



Article

# Model-Based Evaluation of the Effects of River Discharge Modulations on Physical Fish Habitat Quality

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**Abstract:** The increase in minimum flows has rarely been considered to mitigate the ecological impact of hydroelectric power plants because it requires a site-specific design and expensive long-term monitoring procedure to identify the most beneficial scenario. This study presents a model-based method to estimate, within the model constraints, the most sustainable scenario of water resource sharing between nature and human needs. We studied physical habitat suitability of the Isar River in Munich (Germany) for three protected fish species: *Thymallus thymallus* L., *Hucho hucho* L., and *Chondostroma nasus* L. The analysis combined a high-resolution two-dimensional (2D) hydromorphological model with expert-based procedures using Computer Aided Simulation Model for Instream Flow Requirements (CASiMiR). We simulated a range of minimum discharges from 5 to 68.5 m<sup>3</sup>/s and four scenarios: (A) maximum use of the resource for humans; (B) slight increase in the minimum water flow; (C) medium increase in the minimum water flow; and, (D) without diversion for hydroelectric production. Under the current hydromorphological conditions, model outputs showed that different life stages of the fish species showed preferences for different scenarios, and that none of the four scenarios provided permanently suitable habitat conditions for the three species. We suggest that discharge management should be combined with hydromorphological restoration actions to re-establish parts of the modified channel slope and/or parts of the previously lost floodplain habitat in order to implement a solution that favors all species at the same time. The modeling procedure that is presented may be helpful to identify the discharge scenario that is most efficient for maintaining target fish species under realistic usage conditions.

**Keywords:** fish habitat modeling; hydromorphological modeling; CASiMiR; sustainable water management; minimum water flow; environmental flows determination

## 1. Introduction

Demands for renewable energy production, e.g., hydroelectric power plants, increase, but their ecological impact remains considerable. In the face of increasing energy needs, a reduction of the

fossil energy sources and climate changes, new policies, such as the Kyoto Protocol [1] and the EU Renewable Energy Directive [2], have been formulated, thus increasing the demand for renewable energy production. Hydropower is one of the two largest contributors to sustainable electricity generation worldwide and represented almost 80% of the electricity generated using renewable resources in 2012 [3]. It is the most affordable renewable energy source, and run-of-river hydroelectric power plants have the highest energy payback ratio (267 versus 39 for wind and nine for solar photovoltaic) [4]. However, they contribute greatly to the degradation of river ecosystems and biodiversity [5,6]: Retention structures are obstacles to the longitudinal connectivity of river habitats [7], reduce hydrodynamics, and foster exotic species invasion [8]; hydropeaking causes dewatering, fish stranding and modifies fish assemblage [9,10]; flow modifications have severe consequences for river ecosystems [8], and particularly for the fish population [11–15].

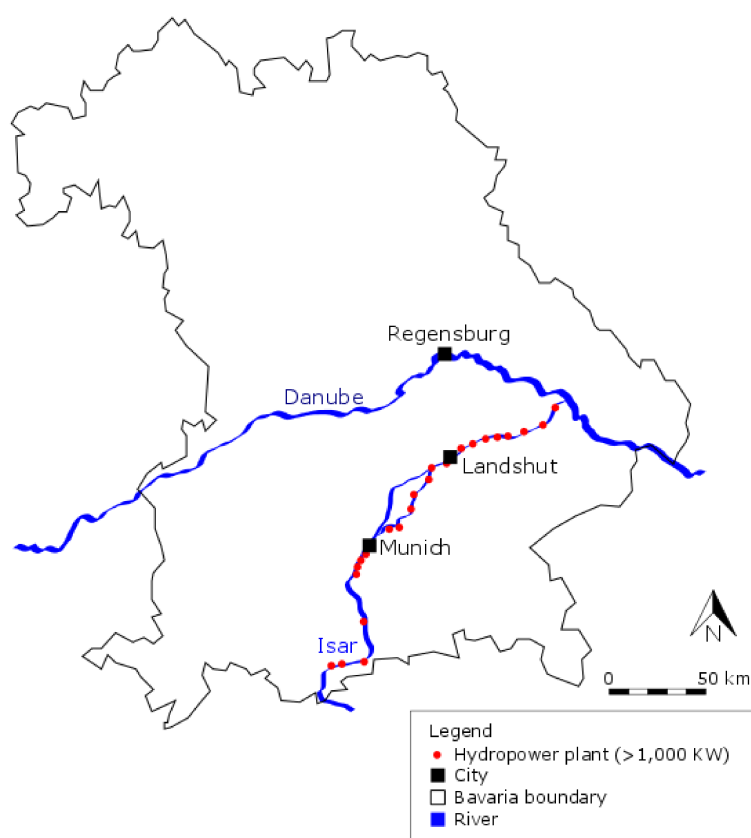
At the same time, awareness of ecological conservation and restoration is also increasing. The EU Water Framework Directive [16] aims at ensuring the quality and sustainable management of EU waters and demands the restoration of all European water bodies in order to achieve a good aquatic habitat quality, even in the case of heavily modified water bodies. Consequently, the EU Renewable Energy Directive (2009) conflicts with the EU Water Framework Directive (2000), and hydropower politics have to find the right balance between energy security, sustainability, climate change prevention and adaptation, biodiversity conservation, and water protection [4,17,18]. Much research has focused on the design of fish-friendly turbines [19], or fish passes [20], and on the formulation of guidelines to decrease the impact of hydropeaking on aquatic habitats [12–14,21,22]. Also, minimum flow requirements for aquatic habitats have been intensively studied during the last three decades and guidelines for sustainable water sharing between hydropower plants and aquatic habitats have been formulated [23].

The quantity, quality, and timing of water flows are the basic requirements for sustainable water sharing and are an issue for river restoration. Water managers must ensure that the water flows required to sustain freshwater ecosystems remain available [23–25]. Unfortunately, for economic reasons, findings on water security for biodiversity are relatively poorly integrated [26]. Surveys of restoration measures in Germany and in France showed that an increase in minimum flows remains a rare restoration measure, namely less than 6% of the rural projects [27] and less than 2% of the urban projects [28]. Most guidelines suggested minimum flow calculations that were based on river hydrology, namely a third of the annual mean low discharge [23] but this standardized approach does not consider the local specificities of aquatic habitats. Therefore, minimum flows should be assessed in relation to local conditions and aquatic habitat demand.

Habitat modeling is a scientific method to assess the (positive or negative) impact of hydromorphological changes on physical in-stream habitats. Fish are a common indicator of aquatic habitat richness because fish habitat preferences are well described, the number of native fish species is low and fish inform about the physical quality of the habitats [29–32]. For example, the European Water Framework Directive [16] defines fish as a key indicator species in determining the ecological status of surface water bodies. Even if the modeling procedures have model uncertainties and limitations, they solve major both temporal and spatial limitations of field observation approaches. Furthermore, advanced modeling procedures can quickly evaluate the success and cost-effectiveness of engineering measures [33,34], and are increasingly used in water resource management [29,34], e.g., to investigate habitat changes caused by hydropeaking [35,36], weir removal [37,38], and reservoirs [39]. The Computer Aided Simulation Model for Instream Flow Requirements (CASiMiR) is a habitat simulation tool for aquatic organisms with a focus on fish and macroinvertebrates. It uses a multivariate fuzzy-logical approach to link abiotic attributes with habitat requirements of aquatic species, resulting in a habitat suitability index (HSI). The use of fuzzy logic enable to deal with highly variable, linguistic, and even vague data [40]. It uses the three physical characteristics of rivers that allow for the determination of the quality of habitats for fish species: flow velocity, water depth, and substratum [41,42] Each parameter is classified by overlapping membership-functions that are described by vague linguistic variables (e.g., low, medium, high). The relationship between these

physical parameters and the biotic response are determined by using IF-THEN rules (fuzzy-rules) [43]. Fuzzy rules are defined for all the possible combinations in close collaboration with biological experts. Hence, the experts themselves define the conditions under which habitat quality is described as 'high', 'medium', or 'low'. This procedure has the significant advantage that expert knowledge of aquatic biologists [44] can be easily transferred into a mathematical approach. The model output enables the predictions of habitat quality and quantity for different fish species and their life stages in the case of defined river sections [45,46].

