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HYDRAULIC DISCRIMINATION OF HYDROMORPHOLOGICAL UNITS IN A MOUNTAIN GRAVEL-BED RIVER: THE CASE OF THE SKAWA RIVER, POLISH CARPATHIANS

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ABSTRACT

Aim of the study
The aim of the study was to characterise the hydromorphological units of a mountain river in terms of flow depth, flow velocity, bed shear stress, the Froude number and bed-material grain size.

Material and methods
The study covered a mountainous section of the Skawa river, where 8 pools, 8 runs, 5 riffles and 7 rapids were identified. The dominant bed-material fraction was determined for each of these units. Additionally, the water-surface slope, the instantaneous flow velocities (60 s at $z/h = 0.4$ from the bed) and the flow depth were measured at eight verticals representative of the unit. On the basis of the field measurements, the following characteristics of the identified unit types were determined and compared: bed-material grain size, flow depth, flow velocity, bed shear stress and the Froude number.

Results and conclusions
The mean depth of individual pools ranged from 0.49 to 0.75 m, compared to 0.31–0.42 m in riffles. The mean point velocity was 0.348 m · s^{-1} in pools and 1.15 m · s^{-1} in rapids. The dominant bed-material fraction did not allow for the unambiguous distinction of HMU types. The mean velocity, Froude number and estimated bed shear stress were found to vary between pools, runs and riffles in the investigated Skawa section and under the surveyed hydrological conditions. However, the applied comparisons did not detect significant differences between riffles and rapids in these variables. This finding does not exclude the possibility of differences in other descriptors or under different flow conditions.

Keywords: hydromorphological unit, Froude number, bed shear stress, bed material, river restoration

INTRODUCTION

Over the past few decades, many rivers have been heavily modified by human activity, channel regulation and hydraulic engineering works. These activities have often disrupted ecological continuity, simplified the morphological structure of rivers, reduced habitat diversity and degraded the ecological status of aquatic ecosystems (Elosegi and Sabater, 2013). In response to these issues, river restoration – the practice of restoring or supporting the natural processes that shape channels and river valleys – is becoming increasingly important (Wohl et al., 2015).

One of the key issues in planning and implementing restoration measures is the proper recognition of channel hydromorphology through the correct

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identification of hydromorphological units (Wang et al., 2023). These are temporally and spatially dynamic units that develop through the interaction between channel hydromorphology and the hydrological regime. From a practical point of view, a hydromorphological unit is an area within the channel located in a zone of uniform flow parameters, such as flow depth and velocity (Maddock, 1999). The basic units initially identified in geomorphology were riffles and pools (Książek et al., 2007). Currently, three basic morphological units are commonly recognised – the pool, the run and the riffle – though some authors additionally also distinguish the rapid (Shoffner and Royall, 2008).

The hydromorphological diversity of rivers is closely related to their biological diversity. The spatial arrangement of these units affects the habitat conditions of aquatic and riparian organisms, determining the distribution of macroinvertebrates, fish and aquatic vegetation (Wegscheider et al., 2020). In the Polish Carpathians, for example, restoration measures aimed at increasing hydromorphological diversity in the neighbouring Raba river catchment have recently been shown to elicit a measurable positive response in macroinvertebrate communities (Kędzior and Michnowska, 2026). The differentiation of hydromorphological units has become a tool both for assessing the current state of rivers and evaluating the effectiveness of improvement measures (Jowett, 1993; Parasiewicz, 2007; Mouton et al., 2009), while the characteristics of flow regime, including flow predictability, have also been linked to the quality of invertebrate communities in Central European rivers (Wałęga et al., 2022). In Belgium, integrated modelling was tested in order to simulate ecological responses to hydraulic changes in the river channel. The predictions were based on a one-dimensional hydraulic model built in HEC-RAS together with the fish habitat module of the CASiMiR software. They were used to examine the effects of dam removal on habitat conditions for the bullhead, among other things (Mouton et al., 2007).

The correct identification of hydromorphological units is important for diagnostic and design purposes. On the one hand, it makes it possible to assess the degree of morphological diversity of a river and to identify sections that are degraded, simplified or excessively modified. On the other hand, it provides a basis for designing the scope of restoration measures directed not only at improving the geometric parameters of a channel but, above all, at rebuilding the natural fluvial processes. However, the identification of the basic hydromorphological units remains a matter of debate (Belletti et al., 2017). Hence the need to seek and verify methods and parameters that discriminate between the hydromorphological units under study. It is also particularly important to verify parameters that can be obtained without complicated and costly measurement techniques, which are widely available in practice and adaptable to local conditions (Akstinas et al., 2022).

The concept of the hydromorphological unit originates from the early classification of river channels into basic morphological elements – pools and riffles (Hawkins et al., 1993; Bisson et al., 1996). Over time, the catalogue of units has been extended to include runs, and in some approaches also rapids or cascades, particularly in channels with steep gradients and coarse bed material (Montgomery and Buffington, 1997).

