Science of the Total Environment 649 (2019) 672–685

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Variations in bar material grain-size and hydraulic conditions of managed and re-naturalized reaches of the gravel-bed Bečva River (Czech Republic)

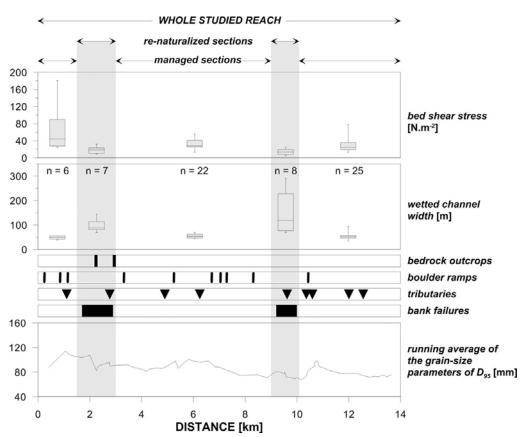
Václav Škarpich [a,]*, Tomáš Galia [a], Stanislav Ruman [a], Zdeněk Máčka [b]

[a] Department of Physical Geography and Geoecology, Faculty of Science, University of Ostrava, Chittussiho 10, Slezská Ostrava, Ostrava 710 00, Czech Republic
[b] Department of Geography, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

HIGHLIGHTS

- Channel geometry corresponded well with modelled hydraulic variables.
- Bar grain size and simulated hydraulics did not produce any clear relationships.
- Sediment inputs and disconnectivities gave better explanation of the grain size.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 February 2018
Received in revised form 22 August 2018
Accepted 24 August 2018
Available online 26 August 2018

Keywords:
Multi-thread river
Channelization
Gravel bar grain-size
Channel hydraulics
Sediment connectivity
The Bečva River

ABSTRACT

European multi-thread rivers have undergone rapid morphological changes during past centuries due to the extensive direct and indirect human impacts on fluvial systems. As a consequence, we can identify altered patterns of bed sediment calibre reflecting disturbed sediment connectivity and modified flow hydraulics. Changes in the grain-sizes of samples collected on 68 gravel bars in August 2015 were studied along 14.0-km river reach of the Bečva River (Outer Western Carpathian Mts., Czech Republic). The grain-size characteristics obtained were confronted with modeled flow hydraulics and the present stage of the channel. The studied channel reach is presently characterized by several distinctive sections: for a long time (ca. 100 years) regulated single channel sections with artificial bank stabilizations incised several meters in the floodplain and by contrast, multi-thread channel patterns of two sections, which have witnessed retrograde development after large floods in 1997 and 2010 with 100- and 50-year recurrence intervals, respectively. The present channel behaviour of managed (regulated) and re-naturalized (multi-thread) river sections corresponded well with the modeled hydraulic variables for one-year discharge recurrence interval. Especially, re-naturalized river sections showed lower values of flow competence which facilitated the deposition of sediment material in the form of gravel bars. The high occurrence of lateral sediment sources (e.g., tributaries, bank failures) together with sediment disconnectivities (e.g., boulder ramps) in the longitudinal river reach were observed, and grain-size parameters did not particularly reflect the

* Corresponding author.
E-mail address: vaclav.skarpich@osu.cz (V. Škarpich).

https://doi.org/10.1016/j.scitotenv.2018.08.329

hydraulic conditions. Especially tributaries as sediment inputs had significant effect on bar grain size and increase of channel diversity, although, in general results indicate a gradual downstream fining.

1. Introduction

Multi-thread river channels are integral parts of fluvial systems, which connect the mountainous landscapes with lowland areas (Schumm, 1977). In the past few centuries, multi-thread river channels have undergone rapid changes induced by human activities (Gregory, 2006; Kondolf, 1997). A large number of studies across the globe have identified the most serious issues of multi-thread channel pattern transformation with regards to progressive narrowing (Korpak, 2007; Liébault and Piégay, 2002; Rinaldi et al., 2005; Surian and Rinaldi, 2003; Škarpich et al., 2013, 2016a, 2016b; Zawiejska and Wyżga, 2010) and incision (Kondolf et al., 2002; Martín-Vide et al., 2010; Preciso et al., 2012; Rovira et al., 2005; Surian and Rinaldi, 2003; Uribelarrea et al., 2003; Wyżga, 2001; Zawiejska and Wyżga, 2010). These alterations resulted in channel flow hydraulics changes and brought a new set of boundary conditions for erosion, transport and deposition processes (Knighton, 1999; Madej, 1995), in which amount, calibre and sorting of sediment as well as its spatial distribution are adjusted to local variations in flow competence (Powell, 1998). The spatial distribution and sorting pattern of sediment have important consequences and implications for the functioning of river ecosystems, e.g., the potential for fish spawning or the suitability of the riverbed as a habitat for benthic macroinvertebrates (Vannote et al., 1980).

Sediment transport within river systems has been described as a cascade system (Schumm, 1977). It can be thought of as a three-dimensional system in the longitudinal, lateral and vertical directions (in the sense of Brierley et al., 2006; Fryirs, 2013; Fryirs et al., 2007; Hooke, 2003). Bed sediment changes along altered or natural river channels have been relatively well recognized (Rengers and Wohl, 2007; Surian, 2002; Zawiejska et al., 2015). In contrast, much less is known about sediment distribution and sorting patterns linkages to specific values of hydraulic parameters in channels.

A characteristic feature of many alluvial rivers is the gradual decrease in bed material grain-size in the downstream direction, which is called 'downstream fining' (Gomez et al., 2001). Two generic mechanisms have been invoked to explain this phenomenon: particle abrasion and hydraulic sorting. The pioneering observations of Sternberg (1875) in a 260 km reach of the Rhine River described an exponential downstream decrease in grain-size due to abrasion. The derived exponential law takes the form:

$$D_i = D_0 e^{-KL}, \quad (1)$$

where D_i is the particle diameter (m), D_0 represents the initial diameter of the particle (m) transported for distance L (m), and K is the coefficient of reduction for given rock resistance. Based on this, abrasion depends on a variety of factors, including the lithology of the material, climate conditions in the basin, human impact, etc. Hydraulic sorting is promoted by the differential entrainment, transport, and deposition of particles, as a function of their size and shape (Gomez et al., 2001; Russell, 1939). There has been discussion about the extent to which condition of equal mobility or departures from it dominate (e.g., Andrews, 1983; Gomez, 1995; Gomez et al., 2001; Wilcock, 1992). The consensus is that there is a tendency for particles of different sizes to be equally mobile when the boundary shear stress greatly exceeds the threshold for motion and that at lower shear stresses, sorting is much less pronounced than would be the case if the size fractions were transported independently (e.g., Wilcock and McArdell, 1993; Gomez, 1995; Gomez et al., 2001).

However, downstream coarsening in some river reaches was observed for gravel-bed alluvial rivers (Dawson, 1988; Knighton, 1980; Powell, 1998). These anomalies are the result of (dis)connectivity (Schumm, 1977; Fryirs et al., 2007; Galia et al., 2016), which disrupts lateral, vertical and/or longitudinal linkages in sediment flux and affects the sediment cascade. The downstream fining disruption of gravel-bed rivers occurs not only in response to sediment supply from tributaries and other lateral inputs but also in response to anthropogenic interventions in the fluvial system (Surian, 2002; Fryirs et al., 2007; Ondráčková and Máčka, 2018). Additionally, a conceptual framework identifying the status of river reaches and linkages between them were proposed by Hooke (2003). Based on this, the types of connectivity including unconnected, partially and potentially connected, connected and disconnected reaches were identified. It has the implications for understanding the sensitivity to perturbations and channel development.

A characteristic feature of low gradient and wide alluvial channels is the accumulation of sediment which is created by reduced flow conveyance (Powell, 1998). In contrast, some channel reaches accelerate the downstream movement of sediments (Fryirs et al., 2007). These boosters are represented by natural predispositions (e.g., by the presence of gorges or bedrock reaches) or as the consequences of regulation works. River channelization includes the narrowing and shortening of the channel together with the steepening of bed gradient, which lead to the increase of flow velocities and forces acting on stream bed and banks (Fryirs et al., 2007; Škarpich et al., 2016a; Wyżga, 1993).

The potential for incision and sediment transport can be assessed via the unit stream power (ω) or the bed shear stress (τ_b). Many studies (Krapesch et al., 2011; Magilligan, 1992; Nardi and Rinaldi, 2015; Zawiejska et al., 2015) have conceptualized this issue via the calculated parameters of ω and τ_b, because obtaining the input variables is easy. The parameter ω (W m^{-2}) was introduced by Bagnold (1966):

$$\omega = (\rho g Q S)/b, \quad (2)$$

where ρ is the density of water (kg m^{-3}), g is the acceleration due to gravity (9.8 m s^{-1}), Q is the discharge (m^3 s^{-1}), S is the channel slope (m m^{-1}), and b is the channel width (m).

The parameter τ_b (N m^{-2}), another fundamental variable in assessing flow conditions, is defined as:

$$\tau_b = \rho g R S, \quad (3)$$

where R is the hydraulic radius (m). In the past few decades, one- or two-dimensional models have allowed us to calculate these hydraulic parameters (Czech et al., 2016; Pasternack et al., 2006).

This study is focused on the grain-size variation of 68 gravel bars in a 14-km long unconfined reach of the gravel-bed Bečva River (Western Carpathians, Czech Republic) and its confrontation with modeled flow hydraulics and the present state of the channel. In the 19th century, the Bečva River had multi-thread characteristics over the entire study reach, which was converted into a uniform single-channel by intensive channelization works at the turn of 20th century. These changes promoted sediment conveyance, acting as boosters and causing a gradual incision of several meters into the floodplain. The high-magnitude floods in 1997 and 2010 partially destroyed artificial channelization structures in some sections. This was accompanied by notable channel widening in these sections and development of gravel bars. This study aims to:

(i) identify contemporary general patterns of channel morphology, lateral sediment inputs (connectivities), potential disconnectivities in sediment flux and erosion/deposition processes in the channel of the laterally unconfined river valley,
(ii) analyse and describe the variations in the grain-size parameters of gravel bars in the context of general patterns of channel morphology and sediment flux (dis)connectivities,
(iii) assess the relationships between the modeled hydraulic variables responsible for the transformation of the gravel bars' surface layer and the grain-size parameters of these bars.

2. Study area

2.1. Basic regional settings

The Bečva River is 61.5 km-long gravel-bed stream with a drainage area of 1620 km^2 (data source: Czech Hydrometeorological Institute) and feather-like or dendritic channel network (Ivan et al., 2000). It is a left side tributary of the Morava River (Danube River basin). The Bečva River begins at the junction of two main source streams, the Rožnovská Bečva River and the Vsetínská Bečva River (see Fig. 1). They drain out Czech part of Western Carpathians, namely the Moravskoslezské Beskydy Mts., Hostýnsko-vsetínská hornatina Mts., Javorníky Mts., Vizovická vrchovina Mts. to the relatively flat piedmont. The locations of the highest and lowest elevations within the Bečva R. basin are, Čertův Mlýn at 1205 m asl, and the mouth to the Morava R. at 195 m asl, respectively.

Annual precipitation in the basin area ranges from 500 mm at the lower parts of the basin to 1200 mm in the mountains (data source: Czech Hydrometeorological Institute). The Bečva River is characterized by the occurrence of frequent floods of moderate magnitude due to snow melting, and large floods caused by prolonged rainfalls, which are connected to summer cyclones.

