8
	Current	2.77	7.23	9.68	9.68	6.53	4.33	4.37
Without food HSI [%]	Juvenile brown trout	-18	-39	-42	-37	-32	-23	-24
	Adult brown trout	4	-1	-9	-10	-1	3	3
	Spawning brown trout	48	73	61	30	39	33	33
	Juvenile bullhead	-17	-38	-40	-36	-32	-21	-22
	Adult bullhead	-5	-23	-31	-29	-19	-10	-11
With food HSI [%]	Juvenile brown trout	-8	-24	-29	-27	-20	-13	-14
	Adult brown trout	20	33	25	14	22	17	17
	Spawning brown trout	48	81	71	39	46	36	36
	Juvenile bullhead	-18	-40	-41	-36	-33	-22	-23
	Adult bullhead	-8	-27	-33	-31	-22	-13	-13

## 5. Discussion

### 5.1. Incipient motion

For the investigated Maggia River reach it is shown, that the three approaches *Meyer-Peter and Müller [1948]*, *Egiazaroff [1965]* and *Parker [1990]* deliver totally different results for the incipient motion of grains. Nonetheless, they agree on the fact, that there is hardly no incipient motion for any characteristic grain size at the actual (year 2019) minimum flow releases. River reaches, which are impacted by hydropower operations are occasionally at the mercy of flushing events, where fine sediments are being washed out of the reservoir. Those areas in the Maggia River reach, where incipient motion due to the new flow releases occurs, are less prone to internal siltation with these fine sediments. Thus, the higher summer month discharges are beneficial for the development of fish eggs, alevins (newly hatched fish) and benthic invertebrates, which depend on the sufficient flushing of the interstitial spaces with water, nutrients and oxygen. (Jorde [2018]) Areas, in which no sediment mobilization takes places, the clogging of the armoured layer is prevented by larger flood events.

Apart from the uncertainties going hand in hand with the choice of the incipient motion method, there are other factors, which might change the outcome of the sediment mobility analysis. For instance the dimensionless critical shear stress is not corrected for local slope effects in this paper. However, it is assumed that the average bed slope of the braided river reach (8 ‰) is low in order to change the outcome significantly. Furthermore, *Miwa and Parker [2017]* have shown in their current study, that incipient motion is far more complex, than just taking the hiding effect, local slope effect and embeddedness of larger sediments into account. Based on flume experiments they have shown, that for river reaches containing less than 40 % of sand in the river bed, an increase in the sand fraction can activate incipient motion already at lower critical Shields stresses. The explanation for this observation is found in the fact, that the angle of repose of gravel gets reduced as the sand content of the river bed increases. The Maggia River reach is shown to have a sand fraction lower than 40 % in the subsurface of the bed (Ruf [2007]), thus an increase in sand supply resulting from reservoir flushing events has the ability to mobilize grains at lower critical Shields stresses. Even the breaking up of the armoured layer is facilitated. (Miwa and Parker [2017])

The spatially variable Shields parameter depends on the river hydrodynamics, which is in turn dependent on the topographic characteristics of the river bed. Therefore, the basis for a precise incipient motion modelling is a correct computational mesh. Since no bathymetric data are available to validate the mesh, it has to be assumed, that the computational mesh is associated with uncertainties (DTM corrected for water depth, which is uncertain). Another source of uncertainty is the grain size distribution. In this work the GSD is lumped over the whole investigated river reach instead of using a spatially variable GSD to account for downstream fining of the sediment.

## 5.2. Aquatic habitat modelling without food

The suitability curves used within the framework of this project establish the link between physical habitat variables and the preferences of the indicator species. Many papers state, that the outcome of the physical habitat modelling is therefore most sensitive to the shape of the suitability curves (Ayllón et al. [2012], Rosenfeld and Ptolemy [2012], Rosenfeld et al. [2014]). The uncertainties coming along with the preference curves are discussed in the following.

Since no electrofishing data were acquired, there are no specific frequency-based preference curves for the investigated Maggia River reach available. Therefore, suitability curves derived from other rivers are applied to the Maggia River, which implicitly assumes their transferability. To a certain degree this transferability is granted, as the rivers, from which the suitability curves are taken from, show similarities with the Maggia River in their morphological characteristics and in their exposure to hydropower generation. Nonetheless, greater deviations for the bullhead preference curves must be expected, because the curves originate from a small Belgian river, which has nothing in common with the Maggia River from a morphological point of view (compare chapter 2 and B.3). By applying the univariate preference functions in this work, it is assumed, that the physical habitat variables are independent of each other. In nature it is well observed, that the fish can bare much larger flow velocities, if large boulders are present, which reduce the hydraulic forces acting on the fish's body. (Jorde [2018]) In order to account for these feedbacks, it would be necessary to collect spatially variable substrate data and cover data. This in turn requires much larger grid cell resolution, which is at the expense of the computational time. As already mentioned, suitability curves are assumed to be discharge independent. In reality, habitat quality is indeed a function of discharge, as swimming cost, food availability, fish density and temperature are all subject to variations in discharge (Rosenfeld et al. [2014]). But more about this can be read in the next chapter, in which the importance of the food availability is discussed. Even seasonality is claimed to have a huge importance on the shape of the suitability curves. *Liefferinge et al. [2005]* for instance have shown, that the flow velocity and water depth preference curves for bullhead are different during summer and winter months.

*Skourtis [2018]* has pointed out in his work, that the choice of the method for computing the composite suitability index CSI (arithmetic mean, geometric mean and min-approach) can significantly alter the outcome of the habitat quality assessment (WUA and HSI). Since this paper is mainly interested in the relative difference of the habitat quality between previous and actual flow releases, the geometric mean approach delivers comparable results as the other two methods (Jorde [2018]).

All simulations performed with BASEMENT are based on an immobile river bed. Hence, the feedbacks, which morphological changes exert on the habitat quality, are not taken into account here. For instance, erosion of sediments might change a shallow river section to a deep pool, which is governed by different hydrodynamic conditions. This plano-altimetric response of the river would inevitably lead to shift from juvenile bullhead preferred habitat to an adult brown trout preferred habitat. Since the incipient motion assessment has revealed, that there is hardly no grain in motion within the investigated Maggia River reach at the current discharges, morphological feedbacks on habitat quality are negligible. Moreover, it has to be kept in mind, that the results of the physical habitat modelling are a snapshot in time and the river bed has for sure undergone cross-sectional changes due to larger flood events since 2012, when the DTM was acquired.



Despite all these uncertainties there is no qualitative data from electrofishing to validate the model. The only study, which gives an insight into the population dynamics of the brown trout at the Maggia River, is the one conducted by *Peter and Schölzel [2017]*. Some of their findings, which are summarized in the following, underline the validity of the sectional habitat quality assessment.

