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Channel-reach morphometric analysis on a headwater stream in a low-mountainous region: A case study from Mecsek Hills

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Abstract

Small catchments in mountainous regions affect downstream rivers as a primary source of sediment supply and also generate flash swasfloods, especially during extreme events. These floods have significantly shaped the catchments of small streams in the Mecsek Hills and some rural areas over the past two decades. However, there has been no previous study examining the hydromorphology of headwater catchments in low mountain environments in Hungary. The present study was meant to investigate the fundamental hydrogeomorphological properties of a first-order catchment. A customary and detailed GIS survey of 50-metre sections was aimed at deciphering flash flood vulnerability and geomorphic interrelations within a micro-watershed. We found moderate susceptibility to flash floods compared to the whole Mecsek Hills. Stable large woody debris jams were identified during the field survey as major geomorphic channel features functioning as natural barriers which drive channel evolution and reduce flood hazards.

Keywords: hydromorphometry, large woody debris, semi-natural, stream reach, field survey, Öreg-patak stream

Introduction

An important aspect of fluvial landscape evolution research involves streams and their channel characterisation from various perspectives. This topic is widespread and has an extensive global scientific literature, dating back to the late 19th century and continuing to the present day, evidenced by the numerous papers published on the description and systematic classification of streams (Leopold, L.B. and Markley, G.W. 1957; Kaszowski, L. and Krzemien, K. 1999; Lóczy, D. 2012; Buffington, J.M. and Montgomery, D.R. 2013; Bisson, P.A. *et al*. 2017, and references therein).

The streams and their immediate environment (floodplains and valleys) are often described by their hydrogeomorphological characteristics. In addition, essential parameters can be derived from the geological, hydrological, land cover, land use, and ecological features of the catchment (Rosgen, D.L. 1994; Fryirs, K.A. and Brierley, G.J. 2001; Fryirs, K.A. *et al*. 2007; Gurnell, A.M. and Grabowski, R.C. 2016; Grabowski, R.C. *et al*. 2019, and references therein). At present, anthropogenic influences such as flood control measures, channelisation, and forestry are increasing in frequency and intensity. The literature overview demonstrates the lack of a uni-

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versal classification system valid across all geographical locations. Nonetheless, the available classification techniques enable the adoption of a suitable survey approach that considers all the relevant attributes of the area under study.

The hierarchical classification system is well suited to streams with various features. A clear advantage is that the units within a given catchment are split along the scale into smaller and more interpretable segments. These units, such as valley segment (100–10,000 m), stream reach (10–1,000 m), and channel unit (1–10 m) make the investigations of headwater streams possible. Thus, even for small streams, as well as larger rivers, qualitative and quantitative parameters can be assessed both along the longitudinal profile and at cross-sections (Płaczkowska, E. 2016; Bisson, P.A. *et al*. 2017).

The longitudinal profile allows differentiation of segments according to stream power, incision rate, accumulation zones, and sediment load in terms of quantity, composition, and particle size (Buffington, J.M. and Montgomery, D.R. 2013). The sections offer key information on changes in channel shape and sinuosity (such as straight, meandering, and braided). These processes significantly affect cross-section parameters (for example, bankfull width and/or depth, channel shape index) and channel forms (including cutbanks, steps, alluvial bars, potholes, riffles, and pools) (Kamykowska, M. *et al*. 1999).

Organic material accumulation also significantly affects bed morphology. This effect is especially noticeable in headwater areas covered by mountain forests, where organic matter is abundant, ranging from tiny seeds, leaves, twigs (Jeffries, R. *et al*. 2003) to branches and woody debris of much larger size (Galia, T. *et al*. 2018; Thompson, M.S.A. *et al*. 2018). Its impact on the channel and processes is diversified and complex. Woody debris accumulation can transform the flow conditions and thalweg of the channel. Therefore, it cannot be neglected in bank evolution either since it can accelerate streambank erosion or protect streambanks (Bilby, R.E. and Ward, J.W. 1991; Abbe, T.B. and Montgomery, D.R. 2003; Comiti, F. *et al*. 2006; Ruiz Villanueva, V. *et al*. 2014; Short, L.E. *et al*. 2015; Wohl, E. *et al*. 2017, and references therein). It is important to note that the organic materials in channels also contribute to trapping sediment. This can have spectacular consequences in the formation of impoundments and steps in the channel, whereby the morphological conditions and processes can change (e.g., erosion potholes can be created) (Galia, T. *et al*. 2017; Zhang, N. *et al*. 2020). Furthermore, these accumulations promote the precipitation of travertine, which can enhance the stability of natural dams (Carter, C.D. and Marks, J.C. 2007; Compson, Z.G. *et al*. 2009; Fuller, B. *et al*. 2011).

A comprehensive understanding of their features can be achieved through examining the aforementioned forms, factors and impacts along the longitudinal profile of streams. The distinction between segments is aided by the detailed field survey protocols developed for this purpose (Myers, T.J. and Swanson, S. 1997; Kamykowska, M. *et al*. 1999; Galia, T. *et al*. 2018). Numerous studies using a similar approach have been completed over the last decade, but typically conducted in high and mid-mountain watersheds and streams (Galia, T. and Hradecký, J. 2011; Galia, T. and Škarpich, V. 2013; Płaczkowska, E. *et al*. 2015; Płaczkowska, E. and Krzemień, K. 2018; Ondráčková, L. and Máčka, Z. 2019; Prokop, P. *et al*. 2020).

Nonetheless, many field methods can be adapted for small watercourses with lower relief, even in hilly regions. Comparable studies have already been carried out in Hungary (Kalmár, P. *et al*. 2013; Fábián, Sz.Á. *et al*. 2016), but they are few in number at the national level.

The objective of this paper was twofold. Firstly, it aimed to describe and analyse the trunk channel of the micro-catchment for bed types, shapes, and evolution, based on a comprehensive field survey. Particular emphasis was placed on the formation and evolution of natural log jams affecting sediment transport. Secondly, it was meant to estimate the flash flood susceptibility (FFS) value for the selected micro-catchment since flash floods have increased in frequency in Hungary due to recent extreme weather events.

