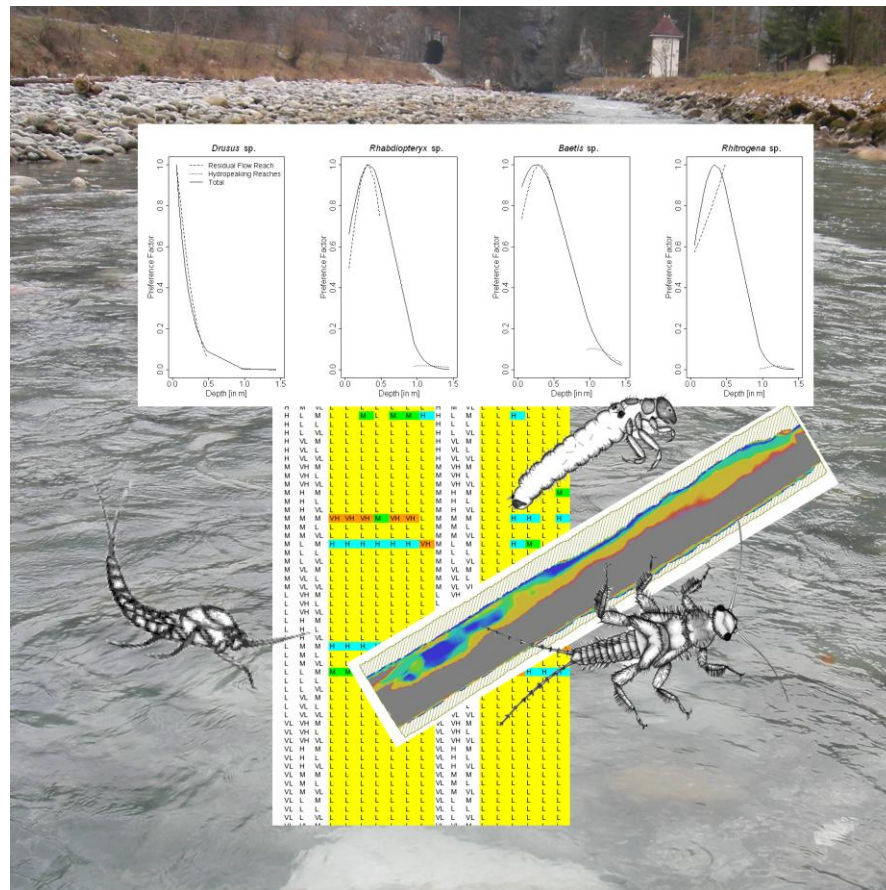# Physical habitat modeling for the assessment of macroinvertebrate response to hydropeaking

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ABSTRACT

Hydropower plants with storage reservoirs cause artificial discharge fluctuations by water imput into the river, termed hydropeaking. These rapid fluctuations in discharge lead to unnatural changes in physical parameters such as water depth, flow velocity, temperature and turbidity and has many ecological impacts on river ecosystems. Hydropeaking leads to increased drift of invertebrates, stranding of juvenile fishes at low flows and increased colmation of the riverbed. As a long-term consequence, it leads to a reduction in biomass and density of stream-dwelling organisms. A fuzzy rule based modeling approach, using CASiMiR, was used to simulate macroinvertebrate habitat suitability under current hydropeaking conditions in three different channel morphologies during winter, spring and summer in Hasliaare River (BE). The results showed that the effects of hydropeaking are most pronounced during the low flow period in winter. In spring and summer, hydropeaking had a minor role, as the higher natural base flows already decreased most available habitats. The major impact could be traced back to the channelized morphology of the river. Further, it turned out that structure and spatial heterogeneity introduced by gravel bars increased the amount of suitable habitats for macroinvertebrates and was more resistant against higher flows in comparison to a channelized morphology or with groynes. Thirdly, it was found that the emergence period of macroinvertebrates in spring and summer is a sensitive phase in their life cycle as they prefer shallow habitats that are sparse in hydropeaking reaches.

ZUSAMMENFASSUNG

Speicherwasserkraftwerke verursachen künstliche Pegelschwankungen in Fliessgewässern durch die Rückgabe von turbiniertem Wasser, ein Phänomen, das als Schwall/Sunk bezeichnet wird. Die künstlichen Pegelschwankungen führen zu unnatürlichen Veränderungen von physikalischen Parametern wie Wassertiefe, Fliessgeschwindigkeit, Temperatur und Trübung. Dies hat viele ökologische Konsequenzen für Fliessgewässer. Der Schwallbetrieb führt zu erhöhter Verdriftung von Makroinvertebraten ("Katastrophendrift"), Strandung von Jungfischen während der Sunkphase und zu einer erhöhten Kolmation durch Eintrag von Feinmaterial aus den Reservoirs. Langfristige Auswirkungen des Schwallbetriebes sind die Reduktion von Biomasse und Abundanz von Gewässerorganismen in den betroffenen Abschnitten. Ein Habitatmodell basierend auf unscharfen Berechnungsansätzen (Fuzzy-Logik) wurde erstellt und verwendet um die Habitateignungen für Makroinvertebraten unter Schwall/Sunk-Bedingungen in der Hasliaare (BE) zu simulieren. Es wurden die Habitateignungen in drei Gewässerabschnitten mit unterschiedlicher Morphologie während einer typischen Winter-, Frühlings- und Sommersituation mit CASiMiR simuliert. Es zeigte sich, dass die Auswirkungen auf die verfügbaren Habitate im Winter am stärksten waren. Hingegen war der Schwallbetrieb im Frühling und Sommer nur von untergeordneter Bedeutung, da die natürlichen, höheren Basisabflüsse die Verfügbarkeit von geeigneten Habitaten schon stark herabsetzten. Den grössten Einfluss im Sommerhalbjahr hatte die kanalisierte Morphologie. Weiter stellte sich heraus, dass Kiesbänke die Anzahl verfügbarer Habitate erhöhten und resistenter gegen erhöhte Abflüsse waren, da sie mehr Struktur und räumliche Heterogenität einführten als eine stark kanalisierte Strecke oder Buhnen. Ebenfalls konnte gezeigt werden, dass die Emergenzperiode im Frühling und Sommer eine sehr sensible Phase im Lebenszyklus von Makroinvertebraten ist und sie seichte Habitate bevorzugen, die in der Schwallstrecke selten sind.

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1. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Hydropower is an important renewable energy source. In Switzerland, for example, there are 556 Hydropower plants that produce 38 TWh, about 60% of Swiss electricity (BFE, 2012). Switzerland is, together with Austria, Norway and Japan, among the countries that have the highest hydroelectricity production per surface area in the world. It is therefore not surprising that about 80% of Swiss Alpine rivers are influenced by hydropower production and are flow regulated by dams (Truffer *et al.*, 2001). As it is a renewable energy, hydropower also will play an important role in energy production in the future. However, beside numerous positive aspects of hydropower, it is also responsible for major disturbances to the integrity of river ecosystems as stressed by many authors (e.g. Truffer *et al.*, 2003; Meile *et al.*, 2005; Bruno *et al.*, 2009, 2010). First, dams of storage reservoirs interrupt the natural river continuum and reduce the connectivity of channel, floodplain, groundwater and upstream reaches (Stanford *et al.*, 1996), disrupt biogeochemical processes (Friedl & Wüest 2002; Wüest 2002) and alter the natural flow regime (Ward & Stanford, 1979; Vinson 2001; Graf, 2006). Second, short-term increases of electricity production at high demand times lead to increased water inputs in rivers and cause artificial discharge fluctuations, a phenomenon known as hydropeaking or Schwall/Sunk in German (Fette *et al.*, 2007; Schweizer *et al.*, 2009). These rapid fluctuations in discharge lead to unnatural changes in hydraulic parameters such as water depth and flow velocity (Meile *et al.*, 2011).

Short-term increases in discharge lead to "catastrophic" drift of benthic invertebrates as found in many hydropeaking-affected rivers (Cereghino & Lavandier, 1998; Cereghino *et al.*, 2004; Limnex, 2009; Bruno *et al.*, 2010). As revealed by various studies, decreased densities and biomass of populations are found below hydropeaking water inputs (Cereghino & Lavandier, 1998; Cereghino *et al.*, 2004). Further, the increased drift has been shown to clearly affect the longitudinal zonation of benthic invertebrates (Cereghino *et al.*, 2002). Some species become less abundant below water imports, whereas other species disappear completely, which shows how hydropeaking can affect species distribution (Cereghino *et al.*, 2002). Not only do discharge peaks seem

to matter for organisms in rivers, low discharges at times of no electricity production (i.e. water storage) also are important. It has been shown that the rapid return of the water level after the hydropeaking wave, and the falling dry of side arms and margins, leads to an increased stranding of organisms (Baumann & Klaus, 2003). Juvenile fishes are especially susceptible to stranding because they are often in the shallow parts of the river (Salveit et al., 2001; Hallebraker et al., 2003). The physical properties of the water also have been found to be altered, such as temperature, also referred to as thermopeaking (Carolli et al., 2011; Toffolon et al., 2011; Zolezzi et al., 2011), or turbidity which affects light penetration necessary for primary production (Portmann et al., 2004). Further, hydropeaking causes colmation of the riverbed, caused by the intrusion and deposition of suspended fine material in or on the top layer of the streambed (Cunnigham et al., 1987; ARGE Trübung Alpenrhein, 2001). This results in tightly packed sediments with reduced pore space, reduced hydraulic conductivity and a high resistance against increasing discharges (Schälchli 1992). Especially during hydropeaking waves, when hypolimnetic water is released into the river, turbidity is increased and more fine material is released and becomes deposited on or in the riverbed (ARGE Trübung Alpenrhein, 2001; Meile et al., 2005; Anselmetti et al., 2007). The clogging by fine particles constrains the exchange and permeability between surface water and groundwater (Fette et al., 2004). For many insects, this is a loss of habitat because they inhabit the interstitials at certain life stages or use it as a refugium from predation (Brunke & Gonser, 1997; Gonser, 2000).

The revised Swiss water protection legislation demands from each hydropower scheme that causes hydropeaking with a ratio Q_{max} (discharge peak) to Q_{min} (minimal discharge) higher than 1.5 to remediate these negative effects and to restore the natural functions of regulated rivers (Pfaundler et al., 2011; Baumann et al., 2012). In these river management projects, attention is often put on fish, although macroinvertebrates fulfill many important ecological functions in stream food webs and are also affected strongly by hydropeaking. A diverse range of functions is performed by Zoobenthos: They impact nutrient cycling and material translocation by decomposition of detritus, and release nutrients through their feeding, excretion and burrowing activities, making these nutrients available for primary production and other benthic macroinvertebrate species (Anderson & Sedell, 1979; Covich et al., 1999). Further, they control prey populations by predation

and grazing, and are themselves an important food source for vertebrate predators like fish and birds (Wallace & Webster, 1996).

To assess habitat quality and its change, a predictive modeling approach is a good option. For minimal flow evaluations, they are routine today and it is also a method with increasing importance in the evaluation of hydropeaking problems (Kopecki *et al.*, 2012). With physical habitat models, the suitability of habitats under current hydropeaking conditions can be simulated and also remediation projects can be simulated to investigate potential outcomes. Traditionally, habitat models in stream ecology link physical parameters of a stream like depth, flow velocity or substrate with the habitat suitability or preference of an organism (Jorde & Schneider , 2010). Bovee (1982) developed the instream flow incremental methodology (IFIM), which evaluates the suitability of physical habitats using univariate preference curves. Associated with softwares such as the Physical Habitat Simulation Model (PHABSIM; Milhous *et al.*, 1989) or RHYHABSIM (River HYdraulic HABitat SIMulation; Jowett, 1997), it has been applied world-wide in river management projects (Gore *et al.*, 2001). An approach that is more recent and has some important advantages over the classical preference curve method is the CASiMiR model (Computer Aided Simulation Model for Instream Flow Requirements; Jorde, 1997; Schneider, 2001). This modeling tool has been widely applied. It uses a fuzzy logic approach that is based on fuzzy sets and fuzzy rules and represents an extension of normal set theory (Zadeh, 1965; Jorde & Schneider, 2010). As these models use liguistic rules instead of complex mathematical expressions, they are more transparent and easier to understand, thus allowing the integration of stream managers in the development process more easily (Adraenssens *et al.*, 2004). CASiMiR has been used to simulate the effects of hydropower plants and restoration projects on habitat suitability for fish and macroinvertebrates in various countries (e.g. Kerle *et al.*, 2002; Mouton *et al.*, 2007; Garcia *et al.*,2011; Eberstaller *et al.*, 2012a,b; Kopecki *et al.*, 2012; Person & Peter, 2012).

1.2 GOALS AND RESEARCH QUESTIONS

The first goal of this thesis was to fit preference curves for macroinvertebrates to investigate how they respond to physical habitat variables , such as depth, flow velocity and substrate size.

A second goal was to develop a fuzzy rule habitat model based on the preference curves and additional information from literature.

The research questions in this thesis were:

i) How are instream habitats distributed under current hydropeaking situations over three seasons (using CASiMiR)?

ii) how do different channel morphology types affect habitat availability in a hydropeaking river?

iii) what are the implications of model outputs for remediation projects?

2.MATERIAL AND METHODS

2.1 STUDY SITE

The upper Aare River (also referred to as Hasliaare) originates from Unteraar and Oberaar Glaciers at 2000 m a. s. l. and flows through three reservoirs (Oberaar, Grimsel and Räterichsboden) where the main part of the water is stored and used for energy production. Below the three reservoirs, the Aare flows as a residual flow reach until the turbinated water is released at Innertkirchen at 620 m a. s. l. below the confluence with Gadmerwasser (Fig. 1, blue arrow). Below the water outlet, it is a hydropeaking influenced river until Lake Brienz at 564 m a. s. l and has different channel morphology types (Bieri & Schleiss, 2011). The watershed above Innertkirchen covers 450 km^2 of which 350 km^2 are used for energy production.
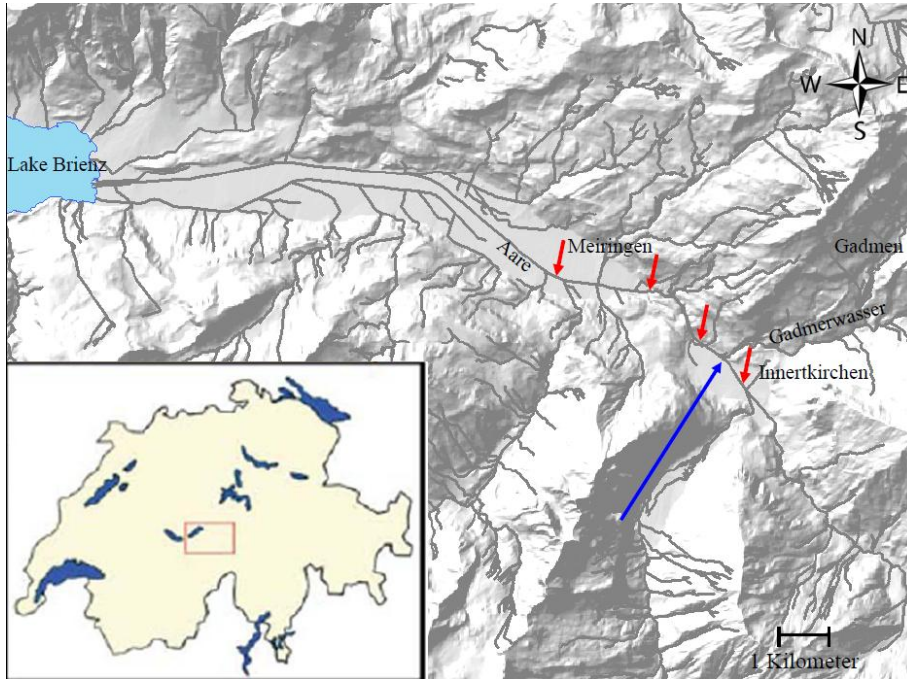

FIG. 1: Study sites at the Aare indicated by the red arrows. Sections are (from right to left): Residual flow reach Groyne reach, Gravel bar reach and Channel reach. Blue arrow indicates water outlet in Innertkirchen. Source: modified from ESRI Published Maps and Schweizer *et al.* (2010)

At 27 sites from the two main valleys, Aare and Gadmen valley, water is diverted for hydropower production (Schweizer *et al.*, 2010). The mean annual discharge from 2001-

2011 ranged from 32-40m^3/s (BAFU, 2012). However, as electricity production is dependent on how much electricity is used at the moment, discharge in the hydropeaking reaches is highly unpredictable and can fluctuate strongly during any day. The hydrologic regime is kryal (glacier dominated) or nival (meltwater dominated), dependend on the altitude, and the proportion of glacier in the catchment is about 21% (Schweizer *et al.*, 2010; Bieri & Schleiss, 2011).

Four sites were studied: 1) Residual flow reach, which is upstream of the water outlet in Innerkirchen below the confluence with the Urbachwasser and is embanked by levees but still has some remaining structural heterogeneity. It is not influenced by hydropeaking. 2) Groyne reach is located downstream of the water outlet in Innertkirchen and the confluence with the Gadmerwasser and flows 700 m down to the Aare Gorge. The morphology is characterized by groynes on both river sides and is 25 m wide. 3) Gravel bar reach is located below the Aare Gorge and is 1.5 Kilometers long and characterized by alternating gravel bars. It also is 25 m wide. 4) Channel reach is 12 km long, a straight channel and flows from Meiringen down to Lake Brienz (FIG. 1). Here the river is 18 m wide. All three Hydropeaking reaches (2-4) are highly channelized and embanked by levees. The substrate is dominantly coarse with a mean diameter of 13 cm (Schweizer *et al.*, 2008). A two-dimensional hydraulic model was available for sections of 150 meters length in the three Hydropeaking reaches (by sje Schneider & Jorde Ecological Engineering GmbH, 2009).

2.2 DATA COLLECTION AND TREATMENT

Samples were taken on 8.12.2011 and 17.2.2012 in winter, 08.05.2012 in spring and 14.08.2012 in summer. The three Hydropeaking reaches were sampled only once on the 17.2.2012 (each Reach N=12), whereas the Residual flow reach was sampled on all other dates (each time N=20). To enter the Hydropeaking reaches, the power plant was shut down and sampling took place at low discharge (ca. 4m^3/s). In each reach, transects were set across the wetted area of the river ca. 10 m apart from each other. In every transect, a point was selected for sampling. The points were selected to cover as wide a

range of physical habitat variables found at a reach. At each point, a macroinvertebrate sample was taken using a Hess-Sampler (diameter 25 cm) and the samples were frozen or put in 70% ethanol. Further, physical habitat variables of depth, flow velocity and size class of the dominant substrate were measured. Depth was measured using a meter stick, flow velocity with a Mini Air$^®$ 2 (Schildknecht) velocity meter and size class of substrate was recorded. For the classification of substrate, nine size classes were defined according to Eberstaller *et al.* (2012a) and are listed in Appendix 1. Additionally, colmation and percentage of algal coverage were estimated, coordinates were recorded using GPS, and three stones were taken at each point to determine periphyton biomass.

The collected organisms were enumerated using a binocular microscope and determined to the lowest possible level using determination keys by Waringer & Graf (1997) and Tachet *et al.* (2010). Body length was measured at a precision of 1 mm. The most common taxa were used to fit preference curves for depth and flow velocity. For the determination of macroinvertebrate biomass, length-dry mass relationships elaborated by Burgherr & Meyer (1997) were applied. For periphyton biomass determination, the biofilm was scrubbed off the stones with a steel brush and filtered through a glass microfibre filter with a pore size of 0.7 μm (Whatmann™). The filters were dried for 48 hours at 60°C, weighed and the biomass burned at 550°C for four hours and then weighed again. The difference between the two weights was calculated as ash free dry mass (AFDM).

