https://doi.org/10.5194/hess-2021-196
Preprint. Discussion started: 11 May 2021

Hydrology and Earth System Sciences
Discussions

Macroinvertebrate habitat requirements in rivers: overestimation of environmental flow calculations in incised rivers

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Abstract. Flow variability determines the conditions of river ecosystem and river ecological functioning. The variability of ecological processes in river ecosystems gradually decreases. Prediction of the environmental flow allowing to keep biological diversity and river health develops as a response to the degradation of aquatic ecosystems overexploited by humen. The goal of the study was to test the influence of river incision on environmental flow estimation based on the macroinvertebrate BMWP_PL index. The 240 macroinvertebrate assemblages of 12 waterbodies varying in the bed substrate, amplitude of discharge were surveyed in southern Poland. The variations in the distribution of 151 466 macroinvertebrates belonging to 92 families were analysed. The similarity of benthic macroinvertebrates reflects the typological division of the rivers into three classes: mountain Tatra streams, mountain flysch rivers, and upland carbonate and silicate rivers (NMDS, ANOSIM, $p<0.001$). As a response variable reflecting the macroinvertebrate distribution in the river, environmental parameters, BMWP_PL index was chosen. Our results show that the BMWP_PL index reached its highest values in shallower zones (by the shores) and at high water velocity in the Tatra Rivers or low velocity in most lowland rivers. The river incision significantly increased the values of e-flow calculations in relation to redeposited channels. The area of habitat suitability decreased with the bed incision intensity. In highly incised rivers, the environmental flow values are close to the mean annual flow, suggesting that a high volume of water is needed to obtain good macroinvertebrate conditions. As a consequence, the river downcutting processes and impoverishment of suitable habitats will proceed.

1 Introduction

Human water demand, including irrigation to increase crop productivity, dams, and reservoirs to control the timing of stream flow, and water withdrawal from rivers, has increased dramatically over the last 100 years (Vörösmarty et al., 2010; Veldkamp et al., 2019). Maintenance of a suitable water flow in an active river channel should not only secure human needs, but above all ensure the proper functioning of aquatic ecosystems (Anderson et al., 2006). This has become particularly important since river beds began to be perceived not only as channels filled with water, but as complex ecological systems, in which biological elements play a key role (Poff et al., 1997; Bunn and Arthington, 2002; White et al., 2016). The Water Framework Directive (WFD, European Community, 2000/60/EC) was introduced by European countries to protect and improve the state of aquatic ecosystems and formalize a water flow framework that would maintain this state (Chen and Olden, 2017).

Water flow intensity is one of the most important factors influencing multispecies communities of aquatic and water-dependent organisms (Tharme, 2003; Arthington et al., 2006; Higgisson et al., 2019). It is a parameter which shapes the morphology (Michalik and Książek, 2009) and hydraulic flow conditions (water depth, flow velocity) and influences the diversity and quality of habitats for fauna and flora in the active channel and in the floodplain (Allan, 1995; Poff et al., 1997; Ward and Tockner, 2001; Skalski et al., 2016; Skalski et al., 2020). Furthermore, this parameter significantly influences abiotic elements, such as water temperature and oxygenation, as well as nutrient cycles in the aquatic ecosystem (Monk et al., 2008; Laini et al., 2019). This applies in particular to rivers subjected to strong human impact (e.g., channel regulation and incision dams, or retention reservoirs, as well as a continuous increase in water demand). Artificial restriction and control of a range of water flow values leads to substantial impoverishment of biological diversity (Pander et al., 2019). Therefore, it appears crucial to define ranges of environmental flows that ensure optimal habitat conditions for living organisms (Bunn and Arthington, 2002; Acreman et al., 2014).

Environmental flow has been studied by many researchers, resulting in numerous methods for determining it. The simpler ones include hydrological methods, which are based on historical hydrological data and mean annual discharge (Tennant, 1976; Jowett, 1997; Tharme, 2003; Rosenfeld, 2017). Analysis of such data makes it possible to specify a percentage of the mean annual flow as the critical value below which severe degradation of biotic elements occurs. Unfortunately, hydrological methods do not take into account the morphology of the river bed, which is a key factor shaping the river habitat (Książek et al., 2020). Therefore, a number of hydraulic methods based on simple hydraulic variables such as wetted area/wetted perimeter have been introduced (Książek et al., 2019). Determination of Q for environmental flow involves defining the breaking point of the hydraulic variable discharge curves as the e-flow. Over time, hydraulic methods have developed in the direction of habitat simulation methods. They have additionally focused on the habitat requirements of selected groups of model organisms, most commonly water depth, flow velocity, and bed substrate (Jowett and Davey, 2007; Li et al., 2009; Muñoz-Mas et al., 2016). Based on the analysis of these environmental factors, habitat-discharge curves were drawn for organisms, and from these it was possible to read the optimal flows maintaining the normal ecological functions of aquatic ecosystems. Another type of method, which emphasizes the importance of the natural flow regime for the entire ecosystem, is holistic methods. They attempt to maintain the natural flow regime as well as flow variability. In this case, environmental flow is defined in the category of deviation from the natural flow regime.