Study area

This study focused on the southern branch of the Öreg-patak (Öreg Stream) Mecseknádasd, which originates from a spring in eastern Mecsek. It runs in a north-easterly direction for just over seven and a half kilometres, where it joins the Puszta-árok (Óbányai-patak) between the villages Mecseknádasd and Óbánya. The studied watercourse and its associated permanent and ephemeral streams have a catchment area of 9.75 km^2, which just falls into the micro-watershed category (Daipan, B.P.O. 2020). The highest point of the catchment is the Zengő (682 m), the lowest near the confluence is at 224 m *(Figure 1)*. Relative relief ranges from 123 to 247 m/km^2. Although the studied stream may be considered relatively natural, intensive forest management by the Mecsekerdő Zrt. (Mecsek Forestry Co. Ltd.) and the popularity of the marked hiking trails indicate significant anthropogenic impact.

Sedimentary rocks dominate the geological setting. The Lower Jurassic Pliensbachian and Toarcian beds of limestone, chalk marl and siltstone (Óbánya Aleurolite Formation), locally intercalated by Lower Cretaceous (Valanginian) alkaline basalts (Mecsekjános Basalt Formation), are the most widespread formations. They are mostly covered by young Quaternary sediments, including slope deposits, loess, and its derivates. Sporadically, sedimentary and sub-volcanic rocks are exposed (Raucsik, B. and Varga, A. 2008; Haas, J. 2013).

The studied catchment and its immediate surroundings display the characteristic subdued, denuded shape of the Eastern Mecsek

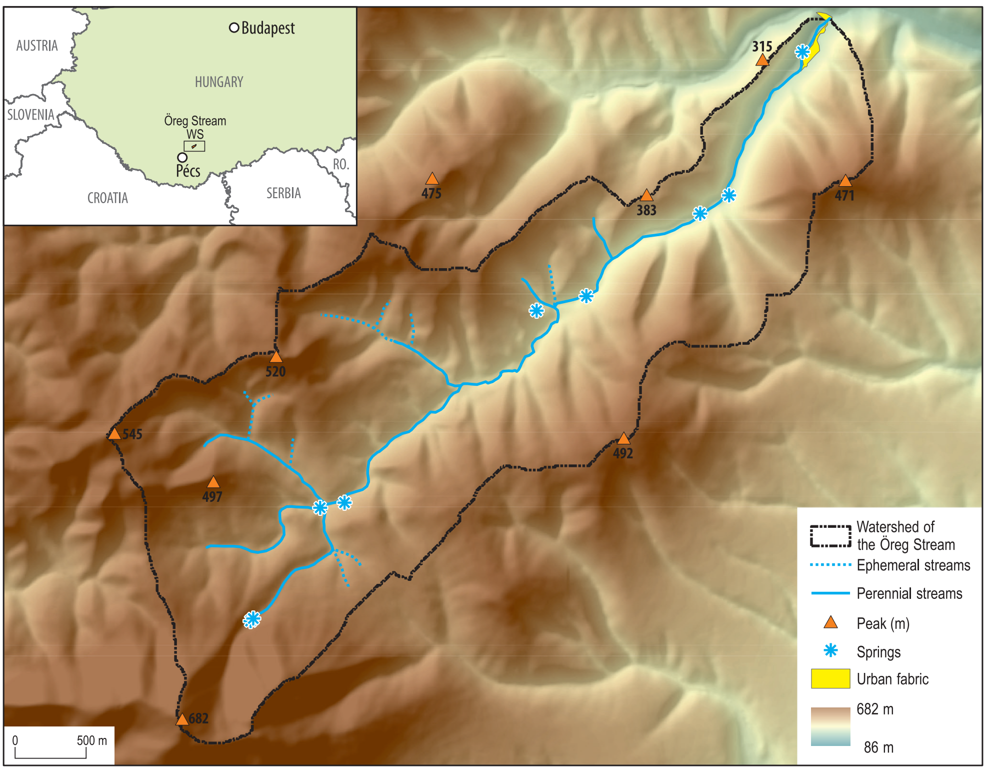


Fig. 1. Map of the study area.

region. Main features of the topography are the radially spreading horsts and connecting ridges on which the boundary of the watershed (divide) runs. The valley shoulders are described in several places in the valleys and the higher hilly surfaces are dissected by erosional-derasional valleys (Ádám, L. *et al*. 1981; Kocsis, K. 2018). Slope angles range from 0 to 35 degrees. The majority of the study area is represented by the range from 7 to 25 degrees (mean 15.47; Std. dev. 6.24; 8.31 km^2; 85.2%) *(Figure 2).*

The climate is notably influenced by the north-northeast orientation of the catchment and its main valley. Mean annual air temperatures (MAAT) vary between 7 and 9 °C; mean annual precipitation (MAP) totals are 750–850 mm. However, in certain years the MAP reaches very extreme values, for example, in exceptionally wet 2010 and 2014 years and in the arid year 2011 (Czigány, Sz. *et al*. 2010; Hungarian Meteorological Service, n.d.).

The Öreg-patak (second-order stream at the mouth) and a few short, perennial and ephemeral streams are all part of the Danube water system, reaching the Danube via the Völgységi-patak (Völgységi Stream) and the Sió canal (Kocsis, K. 2018). The length of streams which are considered permanent is 9.9 km.