2.3 FITTING OF PREFERENCE CURVES

To gain insight into the preference of physical habitats, preference curves for the most frequent macroinvertebrate taxa (*Drusus* sp. (only in winter), *Rhabdiopteryx* sp., *Baetis* sp., *Rhitrogena* sp. and Simulidae (only in summer)), total biomass, total density and taxon richness were fitted for the habitat variables depth and flow velocity. Generalized Linear Regression Models (GLM) with second or fourth polynomial order were applied assuming a Poisson distribution, except a gaussian distribution was assumed for total biomass. In the IFIM methodology developed by Bovee (1982), preference

curves were described by a habitat variable (e.g. flow velocity) on the x-axis and, on the y-axis, a preference factor ranging from 0 to 1 indicated the suitability of the physical habitat (see also Orth & Maughan, 1983). Therefore, the fitted values of the GLM for depth and flow velocity were normalized to range from 0 to 1. All fitted values of the GLM, e.g. total density, were divided by the maximum estimated value of the GLM. For total density the Preference Factor (PF) was calculated as indicated in equation 1.1.

$$PF_{Density} = \frac{Density_i}{Density_{max}} \qquad [-] \qquad (1.1)$$

With this procedure, preference curves for flow velocity and depth were fitted for the three seasons based on the macroinvertebrate samples, winter (N=56), spring (N=20) and summer (N=19, removal of one outlier). In winter, data from the three Hydropeaking reaches and Residual flow reach could be sampled, preference curves were fitted for the residual flow reach (N=20), the three Hydropeaking reaches (N=36) and for all reaches combined. This was not possible in spring and summer, when only the Residual flow reach was sampled due to high discharge in the other reaches.

Since substrate size classes are factorial, no curve was fitted. Instead the number of individuals, taxa or biomass was normalized by the maximum number per reach. In this way, preference for a certain substrate was not masked and biased by the much lower numbers and biomass in the Hydropeaking reaches. The means per size class were then normalized by the highest mean, to have a preference factor as done for depth and flow velocity.

The values for depth and flow velocity in the Hydropeaking reaches changed during the day with changing discharge. Therefore, it made it more complicated to measure the physical habitat variables. It was assumed that the values at flow peaks are most important as they represent the highest shear stress. For depth, it could be estimated how deep the water was before the power plant was shut down, but for velocity this was not possible, and therefore the measured values at low discharge were taken for the preference curves.

For AFDM-preference curves, a gaussian distribution was assumed and they were not normalized as indicated in equation 1.1. Preference curves were fitted for data from December, February (Hydropeaking Reaches), May and August. As an indication for the

goodness of fit, deviance (D^2-values) was calculated for each preference curve (Macroinvertebrates and AFDM) as indicated in equation 1.2. All statistical procedures were conducted in R (R Development Core Team, 2011).

$$D^2 = \frac{\left(Null\ Deviance - Residual\ Deviance\right)}{Null\ Deviance} \qquad [-] \qquad (1.2)$$

2.4 FUZZY-RULE BASED MODEL

The use of preference curves to model habitat suitability in rivers has the disadvantage that it cannot account for interactions between the different habitat variables (Mouton *et al.*, 2007; Kopecki, 2008). For example, if a small substrate is present at a certain point in the river, a flow velocity of 0.5 m/s will not result in the same conditions than with a larger substrate and the same flow velocity. A second problem is that precise functions describe imprecise habitat requirements (Jorde & Schneider, 2010). This means that the maximal habitat suitability cannot be described by a discrete peak of the preference curve. Instead, ranges of flow velocities, depth or substrate have to be considered. Thirdly, total suitability, also known as Joint Preference Factor, is dependent on how the three suitability values are integrated (product, arithmetic mean, geometric mean). Each method leads to different predictions. For that reason, a fuzzy-rule based model was derived as developed by Schneider (2001). Fuzzy Models are based on Fuzzy Logic which represents an extension to normal set theory and was first introduced by Zadeh (1965).

In contrast to classical set theory with crisp sets, where a value can only belong or not belong to a set, in fuzzy set theory it can partly belong to one fuzzy set and partly to others, with its membership degree between 0 and 1 (Adriaenssens *et al.*, 2004). Fuzzy sets were defined for the values assigned to the three habitat variables at the community ecology level (total biomass, total density and taxon richness) and for the different taxa. For the output variable "Habitat Suitability Index" default fuzzy sets were adopted from CASiMiR software. Fuzzy sets for the habitat variables were always selected the way

they represent preference curves best. For that reason fuzzy sets differed between seasons and also between community measures and taxa. Fuzzy sets are described by their membership function, which indicates the degree of membership of a value to a set. The membership functions for the fuzzy sets for community measures and for selected taxa in winter are listed in Table 1 and for spring and summer in Appendix A2. All membership functions had a trapezoidal or triangular shape and were described by the parameters p_1, p_2, p_3 (and p_4). The membership increases from 0 to 1 between p_1 and p_2, stays 1 between p_2 and p_3 and decreases from 1 to 0 between p_3 and p_4. For triangular shaped functions, membership increases from 0 to 1 between p_1 and p_2, p_2 equals 1, and decreases from 1 to 0 between p_2 and p_3. The fuzzy sets are then named, using linguistic expressions like Very Low, Low, Medium, High or Very High for the three habitat variables (Table 1).

TABLE 1: Physical habitat variables and the fuzzy sets assigned to the values for the fuzzy models for community ecology and for the 4 selected taxa.

Variable	Set Name	Community Parameters p_1, p_2, p_3, (p_4)	Taxon Parameters p_1, p_2, p_3, (p_4)
Depth (m)	Very Low	(0, 0, 0, 0)	(0, 0, 0, 0)
	Low	(0, 0, 0.1)	(0, 0, 0.1)
	Medium	(0, 0.1, 0.4, 0.6)	(0, 0.1, 0.4, 0.6)
	High	(0.4, 0.6, 1, 1.2)	(0.4, 0.6, 1, 1.2)
	Very High	(1, 1.2, 100, 100)	(1, 1.2, 100, 100)
Flow velocity (m/s)	Very Low	(0, 0, 0, 0.1)	(0, 0, 0, 0.1)
	Low	(0, 0.1, 0.3, 0.4)	(0, 0.1, 0.4, 0.5)
	Medium	(0.3, 0.4, 0.7, 0.9)	(0.4, 0.5, 0.8, 0.9)
	High	(0.7, 0.9, 1.4, 1.6)	(0.8, 0.9, 1.4, 1.6)
	Very High	(1.4, 1.6, 100, 100)	(1.4, 1.6, 100, 100)
Dominant Substrate	Low	(0, 0, 3, 4)	(0, 0, 3, 4)
	Medium	(3, 4, 8, 9)	(3, 4, 8, 9)
	Very Low	(8, 9, 100, 100)	(8, 9, 100, 100)

Fuzzy rules combine the abiotic habitat variables with habitat suitability. However, instead of using mathematical expressions, fuzzy-rule based models use linguistic expressions. Fuzzy rules are IF-THEN rules. For example, IF depth is HIGH and flow velocity is HIGH and substrate is MEDIUM, THEN Habitat Suitability is LOW. The IF-part or the antecedent part of each rule describes the conditions, whereas the THEN-part describes the consequence. For each combination of the three variables, a rule with the habitat suitability is defined. For depth and flow velocity with 5 sets and substrate with 3 sets, 75 rules were defined for all community ecology parameters and for the selected taxa.

The ranges of the fuzzy sets that belong 100% to a set were labeled on the preference curves (Fig. 2). Each set was coded with 2 = suitable, 1 = useable or 0 = unsuitable. An exception was substrate. It was coded to be suitable = 1 or unsuitable = 0. Preference factors greater than 0.7 were coded 2, between 0.3 and 0.7 coded 1 and below 0.3 were coded with 0, as indicated in Figure 2 for flow velocity.
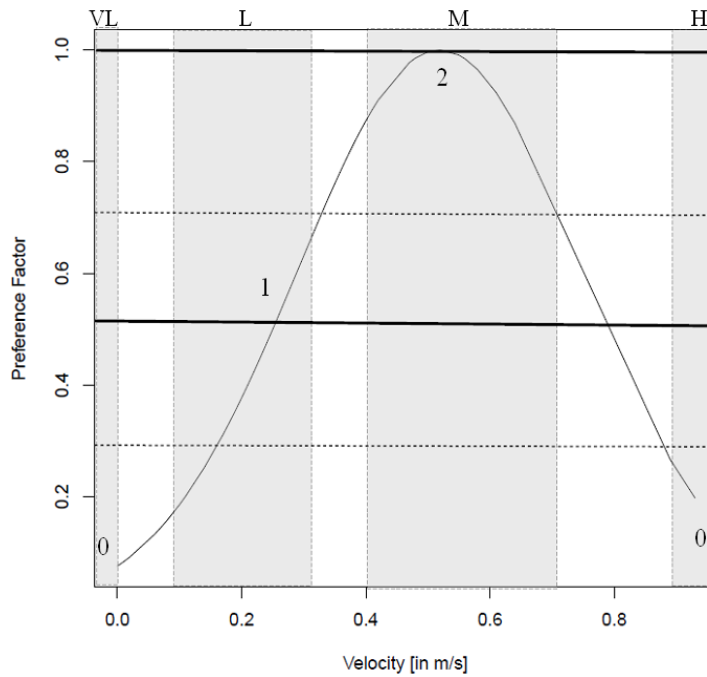

FIG. 2: Coding of the Preference Curves for flow velocity. 0=unsuitable; 1=useable and 2=suitable. VL=Very Low, L=Low, M=Medium and H=High (VH=Very High, is not on the graph).

This procedure has been done for depth, flow velocity and substrate. Additionally, literature was used to support the coding as suitable, useable or unsuitable, e.g. Orth & Maughan (1983), Jowett &Richardson (1990) or Gore *et al.* (2001) especially for substrate. The overall habitat suitability was calculated according to Neary (2006) and Eberstaller *et al.* (2012a) as the product of the three suitability codes (Tab. 2). Multiplication of the three codes allows eliminating combinations that are not suitable (Neary, 2006). If, for instance, depth was 2 and substrate was 1, but the flow velocity was too high (=0), the product is 0 and the overall habitat suitability is low. In this way, habitat suitabilities were calculated for all fuzzy rules. Table 2 lists the possible combinations of the codes with positive results. A 4 was the maximal result and was considered "Very High", 2 was considered "High", and 1 was considered "Medium". All combinations with product 0 were considered "Low".

TABLE 2: Possible combinations of habitat suitability codes for macroinvertebrates.

Depth	Flow Velocity	Substrate	Product	Habitat Suitability
2	2	1	4	**Very High**
2	1	1	2	**High**
1	2	1	2	**High**
1	1	1	1	**Medium**

Table 3 summarizes all the suitability codes of the seven fuzzy models for community metrics and selected taxa in the winter season. Suitability codes for spring and summer are listed in Appendix A3. No fuzzy model was made for Taxon Richness in summer due to no observable trend in the preference curves, therefore a fuzzy model for very frequent Simulidae was made. Preference curves which were similar to each other received the same habitat suitability codes as *Rhabdiopteryx* sp. and *Baetis* sp. in winter (Tab. 3) or total biomass and total density in spring and summer (Appendix A3).

TABLE 3: Suitability Index (SI) Codes of the Fuzzy sets for the three habitat variables for the winter models. VL=Very Low; L=Low; M=Medium; H=High; VH=Very High

Habitat Variable	Set	SI Code Total Biomass	SI Code Total Density	SI Code Taxon Richness	SI Code *Drusus* sp.	SI Code *Rhabdiopteryx* sp.	SI Code *Baetis* sp.	SI Code *Rhitrogena* sp.
Depth	VL	0	0	0	0	0	0	0
	L	1	1	1	2	1	1	1
	M	2	2	2	1	2	2	2
	H	0	0	1	0	1	1	1
	VH	0	0	0	0	0	0	0
Velocity	VL	0	0	0	0	0	0	0
	L	1	1	1	2	1	1	2
	M	2	2	2	1	2	2	0
	H	0	0	0	0	0	0	0
	VH	0	0	0	0	0	0	0
Substrate	L	0	0	0	0	0	0	0
	M	1	1	1	1	1	1	1
	VL	0	0	0	0	0	0	0

2.5 MODELING IN CASiMiR

CASiMiR simulations were conducted for the three Hydropeaking reaches described above. Based on hydrological data from the gauging station in Brienzwiler (BE) for the years 1913-1921 prior to dam construction and 2009 -2012, a statistical analysis was conducted to find out what the most frequent discharge was in each season (see Appendix A4) and monthly Pardé-Coefficients (Pardé, 1933) were calculated for both periods (Appendix A5). It turned out that more than 50% of the discharges for the winters 2010-2012 (December-March) were between 15 m^3/s and 20 m^3/s and that extreme low (3-4 m^3/s) and extreme high discharges (> 40 m^3/s) occurred only rarely and on average not longer than two hours. Because of those findings, the following four discharges were selected: 4 m^3/s as an extreme minimum which corresponds to baseflow, 15 m^3/s and 30 m^3/s as range with most frequent discharges and with 95% of the discharges being less

than 30 m³/s, and 55 m³/s as an extreme hydropeak. For springs 2009-2011 (April-June), higher discharges were chosen due to starting snowmelt and higher baseflows: 15 m³/s as baseflow, 20 m³/s and 60 m³/s as range with 90% of the discharges, and 80 m³/s as a peak, which occurs only rarely. For summers 2009-2011 (June-September), the following discharges were chosen: 30 m³/s as baseflow, 40 m³/s and 80 m³/s as the range with 86% of the discharges, and 100 m³/s as a maximum peak. The selected discharges were used to simulate habitat suitabilities in CASiMiR (Jorde, 1997; Schneider, 2001) with the fuzzy models, developed for the community parameters and selected taxa for the three seasons (winter, spring and summer). CASiMiR 2D Fish Module was applied to generate habitat maps. For each model, the Weighted Useable Area (WUA) (Bovee, 1982) and the Hydraulic Habitat Suitability Index (HHS) (Jorde, 1997) were calculated for each river reach (see also Kopecki, 2008):

$$WUA = \sum_{i=1}^{N} A_i \cdot HSI_i \qquad [m^2] \qquad (1.3)$$

$$HHS = \frac{WUA}{\sum\limits_{i=1}^{N} A_i} \qquad [-] \qquad (1.4)$$

with: A_i: area of single cell i

HSI_i: Habitat Suitability Index of cell i

N: Total number of cells in a reach

Weighted Useable Area (equation 1.3) is the area weighted summation of habitat suitability per cell and integrates habitat quality over the investigated area at a certain discharge. The Hydraulic Habitat Suitability Index (equation 1.4) is the WUA divided by the inundated area and ranges from 0 to 1. It indicates if habitat availability changes due to changes in depth or flow velocity leading to an altered WUA or if habitat availability changes due to changed inundated area. Both values are calculated as a function of discharge for the three Hydropeaking reaches. Habitats with best quality show HHS values against 1 and habitats with very low quality result in HHS approaching to 0 (Kerle *et al.*, 2002).

3. RESULTS

3.1 PREFERNCE CURVES

The preference curves for the community measures in winter are presented in Figure 3. The D^2-values ranged for depth from 0.50 to 0.80 and for velocity from 0.14 to 0.20. Substrate classes c2, c3, c4 and c8 were found only once. Wilcox test revealed no significant difference between the different size classes for total biomass, total density and taxon richness (p> 0.05) despite the trend of higher preference in larger substrate. In Figure 4, the preference curves for the four selected taxa *Drusus* sp., *Rhabdiopteryx* sp., *Baetis* sp. and *Rhitrogena* sp. in winter are shown for the Residual flow reach, Hydropeaking Reaches and both combined (Total). The D^2-values for the Total curves ranged for depth from 0.56 to 0.76 and for velocity from 0.045 to 0.19. Preferences for substrate size of the four taxa are shown in Appendix B1. The four taxa show also higher preference in larger substrates but Wilcox test revealed no significant difference between the different size classes either (p> 0.05).

Preference curves of the spring sampling showed similar preferences for flow velocities at around 0.5 m/s but different depth preferences. Macroinvertebrates seemed to prefer shallower parts of the river. D^2-values for depth for the community measures ranged from 0.16 to 0.40 and for flow velocity from 0.15 to 0.22 (Fig. 5). D^2-values for depth for the three considered taxa ranged from 0.26 to 0.49 and for flow velocity from 0.08 to 0.24 (Fig.6). Preferences for substrate size are presented in Appendix B2. No significant difference in substrate preference was found applying Wilcox test for either the community measures or for the three selected taxa (p>0.05).

The preference curves for the community measures and taxa in summer showed similar flow velocity patterns than in winter and spring but an increasing preference for deeper habitats compared to spring (Figs. 7, 8). The D^2-values of the community measures ranged for depth from 0.11 to 0.27 and for velocity from 0.04 to 0.25. Wilcox test revealed no significant difference between the different size classes for total biomass, total density and taxon richness (p> 0.05) but showed a clear trend towards larger substrate sizes. The D^2-values for the four selected taxa *Rhabdiopteryx* sp., *Baetis* sp.

Rhitrogena sp. and Simulidae ranged for depth from 0.08 to 0.21 and for velocity from 0.16 to 0.49. Preferences for substrate size of the four taxa are shown in Appendix B3. Wilcox test revealed no significant difference between the different size classes for the four taxa ($p>0.05$) but also showed a trend of higher preferences in larger substrates.

Deviance values for AFDM preference curves (December, February and August) ranged for depth from 0.009 to 0.07 and for flow velocity from 0.007 to 0.019. These curves showed no clear pattern either (Fig. 9). The preference curves from May revealed better values with 0.19 for depth and 0.14 for velocity and showed a slight preference for medium range velocities between 0.4-0.7 m/s. Significant seasonal differences in AFDM between the seasons from December 2011-August 2012 were found (Wilcox Test , $p<0.02$).

3.2 HABITAT SUITABILITY SIMULATIONS IN CASiMiR

Figures 10-12 show the habitat suitability maps in winter for the community measures and for the four selected taxa. All, except *Drusus* sp. and *Rhitrogena* sp., show relatively good habitat suitabilities at baseflow ($4m^3$/s), also in the middle of the channel. At $15m^3$/s, which is among the most frequent discharges, the middle channel provides low habitat suitabilities in all three reaches. The gravel bar still had relatively good habitats at this flow. The middle channel already has flow velocities of 1.2 m/s at a discharge of $15m^3$/s. With increasing discharge, good habitats move to the river margins, where flow velocities and depths are still lower but fall dry at low discharges. WUA and HHS curves (Fig. 13) show similar patterns to the habitat suitability maps. Many areas with good habitats at 4 m^3/s had a fast decrease of good habitats at around 10 m^3/s. Groyne reach seems to be the worst of the three sites modeled, but becomes better with increasing discharge. Gravel bar reach shows a more resilient pattern with more areas of good habitats around $15m^3$/s.

As community metrics and taxa seem to prefer shallow parts in spring, this is also reflected in the habitat suitability simulations. At higher discharges, as shown in Figures 14-16, only a few areas remain with suitable habitats. Again, the Gravel bar reach provides most areas with suitable conditions but has only marginally useable areas at

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discharges higher than 30m^3/s. In contrast to the winter situation, lower WUA's have been found in spring, except for *Rhitrogena* sp. which showed higher WUA's in spring (Fig. 14).

