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Research article

The impact of anthropogenic modification of a mountain river channel on the quality of aquatic habitats

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1. Introduction

Mountain rivers are dynamic ecosystems that have been altered by human activities such as agriculture, industry, and urbanization, affecting hydrology and habitat conditions. Therefore, it is important to find solutions to analyze the impact of different pressures on water bodies and to mitigate their effects (Kun et al., 2012; Yıldız et al., 2025). Technical regulations have standardized flow and sediment transport, leading to ecological degradation and disrupting geomorphological processes. The construction of hydraulic structures has fragmented river systems, hindering species migration and the transport of sediment and nutrients (Dynesius and Nilsson, 1994; Wohl, 2006; Bombino et al., 2014; Mathers et al., 2021; Parasiewicz et al., 2023; Korpak and Lenar-Matyas, 2025). Engineering interventions have modified river channels by straightening courses, narrowing flow paths, adjusting bed gradient with grade control structures, and stabilizing banks and riverbeds. The application of standardized geometric and hydraulic over long stretches have reduced ecosystem complexity and biodiversity (Wohl, 2006; Korpak, 2018).

The modern approach to river management seeks to balance economic use with ecological preservation. Rivers with diverse ichthyofauna hold significant ecological and economic value, requiring efforts for preservation or restoration. Maintaining an optimal hydrological regime with seasonal discharge and water level variations is essential for aquatic ecosystems (Wilcox et al., 2017). Equally important is the presence of diverse habitats that support a rich biotic community. Habitat studies are also extremely important from the perspective of determining and maintaining environmental flow (Wałęga et al., 2025). They make it possible to adjust river flows in such a way as to ensure suitable living conditions for aquatic organisms and to preserve natural ecological processes.

River habitat studies involve specialists from various fields. Recent efforts have focused on integrating different research approaches to better understand ecosystem interactions and predict environmental changes, with an emphasis on key indicators to define flow regime zones supporting diverse organisms (Bovee, 1982; Sullivan et al., 1987; Wadeson and Rowntree, 1998). Current research indicates that flow depth, velocity, and substrate size are the most critical habitat quality indicators (Moir and Pasternack, 2008). Additionally, the Froude number is recognized as a key hydraulic variable for characterizing surface flow types and quantifying habitat heterogeneity (Jowett, 1993; Wadeson, 1994; Padmore, 1998; Kemp et al., 2000; Entwistle et al., 2019). The flow velocity is considered the most important environmental factor affecting organisms living in rivers. Many species occur either in sections of streams with high flow velocity or in slow-flowing waters, but never in both environments (Allan and Castillo, 2007). A change in the natural flow velocity can lead to the weakening or elimination of a given species. Macura et al. (2016) highlights the importance of flow depth, especially during low flows, when velocity plays a secondary role. Appropriate depth is also frequently mentioned as a parameter affecting the quality of spawning grounds and fish reproduction opportunities, as well as the survival of juvenile individuals (Garbe et al., 2016).

Flow depth, velocity, and substrate type are key parameters in Habitat Suitability Curves (HSC), which rate habitat suitability (0–1) for a species under specific flow conditions based on observed distributions. Introduced in the 1950s for salmon, HSCs are now integral to advanced habitat models like PHABSIM, MesoHABSIM, and CASiMiR (Briggs, 1953; Chambers et al., 1955; Bovee, 1982; Orth and Leonard, 1990; Parasiewicz, 2001; Vilizzi et al., 2004; Garbe et al., 2016; Nestler et al., 2019; Pinna et al., 2024). They form the basis for the Habitat Suitability Index (HSI), a widely used measure of habitat quality (Vismara et al., 2001; Beecher et al., 2002). HSC-based analyses have been applied to both natural and regulated rivers at various scales (Parasiewicz, 2008; Vezza et al., 2014; Szałkiewicz et al., 2022; Wang et al., 2023; Wilding et al., 2014; Wegscheider et al., 2020). An example of HSC curve

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application can be found in the studies by Macura et al. (2012, 2016, 2018), where brown trout habitats were monitored in mountainous sections of Slovak rivers.

Although widely used, the HSI index has notable limitations, including its time-consuming nature and sensitivity to species selection and flow conditions (Vilizzi et al., 2004). As an alternative, Gostner et al. (2013a) proposed assessing habitat quality through hydromorphological diversity, measured by the HMID (The hydromorphological index of diversity), which analyzes variations in flow depth and velocity.

Most habitat studies rely on current, verifiable field data, but tools for analyzing historical changes are lacking. Interesting research questions would include the changes in aquatic habitat conditions under the influence of various anthropogenic pressures, occurring both within the river channel and in the watershed area: channel regulation, mining activities, urbanization, industrialization, forestry, etc. (Tost et al., 2020; Yıldız, 2025; Yıldız et al., 2025). Understanding long-term interactions in complex, interconnected ecosystems would enable sustainable river management and rational, effective revitalization in the watershed area (Kun et al., 2012; Yıldız, 2020).

To separate hydrological effects from other ones, research should begin with flow regime analysis using indicators like Indicators of Hydrological Alterations (IHA), which often is used to assess dam impact, but also can link hydrology to macroinvertebrate biodiversity (González del Tánago et al., 2016; Pumo et al., 2018; Wałęga et al., 2022).

This study examines changes in hydraulic conditions caused by river engineering works in the lower stretch of the Biały Dunajec River, which has been repeatedly modified over the past 40 years. The main goal is to assess habitat quality over time and evaluate the impact of different regulation methods on river habitats, including the potential for restoration. An additional objective was to adapt existing river habitat assessment methods for use with historical data and evaluate their effectiveness.

The novelty and uniqueness of this study lies in the analysis of changes in the quality of aquatic habitats in a mountain river stretch over a long, 40-year period, taking into account and distinguishing the impact of specific technical regulation systems. By assessing how past interventions have influenced habitats over time, this research contributes valuable knowledge to the understanding of river ecology. This is particularly important in the context of the EU Water Framework Directive, in effect in Poland since 2004, which aims for good ecological and hydromorphological conditions in rivers. Although restoration projects have been launched, their full objectives have not yet been met, partly due to a lack of understanding of past regulation impacts. The findings provide crucial insights for guiding future restoration strategies and decision-making in mountain river management.

2. Research area

The research was conducted in the Carpathian river Biały Dunajec, which is 35 km long (Korpak, 2020). It originates from the Tatra Mountains at an elevation of 2004 m above sea level. The river then flows through the following geographical regions: the Podtatrzański Basin, the Gubałówka Foothills, the Pieniny Rock Belt, and the Orawsko-Nowotarska Basin (Klimaszewski, 1972) (Fig. 1). The river flows into the Dunajec River in Nowy Targ at an elevation of 580 m above sea level. The catchment area covers 224 km^2.

The catchment area is characterized by diverse geological formations. Crystalline rocks dominate in the Tatra Mts., while in the Podhale region dominate: the Podhalański flysch (sandstone, shale with insetting agglomerate of the zakopiańskie and chochołowskie layers), limestone and marl within the Pieniny Klippen Belt and finally the Magurski flysch (sandstone and shale). The riverbed material mainly consists of granite stones and gravels, with an admixture of sandstones and shales.

The climatic conditions in the catchment area are highly diverse. The average annual temperature ranges from −0.8 °C on Kasprowy Wierch to 5.3 °C in Nowy Targ, while the average annual precipitation varies from 1610 mm to 760 mm, respectively (Hess, 1965). This climate, combined with the high-altitude location of the catchment, its elongated shape, and steep slopes, contributes to the high-mountain hydrological regime of the Biały Dunajec. This regime is characterized by a rapid flood wave build-up and highly dynamic flood events.

