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Changes in the hydrodynamics of a mountain river induced by dam reservoir backwater

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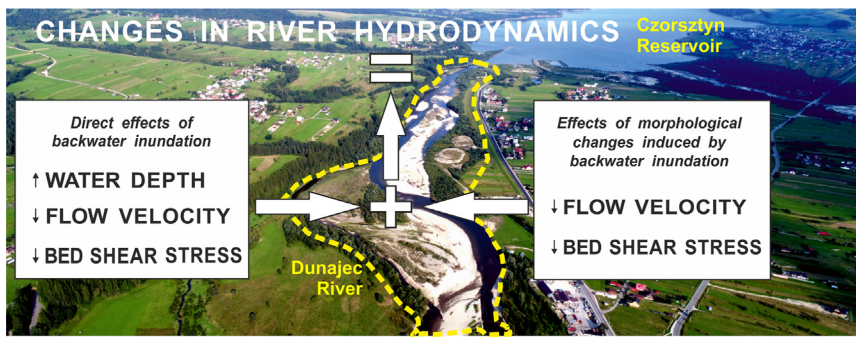
HIGHLIGHTS

- Effects of backwater inundation on river hydrodynamics upstream from dam reservoir were investigated.
- Hydraulic modelling of flood flows in backwater and control reaches and with/without backwater inundation was performed.
- Backwater inundation increases water depth and decreases velocity and bed shear stress of the channel and floodplain flows.
- Backwater-induced morphological river changes additionally modify river hydrodynamics.
- Conceptual model of hydrodynamics–morphology adjustments downstream and upstream of a dam reservoir was presented.

GRAPHICAL ABSTRACT



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ABSTRACT

Upstream from a dam reservoir, river hydrodynamics may be directly changed by temporary inundation driven by the reservoir. This triggers morphological river changes which may additionally modify the initial hydrodynamics, even at the time when backwater inundation does not occur (indirect effects of backwater). We verified these hypotheses, applying two-dimensional hydraulic modelling of flood flows to a section of the mountainous Dunajec River upstream from the Czorsztyn Reservoir. The modelling was performed for small, medium and large floods, and hydraulic conditions were compared between the scenarios with lacking and maximum backwater inundation and between the river reaches subjected to backwater inundation and unaffected by backwater fluctuations. Direct effects of reservoir level fluctuations were limited to the reach subjected to backwater inundation during floods and comprised: significantly increased water depth and decreased flow velocity and bed shear stress in the channel and on the floodplain, as well as a re-established hydrological connectivity between the channel and floodplain during small and medium floods. Indirect effects of backwater inundation reflected channel widening and bed aggradation that triggered a positive feedback with changes in hydrodynamics, mostly by reducing the velocity of flood flows in the channel zone. These latter changes occurred on a longer distance upstream from the reservoir than the backwater reach itself, and they modified the river hydrodynamics even when backwater inundation did not occur. We propose a conceptual model which indicates that changes of mountain rivers upstream from dam reservoirs are driven by modified hydrodynamics and lead to different morphological adjustments than those induced by waters underloaded with sediment downstream from dams. Changes in

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hydrodynamics and the associated morphological and sedimentary adjustments of mountain rivers recorded upstream from dam reservoirs may locally mitigate impacts of channelization and channel incision on riverine and riparian ecosystems of these rivers.

1. Introduction

Natural flow regime is a key factor shaping abiotic and biotic components of river ecosystems and human life in riverine landscapes (Poff et al., 1997). Large dam reservoirs profoundly disturb this regime (Dynesius and Nilsson, 1994; Best, 2019; Grill et al., 2019), affecting river functioning downstream (Williams and Wolman, 1984; Petts and Gurnell, 2005; Graf, 2006; Grant, 2012; Kondolf et al., 2019) and upstream from them (Xu and Shi, 1997; Liro, 2014, 2017, 2019; Bao et al., 2015; Volke et al., 2015, 2019; Hanks, 2020). Despite an increasing body of literature on dam effects on rivers, upstream effects are much less recognized than downstream ones (Liro, 2014, 2019; Volke et al., 2019). This gap in knowledge may result from the relatively small spatial extent of the upstream impacts of dams along the rivers (typically from a few to tens of kilometres; cf. Williams and Wolman, 1984; Brandt, 2000). Nevertheless, 57,985 large dams functioning worldwide (ICOLD, 2019) justify asking questions concerning the direction, magnitude and extent of changes in river hydrodynamics occurring upstream from a dam reservoir. Answering these questions is challenging, but it would give a more holistic view of dam impacts on rivers and the functioning of Anthropocene rivers in general.