In parallel, the concept of the hydraulic biotope was developed (Wadeson, 1996; Wadeson and Rowntree, 1998), in which units are distinguished not on the basis of the morphological features of a channel but on the basis of uniform hydraulic conditions – depth, velocity and the character of the flow at the water surface. Both the morphological and hydraulic approaches are reflected in later formalised classification systems, such as the Mesohabitat Evaluation Model (MEM), which is based on LiDAR data (Hauer et al., 2008), and the hierarchical Geomorphic Units Survey classification system (GUS), which was developed as part of European work on the hydromorphological assessment of rivers (Belletti et al., 2015, 2017). The hydraulic approach has also been extended to include and objective, statistical classification of mesohabitats using multivariate methods (Wilkes et al., 2014) and to the MesoHABSIM family of models, which combine a hydromorphological description of a channel with modelling of fish habitat preferences (Parasiewicz, 2007; Parasiewicz and Walker, 2007).

Despite the variety of approaches, the selection of parameters that allow individual hydromorphological

units to be distinguished unambiguously and repeatably remains a matter of debate (Belletti et al., 2017). The most frequently applied variables are flow depth and velocity. Jowett (1993), who studied gravel-bed rivers in New Zealand, was one of the first to propose quantitative criteria for distinguishing between pools, runs and riffles based on these variables, including threshold values of the Froude number. However, this approach was later criticised by, among others, Clifford et al. (2006), who pointed out that the same Froude numbers can occur for different combinations of depth and velocity. This limits the diagnostic power of the approach, and the wide overlap of Froude number ranges between units was also confirmed by Moir and Pasternack (2008).

Another line of research concerns bed-material grain size as a discriminator of hydromorphological units. According to the classical velocity reversal hypothesis, riffles have coarser bed material than pools at low flows, with a reversal of this relationship at high stages (Sear, 1996; Thompson et al., 1999). However, more recent work, based on laboratory experiments and long-term field observations, points to considerable variability in this pattern depending on sediment supply, changes in bed and water-surface slope and the section's hydrological history (MacVicar and Roy, 2011; Chartrand et al., 2018; Hassan et al., 2021; Lei et al., 2023).

The significance of hydromorphological units extends beyond channel geomorphology, they also constitute the basic spatial unit in ecohydraulic and river ecology studies. The mosaic of units determines the distribution of fish (Wegscheider et al., 2020) and macroinvertebrates (Principe et al., 2007), as are the spawning and growth conditions of aquatic organisms (Wheaton et al., 2004; Enders et al., 2009). Bed shear stress and the associated turbulence are indicated as parameters of particular importance for habitat selection (Robert, 1997; Enders et al., 2009). In mountain and submontane rivers, this subject has been addressed by, among others, Wyżga et al. (2009) and, for the Skawa itself, by Hawryło et al. (2011), who analysed the hydrodynamic conditions favourable to fish.

In the context of Polish Carpathian rivers, research into channel incision and the hydromorphological degradation of mountain rivers is particularly relevant (Wyżga, 2008, Wyżga et al., 2008). In the submontane section of the Skawa, rates of bank retreat locally exceeding 1 m per year have been documented (Bąk et al., 2011). More recent research on the variability of the morphodynamics of regulated mountain river sections is equally relevant (Korpak et al., 2023). This work demonstrates that anthropogenic modifications, such as regulation, gravel extraction and hydraulic engineering structures, lead to the shallowing and homogenisation of the channel structure. Consequently, there is a decrease in the diversity of hydromorphological units. This makes the development of simple, repeatable methods for identifying these units even more pressing. To address this, technologically advanced methods – LiDAR, UAV photogrammetry and machine learning (Akstinas et al., 2022) – are being developed alongside field methods applicable by a broad group of practitioners and citizen scientists (Gurnell et al., 2018).

A previous study (Woś and Książek, 2025) characterised the hydrodynamic parameters of turbulent flow in the three basic hydromorphological units of a mountain river. The present study extends that work by explicitly including rapids and jointly assessing hydraulic and substrate descriptors, with particular emphasis on whether these variables distinguish riffles from rapids. Flow depth, flow velocity, water-surface slope, estimated bed shear stress, the Froude number and dominant bed-material fraction are examined scross pools, runs, riffles and rapids under the surveyed flow conditions. A mountainous section of the Skawa river in southern Poland was selected as an example of a natural gravel-bed channel.

MATERIAL AND METHODS

Study site

The measurements were carried out on the Skawa river in southern Poland. The Skawa is a right-bank tributary of the Vistula, 97 km long, with a catchment area of 1,188 km². It joins the Vistula at km 227+90 in the village of Podolsze and lies within the upper Vistula catchment. The Skawa catchment borders the catchments of the Skawinka and the Raba to the east and the Soła basin to the west. Its southern boundary is formed by the watershed between the Baltic Sea and Black Sea drainage basins (the Czarna Orawa

catchment). The catchment lies in the central part of the Beskid Wysoki and Beskid Średni ranges and in the Lanckorona Foothills, and at its mouth forms part of the Vistula Valley.

The course of the Skawa can be divided into two main sections. The upper course lies entirely within the Beskidy Mountains; its lower boundary is the mouth of the right-bank tributary, the Stryszawka. The upper course of the Skawa is 58 km long and its mean slope is 6.9‰.

A mountain section of the Skawa (upper course) between km 44+87 and km 46+45 (Sucha Beskidzka – Maków Podhalański) was selected for the study. The mountain character of the hydrological regime of the Skawa means that the river has low hydrological inertia and is therefore characterised by a large amplitude of flow variability. It also has considerable flood potential, with rapid but short-lived flood waves. The catchment area at this reach is 607 km². According to the classification of surface water bodies, the river in the study reach is a small flysch river. The mean annual flow at the Sucha Beskidzka gauging station is 7.5 $m^3 \cdot s^{-1}$, and the mean low flow is 1.4 $m^3 \cdot s^{-1}$.