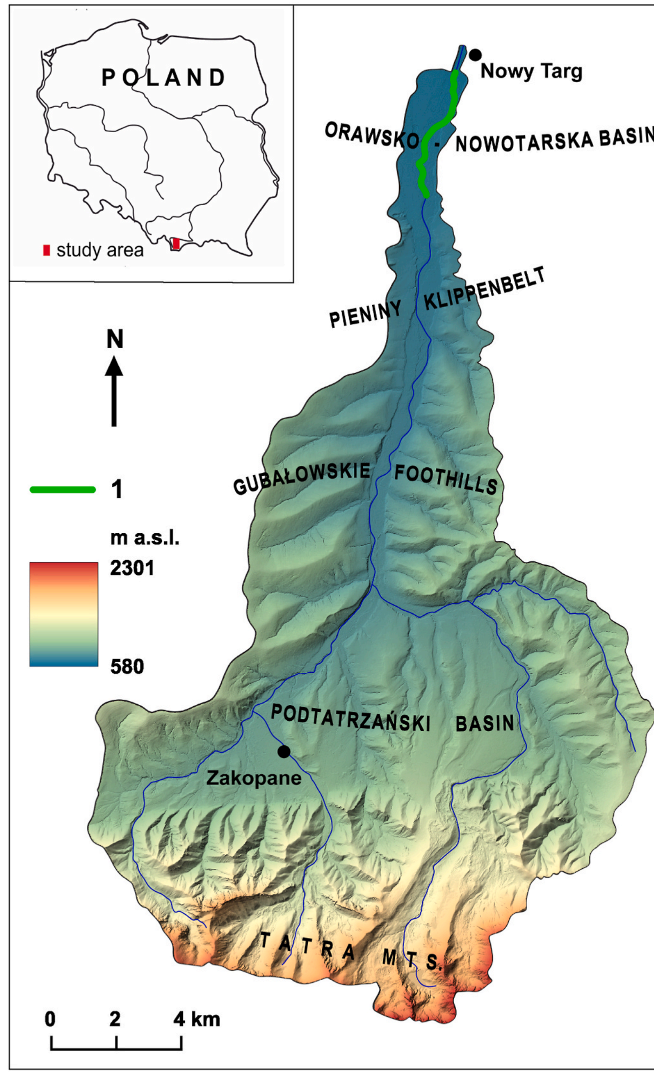

Fig. 1. Study area: 1 – studied river section.

Detailed studies were conducted in the lower stretch of the Biały Dunajec, from km 5.1 to km 0.9, located in the Orawsko-Nowotarska Basin. The nearest water gauge station is in Szaflary at km 7.23 of the river. There are no significant tributaries between the study stretch and the water gauge station, resulting in only a 6.25 % increase in the catchment area. The average annual discharge is 5.7 m^3/s (Designing Project no. 2064).

The examined stretch is a well-documented example of anthropogenic modifications in the channel of a mountain river. This short, 4-km stretch has been repeatedly modified to accommodate economic needs, with various types of river regulations implemented. Analyzing the channel condition after successive hydrotechnical works revealed that part of the examined stretch underwent spontaneous restoration, adding further complexity to the study. An important factor influencing the choice of this river stretch was the availability of extensive archival materials illustrating the successive stages of channel transformation.

3. Materials and methods

3.1. Hydrological calculations

To assess whether there were temporal changes in hydrological regime indicators that could further influence the hydraulic parameters of the analyzed river section, "ecologically relevant" hydrological indicators were applied according to Richter et al. (1996). These indicators typically include a set of 32 parameters used to develop the IHA. The IHA metrics describe five fundamental aspects of the flow regime: magnitude, frequency, duration, timing, and rate of change (Mathews and Richter, 2007; Szmańda et al., 2021). They are used to evaluate hydrological regime changes in relation to habitat conditions for aquatic organisms, particularly fish (Olden and Poff, 2003).

This analysis focused primarily on periodic low flows, determined based on the flow duration curve. The Q_{90} value was adopted as the reference flow, along with extreme low, low, high, and flood flows. High flows were defined as average daily flows exceeding the 25th percentile, whereas low flows were those below the 75th percentile (Richter et al., 1996; Ali et al., 2019).

Hydrological analyses were conducted for the multi-year period 1961–2015 at the Szaflary cross-section on the Biały Dunajec River, upstream of the section subject to intensive river regulation measures. The hydrological data served as input parameters for hydraulic analyses of the lower river section. The dataset used for hydrological assessments consisted of average daily flow values obtained from the resources of the Institute of Meteorology and Water Management – National Research Institute (https://danepubliczne.imgw.pl).

3.2. Historical analysis

The history of regulation and changes in channel morphology was reconstructed based on documents from the Regional Water Management Authority in Kraków, including technical regulation projects, expert reports, and other materials from the years 1962, 1968, 1969, 1977, 1984, 1986, and 2003 (corresponding to Designing Projects nos. 3963, 3964, 2220, 101, 152, 4170, 2064). These materials serve as a valuable source of information on the condition of the river channel and the stages of its gradual regulation over different periods.

The collected documents include topographic and elevation maps, longitudinal profiles, cross-sections, and technical descriptions. However, not all periods have comprehensive documentation covering the entire length of the studied river stretch. The detailed analysis focused on those periods for which the available historical data were the most complete and represented different stages of regulatory works in the examined river channel (Table 1).

Due to the specific nature and scope of past regulatory works, two sections of the analyzed river stretch were distinguished, each with a distinct history and a different set of available data (Table 1). The 1962 project covers a shorter segment of the channel, from km 1.0 to km 3.0. However, it was included in the analysis as it represents an almost natural riverbed with minimal hydrotechnical interventions, making it a valuable reference section.

Archival aerial photographs from 1977 to 1994 were also used for the analysis of morphological changes in the river channel. These images were brought to a uniform scale of 1:10,000 and aligned with the PUWG1992 coordinate system. Additionally, photographs available on the geoportal.gov.pl website were utilized.

Table 1
Division of the analyzed stretch of the Biały Dunajec River into two sections with different regulatory histories.

Year	Analyzed river kilometer (measured from the river mouth) and channel regulation status	
	SECTION 1	SECTION 2
1962		3.0–1.0, natural channel with variable width
1977	5.1–3.3, channel regulated with groynes, straightened, shortened, and narrowed to 30 m	3.3–0.9, channel with local bank reinforcements, located downstream of the groyne regulation, variable width
1987		3.3–0.9, channel regulated through grade control structures, narrowed to 50 m
2003	5.1–3.3, spontaneously restored channel with variable width	

3.3. Hydraulic calculations

For both sections in the periods highlighted above, hydraulic modeling was performed using a one-dimensional model in the HEC-RAS software. Four models were created.

- The 1962 model, based on 21 cross-sections taken from the river channel between km 2.5–1.2,
- The 1977 model, based on 71 cross-sections taken from the river channel between km 6.2–0.8,
- The 1986 model, based on 58 cross-sections taken from the river channel between km 3.3–0.8,
- The 2003 model, based on 44 cross-sections taken from the river channel between km 5.4–3.3.

The cross-sections from 1962, 1977, 1986, and 2003 were taken at similar average distances, ranging from 41 to 57 m. These distances are close to the average width of the Biały Dunajec River channel in section 2 after it was regulated using grade control structures.

In the model, a single value of the roughness coefficient was adopted, n = 0.031, verified in the field in 2024. Due to the lack of archival sediment studies, it was assumed that the sediment size in the analyzed period remained unchanged. The roughness was calculated using the empirical formula by Strickler (1923):

$$n = 0,047 d_{50}^{1/6}$$

The models allowed for capturing the changing flow dynamics in the studied stretch. Modeling was carried out for the Q_{90} flow, as it represents a value close to the environmental flow, which is crucial for the well-being of aquatic organisms (Książek et al., 2019). At such low flows, it is also possible to better characterize habitat quality from a hydraulic perspective. At higher flows, hydraulic conditions become more uniform. Moreover, in regulated mountain rivers, particularly challenging habitat conditions occur during low flows, which is why these flows should be taken into account in potential revitalization plans (Macura et al., 2012, 2016).