The methods presented above focus on the diversity and availability of habitats for freshwater macroinvertebrates, which is the most important and sensitive indicator of the ecological state of the ecosystem (Jowett et al., 2008; Birk et al., 2012). The diversity and taxonomic composition of aquatic organisms living in freshwater streams and rivers are used as indicators in the evaluation of environmental flow (Pander et al., 2019). In many cases, macroinvertebrate assemblages are considered (Hayes et al., 2014; Laini et al., 2019), as numerous studies confirm that they are relatively good indicators of ecological water quality and integrity (Buss et al., 2015; Wyżga et al., 2016; Schneider and Petrin, 2017). Freshwater macroinvertebrates play an important role in the processing of nutrients and organic energy in running water ecosystems, as well as in sustaining ecosystem integrity. Another parameter, which is usually neglected in flow modelling, is associated with morphological channel modification and incision (Wyżga et al., 2012; Skalski et al., 2016). Incision up to the bedrock simplifies the microhabitat array of the river (Neachell, 2014) and can eliminate most habitats (Muñoz-Mas et al., 2016). As a consequence, to preserve optimal areas with heterogeneous habitats, the environmental flow should be vastly increased.

The goal of the study was to test the influence of river incision on environmental flow estimation based on macroinvertebrate habitat preferences. Specific aims of the study were (1) to establish the habitat preferences of macroinvertebrates (240 local assemblages) in mountain and lowland rivers using generalized additive models, (2) to calculate the e-flow values combining the habitat requirements and hydraulic method of environmental flow calculation in relation to river hydromorphological parameters (redeposition and incision) (3) to identify a scale of e-flow overestimation in relation to hydromorphological modifications and hydrological regimes (Low Low Flow, Mean Low flow and Mean Annual flow). (4) to check and visualize the overestimation of e-flow calculations on randomly chosen, incised, and redeposited rivers based on CCED2D model. We expected that e-flow in incised rivers, allowing to obtain the shelf zone level of the river should be much higher than Mean Low Flow. Such assumption could determine the consecutive higher discharges and increase the bed degradation. Firstly, we should restore the sedimentation processes in incised rivers to obtain a hydrodynamic balance and then manage the proper volume of water. As a consequence, suitable habitats for invertebrates and fish will be enlarged.

2. Materials and methods

2.1 Study sites

The survey was conducted in 12 mountainous rivers assigned to three typological classes according to the Polish Water National Authority and the Water Framework Directive (Jusik et al., 2014): Tatra mountain rivers (Biały Dunajec, Dunajec, and Białka - Type 1), mountain flysch rivers (Raba, Brynica, Toszecki Potok, and Nysa Kłodzka - Type 2) and upland carbonate and silicate rivers (Sołokija, Warta, Ropa, Biała, and Odra - Type 3) (Fig. 1), varying in bed modification (incision intensity or redeposition).

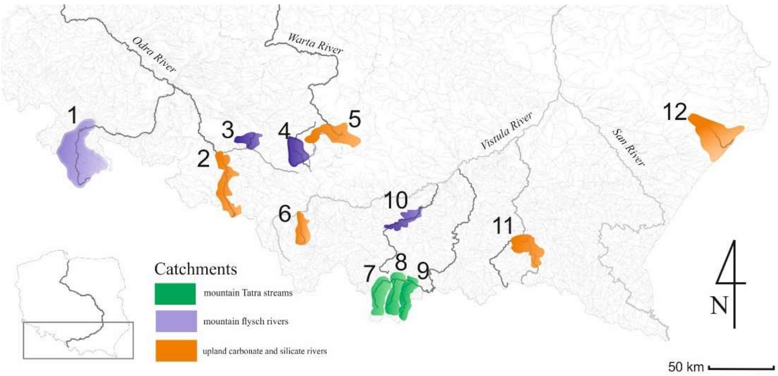

Figure 1. Map of the studied mountainous rivers in Carpatho-Sudetian region of Poland.

The first class comprises rivers located in an alpine granitoid region, characterized by calcareous and silica bedrock. The second group consists of rivers flowing through much lower mountain ranges (up to the timber zone), where the bedrock contains sandstone rock formations. The third group represents rivers of upland landforms with various carbonate and silicate sediments and rocks.

All rivers are routinely monitored by the nearest monitoring station of the Environmental Agency (Environmental Agency Data, 2018), and all twelve rivers have consistently been assigned a similar average chemical status in recent years. ANOVA showed no variation between the river types in incision bed modification (F=1.56, p=0.26) as well as in physicochemical properties: dissolved oxygen, conductivity, hardness, pH_{max}, NH3, NO3-, NO2-, total N, and PO43-. Only water temperature and pH min significantly depended on the river type. All habitat variables (flow, depth and substrate type) were significantly dependent on river type (Table 1), meanwhile the incision was not influenced by the parameters variation.

Table 1 Mean values ± standard deviation of the physicochemical and habitat variables of the three river types, with results of one-way ANOVA.

Environmental data	Type 1		Type 2		Type 3		F	p
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.		
Physicochemical								
Water temperature [°C]	7.27	1.55	11.40	2.43	12.17	0.89	6.76	**0.016**
Dissolved oxygen [mgL^{-1}]	10.73	0.45	9.33	1.34	9.15	0.79	2.39	0.150
Conductivity [$\mu S\ cm^{-1}$]	202.67	91.58	1095.60	1594.59	356.5	93.26	0.85	0.458