The quantitative electrofishing survey in 2015/2016 near the villages Maggia (most downstream of the investigated river reach) and Visletto has shown a drastic decline in brown trout population size since the last investigation in 2013. Thereby, the abundance and the biomass have decreased by 70 % and 80 %, respectively. These numbers clarify the urge to take restoration measures at the Maggia River. Reasons for the decline in the trout population are seen in the fact, that the investigated sites were lacking of mature brown trout, which are able to spawn. According to *Peter and Schölzel [2017]* 50 % of the 3<sup>+</sup> brown trout (average length 26.4 cm) are capable of spawning. However, fishermen are allowed to withdraw all brown trout, which have reached the 24 cm mark (24 cm < 26.4 cm). It is estimated, that 25 % to 68 % of the brown trout being above 24 cm are removed from the river. This project work visualizes, that the lack of mature fish can not only be traced back to not letting the brown trout spawn at least once but also to the worse habitat quality at the previous flow releases. The new flow releases, though, would lead to a significant improvement of the spawning brown trout habitat in all the three sections of the Maggia River reach. The word 'would' in the last sentence is there by purpose, because brown trout are known to spawn from October till January. In order for the increase in flow releases to have its positive effect on spawning brown trout, discharges should also be adjusted in the winter months. This would entail energy production cuts, which are not reasonable for the hydropower operators. Other factors contributing to a decrease in the brown trout population size are associated with the increased summer water temperatures near the village Losone. (Peter and Schölzel [2017])

Furthermore, the fish ecological survey has shown, that throughout the whole investigated river reach spawning activity is most concentrated near the village Maggia. This observation is consistent with the sectional habitat quality assessment, which predicts better habitat conditions for spawning brown trout in section one (village Maggia is situated in section one) than in the other two sections. Interestingly, no spawning activity was registered in the braided river reach near Someo (at the transition from section three to two). An explanation for the absence could be the unfavorable hydrodynamic conditions found in the heavily braided section, because the HSI is really low for the previous minimum flow releases (see figure C.12). Juvenile brown trout are found to be most abundant in section one as well, which is again in accordance with the results of the physical habitat modelling.

### 5.3. Aquatic habitat modelling with food

The comparison between the aquatic habitat modelling without and with food availability (compare table 3) shows, that lower discharges (previous minimum flow releases) are much more beneficial for the indicator species and life-stages in the case without food than in the case with food. This finding highlights the tendency of traditional physical habitat modelling to overestimate habitat quality at low flow conditions. It seems, that at low flows a single discharge-independent suitability curve is not capable of representing the 'true' habitat conditions, since the total energy flux resulting from the consumption of invertebrates is in turn dependent on discharge itself (Rosenfeld and Ptolemy [2012]). Apart from this project work, which emphasises that physical habitat modelling underestimates the negative consequences of minimum flow releases on fish, there are many other papers trying to raise awareness as it comes to low flow conditions (Rosenfeld and Ptolemy [2012], Rosenfeld et al. [2014])

*Rosenfeld and Ptolemy [2012]* deliver clear evidence, that the mismatch between available habitat and available energy flux (productive capacity) is the reason for a biased physical habitat modelling at low flow conditions. To give an example, brown trout are known to be drift-feeders, which prefer to stay in deep slow flowing pools. Their food sources (drifting invertebrates), however, are mainly produced in nearby faster flowing waters such as runs and riffles. As discharges decrease, the total energy flux of drifting invertebrates declines much faster from the riffle/run areas than the habitat availability in pools. In a worst case scenario, when discharge approaches zero, there could still be some habitats left in pools, while drift has already ceased in the dried up riffles/runs. (Rosenfeld and Ptolemy [2012])

Another aspect coming along with low flows, is pointed out by *Rosenfeld et al. [2014]*. Since preference curves are most of the time derived at low flow conditions, they might be affected by fish density effects. Adult brown trout, which defend their territories, are observed to displace subordinate fellow species to poor slow-velocity habitats. Most often juvenile brown trout are affected from this territorial behaviour. That is why their suitability curves are biased towards shallow and slow-velocity waters. From an energetic point of view, this makes no sense as most of the food is produced in faster flowing waters. In this work the HSI of juvenile brown trout is shown to be highest at low discharges, which might exactly be the cause of the above discussed territoriality. Therefore, in reality the HSI of juvenile brown trout could even increase with an increase in the new minimum flow releases. (Rosenfeld et al. [2014])

Even though the simplified conceptual model derived in this project work is able to reproduce some of the complex mechanisms prevailing at low flow conditions, the model has its uncertainties. First, these uncertainties find expression in the low 'catastrophic' drift rates, which in turn lead to low HSI values of adult/spawning brown trout. This is not surprising, because for a discharge of  $9.68 \text{ m}^3/\text{s}$  and a characteristic grain size  $d_{10}$  only 25 % of the total inundated area is in motion, and from the areas in motion only 10 % of the invertebrates get dislodged. In nature drift is not only coupled to sediment transport but also to light intensity, detritus transport, water quality, competition and behaviour (Kennedy et al. [2014]). Secondly, not all the invertebrates go into drift with the same fraction  $p_s$  as assumed in this paper. Based on flume experiments, *Schnauder et al. [2010]* investigated critical threshold shear stresses that lead to invertebrate drift. It has turned out, that different invertebrate species exhibit different susceptibilities to boundary shear stresses. Actually, in many cases incipient motion of invertebrates was shown to occur at higher critical threshold shear stresses than required to mobilize grains. The authors argue,

that different morphological adaptations like increased body weight, streamlined body shape, rheotaxis, suckers, claws and filaments are the reason for the observed discrepancies. Furthermore, in this work drift rates increase with an increase in discharge. Nonetheless, there are papers showing exactly the contrary for some invertebrate species (Kennedy et al. [2014]). *Allogamus auricollis* for instance is known to bury itself deep into the substrate in order to avoid being exposed to the hydraulic forces exerted by large floods (Graf et al. [1992]). For large decreases in discharge it has even been demonstrated, that drift rates increase. Some filter-feeders deliberately enter the drift in order to seek better feeding habitat or to avoid stranding. (Kennedy et al. [2014]) Another uncertainty of the conceptual model can be found in the assumption, that drift occurs within the computational elements. Considering the mean element size of  $32\text{ m}^2$  and the fact, that the mean travel distance of invertebrates is  $10.7\text{ m}$  (McLay [1970]), this simplification can be justified to a certain degree. However, it is not a rarity to observe drift distances of  $45.7\text{ m}$  and larger (McLay [1970], Elliott [1971]). Finally, in nature there are some deviations in food acquisition by fish, which are not modelled in detail here. Especially adult brown trout are not only known to be drift-feeders, but also benthic-feeders. Picking up larger caddisfly larvae from the substrate enables them to feed on more caloric food. (Elliott [1970]) Moreover, food uptake is restricted to the three indicator invertebrate species, while in nature there is a broader food spectrum available. Bullhead and brown trout are known to forage on stoneflies, terrestrial bugs and fish as well (Seifert and Kölbing [2005]). Further, foraging activities are allowed to take place within the homing range, which can be smaller or larger than the ones assumed in this paper. Therefore, a sensitivity analysis is shown in figure C.16. It visualizes, that for adult brown trout a 300 % increase in the initial homing range (50 m to 400 m) leads to a 5 % change of the HSI at a discharge of  $9.68\text{ m}^3/\text{s}$ . If no homing range is applied (-100 %), which means that the brown trout is feeding at its focal point, the outcome of the habitat modelling with food is more sensitive to a change in range. Contrary to that, the comparison between the previous and actual flow releases is insensitive to a change in homing range.