The objectives of this study were (i) to investigate the effect of change of minimum water flow on physical aquatic habitats and (ii) to identify the best minimum water flow strategy in the context of water diversion to secure habitats for target fish species in a case study. The investigations were carried out in the hydromorphologically restored main channel of the Isar River in Munich (Germany) (Figure 1). Most of the Isar water (93% of the mean annual discharge) is diverted into a side channel to supply hydroelectric power plants. As part of a restoration project, intense negotiations were carried out with users, NGOs, and the energy producer to increase the minimal discharge flowing into the restored river section. Identification of the best water-sharing scenario should provide important insights for this and future restoration projects. We hypothesized that an increase in minimal water flow would have a positive effect on the physical habitat suitability for fish species and tested if the overall aquatic habitat quality is the best when water diversion is removed. We tested these hypotheses by modeling habitat suitability under different discharges for three fish species, which were a target of the restoration, i.e., *Thymallus thymallus* L., *Hucho hucho* L., and *Chondrostoma nasus* L.



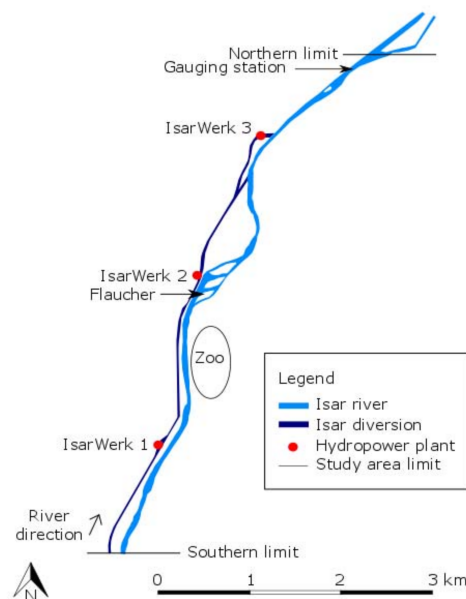
**Figure 1.** Map of Bavaria (Germany) with the location of the Isar River, Munich city and the hydroelectrical power plants at the Isar.

## 2. Material and Methods

### 2.1. Study Area

The pre-alpine Isar River drains the Northern Alps and joins the Danube River. The construction of 43 hydroelectric power plants at the Isar River and its canals began in the 1920s, causing major morphological changes, regulation of the flows, and longitudinal discontinuity. In 1959, the Sylvenstein Reservoir was built in the Alps 75 km upstream of Munich (Germany) as protection against major flood events, in order to avoid dryness and to ensure water supply for hydroelectric power plants and cooling water for nuclear and thermal power plants. Rain events and snowmelt inside the catchment area downstream of the reservoir influence the discharge of the Isar River in Munich. Winter is the driest season, with a mean discharge of  $47.1 \text{ m}^3/\text{s}$  recorded between 1959 and 2012 in Munich city center (<http://www.hnd.bayern.de>). In spring, discharge increases with temperature and snowmelt. During the summer, discharge is higher, but many variations occur. Flood events due to rain are frequent (mean maximum discharge in summer =  $395 \text{ m}^3/\text{s}$ ) and cause very high discharges ( $650\text{--}1050 \text{ m}^3/\text{s}$ ). Summer dryness may also cause sporadic minimal discharges during summer, but are mostly avoided by the Sylvenstein Reservoir. Despite discharge regulations and water flow diversion, the Isar River bed benefits from frequent (at least biannual) major sediment transport during flood events. Furthermore, the water quality at the Isar River benefits from the absence of intensive agriculture and from the absence of industry and major cities upstream of the City of Munich (<http://www.gkd.bayern.de/?sp=en>).

The Isar River is intensively used for hydropower generation. In the Munich metropolitan area, 11 hydroelectric power plants produced 73.5 million kilowatt hours in 2013. At the southern city limit, a weir diverts the water of the Isar into a side canal (maximum discharge of  $90 \text{ m}^3/\text{s}$ ), which supplies three run-of-river hydroelectric power plants: Isarwerk 1 with 15 million kWh in 2011, Isarwerk 2 with 15 million kWh in 2011, and Isarwerk 3 with 17 million kWh in 2011 (Figure 2). Within the river restoration project “New Life for the Isar” (1999–2011), the Bavarian Water Agency and Munich city government intended to improve the morphological status of eight kilometers of the Isar from the southern limit of the city territory to the city center. One of the restoration measures was the increase in minimum flow inside the near-natural original river bed (from  $5$  to  $12 \text{ m}^3/\text{s}$ ) in order to improve riverscape aesthetic, recreational uses, and the quality of aquatic habitats.

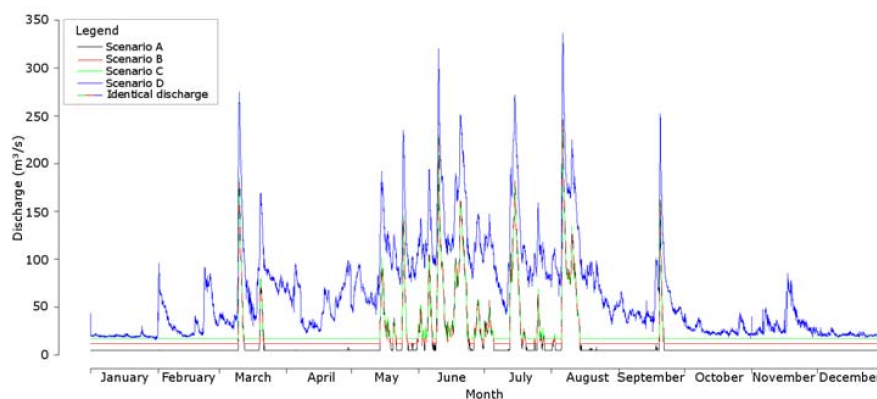


**Figure 2.** Map of the study area with the location of the hydroelectrical power plants at the Isar side canal.

## 2.2. Physical Characteristics

Substratum, flow velocity, and water depth are the most commonly used variables to describe physical habitats of fish species [41,42]. We established a two-dimensional (2D) hydromorphological model of the restored river reach, i.e., from the Großhesseloher Bridge (48°4′29.59″ N, 11°32′25.83″ E) to the Museum Island (48°7′41.42″ N, 11°34′46.88″ E) when considering these three river characteristics on a 5-m grid. First, the substratum characteristics were visually determined by 1628 field measurements performed by boat in summer 2013 during mean low discharge (MNQ = 16.5 m<sup>3</sup>/s). Nine substratum types of the top layer of the river bottom were distinguished according to the grain size of the dominant component: (1) organic matter or detritus; (2) silt, clay, or loam; (3) sand (<2 mm); (4) fine gravel (2–6 mm); (5) medium gravel (6–20 mm); (6) large gravel (20–60 mm); (7) large stones (60–120 mm); (8) boulders (>200 mm); and, (9) rock or concrete. The resulting substratum map was digitalized using the software SMS 10 (Surface Modelling System, Aquaveo, Utah USA). We calculated that the medium gravel substratum (d<sub>50</sub> = 26 mm) in the Munich region started to move at 290 m<sup>3</sup>/s and that the fine-grained sediment (<10 mm) already drifted at 80 m<sup>3</sup>/s. Consequently, substratum characteristics were assumed to be constant over time for discharges below these limits. Then, the hydromorphological model of the study area (160,000 elements)—the riverbed and the floodplain inside the dikes—was established using a two-dimensional hydrodynamic numerical model Hydro\_AS-2D version 3 [47] to simulate the spatial distribution of the water depth and flow velocity for the investigated discharges in the riverbed. The model solved the shallow-water equations using finite volume discretization. In order to extensively calibrate and validate the model, water level measurements for four discharges ranging from 65 to 782 m<sup>3</sup>/s were applied verifying adequate model performance.