Water hardness [mg $CaCO_3$/l]	113.00	55.49	252.10	298.52	148.5	20.87	0.53	0.602
pH_{min}	7.97	0.11	7.52	0.11	7.20	0.08	47.91	**0.000**
pH_{max}	8.43	0.35	8.16	0.15	8.15	0.37	1.04	0.390
NH_3 [mgL^{-1}]	0.20	0.31	0.32	0.36	0.95	0.81	2.09	0.179
NO_3^- [mgL^{-1}]	0.60	0.20	2.11	0.93	2.25	0.92	4.16	0.052
NO_2^- [mgL^{-1}]	0.02	0.01	0.10	0.12	0.17	0.13	1.45	0.284
Total N [mgL^{-1}]	0.97	0.75	3.43	1.78	4.17	2.09	3.12	0.093
PO_4^{3-} [mgL^{-1}]	0.03	0.04	0.09	0.05	0.06	0.02	2.08	0.180
Habitat								
Flow [m^3s^{-1}]	0.83	0.55	0.45	0.39	0.44	0.32	38.06	**0.000**
Depth [m]	0.29	0.14	0.54	0.34	0.50	0.33	25.89	**0.000**
Substrate index	22.31	5.60	7.07	5.58	6.39	3.85	422.95	**0.000**

2.2 Macroinvertebrate sampling

Benthic invertebrate samples were collected in two seasons: autumn (October, 2017) and spring (April, 2018). No flood waves occurred between these surveys, and the channel morphology remained the same throughout the sampling period. We collected 20 subsamples (1 m^2) from each low-flow channel along a representative 100 m section of each river according to a sampling procedure for the BMWP_PL index (Bis and Mikulec, 2013). A total of 480 subsamples were taken from a wide range of water depths and flow velocity. Following Jowett et al. (1991) and Muñoz-Mas et al. (2016), the substrate types were converted to a single index by summing the weighted percentages of each type.

Macroinvertebrate samples were collected with a D-frame net according to the Environmental Agency’s sampling protocol for biomonitoring assessment using a kicking motion for 3 minutes across all habitats (Bis and Mikulec, 2013). All collected material was preserved in the field with 4% formaldehyde. Aquatic macroinvertebrates were separated from the rest of the material in the laboratory using a stereoscopic microscope. Macroinvertebrates were identified to the family level (Tachet et al., 2000), except Oligochaeta, Porifera, and Hydrozoa, which were recorded as such. Due to the varied preferences of macroinvertebrates to habitat conditions, the BMWP_PL index was adopted as the best qualitative index. The Biological Monitoring Working Party (BMWP) is one of the most commonly used biotic indices in various rivers and streams around the world (Roche et al., 2010; Wyżga et al., 2013). It has been adopted in many countries, including Poland (Dz.U. 2019 poz. 2149, 2019). This index best considers the sensitivity of invertebrates to environmental variables, because families with similar stress tolerances are grouped together (Armitage et al., 1983).

2.3 Hydraulic modelling

We used the hydraulic method for the assessment of the environmental flow of each river because of the relationship between the hydraulic parameters of watercourses (depth and velocity) and the quality of the aquatic environment (BMWP_PL GAM relations). The wetted perimeter method (WPM) is based on the relationship between the wetted perimeter for a given cross section of the river and the value of flow with reference to biological requirements (Shang, 2008). Detailed description of the applied hydraulic method of environmental flow calculation is given in Książek et al. (2019). To compare the environmental flow in relation to hydromorphological parameters (incision, redeposition), we used the proportion of Environmental flow (Qenv) to mean hydraulic parameters of low, low flow (LLF), mean low flow (MLF), and mean annual flow (MAF). Those metrics show us the position of the calculated environmental flow in relation to flow characteristics from hydrological year-to-year characteristics.

2.4 Case study 2D modelling methodology

https://doi.org/10.5194/hess-2021-196
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We provided the detailed modelling of a randomly chosen incised and redeposited river based on CCED2D model. The model is a depth-averaged two-dimensional numerical model for simulating unsteady, turbulent, free-surface flow in open channels with a moveable bed. The CCHE2D model solves depth-integrated shallow water equations for all hydraulic calculations (Wu et al., 2000; Duan et al., 2001). The CCHE2D package consists of two modules: a Mesh Generator (MG) and a Graphical User Interface (GUI). The main function of the MG is designing a complex mesh system. The mesh is generated based on the surveyed topography and/or Digital Terrain Model (DTM). The model was applied in two representative rivers, varying in river bed morphology – from incised bed rock channels to a channel with natural sediment structures (with redeposition). The mesh for each sector of the river was generated by interpolating cross sections. A total of 5,112 observations were used: Raba – 3033 (incision) and Ropa – 2079 (redeposition). The shape of the channels was fairly regular along the reach under study, and its pattern presented little complexity (i.e., a single channel with no islands), but riffle-pool sequences were observed. The 153–200 m long meshes were composed of cells and nodes (length and number of modes, respectively, for Ropa 153 m, 49715 and Raba 200 m, 99200). Data used for the initial conditions was extracted from field measurements. Special attention was devoted to bed roughness due to its importance for water surface level. Roughness values ranged from 0.01 in hydraulic smooth bed zones to 0.07 in rough areas. Finally, the model time step was defined at 0.1 s or 0.25 s, depending on the model structure. The model was calibrated by comparing the measured and computed water surface levels for measured discharges in all cells and nodes (Fig. 2).

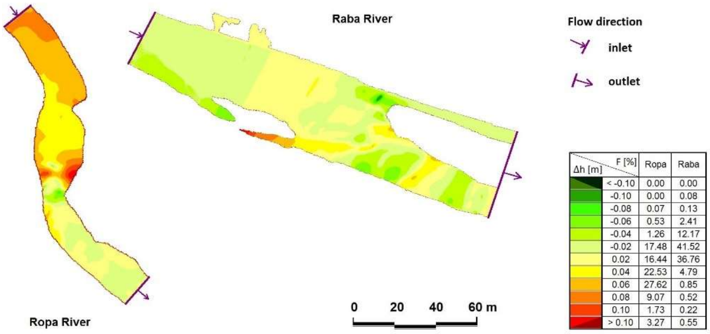

Figure 2. Comparison of calculated and measured water surface levels: The Ropa River for discharge 6.71 m3s-1, and The Raba River for discharge 10.29 m3s-1.