In summer, WUA's and HHS are higher than in spring due to preference for deeper habitats of different taxa, except for *Rhabdiopterxy* sp. which prefered shallow habitats like in spring (Fig. 21). In Groyne reach, suitable habitats can be found only behind the groynes for the community metrics and for the selected taxa (Fig. 18). Channel reach provides only in the blocks at the margins some few good habitats (Fig. 20). Gravel bar reach performs also best in summer, providing areas with good or useable conditions on the gravel bar (Fig. 19). This is also reflected in the WUA/HHS curves with a second peak at discharges around 20 m^3/s (Fig. 21). However, in the range of most frequent discharges in summer between 40 and 80 m^3/s, again only few good habitats for all three reaches can be found.

3.3 BODY LENGTH MEASUREMENTS

Patterns of body length of the three species found in all three seasons could be detected. *Baetis* sp. had an average body length of 4.2mm ± 0.2 in winter, 7.4mm ± 0.3 in spring and 4.4mm ± 0.4 in summer. *Rhabdiopteryx* sp. showed a different pattern with an average body length of 2.6mm ± 0.2 in winter, 4.3mm ± 0.9 in spring and 5.0mm ± 0.2 in summer. *Rhitrogena* sp. had an average body length of 5.3mm ± 0.5 in winter, 9.1mm ± 0.7 in spring and 3.2mm ± 0.4 in summer and showed the same pattern than *Baetis* sp. (see also Appendix B4). Wilcox test revealed significant differences between body length of *Baetis* sp. in winter and spring and spring and summer (p<0.001), body length of *Rhabdiopteryx* sp. in winter and summer (p<0.001). Body length of *Rhitrogena* sp. differed significantly between all three seasons (p<0.0101).
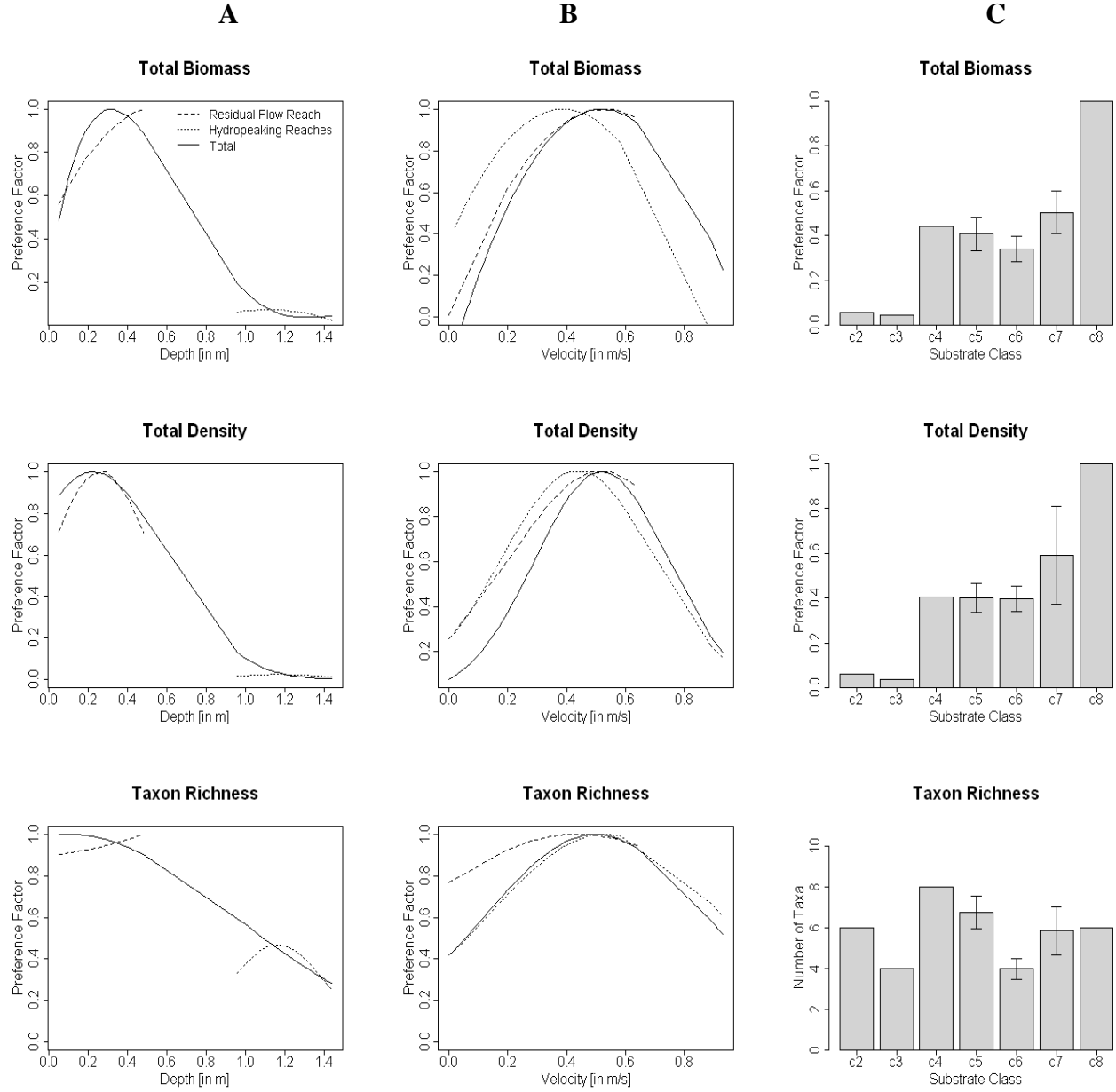
A

B

C

FIG. 3: Preference curves for Total Density, Total Biomass and Taxon Richness (Number of Taxa) for the three physical habitat variables depth (A), velocity (B) and substrate (C) in winter. Data from the Residual flow reach (N=20) and from the three Hydropeaking reaches (N=36). Solid lines represent curves for total data, dashed lines Residual flow reach and dotted lines Hydropeaking reaches.
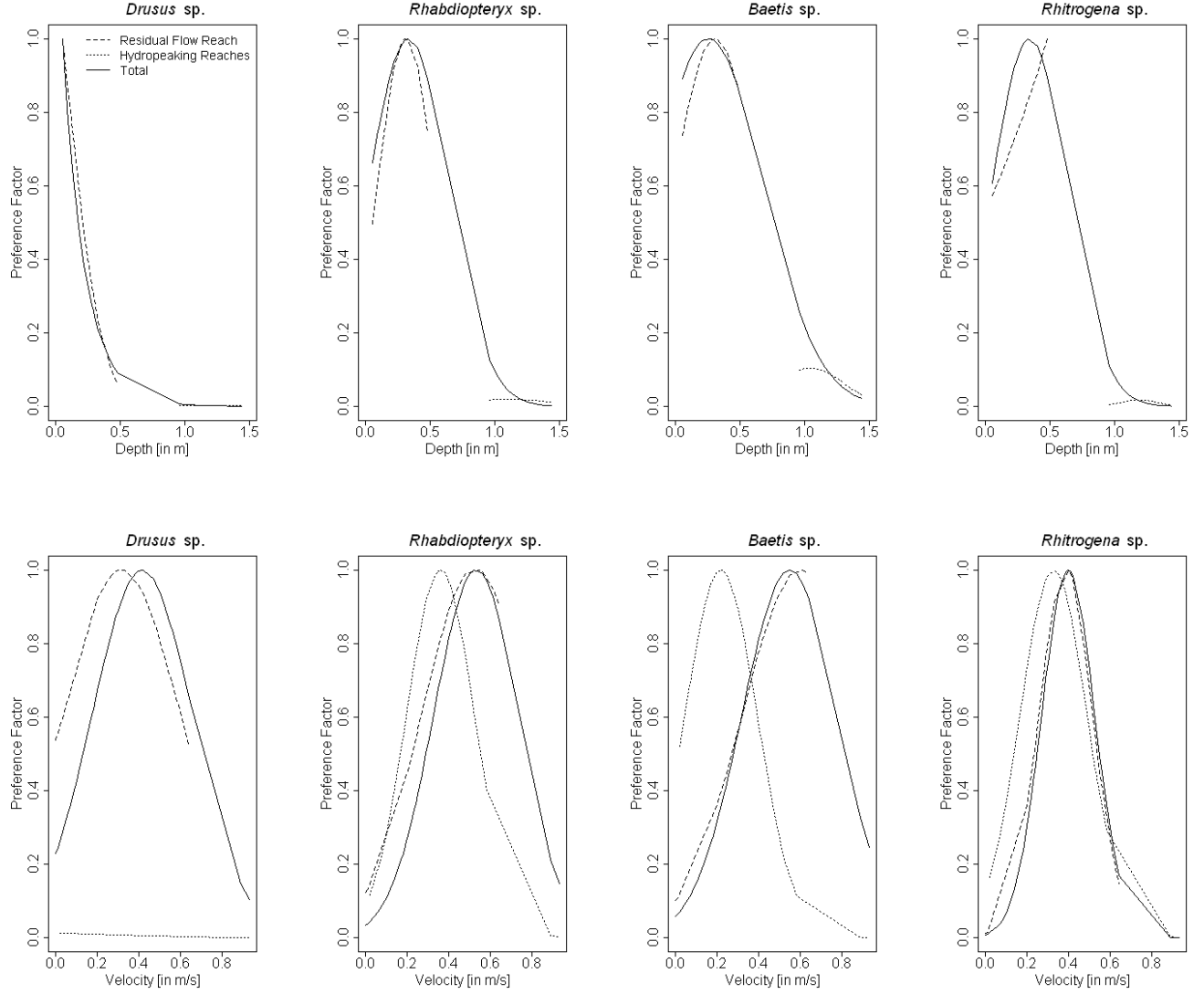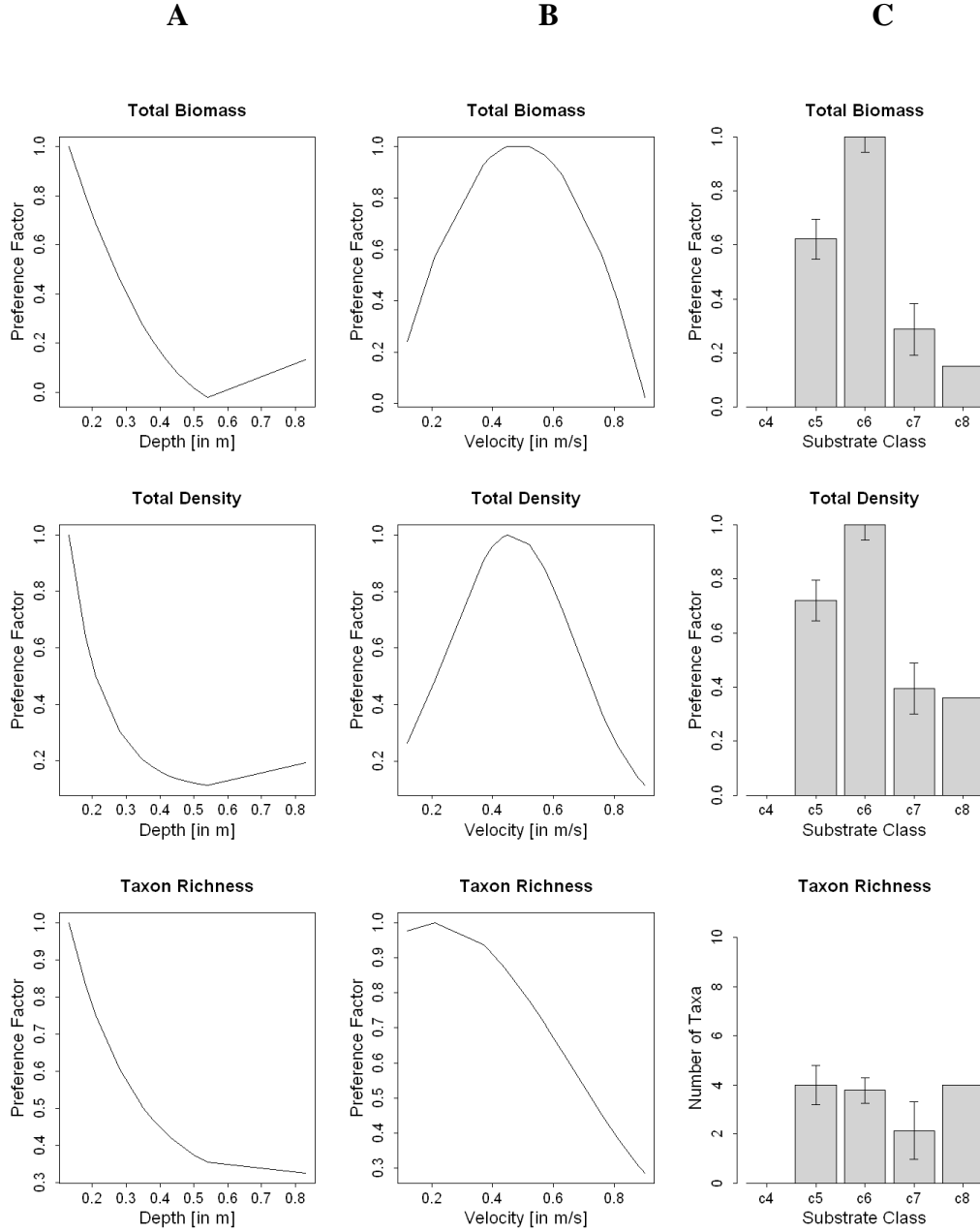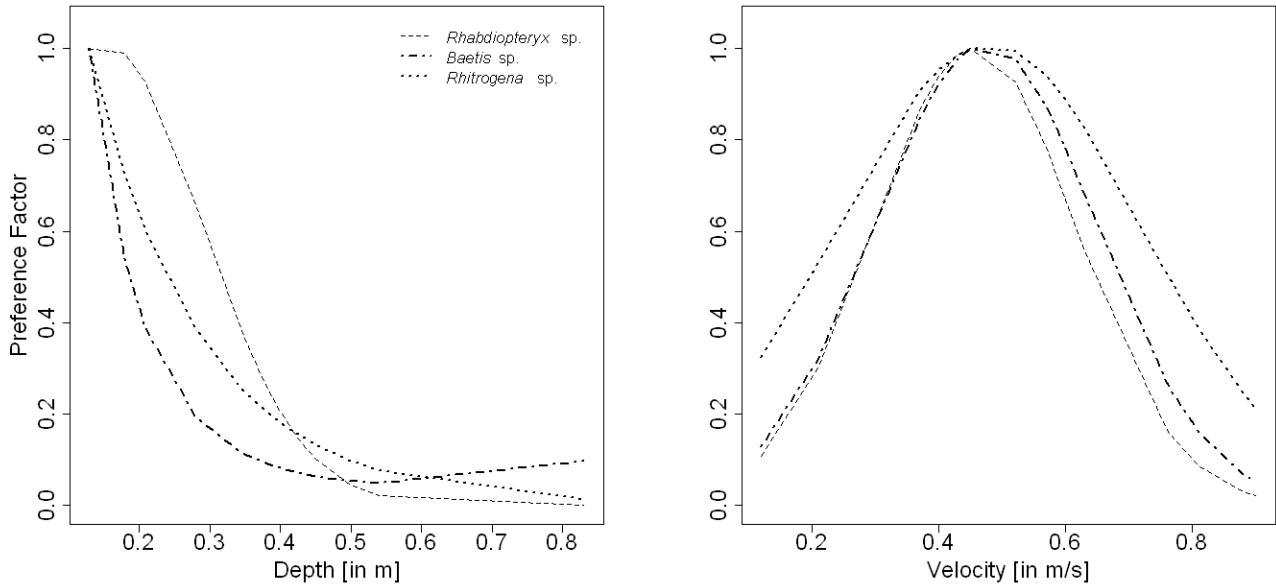
FIG. 4: Preference curves for four selected taxa in winter: *Drusus* sp., *Rhabdiopteryx* sp., *Baetis* sp. and *Rhitrogena* sp. Data from the Residual flow reach (N=20) and the three Hydropeaking reaches (N=36). Solid lines represent curves for total data, dashed lines Residual flow reach and dotted lines Hydropeaking reaches.

FIG. 5: Preference curves for Total Density, Total Biomass and Taxon Richness (Number of Taxa) for the three physical habitat variables depth (A), velocity (B) and substrate (C) for spring. Data only from the Residual flow reach (N=20).

FIG. 6: Preference curves for three selected taxa in spring: *Rhabdiopteryx* sp., *Baetis* sp. and *Rhitrogena* sp. (without *Drusus* sp.). Left side for the habitat variable depth and right side for velocity. Data only from the Residual flow reach (N=20).
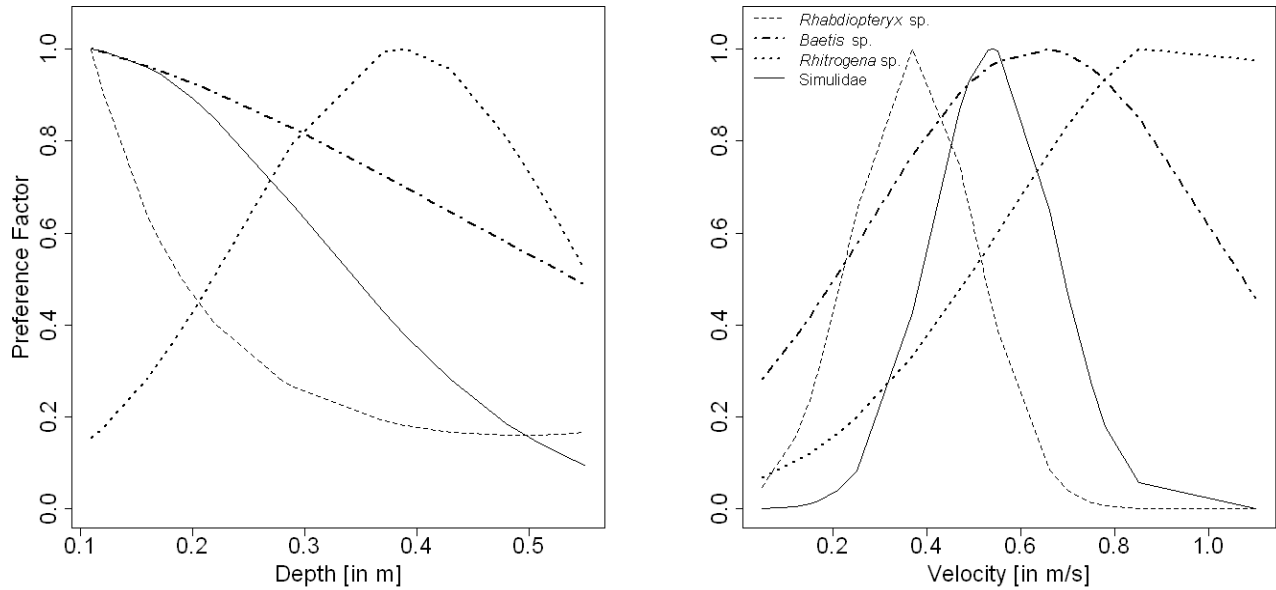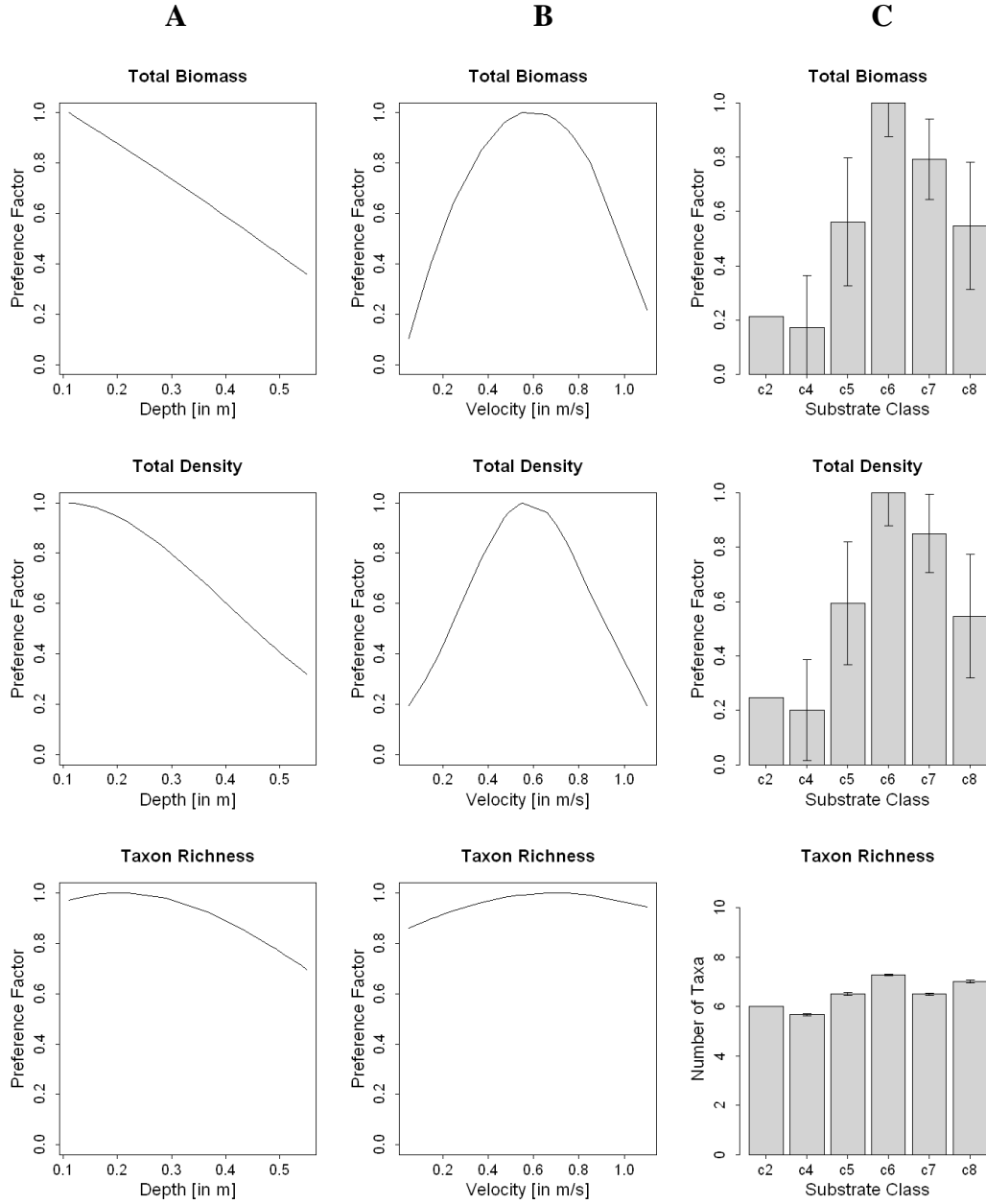