The study was performed in a 14.0-km long river reach of the Bečva River, which was entirely located in an unconfined valley of the piedmont area (i.e., out of primary sediment sources). The main tributary in the studied river reach is left-side gravel-bed tributary of the Juhyně River at 1.1 km downstream the beginning of the studied longitudinal reach. The mean annual discharge is 15.5 $m^3\ s^{-1}$ at the Teplice nad Bečvou gauging station (0.6 km immediately downstream the studied river reach where basin area is 1275 km^2, for location in Fig. 1 see gauging station *a*). Table 1 shows the mean annual discharges and recurrence intervals (R.I.) of flood discharges of additional gauging stations of the Bečva, Vsetínská Bečva and Rožnovská Bečva Rivers.

The study area belongs to the Outer Carpathian Group of flysch nappes. The historical occurrence of the multi-thread channel of the Bečva River was mainly caused by high sediment supply into the channel network from the flysch lithology of the basin's mountainous areas. The predisposition of local flysch lithology to high sediment supply in this area was described by Galia et al. (2016) and Škarpich et al. (2013). Lithology of the mountainous part of the Bečva River drainage basin is mainly composed of alternating layers of claystone, sandstone and conglomerate flysch, from Jurassic to Palaeogene rocks (Chlupáč et al., 2011; Menčík et al., 1983). The valley floors are dominated by unconsolidated Miocene (Badenian) clays and sands, and fluvial

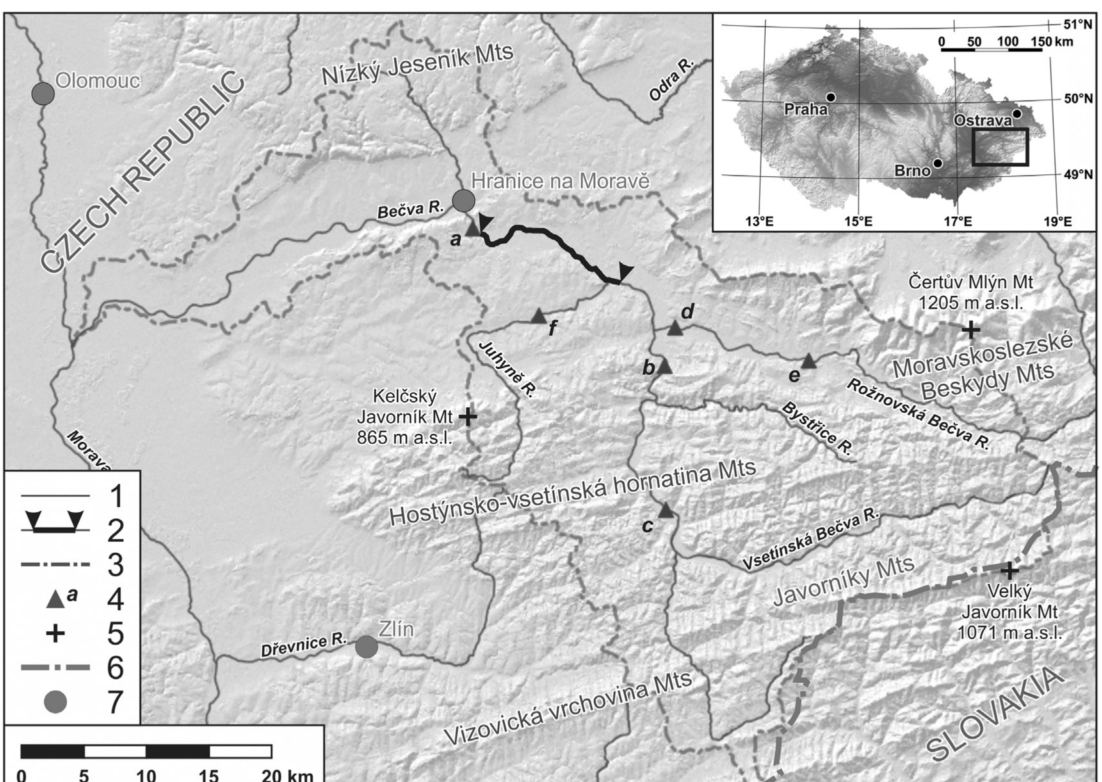


Fig. 1. Geographical position of the studied river reach; legend: 1 — streams, 2 — studied river reach, 3 — the Bečva River basin border, 4 — gauging stations, 5 — mountain peaks; 6 — state border, 7 — settlements; gauging stations: *a* — Teplice nad Bečvou, *b* — Jarcová, *c* — Vsetín, *d* — Valašské Meziříčí, *e* — Rožnov pod Radhoštěm, *f* — Kelč (data source: U.S. Geological Survey — SRTM 1 Arc Second Global; T. G. Masaryk Water Research Institute, public research institution).

Table 1
Mean annual discharge and flood recurrence intervals of the Bečva, Vsetínská Bečva, Rožnovská Bečva and Juhyně Rivers (data source: Povodí Moravy Basin State Enterprise and Czech Hydrometeorological Institute).

Gauging station	River/Stream	Basin area of given gauging station [km^2]	Start year of measurement	Mean annual discharge [$m^3 s^{-1}$]	N-year recurrence interval discharge (Q_N) [$m^3 s^{-1}$]				
					Q_1	Q_5	Q_{10}	Q_{50}	Q_{100}
Teplice nad Bečvou	Bečva	1275.32	1920	15.50	219	452	555	799	908
Jarcová	Vsetínská Bečva	723.87	1939	9.39	151	274	333	479	547
Vsetín	Vsetínská Bečva	505.81	1940	6.79	126	234	279	378	420
Valašské Meziříčí	Rožnovská Bečva	252.45	1941	3.79	66.5	161	214	364	441
Rožnov pod Radhoštěm	Rožnovská Bečva	160.24	1951	2.72	42.8	99.1	134	241	301
Kelč	Juhyně	86.12	1957	0.83	9.3	31.5	43.6	79.8	98.8

Quaternary sediments (Czudek, 2005; Dvořák et al., 2001). The valley floor is formed by a wide (up to 3 km) floodplain fringed by Mid–Late Pleistocene river terraces (Stacke et al., 2014; Macoun et al., 1965). The downstream part of the valley was partly affected by Pleistocene continental glaciation during its maximum advance in the Saalian 1 (Ehlers and Gibbard, 2004).

2.2. History of direct human impact on channel development

At the end of the 19th century, the first channelization works in the study reach were conducted by restricting the flow to a narrow channel through the stabilization of banks and gravel bars with vegetation. At the turn of 20th century, even more systematic regulation was applied, and the Bečva River was completely regulated in the studied 14.0-km long river reach (Havlík, 1999). The original multi-thread river channel pattern was converted into a uniform single-channel. The channel was designed in trapezoidal shape which was accompanied by levees, and the channel bed was stabilized by boulder ramps (Havlík, 1999; Krejčí and Krejčí, 2012). The main reasons for channelization of the Bečva River were flood control and a demand for arable land. As a consequence of river management, the channel has typically incised several meters into the

Fig. 2. View of the Bečva River channelized (managed) single channel sections between (*A*) 0.0–1.7 km, (*C*) 3.0–9.0 km and (*E*) 10.1–14.0 km and retrogradually developed (re-naturalized) multi-thread channel sections between (*B*) 1.7–3.0 km and (*D*) 9.0–10.1 km; designations *A*, *B*, *C*, *D* and *E* are corresponding with designations of channel sections in Fig. 4.

floodplain along its entire reach. The sediment supply balance has also been upset by reforestation of the mountainous part of the Bečva River basin since the end of 19th century (Krejčí and Krejčí, 2012; Pavelka and Trezner, 2001).

The studied channel is presently characterized by several distinctive sections. Regulated single channels with artificial bank stabilizations are incised several meters into the floodplain (see Fig. 2*A*, *C* and *E*). In contrast, the multi-thread channel pattern (see Fig. 2*B* and *D*) has retrogradually developed after the 1997 (Hrádek, 2000) and 2010 (Krejčí and Krejčí, 2012) floods (maximum discharge 950 $m^3 s^{-1}$ with ~100-year R.I. and 799 $m^3 s^{-1}$ with 50-year R.I., respectively; data source: Czech Hydrometeorological Institute) in two short river sections. Before the extreme flood in 1997, the regulated channel was trapezoidal in cross-section, the width was 33–35 m and the depth was 2.6–3.7 m (Mihola, 1992). The bank and bed stabilization structures were systematically repaired by water management agencies after individual floods (e.g., in 1950s). This state was given by the political situation (Communist Era) in the Czech Republic (1948–1989) which aimed to maximal using of land for agriculture (Chloupkova, 2002). However after the last significant floods in 1997 and 2010, these stabilization structures in re-naturalized sections were not repaired again because (i) the arable land along the river reach was no longer suitable for agriculture, and (ii) no larger settlements are present along the river which could be endangered by floods.

3. Methods

3.1. Geomorphic and (dis)connectivity mapping

The contemporary state of channelized/re-naturalized channel sections, lateral sediment inputs and potential disconnectivities in sediment flux were mapped in detail along the entire studied reach. We used conventional method of geomorphic mapping based on combination of field survey, analysis of aerial photos and inspection of digital elevation model obtained by LiDAR altimetry airborne laser scanning in 2013. Aerial photos and LiDAR dataset were produced in S-JTSK/Krovak East North coordinate system by State Administration of Land Surveying and Cadastre of Czech Republic. Aerial photos were collected in year 2016 with spatial resolution of 0.2 m. The LiDAR-based digital elevation model, produced in raster format with spatial resolution 5 × 5 m and mean altitude accuracy 0.3 m, provided us with information about the geometry of the floodplain. We generally distinguished the following patterns: (i) depositional, relatively wide channel-sections with the development of gravel bars as in the re-naturalized multi-thread river pattern, and (ii) transport-balanced channel-sections, which were typically incised several meters into the floodplain as the consequence of river management. Sediment inputs consisted of individual bank failures, bedrock outcrops and tributaries. Nine boulder ramps stabilizing the channel bed decreased upstream bed slopes and local flow competences. Artificial bank stabilizations (riprap and concrete flex mats) were representatives of lateral disconnectivities, which also prevented lateral channel migration.

3.2. Sampling of gravel bars

Investigated gravel bars were sampled during low flow conditions (1.3–1.6 $m^3 s^{-1}$) in August 2015. To avoid differences in sample populations with respect to the position on the gravel bar, all samples were taken from the middle part (in longitudinal direction of the river reach) of the bar, close (~1–1.5 m) to the wetted channel. In total, 68 samples were collected in the 14-km long studied reach. The grain-size characteristics of bar surfaces were obtained by photographic grain-size analysis. This analysis was performed with the Sedimetrics Digital Gravelometer software package (Loughborough University Enterprises Ltd) (Graham et al., 2005a, 2005b). The method enables rapid image-processing-based procedure for the measurement of exposed fluvial gravels from digital photographs. The precision achieved is comparable with conventional pebble count sampling strategy of Wolman (1954) as noted by Graham et al. (2005a). Rice and Church (2010) compared values of D_{50} and D_{95} obtained from paired pebble count and photographic samples of gravel bar surfaces. They revealed that the photographic method has not introduced any significant bias, i.e. the mean-square differences were ±3 and ±9 mm, respectively.

One photo per sampled bar was taken. Photos covered a planar area of 0.75 m^2 which was cleaned of leaves or remains of small branches before taking the photographs. Reference points (plastic targets) were placed at each corner of the rectangular wooden sample patch (see Fig. 3A). After the placing of reference points, rectangular wooden sample patch was removed (see Fig. 3B). The reference points provided a scale and they defined the boundary of the patch in the image. The photographs were taken (see Fig. 3C) using a SAMSUNG ST88 compact camera (35 mm equivalent focal length = 25 mm, 16.1 Mpx). The grid-by number method truncated on the lower bound at 8 mm was applied to obtain D_{50} and D_{95} percentiles (mm) and the value of sediment sorting *SI* at Φ scale (in the sense of Folk and Ward, 1957) as representative of the previous episodes which affected bed conditions in the river channel.