The watershed is almost entirely covered with forests managed by the Mecsekerdő Zrt. The vast majority of tree species are European beech (*Fagus sylvatica*), sessile oak (*Quercus patraea)*, Turkey oak (*Quercus cerris)*, downy oak (*Quercus pubescens)* and hornbeam (*Carpinus betulus*), which are often mixed. Indeed, in more limited spots in the upper reaches of the main streams, planted spruce (*Picea abies*) is also found (Kevey B. 2008). The closed forests are only occasionally dissected by small clearings or seedling orchards, and more significantly, by gaps between forest stands (data from Mecsekerdő

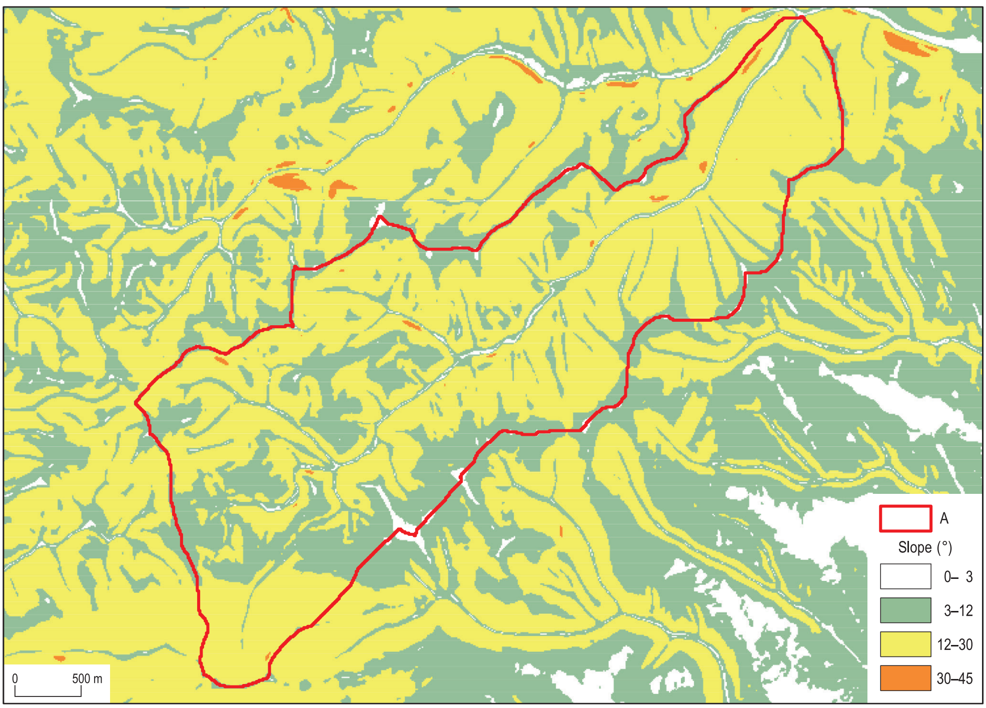


Fig. 2. Slope map of the study area with its border line (A)

Zrt. and Ministry of Agriculture, 2019). Highly acidic Luvisols and Alisols predominate with only small patches of Regosols (Kocsis, K. 2018).

The study area covers parts of the administrative areas of five settlements (Hosszúhetény, Mecseknádasd, Óbánya, Pécsvárad and Zengővárkony). However, only a minute portion of inhabited land is affected, near the mouth of the Óbányai-patak stream (Mecseknádasd Resort Area). Human activities significantly affected the morphology of the riverbed in these areas and near the forest tracks and logging stations of permanent use.

Materials and methods

For the present study, two methodological procedures were applied. Firstly, 25 catchment parameters (e.g., area, perimeter, drainage density, Gravelius coefficient, number of streams, total stream length, max stream order, max and min height, basin relief, forested area) derived from a hydrologically correct digital elevation model (DEM) with 10 m resolution were identified (Schumm, S.A. 1956; Strahler, A.N. 1957; Sassolas-Serrayet, T. *et al*. 2018; Daipan, B.P.O. 2020; Víg, B. *et al*. 2022). For detailed GIS analyses, we also applied the South-Transdanubian Water Management Directorate (STWMD) vector surface water database, the Corine Land Cover 2012 (CLC2012) dataset, the closed sources forestry data of Mecsek Forestry Company (MF), and the ecosystem map of Hungary by Ministry of Agriculture (2019). For the spatial analyses, we used ArcGIS 10.4 (ESRI, 2016) and open-source ArcHydro Toolbox v2.0 (ESRI, 2011).

Relying on previous FFS studies (Esper Angillieri, M.Y. 2008; Singh, P. *et al*. 2013; Abdel-Fattah, M. *et al*. 2017; Puno, G.R. and Puno, R.C.C. 2019; Alam, A. *et al*. 2020; Obeidat, M. *et al*. 2021), the following morphometric parameters had been selected for examination: area (*A*), drainage texture (*Rt*), drainage density (*Dd*), elongation ratio (*Re*), form factor (*Ff*), lemniscate index (*k*), Gravelius coefficient (*GC*), forested area (*Fa*), relief ratio (*Rr*). Among them, *A*, *Dd* and *Rr* were assumed as directly related to the probability of flash flood generation, while *Rt*, *Re*, *Fa*, *Ff*, *k*, and *GC* were inversely related to flash floods. All selected factors are related to runoff intensity and flash flood generation; therefore, they could be applied, using the approach of Víg, B. *et al*. (2022), for assessing FFS at the watershed level. Thus, the currently studied watershed parameters were compared with previously published data for the Mecsek Hills region.

Secondly, a comprehensive field survey was conducted to record in detail geology, bed morphometry, geomorphology and land cover of the Öreg-patak catchment. The field survey was essentially carried out following the paper of Kamykowska, M. *et al*. (1999), from the source to the mouth, over a length of more than 7,700 m, divided into 155 fifty-metre-long sections. The protocol developed in Polish Carpathian Mountains was applied to low-mountainous environments and low-discharge streams (Kalmár, P. *et al*. 2013; Kalmár, P. 2015; Fábián, Sz.Á. *et al*. 2016). About four-fifths of the original protocol has been used, supplemented by measuring woody debris jams (WDJ) in the channel, which strongly influence hydromorphological features (Bilby, R.E. and Likens, G.E. 1980; Dahlström, N. and Nilsson, C. 2004; Galia, T. and Hradecky, J. 2014). Following the original protocol's logic, the WDJ parameters survey was structured to collect the data detailed below.