In order to identify the most realistic scenarios to be tested with the CASiMIR modelling procedure, we first carried out open interviews and discussions with groups of recreational users, NGOs, and the energy producer concerning the potential minimal discharges flowing into the restored river section. Resulting from these consultations, we simulated the following four scenarios: Scenario A corresponds to the lowest residual water discharge flowing inside the riverbed, i.e., 5 m<sup>3</sup>/s at the southern city border, according to the water use agreement prior to restoration and established in the early begin of the nineteenth century; Scenario B corresponds to an daily increase of 7 m<sup>3</sup>/s (from 5 to 12 m<sup>3</sup>/s), and was defined as maximal compromise by the energy producer; Scenario C corresponds to a daily increase of 12 m<sup>3</sup>/s, namely from 5 to 17 m<sup>3</sup>/s, as required by user NGOs as restoration measure; Scenario D corresponds to the mean annual discharge without diversion (68.5 m<sup>3</sup>/s), as required by nature conservation NGOs. The discharges that are applied in the four scenarios correspond to values at the southern (upstream) limit of the modelled restored river segment. Flow variations were calculated applying a two-dimensional hydrodynamic numerical model using a 5 m grid. For all of the scenarios, steady-state boundary conditions were used. The complete discharge of the Isar, i.e., the main channel and the side canal used for hydropower generation, was measured at the gauging station (Figure 2) on an hourly basis by the WWA. The hydrological year 2016 was chosen as hydrological reference to compare the scenarios (Figure 3) because the data were the most recent, very accurate, and no unusual hydrological events, such as extreme floods or droughts (beyond the 500 year maximum/minimum values) happened. It is worth mentioning that for Scenarios A, B, and C, the discharge flowing into the riverbed was constant, except for flood events, which caused important flash floods (Figure 3). Isar flood events in March are due to snow melt and in summer are due to storm with major rain events in the Alps.



**Figure 3.** Hydrograph of the four scenarios based on data of the hydrological year 2016.

### 2.3. Fish Species Studied

The fish species for this study (*Thymallus thymallus* L., *Hucho hucho* L., and *Chondrostoma nasus* L.) were selected due to their status as a target of the restoration, as indicator species of the overall stream ecological quality, and according to historical information on typical Isar fish species [48].

*Thymallus thymallus* L. (European grayling) belongs to the family of Salmonidae and is the only species of the genus *Thymallus* that is native to Europe. It is a widespread species in submontane reaches of cold, fast-flowing, and well-oxygenated rivers with sand or stone substrate [49]. According to the IUCN Red List, the Grayling is classified as “Least Concern” by the European Union but the species suffers locally from river pollution, dam constructions, and river regulations [50]. A very low density of European grayling has been found at the Isar in Munich and its tributaries [51]. Fewer than five fish per 100-m river section have been fished inside the investigated river section, whereas a healthy population should achieve more than 150 individuals per section [52]. Three habitat types that are related to different life cycle stages have been identified [49–51,53–65] and were labeled TTA (Habitat for Adults), TTS (Habitat for Spawning), and TTJ (Habitat for Juveniles) (Table 1).

*Hucho hucho* L., commonly named European huchen or Danube salmon, is the world’s biggest salmonid and it is threatened with extinction. It is a salmonid endemic to the Danube drainage basin in Central Europe, inhabiting fast-flowing and well-oxygenated streams with gravel bars [66,67]. The species is listed in Annex II of the European Flora Fauna Habitat Directive [68], as an endangered species in Appendix III of the Convention on the Conservation of European Wildlife and Natural Habitats [69], and it is classified as “Endangered” on the Red List. The current main threats to the species are flow regulations from dams and water pollution [66,70,71]. The European huchen occurs at a very low density in the Isar in Munich and its tributaries, with fewer than five fishes per 100 m of river [51,52]. Three habitat types that are related to different life cycle stages have been identified [66,67,70–76] and were labeled HHA (Habitat for Adults), HHR (Habitat for Adults during the pre-reproduction period), and HHJS (Habitat for spawning and Juveniles) in this study (Table 1).

*Chondrostoma nasus* L., commonly named Common nase, is an endemic cyprinid in the drainage basins of the Southern Baltic, the Southern North Sea and the Black Sea, e.g., the Danube basin, inhabiting moderately to fast-flowing large to medium-sized rivers with a rock or gravel bottom. According to the Red List Category, the common nase is classified as “Least Concern”. It is protected by the Convention on the Conservation of European Wildlife and Natural Habitats [69] and it is locally threatened by damming, destruction of spawning sites, and pollution [49]. The common nase historically occurred in the investigated urban section of the Isar, but currently, no *C. nasus* can be found [52]. Six habitats have been identified [49,77–81] and were labeled CNS (Habitat for spawning), CNL (Habitat for larval development), CNJ (Habitat for Juveniles), CNR (Habitat for Adults during the pre-reproduction period), CNAS (Habitat for Adults during the summer), and CNAW (Habitat for Adults during the winter) in this study (Table 1).

**Table 1.** List of habitats associated with life-cycle stages of *Thymallus thymallus* L., *Hucho hucho* L., and *Chondrostoma nasus* L. described in terms of their physical characteristics.

Fish Species	Habitat Type	Life Cycle Stage	Season	Water Velocity	Water Depth	Substratum
<i>Thymallus thymallus</i>	TTA	Adults	All	Moderate to high (0.7–1.1 m/s)	High (100–140 cm)	Medium to fine-grained substratum
	TTS	Adults spawning	Spring (January–April)	Very low (0.2–0.4 m/s)	Low to very high (10 cm–230 cm)	Fine-grained substratum
	TTJ	Juveniles	All	Moderate to high (0.7–1.1 m/s)	Moderate (50–80 cm)	Fine-grained to medium substratum
<i>Hucho hucho</i>	HHA	Adults	All	Moderate to very high (>0.7 m/s)	High (>100 cm)	Fine-grained to medium substratum
	HHR	Adults (pre-reproduction)	Spring (February–April)	High to very high (>1.0 m/s)	Moderate to high (30–150 cm)	Medium gravel to large stones
	HHSJ	Adults spawning and Juveniles	Spring (February–May) All	High to very high (>1.0 m/s)	Moderate (20–60 cm)	Medium gravel
<i>Chondrostoma nasus</i>	CNS	Spawning	Spring (March–May)	High (1.0–1.5 m/s)	Moderate (20–40 cm)	Medium to fine-grained substratum
	CNL	Larvae	Spring	Low (0.5–0.7 m/s)	Low (5–10 cm)	Fine-grained substratum
	CNJ	Juveniles	All	Low (under 0.6 m/s)	Low (5–20 cm)	Coarse substratum
	CNAW	Adults	Winter	High (1.0–1.5 m/s)	High (1–2 m)	Variable substratum
	CNR	Adults (pre-reproduction)	Spring (February–May)	Low to very low (less than 0.7 m/s)	Moderate (20–40 cm)	Medium gravel to large stones
CNAS	Adults	Summer	Moderate to high (0.7 to 1.5 m/s)	Moderate (20–50 cm)	Rock to gravel	

## 2.4. Habitat Model

The CASiMiR software (Ecohydraulic Engineering GmbH, Stuttgart, Germany) computes habitat suitability for selected indicator species using a multivariate fuzzy logic approach to link the abiotic attributes with the habitat requirements of fish, e.g., the temporal and spatial variability of water depth, flow velocities, and bed substrate types [43,44]. The calculation uses fuzzy quantities of the descriptive physical properties, as formulated by fish biologists in the form of linguistic categories, i.e., “very high”, “high”, “medium”, “low”, and “very low” (Table 2). The fuzzy logic approach is an excellent modeling technique to overcome the problems of dealing with uncertain and unprecise information, which commonly occur in ecological investigations [82].