FIG. 7: Preference curves for the four selected taxa in summer: *Rhabdiopteryx* sp., *Baetis* sp., *Rhitrogena* sp. and Simulidae (without *Drusus* sp.). Left side for the habitat variable depth and right side for velocity. Data only from the Residual flow reach (N=19).

A   **B**   **C**

FIG.8: Preference curves for Total Density, Total Biomass and Taxon Richness (Number of Taxa) for the three physical habitat variables depth (A), velocity (B) and substrate (C) for summer. Data only from the Residual flow reach (N=19).
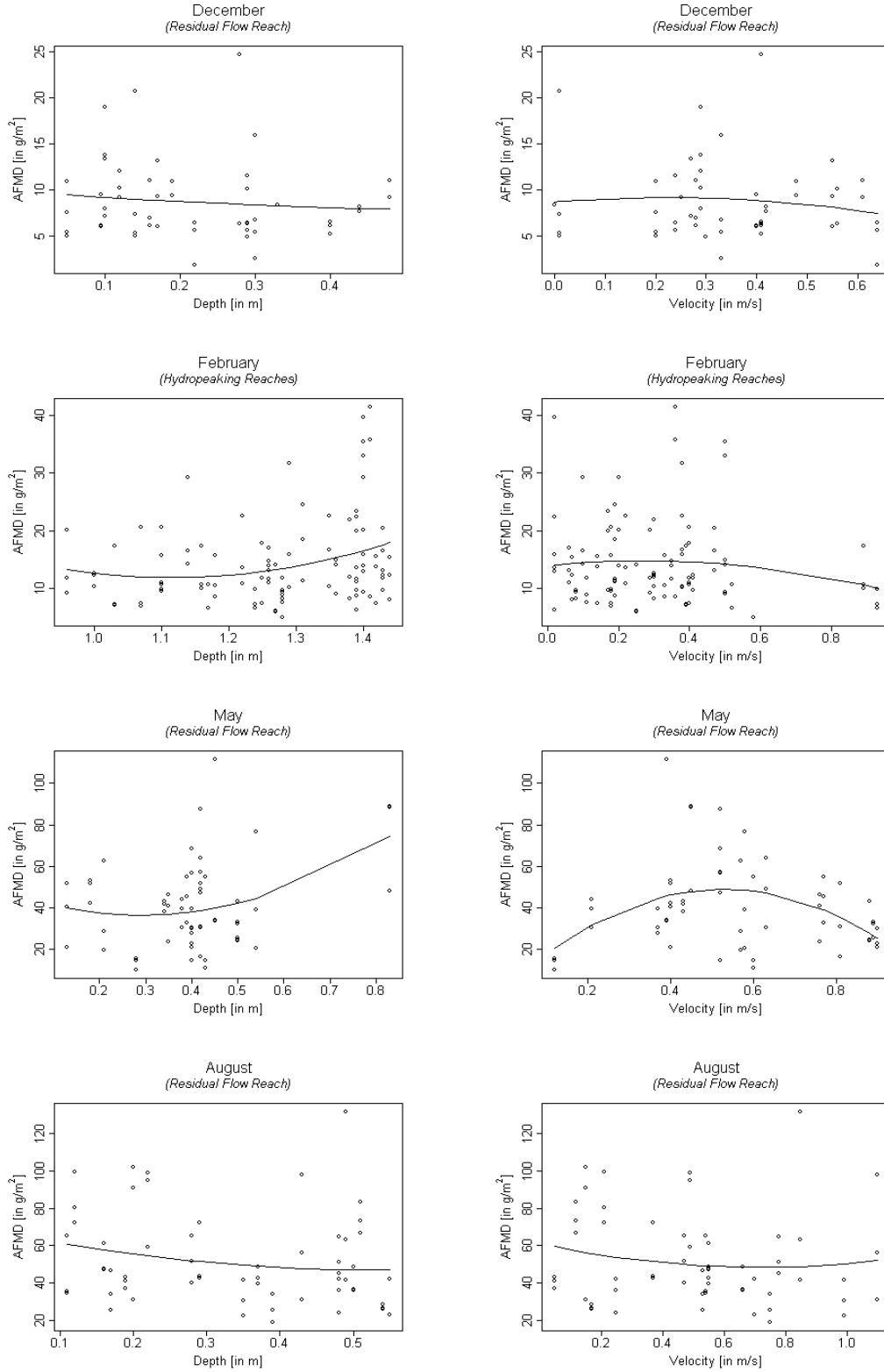
FIG 9: Preference curves for AFDM for December (N=50), February (N=103), May (N=60) and August (N=59). Note that in February, only data from the three Hydropeaking reaches was sampled and in December, May and August only from the Residual flow reach.
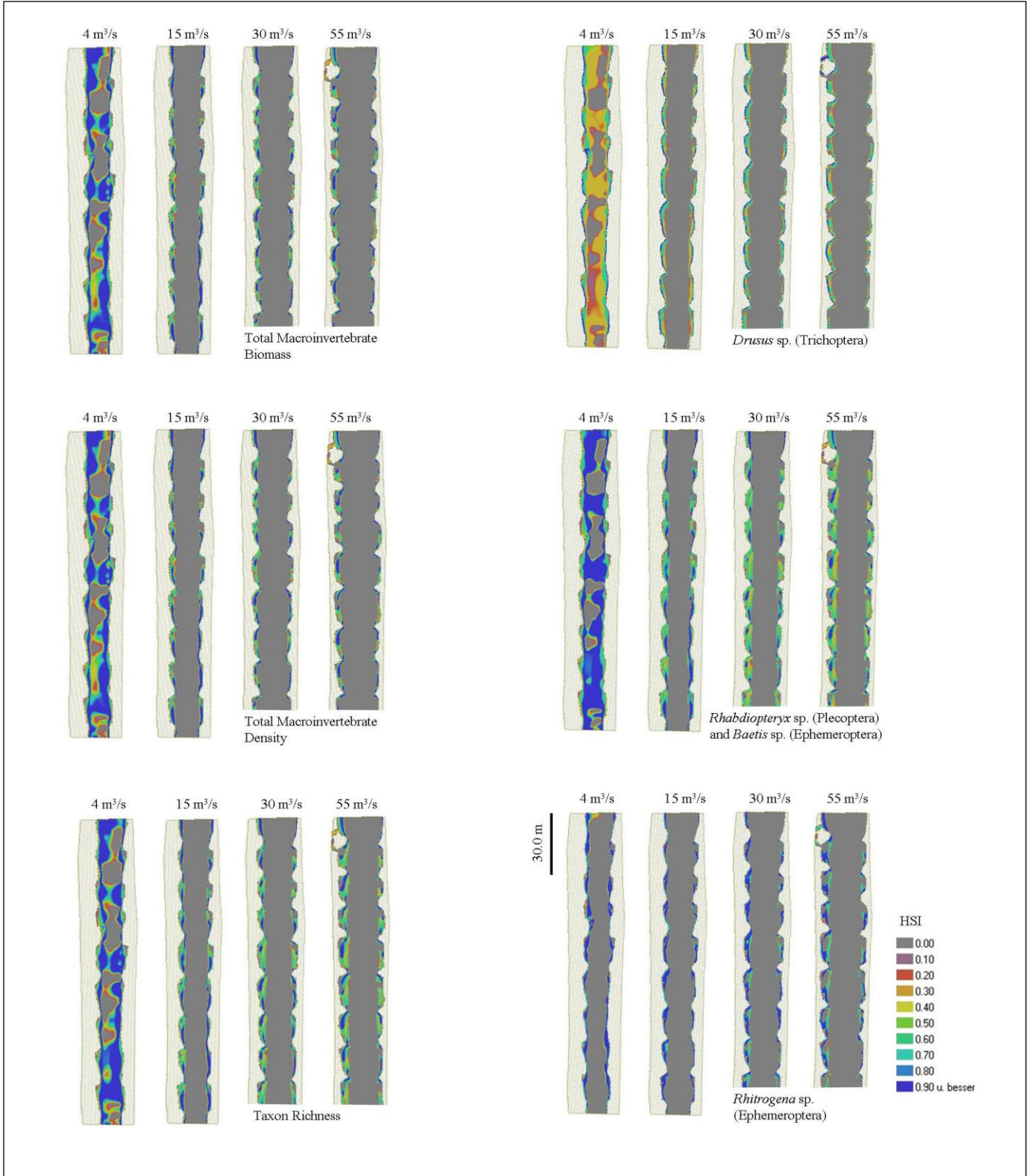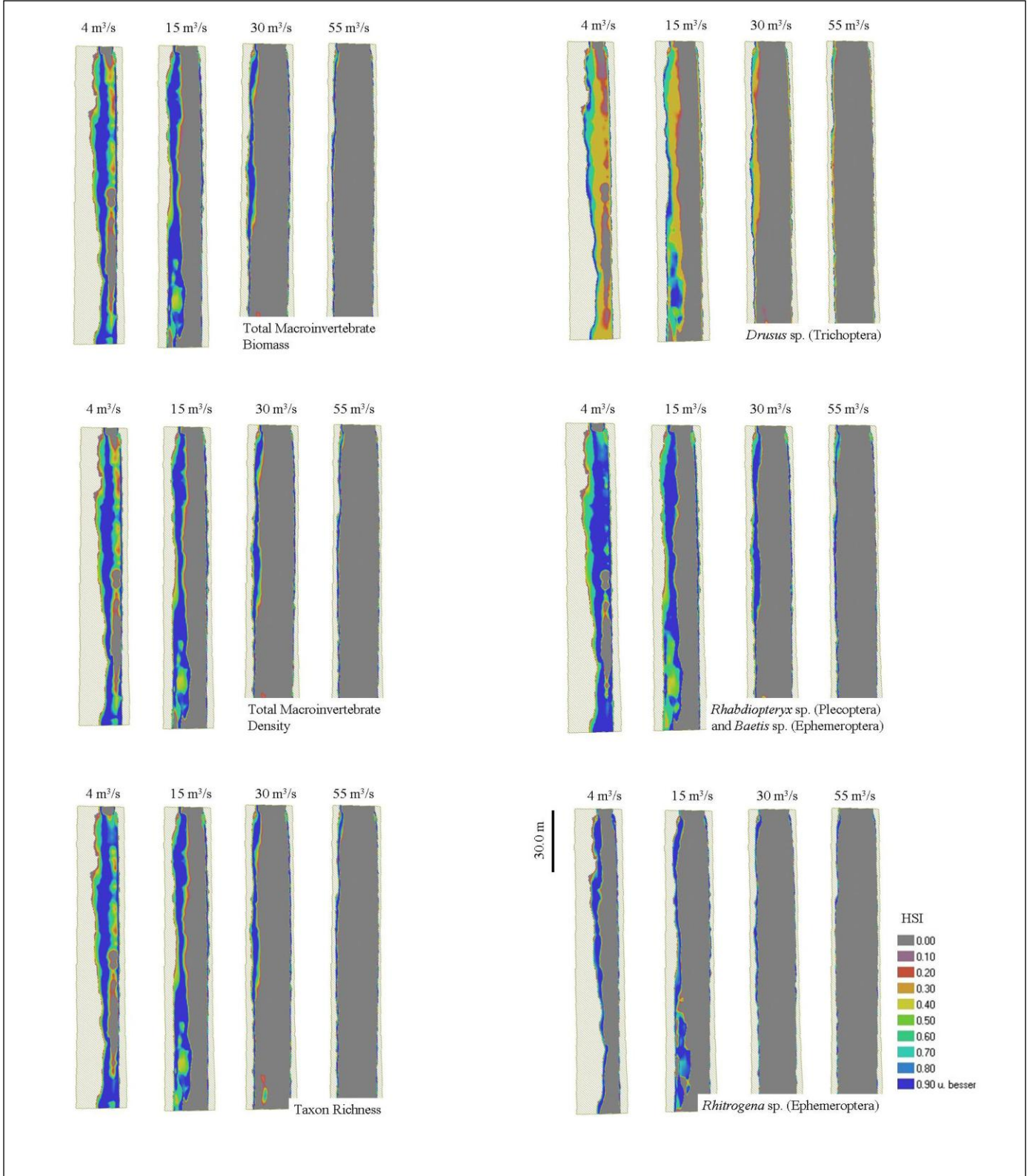
Fɪɢ. 10: CASiMiR output for the four different discharges 4 m³/s (lowest discharge), 15 m³/s, 30 m³/s and 55 m³/s (extreme peak) for Groyne reach in winter. Note: *Rhabdiopteryx* sp. and *Baetis* sp. have the same fuzzy rules due to very similar preference curves.