In the case of the Raba River, for 70% of the calculated nodes, the difference between the calculated and measured water surface level (WSL) was in the range ±0.02 m. 84% of Ropa River nodes were in the range between of –0.02 to 0.06 m. In all described models, Δh in the main channel does not cross ±0.02 m, but the visible differences are related to the horizontal layout of WSL in cross-section. Evaluation of the compatibility measures of the numerical model showed very good accordance (Książek et al., 2010) and the prepared models did not need recalibration.

The habitat suitability index was estimated in the first step by selecting a usable habitat for macroinvertebrates. For each research section, we choose 20 sites differing in water velocity and water depth as the main environmental variables creating habitat heterogeneity for macroinvertebrates. Then, according to the relationship between hydromorphological habitat attributes (water depth and velocity) and the BMWP_PL index values (describing the ecological quality of the river), we constructed a GAM model as the best fitted method to mark out the range of hydromorphological attributes (where the BMWP_PL suitability index is the highest).

Two rivers (located in the same Carpathian region) representing opposite bed modifications (incision and redeposition) were chosen for the model as a case study. The modelled sectors of the river had channels with a pool-riffle sequence and fluvial deposits, but were varied in terms of degradation of the bed structure. The hydrological characteristics of the modelled river are presented in Fig. 3.

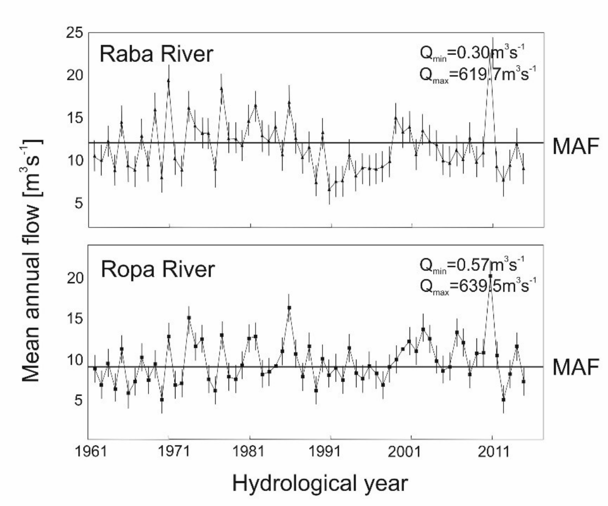

Figure 3. Changes in hydrological regime of the Raba and Ropa Rivers. The horizontal line indicates the mean annual flow (MAF).

The Raba was selected to represent incised channel rivers (bottom material mainly gravel and small stones, substrate index 14.9). The Dobczyce retention reservoir, which influences the hydrology and morphology of the river, is located upstream of the examined sector of the river (12 km). Constructing of the retention reservoir in 1986 led to a significant decline in average annual flow values (MAF values varied from 12.22 m^3/s; in 1951-1985 to 10.57 m^3/s in 1986-2015, $F = 49.90$, $p < 0.0001$). The reduction in flow and longitudinal training work of the Raba led to incision of the riverbed and permanent compactness of the bed material. The Ropa River, chosen to represent the redeposition processes, was located among upland, carbonate, and silicate rivers, with the lowest human impact. The bottom material consists mainly of gravel and sand (substrate index 7.2), where bedload transport remains undisturbed.
To calculate the optimal environmental flow values (Qenv optimal), a WUA vs flow curve was plotted. Optimal environmental flow values were defined as 50% of the WUA values for both rivers. A hydraulic habitat 2D model of each river section was used for spring and autumn as an example to estimate habitat prediction in terms of calculated environmental flow during the season. Environmental flow that did not meet the conditions of 100% habitat suitability was expressed as the critical instream environmental flow value (Q_{env} critical), below which the parameters of aquatic macroinvertebrate communities dramatically declined.

2.5 Data analysis

ANOVA was used to verify the statistical significance of the differences in environmental data between the three river types (Statsoft, 2013). Non-metric multidimensional scaling (NMDS) was used to test the relationship between the macroinvertebrate taxonomic composition of the assemblages of the 12 rivers assigned to three types (Type 1, Type 2 and Type 3) and hydromorphological variables (water velocity and depth) during the spring and autumn. Descriptive physical properties (water depth and velocity) were classified into two or three categories: Low, Medium and High. The significance of differences between depth and velocity classes was tested by ANOSIM on the Bray-Curtis dissimilarity matrix with 499 permutations of the data. PAST software (version 3.13) was used to analyse NMDS and ANOSIM (Hammer et al., 2001).

Generalized additive modelling with Poisson distribution (GAM) was used to develop more defensible habitat preferences for macroinvertebrates (BMWP_PL index) based on their distribution in both dimensions: depth and velocity (Jowett and Davey, 2007). The course of the regression line was obtained using CurveExpert software, where the best fitted line for the set of nonlinear curves was applied and ranked. To compare the variation of the proportion of environmental flow and hydromorphological parameters (which were normally distributed) in relation to abiotic type and channel modifications, general linear modelling was applied.

3. Results

3.1 Environmental flow based on benthic invertebrates distribution in relation to river hydromorphology

A total of 151 466 individuals belonging to 92 benthic invertebrate families from 480 macroinvertebrate assemblages were identified. High variation was shown in the taxonomic composition of aquatic invertebrates depending on the hydromorphological parameters (water depth and velocity) and the season (Fig. 4). In the case of rivers classified as Type 1, water velocity was found to significantly affect the taxonomic composition of the macroinvertebrates in both spring and autumn (Table 2).