**Table 2.** List of the variables used as input for the habitat suitability model.

Linguistic Modalities	Velocity	Water Depth	Substratum
Very low	0–0.4 m/s ( $\pm 0.1$ m/s)	0–0.1 m ( $\pm 5$ cm)	Organic matter
Low	0.5–0.7 m/s ( $\pm 0.1$ m/s)	0.1–0.2 m ( $\pm 5$ cm)	Sand < 6 mm
Medium	0.75–0.9 m/s ( $\pm 0.1$ m/s)	0.2 ( $\pm 5$ cm) to 0.5 ( $\pm 10$ cm)	Gravel from 6 to 120 mm
High	1 m/s ( $\pm 0.15$ m/s) to 1.5 m/s ( $\pm 0.25$ m/s)	0.5 ( $\pm 10$ cm) to 1.15 m ( $\pm 25$ cm)	Large stones 12–20 cm
Very high	Start at 1.75 m/s ( $\pm 0.25$ m/s)	Start at 1.25 ( $\pm 25$ cm)	Boulders > 20 cm, Rock

The influence of the interactions between the three physical variables on habitat suitability have been elaborated based on the literature and in collaboration with a fish biology expert from the Bavarian State Research Center for Agriculture (Bayerische Landesanstalt für Landwirtschaft) during a personal interview (Table 3) [81].

**Table 3.** Example of a fuzzy rule set describing the habitat requirements of the European grayling for adult fishes in the Isar River (Germany).

Velocity	Depth	Substrate	HSI	Example
M	H	VH	VL	Rule 1: IF velocity ‘Medium’ AND depth ‘High’ AND substratum ‘Very high’ THEN HSI ‘Very low’
M	H	H	H	Rule 2: IF velocity ‘Medium’ AND depth ‘High’ AND substratum ‘High’ THEN HSI ‘High’
M	H	M	VH	Rule 3: IF velocity ‘Medium’ AND depth ‘High’ AND substratum ‘Medium’ THEN HSI ‘Very high’
M	M	H	M	Rule 4: IF velocity ‘Medium’ AND depth ‘Medium’ AND substratum ‘High’ THEN HSI ‘Medium’
M	M	M	H	Rule 5: IF velocity ‘Medium’ AND depth ‘Medium’ AND substratum ‘Medium’ THEN HSI ‘High’

## 2.5. Data Analysis

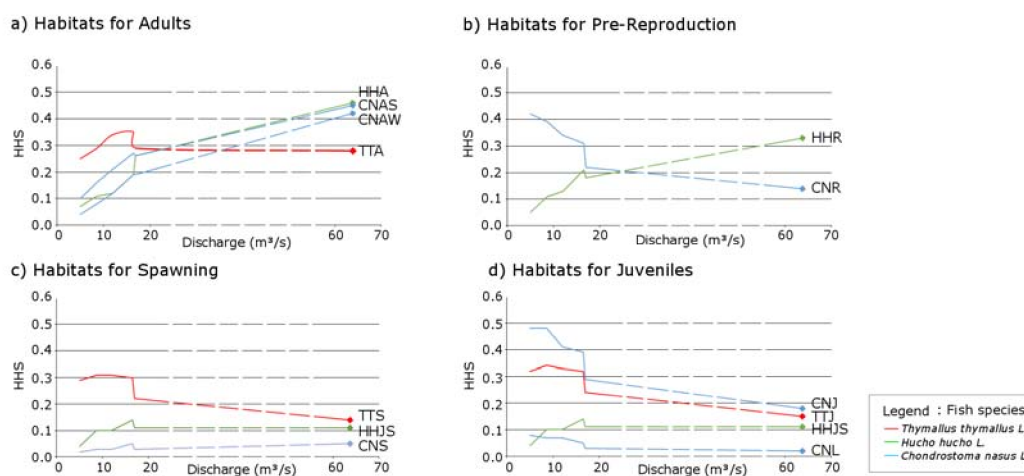
The model was run for the three fish species to investigate the influence of increased minimum and annual mean discharges on the physical habitat suitability. First, we investigated the suitability of the physical habitats when considering a discharge spectrum from the minimal discharge applied ( $5 \text{ m}^3/\text{s}$ ) to the natural mean annual discharge ( $68.5 \text{ m}^3/\text{s}$ ). Then, we investigated which scenario produced the best habitat quality. For comparison we used: The Habitat Suitability Index (HSI), the Weighted Usable Area (WUA) of each HSI value, and the Hydraulic Habitat Suitability index (HHS). The HSI is computed by CASiMiR for each element of the hydromorphological mesh. The HSI is the most common index describing the biological response to abiotic attributes and represents the suitability of a habitat for a target species [43]. The HSI has scalar values between 0 and 1, with the latter representing the most suitable habitat. The mean, median, and standard deviation of the HSI values for the whole river stretch were compared using both Ansari-Bradley test and Wilcoxon-Mann-Whitney-Test, and were plotted for each scenario and habitat types per species. The WUA corresponds to the wetted



area weighted by its suitability for a target fish species and habitat type, and is related to a spectrum of different flow rates for the whole stretch [44]. The HHS removes the effect of changing the surface of the wetted area between discharge on the WUA values [83]. While the HHS provides information about the overall quality of the river for one habitat type, the WUA for each HSI provides information about the quantity of suitable habitats, for example, the surface of the highly suitable habitat ( $SI > 0.6$ ) for one habitat type. For all of the comparisons, we used both the Kruskal–Wallis rank sum test, and a pairwise comparison using t-tests with pooled standard deviation.

### 3. Results

The quality and quantity of the suitable habitat surface varied with discharge. These relationships varied according to habitat type. The proportion of suitable habitats for Adults (HHA, CNAW, CNAS, and TTA) generally increased with discharge (Figure 4a), but for *T. thymallus* (TTA) they decreased at discharges above 17 m<sup>3</sup>/s. The quality of the habitats that were used during the pre-reproduction period decreased with discharge for *C. nasus* (CNR), but increased with discharge for *H. hucho* (HHR) (Figure 4b). Spawning habitats (HHJS, TTS, and CNS) benefited from a slight increase in discharge, but habitat suitability decreased for *T. thymallus* (TTS) and remained stable for *H. hucho* (HHJS) at medium to high discharges (Figure 4c). Increasing discharge led to decreasing habitat suitability for Juveniles (CNJ and TTJ), but Juvenile *H. hucho* (HHJS) benefited from a discharge increase below 16.5 m<sup>3</sup>/s (Figure 4d). Since the trends were different between the fishes, further analyses are presented separately for each species. The following figures represent the results for the entire study area, with the exception of the last, which exemplarily shows maps of the distribution of habitat suitability for the Flaucher area.