F<small>IG</small>. 11: CASiMiR output for the four different discharges 4 m³/s (lowest discharge), 15 m³/s, 30 m³/s and 55 m³/s (extreme peak) for Gravel bar reach in winter. Note: *Rhabdiopteryx* sp. and *Baetis* sp. have the same fuzzy rules due to very similar preference curves.
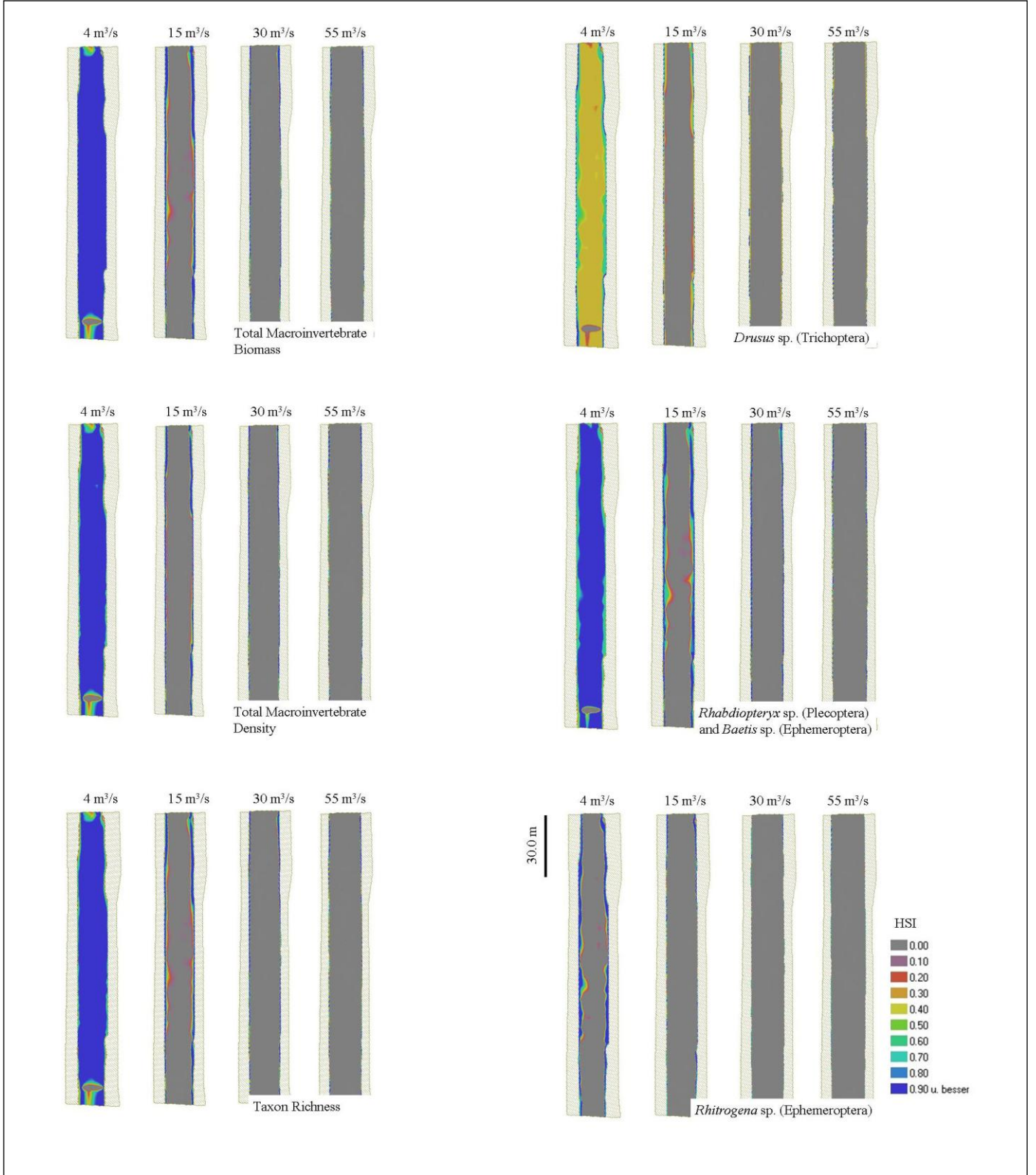
FIG. 12: CASiMiR output for the four different discharges 4 m³/s (lowest discharge), 15 m³/s, 30 m³/s and 55 m³/s (extreme peak) for Channel reach in winter. Note: *Rhabdiopteryx* sp. and *Baetis* sp. have the same fuzzy rules due to very similar preference curves.
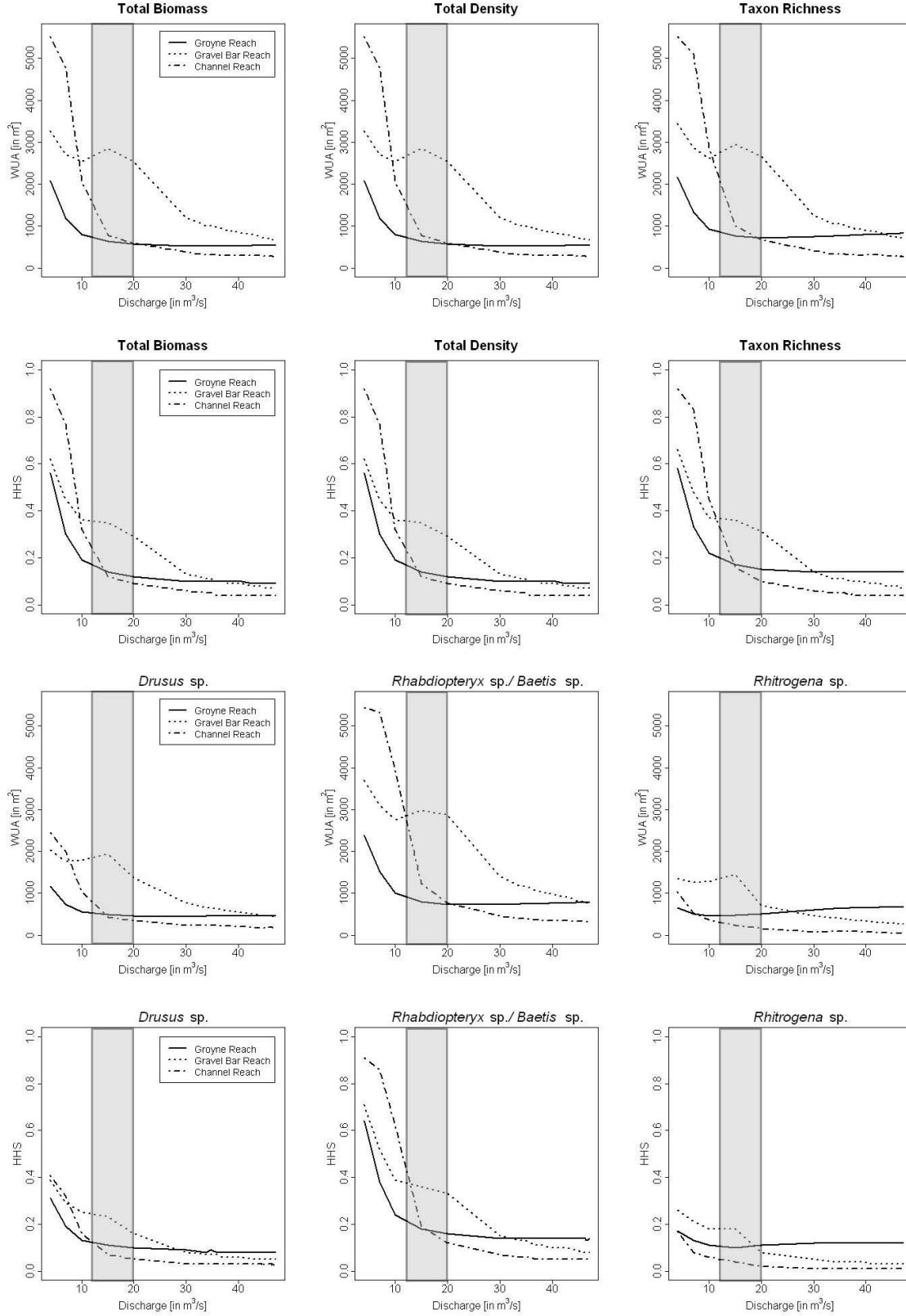
FIG.13: Weighted Useable Area (WUA) and Hydraulic Habitat Suitability Index (HHS) for the three reaches for all winter models. The range with the most frequent discharges is shaded in grey.
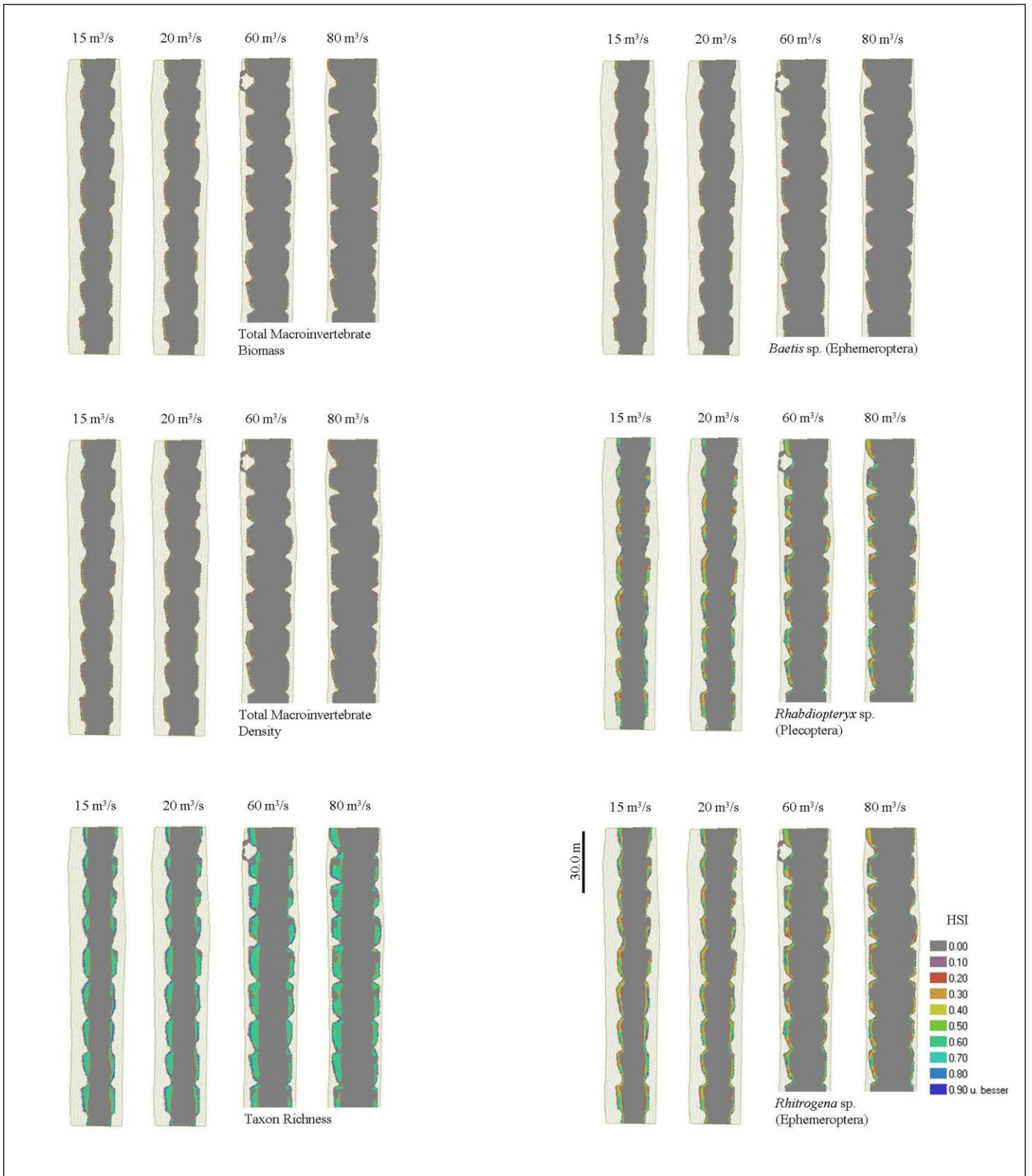
FIG. 14: CASiMiR output for the four different discharges 15 m³/s (lowest discharge), 20 m³/s, 60 m³/s and 80 m³/s (extreme peak) for Groyne reach in spring.
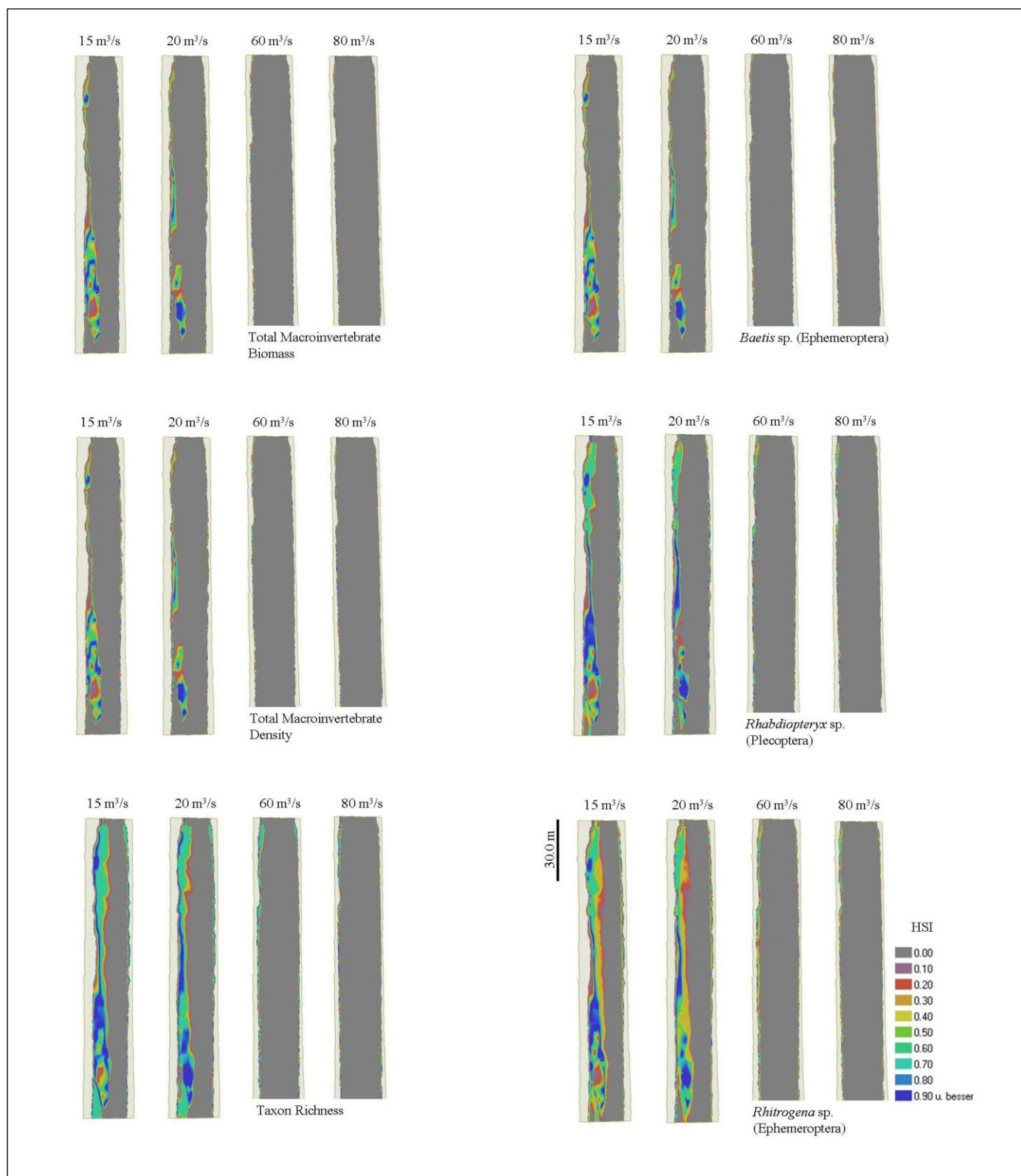
FIG. 15: CASiMiR output for the four different discharges 15 m³/s (lowest discharge), 20 m³/s, 60 m³/s and 80 m³/s (extreme peak) for Gravel bar reach in spring.
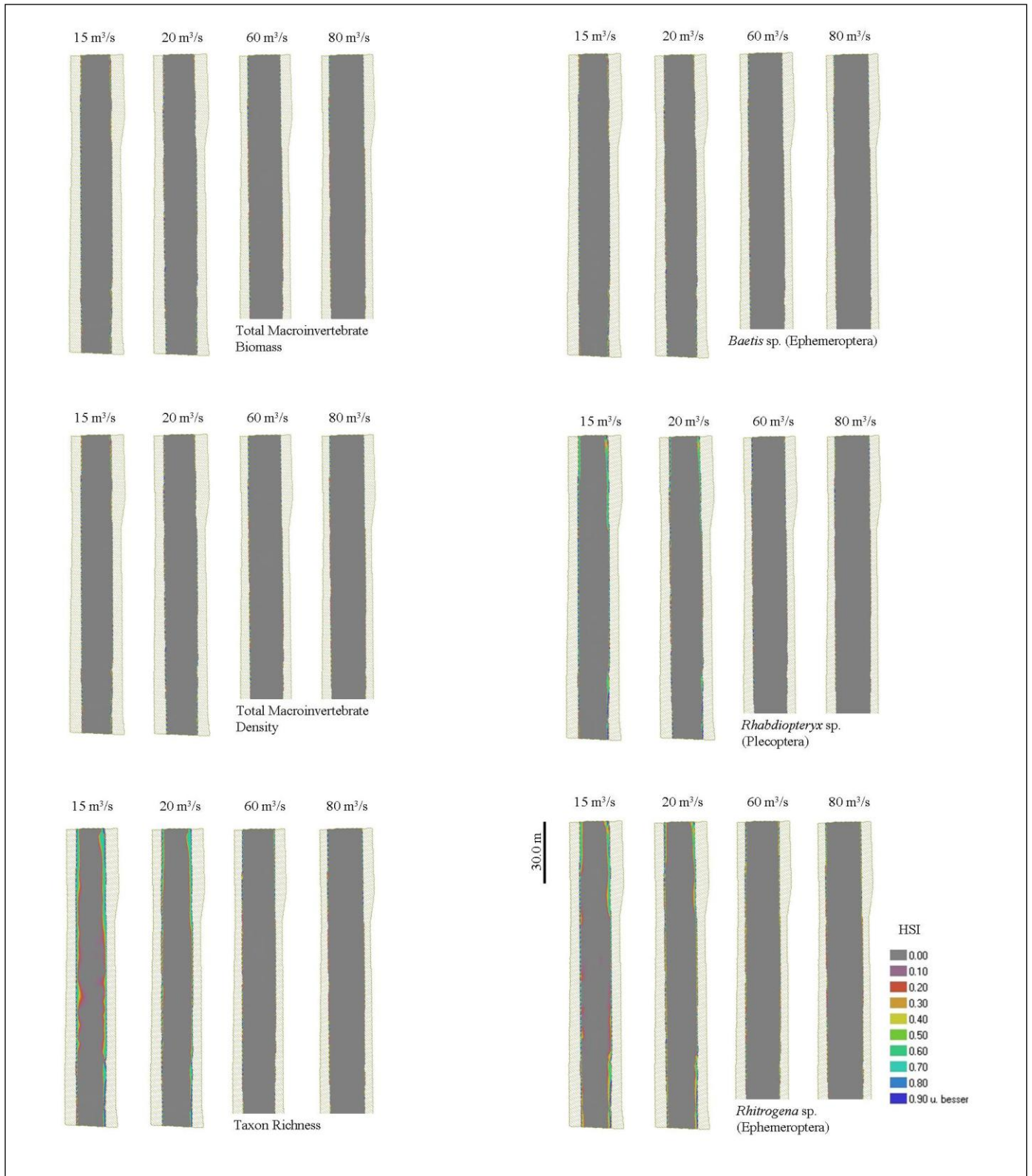
FIG. 16: CASiMiR output for the four different discharges 15 m³/s (lowest discharge), 20 m³/s, 60 m³/s and 80 m³/s (extreme peak) for Channel reach in spring.

FIG.17: Weighted Useable Area (WUA) and Hydraulic Habitat Suitability Index (HHS) for the three reaches for all spring models. The range with the most frequent discharges is shaded in grey.
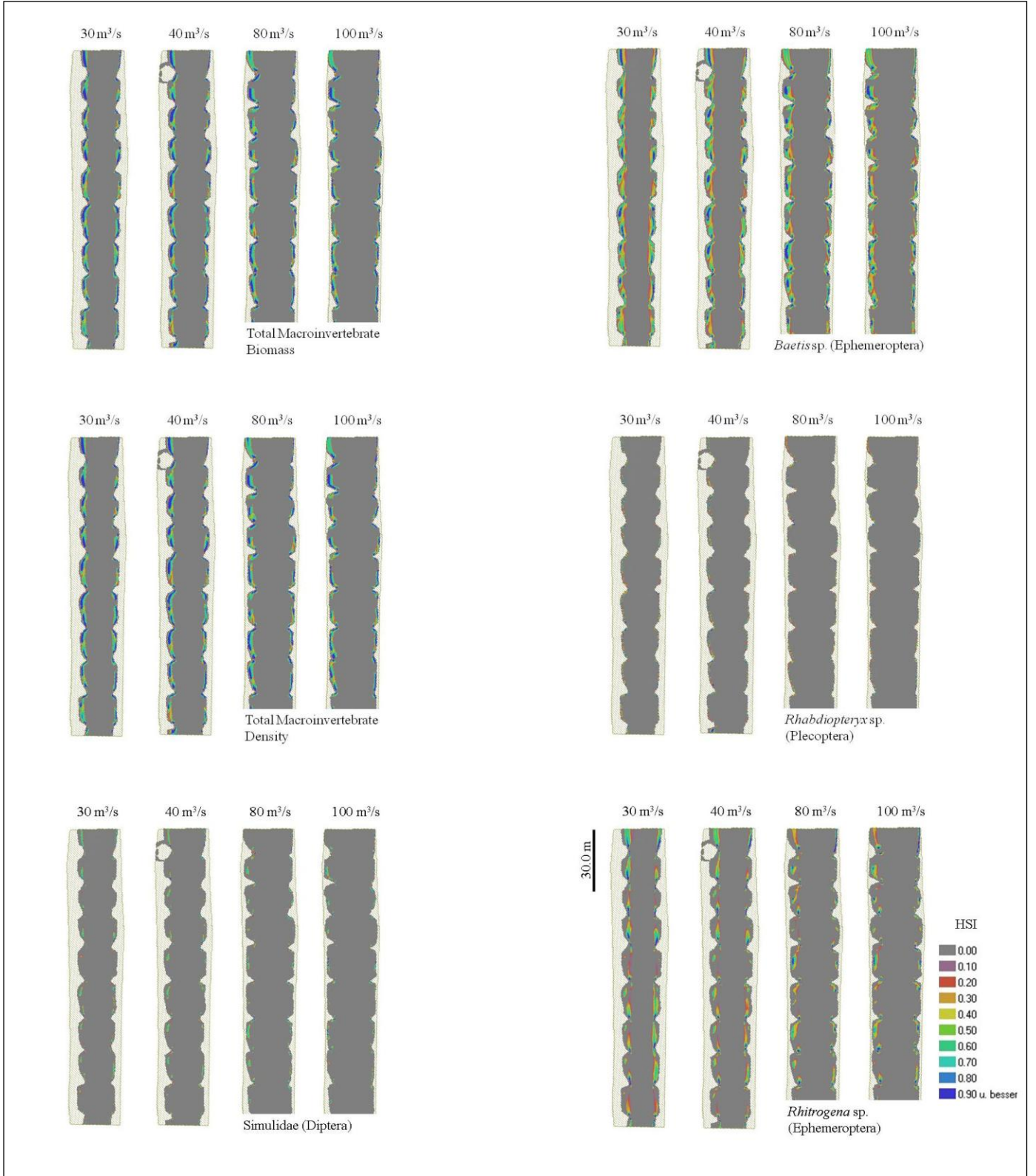
FIG. 18: CASiMiR output output for the four different discharges 30 m^3/s (lowest discharge), 40 m^3/s, 80 m^3/s and 100 m^3/s (extreme peak) for Groyne reach in summer.