## 6. Conclusion

Despite all the uncertainties going hand in hand with the methods to calculate incipient motion, this project work comes to a conclusion, that the newly released minimum flow releases are barely able to initiate sediment motion. Morphological changes, which are important for the proper functioning of the aquatic and riparian ecosystem, are thus associated with larger bed forming floods (HQ<sub>2</sub>, HQ<sub>5</sub> or even HQ<sub>100</sub>).

The aquatic habitat modelling without food highlights the importance of taking different species and their life-stages into account, because a certain hydrodynamic condition might be beneficial for one species/life-stage while being disadvantageous for an other. Hence, an increase in minimum flow releases leads to a large improvement in habitat conditions for spawning brown trout, *Baetis alpinus* and *Allogamus auricollis*. The adult brown trout habitat quality remains more or less uninfluenced by the increased summer month discharges. *Centroptilum luteolum*, juvenile brown trout and all the life-stages of bullhead are negatively impacted on the contrary.

Habitat modelling should not only take abiotic factors into account, but also biotic components, which become more important as discharges decrease. This paper like many others emphasises, that at low flow conditions not the physical habitat availability is the limiting factor for population size of fish, but the energy flux of drifting invertebrates. Taking the indicator invertebrate species as a food source for fish into account has shown, that habitat conditions for brown trout are much better at higher discharges. This is contradictory to what the traditional physical habitat modelling is predicting. Thus, frequency-based habitat suitability curves are said to overestimate the habitat quality of brown trout at low flows. Nevertheless, the habitat modelling with food also visualizes, that brown trout may benefit from larger drift rates at higher discharges, while the food source of the benthic-living bullhead diminishes.

The consideration of all aquatic species and their life-stages would require an optimisation procedure, that allows to minimize the habitat loss of each stream-dwelling species (Jorde [2018]). But sometimes it is more suitable to concentrate on a life-stage, that is seen to limit the population size. The fish ecological survey of *Peter and Schölzel [2017]* has shown, that the brown trout population in the the Maggia River is lacking of mature trout, which are able to spawn. Therefore, river restoration measures should focus most on this life-stage.

The weakest component of the conceptual model developed in the framework of this project work is how drift is modelled. Further studies are required, which investigate the entrainment mechanism of invertebrates, their transport and their settlement. There are some studies, which model drift by means of solving the advective-dispersion equation or by particle tracking (random walk) (Naman et al. [2016], Anderson et al. [2013]). However, these approaches fail to take into account, that some invertebrates can actively leave drift by swimming. *Baetis alpinus* for instance is known for its abdominal contraction, which enables it to swim. (Sander [1961]) For further studies at the Maggia River reach it is also recommended to include temperature in the aquatic habitat modelling, because *Schölzel and Peter [2017]* have shown, that at the previous minimum flow releases the water is too hot to sustain a healthy brown trout population.

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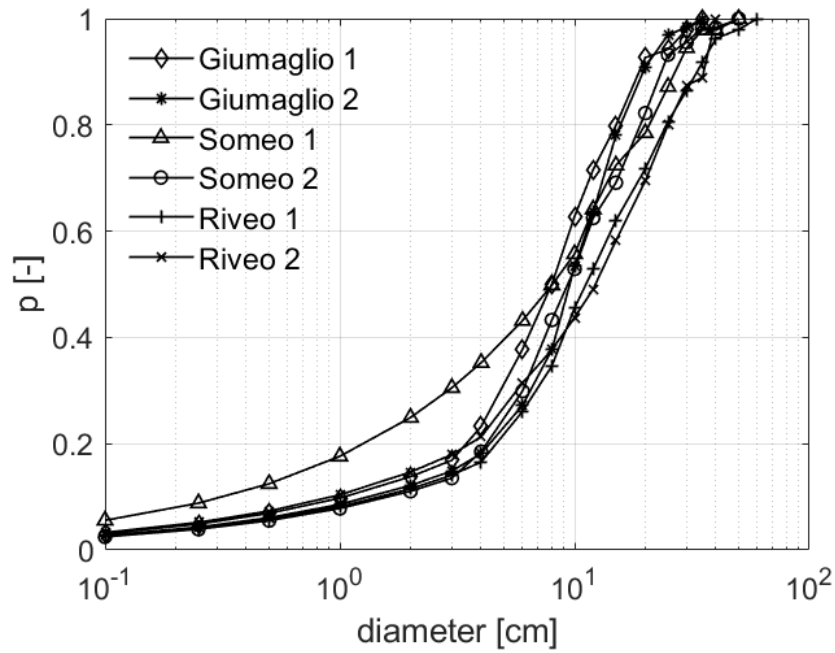
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## Appendix A Data



**Figure A.6:** Six line-samples were taken at the locations Giumaglio 1 (695'287 / 125'638), Giumaglio 2 (694'777 / 125'919), Someo 1 (693'921 / 126'672), Someo 2 (693'863 / 126'823), Riveo 1 (692'321 / 127'461) and Riveo 2 (692'308 / 127'448) by *Wolfgang [2003]* and *Sturzenegger [2005]*.

**Table A.4:** Mean characteristic grain size diameters of the studied river reach.  $\sigma$  represents the mean spread of the samples.