3.3. Hydraulic modeling

HEC-RAS 5.0.3 software (U.S. Army Corps of Engineers - USACE) was used to calculate hydraulic parameters in the positions of investigated sediment samples; namely, (i) the water surface slope ($m\ m^{-1}$) − S_{ws}, (ii) the wetted channel width (m) − W_f, (iii) the flow area (m^2) − A_f, (iv) the bed shear stress ($N\ m^{-2}$) − τ_b, (v) the unit stream power ($W\ m^{-2}$) − ω, and (vi) the mean flow depth (m) − d.

The software has been widely used in numerous studies at various scales in relation to sediment processes (Song et al., 2015), hydrokinetic assessment (Punys et al., 2015), river restoration (Pregun, 2016) and flood hydraulics (Czech et al., 2016).

1-year R.I. discharge (219 $m^3 s^{-1}$ in Teplice nad Bečvou gauging station) was simulated by 1D model running in unsteady mode and hydraulic parameters were calculated in the positions of investigated sediment samples. We observed complete submergence and morphological changes of studied gravel bars on 5/15/2014 (260 $m^3 s^{-1}$, ~1–2-year R.I.) and 1/11/2015 (136 $m^3 s^{-1}$, <1-year R.I., data source: Czech Hydrometeorological Institute). Based on these observations, we consider 1-year R.I. discharge as the discharge which was sufficient to rework the surface layer of all studied bars.

Hydraulic modeling consists of several crucial steps. The present digital elevation model obtained by airborne laser scanning (LiDAR) is not able to capture terrain under water surfaces, so the bathymetry of the river channel was added from geodetically measured cross-sections. These were measured during a low flow stage in February and March 2016 at appropriate positions within the studied river reach, when a higher density of cross-sections was obtained in irregular channel-sections (i.e., in river bends or in the case of the presence of a multi-thread pattern). Every single cross-section was taken with respect to the bank and bed morphology, usually including 10–20 measurement points obtained using the total station TOPCON: GTS 212 − 2000. Mean bed slope between individual cross-sections was taken from the digital elevation model. In total, 32 cross-sections (i.e., 2.3 cross-sections per km) were collected for the studied river reach of the Bečva River. An additional five cross-sections were taken upstream and downstream of the studied 14-km long reach, which served as section for refining of simulated hydraulic variables due to absence of explicit boundary conditions in lower and upper part of the 14-km long reach. In addition, the parameters of boulder ramps (height, length, cross-sections) were geodetically measured and added into the model. To preserve channel sinuosity, parts of the channel between the surveyed cross-sections were inspissated using the shape of originally

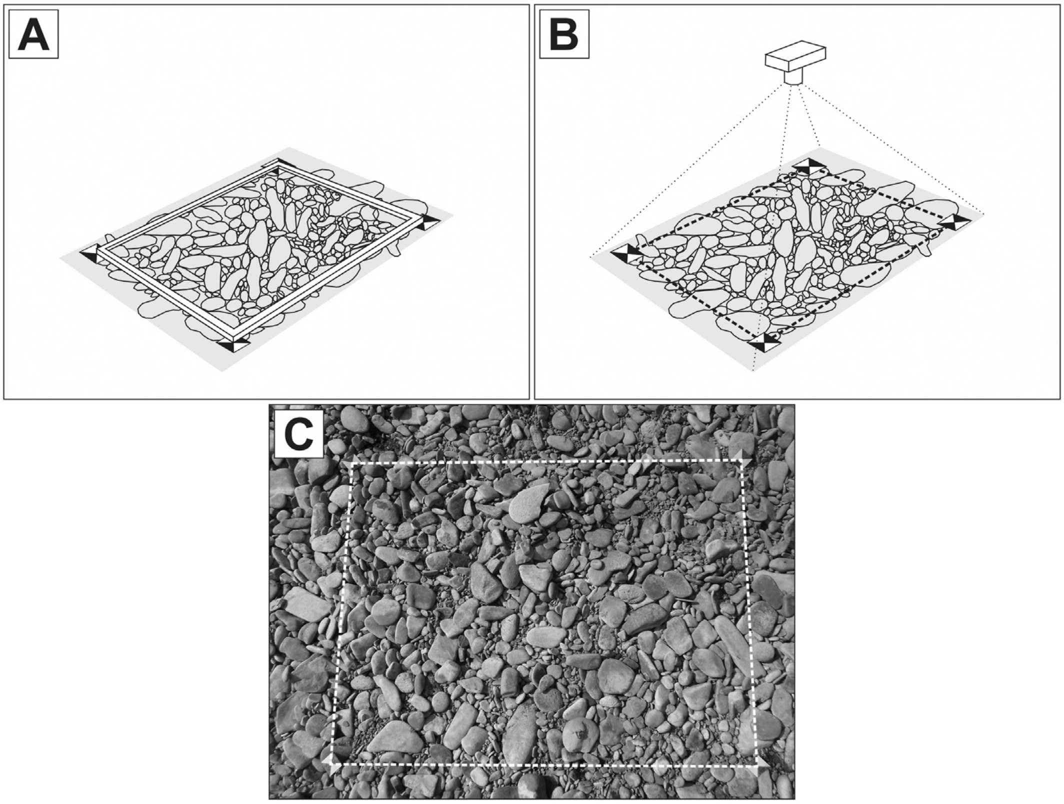


Fig. 3. Illustration of the photographic procedure: (A) placing of reference points (plastic targets) at each corner of the rectangular wooden sample patch, (B) removed wooden sample patch after the placing of reference points and taking approximately vertically photograph by digital camera, (C) scale and defined boundary of the patch in the image provided by reference points in photograph, the photographed area (shaded) in (B) must include all grains intersecting the patch edge (dashed outline).

surveyed cross-sections. The criterion for the selection of original cross-section shape was the channel width, measured from aerial photos in ArcGIS 10.2.1 software, while S-JTSK/Krovak East North coordinate system was applied. Elevation of points in these inspissated cross-sections was recomputed using the elevation from the first point in cross-section obtained from LiDAR. Channel cross-sections were merged with adjacent floodplain (LiDAR) in HEC-RAS software.

The hydrograph of the flood event from 2010 with ~50-year R.I. peak discharge was used for basic calibration of the model. Discharge data from the time span between 5/11/2010 (12:00 a.m.) and 06/10/2010 (11:00 p.m.) at 1 h intervals were provided by the Czech Hydrometeorological Institute. The model was calibrated by adjusting Manning's *n* hydraulic roughness. Simulated discharge was calibrated for the timing of flood peak (799 $m^3 s^{-1}$) and for the value of maximum flood peak with the Manning's *n*-values and compared with the flood hydrograph observed at the outlet gauging station Teplice nad Bečvou (see Fig. 1 for location).

Additional calibration of water levels at individual cross-sections for 1-year R.I discharge reflected known water level in Teplice nad Bečvou gauging station. The maximal water level error was 0.07 m, simulated time of flood peak occurred 0.25 h later and maximal simulated flood peak was equal to the observed one. Finally, the Manning's *n*-value 0.035 in the channel was established in accordance with this calibration process. To preserve gradual increase in discharges from upper to lower part of studied reach, boundary conditions of modeled river reach were based on the linear relation between the increasing basin area and discharges from upstream and downstream gauging stations in the Bečva River basin. In the lower part of the river reach, the normal depth was applied as the water level was unknown. Because the normal depth is the estimation of the measured water depth, the lower part was prolonged to refine simulated hydraulic variables. Furthermore, Teplice nad Bečvou gauging station (in Fig. 1, see gauging station *a*) was a part of this extended reach. The same extension took place in the upper part, because the discharge data from two gauging stations (in Fig. 1, see gauging station *b* — Jarcová and *d* — Valašské Meziříčí) were available here. It implies that the extended river reach for hydraulic modeling has in total 21 km length. There occurred fourteen tributaries the contributions of which to discharge were modeled as lateral inflow boundary conditions. The 1-year R.I. discharge was derived from the contributing area of individual tributaries. The discharge was computed from direct relationship ($Q_1 = 1.0457A^{0.7486}$, $R^2 = 0.98$, $p < 0.001$) between the 1-year R.I. discharge (Q_1) and the basin area (A) of gauging stations in the Bečva River basin. The similar approach of discharge derivation was applied in the studies of Buttle et al. (2016) and Galia and Škarpich (2016). The contributing area was computed by ArcGIS on the basis of LiDAR digital elevation model and ArcHydro 10.2 extension.

3.4. Data analysis

Calculated values of the transport stage (*TS*) were used for the assessment of flow competence. *TS* is described as a ratio between the available bed shear stress (τ_b) and the reference (critical) shear stress (τ_r) producing a very small, but measurable bedload transport rate (Parker, 1990):

$$TS = \tau_b / \tau_r. \tag{4}$$

It implies that the threshold for measurable bedload transport rates assumes the value of *TS* is >1.

The bed shear stress values were calculated by HEC-RAS model with Eq. (3) for shallow and wide channels. The reference shear stress for the representative bed grain-size takes the form (Shields, 1936):

$$\tau_r = (\rho_s - \rho)\theta g D_i, \quad (5)$$

where ρ_s is the density of grain, θ is the dimensionless shear stress and D_i is the representative grain diameter (e.g., D_{50}). The assessment of the θ value is the subject of ongoing discussions in bedload calculations for gravel-bed rivers (e.g., Buffington and Montgomery, 1997; Lamb et al., 2008). For our purposes, we used the slope-dependent equation of Parker et al. (2011):

$$\theta = 0.19 S_{ws}{}^{0.28}, \quad (6)$$

where S_{ws} is the water surface slope (m m^{-1}). The Parker et al. (2011) equation was derived from an extensive dataset of field measurements in gravel-bed rivers covering a wide range of channel slopes. The parameter of S_{ws} was calculated by HEC-RAS for individual cross-sections adjacent to investigated gravel bars.

3.5. Statistical methods

Hydraulic (S_{ws}, W_f, A_f, τ_b, ω, d, TS) and grain-size (D_{50}, D_{95}, SI) parameters were statistically analysed. Because the majority of hydraulic and grain-size parameters were not normally distributed and they showed differences in variance between the channelized (managed) and re-naturalized channel sections, the nonparametric Kruskal-Wallis (KW) test was used. This test was used to examine the differences in the hydraulic and grain-size variables among three channelized (managed) and two re-naturalized channel sections. If KW tests indicated a significant difference ($p < 0.05$) in a particular variable, multiple pairwise comparison was performed using Dunn's procedure with the Bonferroni corrected significance level to identify mutually different channel sections.

A principle components analysis (PCA) with varimax rotation was used to find potential relationships between the grain-size of gravel bars (SI and D_{50}, D_{95}) and hydraulic parameters (W_f, A_f, ω, τ_b, d, S_{ws}, TS) of examined cross-sections. The PCA was chosen because of its capability to reduce the number of entering variables (nine in our case). Resulting components are represented by a linear combination of variables to summarize the patterns of intercorrelation between the variables, yet the components are mutually independent.

Varimax rotation is a change of coordinates in PCA by rotating the axes of two-dimensional plane while keeping the 90-degree angle between them. This maximizes the sum of the variances of the squared loadings. Thus, all the coefficients (squared correlation with factors) will be either large or near zero, with a few intermediate values, which helps to easier interpretation of calculated results (Kaiser, 1958).

4. Results

4.1. Contemporary patterns in the channel morphology

General patterns of channel morphology varied considerably along the entire studied reach. The river sections between 0.0 and 1.7 km (designated *A* in Fig. 4), 3.0–9.0 km (designated *C* in Fig. 4) and 10.1–14.0 km (designated *E* in Fig. 4) exhibited channelized (managed) sections. They were characterized by a narrow channel with a trapezoidal cross-section and artificial bank stabilizations (riprap and locally concrete flex mats). These structures represented lateral disconnectivity, which prevented lateral channel migration and sediment supply from adjacent river terraces. In total, nine artificial boulder ramps were observed in the river section *A*, *C* and *E*, which stabilized the channel bed. In addition, they acted as potential longitudinal forms of sediment disconnectivity due to the local decrease in bed slope upstream from these structures. At 10.5 km, an additional boulder ramp was partially destroyed to the present height of ~0.3 m.