FIG. 19: CASiMiR output output for the four different discharges 30 m³/s (lowest discharge), 40 m³/s, 80 m³/s and 100 m³/s (extreme peak) for Gravel bar reach in summer.

FIG. 20: CASiMiR output output for the four different discharges 30 m^3/s (lowest discharge), 40 m^3/s, 80 m^3/s and 100 m^3/s (extreme peak) for Channel reach in summer.
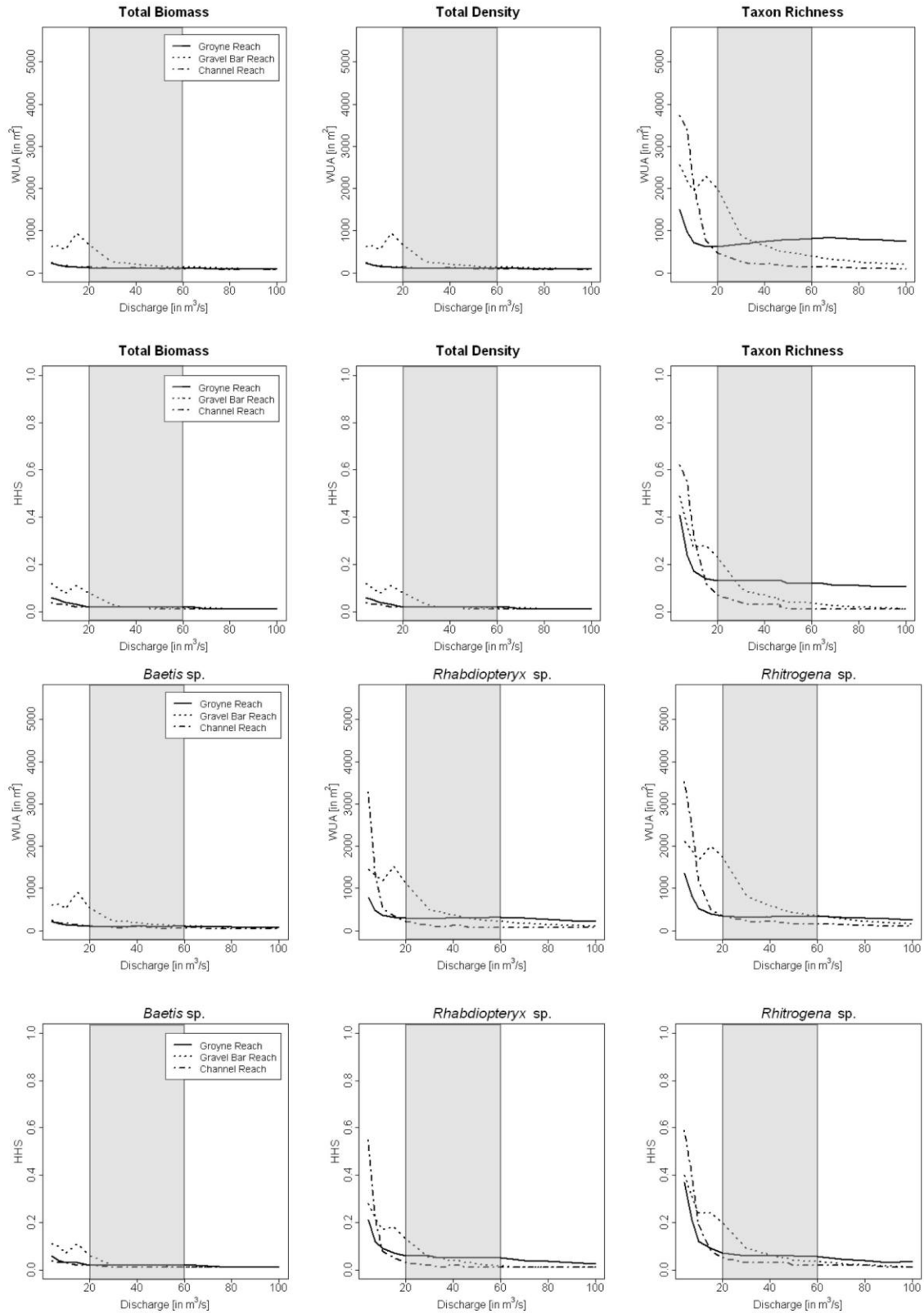
FIG. 21: Weighted Useable Area (WUA) and Hydraulic Habitat Suitability Index (HHS) for the three reaches for all summer models. The range with the most frequent discharges is shaded in grey.
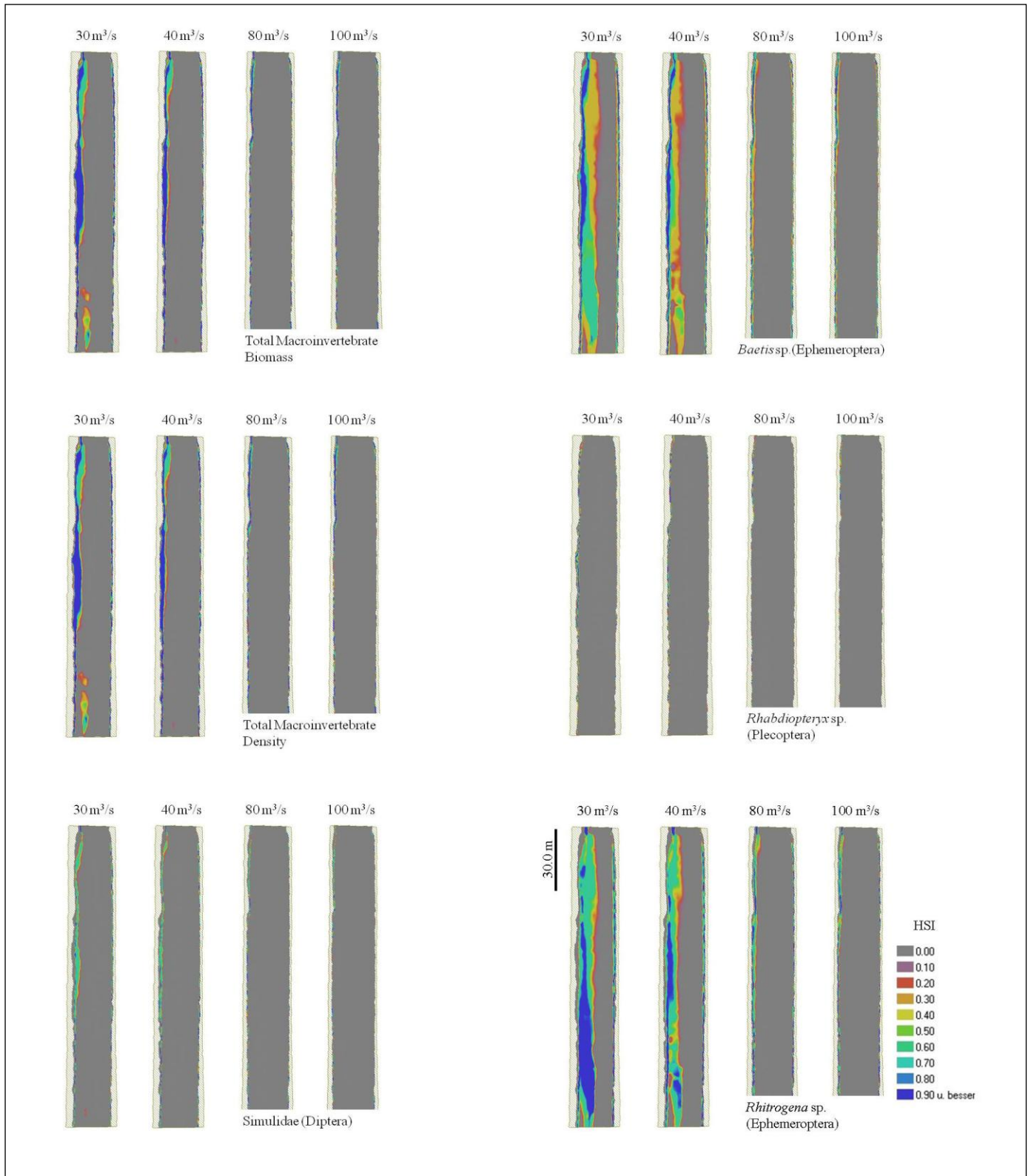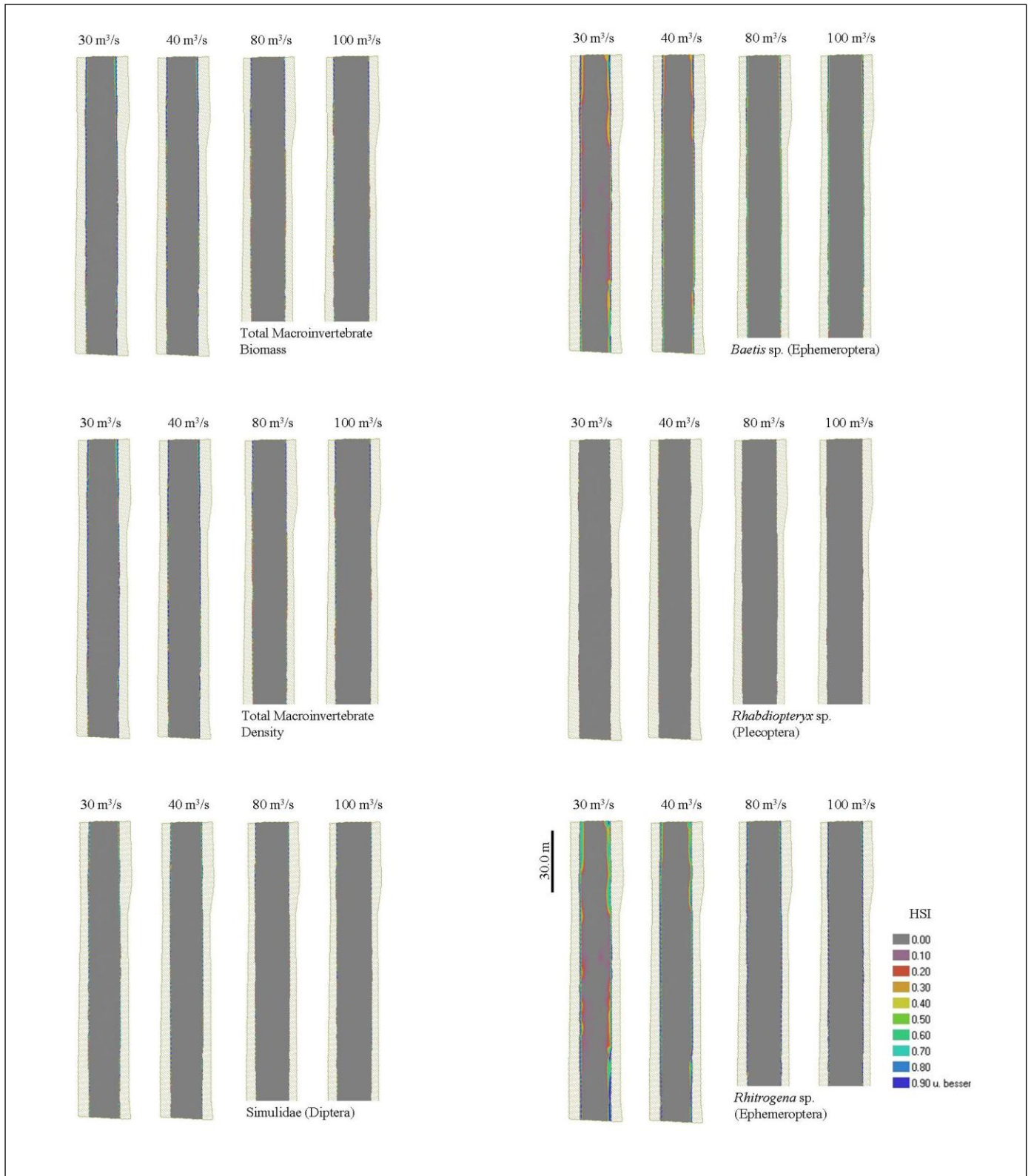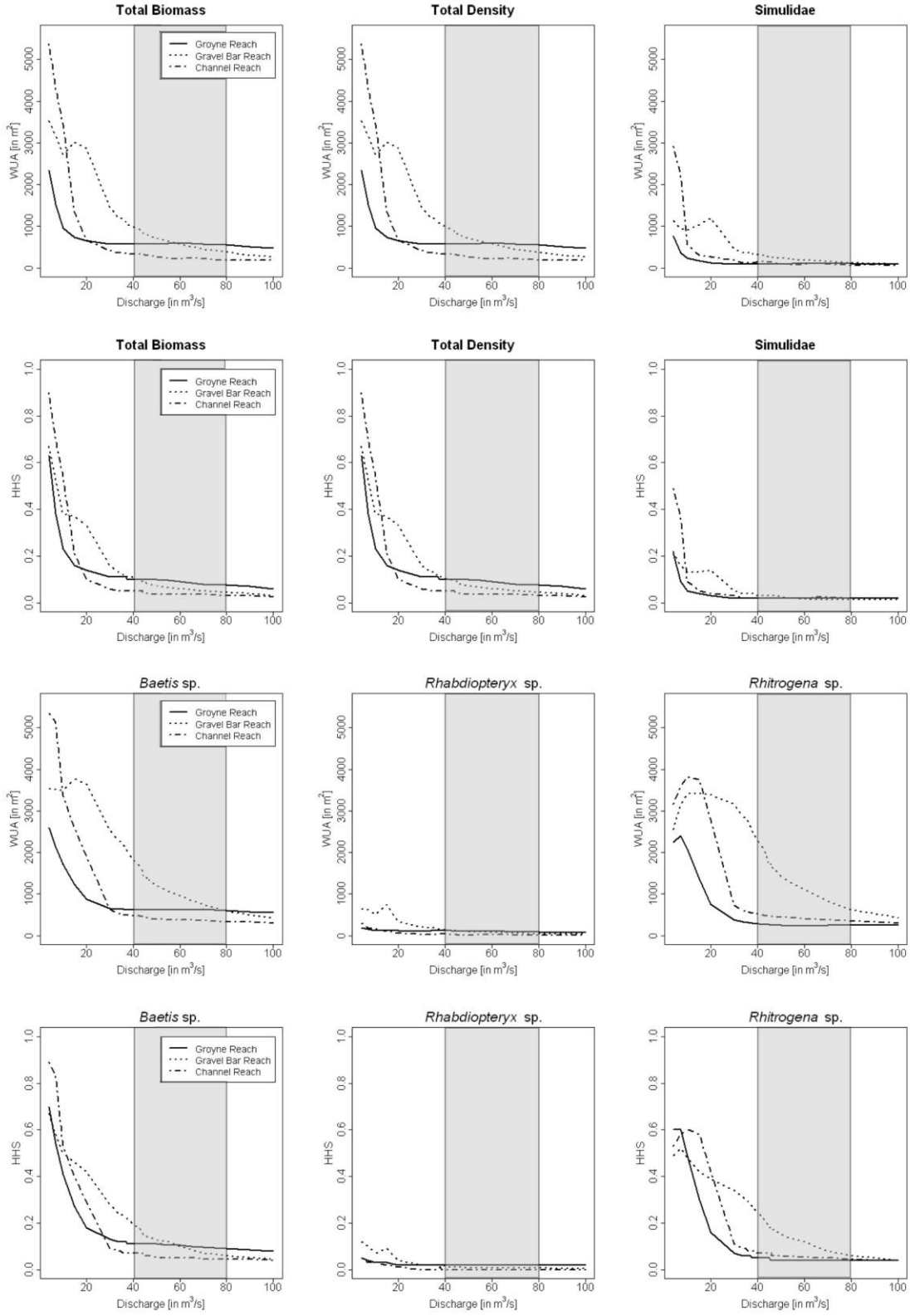
4. DISCUSSION

4.1 SEASONALITY

Before dam construction in the 1920's in winter, a relatively stable and low discharge was found in the Hasliaare River (Appendix A4). Through dam construction, the flow regimes of rivers are generally altered (Appendix A5; Petts, 1980; Vinson, 2001; Graf, 2006). Hydropeaking artificially elevates the low baseflows in winter up to 10 times higher discharges in the Hasliaare River leading to severe impacts on habitats of stream dwelling species. The habitat maps (Figs. 10-12) and WUA/HHS curves (Fig. 13) show that in winter many good habitats are available at base flow of 4 m^3/s for the community metrics, *Baetis* sp. and *Rhabdiopteryx* sp. In contrast, *Drusus* sp. and *Rhitrogena* sp. had at baseflow relatively few suitable areas. This can be explained by a strong preference of *Drusus* sp. for shallow habitats that are rare in the channelized Hydropeaking reaches, and *Rhitrogena* sp. preferred a narrow range in flow velocity (Fig. 4) which was exceeded already at base flow. At these low flows, organisms can recolonize habitats. It has been shown that drifting organisms from upstream reaches can quickly colonize new habitats under natural conditions (Townsend & Hildrew, 1976; Smith & Brown, 2006). However, due to hydropeaking such low discharges are rare and only of short duration, so that the middle channel of all reaches does not provide good habitats. The habitat maps and WUA/HHS curves show that already at a discharge of 15 m^3/s, which is among the most frequent discharges (Appendix A4), only a small fraction of the channel provides good habitats. Discharges higher than 15 m^3/s can occur up to one week without falling below, which makes most habitats unsuitable and might remove many invertebrates through drift. During these periods, access to refugia from high discharges in the hyporheos are very important to escape from the high shear stress (Ward, 1992; Brunke & Gonser, 1997). Bruno *et al.* (2010) showed that drift increases five to ten minutes after the arrival of the hydropeaking wave and decreases again even if the discharge is still high. How such high discharges over a longer period affect macroinvertebrate drift has not been studied yet. Extreme hydropeaks higher than 50 m^3/s are also rare and last on average not longer than one hour. The large difference between

baseflow and elevated discharges due to hydropeaking confirms in a quantitative way that hydropeaking is most pronounced during the low water period in winter and its ecological effects most severe, as macroinvertebrates and fish are in sensitive life stages (Imhof *et al*., 2003; Meile *et al.*, 2005; Limnex, 2009).

In spring, snowmelt leads to naturally higher flows but discharge peaks caused by energy production elevate the flows further. In the range of most frequent discharges today (20-60 m^3/s), the habitat suitabilities and WUA/HHS values are generally lower than in winter, as presented by the habitat maps (Figs. 14-16) and WUA/HHS curves (Fig. 17). However, the habitat suitabilities are already low at baseflow (15 m^3/s) in spring. This finding can be explained by the fact that the investigated taxa preferred shallow habitats on the river margins which still had a flow velocity around 0.5 m/s. Such habitats were only present on the gravel bar and partly behind the groynes. This preference for shallower habitats in spring might be linked to emergence because investigated taxa were larger than in winter (Appendix A6) and about to emerge. All the investigated taxa are known to emerge in spring and summer (Graf *et al.*, 2008, 2009; Buffagni *et al.*, 2009). Another possible explanation is that habitats with the preferred velocity range move to the margins in the shallower parts. That way, flow velocity could be the limiting factor for species distribution. Taxon richness had more suitable areas than the other community measures, which is due to a weaker relationship to depth and flow velocity (Fig. 5). This is consistent with findings of other years where the number of taxa was only slightly lower in the hydropeaking sections of the Hasliaare (Baumann & Klaus, 2003; Schweizer *et al*., 2010). *Rhitrogena* sp. showed higher WUA/HHS values and habitat suitabilities on the gravel bar at the same discharges than in winter. As they were significantly greater in spring compared to winter (Appendix A6) this might explain the broader range of velocity with suitable areas and hence the higher WUA/HHS values and habitat suitabilities.