Upstream from a dam reservoir, the natural flow regime of a reservoir tributary is disturbed by so-called *backwater fluctuations* (BF), that is changes in the extent and magnitude of the river valley inundation connected with the operation of the downstream reservoir (Liro, 2019). In mountain rivers, which typically transport coarse bed sediments only during floods (Grant, 2012), BF-induced disturbance in hydrodynamics may be particularly important for their functioning because it may induce intensive in-channel sedimentation and related morphological changes (Leopold et al., 1964; Knighton, 1998; Książek, 2006; Łajczak, 2006; Evans et al., 2007; Wiejaczka et al., 2014; Xiao et al., 2015; Liro, 2016; Luo et al., 2018; Masselli et al., 2018; Li et al., 2019), which may additionally influence river hydrodynamics, flood hazard and river ecology, even in the periods when BF do not occur (Liro, 2016, 2019). In-channel sedimentation and morphological channel changes in the backwater zone of dam reservoirs were previously documented by remote sensing and hydraulic modelling (cf. Liro, 2016; Luo et al., 2018). To date, few studies have used numerical modelling to quantify hydraulic, sedimentary and morphological effects of reservoir backwater fluctuations (Luo et al., 2018; Hosseiny and Smith, 2019). Notably, none of the studies has examined feedbacks between backwater-induced morphological changes and river hydrodynamics in the periods when backwater inundation does not occur. In this work, we aim to fill this gap using the example of the gravel-bed Dunajec River upstream from the Czorsztyn Reservoir (south Poland) completed in 1997, for which a database of daily river discharges and reservoir stages as well as detailed morphological and sedimentological observations are available (Liro, 2015, 2016).

With extensive literature on river adjustments downstream from dam reservoirs, major patterns of such adjustments are now well recognized. They include the disequilibrium between the energy of flows released from dams and their sediment load as a principal driver of the adjustments (Kondolf, 1997) and channel incision and narrowing as their morphological effects (e.g., Brandt, 2000; Grant, 2012), downstream propagation of the adjustments (Williams and Wolman, 1984) and their relatively large extent along rivers (e.g., Graf, 2006; Petts and Gurnell, 2005). The analysis of changes in the river hydrodynamics upstream from the Czorsztyn Reservoir presented in this study, together with results of other works on morphological, sedimentary and hydraulic changes of mountain rivers upstream from dam reservoirs (Liro, 2014, 2019; Luo et al., 2018), provide an opportunity to compare major patterns of the adjustments occurring downstream and upstream from dam reservoirs.

During the twentieth century most mountain rivers in Europe experienced two types of morphological changes: channel narrowing and incision (Rinaldi et al., 2013) in response to widespread human impacts on channels (Wohl, 2006) and alterations in sediment fluxes (e.g., Liébault and Piégay, 2002). These channel changes caused substantial degradation of hydromorphological integrity of mountain rivers (Muhar and Jungwirth, 1998; Hajdukiewicz et al., 2019)—including simplification of flow patterns and a reduction of habitat heterogeneity, increase in flow velocities and disconnection of floodplains from the channels—that was reflected in adverse changes of riverine and riparian ecosystems (Malmqvist and Rundle, 2002). It is interesting to consider whether these negative hydromorphological alterations of mountain rivers can be mitigated, even if only in short river reaches, by changes in hydrodynamics and associated morphological and sedimentary adjustments induced by backwater fluctuation upstream from dam reservoirs.