3.4. Data analysis

In evaluating habitat quality along the analyzed stretch of the Biały Dunajec River, the following hydraulic parameters were considered: flow depth (d), flow velocity (v), and the Froude number (Fr). These parameters were derived from the hydraulic models developed. Habitat quality studies are usually conducted in the field at cross-sectional profiles, where measurements of relevant parameters are taken at each point of a section. Since our study relied on historical data, we were unable to conduct field surveys of habitat conditions from the past. For this reason, an important habitat characteristic, substrate particle size, was not included (due to the lack of accurate sediment measurements from the past). However, it is known that the material in the Biały Dunajec consists of gravel and cobble (Korpak et al., 2023), which is preferred by salmonids because its size allows penetration for redd construction (Bovee, 1978; Armstrong et al., 2003). The analysis considered model-based values for flow depth, velocity, and the Froude number at the lowest point of each cross-section. The hydraulic conditions were thus analyzed along the river's longitudinal profile, following the flow current. The results of these analyses cannot be directly compared to standard field-based studies. However, the results obtained in the different years can be compared to assess potential changes in habitat quality.

The flow depth and velocity values obtained from the models were assessed for their suitability for brown trout habitat. It was decided to consider the habitat preferences of brown trout, as it is recognized as the most sensitive bioindicator species, responding to changes in any hydraulic conditions such as flow depth, velocity, and substrate type (Macura et al., 2012, 2018; Štefunková et al., 2021). This analysis only considered the potential preferences of the species based on morphological and hydraulic factors, as no historical biological data regarding the presence of brown trout in the Biały Dunajec River were available. Reference conditions for trout are well understood and represented using Habitat Suitability Curves (HSCs). The literature stresses the importance of using local curves developed for the river in question or for rivers in similar natural conditions (Vismara et al., 2001). Therefore, curves developed for 43 Slovak streams, located relatively close to the Biały Dunajec in watersheds with similar topographical and geological characteristics and flow regimes, were used (Macura et al., 2012, 2018). The choice of these HSCs was also influenced by the fact that the habitat preferences of brown trout in Slovak rivers were studied at low flows, close to the Q_{90} flow. The curves used specify optimal, suboptimal, and unsuitable values for flow depth and velocity from the perspective of adult brown trout preferences (Table 2).

The reference values of the Froude number were taken from Kemp et al. (2000), who demonstrated that different functional habitats (also known as mesohabitats) are associated with specific ranges of not only flow depth and velocity but also the Froude number. The studied section of the Biały Dunajec corresponds to functional habitats classified as "cobbles" and "gravels" (according to Harper and Smith, 1995). Therefore, the reference Froude number values used in the analysis relate specifically to these habitat types (Table 2).

The study also explored a different approach to habitat assessment proposed by Gostner et al. (2013a). Instead of evaluating and categorizing habitats based on the optimal hydraulic conditions for specific species, this method focuses on the HMID – The Hydromorphological Index of Diversity – as a measure of overall hydraulic variability. The underlying assumption is that diverse hydraulic conditions indicate varied hydrological and morphological features, which, in turn, contribute to a greater range of habitat conditions. This concept assumes that the greater the hydraulic (hydromorphological) diversity, the closer river conditions are to their natural state, where a variety of habitats can provide optimal conditions for the development of different aquatic organisms at various life stages. The HMID parameter can be used as a supporting tool in selecting the best rehabilitation scenario for a given river section (Gostner et al., 2013a).

Although HMID was developed for mean flow conditions, it has been successfully applied to various flow scenarios, including low flows (van Rooijen et al., 2022).

To determine the HMID index, only two hydraulic parameters are considered: flow depth and flow velocity (the same parameters used in habitat suitability curve assessments). First, the coefficients of variation for both parameters are calculated, which are then used to compute the HMID:

$$HMID_{Reach} = \Pi_i(1+CV_i)^2 = (1+\mu_d/\sigma_h d)^2 \cdot (1+\mu_v/\sigma_v)^2$$

where: CV = coefficient of variation (−); μ = mean value of flow depth (m) or flow velocity (m/s); σ = standard deviation of flow depth (m) or flow velocity (m/s)

Originally, the coefficients of variation, CV_d and CV_v, are calculated using data on flow depth and velocity measured in cross-sections. As a result, the HMID index reflects hydromorphological diversity within these cross-sections. It has been found that higher HMID values indicate greater hydromorphological variability, meaning more natural channel conditions that contribute to improved habitat quality. HMID values below 5 suggest a heavily modified (regulated) channel with uniform hydromorphology, while values between 5 and 9 indicate a slightly altered channel with moderate hydraulic diversity. In contrast, HMID values above 9 are characteristic of natural riverbeds with highly diverse habitat conditions (Gostner et al., 2013a).

In this study, the approach was modified due to the lack of appropriate historical data. The values of hydraulic parameters (flow depths and average velocities) used in the models, based on which the HMID index was also calculated, represented habitat conditions at individual points located along the flow current of the river. Therefore, they reflect the variability of hydromorphological (habitat) conditions along the longitudinal profile of the river and cannot be directly compared to values obtained through traditional methods, which show variability in cross-sections or polygons. However, following the definition of the current as the "path of maximum depth and velocity within the channel" (Knighton, 1998; Schwartz, 2016), it can be assumed that in other areas of the riverbed, the values of these parameters are lower, and thus, under the analyzed low-flow conditions, habitat conditions are worse there.

3.5. Statistical analysis

A comparative analysis of various hydraulic parameters during the analyzed study periods was conducted. For this purpose, the non-parametric Mann-Whitney test was applied. Differences were considered statistically significant if the p-value <0.05.

To explore the relationship between selected hydraulic parameters in both sections of the studied river stretch, correlations were analyzed, with the assumption that the correlation is statistically significant if the p-value <0.05.

4. Results

4.1. Changes in the morphology of the studied stretch of the Biały Dunajec river under the influence of various engineering interventions in the years 1962–2003

The first section covers the stretch of the river between km 5.1 and 3.3. Initially, the river on this section had a slight gradient, with a wide and braided channel (in some places, the channel width reached up to 350 m, Fig. 2a). The dominant process was sediment deposition (Korpak, 2018). This state persisted until around 1971, when regulation works using groynes were carried out. The goal of the regulation was to concentrate the channel and acquire new land for cultivation. It was also decided to reinforce the banks to prevent erosion that could threaten the surrounding farmland. As a result of these works, the channel was completely transformed into a uniform trapezoidal shape with a width of 30 m (Fig. 2a). The regulatory route was almost straight, significantly shortening the river's course by about 524 m. As a result, the gradient and flow velocity increased, contributing to the intensification of bed erosion. Lateral erosion was limited, reducing sediment supply to the

Table 2
Reference values of flow depth (d) and velocity (v) (simplified based on Macura et al., 2012) and Froude number (Fr) (simplified based on Kemp et al., 2000) for brown trout.

Hydraulic Parameter	Optimal Values	Suboptimal Values
d	0.2–0.5	0.1–0.2 0.5–0.65
v	0.4–0.7	0.15–0.4 0.7–0.9
Fr	0.05–0.75	

Fig. 2. Changes in the morphology of the Biały Dunajec channel in section 1, with the pre-regulation channel extent marked by a red dashed line.

Fig. 3. Changes in the morphology of the Biały Dunajec channel in section 2.

channel. The increased transport capacity of the Biały Dunajec, combined with a reduced sediment supply, led to rapid incision of the riverbed. Vertical erosion was most intense immediately after the regulation. Between 1971 and 1977, the channel deepened by 1–3 m (Korpak, 2018). The significant lowering of the riverbed resulted in an increase in the height of the riverbanks. The spaces between the groynes were filled with sediment, forming a terrace where vegetation began to develop (Fig. 2a and b). The ongoing vertical erosion caused the loss of stability of the groyne structures, contributing to their destruction. The final destruction of the groynes, which occurred due to extreme floods in 1997 and 2001, allowed the river to migrate laterally, resulting in an increase in the length, sinuosity, and width of the channel (Korpak et al., 2023) (Fig. 2c). After about 30 years, natural spontaneous restoration of the section occurred. The river freely shaped its channel, leading to an increase in the diversity of geomorphological conditions (Fig. 2d).