Overall, the river sections *A*, *C* and *E* were characterized as transport-balanced zones with the presence of small gravel bars. Between 11.7 and 14.0 km (the part of *E* section), several relatively larger gravel bars were observed despite the stream channelization.

In contrast, the river sections between 1.7 and 3.0 km (designated *B* in Fig. 4) and between 9.0 and 10.1 km (designated *D* in Fig. 4) exhibited the multi-thread pattern with the occurrence of larger gravel bars and the absence of artificial bank stabilizations. Original artificial bank stabilization structures were destroyed by large floods in 1997 and 2010. The removal of bank stabilizations enabled lateral channel migration accompanied by the development of large bank failures in outer river bends and increased sediment supply to the channel. These sections *B* and *D* were characterized as accumulation zones with active deposition of

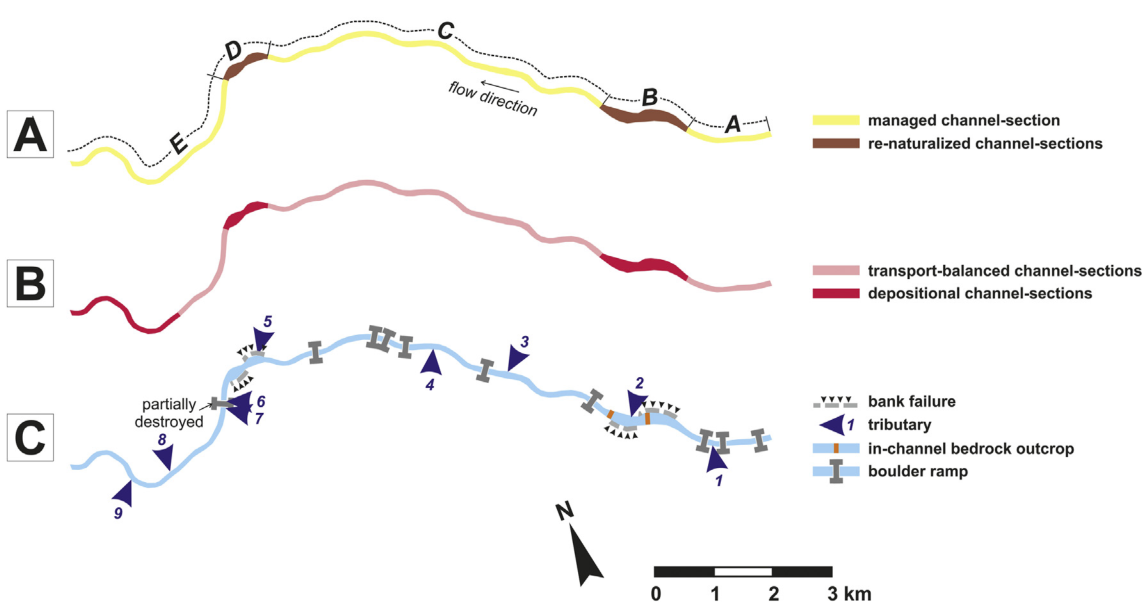


Fig. 4. (A) Contemporary state of channelization/re-naturalization, (B) patterns in the channel, (C) lateral sediment inputs and potential disconnectivities in sediment flux.

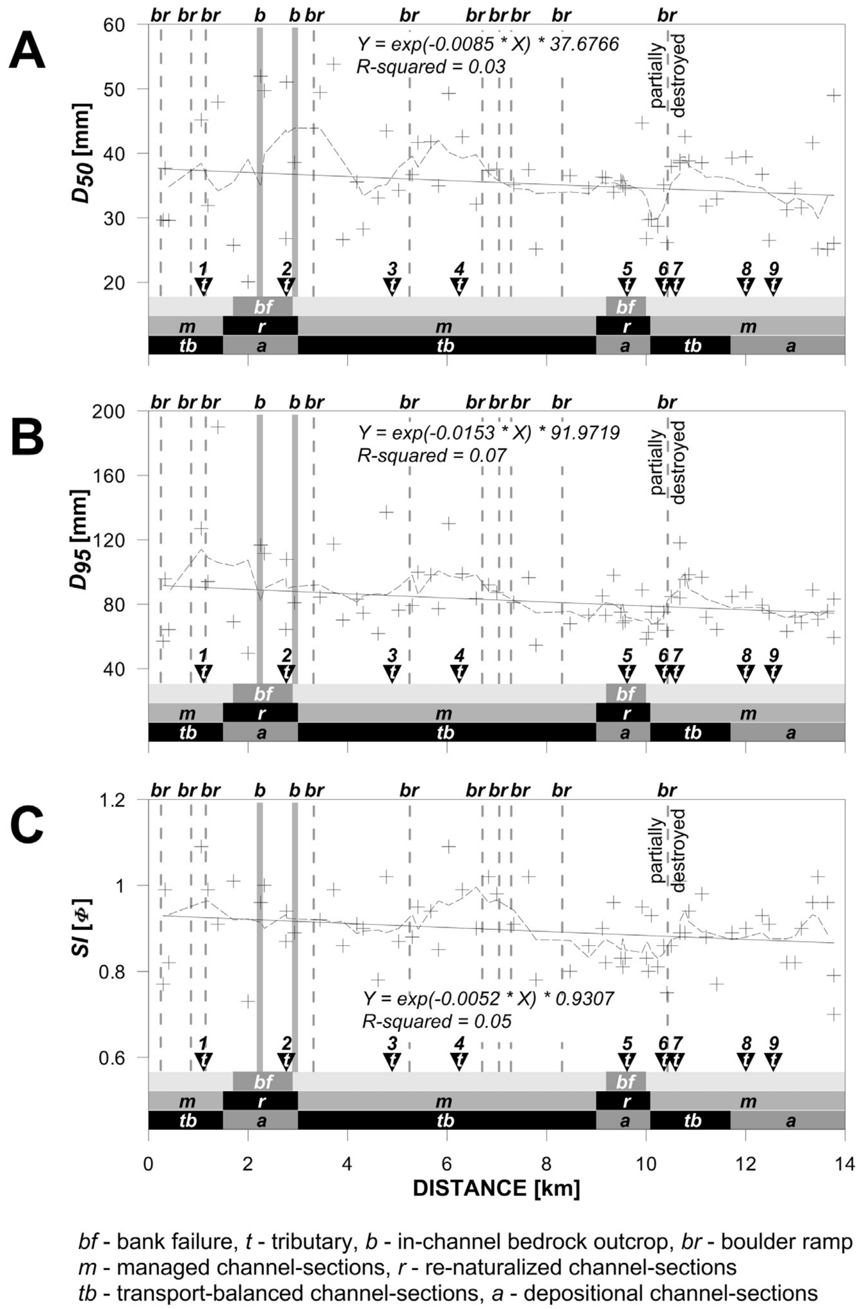


Fig. 5. The downstream variations in (A) D_{50}, (B) D_{95} and (C) *SI* along the Bečva River entire studied reach; solid lines show exponential trends/tendencies and dashed lines show running average of the grain-size parameters of D_{50}, D_{95} and *SI*.

sediment material. The occurrence of large woody debris was observed locally in the re-naturalized river section *D*. Partially, the effect of vegetation succession stabilizing gravel bars was observed in the re-naturalized channel sections.

Along the entire studied reach, the channel bed was formed by gravel-size material. No visible outcrops of bedrock were observed in the channel except in cross-sections at ~2.5 km and at ~3.0 km, where bedrock outcrops of unconsolidated Miocene (Badenian) clays and sands occurred. Except the left-side Juhyně River tributary, other eight short tributaries were observed in the entire studied reach of the Bečva River, which operated as sediment inputs of various grain-size and magnitudes. Based on the field observations, left-side Juhyně River (see tributary number ***1*** in Figs. 4 and 5) and two tributaries (see tributaries number ***7*** and ***9*** in Figs. 4 and 5) were gravel-carrying with developed gravel bed surface layer. Other tributaries (see tributaries number ***2***–***6*** and ***8*** in Figs. 4 and 5) were distinguished as sand-carrying because developed sand bed surface layer was observed.

4.2. Downstream variations in grain-size parameters

Along the entire studied reach, the D_{50} demonstrated a non-significant exponential tendency in downstream fining (see Fig. 5A; $D_{50} = 37.6766e^{-0.0085L}$, $R^2 = 0.03$, $p = 0.17$). It implies that the exponential model produced a very low reduction (fining) coefficient of 0.0085 mm km^{-1}. The exponential model produced a significant trend in D_{95} of downstream fining (see Fig. 5B; $D_{95} = 91.9719e^{-0.0153L}$, $R^2 = 0.07$, $p = 0.03$) and the exponential model gave a reduction (fining) coefficient equal to 0.0153 mm km^{-1}. The disruption of downstream fining in D_{95} was observed at the 1.0–2.0 km (in section *A*), at 5.0–6.5 km (in section *C*) and also at 10.0–10.5 km (in section *E*).

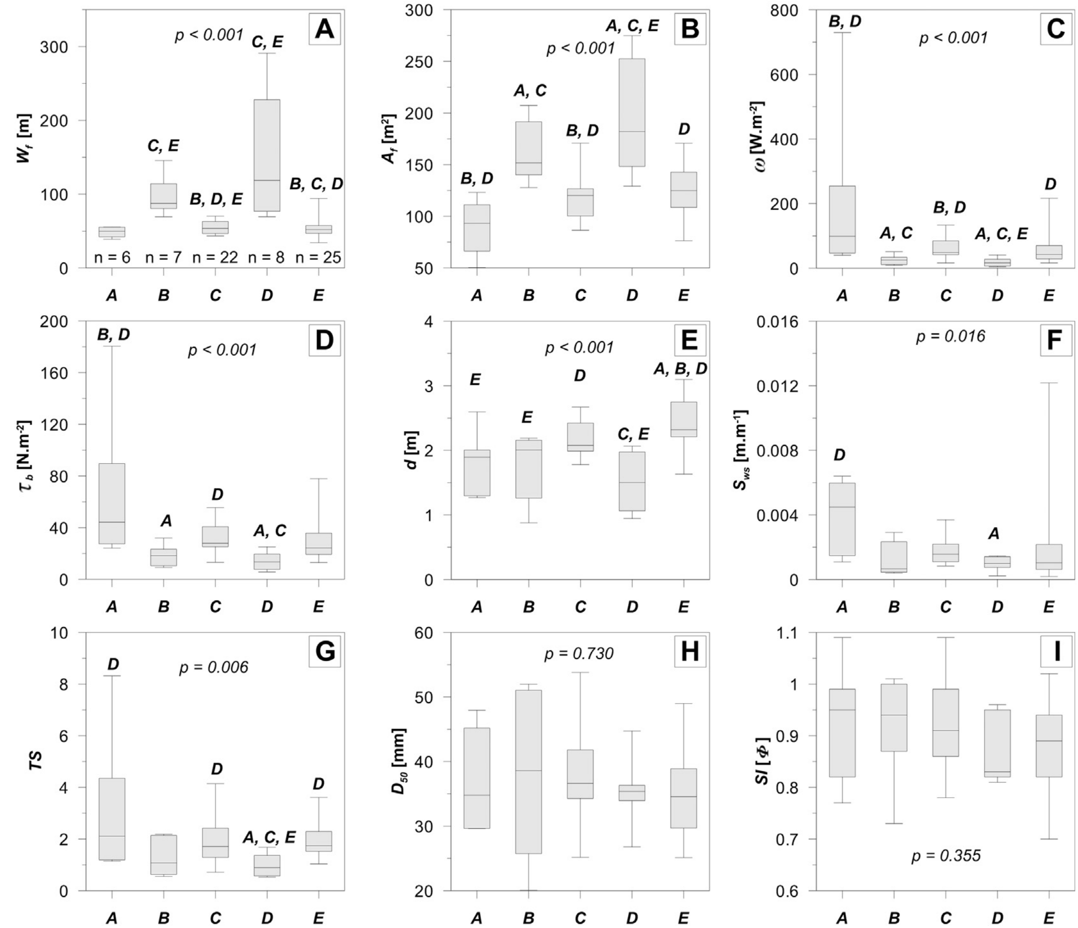


Fig. 6. Boxplots of hydraulic and grain-size parameters of managed channel-sections (*A*, *C* and *E*) and re-naturalized channel-sections (*B* and *D*); letters above boxes show significantly different channel-sections obtained by Kruskal-Wallis test and followed by multiple pairwise comparisons (Dunn's procedure with Bonferroni corrected significance level); the centreline shows the median and the edges of the box represent the first and third quartile.