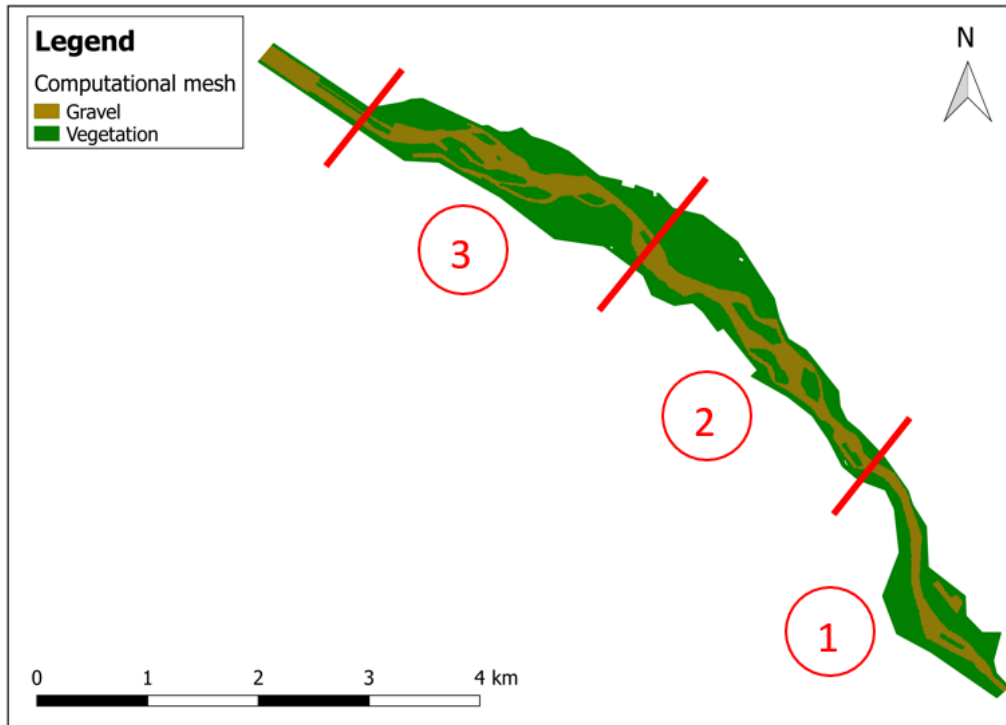
Parameter	Characteristic grain size										
	d <sub>10</sub>	d <sub>20</sub>	d <sub>30</sub>	d <sub>40</sub>	d <sub>50</sub>	d <sub>m</sub>	d <sub>60</sub>	d <sub>70</sub>	d <sub>80</sub>	d <sub>90</sub>	$\sigma$
diameter [cm]	1.2	3.6	5.5	7.5	9.8	12.0	12.2	15.6	20.1	26.3	3.0

## Appendix B Methods

### B.1 Computational mesh

**Table B.5:** Specifications of the computational mesh can be seen.

Parameter	Value
Channel length [m]	1'000
Replicated channel length [m]	500
Trapezoidal channel length [m]	500
Channel width [m]	216
Trapezoidal channel bottom width [m]	173
Embankment slope [V:H]	1:1.5
Slope [‰]	8
Number of elements [-]	130'534
Average element size [ $m^2$ ]	32.2



**Figure B.7:** The computational mesh is the basis for all 2D hydrodynamic simulations with BASEMENT. The fictitious channel in the upstream region is created with the BASEmesh plugin in QGIS. In red the sectional investigation of the habitat quality without food can be seen.

## B.2 2D hydrodynamic simulations with BASEMENT

$$k_{St} = \frac{21.1}{d_{90}^{1/6}} \quad (14)$$

with

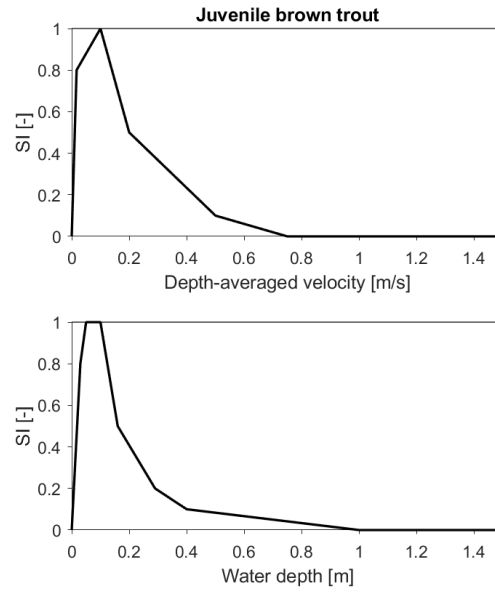
- $k_{St}$  Strickler-coefficient of gravel [ $m^{1/3}/s$ ]  
 $d_{90}$  characteristic diameter, with 90 % of the grains being smaller than  $d_{90}$  [m]

**Table B.6:** Shown are the settings and parameters to run steady state 2D hydrodynamic simulations with BASEMENT.

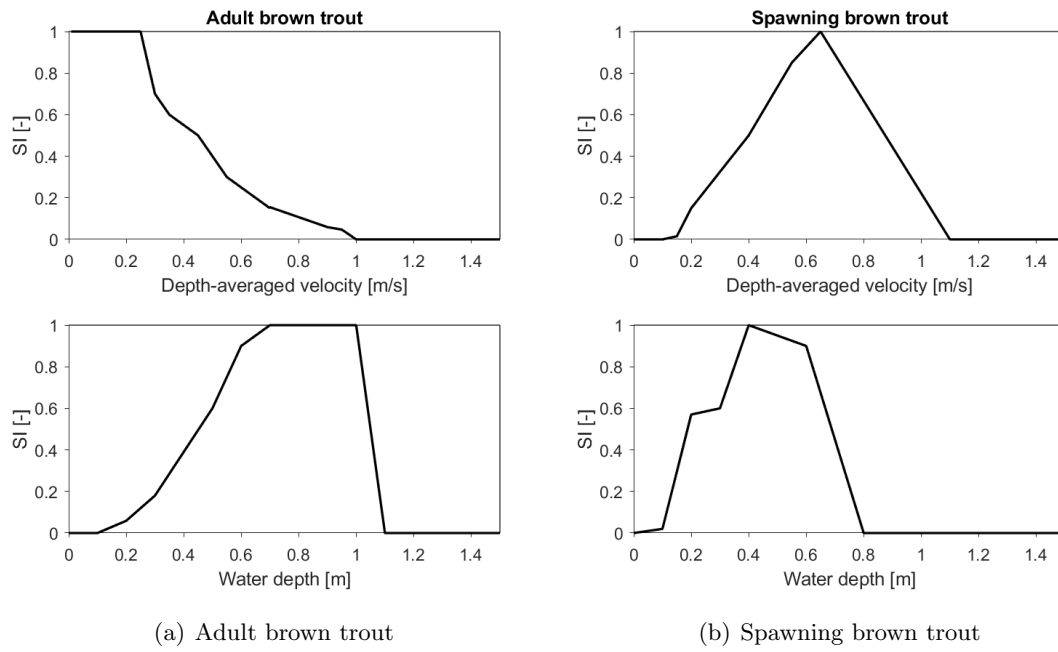
Settings/Parameters	Value
Minimum water depth [m]	0.05
Riemann solver	HLLC (Harten-Lax-van Leer-contact)
CFL number [-]	1
Friction type	Strickler
Roughness value gravel [ $m^{1/3}/s$ ]	29
Roughness value vegetation [ $m^{1/3}/s$ ]	20
Initial condition	dry river bed
Upstream boundary condition	hydrograph
Downstream boundary condition	hq-relation
Slope at inflow/outflow boundary [‰]	8
Total run time [s]	345'600

## B.3 Aquatic habitat modelling without food

The suitability curves for juvenile brown trout are taken from *Hauer et al. [2014]* (see figure B.8). These generalized suitability curves were derived from field observations of 16 Austrian river reaches (6 rivers), expert knowledge and literature. All the reaches were affected by hydropowering and were characterized by plane or riffle-pool morphology. The suitability curves for adult and spawning trout are provided by *Person [2013]* (see figure B.9). These curves were applied at residual flow river reaches of the Vorderrhein River, mainly characterized by riffle-pool sequences and gravel bars (braided). The preference curves used for juvenile and adult bullhead are selected from *Liefferinge et al. [2005]* (see figure B.10). These curves were derived from electrofishing surveys in a Belgian narrow river consisting of riffle-pool sequences.