Table 2 Results of ANOSIM analysis comparing macroinvertebrate assemblages between classes of velocity and depth measured for three river types in the spring and autumn season. Values below the diagonal are dissimilarity indices, and the above are p-values (p<0.05 in bold).

			Velocity			Depth		
			Low	Medium	High	Low	Medium	High
Spring	Type 1	Low		**0.043**	**0.023**		0.543	-
		Medium	0.10		**0.002**	- 0.01		-
		High	0.10	0.21		-	-	
	Type 2	Low		**0.009**	**0.0002**		0.632	**0.001**
		Medium	0.09		**0.006**	- 0.01		**0.0003**
		High	0.16	0.09		0.13	0.16	
	Type 3	Low		**0.026**	**0.244**		0.161	**0.0002**
		Medium	0.07		**0.004**	0.02		**0.045**
		High	0.01	0.12		0.26	0.08	
Autumn	Type 1	Low		0.138	0.067		0.356	-
		Medium	0.04		**0.030**	0.0001		-
		High	0.06	0.09		-	-	
	Type 2	Low		**0.0004**	**0.0001**		**0.017**	**0.0001**
		Medium	0.15		**0.0001**	0.07		**0.0004**
		High	0.25	0.39		0.30	0.13	
	Type 3	Low		0.119	0.139		0.186	**0.008**
		Medium	0.04		0.154	0.03		0.365
		High	0.03	0.03		0.11	0.01	

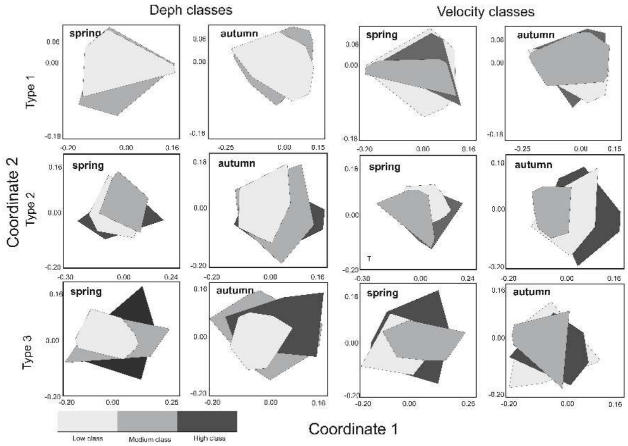

Figure 4. Non-metric multidimensional scaling (NMDS) of macroinvertebrates taxonomic composition of three types of rivers (Type 1, Type 2, and Type 3) in the spring and autumn season according to velocity and depth ranges.

In spring, there were significant differences between velocity classes low and high and medium and high, while in autumn, before overwintering, significant differences were only noted for medium and high classes. In neither season, the differences noted in taxonomic composition depending on the range of depth were statistically significant in the case of rivers of the second abiotic type (Type 2), more significant differences were observed between velocity and depth classes (three depth classes were adopted due to the greater amplitude of these parameters). In the spring, significant differences were visible in all velocity classes, while in the case of depth they were noted only in the comparison of the low and middle depth classes. In autumn, differences were found for all classes in the case of variation in both velocity and depth. In the case of Type 3 rivers (carbonate and silicate fine sediments and rocks), the velocity parameter taxonomically differentiated macroinvertebrate communities only in the spring between the high and medium velocity classes. In the case of depth, differences were observed in both seasons – in spring between the deepest and shallowest environments and those with medium depth, and in autumn only between the deepest and the shallowest zones (Table 2).

Each of the hydromorphological parameters was evaluated by the GAM model, which provided the best fit to the data (Table 3). The curves of the generalized additive models for the biotic index BMWP_PL in spring and autumn are presented in Fig. 5.

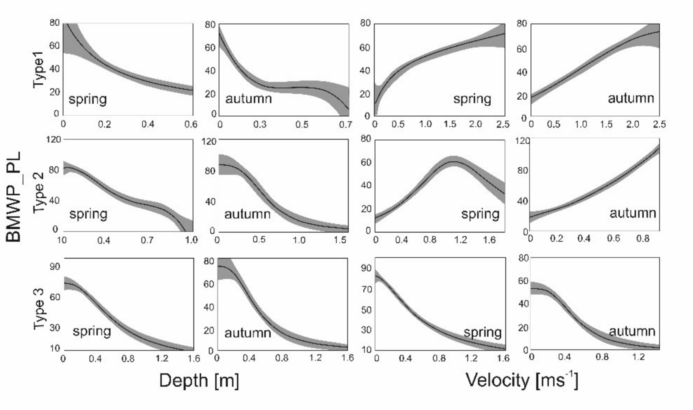

Figure 5. Habitat suitability models of BMWP_PL for water velocity and depth in spring and autumn season for three river types.

These models were made for each of the three river types: calcareous and silica bedrock alpine rivers (Type 1), sandstone mountain rivers (Type 2), and carbonate and silicate upland rivers (Type 3). In the first type, with a gravel bottom, the BMWP_PL index reached its highest values at high water velocity and in shallower zones (by the shores). In the second type of river, the BMWP_PL index was highest at medium velocities in spring and at high velocities in autumn. In both seasons, higher values for the biotic index were associated with shelf environments, as in the case of Type 1. Similar relationships with depth were noted in the Type 3 rivers, where BMWP_PL values were highest in low-depth environments at low velocity in both spring and autumn (Fig. 5).