We used a laser rangefinder (Hecht 2006 laser distance meter) to record the relative position of the WDJ in the channel and their basic physical parameters including the predominant and maximum height, width, and length. Furthermore, the WDJ's orientation to the flow direction and the effect of organic matter (such as leaf litter, green leaves, senescent leaves, and small wood fragments) accumulation in the channel was also recorded, as they can influence flow conditions independently of log jams (Přibyla, Z. *et al*. 2016).

Using a portable GPS device (Garmin 60 CSx), we recorded all the features (including bedrock steps, anthropogenic elements, and WDJ) that impact the hydromorphological processes in the riverbed according to the HD72/EOV reference system (EPSG:23700). In addition, springs, tributaries, and even short ephemeral or perennial watercourses were surveyed to augment our primary database.

Mean stream gradient was measured using a digital level (SOKKIA SDL50). The limiting factor was the dense vegetation in the incised stream bed and the steep valley side. Sinuosity was calculated as a ratio between the unit (50 m) curvilinear length of the channel centreline and the straight distance of each unit endpoint. Data could not be obtained in 67 out of the 155 surveyed sections, mainly in the upstream segment with a steep slope and incision. There was also sporadic data loss downstream due to dense vegetation hindering the survey even in winter.

The extent of the bedrock outcrop (estimated proportion) was recorded in the surveyed sections. The rock types identified in the field were checked with the help of the detailed geological maps (scale 1:10,000) available for the Mecsek Hills area. The genetic types of any riverbed sediments and their grain size categories were also documented.

Cross-sections and longitudinal profiles were classified according to the protocol categories (Kamykowska, M. *et al*. 1999) by channel section. Where applicable, qualitative data were recoded (e.g., cross sections of channel types). Among the quantitative characteristics, we measured the channel gradient (∑m/50m), the bank height and the total bankfull depth and width. These measurements yielded the channel shape index (bankfull width/maximum bankfull depth) for each channel section. We collected over 2,000 data points, which were then recorded in a Microsoft Excel spreadsheet, also used to perform the necessary statistical analysis to interpret and evaluate data. Eleven campaigns were conducted between March 2019 and May 2020, primarily during low water stages.

Results and discussion

Watershed morphometric analysis and flash flood susceptibility

A complex hydrological, relief and land use analysis of the Öreg-patak catchment provided valuable information on the FFS of the region. The relatively small area and the associated maximum catchment basin length (*L*) imply a high flash flood sensitivity due to the low accumulation time. However, this is offset by low (≤ 2) drainage texture and drainage density, which decreases the likelihood of flash floods occurrence. Among the areal parameters, low (highly elongated, ≤ 0.5, or elongated, 0.5–0.7) values of elongation ratio, form factor and circularity ratio also reduce FFS due to the highly elongated shape. High values of the Lemniscate index and Gravelius coefficient, as well as the high degree of forest cover, were also interpreted as moderating effects on the studied catchment. Comparing the presented values in this paper with the former general FFS analysis of the Mecsek region by Sarkadi, N. *et al*. (2022), and Víg, B. *et al*. (2022), FFS in the catchment was estimated to be moderate or medium. Based on the flash flood events observed in the past decade, mud and woody debris 'floods' can only be caused by extreme precipitation at the confluence of headwater branches *(Table 1, Photo 1).*

Channel reach analysis

The field survey was carried out on 155 channel sections with a length of 50 m from the source of the southern headwater of the Öreg-patak to the mouth of the watercourse. Of these, 30 sections are located upstream the confluence of the three headwaters.

Early Jurassic (Pliensbachian and Toarcian) sediments dominate the examined sections (n = 144). Further eleven sections overlie thin alkali basalt, trachybasalt, and phonolite dykes of Early Cretaceous (Valanginian) age. We estimated the percentage of bedrock

Table 1. Fundamental morphometric parameters of the studied catchment with the highlighted FFS relevant data

Parameters	Formula	Value	References
FFS parameters			
Area (A), km^2	–	9.75	–
Max. basin length (L), km	–	6.80	Kamykowska, M. *et al.* 1999
Drainage texture (Rt)	$Rt = Nu/P$	0.31	Horton, R.E. 1945
Drainage density (Dd), km/km^2	$Dd = \sum L/A$	1.01	Strahler, A.N. 1957
Elongation ratio (Re)	$Re = D$	0.52	Schumm, S.A. 1956
Form factor (Ff)	$Ff = A/L^2$	0.21	Mesa, L.M. 2006
Circularity ratio (Rc)	$Rc = 4\pi A/P^2$	0.24	Mesa, L.M. 2006
Lemniscate index (k)	$k = L^2\pi/4A$	3.69	Moores, E.A. 1966
Gravelius coefficient (GC)	$GC = P/2\sqrt{\pi A}$	2.03	Sassolas-Serrayet, T. *et al*. 2018
Forested area (Fa), %	–	100.00	Kamykowska, M. *et al*. 1999
Traditional further parameters			
Perimeter (P), km	–	22.5	–
Fitness ratio (Rf)	$Rf = Cl/P$	0.29	Pareta, K. and Pareta, U. 2011
Number of streams (Nu)	–	7	–
Integration index (C), km^2/km	$C = A/L$	1.40	Kamykowska, M. *et al*. 1999
Total stream length (ΣL), km	–	9.90	–
Max stream order (u max)	–	2	Morisawa, M.E. 1962
Total length of stream order (∑u), km	–	4.44 (u1); 5.46 (u2)	–
Mean stream length (Lu), km	$Lu = SL/Nu$	1.40	Biswas, S.S. 2016
Length of main channel (Cl), km	–	6.50	–
Maximum height (H), m	–	680	–
Minimum height (h), m	–	224	–
Basin relief (r), m	$r = H – h$	456	–
Relief ratio (Rr)	$Rr = H – h\text{-}L$	67.28	Schumm, S.A. 1956
Grassland area (Ga), %	–	0	Kamykowska, M. *et al*. 1999
Arable land area (Aa), %	–	0	Kamykowska, M. *et al*. 1999