METHODS

Field measurements were carried out during a period of low and mean flows in accordance with the recommendations for surveys of morphological units as habitats of aquatic organisms (Parasiewicz and Walker, 2007).

Four types of unit were distinguished: pools, runs, riffles and rapids (Hauer et al., 2008). Areas with a large flow depth and tranquil flow were classified as pools (p); areas with a well-developed thalweg and a flatbed passing into a negative slope were classified as runs (n); shallow areas with a relatively high flow velocity, a marked slope and visible turbulence at the water surface as riffles (r); and areas with uniformly fast flow, a large slope, greater roughness, and turbulence at the water surface were classified as rapids (f) (Bisson et al., 1996; Parasiewicz, 2007). In the present study, a rapid is defined as a high-energy unit that is distinguished from a riffle by a concentration of flow along one bank, with increased velocity and depth. In total, 8 pools, 8 runs, 5 riffles and 7 rapids were surveyed.

Water-surface elevations were measured at the identified units using GPS RTK to determine the water-surface slope. Water-surface slope was calculated by dividing the elevation difference by the horizontal distance between these points between two RTK-GPS elevation measurements per HMU, one at the upstream end and one at the downstream end. Vertical accuracy was up to 2.4 mm, and the smallest units, rapids, were at least 15 m long. This procedure was applied consistently across all surveyed HMUs.

The description of the hydromorphological units included a visual assessment of the dominant bed-material fraction within the unit (Table 1).

Table 1. Bed-material classification adopted in this study, based on the PN-EN ISO 14688 standard and modified with an additional grain-size interval taken from the Wentworth classification, showing the grain-size range and midpoint value of each fraction

Fraction name	Grain size (cm)	Fraction midpoint (cm)
Large boulders LBo	>63	–
Boulders Bo	20–63	41.5
Cobbles II (Co II)	13–20	16.5
Cobbles I (Co I)	6.3–13	9.7
Coarse gravel CGr	2–6.3	4.2
Medium gravel MGr	0.63–2	1.3
Fine gravel FGr	0.2–0.63	0.42
Sand Sa	<0.2	–

Within each identified HMU, eight locations were selected to represent the depth area. The local flow depth was determined at each location. The ADV sampling volume was positioned at $z/h = 0.4$, where z is the height above the local bed. This position was selected following the six-tenths-depth method, in which the time-averaged point velocity is used to approximate the depth-averaged velocity of the water column (Turnipseed and Sauer, 2010). Time series of the three instantaneous velocity components (u – streamwise, v – transverse, and w – vertical) were recorded for 60 s at a sampling frequency of 20 Hz, using a Sontek MicroADV (Micro Acoustic Doppler Velocimeter) probe. To ensure data quality during post-processing,

a minimum signal-to-noise ratio of SNR >5 and a correlation coefficient of COR >40% were applied, which is acceptable for highly turbulent flows (Martin et al., 2002). Outliers were removed using the phase-space threshold despiking method (Goring and Nikora, 2002; Wahl, 2002). At the end of post-processing, time series containing fewer than 1,000 individual records were automatically excluded from further analysis.

Each HMU was surveyed at eight measurement locations. Of the 224 expected ADV time series, 215 were retained after quality control: 63 for pools, 64 for runs, 38 for riffles and 50 for rapids. The depth comparison used the same measurement locations as the accepted velocity dataset. Consequently, the analyses depth, velocity and Froude number had identical sample sizes. Bed shear stress was calculated using depth and water-surface slope; observations for which the slope was unavailable were omitted from this comparison.

The magnitude of the three-dimensional velocity vector (*Muvw*) was used as the mean velocity (u – streamwise, v – transverse, and w – vertical):

$$Muvw = (U^2 + V^2 + W^2)^{0.5} \quad (1)$$

Bed shear stress was estimated from the hydraulic gradient using the following equation:

$$\tau_0 = \rho g h I \quad (2)$$

where:

τ_0 – the bed shear stress (N · m^{-2}),
h – the flow depth (m),
I – the hydraulic slope, taken as the slope of the water table (–),
ρ – the water density (kg · m^{-3}),
g – the acceleration due to gravity (m · s^{-2}).

The water-surface slope was used to estimate bed shear stress, on the assumption that hydraulic conditions within each hydromorphological unit were homogeneous.

The standard hydraulic variable, the Froude number (Fr), was also considered, calculated for each location using the magnitude velocity at 0.4 h:

$$\mathrm{Fr} = Muvw / (g \cdot h)^{0.5} \quad (3)$$

where:

Muvw – the magnitude of the three-dimensional velocity at the position $z/h = 0.4$ (m · s^{-1}),
h – the flow depth (m),
g – the acceleration due to gravity (m · s^{-2}).

As the study aimed to compare the hydraulic characteristics of different HMU types, measurements collected within individual units of the same type were pooled. For example, data obtained from eight separate pools were treated collectively as representative of the pool HMU category. Consequently, the mean values of the analysed variables used in the statistical comparisons were derived from all measurement verticals within each HMU type.