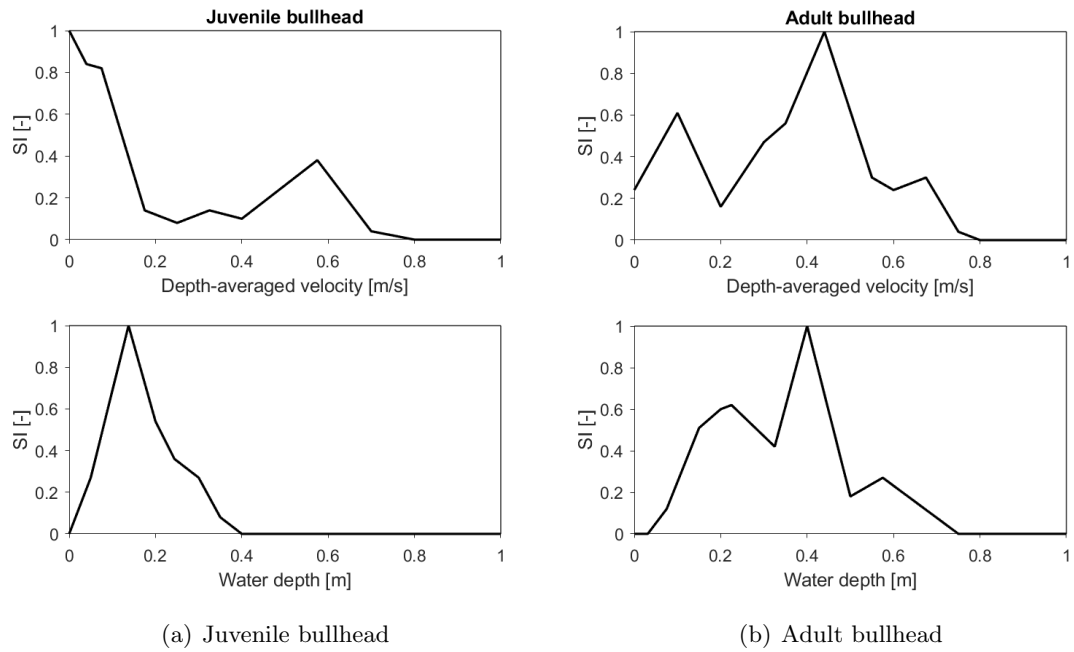
**Figure B.8:** Habitat suitability curves for juvenile brown trout from *Hauer et al. [2014]*.



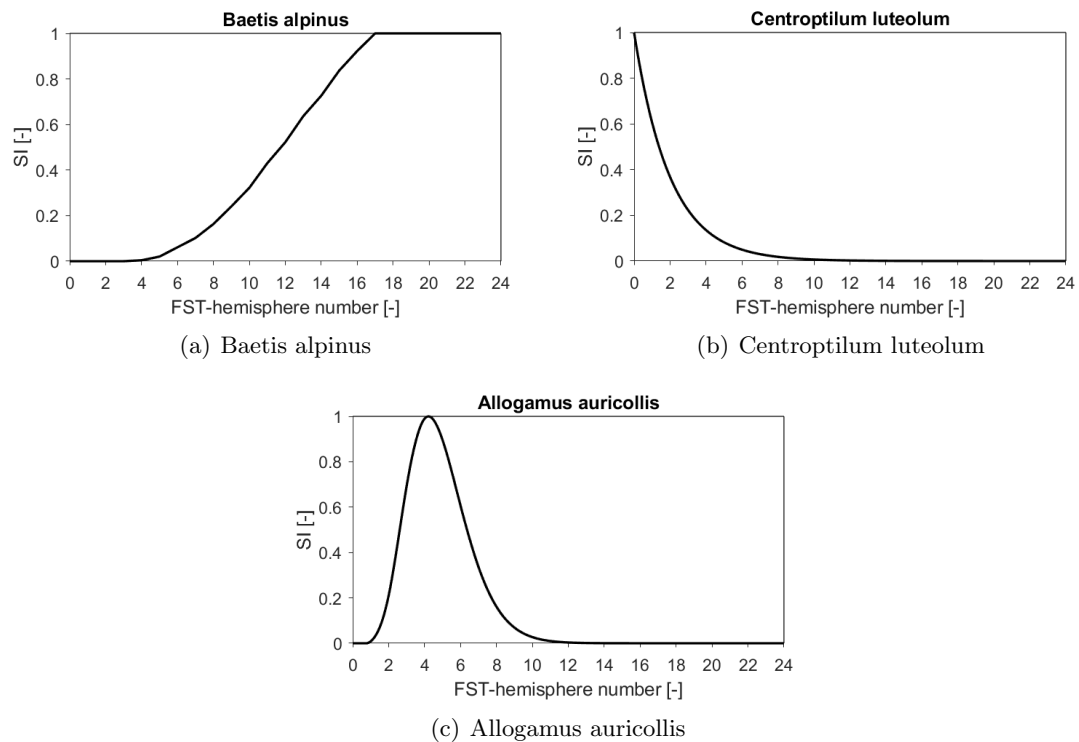
(a) Adult brown trout

(b) Spawning brown trout

**Figure B.9:** Habitat suitability curves for adult and spawning brown trout from *Person [2013]*.



**Figure B.10:** Habitat suitability curves for juvenile and adult bullhead from *Liefferinge et al. [2005]*.



**Figure B.11:** Habitat suitability curves for benthic living invertebrates from *Mürle [2000]*, *Dittrich and Schmedtje [1995]* and *Cabaltica et al. [2013]*, respectively.

## Appendix C Results

### C.1 Incipient motion

**Table C.7:** Incipient motion according to *Meyer-Peter and Müller [1948]*. Q is the discharge and A is the total inundated area of the corresponding discharge.