In summer, the baseflows are between 30 and 40 m^3/s. In this range the community metrics, *Rhabdiopteryx* sp. and Simulidae have again only few areas with suitable conditions, i.e. behind the groynes or margins of the gravel bar (Figs. 18-21). *Rhabdiopteryx* sp. was still in the phase of emergence and preferred the same shallow habitats than in spring. Simulidae preferred a narrow range of flow velocity, which might be optimal for filter feeding (Fig. 7). These physical habitats were sparse at higher base

flow in summer in all three morphology types. In contrast, *Baetis* sp. and *Rhitrogena* sp. had on the gravel bar relatively large areas with good habitat suitabilities, which is due to preference for higher depths and velocities which make these habitats optimal. Especially, *Rhitrogena* sp. preferred different flow velocities than in winter and spring. As the larvae were of similar size than in winter, the preference for higher flow velocities might be caused by biological factors like predation, concurrence or by resource distribution which are not visible in the preference curves. As most taxa preferred deeper habitats than in spring, this is also reflected in the community metrics total density and biomass which have more available habitats at the same discharges than in spring. For taxon richness, no fuzzy model was made for summer due to no visible preference for the physical parameters. This supports the finding that taxon richness is not or only weakly correlated to the physical parameters used for modeling. As the discharges are elevated up to 80 m^3/s due to hydropeaking, this changes the last good habitats at baseflow into unsuitable habitats in the range of frequent flows (Fig. 21).

Generally, in all three seasons in the range of frequent discharges, few areas with good or medium habitat suitability can be found, with the exception of the gravel bar in winter. The high flows reduce macroinvertebrate densities and biomasses through drift (Lauters *et al*., 1996; Bruno *et al*., 2010) and lead to relatively low densities and biomasses in the Hydropeaking sections (own observation; Limnex, 2008; Schweizer *et al*., 2008, 2010) However, in spring and summer hydropeaking does not decrease the amount of suitable areas as strong as in winter because already at baseflow low WUA/HHS values and suitabilities were found. This result implies that in spring and summer, channelization is the main factor that decreases suitable areas (Baumann, 2004) and hydropeaking as a second order impact.

4.2 MORPHOLOGY

The Gravel bar reach provided higher amounts of structure and heterogeneity than the other two morphologies, as reflected in the rather good habitat suitabilities on the gravel bar (Figs. 11, 15, 19). Also, the WUA/HHS curves (Figs. 13, 17, 21) show with

their second peak between 15 and 20 m^3/s some resilience to an increased discharge. This second peak can be explained by the fact that with increasing discharge the inundated area increases by flooding of the gravel bar (see also Appendix A6). The physical conditions, namely depth and flow velocity, are with increasing discharge still in an optimal range on the gravel bar. In fact, significantly higher densities, biomasses and number of taxa were found in winter in the whole Gravel bar reach than in the Groyne reach upstream (own observation; Lubini *et al.*, 2007; Schweizer *et al.*, 2008; Limnex, 2009). However, at discharges greater than 30 m^3/s, large parts of the gravel bar become unsuitable habitats and the WUA/HHS values become similar to the other two reaches. These discharges occurred rarely during winters 2010-2012 but are normal in spring and summer due to naturally higher baseflow plus hydropeaking (Appendix A4).

Groyne reach showed in most cases at baseflow lower WUA and HHS values than Gravel bar reach and Channel reach or values equal to Channel reach and the curves stabilized at discharges around 20 m^3/s. Behind the groynes, also at high discharges, some suitable or at least useable habitats remained. However, the areas behind the groynes are mostly dominated by sand which has been found to be avoided by macroinvertebrates due to bed instability and small pore sizes that constrain the access to refugia (Wood & Armitage, 1997; Limnex, 2009).

Channel reach showed in all models a rapid decrease of WUA and HHS with increasing discharges. The suitable habitats moved to the margins and were mainly found in the blocks of the levee, as also observed in physical habitat models for other channelized reaches (Kopecki *et al.*, 2012; Eberstaller *et al.*, 2012b). Appendix A6 shows that the inundated area increases only slightly with discharge compared two the other two morphology types. Through this, flow velocities and depths increase already at medium discharges and hence also the dimensionless shear stress increases and leads to low suitability values.

This result suggests that structured morphology such as gravel bars increases the resilience of the system to increased discharges and can act as a buffer to the negative consequences of higher flows in a certain range. In a physical habitat model from the River Rhine, similar model outputs were found in a reach with gravel bars and tributaries (Eberstaller *et al.*, 2012b). These shallow stream margins offer refugia for macroinvertebrates during high discharges. In a drift experiment conducted in the

Hasliaare in March/April 2008, Gravel Bar Reach had significantly less drifting biomass and density at hydropeaks than Channel Reach (Limnex, 2009), which supports especially the model outputs in winter.

4.3 DISTRIBUTION OF PERIPHYTON

The finding that periphyton is only very weakly correlated to physical variables depth and flow velocity suggests that periphyton, which is an important food source for macroinvertebrates, is rather equally distributed over the range of sampled depths and flow velocities. The preferences in May have to considered with caution as in some ranges only a few samples were taken, i.e. lower velocity range and high depth range. This could also lead to an artifact in the curve. However, Biggs & Stokseth (1996) found preferences for flow velocities which depended on the age of the periphyton biofilm. An effect like this could also have contributed to the large variation found in response to depth and flow velocity, but during sample processing no attention was paid to the age of different biofilms.

The higher temperatures and better light conditions explain the higher AFDM values in spring and summer, which can be expected. However, as the AFDM samples in spring and summer were only from the residual flow reach, which is not affected by hydropeaking, and the altered turbidity regime might not be as representative for the Hydropeaking reaches.

4.4 IMPLICATIONS FOR REMEDIATION PROJECTS

According to the Swiss water protection legislation, hydropower schemes that causes discharge fluctuations with a ratio of Q_{max}/Q_{min} equal or greater than 1.5 and if stream-dwelling organisms are severely affected need to be remediated by dampening efforts (Baumann *et al*., 2012). The ratio of Q_{max}/Q_{min} is calculated in the sense of a pure

ratio (without any other factors) as described in HYDMOD by Pfaundler *et al.* (2011). This approach would lead to dampened flow peaks but does not necessarily increase the suitable area for macroinvertebrates. It is also highly dependent on the discharge itself. As all WUA/HHS curves show, there is a critical discharge, which depends on the taxa/community measure and the morphology, and if it is exceeded, only few suitable areas remain. A situation with a ratio Q_{max}/Q_{min} of 1.5 but higher flows than the critical threshold would not improve the situation for macroinvertebrates. Further research would be necessary to investigate how long and how often such a threshold can be exceeded without having negative consequences on the river fauna.

As morphology has such a large influence on habitat availability, additional building measures to open up the channelized parts and introduction of structural heterogeneity could shift these critical discharges to higher values. Especially, structure by gravel bars has been shown to increase suitable areas in reaches. This would also be important in the context of higher baseflows in spring and summer where the channelization alone increases the physical parameters to an unsuitable level for macroinvertebrates.

4.5 VALIDITY OF METHODOLOGY

Physical habitat models are widespread procedure for the quantitative assessment of the consequences of hydropeaking and for evaluation of future remediation efforts (Kopecki *et al.*, 2012). Simulations help to predict the quantity and quality of habitats at different discharges and flow-ramping rates. There are different methods to model habitat requirements of stream-dwelling species. The "classical" approach using univariate preference curves (Bovee, 1982) has been widely applied. However, these preference curve approaches have often been criticized for their disadvantages: They do not account for interactions of the different parameters such as velocity, depth and substrate (Mouton *et al.*, 2007, Kopecki, 2008). Further, they can not easily be transferred to other river systems because they often do not contain enough information about the physical environment of macroinvertebrates. This can cause different density responses at the

same velocities (Statzner *et al.*, 1988). Another important disadvantage of preference curves (univariate or multivariate) is that they have discrete maxima (i.e. suitability index 1.0 at flow velocity of 0.6m/s). This does not really reflect macroinvertebrates habitat requirements (Jorde & Schneider, 2010). It rather makes sense to define ranges of flow velocity, depth or substrate where good or low preferences can be found. A fuzzy logic approach can therefore be a good alternative to the "classical" preference curves, and it can also easily account for interactions between the different parameters. However, to gain information about preferences of dominant species in the Hasliaare River, univariate preference curves were fitted and used to formulate fuzzy rules. That way, fuzzy rules were based on field data for this particular river.

Preference curves in the literature are very different but they all agree that above depth of 0.9-1 meter and above flow velocity of about 1 m/s, suitabilities for most taxa, biomass, density or taxon richness are low (Orth & Maughan, 1983; Jowett & Richardson, 1990; Jowett *et al.*, 1991; Gore *et al.*, 2001; Eberstaller *et al.*, 2012b). The optima for depths are between 0.4 and 0.8 meter and for flow velocities 0.3 and 0.8 m/s depending on the taxa or community measure. The preference curves of this study are clearly in these ranges. This result partly validates the preference curves that had low D^2-values. As similar velocity preference curves have been found in all three seasons, also supports these relationships. However, many other factors that are known to influence species distribution like biological interactions, food resource distribution but also physical parameters like colmation, water temperature or turbidity are not considered in this approach (Haro & Brusven, 1994; ARGE Trübung Alpenrhein, 2001; Baumann & Klaus, 2003; Bo *et* al., 2007).

Another point is that total preference curves in winter that were used for the formulation of fuzzy rules contained data from the residual flow reach and the three Hydropeaking reaches (Figs. 3 and 4). In the Residual flow reach, conditions are quite stable but high values of depth, flow velocity and turbidity are missing and thermal regime is also different as it is not influenced by thermopeaking (Zolezzi *et al.*, 2011). The Hydropeaking sections have higher flow velocities and depths but they fluctuate with discharge. This fact complicated the fitting of curves. Depth at frequent flows could be estimated at each sampling spot but not flow velocity. As shown in Figures 3 and 4, depth in the Hydropeaking reaches ranged from 1 to 1.5 meters. Here, no preference could be

detected, which indicates that all these depth are too high for most macroinvertebrates. Although these values can be lower than 1 meter at low discharges, it seems that the higher values limit the availability of habitats and not the lower ones. Flow velocity preference curves from the Hydropeaking sections were based on measurements at low discharge. At frequent flows in all seasons, much higher velocities occur. For that reason, flow velocity preference curves for Hydropeaking reaches have to be treated with caution and preference of these curves should not be over-estimated because preference factors (PF) decrease already in the range of velocities at low discharge. Further, recent studies have revealed that not only the hydrodynamic hydropeaking wave increases drift, also the subsequent thermopeaking wave induces a "behavioral" drift (Carolli *et al*., 2011; Bruno *et al*., 2012). This might additionally bias the relationships in the curves for Hydropeaking reaches and total curves. Therefore, curves from Residual flow reach are more reliable, as the physical conditions are more stable.

Substrate sizes of 0.6 up to 20 cm and greater were preferred (Appendix A1), but no finer differentiation between these size classes could be made. It is generally accepted that small particle size such as sand, silt and fine gravel but also bedrock provide poor habitats, whereas larger sizes such as cobbles and boulders provide better habitats (Pennak & van Gerpen, 1947; Barber & Kevern, 1973; Ward, 1975; Jowett & Richardson, 1990; Gore *et al.*, 2001. However, in the major reviews on European freshwater organisms, no differentiation between the larger size substrate was made for the investigated taxa (Graf *et al.*, 2008, 2009; Buffagni *et al.*, 2009). The fact that no significant differences between size classes were found throughout the year could also be explained with the low number of samples with small particle size (class 2 and 3) and large particle size (class 8). Often only one or two samples could be taken of these sizes due to their low frequency in the reaches and therefore might not be as relevant for the assessment of the entire Hasliaare River.

4.6 Conclusions and Outlook

The results of this thesis have quantitatively confirmed that hydropeaking has the most pronounced effects in winter on the amount of suitable areas for macroinvertebrates because physical parameters like depth, flow velocity or shear stress are strongly modified by the higher mean daily discharges through hydropeaking (Meile *et al*., 2011). In contrast, in spring and summer, the higher natural baseflows decrease available habitats and suggests a minor role of hydropeaking on the amount of habitats. The major impact can be traced back to channelized morphology. Further, it has been shown that structure and heterogeneity introduced by gravel bars increased the amount of suitable habitats and was more resistant against higher flows. Groynes and channelized morphology provided few suitable habitats in the range of frequent discharges. Thirdly, it turned out that the emergence period of the investigated taxa is a sensitive phase in their life cycle as they prefer shallow habitats which are sparse in the Hydropeaking reaches.

Further modeling studies should consider, in addition to discharge, flow-ramping rates which describe the gradient in flow change (Meile *et al*., 2011). The time dimension seems to be important for stream-dwelling organisms and could be included in further assessments of improvements brought about by retention basins which are supposed to decrease flow-ramping rates by 50 % (Schweizer *et al*., 2008). This might also extend the reaction time for organisms to seek shelter from higher shear stress. Another focus could be put on the optimization of the channel morphology by designing and testing different structures that could be introduced, like special groynes and gravel bars. Speerli & Schneider (2012) found in a model experiment that alternating, prolonged groynes increase the variability of flow velocities and water depths and lead to the formation of gravel bars. Building measures like this could increase heterogeneity and might provide still good habitats under hydropeaking conditions.

5. ACKNOWLEDGEMENTS

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7. APPENDIX

APPENDIX A1

TABLE A1: Codes for substrate size used for modeling.

Code	Substrate Type	Diameter (cm)
0	Clay	
1	org. Material, Detritus	
2	Sand, Silt	< 0.2cm
3	Fine Gravel	0.2cm - 0.6cm
4	Medium Gravel	0.6cm - 2cm
5	Rubble	2cm - 6cm
6	Cobble	6cm - 12cm
7	larger Cobble	12cm - 20cm
8	Boulder	> 20cm
9	Bedrock	

APPENDIX A2

TABLE A2: Physical habitat variables and the fuzzy sets assigned to the values for the fuzzy models for community ecology and for the selected taxa in spring and summer.

Variable	Set Name	Community Parameters (Spring)	Taxon Parameters (Spring)	Community Parameters (Summer)	Taxon Parameters (Summer)
		$p_1, p_2, p_3, (p_4)$	$p_1, p_2, p_3, (p_4)$	$p_1, p_2, p_3, (p_4)$	$p_1, p_2, p_3, (p_4)$
Depth (m)	Very Low	(0, 0, 0, 0.1)	(0, 0, 0, 0.1)	(0, 0, 0, 0.1)	(0, 0, 0, 0.1)
	Low	(0, 0.1, 0.2)	(0, 0.1, 0.2)	(0, 0.1, 0.2)	(0, 0.1, 0.2)
	Medium	(0.1, 0.2, 0.4, 0.6)	(0.1, 0.2, 0.4, 0.6)	(0.1, 0.2, 0.3, 0.4)	(0.1, 0.2, 0.4, 0.5)
	High	(0.4, 0.6, 1, 1.2)	(0.4, 0.6, 1, 1.2)	(0.3, 0.4, 0.6, 0.7)	(0.4, 0.5, 0.7, 1)
	Very High	(1, 1.2, 100)	(1, 1.2, 100)	(0.6, 0.7, 100)	(0.7, 1, 100)
Flow velocity (m/s)	Very Low	(0, 0, 0, 0.1)	(0, 0, 0, 0.1)	(0, 0, 0, 0.1)	(0, 0, 0, 0.2)
	Low	(0, 0.1, 0.3, 0.4)	(0, 0.1, 0.3, 0.4)	(0, 0.1, 0.2, 0.3)	(0, 0.2, 0.4, 0.5)
	Medium	(0.3, 0.4, 0.7, 0.9)	(0.3, 0.4, 0.6, 0.7)	(0.2, 0.3, 0.8, 1.0)	(0.4, 0.5, 0.7, 0.8)
	High	(0.7, 0.9, 1.4, 1.6)	(0.6, 0.7, 0.9, 1)	(0.8, 1.0, 1.2, 1.4)	(0.7, 0.8, 1.2, 1.4)
	Very High	(1.4, 1.6, 100)	(0.9, 1, 100)	(1.2, 1.4, 100)	(1.2, 1.4, 100)
Dominant Substrate	Low	(0, 0, 3, 4)	(0, 0, 3, 4)	(0, 0, 3, 4)	(0, 0, 3, 4)
	Medium	(3, 4, 8, 9)	(3, 4, 8, 9)	(3, 4, 8, 9)	(3, 4, 8, 9)
	Very Low	(8, 9, 100)	(8, 9, 100)	(8, 9, 100)	(8, 9, 100)

APPENDIX A3

TABLE A3: Suitability Index (SI) Codes of the Fuzzy sets for the three habitat variables for the spring and summer models. VL=Very Low; L=Low; M=Medium; H=High; VH=Very High

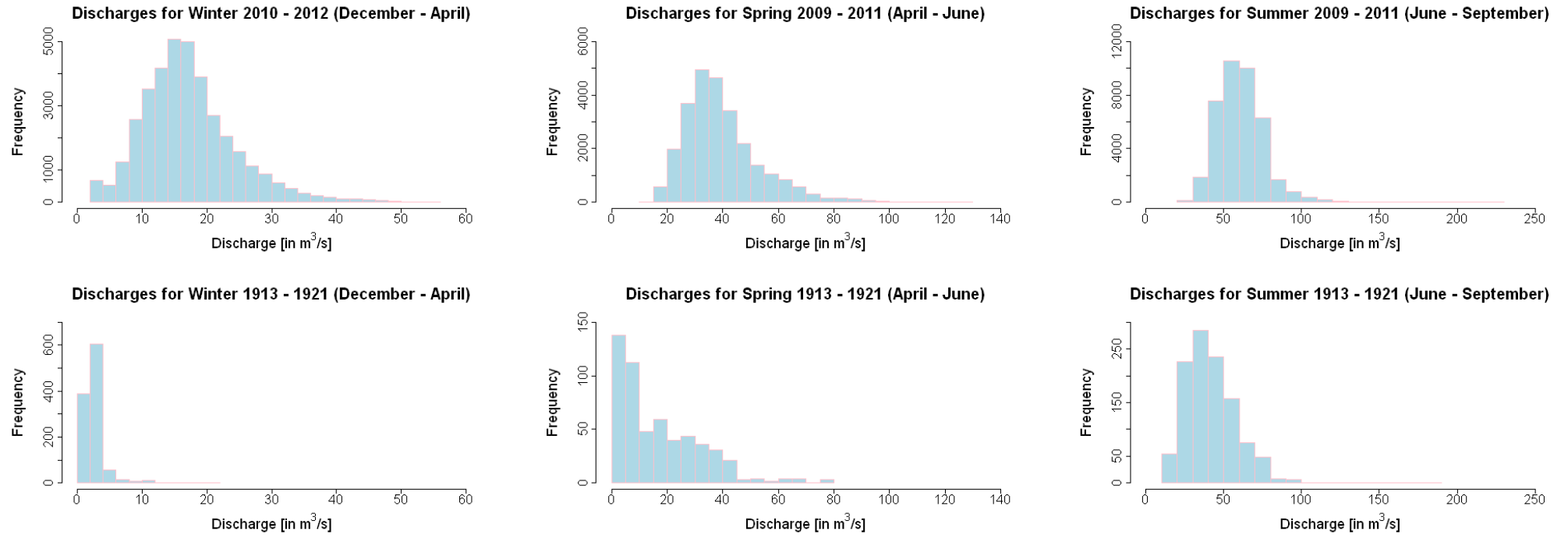| Habitat Variable	Set	SI Code Total Density (Spring)	SI Code Total Biomass (Spring)	SI Code Taxon Richness (Spring)	SI Code *Rhabdiopteryx* sp. (Spring)	SI Code *Baetis* sp. (Spring).	SI Code *Rhitrogena* sp. (Spring)	SI Code Total Density (Summer)	SI Code Total Biomass (Summer)	SI Code *Rhabdiopteryx* sp. (Summer)	SI Code *Baetis* sp. (Summer).	SI Code *Rhitrogena* sp. (Summer)	SI Code Simulidae (Summer)
Depth	VL	0	0	0	0	0	0	0	0	0	0	0	0
	L	2	2	2	2	2	2	2	2	2	2	0	2
	M	0	0	1	1	0	1	2	2	0	2	2	1
	H	0	0	1	0	0	0	1	1	0	1	1	0
	VH	0	0	0	0	0	0	0	0	0	0	0	0
Velocity	VL	0	0	0	0	0	0	0	0	0	0	0	0
	L	1	1	2	1	1	1	1	1	2	1	0	0
	M	2	2	2	2	2	2	2	2	0	2	1	2
	H	0	0	0	0	0	1	0	0	0	1	2	0
	VH	0	0	0	0	0	0	0	0	0	0	0	0
Substrate	L	0	0	0	0	0	0	0	0	0	0	0	0
	M	1	1	1	1	1	1	1	1	1	1	1	1
	VL	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX A4