The distribution of the variables was tested for normality using the Kolmogorov–Smirnov test, and for homogeneity of variances using Levene's test. As the assumption of variance homogeneity was not satisfied, differences between unit types were assessed using the non-parametric Kruskal–Wallis test, with the level of statistical significance set at $p < 0.05$. Post-hoc pairwise comparisons were performed using Dunn's test with Bonferroni correction for multiple comparisons, on the basis of which the letters a, b and c were assigned. These letters denote statistically significant differences between the groups. All analyses were performed in R version 4.3.2 (R Core Team, 2023) using the rstatix (Kassambara, 2023) and multcompView (Graves et al., 2019) packages for the statistical tests, and the ggstatsplot (Patil, 2021) package for visualization.

RESULTS

General characteristics of all the studied units are summarized in Table 2. It should be noted that not all variables are complete for every unit. In particular, water-surface slope values are missing in several cases, as this parameter could not always be measured with sufficient accuracy due to field conditions affecting signal quality and measurement precision. Depth, velocity and Froude number comparisons included 63 observations for pools, 64 for runs, 38 for riffles and 50 for rapids. The reduction in the available samples for bed shear-stress estimation, particularly for rapids, was due to missing water-surface slopes, which limited the representativeness of this comparison.

Table 2. Characteristics of the hydromorphological units studied (Bed – bed-material fraction dominant within the unit, and *d* – midpoint diameter of that fraction; *H* – mean flow depth ± standard deviation; *I* – water-surface slope; *Q* – discharge at the gauging station at the time of measurement), n.d. – no data

Type	Unit	Bed material		***H* [cm]**	***I* [‰]**	***Q* [m³ · s⁻¹]**
		Fraction	***d* [cm]**			
POOL (p)	p1	CGr	4.2	49 ± 7	0.8	3.8
	p2	CGr	4.2	60 ± 13	0.8	3.8
	p3	CGr	4.2	66 ± 10	0.8	3.8
	p4	CGr	4.2	58 ± 7	0.5	3.8
	p5	MGr	1.3	65 ± 8	1.0	3.6
	p6	MGr	1.3	74 ± 8	1.0	3.6
	p7	CGr	4.2	75 ± 18	n.d.	3.8
	p8	Co I	9.7	61 ± 21	0.7	2.9
RUN (n)	n1	CGr	4.2	43 ± 6	1.7	3.8
	n2	CGr	4.2	41 ± 4	n.d.	3.8
	n3	Co I	9.7	48 ± 3	3.2	3.8
	n4	Co I	9.7	43 ± 3	n.d.	3.8
	n5	CGr	4.2	41 ± 8	5.0	3.6
	n6	CGr	4.2	35 ± 5	4.1	3.6
	n7	CGr	4.2	58 ± 13	6.5	8.7
	n8	Co II	16.5	62 ± 5	n.d.	2.9
RIFFLE (r)	r1	Co II	16.5	34 ± 7	9.5	3.8
	r2	Co II	16.5	42 ± 6	9.9	3.8
	r3	Bo	41.5	32 ± 4	12.8	3.6
	r4	Co II	16.5	31 ± 5	6.0	8.3
	r5	Co II	16.5	36 ± 5	n.d.	n.d.
RAPID (f)	f1	Co I	9.7	38 ± 5	9.1	3.8
	f2	Co II	16.5	56 ± 6	n.d.	3.8
	f3	Bo	41.5	49 ± 8	14.2	3.8
	f4	Bo	41.5	47 ± 9	n.d.	3.8
	f5	Bo	41.5	48 ± 12	n.d.	2.9
	f6	Co II	16.5	56 ± 3	11.6	n.d.
	f7	Bo	41.5	64 ± 12	n.d.	n.d.

Flow depth and bed-material characteristics

The highest mean flow depths among the hydromorphological units studied were found in pools. At the same time, pools also showed the greatest variability of depth, ranging from 49 cm to 75 cm. Runs were less variable in depth within a given unit than pools; mean depths in runs ranged from 35 cm to 62 cm. Rapids were characterised by depths similar to those of runs (from 38 cm to 64 cm). The lowest depths among the units studied were recorded in riffles, where this parameter ranged from 31 cm to 42 cm (Figure 1).