The non-significant linear tendency in *SI* were observed for the entire studied river reach (see Fig. 5C; $SI = 0.9307e^{-0.0052L}$, $R^2 = 0.05$, $p = 0.07$). According to common classifications (in the sense of Folk and Ward, 1957) of *SI*, gravel bars (where *SI* ranges between 0.7 and 1.1Φ) were moderately or poorly sorted.

4.3. Differences in hydraulic and grain-size variables between managed and re-naturalized channel-sections

Differences in modeled flow hydraulics during 1-year R.I. discharges and obtained grain-size parameters of bars between managed sections (*A*, *C* and *E*) and re-naturalized sections (*B* and *D*) were tested (Fig. 6).

The hydraulic parameter of W_f ($p < 0.001$) reflected that the re-naturalized sections *B* and *D* had larger wetted widths than channelized sections *C* and *E*. In addition, difference in W_f was observed between the channelized sections *C* and *E* where section *E* had wider wetted channel during 1-year R.I. discharge. Additionally, the hydraulic parameter S_{ws} showed the only significant difference between the channelized section *A* and the re-naturalized section *D* where section *A* had higher values of S_{ws} than section *D* ($p = 0.016$). The hydraulic parameter ω ($p < 0.001$) showed the differences, when re-naturalized channel sections *B* and *D* had lower values of the unit stream power than the channelized sections *A* and *C*. Moreover, significant differences were reported between the re-naturalized section *D* and channelized section *E*, when section *D* had lower ω than section *E*. Significant differences between re-naturalized section *D* and channelized sections *A*, *C* and *E* occurred in respect to *TS* parameter ($p = 0.006$). No significant differences in grain-size parameters D_{50} ($p = 0.730$) and *SI* ($p = 0.355$) were found between the re-naturalized and the channelized sections (see Fig. 6H and I).

4.4. Potential relationships between the grain-size and hydraulic variables

Principal components PC1 and PC2 accounted only for 40.4% and 22.8% of the total variance, respectively. The added third component

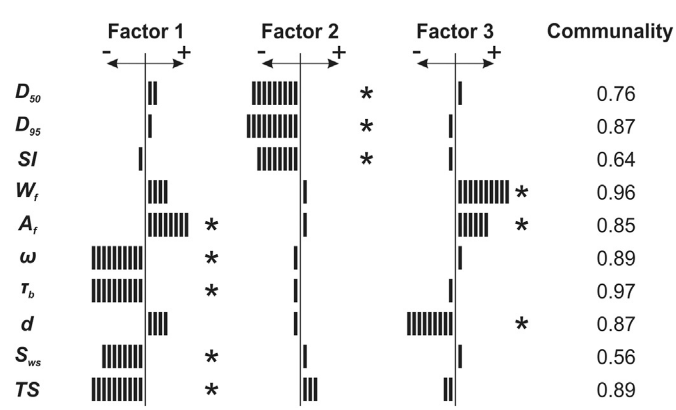


Fig. 7. Bar chart of factor loadings of individual PCs rotation and the communalities of principal components after varimax rotation; significant correlations at $\alpha = 0.05$ are marked by an asterisk (*); D_{50} and D_{95} — 50th and 95th percentile of grain-size parameters, *SI* — sorting index, W_f — wetted channel width, A_f — flow area, ω — unit stream power, τ_b — bed shear stress, *d* — mean depth, S_{ws} — water surface slope, *TS* — transport stage.

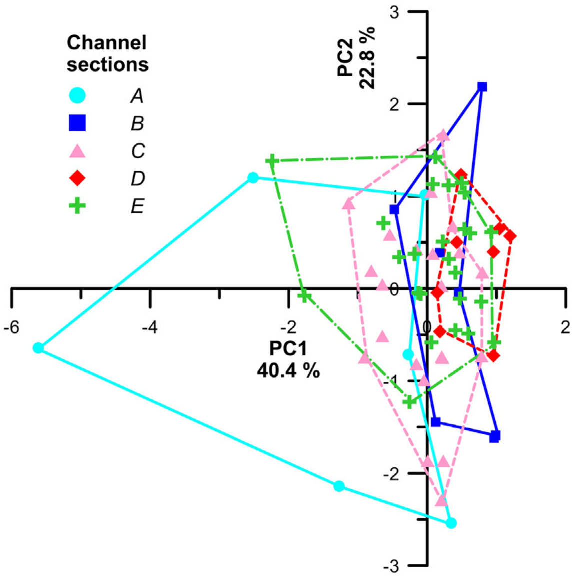


Fig. 8. Plotting of the first two principal components and loadings of individual PCs; designation *A*, *B*, *C*, *D* and *E* is corresponding with designation of channel sections in Fig. 4.

PC3 (19.5%) increased the total communality to 82.7% (Fig. 7). PC1 included hydraulic parameters A_f, ω, τ_b, S_{ws}, and *TS*. The grain-size parameters of D_{50}, D_{95} and *SI* were included in PC2. Principal component PC3 clustered hydraulic parameters W_f, A_f and *d*. W_f and A_f have an inverse relationship with *d* (Fig. 7). It implies that PCA analysis did not demonstrate any clear relationship between the grain-size parameters (D_{50}, D_{95} and *SI* grouped in PC2) and the hydraulic parameters modeled for 1-year R.I. discharge.

We observed some distinctions among the hydraulic variables after plotting the evaluated channel sections, where the x-axis and y-axis are represented by PC1 and PC2 (Fig. 8), respectively. Based on this analysis, the hydraulic parameters (PC1) were more important to distinguish between managed and re-naturalized sections than the grain-size parameters (PC2) while the high downstream variability of the grain-size parameters was observed in PC2 in relative independence on channelized/re-naturalized state of the river.

5. Discussion

The dominant downstream fining trend (in the sense of Sternberg, 1875) of many alluvial rivers is punctuated by positive grain-size steps at coarse-sediment recruitment points such as tributaries, bedrock outcrops or bank failures (Rengers and Wohl, 2007; Rice, 1999; Rice and Church, 1996; Surian, 2002), barriers in sediment flux (Knighton, 1999; Surian, 2002) or changes of channel pattern (Constantine et al., 2003; Zawiejska et al., 2015). Detection of these coarse-sediment recruitment sources and subsequent identification of barriers can help mapping of connectivity in fluvial system, which is necessary for sustainable management of dynamic fluvial systems (e.g., gravel-bed rivers) in cultural landscape (Fryirs, 2013). In the entire studied reach of the Bečva River, the analysis of gradual downstream decrease in bed grain-size produced very low reduction coefficients in D_{50} (non-significant exponential tendency) and D_{95} (significant exponential trend), where the effect of relatively short evaluated longitudinal distance (only 14 km) should also be considered. The better goodness-of-fit between D_{95} and the stream length than for D_{50} was also previously observed by Zawiejska et al. (2015) in a Carpathian gravel-bed river of similar dimensions to our case. The rates of grain-size reduction were relatively similar compared with those reported by other studies of gravel-bed rivers from the Polish and Ukraine Carpathians (see Table 2) reported by Malarz (2004) or Zawiejska et al. (2015). On the other hand, higher rates of reduction were observed in headwater reaches (Galia et al., 2015) and braided reaches (Dawson, 1988; Cowie and Brierley, 2008; Surian, 2002). In these channel patterns, relatively higher bed slope accelerates sediment flux connectivity and produces more intensive abrasion and sorting, which is reflected in rapid downstream fining of bed sediments (Dawson, 1988).

As expected, grain-size parameters in the studied reach did not show a consistent downstream decrease but a much more complex pattern occurred (see in Fig. 5 dashed lines showing running average of the grain-size parameters and in Fig. 6H variation in grain-size parameters for sections *A*–*E*). Similar complex patterns were previously described in other gravel-bed rivers (Dawson, 1988; Surian, 2002). A high

Table 2
Reduction coefficients and basic morphological parameters of (active) channel[a] width and bed slope from field studies in braided, multi-thread and single streams.

River	Reduction coefficient [mm km^{-1}]	Base analysis	Length of study reach [km]	(Active) channel width [m]	Bed slope [m·m^{-1}]	Channel pattern	Reference
Piave River (Italy)	0.027	Mean grain diameter	50	225	0.008	Braided/multiple-thread	Surian (2002)
Ngaruroro River (New Zealand)	0.052	Mean grain diameter	19	50–750	0.005	Braided	Cowie and Brierley (2008)
Sunwapta River (Alberta, Canada)	0.104	Mean grain diameter	11.5	300–500	0.007	Braided	Dawson (1988)
Rio Chagres (Panama)	0.013–0.017	Mean grain diameter	40	20–100[a]	0.009	Multiple-thread/single	Rengers and Wohl (2007)
Rhine River (Switzerland)	0.003–0.016	Largest pebbles	42	85–115	0.003	Multiple-thread	Mikos (1994)
Cosumnes River (California, USA)	0.072	Mean grain diameter	43	10–80	0.001	Multiple-thread	Constantine et al. (2003)
Ringarooma (Tasmania)	0.009–0.015	Mean grain diameter	60	20–200[a]	0.009	Multiple-thread/single	Knighton (1999)
Czarny Dunajec (Poland)	0.012	Mean grain diameter	18	20–120	0.007	Multiple-thread/single	Zawiejska et al. (2015)
Sola River (Poland)	0.032	Largest pebbles	25	50–300[a]	0.002	Multiple-thread/single	Malarz (2004)
Skawa River (Poland)	0.036	Largest pebbles	21	30–150[a]	0.002	Multiple-thread/single	Malarz (2004)
Prut River (Ukraine)	0.015	Largest pebbles	85	150–300[a]	0.002	Multiple-thread	Malarz (2004)
Cheremosh River (Ukraine)	0.010	Largest pebbles	33	200–300[a]	0.003	Multiple-thread	Malarz (2004)
Bečva River (Czech Republic)	0.009–0.015	Mean grain diameter	14	34–291	0.006	Multiple-thread/single	This study
Carpathian headwaters	0.283–0.465	Largest particles	0.63–1.08	1.2–3.8	0.050–0.280	Single	Galia et al. (2015)

[a] (Active) channel width measured using Google Maps (Image © 2018 CNES/Airbus).

occurrence of lateral sediment sources (as tributaries, bank failures) along with sediment disconnectivities in the river reach (as boulder ramps) disrupted downstream fining (see Figs. 4 and 5).