This study aims to quantify the scale and spatial extent of changes in water depth, flow velocity and bed shear stress caused by the presence of backwater during low (1-year), medium (2-year) and high (20-year) floods. We hypothesize that the backwater statistically significantly increases water depth and decreases flow velocity and bed shear stress in the reach of the Dunajec River immediately upstream from the Czorsztyn Reservoir (direct effects of backwater; Hypothesis 1). We also hypothesize that channel widening and the formation of large bars documented in this reach (Liro, 2016) modify the river hydrodynamics even in the periods when backwater effects do not occur (indirect effects of backwater; Hypothesis 2). Additionally, the study aims to demonstrate a conceptual model summarizing major patterns of the adjustments of mountain rivers downstream and upstream of dam reservoirs, and to discuss the implications of reservoir-backwater induced changes in the river hydrodynamics for riverine and riparian ecosystems.

2. Study area

2.1. Dunajec River

The analysis was conducted for a 4.5-km-long section of the gravel-bed Dunajec River upstream from the Czorsztyn Reservoir in southern Poland (Fig. 1). The river catchment upstream from the Czorsztyn Reservoir has an area of 796 km^2 and elevations range from 528 to 2301 m a.s.l. (Fig. 1). The catchment is underlain by metamorphic rocks, granites, limestones, dolomites, and flysch complexes (Zawiejska and Krzemień, 2004). The flow regime of the river is determined by the high-mountain part of the catchment (Kundzewicz et al., 2014) with average annual precipitation totals reaching up to 1700 mm (Niedźwiedź and Obrębska-Starklowa, 1991). Flow maxima of the river typically occur during late spring and summer (Kundzewicz et al., 2014), and the average for maximum annual discharges (1970–2012) at the Kowaniec water-gauge station located ca. 13.5 km upstream from the Czorsztyn Reservoir equals 251.5 m^3 s^{-1}. The Dunajec River was heavily channelized in the past 100 years (Krzemień, 1981; Zawiejska and Krzemień, 2004; Wyżga et al., 2012), which resulted in significant channel narrowing and incision, and the change of the multi-thread channel pattern to a single-thread pattern (Zawiejska and Wyżga, 2010). This change in channel pattern was