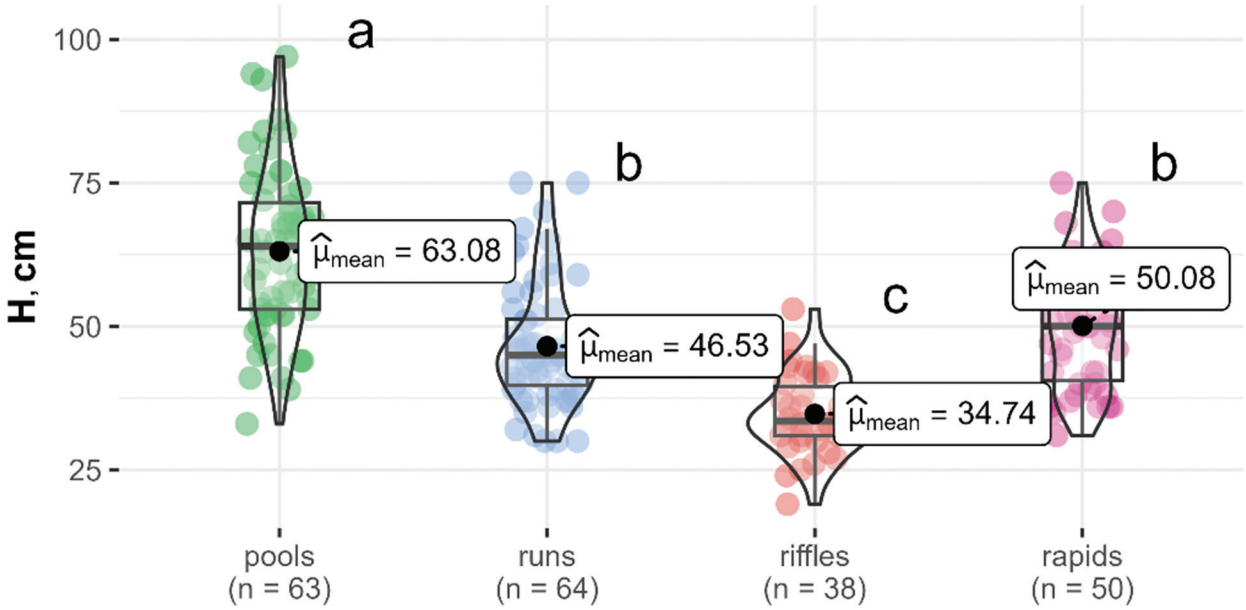


Fig. 1. Mean flow depth of the hydromorphological unit types (letters a, b, c indicate statistically significant differences between groups, $p < 0.05$) (Author's own elaboration)

Bed material in pools was identified mainly as coarse gravel (CGr). In runs, coarse gravel (CGr) and cobbles (Co I) predominated. The deepest unit of this type, with a mean depth of 62 cm, had the coarsest bed material (Co II). In riffles, a higher proportion of the 6.3–20 cm cobble fraction (Co II) was observed. Rapids were the hydromorphological unit with the coarsest bed material, dominated by cobbles (Co II) and boulders (Bo) (Figure 2).

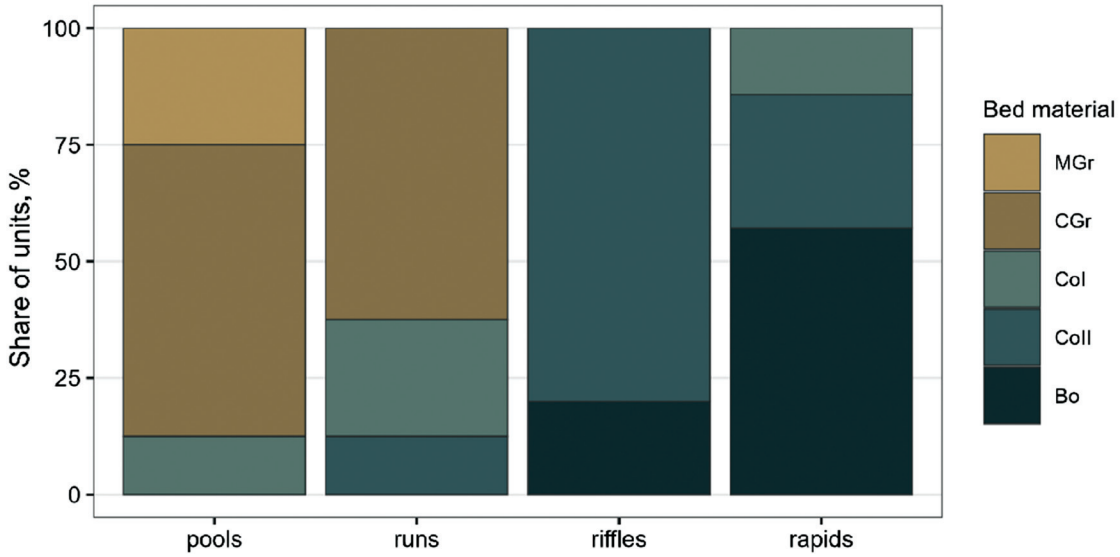


Fig. 2. Proportion of the dominant bed-material fractions in the individual types of hydromorphological unit (Author's own elaboration)

On the basis of the observations of the dominant bed-material fraction in the four types of hydromorphological unit, it is not possible to unambiguously identify a particular grain size as a characteristic of a given type. As expected, the bed material in pools and runs is somewhat finer than in rapids. On the other hand, different bed-material types may be found in hydromorphological units of the same type.

Mean flow velocities

Mean flow velocities differed significantly between the analysed types of hydromorphological unit. The lowest values were recorded in pools, where the mean velocity was 34.77 cm · s^{-1}. Significantly higher values occurred in runs, for which the mean velocity reached 63.40 cm · s^{-1}. Higher values still were found in riffles and rapids, where mean velocities amounted to 90.14 cm · s^{-1} and 115.01 cm · s^{-1} respectively (Figure 3).

The greatest variability of velocity was observed in riffles and rapids, which indicates more heterogeneous hydraulic conditions in units of higher flow energy. Pools were characterised by the lowest and least dynamic flow conditions, whereas rapids reached the highest velocities, locally exceeding 150 cm · s^{-1}. Mean local velocity differed significantly between pools, runs, and riffles together with rapids, thus distinguishing three types of unit (Figure 3).