Photo 1. Woody debris ‘flood’ after an extreme precipitation event at the end of May, 2019. (Photo taken by Attila Szalay, Mecsek Forestry Co. Ltd, 2019).

outcrops exposed in each section and classified the sections into four categories. Some bedrock was found in 58 percent (n = 90) of the surveyed sections. The lowest proportion of bedrock (< 10%) was found in 66 sections. It was measured between 10–50 percent in 21 sections, and the highest outcrop rate was between 50–90 percent in only three sections. In the remaining 65 sections (42% of the total surveyed), no bedrock could be detected. No definite pattern or regularity of the bedrock distribution can be discerned along the longitudinal profile. However, rocks could be traced in all sections from 39 to 59, and from 67 to 90. Furthermore, the 10 to 50 percent occurrence was dominant in sections from 86 to 94 (n = 7). In all the sections where volcanic or subvolcanic rocks were present, bedrock also occurred in the stream bed. In addition, the 11 sections mentioned above alternated between the 10–50 percent, and 50–90 percent categories. A decrease in rock occurrence was observed downstream section 100, justified by the thickness and accumulation of younger cover sediments. The low proportion of the bedrock outcrops (only 24 sections have >10% outcrop ratio) is typical of the low-mountain region in the Pannonian Basin (i.e., low altitude, relief, channel gradient, water discharge and bedload transport intensity, and high portion of alluvial fans) (Mezősi, G. 2015; Kocsis, K. 2018). Furthermore, this feature is reinforced by the laws governing catchments and stream channel conditions (i.e., low gradient, stream power, sinuosity), which inhibit the evolution of bedrock and colluvial channels (Bisson, P.A. *et al*. 2017).

Slope (waste mantle) and alluvial sediments could be observed in channel deposits for most of the sections (n = 151; 91%). In the remaining minority of sections (n = 4), the same could be assumed but could not be assessed adequately due to thick leaf litter cover. Sediment grain size showed slight variation. The upstream sections (5–15) were characterised by clay and silt, while the remaining sections contained all grain sizes from clay (< 0.004 mm) to small boulders (> 256 mm) in varying amounts. Similar sediment size distributions have been reported in the streambed for small headwater streams (Galia, T. *et al*. 2015). Estimating the number of different grain sizes over such a long reach would be difficult, imprecise, and impossible in the field. According to Russel, R.J. (1954) and Charlton, R. (2008), alluvial channels can contain a mixture of grain sizes from boulders to clay. The variable grain size may also be explained by the low channel gradient and the 'semi-alluvial' nature of the stream. The relatively low sediment transport capacity only changes during extreme debris floods (Bywater-Reyes, S. *et al*. 2017).

In the longitudinal profile four types were identified, such as stepped, irregular, levelled and undulating. The fifth possible type (toothed) was not observed. The occurrence of the observed types did not show a clear regularity along the stream. The four types being quite similar, only 60 of the measured sections the reaches could be classified unequivocally. The vast majority of them (n = 49) were either irregular or levelled. However, the entire longitudinal profile of the studied stream displayed a concave curvature with a steep upper course (0–1,500 m) and a gentle lower course downstream (1,500–7,700 m) (see upper part of *Photo 1*), a typical longitudinal profile for alluvial streams (Rice, S.P. and Church, M. 2001). Earlier research also confirmed that natural alluvial streams usually have an irregular longitudinal profile (Western, A.W. *et al*. 1997; Schumm, S.A. 2005).

The width/depth ratio, measured in a total of 120 sections, characterises cross-section geometry. The upstream segment (0–1,500 m) of the watercourse had a narrow and relatively deep valley floor with a low discharge (estimated mean annual discharge at the confluence < 0.015 m^3/s), resulting in an ill-defined stream channel. In the sections spanning from 30 to 155, the dominant types of beds were those whose width was much greater than depth. From 1,500 to 3,000 m, the width of the bed varied between 0.3 and 0.8 m (average 0.54 m). Then, the width increased significantly. Up to the confluence, the width varied between 1.26 and 12.05 m (average 4.33 m). Channel depth was only measured from section 30 onwards. The 125 sections from here up to the confluence ranged from 0.05 to 1.2 m in depth (average is only 0.3 m). Deeper channels were often linked to anthropogenic influence. Moreover, the pools due to organic dams or bedrock steps induced higher-than-average values. The width/depth ratio (W/D) ranged from 2.5 to 143.2, with an average of 21.67 and was used for the fundamental Rosgen's classification (Rosgen, D.L. 1994). The first group consisted of forty-four sections with low values (W/D < 12; mean 8.56), which were dominated by alluvial deposits with floodplain and riffle/pool bed morphology. The next class (moderate W/D values between 12 and 40) characterised 69 sections (mean 21.24) with moderate or low channel gradient, riffle/pool bed morphology, and high bank-erosion anastomosed channel. In the third class (high W/D values > 40), 12 sections were included (mean 72.17) with broad valleys and considerable amounts of alluvial deposits. The channel types and bed morphology defined by the W/D values (Buffington, J.M. and Montgomery, D.R. 2013) can also be identified in the current study area.