The second section is located downstream from the previously described section, between km 3.3 and 0.9. In 1962, this section was almost natural, wide, and braided (Korpak et al., 2023). In the late 1960s, bank protections were implemented in several places and some side channels were cut off. The channel was heavily filled with sediment transported from the upstream section, which caused difficulties in its maintenance and generated flood risks (Fig. 3a). In 1979, work began on regulation through grade control structures (GCSs). The project involved constructing 11 GCSs, each 1 m high. The planned channel gradient between the GCSs was 0.004. A trapezoidal channel with a width of 50 m was formed. The regulatory works lasted for 6 years. Since the completion of this regulation, the morphology of the channel in section 2 has not changed significantly, as evidenced by aerial photographs from 1994, 2003, and 2009 (Fig. 3b, c, d).

The number of fish living naturally depends on the passability of a given section and the possibility of migration for these fish (Sun et al., 2023). Although the grade control structures in the Biały Dunajec are not high constructions, they are insurmountable obstacles for the fish. Therefore, in the analyzed section of the Biały Dunajec, there are mainly non-migratory fish or those resulting from stocking. The dominant species are brown trout, brook char, and grayling.

4.2. Formation of hydrological regime indicators of the Biały Dunajec river

4.2.1. Flow duration curve (FDC)

The FDC shows significant variability in the analyzed months compared to the annual curve for the multi-year period (Fig. 4). The highest flows were recorded in August throughout the variability of the curve. This indicates a large contribution of summer precipitation with varying durations to the flow of the Biały Dunajec River. The annual curve has a regular shape, indicating a stable hydrological regime. The lowest flows (with the highest exceedance probabilities) occur in May. Thus, May experienced periods of prolonged lack of precipitation, which

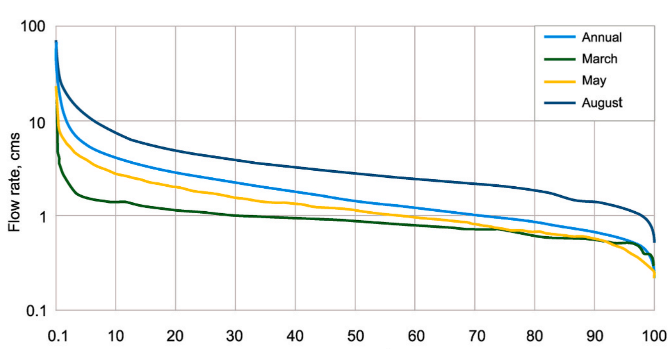

Fig. 4. Flow duration curves for selected months in the multi-year period 1962–2016 at the Szaflary cross-section.

led to groundwater feeding of the stream during low flow periods. Since the high flows in May were lower than the multi-year average, this indicates that this month had below-average water availability. For high flows (with low exceedance probabilities), the lowest values occur in March. Regarding Q_{90} flows, the highest were recorded in August at 1.386 m^3/s, while the lowest were in May at 0.573 m^3/s. The Q_{90} flow for the average year from the multi-year period was 0.674 m^3/s.

4.2.2. Variability of environmental parameters of the hydrological regime

As shown in Fig. 5, small and large floods occurred until 2008. Large floods typically transform both the biological and physical structure of the river and its floodplain (Zhang et al., 2019). Large floods can wash away many organisms, thereby depleting some populations, but in many cases, they also create new competitive advantages for certain species. They can also play a significant role in shaping key habitats and the dynamics of morphological processes in the channel (Gierszewski et al., 2020) and mitigate the adverse effects of low flows on the life of organisms (Zheng et al., 2021). In the case of small floods, fish and other aquatic organisms can move upstream, downstream, and into floodplains or flooded wetlands to access additional habitats, such as side channels, bays, floodplains, and shallow inundated areas. These typically hard-to-reach areas can provide substantial food resources. Shallow inundated areas are usually warmer than the main channel and are full of nutrients and insects that promote the rapid growth of aquatic organisms. In this context, "small floods" include any rise in river level above the main channel but do not encompass more extreme and rarer floods. Up until 2008, there was a positive trend in the occurrence of small and large floods on the habitat conditions of organisms. After 2008, small and large floods have disappeared, which may be the result of stream regulation and changes in the hydraulic parameters of the river. Large floods were also not observed during the period between 1974 and 1999. As reported by Wałęga et al. (2024), this period was frequently affected by droughts, which led to a decrease in water resources and, consequently, a reduced frequency of high flows. High flow pulses occurred evenly throughout the entire studied period. During heavy rainfall or short periods of snowmelt, the water level in the river rises above its normal level. In this context, high flow periods include any rises in water level that do not exceed the riverbanks. These flow periods provide important and necessary breaks in low flow periods. Even a small or short-term influx of water can provide much-needed relief from the effects of high water temperatures or low oxygen concentrations, which are characteristic of low flow periods, and supply nourishing organic matter.

Seasonally variable low flows in the river create limitations for the development of organisms, as they determine the amount of available aquatic habitat for most of the year. This has a strong impact on the diversity and abundance of organisms that can live in the river. It is also related to the amount of sediment and nutrients being transported by the river (Szatten et al., 2021). A previous study by Wałęga et al. (2022), which also examined the Biały Dunajec River, demonstrated that hydrological seasonality, expressed through predictability, is significantly correlated with macroinvertebrate biodiversity. The response of aquatic invertebrate communities to flow regimes is useful for resolving flow conflicts and determining appropriate flow levels to support river ecosystem health. Fig. 5 shows that both high-flow pulses and low-flow periods exhibit consistent seasonality and regularity throughout the study period. This suggests that aquatic communities in the Biały Dunajec experience stable hydrological conditions. In the case of Biały Dunajec, a positive trend in the number of low flow periods is observed. The analysis indicates that in the studied multi-year period, a change in the hydrological regime occurred due to low flows and the reduction of large and small floods, especially after 2008. Therefore, it can be concluded that in the years for which the analysis of habitat conditions in the Biały Dunajec River was carried out, the hydrological regime remained stable without pressure from urbanization, industry and other human activity and did not influence, as an additional factor, changes in

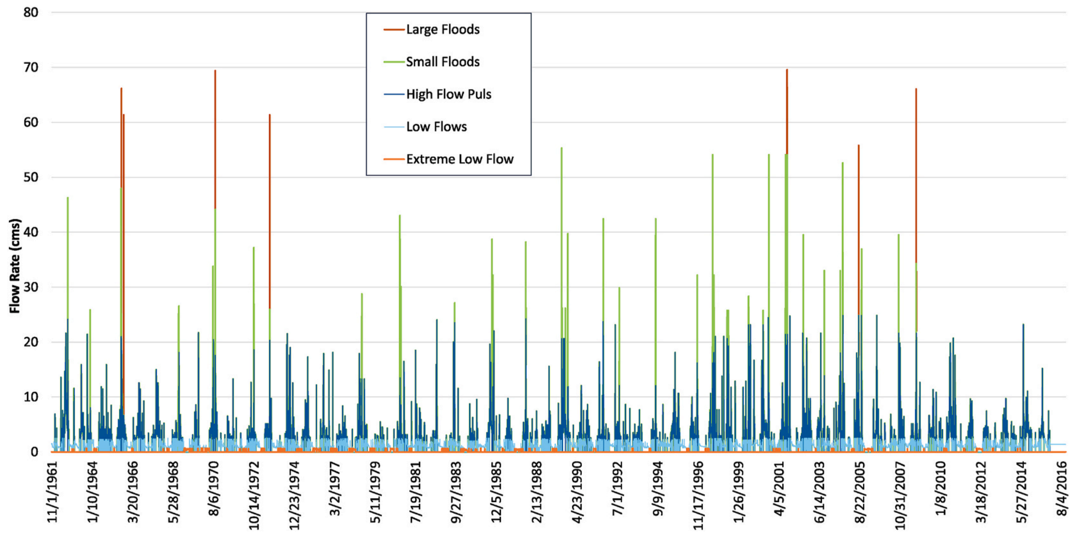

Fig. 5. Course of ecohydrological components of the hydrological regime of the Biały Dunajec river at the Szaflary cross-section.

the hydraulic parameters of the riverbed.