Froude number

Mean Froude numbers differed significantly between pools, runs and riffles, whereas the values obtained in rapids did not differ significantly from those in riffles. Pools were characterised by Froude numbers not exceeding 0.3, and runs by values in the range from 0.2 to 0.5. In riffles, as in rapids, Froude numbers ranged from 0.3 to 0.8. In all the studied units, the Froude

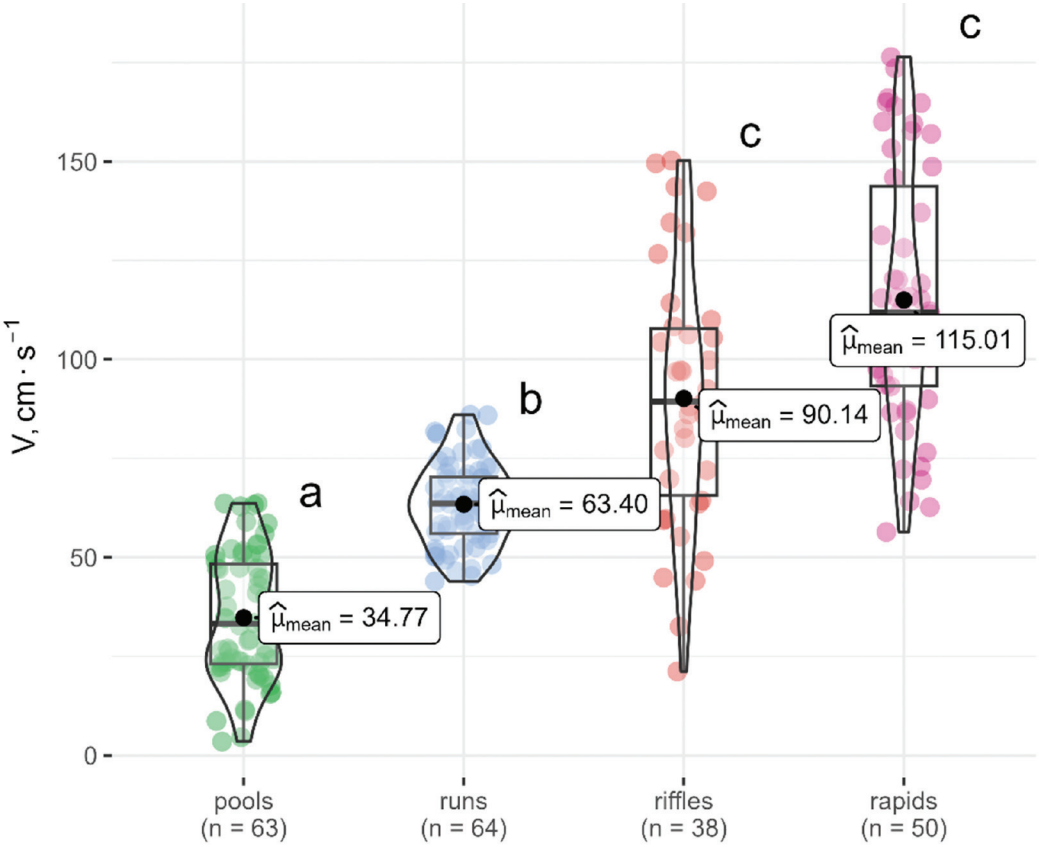


Fig. 3. Mean flow velocity of the hydromorphological unit types (letters a, b, c indicate statistically significant differences between groups, $p < 0.05$) (Author's own elaboration)

number did not exceed the critical value of Fr = 1, which indicates subcritical flow (Figure 4).

Bed shear stress

The statistical analysis showed significant differences in the mean bed shear stress between the groups of hydromorphological units of the three types. Local shear stresses in pools did not exceed 10 N · m^{-2}. Runs exhibited highly variable shear stresses, from 7 to 50 N · m^{-2}. Riffles were characterised by shear stresses of up to more than 50 N · m^{-2}. The highest bed shear stresses were found in rapids, with a mean above 50 N · m^{-2}. However, due to the number of measurements and the large scatter of values, the statistical analysis did not reveal differences between riffles and rapids (Figure 5).