Both river sections *A* (managed) and *B* (re-naturalized) produced a high variability in grain-sizes (see Fig. 5 and Fig. 6H). The role of sediment supply from the major left-side Juhyně River (see tributary number ***1*** in Fig. 5) (in sections *A* and *B*), and partially from bank failures (in section *B*) was reflected in the fluctuations of measured grain-size parameters. Decreased values of the bed slope upstream of three additional highest boulder ramps in section *A* led to the reduction of local stream power and bed shear stress upstream of these ramps, which directly affected the intensity of bedload transport in these locations. The relationship between the presence of grade-control structures and decrease of bedload transport rates in a Carpathian stream via reduced bed slope was documented by Galia et al. (2016), who reported gradual downstream coarsening of bed sediments. Such downstream coarsening through the sequence of check-dams was also previously documented in Mediterranean rivers (Boix-Fayos et al., 2007).

The entire section *C* was affected by channelization and higher values of ω, τ_b and *TS* were observed and compared with the re-naturalized section *D* (Fig. 7). Section *C* was characterized as a transport-balanced section, where deposition processes are limited by higher rate of flow competence. At the uppermost part of this section, the increased rate of flow competence of the regulated channel and only one boulder ramp partially reduced the bed slope, potentially decreasing sediment transport rates. Absence of boulder ramps reduced the bed slope in the middle part of this section *C* and affected disruption of downstream fining where the increased rate of flow competence of the regulated channel was observed. In the downstream part of the channelized section *C*, initial bed slope was reduced by four boulder ramps (6.7, 7.1, 7.3 and 8.3 km) which decrease the potential in sediment flux by decreased rate of flow competence. The river section *D* with large gravel bars developed by re-naturalization processes by 1997 and 2010 floods was predisposed to deposition, the general fining of sediment material and lower values of ω, τ_b or *TS* (Fig. 7) compared with sections *A*, *C* and *E*. The large woody debris observed in the channel of section *D* most likely disrupted sediment flux coming from the downstream part of section *C*. The abrupt local decline in bed grain-sizes may be attributed to the presence of large woody debris, which is in accordance with the works of Beschta (1979) who studied the effect of large woody debris removal on bed grain size, Buffington and Montgomery (1999) who modeled the influence of bank irregularities, large woody debris and gravel bars on sediment fining and Brooks et al. (2004) who monitored bed grain-size changes after the addition of engineered log jams.

Section *E* represented a channelized single channel pattern. The left-side tributary (see tributary number **7** in Fig. 5) and destroyed boulder ramp (at 10.5 km), where the increased rate of flow competence of the regulated channel was assumed, produced occurrence of coarser material in the part downstream from the 10.5 km (see Fig. 5A and B). The difference in W_f was observed between the channelized sections *C* and *E*, where section *E* had larger W_f during 1-year R.I. discharge. Reported hydraulic conditions in section *E* were more prone to deposition than the transport-balanced conditions in sections *C* or *A*. At the lowermost part of section *E*, the deposition was observed in the form of large gravel bars. The high variation in D_{50} (see Fig. 5A) at the lowermost part of section *E* was linked to larger tributaries supplying sediments to the main channel.

Mapping of channel behaviour (transport-balanced and depositional sections) in the studied Bečva River reach corresponded well with the modeled hydraulic variables for 1-year R.I. discharge (see Fig. 6A–G or Fig. 8). In particular, the re-naturalized river sections showed lower values of flow competence (ω, τ_b) and facilitated deposition of sediment material in the form of larger gravel bars compared with the channelized river sections characterized by limited presence of small gravel bars. A similar situation was documented by Czech et al. (2016) on the gravel-bed Biała River (Polish Carpathians) who described that within unmanaged channel reaches the flows can be conveyed with relatively low shear forces in contrast with channelized reaches, where the flow velocity and shear forces are substantially higher.

The wide multi-thread channels with low values of ω and τ_b and high channel-form roughness facilitated sediment deposition and reflected relatively fine grades of sediment (Komar and Carling, 1991; Constantine et al., 2003; Zawiejska et al., 2015; Babej et al., 2016). In contrast, channelized sections (sometimes referred to as conveyor belts) where higher rates of flow competence and low channel-form roughness, facilitated downstream transfer of the bed material (Komar and Carling, 1991; Fryirs et al., 2007; Zawiejska et al., 2015). The assessment of potential correlations between the grain-size and hydraulic variables modeled for 1-year R.I. discharge in the Bečva River did not demonstrate any clear relationships. The PCA analysis clustered the hydraulic variables in the first and third component and the grain-size parameters in the second component. Rice and Church (2010) documented that single bed material samples cannot be representative of the grain-sizes apparent on a bar or across a channel width because high local variability of sediment sizes. But in the case of the Bečva River and in another Carpathian gravel bed river Czarny Dunajec of similar dimensions (Zawiejska et al., 2015), this local variability is low. Despite the occurrence of re-naturalized channel sections in the Bečva and the Czarny Dunajec, their channels are relatively stable, much narrower, and the elevations between the channel bed and top of the gravel bars are lower (in the Bečva River channel max. ~2 m) by contrast to the braided, very dynamic Fraser River where Rice and Church (2010) performed their research. Additional question arises which parameters of grain-size distribution (ranging from the median D_{50} to the 95th percentile D_{95}) are suitable for the assessment of flow competence. The use of largest particles on the upper tail of the grain-size curve has potential uncertainties. It may be difficult to recognize the largest particles within the flood deposits, and there are questions concerning how representative one or a few large particles might be of the transported sediments and therefore of the flood hydraulics. However, the analysis of Komar and Carling (1991) showed that the trend of increasing sizes of the largest particles in the bed sediment with increasing flow competence is consistent within interval D_{50}–D_{95}.

Limits concerning the hydraulic modeling are mainly connected with the model selection, accuracy of digital elevation model together with resolution of bathymetry obtained from geodetically surveyed cross-section, as well as with the boundary conditions and model calibration (Ferguson and Church, 2009). Also typically, 1D hydrodynamic models are used as 1D representation of the main channel and 2D representation of the floodplain (Vojinovic and Tutulic, 2009). Crowder and Diplas (2000) or Benjankar et al. (2015) stated that 1D model may be sufficient for a study requiring only a description of the general flow patterns (e.g. flow depth, water surface elevation) at a macro-spatial scale similar to our case. Furthermore, based on another factors such as available input data, model set-up and computational time results obtained by 1D model HEC-RAS are reliable and sufficiently accurate (Horritt and Bates, 2002; Ferguson and Church, 2009). Jowett and Duncan (2012) and Dimitriadis et al. (2016) applied 1D and 2D model to braided and single channel rivers, respectively. They compared measured and predicted hydraulic parameters (e.g., water depths and velocities) and suggest that the differences in predicted hydraulic variables between 1D and 2D modeling approach are within units of percent.

Following the results of Casas et al. (2006), combination of geodetically surveyed cross-sections and LiDAR are cost-effective tools for developing of a digital elevation model and possible errors in simulated hydraulic variables are sufficiently low. There remain uncertainties in the calibrated uniform Manning's values in single cross-section. More detailed calibration data from gauging stations, hydrometric measurements, aerial photos of flooded area or wreck marks elevations measurement would reduce uncertainty inherent in the calibration procedure and supplied uniform Manning's value, but at the expanse of high economical and time requirements. The similar approach of uniform values was applied in the study of Ferguson and Church (2009) who simulate gravel transport and aggradation along a highly irregular 38-km reach of lower Fraser River.

The one of the main factors affecting potential relationships between the hydraulic and grain-size variables was the short length of studied reach where high occurrence of lateral sediment sources with sediment disconnectivities in the longitudinal river reach was observed and grain-size parameters did not reflect hydraulic conditions. The frequent occurrence of lateral sediment inputs with sediment disconnectivities created no differences in D_{50} and *SI* ($p = 0.355$) between the re-naturalized and the channelized sections (Fig. 6H and I) and high downstream variability of the grain-size parameters observed in PC2 (see Fig. 8). It implies that sediment inputs and longitudinal disconnectivities provided better explanation of the grain-size patterns along the studied Bečva River reach than hydraulic conditions calculated for 1 to 2-year R.I. discharge. The downstream variations in bed material through identification of disconnectivities and sediment inputs were comprehensively described by Surian (2002). He explained that a regular downstream fining pattern was observable only in those reaches of 120-km examined length of the Piave River, where infrequent lateral sediment inputs and the barriers had minor effects on the resulting bed grain sizes. Similarly, Rice and Church (1998) documented that identification of sediment inputs were fundamental for understanding bed sediment grain-size variations within the studied length of the gravel-bed Pine and Sukunka Rivers in British Columbia. In the Bečva River studied reach, some tributaries caused local coarsening of the bar grain-sizes which interrupted downstream fining trend (see tributary numbers ***1*** and ***7*** in Fig. 5). Benda et al. (2004) studied the role of tributaries on downstream fining in main-stem river channels. They found that a higher probability of significant effect on changing grain-size in main-stem channel had tributaries with dendritic channel network compared to rectangular or trellis channel networks with lower significant effect. These findings support conclusion that the tributaries of the Bečva River affected significantly change in the grain-sizes because feather-like or dendritic channel network of these tributaries were documented here by Ivan et al. (2000). Benda et al. (2004) and Rice (1998) also discussed the importance of tributaries in resetting geomorphic and sedimentary characteristics and the effect of tributaries on morphological heterogeneity. The local coarsening was also observed in the regulated channel reaches where the increased rate of flow competence was assumed and the grade control structures (boulder ramps or weirs) were missing. Additional factors as sediment inputs from bank failures as well as sediment flux disconnectivities caused by boulder ramps, weirs and partially large woody debris or vegetation succession produced less significant changes in the bar grain size in the Bečva River reach. In future, more detailed research will be necessary to explain and identify effect of vegetation and woody debris on bar material stabilization, e.g. by the analysis of time-lapse aerial photos or detailed repeated mapping.

Reversal re-naturalization of gravel-bed channelized reaches to multi-thread pattern helps to progressive improvement of the condition for aquatic and riparian communities (Wyżga et al., 2018). In the multi-thread channel, lower transport capacity affects deposition and fining of bed sediments in contrast to channelized reaches with higher transport capacity, coarsening of bed sediment and incision or lateral erosion processes (Zawiejska et al., 2015). Multi-thread gravel bed channels are dependent on supply of larger volumes of coarse sediments which are deposited in channel in the form of gravel bars (Gurnell et al., 2009). Therefore, identification and mapping of sediment inputs and disconnectivities are necessary for future possibilities of restoration, natural spontaneous or reversal re-naturalization of these types of river channels.

6. Conclusions

In the past few centuries, European multi-thread gravel-bed rivers have undergone rapid changes induced by human activities. These alterations resulted in changes to channel morphologies and flow hydraulics. Similar trends are apparent in the Bečva River, where an original multi-thread river channel pattern was converted into a uniform single-channel. As a consequence of river management of multi-thread gravel-bed rivers, including our studied case, channels were typically incised several meters into the floodplain (Škarpich et al., 2013; Zawiejska and Wyżga, 2010; Wyżga, 2001). However, within the studied reach of the Bečva River, the multi-thread channel pattern has retrogradually developed after two large floods (1997 and 2010) in two sections.

The mapping of sediment (dis)connectivity brought important findings about the character of sediment flux in the studied reach, which were confronted with simulated cross-sectional hydraulics. We demonstrated that in the case of a high occurrence of lateral sediment inputs (tributaries, bank failures) and longitudinal sediment flux disconnectivities (weirs or boulder ramps), the assessment of the longitudinal distance, bar grain size and simulated hydraulics submerging bars did not produce any clear relationships. Although the sections with re-naturalized multi-thread patterns showed distinctive hydraulic variables (i.e., larger wetted width or lower unit stream power), we did not observe direct relationships with their bar sediment sizes. This implies that for complex fluvial systems of multi-thread rivers as the transition reaches connecting mountainous and lowland areas, even those in unconfined valley settings out of the primary sediment sources, additional factors (i.e., effect of bank failures and especially tributaries as sediment inputs, weirs or boulder ramps as sediment flux disconnectivities) beyond local flow hydraulics and distance from the main sediment sources contribute to better explanation of the downstream evolution of grain-size patterns. Especially tributaries reset the sedimentary characteristics of the main-stem Bečva River. It implies that detailed mapping of sediment (dis)connectivity at basin scale (or at least at reach scale) including particular elements of sediment flux is crucial for sustainable management of gravel-bed rivers. The explanations of the bar-scale variability in relatively narrow gravel bed rivers (e.g. managed Flysch Carpathian Rivers) will be necessary for the identification of simple predictive models in the context of channel morphology and hydraulic parameters.