Q [ $m^3/s$ ]	A [ $10^5 m^2$ ]	Area in motion [ $m^2$ ]								
		$d_{10}$	$d_{20}$	$d_{30}$	$d_{40}$	$d_{50}$	$d_{60}$	$d_{70}$	$d_{80}$	$d_{90}$
1.2	2.32	16'125	512	0	0	0	0	0	0	0
1.8	2.64	26'614	1'468	129	0	0	0	0	0	0
2.77	2.87	39'958	3'799	596	29	0	0	0	0	0
4.33	3.19	59'119	7'537	2'070	404	132	0	0	0	0
4.37	3.20	59'381	7'651	1'960	330	132	30	0	0	0
6.53	3.49	81'321	13'887	4'094	1'244	368	100	36	36	36
7.23	3.57	87'997	15'817	4'914	1'681	460	169	37	7	7
9.68	4.09	110'657	21'805	7'199	2'469	879	216	30	30	0

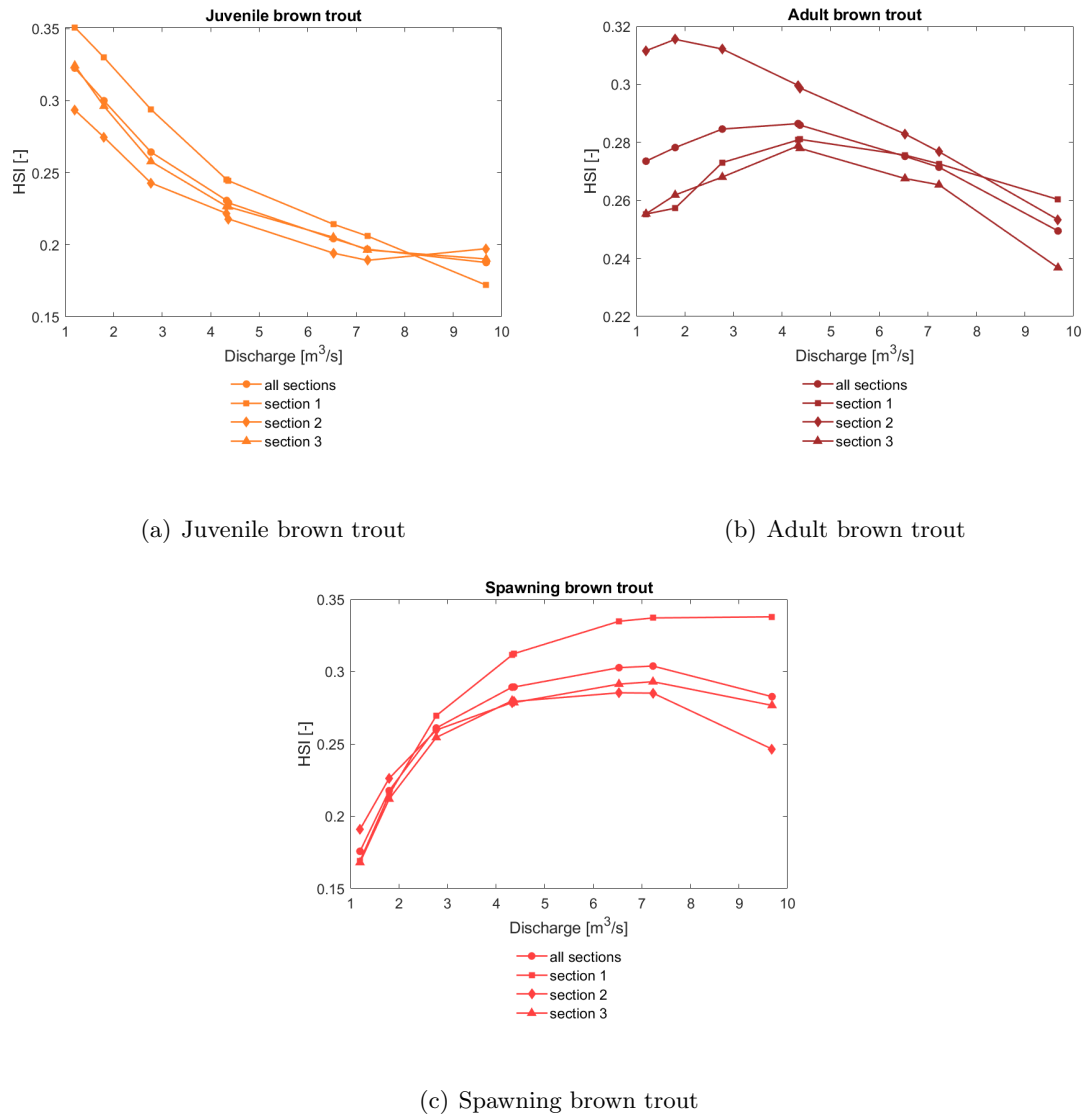
**Table C.8:** Incipient motion according to *Egiazaroff [1965]*. Q is the discharge and A is the total inundated area of the corresponding discharge.

Q [ $m^3/s$ ]	A [ $10^5 m^2$ ]	Area in motion [ $m^2$ ]								
		$d_{10}$	$d_{20}$	$d_{30}$	$d_{40}$	$d_{50}$	$d_{60}$	$d_{70}$	$d_{80}$	$d_{90}$
1.2	2.32	0	0	0	0	0	0	0	0	0
1.8	2.64	0	0	0	0	0	0	0	0	0
2.77	2.87	0	0	0	0	0	0	0	0	0
4.33	3.19	0	71	71	71	30	30	0	0	0
4.37	3.20	0	71	99	71	30	30	0	0	0
6.53	3.49	36	224	253	193	193	100	66	66	36
7.23	3.57	7	303	343	201	169	169	65	37	37
9.68	4.09	0	760	786	699	414	216	122	57	30

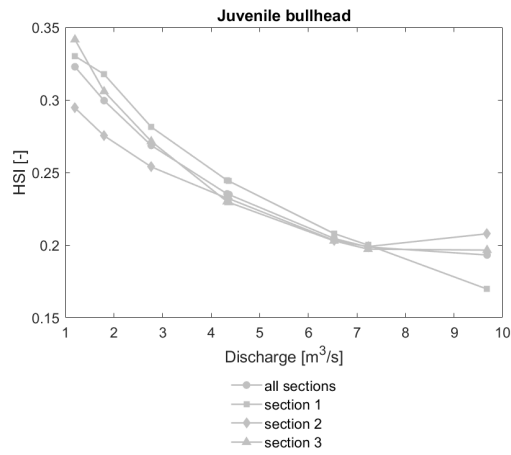
**Table C.9:** Incipient motion according to *Parker [1990]*. Q is the discharge and A is the total inundated area of the corresponding discharge.