4.3. Analysis of hydraulic parameters

To compare the course of water level, velocity, and Froude number values in the longitudinal profile of the river, these parameters were plotted on a single graph, with reference values for brown trout also indicated (Fig. 6). Both the average values of these parameters, their ranges, and variability differ significantly between the two sections and across the individual years (Figs. 6 and 7). However, these values show mutual dependence, as indicated by statistically significant correlations between them (Table 3). Generally, at a given discharge, high flow depths generate low velocities and low Froude numbers. Higher velocities and greater Froude number values occur at shallow flow depths.

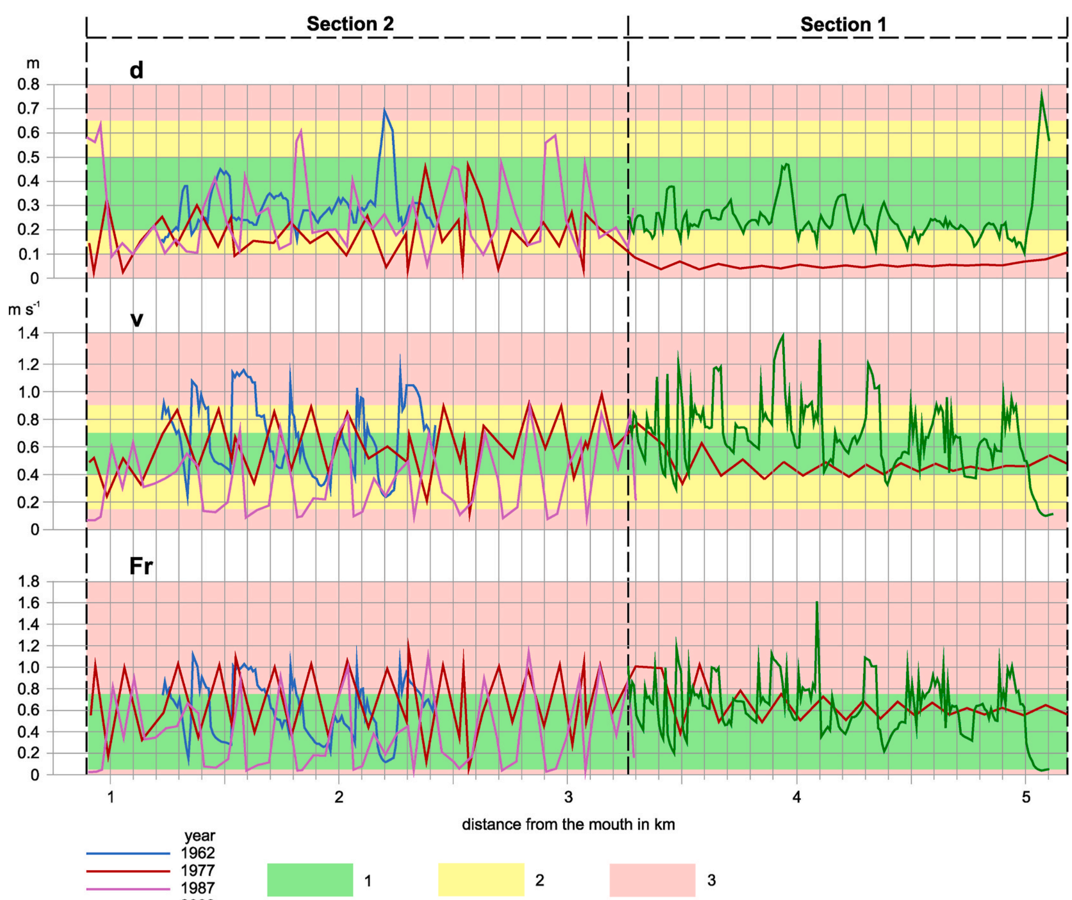

Fig. 6. Hydraulic parameters (flow depth d, flow velocity v and Froude number Fr) over the years in the longitudinal profile of the analyzed river sections: 1 – optimal conditions for brown trout, 2 – suboptimal conditions for brown trout, 3 – unsuitable conditions for brown trout.

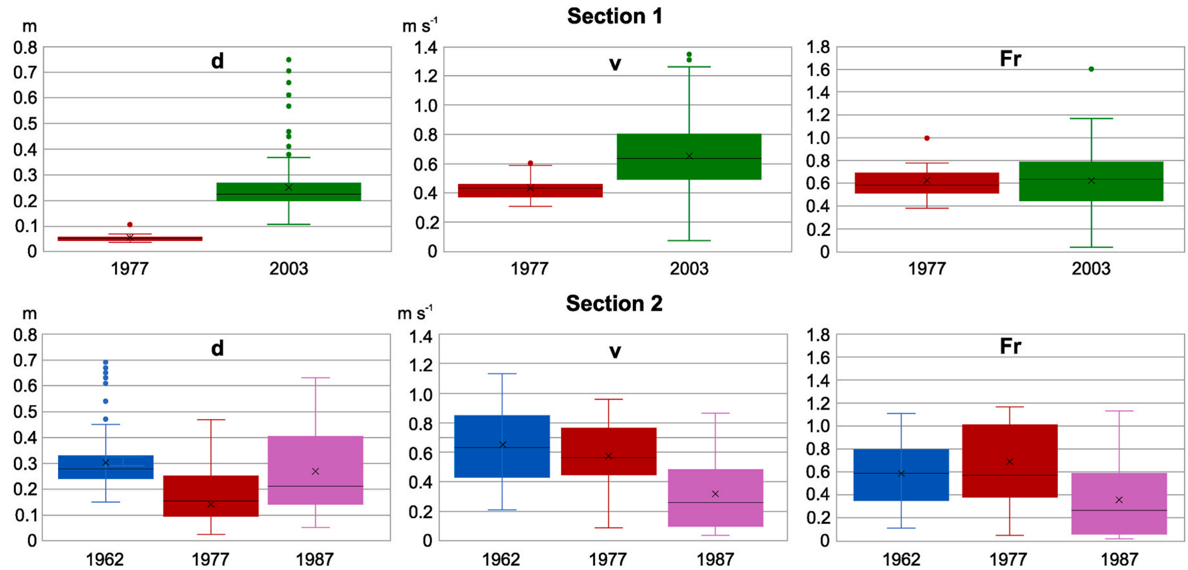

Fig. 7. Values of the analyzed hydraulic parameters of the river in sections 1 and 2 over the years.

Table 3
Correlations between the analyzed parameters.

		1962	1977	1986	2003
SECTION 1	**d-v**	–	−0.772 (p < 0.001)	–	−0.368 (p < 0.001)
	d-Fr	–	−0.704 (p < 0.001)	–	−0.489 (p < 0.001)
	v-Fr	–	0.959 (p < 0.001)	–	0.942 (p < 0.001)
SECTION 2	**d-v**	−0.603 (p < 0.001)	−0.422 (p = 0.008)	−0.747 (p < 0.001)	–
	d-Fr	−0.683 (p < 0.001)	−0.813 (p < 0.001)	−0.741 (p < 0.001)	–
	v-Fr	0.969 (p < 0.001)	0.735 (p < 0.001)	0.979 (p < 0.001)	–

This pattern is related to the varied channel bed morphology and the alternating occurrence of riffles and pools.

In 1977, section 1 of the river, regulated by groynes, had very low flow depth and relatively low average flow velocity (Figs. 6 and 7). The slight variation in both parameters indicated uniform and stable hydraulic conditions along this stretch. By 2003, after the channel underwent spontaneous restoration, the average flow depths and flow velocities increased significantly and became much more diverse. This change in flow depth was statistically significant (Table 4). The Froude number showed the least change, with its values becoming slightly more varied following the destruction of the groynes.

In section 2, in 1962, when the river was still in its almost natural state, the average depth at the studied flow was 30 cm and showed significant variation (Figs. 6 and 7). The river was characterized by diverse flow velocities and Froude number values. By 1977, when this section was still only slightly regulated but located just downstream of a groyne-regulated section, flow velocity and Froude number values remained similar to those observed in 1962. However, flow depths significantly decreased, and this change was statistically significant (Table 4). After regulation with grade control structures was introduced, the average flow depth increased, and the variability in flow depths also grew. Meanwhile, the average flow velocity and Froude number decreased significantly due to the reduced channel gradient caused by the applied regulation. Nevertheless, the values of these parameters remained highly variable.