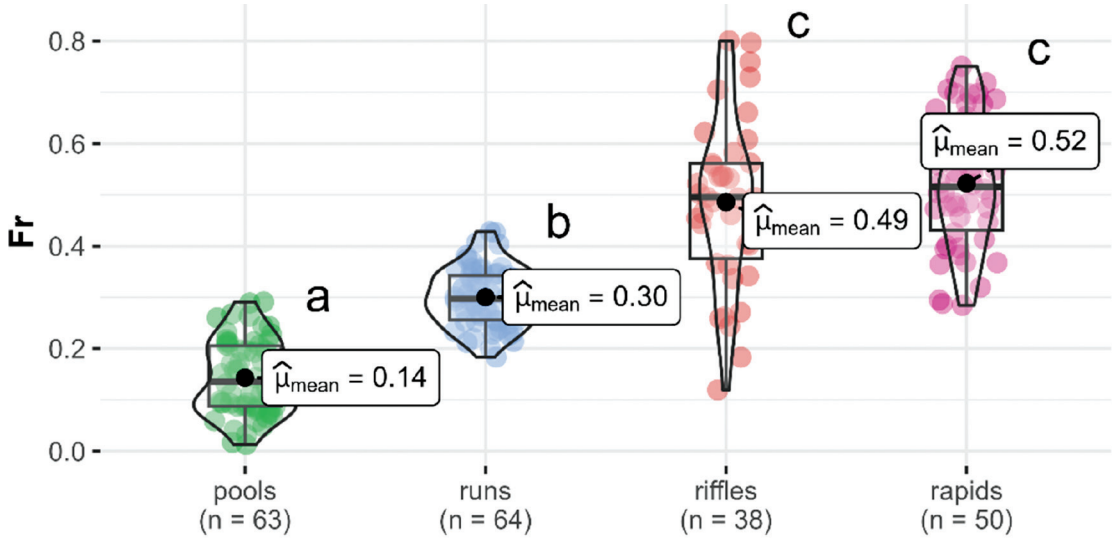


Fig. 4. Froude number of the hydromorphological unit types (letters a, b, c indicate statistically significant differences between groups, $p < 0.05$) (Author's own elaboration)

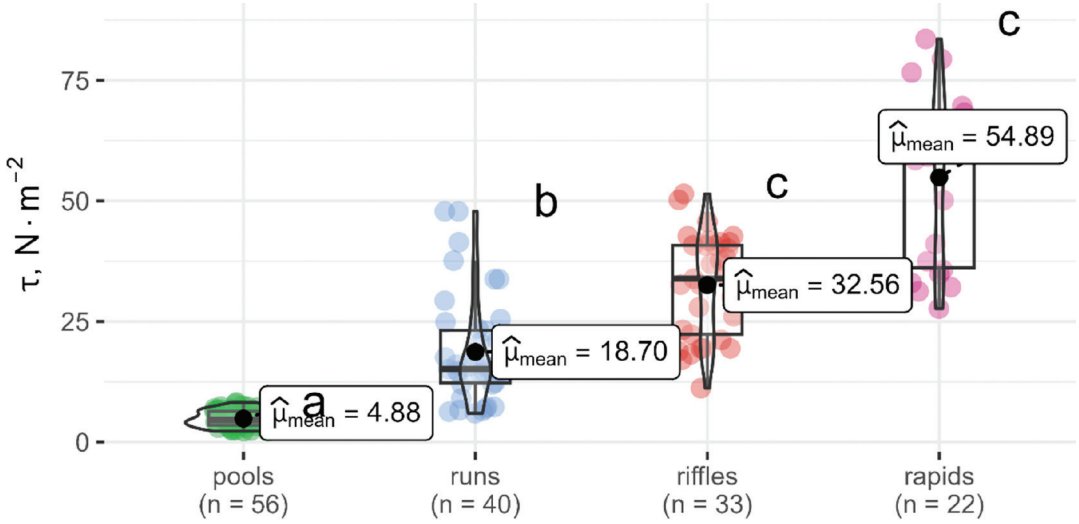


Fig. 5. Bed shear stress of the hydromorphological unit types (letters a, b, c indicate statistically significant differences between groups, $p < 0.05$) (Author's own elaboration)

DISCUSSION

The results indicate that the dominant bed-material fraction cannot be unambiguously assigned to a particular type of unit. There is, however, a tendency towards finer bed material in pools and runs than in rapids. The available literature contains conflicting information on differences in bed-material grain size between hydromorphological units (Hassan et al., 2021). Riffles are usually characterised by coarser bed material than pools (Sear, 1996; MacVicar and Roy, 2011). However, the opposite pattern has also been observed (Thompson et al., 1999), as has a lack of differences in grain size between the units studied (Jowett, 1993; Chartrand et al., 2018; Hassan et al., 2021). The reported differences may result, for example, from different mechanisms of sediment deposition in the selected units at low and high stages (Hassan et al., 2021). They can also be caused by changes in bed and water-surface slope and by changes in the supply of sediment of different grain sizes caused, for instance, by landslides or by human activities, such as the construction or removal of dams, gravel extraction, deforestation and land-use change (Lei et al., 2023). Another cause can be the processes maintaining pool-riffle morphology through flow convergence routing, which in gravel-bed rivers may mask a simple, unidirectional relationship between unit type and bed grain size (Sawyer et al., 2010).

The Froude number recognises three hydromorphological units – pools, runs and riffles – but not rapids. Different authors assess the usefulness of the Froude number for distinguishing hydromorphological units is assessed differently. Jowett (1993) suggests that the Froude number is a good parameter for separating distinct units. However, it appears to be difficult to indicate specific Froude number ranges that discriminate between the studied units. The older, and rather arbitrary, classification of Allen (after Jowett, 1993) gives a Froude number below 0.15 for pools and above 0.25 for riffles. Jowett (1993), working on a gravel-bed river, indicated that pools are characterised by Froude numbers below 0.18 and riffles by values above 0.41. In the submontane section of the Skawa, mean Froude numbers amounted to 0.16 for pools, 0.37 for runs and 0.51 for rapids. As in the studied mountain section, the Froude number did not allow rapids to be distinguished from riffles in the submontane section (Woś and Książek, 2022). Clifford et al. (2006) pointed to the limited applicability of the Froude number for distinguishing between hydromorphological units, as the same Froude numbers can be obtained for different combinations of velocity and depth. A very large scatter of values and the occurrence of identical Froude number ranges in several types of hydromorphological unit have also been reported (Moir and Pasternack, 2008).