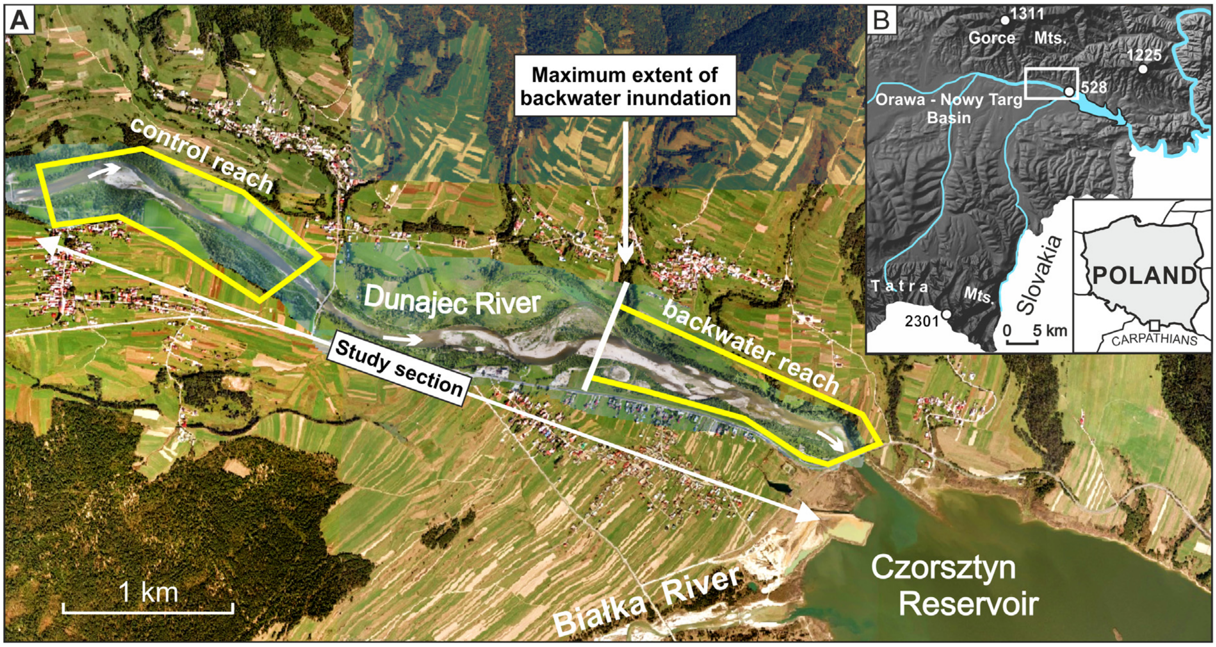

Fig. 1. Study section of the Dunajec River upstream from the Czorsztyn Reservoir (A) and its location in the Polish Carpathians (B). The orthophoto was taken at the water stage in the reservoir that does not affect the river flow in the backwater reach.

also facilitated by a reduction in sediment supply to the river resulting from environmental and land use changes in the catchment (Wyżga et al., 2012, 2016a).

Two reaches were delimited within the study section for the evaluation of reservoir backwater effects on the river hydrodynamics. A lower reach, called *backwater reach*, extends between 0 and 1.5 km from the reservoir (Fig. 1A) and its upper limit coincides with the extent of backwater defined by the intersection of the maximum water level in the reservoir (532.35 m a.s.l. recorded in 2010) and the elevation of the river bed measured on a Digital Elevation Model from 2019. In this reach, the river runs from 532.35 to 527 m of altitude. In the upper reach, called *control reach*, the river flows from 545 to 538.5 m of altitude at a distance of 3.15–4.5 km from the reservoir (Fig. 1A). The location of this reach was selected to fulfil two criteria: (i) it is beyond a backwater influence on the river morphodynamics (Liro, 2016), and (ii) in the pre-dam period it was typified by the same channel morphodynamics and human impacts as the current backwater reach (Liro, 2015, 2016). The location of the control reach is the same as in previous studies dealing with the impacts of reservoir backwater on channel processes and channel evolution of the Dunajec River (cf. Liro, 2015, 2016).

In the study section, the Dunajec receives no significant tributaries. Immediately before the construction of the Czorsztyn Reservoir (1997), the river in both reaches flowed in a single-thread, regulated channel with the width of 60–90 m and very gentle channel bends. Such channel planform was an effect of channelization works carried out in the 1920s–1930s and again in the 1960s–1970s (Zawiejska and Krzemień, 2004). While before the reservoir construction both reaches were typified by similar trajectories of channel width, bank erosion and bar area changes (Liro, 2015, 2016), the reservoir operation caused the lower, backwater-affected part of the study section to be subjected to intense in-channel sediment deposition and bank erosion (Liro, 2016).

In the control reach, channel slope is 0.0053 m m^{-1}. The river is 60–90 m wide and its bankfull depth amounts to 3–3.5 m. The channel almost lacks gravel bars, except a single point bar in the upper part of the reach (Figs. 1A, 2A); however, this does not reflect in-channel gravel mining but rather unfavourable conditions for their formation in the narrow, regulated channel. Surface bed sediments in the reach consist of pebble to cobble material with median grain size (D_{50}) varying between 77 and 127 mm in low-flow channels (with the average of 99 mm) and between 77 and 85 mm on gravel bars (81 mm on average). Channel banks are composed of a 2–2.5 m thick layer of gravels covered by fine-grained overbank deposits 0.5–1 m thick. The banks are overgrown with mature riparian forest (Fig. 2A) dominated by willows and spruce with no signs of clearance.