Table 4
Comparison of hydraulic parameters in different years using the Mann-Whitney test (statistically significant differences are in bold).

	The compared years	d	v	Fr
SECTION 1	1977–2003	**p = 0.007**	0.156	0.834
SECTION 2	1962–1977	**p = 0.034**	0.660	0.624
	1977–1986	p = 0.373	0.103	0.660
	1962–1986	p = 0.529	0.177	0.180

In summary, the values of the analyzed hydraulic parameters exhibited significant variability due to various interventions in the channel, although these changes were mostly not statistically significant (Table 4). The section regulated by groynes was primarily characterized by uniform hydraulic conditions and low flow depths. The section with grade control structures had highly diverse hydraulic conditions, as well as low flow velocity and Froude number.

4.4. *Analysis of hydraulic habitat quality*

To analyze the multiyear variability of habitat conditions for brown trout, histograms were created showing the frequency of occurrence of hydraulic parameters in sections 1 and 2 against the hydraulic conditions preferred by brown trout (Fig. 8).

The following observations were made.

1. The hydraulic conditions in section 1, regulated by groynes, significantly improved after the spontaneous restoration of the channel.
2. The hydraulic conditions in section 2 gradually worsened with the progress of regulation works.
3. The hydraulic conditions in the natural and spontaneously restored channels were nearly identical, characterized by a clear dominance of optimal flow depths and significant variation in flow velocities.
4. The channel regulated by groynes had very low, unsuitable flow depths for brown trout, along with optimal and suboptimal flow velocities.
5. The channel regulated by grade control structures had suitable for brown trout flow depths and highly variable flow velocities, with a dominance of suboptimal and unsuitable values.
6. The channel in section 2 in 1977 (below the groyne-regulated section, nearly in its natural state) had worse hydraulic conditions than the natural and spontaneously restored channels but better than the regulated channels.

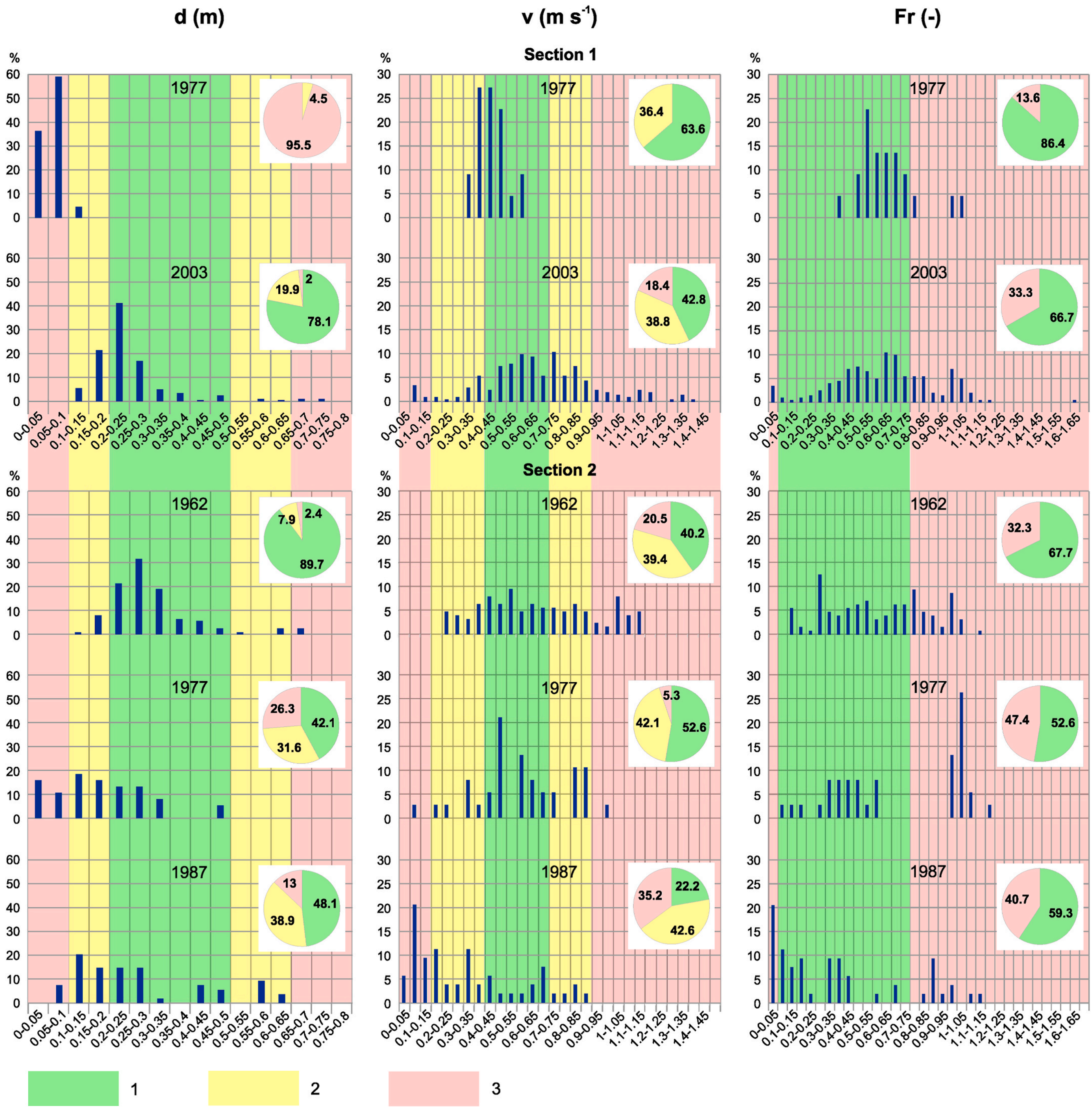

Fig. 8. Frequency histograms of occurrence of specific hydraulic conditions at cross-sections in different years in sections 1 and 2 against the hydraulic conditions preferred by brown trout: 1 – optimal conditions for brown trout, 2 – suboptimal conditions for brown trout, 3 – unsuitable conditions for brown trout.

7. The values of the Froude number changed only slightly over the periods in both sections. In each case, values suitable for brown trout dominated, most notably in section 1 in 1977, and least in section 2, also in 1977. For the analyzed stretch, the Froude number did not prove to be a useful parameter for characterizing habitat quality. Therefore, it was excluded from further analysis.

The proportion of optimal, suboptimal, and unsuitable conditions for brown trout varies between the two sections from year to year. Another important aspect is their distribution along the longitudinal profile, as well as their quantity and length. An analysis of flow depth and velocity in the river's longitudinal profile revealed that these parameters do not always fall within the same preference range at a given location (Fig. 8). Such agreement was found in only 47.2 % of points in 1962, 52.6 % of points in 1977 in section 2, 0 % of points in 1977 in section 1, 31.5 % of points in 1987, and 41.3 % of points in 2003. This alignment is more prevalent in natural, near-natural, or restored riverbeds than in regulated channels, especially those modified with groynes.