Bed shear stress also distinguished between three types of habitat. Hauer et al. (2008), in developing the Mesohabitat Evaluation Model (MEM), included shear stress as an important factor in distinguishing hydromorphological units. Their work was based on measurements taken in both a mountain river and a lowland river. Shear stress was also considered as an important parameter from a biological point of view by Wheaton et al. (2004) and Enders et al. (2009). Beyond its role in distinguishing hydromorphological units, shear stress is closely related to stream power. Stream power has been used as a large-scale indicator of channel erosion and deposition potential (Marcinkowski et al., 2022) and to detect operational problems in reservoirs through the spatial analysis of shear stress and stream power distributions (Wicher-Dysarz, 2019). This underlines the broader geomorphological and engineering relevance of the hydraulic variables examined in this study. While riffles and rapids are visibly different habitats, they are difficult to distinguish on the basis of measurable hydraulic properties. Rapids are generally deeper and more visually turbulent, but the parameters measured within the presented range do not permit separation. Similarly, in the submontane reach of the Skawa, the three-dimensional velocity structure and turbulence characteristics did not differentiate between riffles and rapids (Woś and Książek, 2022).

The practical implications of the results obtained form part of a broader discussion on selecting methods to identify hydromorphological units that can be applied in river inventory and restoration planning (Belletti et al., 2017; Akstinas et al., 2022). Restoration measures, whether spontaneous or actively induced, have been shown to improve hydromorphological conditions in lowland rivers (Zaborowski et al., 2023), highlighting the practical value of reliable, transferable methods for assessing the diversity of hydromor-

phological units across different river types. Although bed shear stress and the Froude number require somewhat more complex computation than simple measurements of depth or slope, they can be determined from relatively easily available field data, eliminating the need for costly measurement techniques such as LiDAR or multidimensional modelling. This is consistent with the postulate of seeking parameters that are at the same time reliable and widely available in practice, and adapted to local conditions (Akstinas et al., 2022).

However, this study is limited to one Skawa river section, a small number of independent HMUs and low-to-mean flows. Visual HMU classification introduces observer dependence and potential circularity, while uncertainty in water-surface slope and simplifying assumptions affect bed shear-stress estimates. The findings therefore apply only to the investigated section and the surveyed flow conditions.

CONCLUSIONS

Flow depth and mean velocity showed clear and consistent patterns across the unit types studied. Pools were characterised by the greatest flow depth and the lowest mean velocity, while riffles had the smallest depth values and rapids reached the highest mean velocities. Mean velocity distinguished three groups of units – pools, runs, and riffles together with rapids – confirming that, unlike bed-material grain size, flow depth and velocity showed differences among the visually identified HMU types in the investigated Skawa section under the surveyed hydrological conditions.

In the examined section, the dominant bed-material fraction did not unambiguously distinguish HMU types. Despite a general tendency for bed grain size to increase across the distinguished unit types in the order: pool, run, riffle, rapid – units of the same type differed considerably in bed-material grain size.

In the investigated Skawa section and under the surveyed hydrological conditions, the Froude number and estimated bed shear stress differentiated between pools, runs and riffles. However, the applied comparisons did not detect significant differences between riffles and rapids in these variables. This finding does not exclude differences in other descriptors or under different flow conditions.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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HYDRAULICZNE ROZRÓŻNIANIE JEDNOSTEK HYDROMORFOLOGICZNYCH ŻWIRODENNEJ RZEKI GÓRSKIEJ NA PRZYKŁADZIE RZEKI SKAWY, KARPATY POLSKIE

Streszczenie

Cel pracy
Celem pracy było scharakteryzowanie jednostek hydromorfologicznych rzeki górskiej pod względem głębokości, prędkości przepływu, naprężeń stycznych na dno, liczby Frouda oraz uziarnienia rumowiska dennego.

Materiały i metody
Badaniami objęto odcinek górski Skawy, w którym zidentyfikowano 8 plos, 8 nurtów, 5 bystrzy i 7 rwących nurtów. W każdej z tych jednostek określono przeważającą frakcję rumowiska dennego oraz wykonano pomiary spadku zwierciadła wody, prędkości chwilowych (60 s przy $z/h = 0{,}4$) i głębokości przepływu w ośmiu reprezentatywnych dla danej jednostki pionach.

Wyniki i wnioski
Średnie głębokości poszczególnych plos wynosiły od 0,49 do 0,75 m, natomiast bystrzy od 0,31 do 0,42 m. Średnie prędkości punktowe wynosiły 0,348 m · s^{-1} w plosach i 1,15 m · s^{-1} w rwących nurtach. Przeważająca frakcja rumowiska dennego nie pozwalała jednoznacznie rozróżnić typów jednostek hydromorfologicznych. Na badanym odcinku Skawy i w badanych warunkach hydrologicznych średnia prędkość, liczba Frouda oraz oszacowane naprężenia styczne na dno pozwalały rozróżnić plosa, nurty i bystrza, jednak zastosowane porównania nie wykazały istotnych różnic między bystrzami a rwącymi nurtami w zakresie tych parametrów. Wynik ten nie wyklucza różnic w innych charakterystykach lub w innych warunkach przepływu.

Słowa kluczowe: jednostka hydromorfologiczna, liczba Frouda, naprężenia styczne na dno, rumowisko denne, renaturyzacja rzek