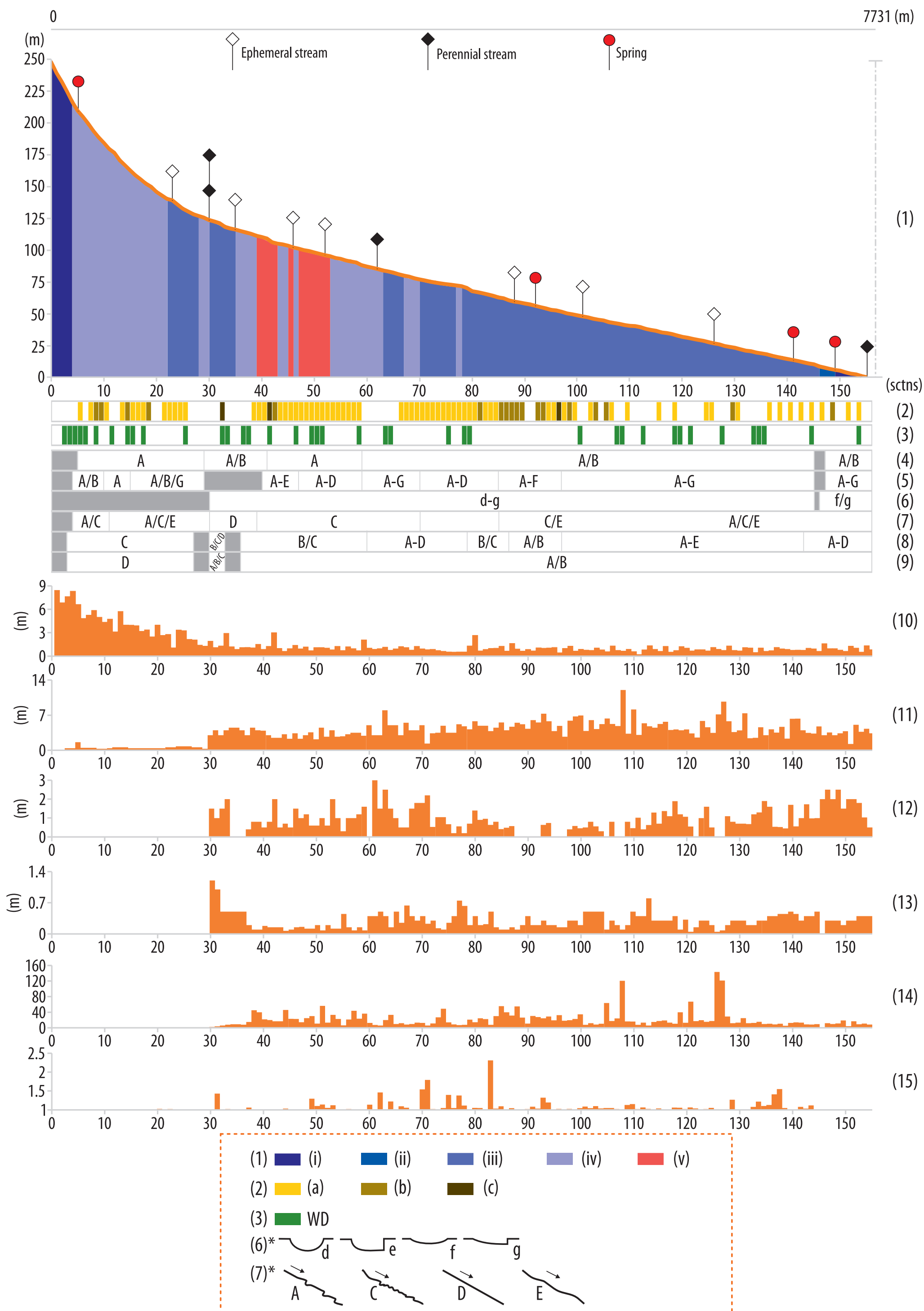
The slope, stability and maximum height of the natural banks were also surveyed since they significantly affect bank erosion and sediment transport (Sass, C.K. and Keane, T.D. 2012; Willett, C.D. *et al*. 2012; Buffington, J.M. and Montgomery, D.R. 2013). Banks were classified as very gentle, gentle, steep, vertical or overhanging along the stream. Establishing any regularity was not possible, as the pattern was found to be highly variable even within sections. The valley side characteristics were estimated in the upstream segment (3–29) due to the lack of definite banks. Here the steep class predominated. With few exceptions, the downstream segment (30–155) was dominated by stable and semi-stable banks. The maximum relative height of the banks ranged from 0.2 to 3 m (average 1.06 m). It is important to note that in sections with vertical or overhanging bank types, the banks were still considered semi-stable due to anthropogenic influences (i.e., gabion walls) or to stabilising vegetation *(Photo 2).*

The segment upstream had a steeper gradient (average 8.3%), whilst the downstream segment had only 2 percent. The downstream segment showed a consistently higher ratio (≥ 4%, n = 4) in sites where both bedrock outcrops and woody debris with a step system were present. Sections with a gradient of 2–4 percent (n = 48), either bedrock steps or woody debris, were reported in 39 cases. The entire longitudinal profile exhibited slope values ranging from 0.44–16.9 percent. Bed slopes (0.2–1%), typical according to Bisson, P.A. *et al*. (2017), dominated on the pool-riffle reaches (n = 3 all downstream), 1–3 percent on the plane-bed reaches (n = 118 dominated downstream), 3–8 percent on the step-pool reaches (n = 21) and 8–26 percent on the cascade stream reaches (n = 13 all upstream but not cascade types).

Sinuosity ranged from 1 to 2.31 (mean: 1.12, standard deviation: 0.19). The sinuosity ratio (*SR*) of the whole valley (6,310 m) was also estimated as 1.22. Traditionally, channels are classified into three categories: straight (SR < 1.1), sinuous (1.1–1.5) and meandering (> 1.5) (Leopold, L.B. and Markley, G.W. 1957). In the sections we surveyed, straight type occurred in 63, sinuous in 21 and meandering only in 4 cases (see *Figure 3*). We agreed with Charlton's notes that the SR descriptions are confused in the literature, thus, making it hard to compare and interpret recent results (Charlton, R. 2008).