Based on these observations, the analyzed river sections was divided into reaches with favorable, moderately favorable, and unfavorable habitat conditions during each study period (Fig. 9). Reaches were classified as favorable when both flow depth and velocity fell within the

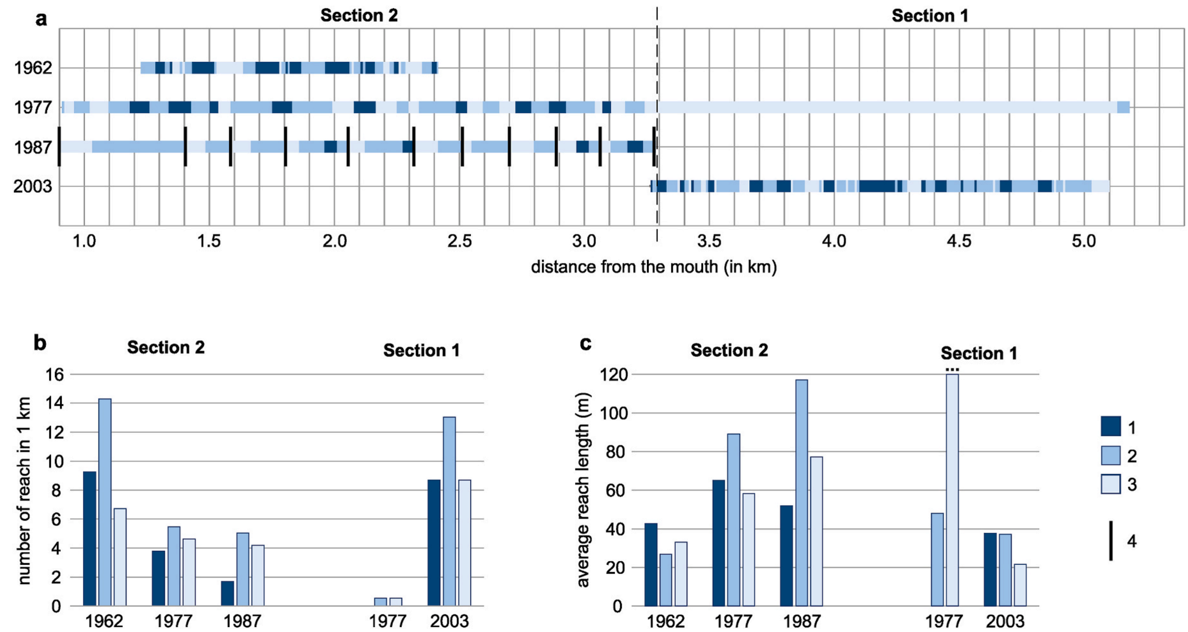

Fig. 9. Reaches with varying habitat conditions over different years: a) distribution along the river's longitudinal profile, b) number of reaches per kilometer of the river, c) average length of the reaches: 1 – favorable habitat conditions, 2 – moderately favorable habitat conditions, 3 – unfavorable habitat conditions, 4 – grade control structure.

optimal range for brown trout. Moderately favorable conditions were identified where at least one of these parameters (flow depth or velocity) had a suboptimal value. Unfavorable sections were those where at least one parameter had values unsuitable for trout habitation.

In 1962, the longitudinal profile of section 2 displayed alternating segments with longer reaches of specific habitat conditions and segments with very short reaches (Fig. 9a). A similar pattern was observed in the river channel in 2003. In contrast, the channel in section 1 of 1977 was highly uniform, characterized by unfavorable habitat conditions. Meanwhile, in section 2 of 1977, the channel exhibited much greater variability, with reaches of specific habitat conditions being of similar length. In 1987, within the channel with grade control structures, a distinct regularity in the distribution of different habitat conditions was noticeable—the unfavorable conditions were found upstream of the structures, while favorable or moderately favorable conditions occurred downstream of them.

In all years, moderately favorable habitat conditions were the most common (Fig. 9b). The highest number of favorable habitat reaches was observed in the natural channel (1962) and the spontaneously restored channel (2003). The worst and least diverse conditions were recorded in section 1 of 1977, where over a stretch of nearly 1.8 km, there was not a single reach with favorable conditions and only one short reach with moderately favorable conditions (Fig. 9b and c). In section 2, habitat conditions gradually deteriorated. By 1977, the number of unfavorable reaches exceeded that of favorable ones, although their total length was still shorter. By 1987, the dominance of unfavorable reaches had increased even further, with only four reaches classified as favorable. Additionally, by that year, the total length of unfavorable reaches had exceeded that of favorable ones.

Table 5
Characteristics of river hydromorphological diversity parameters in sections 1 and 2 (d – flow depth, v – flow velocity, μ – mean value, σ – standard of variation, CVd – coefficient of variation of flow depth, CVv – coefficient of variation of flow velocity, HMID – the hydromorphological index of diversity).

	Parameters		1962	1977	1987	2003
SECTION 1	**d**	**μ**	–	0.055	–	0.250
		σ	–	0.015	–	0.101
	v	**μ**	–	0.431	–	0.652
		σ	–	0.072	–	0.262
	CVd			**0.284**		**0.402**
	CVv			**0.168**		**0.401**
	HMID			**2.246**		**3.861**
SECTION 2	**d**	**μ**	0.303	0.178	0.269	–
		σ	0.104	0.109	0.163	–
	v	**μ**	0.650	0.574	0.318	–
		σ	0.261	0.216	0.247	–
	CVd		**0.344**	**0.613**	**0.606**	
	CVv		**0.401**	**0.376**	**0.777**	
	HMID		**3.545**	**4.926**	**8.137**	

4.5. Analysis of hydromorphological diversity

The values of the hydromorphological index of diversity (HMID) calculated for both sections in different years are not easy to interpret (Table 5, Fig. 10).

The lowest HMID index is observed in section 1 in 1977 (regulated with groynes). Here, both flow depths and flow velocities exhibit low variability. This is not surprising, as the channel was highly uniform at that time, both in its longitudinal profile and cross-sections. One might expect that the highest HMID index would be found in the natural channel (section 2 in 1962) and the renaturalized channel (section 1 in 2003). However, the index values here are only slightly higher, not exceeding 4. The variability of velocity and depth flow remains at a moderate level. Most values are concentrated around the mean, though there are many outliers. Section 2 in 1977, which had minor technical modifications at the time, shows slightly greater hydromorphological variability, with particularly strong fluctuations in water depths. The highest HMID index is found in section 2 in 1987, which was regulated using grade control structures. The high coefficients of variation in flow depth and flow velocity do not reflect natural conditions but rather the specific channel regulation. This resulted in alternating deep areas with minimal velocity (upstream of the GCSs) and shallow areas with significantly higher velocity (downstream of the GCSs). Few values are close to the mean (Figs. 6 and 7).

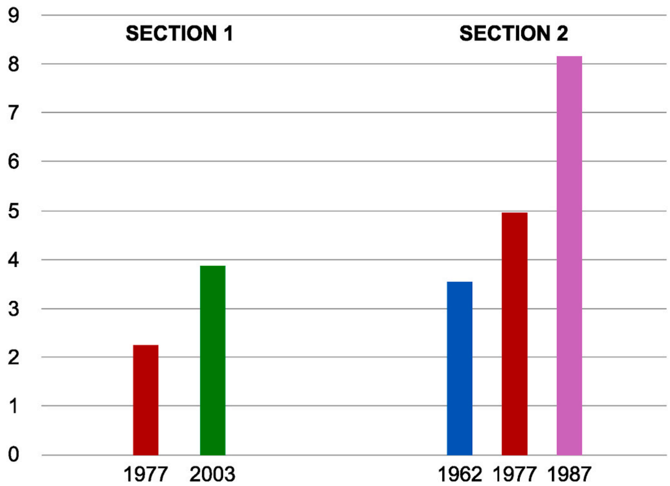

Fig. 10. The hydromorphological index of diversity (HMID).

5. Discussion

The conducted analyses revealed not only different hydromorphological and hydraulic conditions in natural and regulated river channels but also variations among differently regulated channels. The research also enabled an assessment of the feasibility and direction of potential river restoration efforts. This confirms the thesis proposed by Štefunková et al. (2021) that, based on morphological changes in the river channel, and therefore on hydraulic parameters, it is possible to evaluate the impact of river regulation or predict the effects of stream restoration.

In a natural channel, where the flow regime is undisturbed and the river can freely shape its course, there are significantly more reaches with flow depth and velocity values favorable for brown trout compared to regulated channels. Moreover, sections with unfavorable conditions are shorter in natural channels, increasing the likelihood that organisms can traverse them during their migration along the river.