Acknowledgements

The authors sincerely appreciate the comments and suggestions of the four anonymous reviewers leading to a significant improvement of the manuscript. The study was funded by the Student grant competition of the University of Ostrava [SGS05/PřF/2017-2018] and Specific Research project MUNI/A/1251/2017 of the Masaryk University.

References

Andrews, E.D., 1983. Entrainment of gravel from naturally sorted riverbed material. GSA Bull. 94 (10), 1225–1231. https://doi.org/10.1130/0016-7606(1983)94<1225:EOGFNS>2.0.CO;2.

Babej, J., Máčka, Z., Onderka, P., Peterová, P., 2016. Surface grain size variation within gravel bars: a case study of the River Opava, Czech Republic. Geogr. Fis. Din. Quat. 39 (1), 3–12. https://doi.org/10.4461/GFDQ.2016.39.1.

Bagnold, R.A., 1966. An approach to the sediment transport problem from general physics. United States Department of the Interior, U.S. Geological Survey, Professional Paper 422-I.

Benda, L., Andras, K., Miller, D., Bigelow, P., 2004. Confluence effects in rivers: interactions of basin scale, network geometry, and disturbance regimes. Water Resour. Res. 40, W05402. https://doi.org/10.1029/2003WR002583.

Benjankar, R., Tonina, D., McKean, J., 2015. One-dimensional and two-dimensional hydrodynamic modeling derived flow properties: impacts on aquatic habitat quality predictions. Earth Surf. Process. Landf. 40 (3), 340–356. https://doi.org/10.1002/esp.3637.

Beschta, R.L., 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Sci. 53 (1), 71–77.

Boix-Fayos, C., Barberá, G.G., López-Bermúdez, F., Castillo, V.M., 2007. Effects of check dams, reforestation and land-use changes on river channel morphology: case study of the Rogativa catchment (Murcia, Spain). Geomorphology 91, 103–123. https://doi.org/10.1016/j.geomorph.2007.02.003.
Brierley, G.J., Fryirs, K., Jain, V., 2006. Landscape connectivity: the geographic basis of geomorphic applications. Area 38 (2), 165–174. https://doi.org/10.1111/j.1475-4762.2006.00671.x.
Brooks, A.P., Gehrke, P.C., Jansen, J.D., Abbe, T.B., 2004. Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic and ecological responses. River Res. Appl. 20 (5), 513–536. https://doi.org/10.1002/rra.764.
Buffington, J.M., Montgomery, D.R., 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resour. Res. 33 (8), 1993–2029. https://doi.org/10.1029/96WR03190.
Buffington, J.M., Montgomery, D.R., 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resour. Res. 35 (11), 3507–3521. https://doi.org/10.1029/1999WR900138.
Buttle, J.M., Allen, D.M., Caissie, D., Davison, B., Hayashi, M., Peters, D.L., Pomeroy, J.W., Simonovic, S., St-Hilaire, A., Whitfield, P.H., 2016. Flood processes in Canada: regional and special aspects. Can. Water Resour. J. 41 (1–2), 7–30. https://doi.org/10.1080/07011784.2015.1131629.
Casas, A., Benito, G., Thorndycraft, V.R., Rico, M., 2006. The topographic data source of digital terrain models as a key element in the accuracy of hydraulic flood modelling. Earth Surf. Process. Landf. 31 (4), 444–456. https://doi.org/10.1002/esp.1278.
Chloupkova, J., 2002. Czech agricultural sector: organisational structure and its transformation. Unit of Economics Working Papers 2002/1. Institute of Food and Resource Economics, University of Copenhagen, Copenhagen, Denmark.
Chlupáč, I., Brzobohatý, R., Kovanda, J., Stráník, Z., 2011. Geologická minulost České republiky, revisited. second ed. Academia, Praha (in Czech with English summary).
Constantine, C.R., Mount, J.F., Florsheim, J.L., 2003. The effects of longitudinal differences in gravel mobility on the downstream fining pattern in the Cosumnes River, California. J. Geol. 111, 233–241. https://doi.org/10.1086/345844.
Cowie, M., Brierley, G., 2008. The influence of lateral confinement upon the downstream gradation in grain size of the lower Ngaruroro River, New Zealand. Open Geol. J. 2, 46–63. https://doi.org/10.2174/1874262900802010046.
Crowder, D.W., Diplas, P., 2000. Using two-dimensional hydrodynamic models at scales of ecological importance. J. Hydrol. 230, 172–191. https://doi.org/10.1016/S0022-1694(00)00177-3.
Czech, W., Radecki-Pawlik, A., Wyżga, B., Hajdukiewicz, H., 2016. Modelling the flooding capacity of a Polish Carpathian river: a comparison of constrained and free channel conditions. Geomorphology 272, 32–42. https://doi.org/10.1016/j.geomorph.2015.09.025.
Czudek, T., 2005. Quaternary Development of Landscape Relief in the Czech Republic. The Moravian Museum, Brno (in Czech, with English summary).
Dawson, M., 1988. Sediment size variation in a braided reach of the Sunwapta River, Alberta, Canada. Earth Surf. Process. Landf. 13, 599–618. https://doi.org/10.1002/esp.3290130705.
Dimitriadis, P., Tegos, A., Oikonomou, A., Pagana, V., Koukouvinos, A., Mamassis, N., Koutsoyiannis, D., Efstratiadis, A., 2016. Comparative evaluation of 1D and quasi-2D hydraulic models based on benchmark and real-world applications for uncertainty assessment in flood mapping. J. Hydrol. 534, 478–492. https://doi.org/10.1016/j.jhydrol.2016.01.020.
Dvořák, J., Stráník, Z., Tyráček, J., 2001. Geologická mapa, list 25-14 Valašské Meziříčí. Czech Geological Survey (in Czech).
Ehlers, J., Gibbard, P.L., 2004. Quaternary Glaciations — Extent and Chronology: Part I: Europe. Elsevier, Amsterdam.
Ferguson, R., Church, M., 2009. A critical perspective on 1-D modeling of river processes: gravel load and aggradation in lower Fraser River. Water Resour. Res. 45, W11424. https://doi.org/10.1029/2009WR007740.
Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. J. Sediment. Petrol. 27, 3–26. https://doi.org/10.1306/74D70646-2B21-11D7-8648000102C1865D.
Fryirs, K., 2013. (Dis)connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Process. Landf. 38, 30–46. https://doi.org/10.1002/esp.3242.
Fryirs, K., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers and blankets: the (dis)connectivity of catchment-scale sediment cascades. Catena 70, 49–67. https://doi.org/10.1016/j.catena.2006.07.007.
Galia, T., Škarpich, V., 2016. Do the coarsest bed fraction and stream power record contemporary trends in steep headwater channels? Geomorphology 272, 115–126. https://doi.org/10.1016/j.geomorph.2015.07.047.
Galia, T., Škarpich, V., Hradecký, J., 2015. Connectivity of the coarsest fraction in headwater channels: imprints of fluvial processes and debris-flow activity. Geogr. Ann. Ser. A Phys. Geogr. 97, 437–452. https://doi.org/10.1111/geoa.12086.
Galia, T., Škarpich, V., Přibyla, Z., Hradecký, J., 2016. Effect of grade-control structures at various stages of their destruction on local channel parameters. Geomorphology 253, 305–317. https://doi.org/10.1016/j.geomorph.2015.10.033.
Gomez, B., 1995. Bedload transport and changing grain size distributions. In: Gurnell, A., Petts, G. (Eds.), Changing River Channels. John Wiley, New York, pp. 177–199.
Gomez, B., Rosser, B.J., Peacock, D.H., Hicks, D.M., Palmer, J.A., 2001. Downstream fining in a rapidly aggrading gravel bed river. Water Resour. Res. 37 (6), 1813–1823. https://doi.org/10.1029/2001WR900007.
Graham, D.J., Rice, S.P., Reid, I., 2005a. A transferable method for the automated grain sizing of river gravels. Water Resour. Res. 41, W07020. https://doi.org/10.1029/2004WR003868.
Graham, D.J., Reid, I., Rice, S., P., 2005b. Automated sizing of coarse-grained sediments: image-processing procedures. Math. Geol. 37 (1), 1–28. https://doi.org/10.1007/s11004-005-8745-x.
Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79, 172–191. https://doi.org/10.1016/j.geomorph.2006.06.018.
Gurnell, A., Surian, N., Zanoni, L., 2009. Multi-thread river channels: a perspective on changing European alpine river systems. Aquat. Sci. 71, 253–265. https://doi.org/10.1007/s00027-009-9186-2.
Havlík, A., 1999. Pilotní projekt Spojená Bečva — studie. Revital — inženýrská a projekční kancelář, Praha (in Czech).
Hooke, J.M., 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. Geomorphology 56, 79–94. https://doi.org/10.1016/S0169-555X(03)00047-3.
Horritt, M.S., Bates, P.D., 2002. Evaluation of 1D and 2D numerical models for predicting river flood inundation. J. Hydrol. 268, 87–99. https://doi.org/10.1016/S0022-1694(02)00121-X.
Hrádek, M., 2000. Geomorphic effect of the July 1997 flood in the North Moravia and Silesia (Czech Republic). Geogr. Časopis 52, 303–321 (in Czech with English summary).
Ivan, A., Kirchner, K., Krejčí, O., 2000. The morphostructural features of the Moravian part of the Western Carpathians and Pannonian Basin. Geogr. Časopis 52 (3), 221–230 (in Czech with English summary).
Jowett, I.G., Duncan, M.J., 2012. Effectiveness of 1D and 2D hydraulic models for instream habitat analysis in a braided river. Ecol. Eng. 48, 92–100. https://doi.org/10.1016/j.ecoleng.2011.06.036.
Kaiser, H.F., 1958. The varimax criterion for analytic rotation in factor analysis. Psychometrika 23 (3), 187–200. https://doi.org/10.1007/BF02289233.
Knighton, A.D., 1980. Longitudinal changes in size and sorting of stream-bed material in four English rivers. Geol. Soc. Am. Bull. 91, 55–62. https://doi.org/10.1130/0016-7606(1980)91<55:LCISAS>2.0.CO;2.
Knighton, A.D., 1999. The gravel–sand transition in a disturbed catchment. Geomorphology 27, 325–341. https://doi.org/10.1016/S0169-555X(98)00078-6.
Komar, P.D., Carling, P.A., 1991. Grain sorting in gravel-bed streams and the choice of particle sizes for flow-competence evaluations. Sedimentology 38 (3), 489–502. https://doi.org/10.1111/j.1365-3091.1991.tb00363.x.
Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. Environ. Manag. 21, 533–551. https://doi.org/10.1007/s002679900048.
Kondolf, G.M., Piégay, H., Landon, N., 2002. Channel response to increased and decreased bedload supply from land use change: contrast between two catchments. Geomorphology 45, 35–51. https://doi.org/10.1016/S0169-555X(01)00188-X.
Korpak, J., 2007. The influence of river training on mountain channel changes (Polish Carpathian Mountains). Geomorphology 92, 166–181. https://doi.org/10.1016/j.geomorph.2006.07.037.
Krapesch, G., Hauer, C., Habersack, H., 2011. Scale orientated analysis of river width changes due to extreme flood hazards. Nat. Hazards Earth Syst. Sci. 11, 2137–2147. https://doi.org/10.5194/nhess-11-2137-2011.
Krejčí, L., Krejčí, M., 2012. Živá Bečva – cesta z regulace. Vodní Hospodářství 62 (12), 358–390 (in Czech with English summary).
Lamb, M., Dietrich, W., Venditti, J., 2008. Is the critical shear stress of incipient sediment motion dependent on channel-bed slope? J. Geophys. Res. Earth Surf. 113. https://doi.org/10.1029/2007JF000831.
Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France. Earth Surf. Process. Landf. 27, 425–444. https://doi.org/10.1002/esp.328.
Macoun, J., Šibrava, V., Tyráček, J., Kneblová-Vodičková, V., 1965. Kvartér Ostravska a Moravské Brány. Nakladatelství ČSAV, Praha.
Madej, M.A., 1995. Changes in channel-stored sediment, Redwood Creek, northwestern California. US Geological Survey Professional Paper 1454-P.
Magilligan, F.J., 1992. Thresholds and the spatial variability of flood power during extreme floods. Geomorphology 5, 373–390. https://doi.org/10.1016/0169-555X(92)90014-F.
Malarz, R., 2004. The rate of gravel abrasion in the Carpathian rivers. Geogr. Časopis 56, 99–109.
Martín-Vide, J., Ferrer-Boix, C., Ollero, A., 2010. Incision due to gravel mining: modelling a case study from the Gállego River, Spain. Geomorphology 117, 261–271. https://doi.org/10.1016/j.geomorph.2009.01.019.
Menčík, E., Adamová, M., Dvořák, J., Dudek, A., Jetel, J., Jurková, A., Hanzlíková, E., Houša, V., Peslová, H., Rybářová, L., Šmíd, B., Šebesta, J., Tyřáček, J., Vašíček, Z., 1983. Geologie Moravskoslezských Beskyd a Podbeskydské pahorkatiny (Geology of the Moravskoslezské Beskydy Mts and Podbeskydská pahorkatina Hilly land). ÚÚV v nakladatelství ČSAV, Praha (in Czech, with English summary).
Mihola, L., 1992. 100 let úprav řeky Bečvy. Vodní hospodářství 2, 90–93 (in Czech with English summary).
Mikos, M., 1994. The downstream fining of gravel-bed sediments in the Alpine Rhine River. In: Ergenzinger, P., Schmidt, K.H. (Eds.), Dynamics and Geomorphology of Mountains Rivers. Springer, Berlin, pp. 93–108.
Nardi, L., Rinaldi, M., 2015. Spatio-temporal patterns of channel changes in response to a major flood event: the case of the Magra River (central-northern Italy). Earth Surf. Process. Landf. 40, 326–339. https://doi.org/10.1002/esp.3636.
Ondráčková, L., Máčka, Z., 2018. Geomorphic (dis)connectivity in a middle-mountain context: human interventions in the landscape modify catchment-scale sediment cascades. Area https://doi.org/10.1111/area.12424.
Parker, G., 1990. Surface-based bedload transport relation for gravel rivers. J. Hydraul. Res. 28, 417–436. https://doi.org/10.1080/00221689009499058.
Parker, G., Clifford, N.J., Thorne, C.R., 2011. Understanding the influence of slope on the threshold of coarse grain motion: revisiting critical stream power. Geomorphology 126, 51–65. https://doi.org/10.1016/j.geomorph.2010.10.027.
Pasternack, G.B., Gilbert, A.T., Wheaton, J.M., Buckland, E.M., 2006. Error propagation for velocity and shear stress prediction using 2D models for environmental management. J. Hydrol. 328, 227–241. https://doi.org/10.1016/j.jhydrol.2005.12.003.