The total number of large woody debris sites obstructing the riverbed was 48, located in 25 percent of the sections (n = 39). In most cases (79%), only one log jam per section was documented (n = 31 sections). The maximum number of dams observed in a section was three, which occurred in only one case (section 109). The overall average was c. 0.62 WDJs per 100 m *(Figure 4).*

The interpretation of our results is difficult since no similar survey has been conducted in the Pannonian Basin yet. However, the



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7731 (m)
(m)
Ephemeral stream
Perennial stream
Spring
(sctns)
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B/C
(1) (i) (ii) (iii) (iv) (v)
(2) (a) (b) (c)
(3) WD
(6)* d e f g
(7)* A C D E

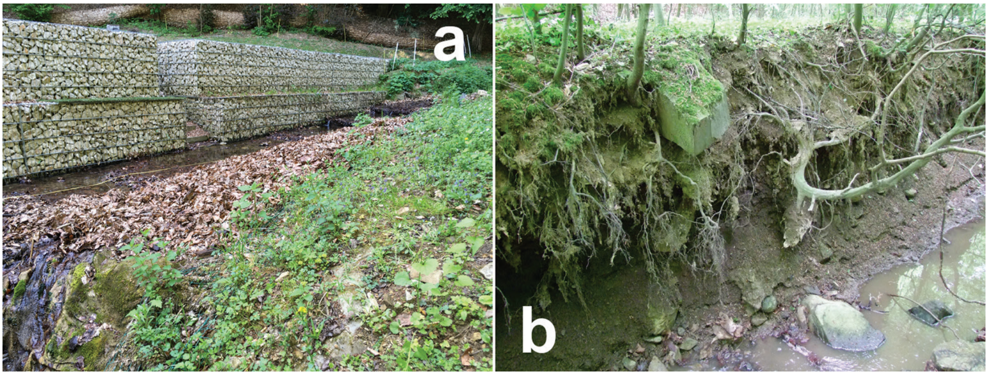

Photo 2. Examples of semi-stable stream banks: Technically fixed by retaining gabion walls (a), naturally semi-fixed by roots (b). (Photos taken by the authors.)

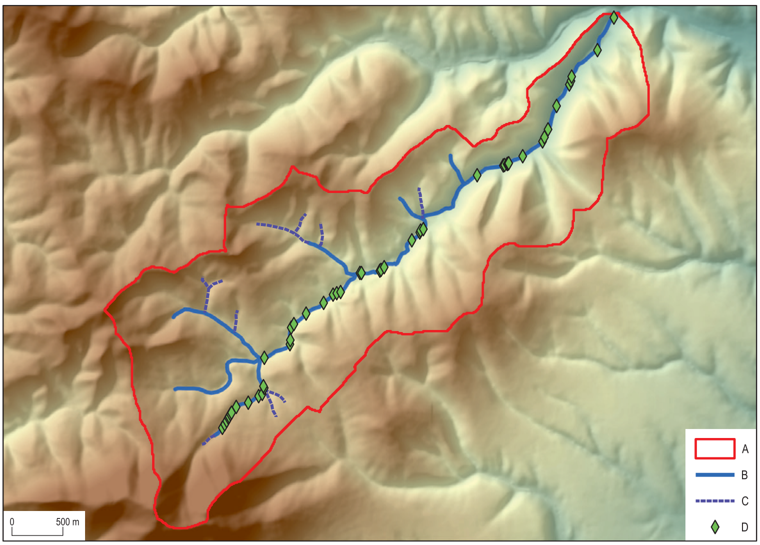

Fig. 4. Map of the woody debris along the Öreg-patak (Öreg Stream): Borderline of the study area (A), perennial/ephemeral stream (B/C), woody debris (D).

←
Fig. 3. Longitudinal profile of Öreg-patak (Öreg Stream) with the main measured stream channel characteristics (on the right side axis, 1–15). *Geology* (1) = Lower Jurassic Pliensbachian marl (i); Lower Jurassic Pliensbachian marl and marlstone (ii); Lower Jurassic Pliensbachian marl and siltstone (iii); Lower Jurassic Toarcian marl and silt (iv); Lower Cretaceous (Valanginian) alkaline basalts (v). *Surface of outcrops* (2) = <10% (a); 10–50% (b); 50–90% (c). *Woody debris* (3). *Genetic type of sediment* (4) = slope origin (A); alluvial (B). *Size composition of sediments* (5) = clay (A); silt (B); sand (C); granules, 2–8 mm (D); pebbles, 8–64 mm (E); cobbles, 64–256 mm (F); boulders, > 256 mm (G). *Cross-section of the channel* (6) = triangular, depth > width (d); trapezoidal, depth = width (e); (f) elliptical, depth < width (f); parabolic, depth < width (g). *Longitudinal profile* (7) = atepped (A); irregular (C); levelled (D); undulating(E). *Bank slope* (8) = very gentle banks (A); gentle banks (B); steep banks (C); vertical banks (D); overhanging banks (E). *River bank fixation* (9) = naturally fixed (A); artificially fixed – biologically (B); artificially fixed – technically (C); unfixed (E). *Stream gradient* (10). *Max bankfull width* (1). *Max height of the natural banks* (12). *Max bankfull depth* (all in metre) (13). *Channel shape index* (14). *Sinuosity* (15).

frequency of WDJ is considered extremely low. Previous studies measured significantly higher values (range 2.4 to 8.6) with matching catchment areas (≤ 10 km^2) and comparable reach lengths (≤ 50 m) (Jackson, K.J. and Wohl, E. 2015.). A higher value (1.2–1.4) with similar catchment parameters (channel length approx. 8 km, stream order HS ≥ 2, forested ratio close to 100%) was also reported (Comiti, F. *et al*. 2006). We assumed that low WDJ frequency is predominantly related to regular forest management, as the managed forest provides less wood than the old-growth forest to develop jams (Dahlström, N. and Nilsson, C. 2004; Motta, R. *et al*. 2006; Wohl, E. *et al*. 2017). The composition of debris jams (grain size, length, and diameter) varied along the stream. All surveyed WDJ contained organic material of the smallest dimension (leaves, seeds, and twigs) as well as elements classified in the literature as coarse woody debris (CWD) and large woody debris (LWD). This hybrid structure and grain size are consistent with most WDJ in the forest-covered headwater channels in low-mountainous regions (Manners, R.B. *et al*. 2007; Přibyla, Z. *et al*. 2016). The CWD and LWD consisted of pieces from deciduous trees dominated by *agus sylvatica* and *Carpinus betulus.* The increased ratio of *Fagus sylvatica* in the WDJ and other in-stream wood material has also been observed in the Czech Carpathians when this species is mixed with conifers to a much greater extent (Galia, T. *et al*., 2017). It may be assumed that *Fagus sylvatica* has a unique role in WDJ generation in Central European low- and mid-mountainous mixed forests.