Q [ $m^3/s$ ]	A [ $10^5 m^2$ ]	Area in motion [ $m^2$ ]								
		$d_{10}$	$d_{20}$	$d_{30}$	$d_{40}$	$d_{50}$	$d_{60}$	$d_{70}$	$d_{80}$	$d_{90}$
1.2	2.32	0	0	0	0	0	0	0	0	0
1.8	2.64	0	0	0	0	0	0	0	0	0
2.77	2.87	29	0	0	0	0	0	0	0	0
4.33	3.19	271	132	132	132	132	99	99	71	71
4.37	3.20	271	132	132	132	132	99	99	71	71
6.53	3.49	1'034	660	555	463	408	368	253	224	193
7.23	3.57	1'360	824	645	553	526	426	343	234	201
9.68	4.09	2'106	1'573	1'292	1'113	916	817	817	760	699

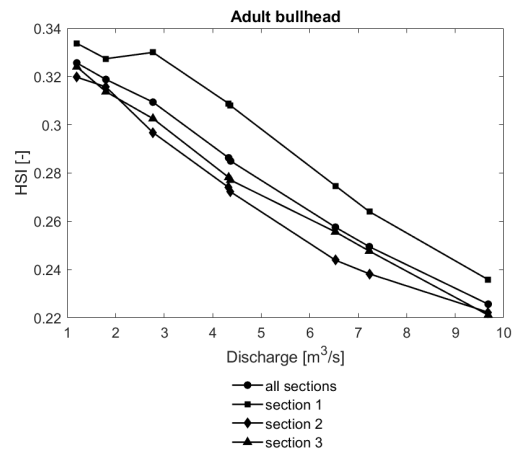
## C.2 Aquatic habitat modelling without food



**Figure C.12:** Sectional habitat quality assessment for brown trout without food. Furthermore, the HSI curve of the whole river reach is provided as a comparison. The situation of the sections can be seen in figure B.7.



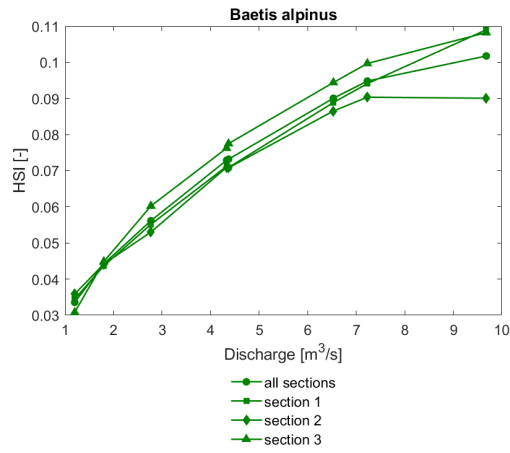
(a) Juvenile bullhead



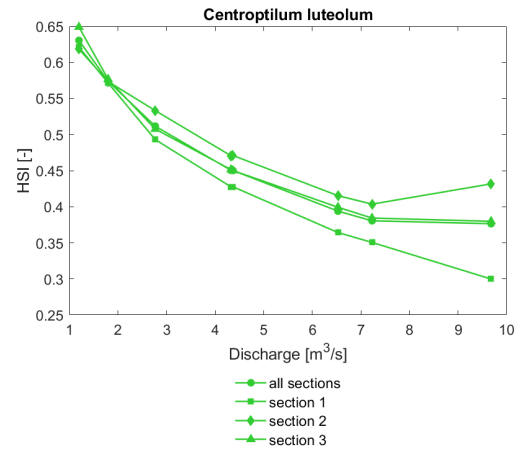
(b) Adult bullhead

**Figure C.13:** Sectional habitat quality assessment for bullhead without food. Furthermore, the HSI curve of the whole river reach is provided as a comparison. The situation of the sections can be seen in figure B.7.

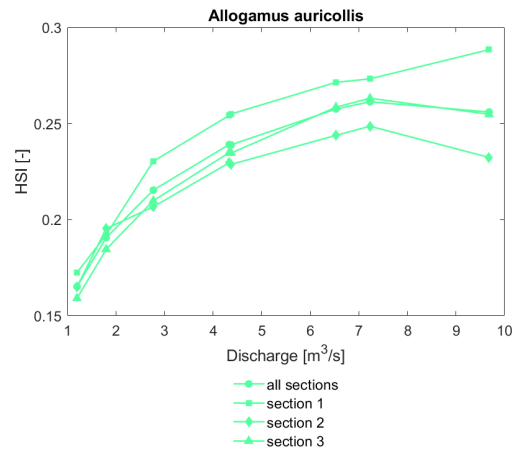




(a) *Baetis alpinus*



(b) *Centropilum luteolum*



(c) *Allogamus auricollis*

**Figure C.14:** Sectional habitat quality assessment for indicator invertebrates without food. Furthermore, the HSI curve of the whole river reach is provided as a comparison. The situation of the sections can be seen in figure B.7.

**Table C.10:** Brown trout HSI comparison (relative changes) between the previous and current minimum flow releases for the three sections without food.

Month		Apr.	May	Jun.	Jul.	Aug.	Sep.
Minimum flow release [ $m^3/s$ ]	Previous	1.2	1.2	1.2	1.8	1.8	1.8
	Current	2.77	7.23	9.68	9.68	6.53	4.37
Juvenile brown trout HSI [%]	Section 1	-16	-41	-51	-48	-35	-26
	Section 2	-17	-36	-33	-28	-29	-19
	Section 3	-21	-39	-41	-36	-31	-24
Adult brown trout HSI [%]	Section 1	7	7	2	1	7	9
	Section 2	0	-11	-19	-20	-10	-5
	Section 3	5	4	-7	-10	2	6
Spawning brown trout HSI [%]	Section 1	59	99	100	57	56	45
	Section 2	36	49	29	9	26	23
	Section 3	51	74	65	31	37	31

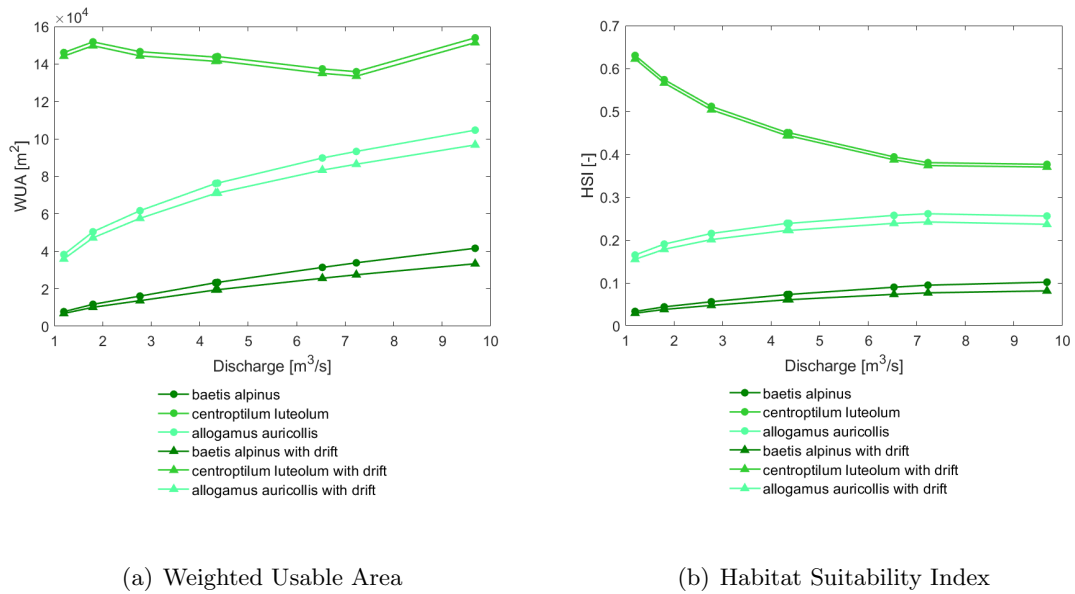
**Table C.11:** Bullhead HSI comparison (relative changes) between the previous and current minimum flow releases for the three sections without food.