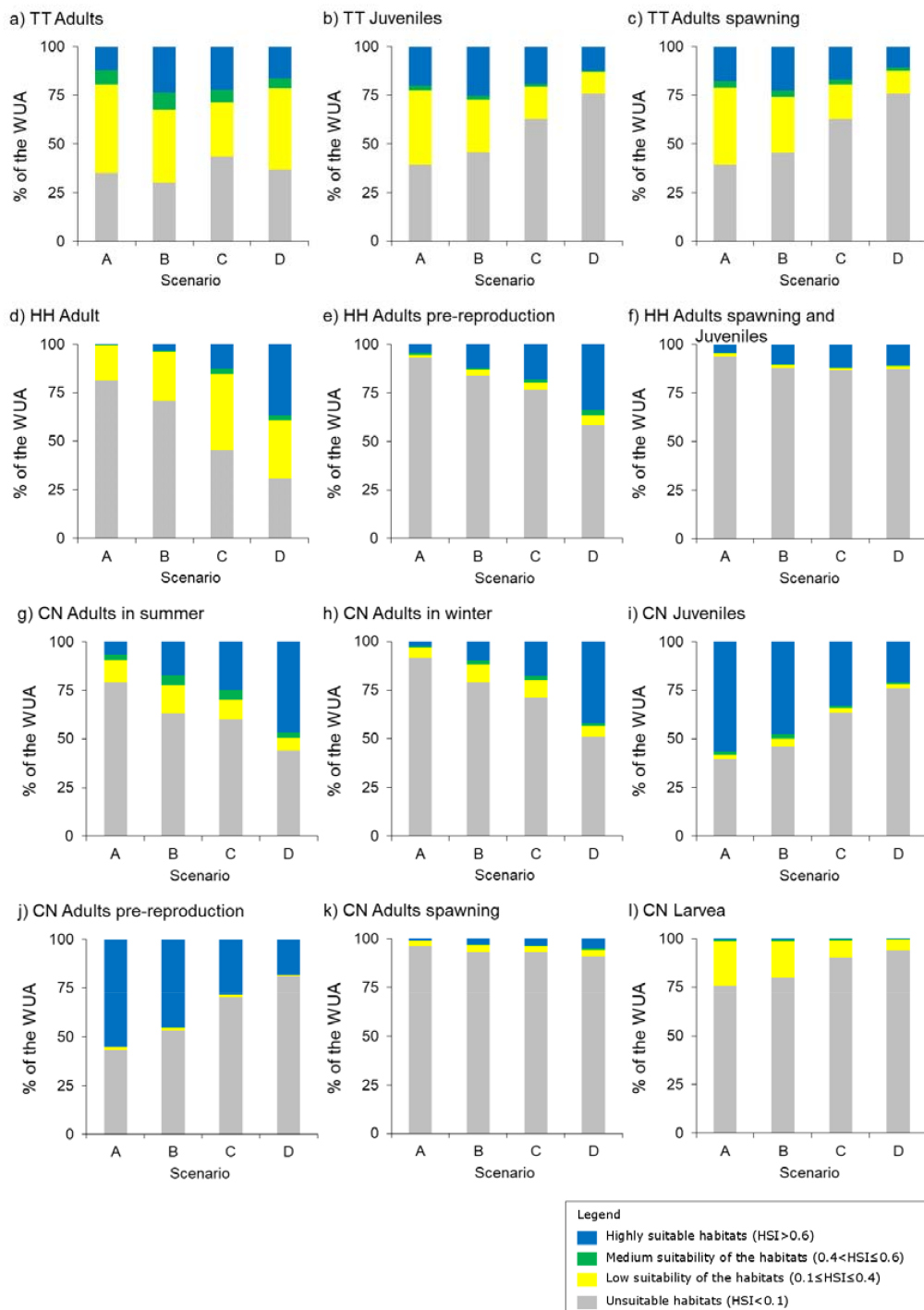


**Figure 4.** Hydraulic habitat suitability (HHS) for the twelve habitat types considering discharge variations from 5 to 68.5 m<sup>3</sup>/s: (a) Habitat for Adults *C. nasus* in winter (CNAW), *C. nasus* in summer (CNAS), *T. thymallus* (TTA), and *H. hucho* (HHA); (b) Habitat types for Adults pre-reproduction *H. hucho* (HHR) and *C. nasus* (CNR); (c) Habitat type for Adults spawning *T. thymallus* (TTS), *H. hucho* (HHJS), and *C. nasus* (CNS); (d) Habitat types for Juveniles *C. nasus* (CNJ), *T. thymallus* (TTJ), and *H. hucho* (HHJS), and for larval development of *C. nasus* (CNL).

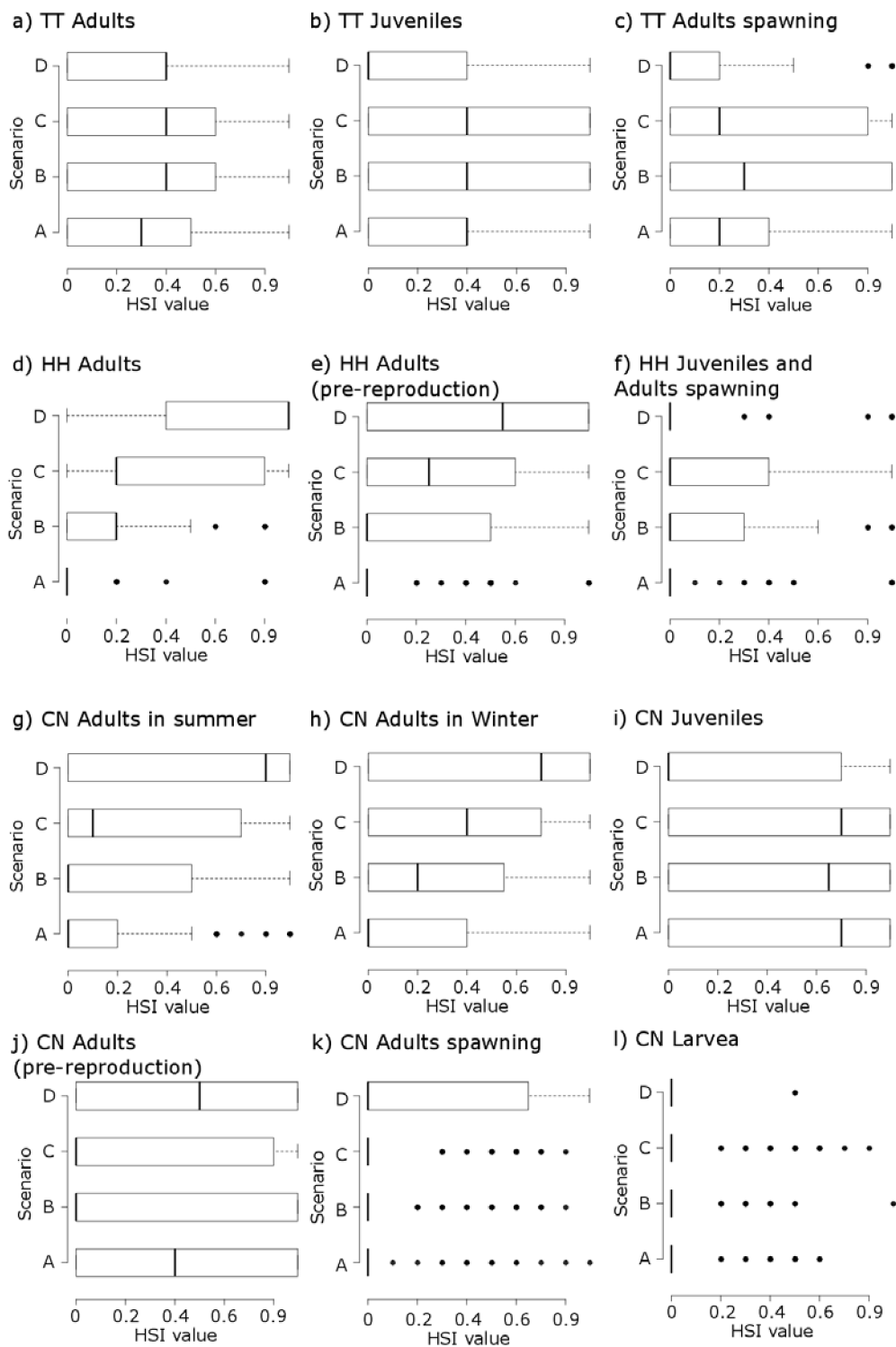
#### 3.1. *Thymallus thymallus* L.