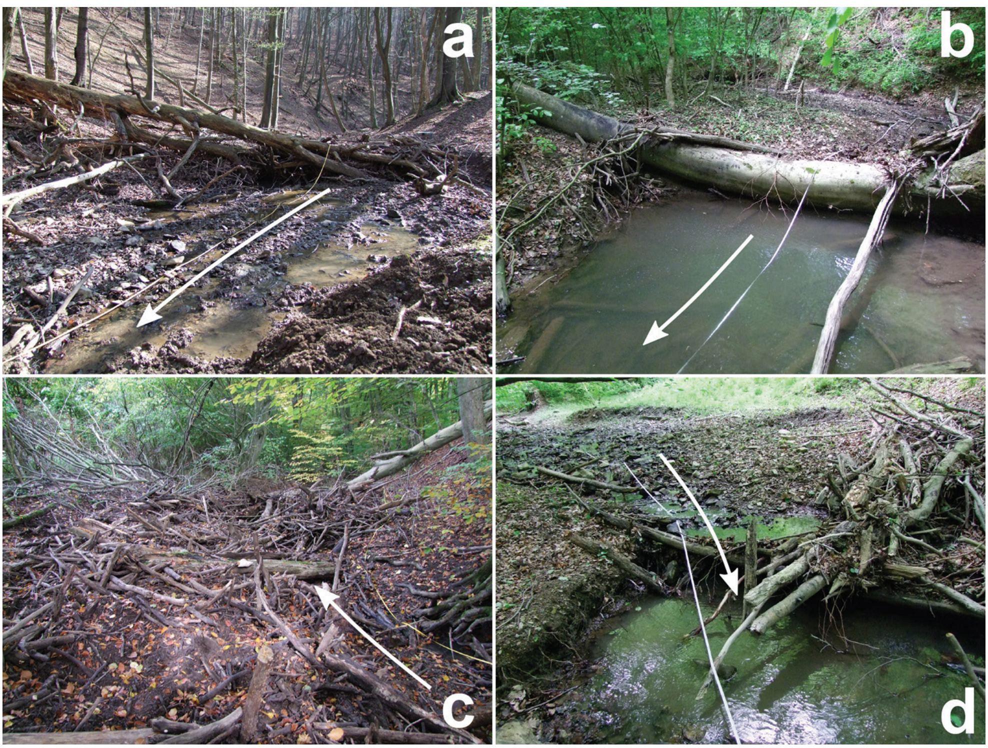

Photo 3. Examples of woody debris jams (arrows show the flow direction): Log jam in juvenile phase (a), log jam with massive trunk and soil ball (b), typical log jam in mature phase (c), log jam with steps and pothole (d). (Photos taken by the authors.)

A separate group is formed by types that usually contain massive trunks (≥ 25–30 cm diameter, ≥ 2 m length) typically found in the bed with soil ball (n = 3), all of them *Fagus sylvatica*. These are referred to as stable types in this study, as their potential for displacement is relatively small, mainly due to their large mass and low average discharge of the trunk stream. They form a step in the bed, enhance the accumulation of sediment and the upwelling of wood, and promote the creation of erosional depressions after blockage. This way, they also have a complex and essential influence on bed morphology *(Photo 3).* Our findings on this issue are the same as Ondráčková and Máčka's results on the role of in-stream wood and rootball accumulations (Ondráčková, L. and Máčka, Z. 2019). Geomorphic (dis)connectivity in a middle-mountain context: Human interventions in the landscape. Furthermore, we consider the type we defined as stable WDJ comparable to the "active jam" type published by Cashman, M.J. *et al*. (2021), which increases the jam's structural complexity and hydromorphological diversity.

Conclusions

This study delineated the Öreg-patak watershed using standard GIS processes on a 10 m DEM. To estimate FFS for the catchment, we evaluated the computed parameters of the basin and the modelled data for this area. The FFS of the studied watershed can be assessed as medium to moderate. However, extreme meteorological events can generate severe sediment and woody debris 'floods', easily observed during the fieldwork, especially in the upstream segment. With slight modifications and additions, the method we developed and utilised for the field survey of stream morphology was successfully applied in the Mecsek Hills and low-mountainous relief.

Channel types and reaches were surveyed based on measured and estimated streambed morphological properties and classified according to a currently accepted geomorphological system (Buffington, J.M. and Montgomery, D.R. 2013). The upstream part was identified as a colluvial channel of 0 or 1 stream order and low streamflow discharge, incised into a colluvial valley. On the downstream segment, step-pool (steps formed by woody debris and bedrock), pool-riffle (moderate or low gradient) and braided channel (large W/D ratio) types dominated without any regularity. The bedrock channel reach occurred in less than 2 percent of all measured sections; the typical cascade, plane-bed and dune-ripple stream reaches could not be observed in the study area.

The measured and estimated sporadic data of the natural streambanks (e.g. height, stability, and slope) may be suitable to determine the potential stages of bank erosion activity (Rosgen's BEHI Index) at different levels.

In this study, we recorded all woody debris jams in the channel, built up of either CWD or LWD. We focused on the 'stable' type of these log jams because they significantly affect streambed morphology. Forming natural barriers in the channel, wood jams can block or reduce sediment and organic material transport. Furthermore, their stability can be increased by travertine formation.

Analysis of small headwater streams is lacking in Hungary as fluvial geomorphological studies focus mainly on larger rivers and their floods. However, increasingly frequent extreme rainfall events and flash floods justify complex morphological studies of small catchments and headwater streams.

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