Table 3 Summary of the generalized additive models for BMWP_PL according to velocity and water depth ranges in three river types for spring and autumn season.

		Spring			Autumn		
		Type 1	Type 2	Type 3	Type 1	Type 2	Type 3
Velocity [ms^{-1}]	F	17.49	5.05	9.48	11.62	26.97	13.76
	p	**0.000**	**0.01**	**0.000**	**0.000**	**0.000**	**0.000**
	AIC	324.06	1243.75	655.12	982.35	3552.36	1429.16
Depth [m]	F	2.8	14.49	3.28	0.28	24.33	5.47
	p	**0.06**	**0.000**	**0.04**	0.163	**0.000**	**0.003**
	AIC	479.81	1061	763.05	1198.16	3650.93	1589.24

Using the optimal depth characteristics reflecting the habitat suitability, the environmental flow based on the wetted perimeter method was calculated. The results are shown in Table 4.

Table 4 Environmental flow and flow proportion (S) in different abiotic and bed modification types of 12 mountainous rivers.

River name	Ab. type	River bed mod.	Environmental flow (Q_{env}) [m^{3}s^{-1}]		Hydrological characteristics [m^{3}s^{-1}]			Environmental flow proportion (S)					
			spring	autumn	LLF	MLF	MAF	SLLF spring	SLLF autumn	SMLF spring	SMLF autumn	SMAF spring	SMAF autumn
Biały Dunajec	I	I	0.89	1.10	0.22	0.54	2.26	4.02	4.97	1.66	2.05	0.39	0.49
Dunajec	I	R	0.64	0.86	0.19	0.68	3.09	3.43	4.62	0.94	1.27	0.21	0.28
Białka	I	R	0.78	0.98	0.27	0.65	3.88	2.90	3.64	1.20	1.51	0.20	0.25
Brynica	II	I	0.17	0.10	0.02	0.13	0.77	6.89	4.05	1.34	0.79	0.22	0.13
Raba	II	I	4.80	3.60	0.30	3.53	11.45	16.00	12.00	1.36	1.02	0.42	0.31
Toszecki Potok	II	I	0.27	0.18	0.02	0.11	0.59	14.35	9.56	2.43	1.62	0.46	0.30
Biała	II	I	1.20	1.05	0.31	0.96	2.69	3.89	3.41	1.25	1.09	0.45	0.39
Nysa Kłodzka	II	I	1.90	1.50	0.14	0.61	3.68	13.37	10.55	3.12	2.46	0.52	0.41
Sołokija	II	R	0.36	0.50	0.25	0.72	1.34	1.42	1.97	0.50	0.69	0.27	0.37
Warta	III	I	1.75	1.65	0.22	0.96	2.07	8.09	7.63	1.83	1.73	0.85	0.80
Odra	III	R	7.40	7.00	4.22	9.54	42.26	1.75	1.66	0.78	0.73	0.18	0.17
Ropa	III	R	2.15	2.00	0.58	1.79	9.64	3.73	3.47	1.20	1.12	0.22	0.21

There is a high variation of the Q_{env}, related to its own channel properties and volume of water. To obtain the relation to hydraulic river parameters, the mean Q_{env} relative similarity to MAF, MLF, and LLF were measured. There was no relation to the abiotic type of river (Table 5). The only significant relation was linked to channel modification (Fig. 6). In all cases, the relative similarity of flow was significantly higher in incised channels than redeposited ones.

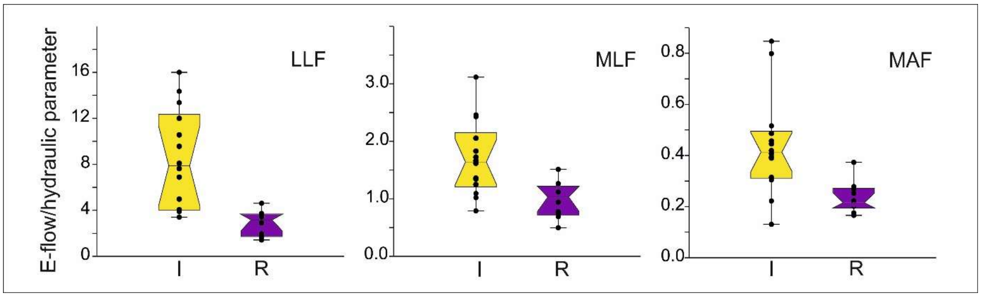

Figure 6.The distribution of e-flow proportion to LLF, MLF, and MAF in relation to river bed modification. I – incision, R – redeposition.

In each type of flow (MAF, MLF, LLF), the relative similarity was higher in incised rivers than redeposited, showing that the incised rivers needed much more volume of water to sustain appropriate conditions for macroinvertebrates compared with the redeposited ones. More detailed analysis and visualization of spatial modelling were predicted by 2D modelling of randomly chosen rivers presented below as a case study.

Table 5 General linear modelling results for hydrological flow similarity (S) in relation to bed modification (incision and redeposition), season, and abiotic river type.