Month		Apr.	May	Jun.	Jul.	Aug.	Sep.
Minimum flow release [ $m^3/s$ ]	Previous	1.2	1.2	1.2	1.8	1.8	1.8
	Current	2.77	7.23	9.68	9.68	6.53	4.37
Juvenile bullhead HSI [%]	Section 1	-15	-39	-49	-47	-34	-23
	Section 2	-14	-32	-29	-25	-26	-16
	Section 3	-21	-42	-42	-36	-34	-25
Adult bullhead HSI [%]	Section 1	-1	-21	-29	-28	-16	-6
	Section 2	-7	-25	-30	-30	-23	-13
	Section 3	-7	-24	-32	-30	-19	-12

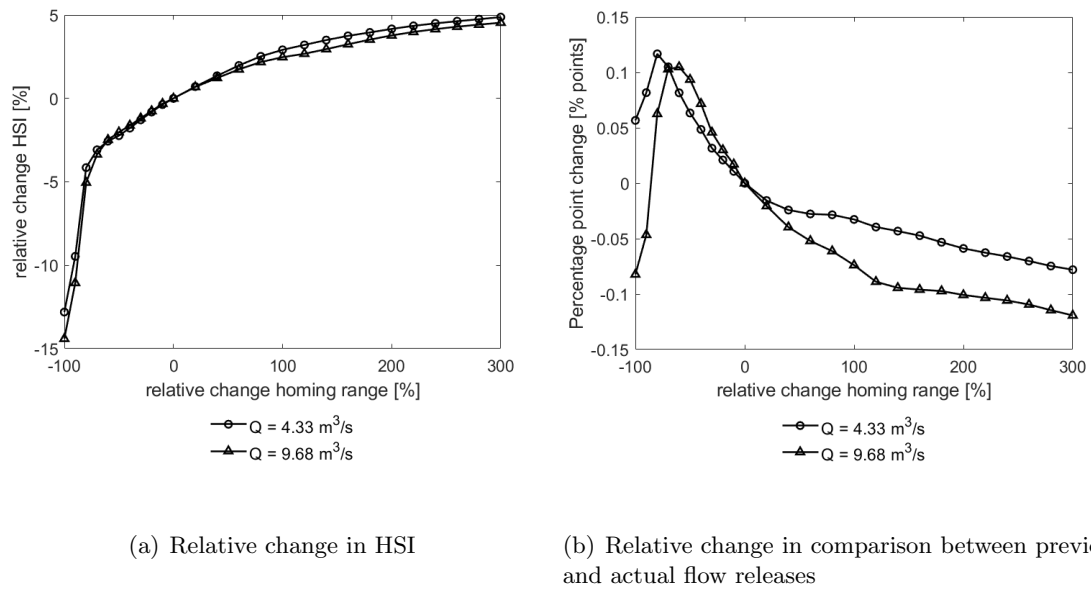
**Table C.12:** Invertebrate HSI comparison (relative changes) between the previous and current minimum flow releases for the three sections without food.

Month		Apr.	May	Jun.	Jul.	Aug.	Sep.
Minimum flow release [ $m^3/s$ ]	Previous	1.2	1.2	1.2	1.8	1.8	1.8
	Current	2.77	7.23	9.68	9.68	6.53	4.37
Baetis alpinus HSI [%]	Section 1	60	173	216	150	104	63
	Section 2	48	152	151	104	96	61
	Section 3	96	224	251	141	111	70
Centroptilum luteolum HSI [%]	Section 1	-21	-44	-52	-48	-36	-25
	Section 2	-14	-35	-30	-25	-28	-18
	Section 3	-22	-41	-41	-34	-31	-22
Allogamus auricollis HSI [%]	Section 1	34	58	67	50	41	32
	Section 2	25	51	41	19	25	18
	Section 3	32	65	60	38	40	27

### C.3 Aquatic habitat modelling with food



**Figure C.15:** Invertebrate WUA and HSI comparison between the cases without food and with food for the whole river reach.



**Figure C.16:** Sensitivity analysis of the homing range for adult brown trout at two different discharges.



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Die unterzeichnete Eigenständigkeitserklärung ist Bestandteil jeder während des Studiums verfassten Semester-, Bachelor- und Master-Arbeit oder anderen Abschlussarbeit (auch der jeweils elektronischen Version).

Die Dozentinnen und Dozenten können auch für andere bei ihnen verfasste schriftliche Arbeiten eine Eigenständigkeitserklärung verlangen.

Ich bestätige, die vorliegende Arbeit selbständig und in eigenen Worten verfasst zu haben. Davon ausgenommen sind sprachliche und inhaltliche Korrekturvorschläge durch die Betreuer und Betreuerinnen der Arbeit.

**Titel der Arbeit** (in Druckschrift):

Assessing impacts of changes in minimum flow releases on aquatic habitat and sediment mobility in the Maggia River

**Verfasst von** (in Druckschrift):

*Bei Gruppenarbeiten sind die Namen aller Verfasserinnen und Verfasser erforderlich.*

**Name(n):**

Paszi

**Vorname(n):**

Patrick

Ich bestätige mit meiner Unterschrift:

- Ich habe keine im Merkblatt „[Zitier-Knigge](#)“ beschriebene Form des Plagiats begangen.
- Ich habe alle Methoden, Daten und Arbeitsabläufe wahrheitsgetreu dokumentiert.
- Ich habe keine Daten manipuliert.
- Ich habe alle Personen erwähnt, welche die Arbeit wesentlich unterstützt haben.

Ich nehme zur Kenntnis, dass die Arbeit mit elektronischen Hilfsmitteln auf Plagiate überprüft werden kann.

**Ort, Datum**

Kollbrunn, 03.03.2019

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