The highest HHS for *T. thymallus* was found at 16.5 m<sup>3</sup>/s and the highest proportion of highly suitable habitats (HIS > 6) for scenario B was: TTA = 26.1% (Figure 5a), TTJ = 25.5% (Figure 5b), and TTS = 22.8% (Figure 5c). The difference between scenarios B and C was not statistically significant. The HSI values differed between scenarios A, B (or C) and D for all of the studied habitats ( $p < 0.01$ , Kruskal–Wallis and pairwise test). Scenario A had significantly lower HSI values than scenarios B and C. An increase from 5 to 12 m<sup>3</sup>/s in minimal water flow (A to B), increased the mean HSI

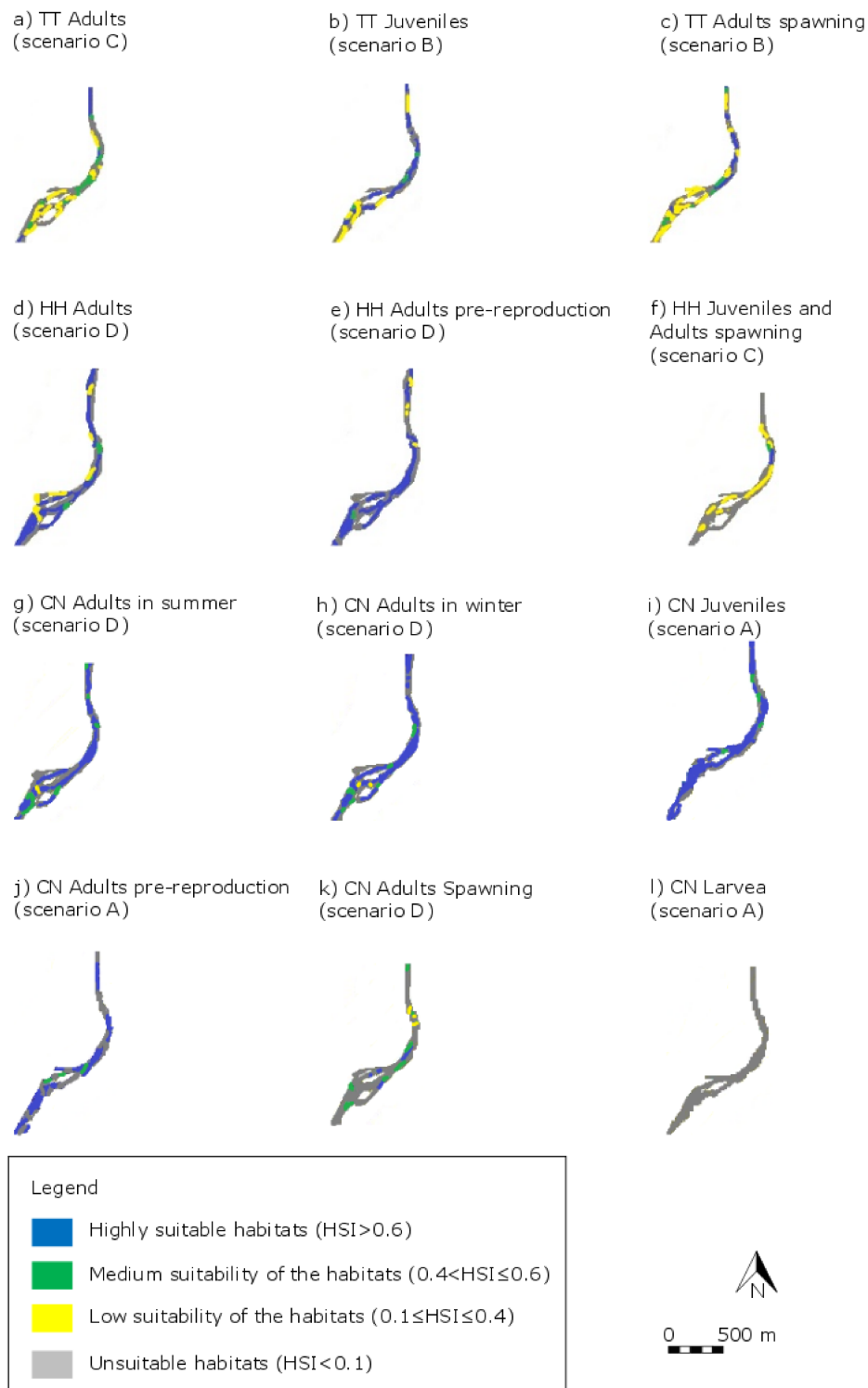
values for all studied habitats, i.e., TTA (Figure 6a), TTJ (Figure 6b), and TTS, (Figure 6c). A major increase in water quantity, as simulated by scenario D, decreased the HSI values of all the investigated habitat types ( $p < 0.01$ , Kruskal–Wallis and pairwise test). The best scenario for Adults was C, but for recruitment, it was B (Table 4). While highly suitable habitats for Adults were near to the zoo (Figure 2), highly suitable habitats for recruitment were located at the Flaucher (Figure 7a–c).



**Figure 5.** Percent of the Weighted Usable Area (WUA) that is characterized from highly suitable to unsuitable habitats for each scenario considering each habitat type of *Thymallus thymallus* L. (a–c), *Hucho hucho* L. (d–f), and *Chondostroma nasus* L. (g–l).



**Figure 6.** Box plots of the Habitat Suitability Index (HSI) value for the different scenarios considering each habitat type of *Thymallus thymallus* L. (a–c), *Hucho hucho* L. (d–f), and *Chondrostoma nasus* L. (g–l). For abbreviations of habitat types see Table 1 (mean is the black line, black dots are outliers).



**Figure 7.** Extract of Habitat suitability maps of the Flaucher site. Model outputs displayed the spatial distribution of the usable area for the best scenario found while considering each habitat type of *Thymallus thymallus* L. (a–c), *Hucho hucho* L. (d–f), and *Chondostroma nasus* L. (g–l) at annual mean discharge.

**Table 4.** Weighted Usable Area (WUA), Hydraulic Habitat Suitability index (HHS), and Mean Habitat Suitability Index (mean HSI) value for each habitat and scenario. The best scenario for each habitat is highlighted.