Parameter	SS	d.f.	MS	F	p
LLF$_{\text{sim}}$					
Intercept	648.66	1	648.66	54.09	0.00
Incision	**101.13**	**1**	**101.13**	**8.43**	**0.01**
Type	11.28	2	5.64	0.47	0.63
Season	6.32	1	6.32	0.53	0.48
Error	227.86	19	11.99		
MLF$_{\text{sim}}$					
Intercept	41.19	1	41.19	138.07	0.00
Incision	**3.14**	**1**	**3.14**	**10.52**	**0.00**
Type	0.50	2	0.25	0.84	0.45
Season	0.10	1	0.10	0.33	0.57
Error	5.67	19	0.30		
MAF$_{\text{sim}}$					
Intercept	2.70	1	2.70	126.31	0.00
Incision	**0.32**	**1**	**0.32**	**15.04**	**0.00**
Type	0.11	2	0.06	2.60	0.10
Season	0.00	1	0.00	0.14	0.71
Error	0.41	19	0.02		

3.2 Case study

We calculated the detailed 2D modelling for two randomly chosen incised and redeposited rivers. According to the GAM macroinvertebrate habitat suitability model, WUA-flow curves were calculated for river s with varying intensity of bed modification, Raba (incised) and Ropa (redeposited), as shown in Fig. 7.

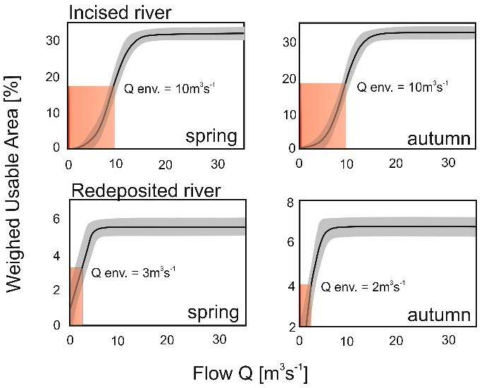

Figure 7. Weighted Usable Area (WUA)- flow relation curves (spring and autumn season) of the rivers varying in bed modification: Raba River with incision and Ropa River with redeposition.

The environmental flow was defined as corresponding to 50% of the value of the usable area, which ensures optimal conditions for the development and functioning of aquatic macroinvertebrates, and thus the maintenance of the good ecological state of the river. Analysis of the curves for the Raba River shows a 50% reduction in the usable area at the flow of about 10 m^{3}s-1 for both spring and autumn. In the case of the Ropa River, the WUA-flow curves show a 50% reduction in the usable area at the flow of about 2 m^{3}s-1 in spring and 3 m^{3}s-1 in autumn (Table 6).

A spatial visualization of habitat suitability for Q_{env} optimal conditions is presented in Fig. 8. In the case of the strongly incised Raba River, a very small suitable habitat area was observed, covering only the shelf zone. In the case of the Ropa, a river with undisturbed sediment transport, the usable areas constitutes more than 20% of the environmental flow. The modelling was also used to determine Q_{env} critical, at which the most valuable areas in terms of habitat (over 80% suitability) disappear (Fig. 8, Table 6). Below this Q_{env} critical value, a dramatic decline in macroinvertebrate diversity would have to be expected.

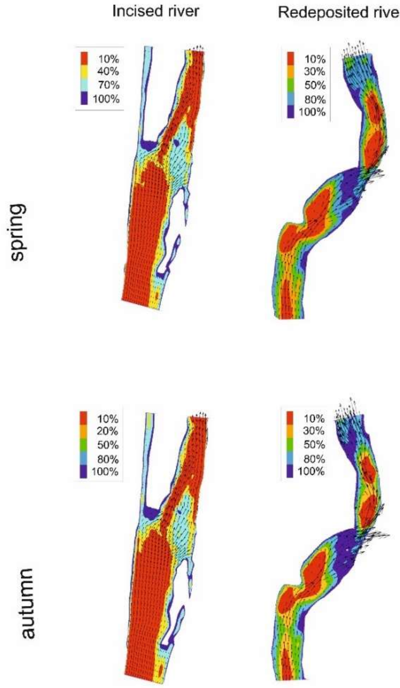

Figure 8. Numerical modelling of incised (Raba), and redeposited (Ropa) rivers for visualization distribution of macroinvertebrates habitat suitability index for calculated Qenv in spring and autumn season.

A comparison of the Q_{env} values (optimal and critical) and means: annual flow (MAF) and low flow (MLF) for the two types of rivers is presented in Table 7. In the highly incised river (Raba River), the Q_{env} optimal requirement for spring was lower but for autumn was higher than MAF, and Q_{env} critical was always higher than MLF. In the redeposited Ropa River, in spring as well as in the autumn season, Q_{env} optimal requirements were much lower than MAF, and MLF was higher than Q_{env} critical. Both findings are congruent with the former hydraulic calculations for all rivers.

Table 6 Environmental optimal and critical flow based on macroinvertebrate habitat suitability models of two mountainous rivers with mean MAF, MLF, and LLF in relation to the seasons.

Season	Flow type [m^3s^{-1}]	River bed modification	
		Incision	Redeposition
		Raba	Ropa
Spring	$Q_{env\ optimal}$	10	2
	$Q_{env\ critical}$	<6	<1
	MAF	14.79	12.94
	MLF	5.20	2.93
Autumn	$Q_{env\ optimal}$	10	3
	$Q_{env\ critical}$	<6	<1
	MAF	7.86	5.81
	MLF	3.80	1.96
Year	MAF	11.45	9.64
	MLF	3.53	1.79
	LLF	0.3	0.58

4. Discussion

The present study showed that river bed transformation, disturbing sedimentation processes and increasing the incision of the river bed vastly increases the environmental flow values for macroinvertebrates habitat suitability.. This is important because incision processes are common in most European rivers (Gore, 1996). Channel incision decreases the area of suitable habitat and increases the potential environmental flow to an extremely high level to obtain the minimum beneficial habitat capacity for macroinvertebrates. (Bravard et al., 1997; Skalski et al., 2020). In incised channels, the degree of lateral connectivity of the river and floodplain is reduced, and the degree of modification of the substrate material is higher (Wyżga et al., 2012). As a consequence of channelization and incision, the continuity of the floodplain and shelf zone along the river is disrupted (Walther and Whiles, 2008; Kędzior et al., 2016; Anim et al., 2018; dos Reis Oliveira et al., 2019). Moreover, incision results in a concomitant decrease in sediment supply to the channels, reducing the microhabitat diversity and the quality of macroinvertebrate habitats (Wyżga, 2007; McKenzie et al., 2020). During the incision process, morphological changes in the channel, especially in the case of highly incised rivers, decrease the area of shelf habitat, and fluvial deposits are drastically reduced. Thus, to keep areas wet, flow requirements must be much higher than the mean annual flow and associated with inundation hazards.