Pavelka, J., Trezner, J., 2001. Příroda Valašska: okres Vsetín. Český svaz ochránců přírody ZO 76/06 Orchidea, Vsetín (in Czech).

Powell, D.M., 1998. Patterns and processes of sediment sorting in gravel-bed rivers. Prog. Phys. Geogr. 22, 1–32. https://doi.org/10.1191/030913398666402127.

Preciso, E., Salemi, E., Billi, P., 2012. Land use changes, torrent control works and sediment mining: effects on channel morphology and sediment flux, case study of the Reno River (Northern Italy). Hydrol. Process. 26, 1134–1148. https://doi.org/10.1002/hyp.8202.

Pregun, C.Z., 2016. Ecohydrological and morphological relationships of a regulated lowland river; based on field studies and hydrological modeling. Ecol. Eng. 94, 608–616. https://doi.org/10.1016/j.ecoleng.2016.06.125.

Punys, P., Adamonyte, I., Kvaraciejus, A., Martinaitis, E., Vyciene, G., Kasiulis, E., 2015. Riverine hydrokinetic resource assessment — a case study of a lowland river in Lithuania. Renew. Sust. Energ. Rev. 50, 643–652. https://doi.org/10.1016/j.rser.2015.04.155.

Rengers, F., Wohl, E., 2007. Trends of grain sizes on gravel bars in the Rio Chagres, Panama. Geomorphology 83, 282–293. https://doi.org/10.1016/j.geomorph.2006.02.019.

Rice, S., 1998. Which tributaries disrupt downstream fining along gravel-bed rivers? Geomorphology 22, 39–56. https://doi.org/10.1016/S0169-555X(97)00052-4.

Rice, S., 1999. The nature and controls on downstream fining within sedimentary links. J. Sediment. Res. 69 (1), 32–39. https://doi.org/10.1306/D426895F-2B26-11D7-8648000102C1865D.

Rice, S., Church, M., 1996. Bed material texture on low order streams in the Queen Charlotte Islands, British Columbia. Earth Surf. Process. Landf. 21, 1–18. https://doi.org/10.1002/(SICI)1096-9837(199601)21:1<1::AID-ESP506>3.0.CO;2-F.

Rice, S., Church, M., 1998. Grain-size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. Earth Surf. Process. Landf. 23, 345–363. https://doi.org/10.1002/(SICI)1096-9837(199804)23:4<345::AID-ESP850>3.0.CO;2-B.

Rice, S., Church, M., 2010. Grain-size sorting within river bars in relation to downstream fining along a wandering channel. Sedimentology 57, 232–251. https://doi.org/10.1111/j.1365-3091.2009.01108.x.

Rinaldi, M., Wyżga, B., Surian, N., 2005. Sediment mining in alluvial channels: physical effects and management perspectives. River Res. Appl. 21, 805–828. https://doi.org/10.1002/rra.884.

Rovira, A., Batalla, R.J., Sala, M., 2005. Response of river sediment budget after historical gravel mining (the lower Tordera, NE Spain). River Res. Appl. 21, 829–847. https://doi.org/10.1002/rra.885.

Russell, D.R., 1939. Effects of transportation on sedimentary particles. In: Trask, P.D. (Ed.), Recent Marine Sediments. AAPG, Tulsa, Oklahoma, pp. 33–47.

Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York.

Shields, A., 1936. Anwendung der aÈhnlichkeitsmechanik und der turbulenzforschung auf die geschiebebewegung. Mitteilung der Preussischen versuchsanstalt fuer Wasserbau und Schiffbau Heft 26 Berlin (trans. Ott, W.P. and van Uchlen, J.C., Pasadena, CA: United States Department of Agriculture, Soil Conservation Service, Coop Lab., California Institute of Technology).

Škarpich, V., Hradecký, J., Dušek, R., 2013. Complex transformation of the geomorphic regime of channels in the forefield of the Moravskoslezské Beskydy Mts: case study of the Morávka River (Czech Republic). Catena 111, 25–40. https://doi.org/10.1016/j.catena.2013.06.028.

Škarpich, V., Galia, T., Hradecký, J., 2016a. Channel bed adjustment to over bankfull discharge magnitudes of the flysch gravel-bed stream — case study from the channelized reach of Olše River (Czech Republic). Z. Geomorphol. 60 (4), 327–341. https://doi.org/10.1127/zfg/2016/0395.

Škarpich, V., Kašpárek, Z., Galia, T., Hradecký, J., 2016b. Anthropogenic impact and morphology channel response of Beskydian gravel-bed rivers: a case study of the Ostravice River, Czechia. Geografie 121, 99–120.

Song, S., Schmalz, B., Fohrer, N., 2015. Simulation, quantification and comparison of in-channel and floodplain sediment processes in a lowland area — a case study of the Upper Stör catchment in northern Germany. Ecol. Indic. 57, 118–127. https://doi.org/10.1016/j.ecolind.2015.03.030.

Stacke, V., Pánek, T., Sedláček, J., 2014. Late Holocene evolution of the Bečva River floodplain (Outer Western Carpathians, Czech Republic). Geomorphology 206, 440–451. https://doi.org/10.1016/j.geomorph.2013.10.015.

Sternberg, H., 1875. Über Längen- und Querprofil geschiebeführender Flüsse. Zeitschr. Bauw. 25, 483–506.

Surian, N., 2002. Downstream variation in grain size along an Alpine river: analysis of controls and processes. Geomorphology 43, 137–149. https://doi.org/10.1016/S0169-555X(01)00127-1.

Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326. https://doi.org/10.1016/S0169-555X(02)00219-2.

Uribelarrea, D., Pérez-González, A., Benito, G., 2003. Channel changes in the Jarama and Tagus rivers (central Spain) over the past 500 years. Quat. Sci. Rev. 22, 2209–2221. https://doi.org/10.1016/S0277-3791(03)00153-7.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37 (1), 130–137. https://doi.org/10.1139/f80-017.

Vojinovic, Z., Tutulic, D., 2009. On the use of 1D and coupled 1D-2D modelling approaches for assessment of flood damage in urban areas. Urban Water J. 6 (3), 183–199. https://doi.org/10.1080/15730620802566877.

Wilcock, P.R., 1992. Experimental investigation of the effects of mixture properties on transport dynamics. In: Billi, P., Hey, R.D., Thorne, C.R., Tacconi, P. (Eds.), Dynamics of Gravel-bed Rivers. John Wiley, New York, pp. 109–131.

Wilcock, P.R., McArdell, B.W., 1993. Surface-based fractional transport rates: mobilization thresholds and partial transport of a sand-gravel sediment. Water Resour. Res. 29, 1297–1312. https://doi.org/10.1029/92WR02748.

Wolman, M.G., 1954. Method of sampling coarse river-bed material. EOS Trans. Am. Geophys. Union 35 (6), 951–956. https://doi.org/10.1029/TR035i006p00951.

Wyżga, B., 1993. River response to channel regulation: case study of the Raba River, Carpathians, Poland. Earth Surf. Process. Landf. 18, 541–556. https://doi.org/10.1002/esp.3290180607.

Wyżga, B., 2001. Impact of the channelization-induced incision of the Skawa and Wisłoka Rivers, Southern Poland, on the conditions of overbank deposition. Regul. Rivers Res. Manag. 17, 85–100. https://doi.org/10.1002/1099-1646(200101/02)17:1<85::AID-RRR605>3.0.CO;2-U.

Wyżga, B., Zawiejska, J., Gurnell, A., 2018. Effects and persistence of river restoration measures: ecological, management and research implications. Sci. Total Environ. 628–629, 1098–1100. https://doi.org/10.1016/j.scitotenv.2018.02.071.

Zawiejska, J., Wyżga, B., 2010. Twentieth-century channel change on the Dunajec River, southern Poland: patterns, causes and controls. Geomorphology 117, 234–246. https://doi.org/10.1016/j.geomorph.2009.01.014.

Zawiejska, J., Wyżga, B., Radecki-Pawlik, A., 2015. Variation in surface bed material along a mountain river modified by gravel extraction and channelization, the Czarny Dunajec, Polish Carpathians. Geomorphology 231, 353–366. https://doi.org/10.1016/j.geomorph.2014.12.026.