Fish species	Life cycle stage (Habitat types)	Indicators	Scenario			
			A	B	C	D
<i>Thymallus thymallus</i>	Adults (TTA)	WUA (1,000 m <sup>2</sup> )	183	274	276	233
		HHS	0.25	0.34	0.29	0.28
		Mean HSI	Low	Low	Medium	Low
	Spawning (TTS)	WUA (1,000 m <sup>2</sup> )	212	255	210	121
		HHS	0.29	0.31	0.22	0.14
		Mean HSI	Low	Low	Medium	Very low
	Juveniles (TTJ)	WUA (1,000 m <sup>2</sup> )	229	270	222	128
		HHS	0.32	0.33	0.24	0.15
		Mean HSI	Low	Low	Low	Very low
<i>Hucho hucho</i>	Adults (HHA)	WUA (1,000 m <sup>2</sup> )	48	94	243	384
		HHS	0.07	0.12	0.26	0.46
		Mean HSI	Very low	Low	Low	High
	Adults pre-reproduction (HHR)	WUA (1,000 m <sup>2</sup> )	35	102	171	277
		HHS	0.05	0.13	0.18	0.33
		Mean HSI	Very low	Very low	Very low	Medium
	Spawning and Juveniles (HHJS)	WUA (1,000 m <sup>2</sup> )	31	79	104	88
		HHS	0.04	0.10	0.11	0.11
		Mean HSI	Very low	Very low	Low	Very low
<i>Chondrostoma nasus</i>	Adults during the summer (CNAS)	WUA (1,000 m <sup>2</sup> )	72	167	241	377
		HHS	0.10	0.21	0.26	0.45
		Mean HSI	Low	Low	Low	Medium
	Adults during the winter (CNAW)	WUA (1,000 m <sup>2</sup> )	30	100	182	355
		HHS	0.04	0.12	0.19	0.42
		Mean HSI	Low	Low	Medium	Medium
	Adults pre-reproduction (CNR)	WUA (1,000 m <sup>2</sup> )	300	277	207	118
		HHS	0.42	0.34	0.22	0.14
		Mean HSI	Medium	Low	Low	Medium
Juvenils (CNJ)	WUA (1,000 m <sup>2</sup> )	341	330	268	153	
	HHS	0.48	0.41	0.29	0.18	
	Mean HSI	Medium	Medium	Medium	Low	
Spawning (CNS)	WUA (1,000 m <sup>2</sup> )	11	27	32	39	
	HHS	0.02	0.03	0.03	0.05	
	Mean HSI	Very low	Very low	Very low	Low	
Larvae (CNL)	WUA (1,000 m <sup>2</sup> )	60	57	31	18	
	HHS	0.08	0.07	0.03	0.02	
	Mean HSI	Very low	Very low	Very low	Very low	

### 3.2. *Hucho hucho* L.

The HHS of all the habitats of *H. hucho* increased with discharge: HHA (Figure 4a), HHR (Figure 4b), and HHJS (Figure 4c). The proportion of highly suitable habitats for Adults (HHA and HHR) increased with discharge reaching 36.7% (Figure 5d) and 34% (Figure 5e) at a discharge of 63.8 m<sup>3</sup>/s. Interestingly, the proportion of highly suitable areas for spawning (HHJS) (Figure 5f) also increased with discharge, but peaked at 16.5 m<sup>3</sup>/s. The HHS remained stable between scenarios C and D, but the proportion of highly suitable areas was higher for scenario B than C and higher for scenario C than D: 15.2%, 11.7%, and 10.9% of the area, respectively (Figure 5f). The mean HSI differed among the scenarios for all of the studied habitats ( $p < 0.01$ , Kruskal–Wallis and pairwise test). From scenario A to D, the mean HSI of the habitats for Adults (HHA) increased from very low to high (Figure 6d) and the mean HSI for habitats for the pre-reproduction period increased from very low to

medium (Figure 6e). It is noteworthy that the trend was different for the habitats for spawning and juvenile growth (HHJS). While from scenario A to C the mean HSI values increased from very low to low, they decreased from scenario C to D (Figure 6f). The best scenario for Adults was D, but for recruitment, it was C (Table 4). While highly suitable habitats for Adults were distributed all around studied area, highly suitable habitats for recruitment were located at the South of the zoo and not at the Flaucher (Figure 7d–f).

### 3.3. *Chondrostoma nasus* L.

The HHS for Adults *C. nasus* increased with discharge (Figure 4a), remained very low for spawning (Figure 4b), and decreased with the discharge for recruitment (Figure 4c,d). The largest proportions of highly suitable habitats (HIS > 6) for Adults during the summer (CNAS) and the winter (CNAW) for scenario D were: 46.7% (Figure 5g) and 42.8% (Figure 5h) of the wetted area, respectively. Contrarily, the largest proportion of highly suitable habitats for Juveniles (CNJ) and for Adults during the pre-reproduction period (type CNR) for scenario A were: 56.5% (Figure 5i) and 54.97% (Figure 5j) of the area, respectively. Highly suitable habitats for spawning and larval development (CNS and CNL) remained rare: 5.22% (Figure 5k) and 5% (Figure 5l) of the wetted area, respectively. While the mean HSI of habitats for Adults during the summer (Figure 6g) and the winter (Figure 6h) increased with discharge, it decreased with discharge for Juveniles (Figure 6i). The mean HSI value for Adults in the pre-reproduction period decreased with discharge, increased for scenario D, and achieved the medium HSI value again (Figure 6j). Interestingly, mean HSI of habitats for spawning remained very low, but for scenario D, the variation in HSI value was important and locally reached a very high value (Figure 6k). However, for larval development habitats remained unsuitable. The best scenario for Adult survival and reproduction was D, but for recruitment, it was A (Table 4). While highly suitable habitats for Adults and Juveniles were located at the two third south of the river section, included the Flaucher (Figure 7g–l), highly suitable habitats for spawning activities and larval development were almost inexistent.

## 4. Discussion

### 4.1. Identification of the Best Scenario

We investigated the effects of an increase in minimal water flow on the quality of the physical habitats for three target fish species in the Isar in Munich (Germany). The presented modeling approach was set up to analyze whether there was a single discharge scenario suitable for all of the fish species, but there was no “one size fits all” solution. None of the four scenarios provided permanently suitable habitat conditions for the three species, rather, different life stages of the fish species showed preferences for different scenarios. However, general trends could be identified. While the slight increase in minimal water flow increased the quality and quantity of almost all of the investigated habitats, a medium or large increase in discharge reduced some of them.

Since all of the investigated species historically occurred in the Isar in Munich, we expected scenario D (no diversion, MQ of 63.8 m<sup>3</sup>/s) to be ecologically the best. It was identified as the best for adult *Hucho hucho*, but it provided too high flow for *Thymallus thymallus*, which benefited more from discharges that were simulated by scenarios B and C (MQ between 12 and 17 m<sup>3</sup>/s). Variations in water depth mostly differentiated *Hucho hucho* habitats [66,71], and the best scenario for juvenile habitats for *Hucho hucho* was C. Habitats of *Chondrostoma nasus* have very different combinations of flow velocities and water depths [79]. While Scenario D was the best for adults, the habitats for juveniles were better and more numerous in scenario A.

Given the current morphological setting of the remaining river, it was not possible to improve all habitats of all three target species by only changing the discharge. Consequently, change of discharge schemes from the hydropower dam could be run to favor one or two species per year (and the schemes could be varied from year to year in order to favor different species over time).

We therefore suggest that restoration procedures should combine the morphological and hydrologic measures. During the two last centuries, the wetted area in the river corridor has been reduced by more than 75% [84–86]. Furthermore, the slope of the river bed has changed dramatically due to an accelerated incision [85]. Morphological restoration, namely the removal of the channelization, meandering and slope reduction, increases the diversity of physical habitats [87,88], and the investigated river reach was hydro-morphologically restored. However, morphological restoration in urban areas, namely of heavily modified water bodies [16], remains difficult because of physical limitations [89]. These findings suggest that despite successfully implemented restoration measures, the slope of the Isar remains too steep to support suitable habitats for all three fish species. Additional measures, specifically the re-establishment of fringing floodplain area, should allow for further braiding and meandering of the river to support a higher diversity of aquatic habitats.

We also like to suggest that nature-like and seasonal discharge modulation should improve the quality and quantity of the habitats when they are most needed. Dynamic minimum water control has already been defined as crucial to assure or improve habitat quality, despite the regulated river system [90]. Further investigations should examine the aspect of timing and the match and mismatch between the actual hydromorphological situation and the specific habitat requirements of the life stage of the studied species. This can determine the “windows of opportunity” or “windows of susceptibility” for individual species, and result in a “serial biodiversity” of assemblages of species that have similar ecological requirements [91–93].