The worst habitat conditions are found in channels regulated with the use of groynes. At low flows, the depth values are so low that trout have no chance of survival, as there is no refuge for them. In this case, favorable velocity conditions are of secondary importance Similar observations were made by Štefunková et al. (2018), who studied the ecohydraulic habitat conditions for brown trout in regulated rivers in Slovakia. This highlights the fact that longitudinal regulation should generally be avoided in mountain rivers. In channels with grade control structures, a certain repeatability in the longitudinal profile can be observed – favorable conditions for trout occur downstream of the structures, while unfavorable conditions are found upstream of them. The organisms can likely cope temporarily with the excessively low velocity that occurs there during low flows, provided that sufficiently high depths are maintained. These, in many cases, result from the progressing upstream erosion in these locations (Korpak et al., 2021). The biggest problem is the GCSs themselves. Considering habitat quality between them while ignoring the structures themselves is theoretical and pointless, since the GCSs break the continuity of migration corridors for aquatic organisms, both fish and macroinvertebrates (Wohl, 2006; Mathers et al., 2021; Szałkiewicz et al., 2022).

Thus, analyses show that in longitudinal regulation, insufficient depth is the main issue for habitat restoration, while in step-regulated rivers, it's the low velocity above GCSs. According to observations by Macura et al. (2012, 2016) and Štefunková et al. (2018), at low flows, sufficient depth is the most crucial factor for aquatic organisms. When velocity becomes too low, brown trout can still seek refuge in deeper areas. From this perspective, channels with grade control structures provide more favorable living conditions for organisms compared to longitudinally regulated channels.

However, restoring rivers with longitudinal regulation seems simpler. In many cases, it is likely sufficient to remove the longitudinal structures and provide the river with an erodible corridor. This approach has been successfully applied to rivers such as the Biała and Raba, and monitoring of the effects conducted five years after the completion of these actions showed a significant improvement in the ecological quality of these rivers (Wyżga et al., 2021). This is also illustrated by the example of the Biały Dunajec River, where, following the destruction of groynes during the 1997 flood, the variability of depth and velocity, the HMID index, as well as the structure and quality of habitats, were, after just six years, very similar to those found in a natural channel.

The most effective approach for restoring channels with grade control structures seems to be transforming the GCSs into boulder ramp structures with an appropriate slope. Research has shown that naturally spawned fish can occur and migrate when the GCS's slope is within≤1:15 (Thomas et al., 2013). Special attention is needed upstream of the GCSs to ensure velocity is not too low. The effectiveness of such restoration in improving river habitat quality has already been confirmed (e.g., Litvan et al., 2008; Mikuś et al., 2021).

The Froude number proved to be the least sensitive parameter to morphological changes in the channel among those analyzed, consistently showing favorable values in most locations. This is because, as Clifford et al. (2006) noted, the Froude number yields similar values across a range of flow depths and velocities. Based on the conducted research, it can be confirmed that the Froude number is not a suitable parameter for assessing habitat quality. However, it can be useful in determining habitat types (e.g., calm vs. fast-flowing), as supported by numerous studies linking the Froude number to specific biotopes (Jowett, 1993; Padmore et al., 1998; Harper et al., 1998; Kemp et al., 1999, 2000).

An interesting observation came from analyzing the HMID index in comparison with habitat quality results obtained by comparing actual values of depth and flow velocity with the values preferred by brown trout. Since both methods assess the same hydraulic parameters, the comparison is valid. Previous studies show that high HMID values typically occur in natural channels with good habitat conditions, while increased human modification lowers both HMID and habitat quality (Gostner et al., 2013a, 2013b; van Rooijen et al., 2022). In the Biały Dunajec, the best habitats are found in natural and spontaneously re-naturalized sections (Fig. 9), yet HMID values there are low (Table 5, Fig. 10). Conversely, the channel with grade control structures, where favorable conditions appear only in short reaches, shows unexpectedly high HMID. This proves HMID alone cannot reliably indicate habitat quality. Similar conclusions were reached by Anim et al. (2019), who stated that improving hydromorphological diversity alone (as indicated by an increase in the HMID index) is not sufficient to restore reference conditions in a river. In other words, high hydromorphological variability does not always mean good habitat conditions. The specific values of the parameters considered (e.g., flow depth and flow velocity) are crucial and must fall within the ranges preferred by specific species. In the case of the Biały Dunajec River, it is evident that the channel with GCSs has high variability coefficients for depth and flow velocity, but a significant portion of these parameter values (especially velocity) falls outside the range preferred by trout. Therefore, good-quality habitats cannot be expected here.

This study modified and implemented existing research methods, originally developed for assessing micro- and meso-scale habitat quality in the present using field data, for use in historical analyses. The results yielded valuable insights and effectively addressed the research questions, confirming the method's potential for application in other rivers, provided historical cross-section data are available. The methodology can also serve as a simple, low-cost tool for future river habitat monitoring. The main cost lies in creating a model based on geodetic cross-sections, while the hydraulic modeling itself can be performed using free software like HEC-RAS.

This method is also suitable for historical analyses and for monitoring of changes in hydromorphological conditions caused by anthropogenic impacts other than river regulation, specifically those that alter flow regimes and key hydraulic parameters. These include mining, forestry, industrialization, urbanization, water extraction, and drainage (Yıldız et al., 2016; Werner et al., 2019, 2020; Yıldız, 2025). These pressures often co-occur within the same area, and their effects may overlap. However, there is a noticeable lack of research on this subject in the scientific literature (Tost et al., 2020). Understanding the complex interactions within ecosystems that have been exposed to various historical pressures is crucial to avoiding mismanagement of such areas in the future (Yıldız et al., 2025). The method applied in this study could support regulatory agencies in managing interconnected ecosystems and in planning rational and effective revitalization measures in river valleys. Of course, full river revitalization is a highly complex process that also involves issues such as river pollution, which require other dedicated methods.

6. Conclusion and suggestions

The main aim of this study was to assess long-term changes in habitat quality in a mountain river subjected to various types of channel regulation. Using archival data and hydraulic modeling, we evaluated how engineering interventions affected habitat conditions for brown trout over a 40-year period. The results significantly contribute to our understanding of the ecological consequences of different river regulation methods and their implications for future restoration strategies.

Key findings.

- Despite a stable flow regime over time, habitat quality varied considerably due to morphological transformations caused by regulation works.
- The best conditions for brown trout were observed in the natural (1962) and spontaneously restored (2003) channel states.
- The worst habitat conditions occur in channels regulated with groynes, as at low flows, the water depths are too shallow for trout to survive.
- While grade control structures (GCSs) maintain sufficient flow depth for trout survival, they interrupt ecological continuity, hindering migration and disrupting habitat connectivity.
- Sections regulated with groynes can recover habitat quality relatively quickly if the groynes are removed and the river is given space to self-adjust. In contrast, restoring ecological function in reaches with GCSs requires re-establishing corridor continuity, for example, by replacing barriers with boulder ramps.

This study highlights the ecological risks associated with river engineering and underscores the importance of interdisciplinary approaches in river restoration planning. Understanding the long-term effects of past interventions is essential for avoiding similar mistakes in future projects.

The main limitation of this study is the availability of hydrological data. The most reliable analyses are based on long-term historical flow time series, which allow for the calibration of hydrological models and the calculation of IHA (Indicators of Hydrologic Alteration) metrics. In the absence of observed data, hydrological modeling can be used to generate the necessary input; however, this approach may introduce additional uncertainty. In historical studies, another limitation may be the availability of archival cross-sectional data.

The obtained results have influenced the authors' further research plans. A valuable idea seems to be checking the current state of habitats in the Biały Dunajec. After 2003, no new hydrotechnical works were carried out on the studied section, but it is worth verifying whether the initiated process of spontaneous restoration has been maintained. The applied methodology will also be used to assess habitat quality for environmental flows determined using various approaches, including a new one based on aquatic macroinvertebrate biodiversity (Wałęga et al., 2025). This analysis will optimize the determination of biota requirements and validate environmental flow methods. The approach presented in this study can also be applied as a simple, low-cost method for monitoring habitat quality in other rivers affected by various anthropogenic interventions that alter flow regimes and key hydraulic parameters.

CRediT authorship contribution statement

A. Lenar-Matyas: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **J. Korpak:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Wałęga:** Writing – original draft, Methodology, Formal analysis, Data curation. **A. Radecki-Pawlik:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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