Linkage between mean annual flow and environmental flow estimation has been the subject of consideration for many years (Tennant, 1976), based on the assumption that to obtain good stream environment conditions, some percentage of the average flow is required (Richter et al., 2012; Van Niekerk et al., 2019). According to Tennant (1976), 10% of the average flow is the minimum flow recommended to sustain short-term survival habitat for most aquatic life forms. Thirty percent was recommended as a base flow to sustain good survival biota conditions. Sixty percent provides excellent to outstanding habitat for most aquatic life forms during their primary periods of growth and for most recreational uses. However, what about strongly channelized and incised rivers, which are the most common channel types in Europe? Our survey indicated that to obtain macroinvertebrate diversity, we need a much higher volume of water than 10% of MAF. In the case of incision, a high volume of water is needed to cover the shelves and sediment storage, which are the principal elements of macroinvertebrate habitats and refuges in a dynamic river system (Duan et al., 2009; Anim et al., 2018).

It is obvious that macroinvertebrates are closely linked to the substrate, which is highly varied in terms of particle size (Bravard et al., 1997; Merz and Ochikubo Chan, 2005; Duan et al., 2009). Alluvial processes are strongly disturbed in an incised river, leading to deepening of the channel and bed degradation (Wyżga, 2007). The areas shown in Fig. 7, which are 100% suitable for macroinvertebrates, are extremely low in incised rivers throughout the spring and autumn. In most rivers with an augmented bed, the sedimentation process is disturbed, and thus only habitats located closer to the surface, where lateral erosion occurs, provide a suitable habitat for macroinvertebrates. Modern restoration efforts often involve the artificial addition of sediments to sand (dos Reis, Oliveira et al., 2019) or modification of channel morphology to restore the sedimentation process (Violin et al., 2011; Anim et al., 2018).

The biotic integrity of rivers is primarily restricted by downstream transport of sediments controlling the integrity of fluvial ecosystems (Katano et al., 2009; White et al., 2016). Substrate characteristics such as size, stability, compactness, quality, and dynamics are a key parameter determining the occurrence and variation in macroinvertebrate communities. High substrate stability, substrate heterogeneity, and low compactness determine high macroinvertebrate diversity (Beisel et al., 2000; Duan et al., 2009). On the other hand, fine sediments can be regarded as a potential stressor for macroinvertebrates (Meißner et al., 2019). In highly incised sectors of the river, a deficiency of sediment and its compactness as well as a lack of food sources (Jowett, 2003) lead to impoverishment of the taxonomic composition of macroinvertebrates and favour taxa adapted to high flow only (Wyżga et al., 2013). Our modelling indicates that prevention of optimal conditions requires more volume of water which exceeds the mean annual flow. This suggestion can be dangerous, because increased discharge augments incision processes. We can thus fall into a kind of ecological trap. A solution may be to pay careful attention to the bed morphology, especially in the case of incised channels. We then have two options to preserve the high biodiversity of invertebrates according to the EU water directive: to vastly increase the water volume or to restore sedimentation processes to obtain a hydrodynamic balance. As a consequence, suitable habitats for invertebrates and fish will be enlarged. The second option seems much more realistic. Only then we will be able to successfully maintain the diversity of aquatic biota.

5. Conclusions

In habitat modelling, careful attention should be paid to the morphology of the modelled river, its geometry, and the fluvial processes in the active channel. In incised channels where sedimentation processes are altered, for example, by dam reservoirs or bedrock downcutting, the area of suitable habitat is limited. Macroinvertebrate habitat preferences are strongly linked to shelf habitats, where sediment storage and redeposition of bed material is the highest. In that case, the recolonization pattern of invertebrates requires much higher flows, even higher than the mean annual flow. As a consequence, the river is endangered by downcutting processes and impoverishment of suitable habitats.

Author contribution: Kędzior Renata: Data curation, Formal analysis, Investigation, Resources, Software, Validation, Writing - review & editing; Kłonowska-Olejnik Małgorzata: Data curation; Dumnicka Elżbieta: Data curation; Woś Agnieszka: Investigation; Wyrębek Maciej: Investigation, Resources, Visualization; Książek Leszek: Investigation, Methodology, Resources, Validation, Writing - review & editing; Paweł Madej: Funding acquisition, Project administration; Grela Jerzy: Funding acquisition, Project administration; Skalski Tomasz: Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Visualization, Writing - original draft.

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgements

The work was partially financed by the National Water Management Authority in Poland "Implementation of the method of estimating environmental flows in Poland" under the project POIS.02.01.00-00.0016/16 (macroinvertebrates and hydrological data) and by Ministry of Science and Higher Education in Poland. The statistical analyses used in the paper were supported by the project “Integrated Program of the University of Agriculture in Krakow” co-financed by European Union under the European Social Fund. We are grateful to native speaker Sara Wild for improvement of the English text.

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