The European Commission [94] has developed a common implementation strategy (CIS) to implement the concept of ecological flows, i.e., the “amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon”, i.e., an improvement of the flow regime to warrant the targets of the European Water Framework Directive. This approach is based upon the natural flow paradigm [95], the Flood Pulse Concept [92], and the environmental flow concept [23,96].

In the case of alpine and pre-alpine rivers, such as the Isar, the flow regime is specifically relevant for the distribution of sediments, the generation of habitats (and refuge) during flood events, and protection from drought and overheating of the water during low-flow periods. Practical discussions among river managers, however, mostly focus on the latter point (minimum flows during summer), whereas our study shows the complexity of the problem and the need to tackle the flow regime, the available habitat space, and the river gradient at the same time. The manipulation of the flow regime via the discharge management of the hydropower dams upstream towards a more natural flow regime can only be seen as a first and (as stand-alone activity) transitory measure to be taken in order to reduce the environmental impact until measures to increase and improve available habitats will be implemented.

In the case of the Isar in Munich for, since no additional water source is available, there are conflicts between ecological requirements of the investigated fish species and the economic needs in the case of the Isar at Munich. The studied fish species need the full discharges to reorganize sediment structures and to create habitats for spawning and juvenile development during winter and spring, while human needs for electrical energy prevail the entire year. Economic feasibility studies to assess the costs of a more nature-like discharge from the hydropower dams are needed. The decision scheme, however, should also include the ecosystem services that are provided by a healthy river. The modeling procedure presented here, combined with an economic feasibility study may help to define the best restoration scenario and to design a dynamic minimum water strategy. The model also provides a cost-efficient method to support the design of future mitigation and restoration projects.

#### 4.2. Habitat Distribution Changes

The modeling procedure showed that spatial distribution of the habitats differs between the species. Accordingly, the method provides important insights to define management preferences in terms of managing for a single habitat in chosen river sections. Spawning habitats for *Chondostroma nasus* L. were rare or absent in the restored stretch of the Isar. This finding is consistent with historical

data indicating that *Chondostroma nasus* L. preferred to spawn in Isar tributaries rather than in the main river channel [79]. Today, the connectivity between the main channel of the Isar and its tributaries is hampered by barriers and degradation [97]. Restoration of the Isar may intend to create instream spawning sites but adult fish are bound to their historical spawning area [77–79,98] and reproduction in new and man-made environments showed only limited success [99]. Therefore, the biological potential of such reconstructed reproduction areas remains unclear [100]. Thus, in the case of the nase, an appropriate restoration goal could be the reestablishment of suitable habitats for adults and juveniles rather than for reproduction activities, which should be established by restoration measures of the tributaries and an improved connectivity between mainstream and tributaries.

Interestingly, in the scenarios with water diversion (scenarios A, B, and C), hydropeaking occurred frequently. It is a major ecological issue and it has been identified as one of the most significant pressures in alpine streams causing quick alterations in habitat quantity and quality [13]. Fish species are the group of aquatic organisms that are best able to adapt to long-term changes in hydropeaking by changing their habitat preferences, provided that heterogeneous river morphology is given [11,13]. Noack and Schneider [101] examined habitat suitability during hydropeaking events and found a significant shift in suitable habitats of juvenile European graylings from the main channel towards gravel bars at river banks. The high flow velocities and water depth in the main channel were above those preferential to the juvenile graylings, while the gravel bar provided a favorable combination of water depths and flow velocities. Further research should also investigate the shifting location of habitats as well as the change in quality and quantity of habitats during minimum flow conditions.

Finally, the impact of climate changes may cause modifications of fish habitat distribution. Another study already proved general distribution shifts of fish species that were caused by temperature increases [102]. Furthermore, climate change causes impacts on the hydrology in the Alps [103–106]. Two of the climatic scenarios (RCP4.5 and RCP8.5) that were adopted by the Intergovernmental Panel on Climate Change ([www.ipcc.ch](http://www.ipcc.ch)) for its fifth Assessment Report in 2014 [107] predicted a decrease in summer precipitation by 25% before 2100, which corresponds to a decrease in discharge of more than 10% [105,106]. For the case of the Isar and other alpine rivers, a further reduction of the already scarce floodplain habitats, and a temporary loss of fish refuges in deep zones can be anticipated. Consequently, the modeling procedure, as presented here, may help to understand climate change effects and help to design adaptation measures.

#### 4.3. Method Discussion

For our model, substratum characteristics have been assumed to be constant for the different discharge scenarios because fine-grained sediment (<10 mm) in the Isar River in Munich began to drift at 80 m<sup>3</sup>/s and the modeling scenarios that were used here were all below this limit. Consequently, only flow velocities and water depth varied between the simulations. Accordingly, the potential effects of sediment dynamics on substratum quality were not considered as a triggering variable by the model. However, this variable may be of interest for the spawning habitats. The quality and quantity of those remained very low for all of the flow velocities and depth variations that were investigated, and no significant variations were found between the scenarios, suggesting that substratum may be the triggering variable for these habitats. The sediment is very important for spawning, since all of the investigated species lay their eggs into or onto the freshly deposited substratum, or even dig redds for oviposition (as with *Hucho hucho*) [50,56,66,76,78,79]. The absence of fine sediments, excessive biofilms, and other organic matter is crucial to the survival of the eggs and early juvenile stages. Future models should consider the sediment dynamics leading to variation in substratum quality of this habitat type [108,109].

Our study may help to define the best restoration scenario in the case of the Isar in Munich for the investigated fish species. It presents a method and a tool to design the best restoration practice. The physical habitat modeling allowed for us to investigate what may happen to habitat quantities and qualities when changing the three driving hydromorphological variables (water depth,



flow velocity, substratum). The habitat suitability model in this study remains at a theoretical level since the predictions have not been verified by field measurements. However, field verifications, e.g., electrofishing, have shown limits in validating model predictions [57]. In fact, false positive or negative predictions may not imply a model error. Fish occurrence might also depend on other variables than those that are included in the habitat suitability model. Furthermore, suitable habitats may occur but may not be used by fish due to additional environmental stressors. Finally, capacities of such physical habitat modeling remain yet limited. Much current research is focused on solving model limitations, for example, integrating different requirements for different seasons, or including sediment transport and morphological dynamic changes [110]. However, further research on habitat modeling still needs to be done to increase model robustness.

## 5. Conclusions

This study has assessed the potential effects of increased minimum discharge on the habitat quality of three fish species, i.e., *Thymallus thymallus* L., *Hucho hucho* L., and *Chondostroma nasus* L. in the Isar in Munich using the modeling procedure CASiMiR. Although a positive effect of a moderate increase in discharge favored all fish species, the four scenarios had different effects on the species and their life stages. Considering that a large part of floodplain water bodies has been lost, and the slope of the channel has been changed considerably in the past, the restoration of the flow regime can only be seen as a part of the solution. The study also showed the potential and the caveats of the modeling approach. Several parameters, such as sediment characteristics, the timing of the discharge variation, extreme events, and historical trends should be considered in greater detail to better understand the quality, quantity, and distribution of suitable habitats. Other site-specific aspects, including the limited accessibility to spawning sites in tributaries, limitations of the river restoration potential due to urbanization and hydroelectric power plants, or the unsuitability of habitats due to recreational pressure [81] are beyond the scope of physical habitat modeling but need to be considered for successful restoration. If they were included, the use of the modeling procedure could help to design restoration trajectories that combine technical and political solutions in order to maximize ecosystem integrity with an adequate and non-destructive use of the natural resources [111–113].

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