FIG. A4: Distributions of Discharges in Winter, Spring and Summer under hydropeaking conditions (2009-2012) and under conditions prior to dam construction (1913-1921).
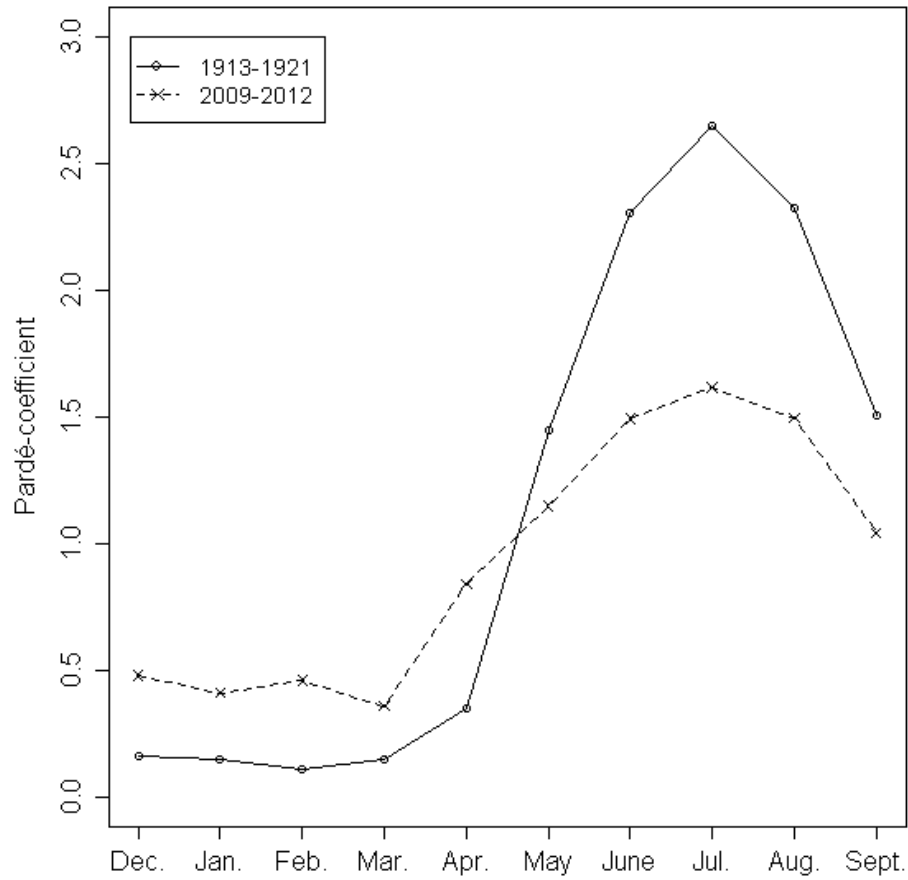
APPENDIX A5

Flow Regime of Hasliaare

FIG. A5: Mean values of Pardé-Coefficients (Pardé, 1933) for the Hasliaare River prior to dam construction (1913-1921) and under today's hydropeaking conditions. Note that data form 1913-1921 consisted only of daily means whereas data from 2009-2012 consisted of 10 minutes means.

APPENDIX A6

Discharge-Area Relationship
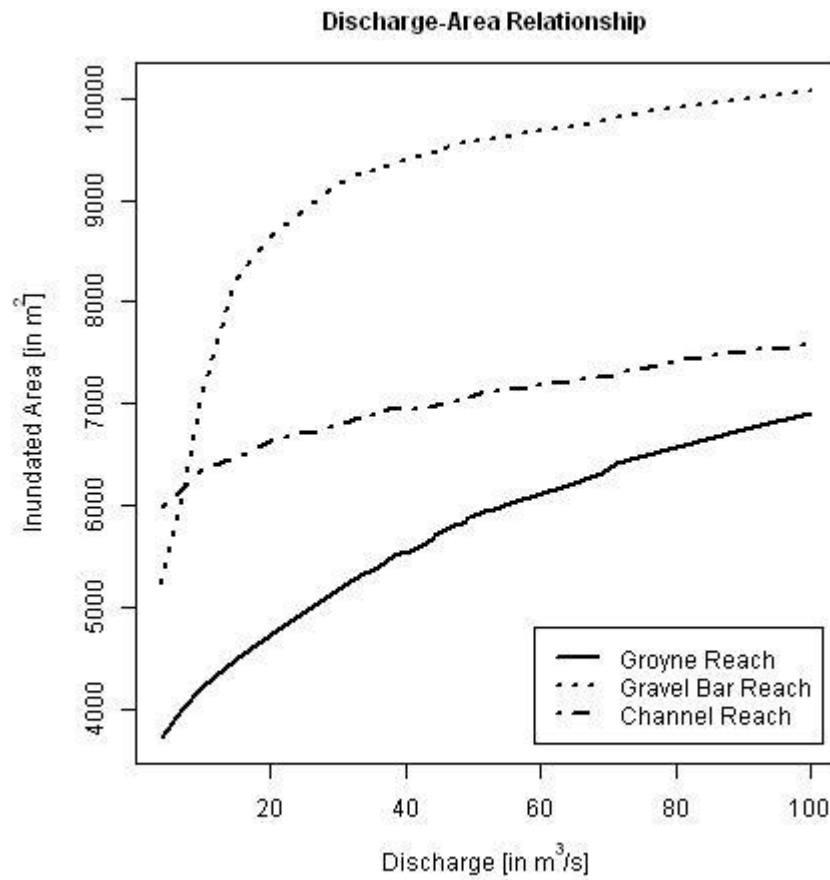
FIG. A6: Relationship between discharge and inundated area for all three morphology types.

APPENDIX A7

FIG. A7: Fuzzy Rules for all three seasons that were used for modeling in CASiMiR.

APPENDIX B1
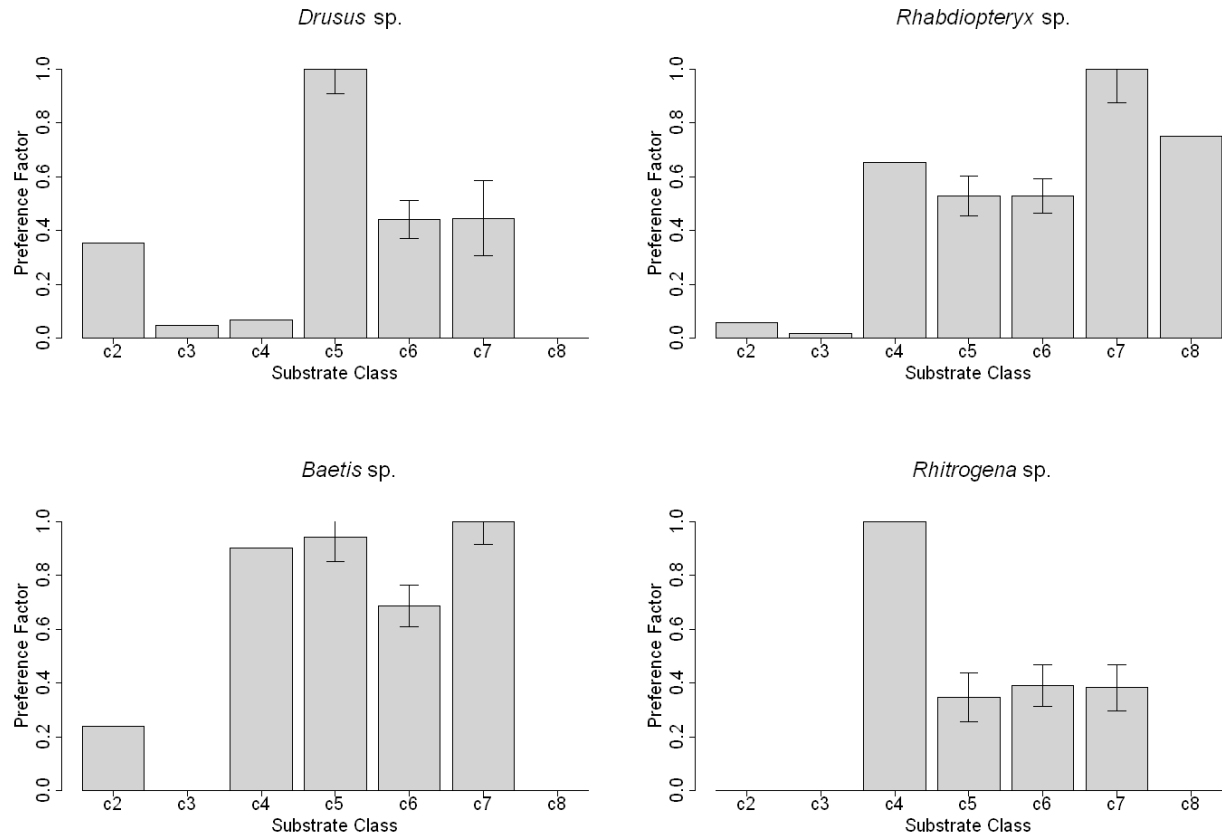
FIG. B1: Substrate preferences of *Drusus* sp., *Rhabdiopteryx* sp., *Baetis* sp. and *Rhitrogena* sp. in winter.
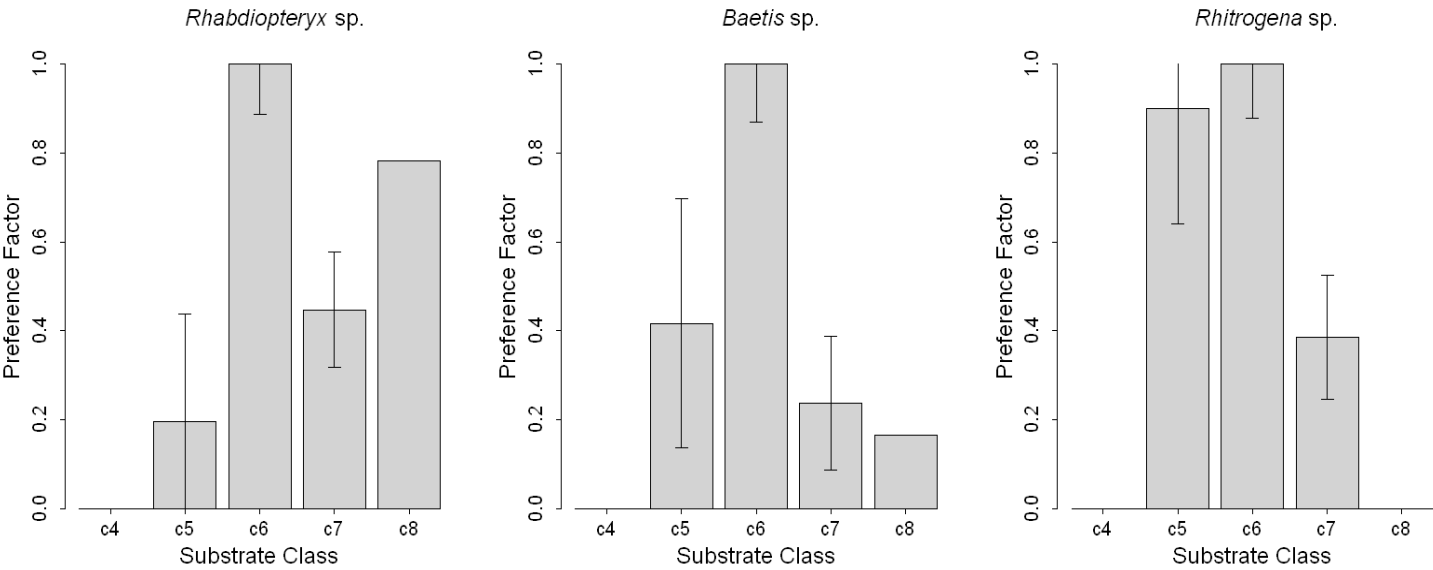
APPENDIX B2

FIG. B2: Substrate preferences of *Rhabdiopteryx* sp., *Baetis* sp. and *Rhitrogena* sp. in spring.
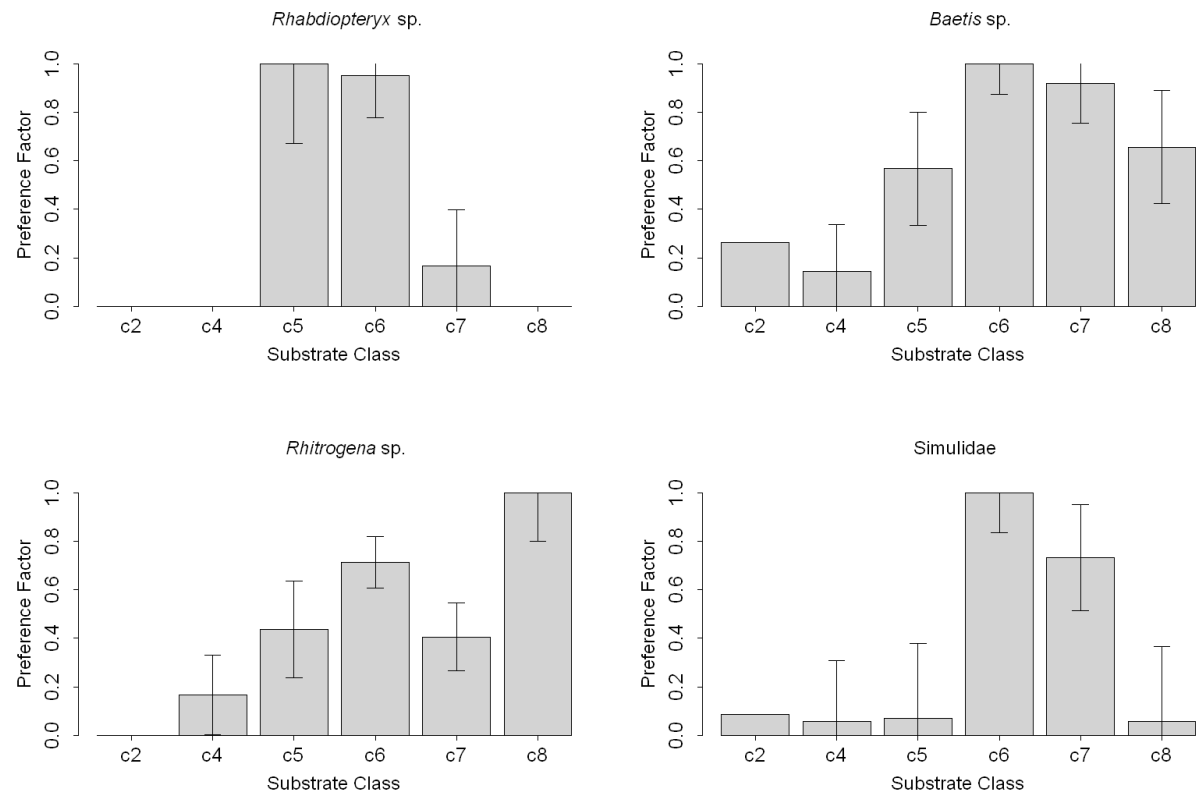
APPENDIX B3

FIG. B3: Substrate preferences of *Rhabdiopteryx* sp., *Baetis* sp., *Rhitrogena* sp. and Simulidae (Diptera) in summer.
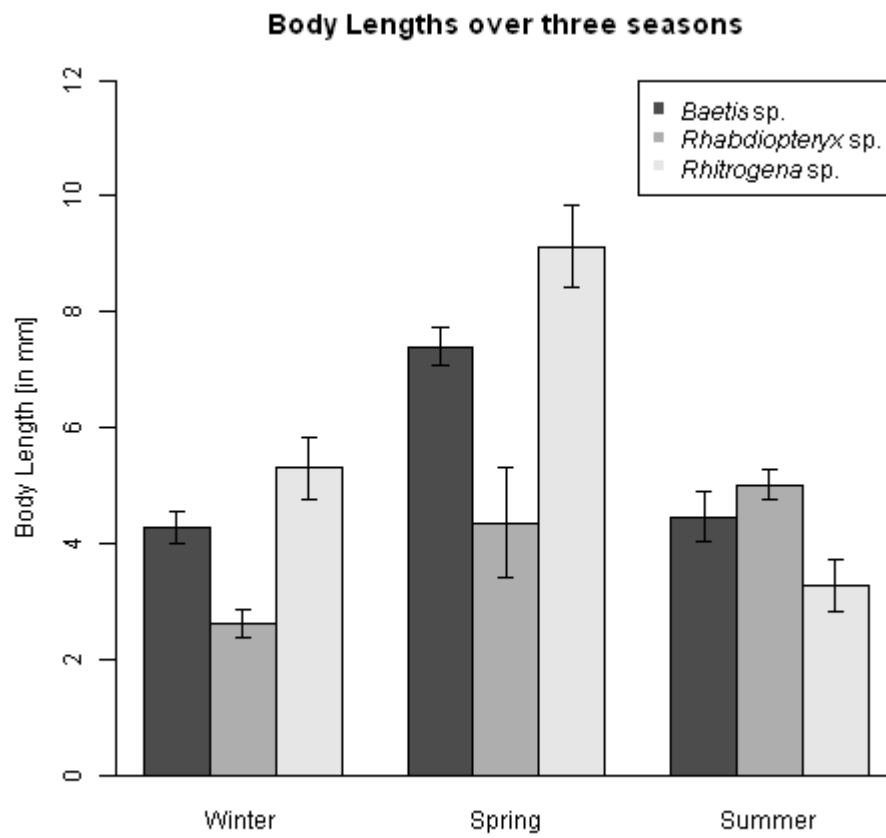
APPENDIX B4

FIG. B4: Size differences of *Rhabdiopteryx* sp., *Baetis* sp. and *Rhitrogena* sp. in all three seasons.