In the backwater reach, on a distance of 1.25 km upstream from the reservoir, the valley floor is confined to the width of 0.2–0.3 km by a flood embankment on the right side and by a valley side on the left. Channel slope decreases from 0.004 m m^{-1} in the higher part of the reach to 0.00085 m m^{-1} in its lowest 0.65 km, which indicates recent adjustment of the longitudinal river profile to a new base level after the river impoundment. The river flows in a multi-thread channel with wide mid-channel and lateral bars and occasional wooded islands and its width changes from about 250 m in the proximal part of the reach to 100 m in its distal part (Figs. 1A, 2C). Since 2017 gravel exploitation from the channel has been conducted in order to obtain aggregate from the material that otherwise would form a delta in the reservoir; however, during floods the removed parts of channel bars are re-established by the river. In this reach, surface bed material also consists of pebble to cobble grades and its median grain size varies between 51 and 85 mm (with the average of 69 mm) in low-flow channels and between 49 and 78 mm on gravel bars (71 mm on average). Bankfull channel depth amounts to 2.5–3 m. Channel banks are composed of a 2-m-thick layer of gravels covered by 0.5–1.5 m of fine-grained overbank deposits. Only in the vicinity of the reservoir, the layer of overbank fines is up to 2.5 m thick and gravelly material does not occur in the bank profile. The floodplain on the right river side is covered with riparian forest dominated by willows, which is periodically cleared, whereas the valley side along the left river bank is overgrown with mature spruce forest (Fig. 2C).

The rise of base level caused by the reservoir construction induced in-channel deposition of gravelly bed material and the resultant bank erosion upstream from the river mouth to the reservoir (Liro, 2016). These processes have not been limited to the reach with a direct influence of reservoir backwater, but they gradually moved backward as

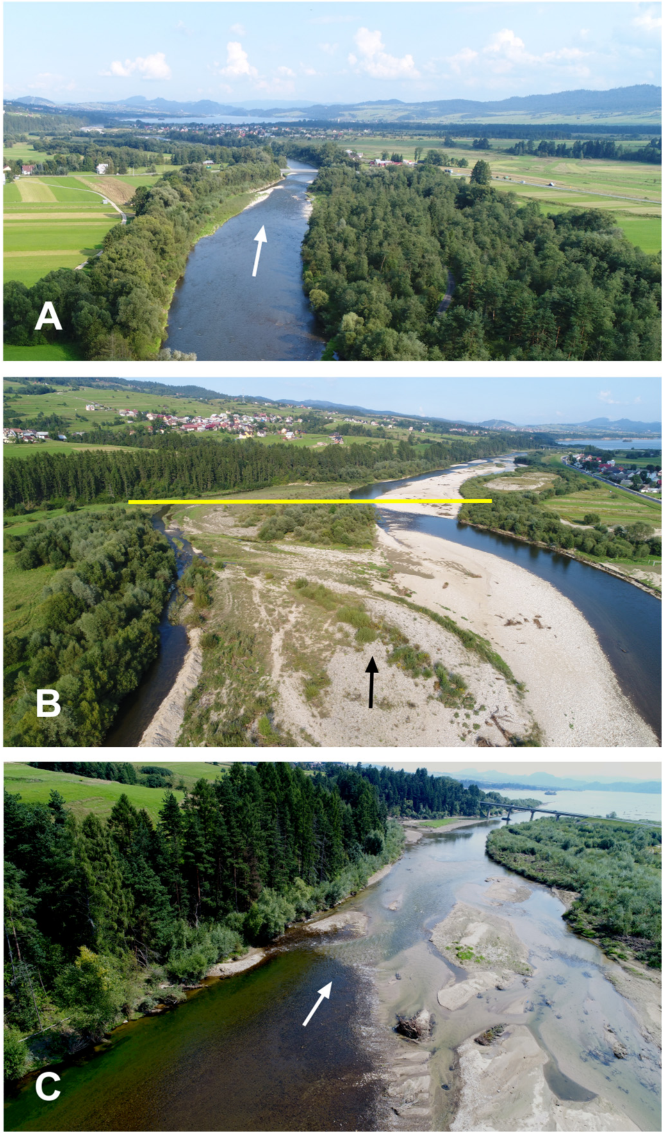

Fig. 2. Oblique aerial views of the Dunajec River in the study section. (A) Downstream view of the control reach. (B) Part of the study section immediately upstream from the backwater reach. The yellow line indicates the beginning of the backwater reach. (C) Downstream view of the backwater reach. The arrows indicate flow direction.

the river bed in the backwater reach aggraded. In 2012 the zone of intensive in-channel deposition and bank erosion reached 2.2 km upstream from the reservoir (Liro, 2016). Currently, the widest channel (250–300 m) occurs just upstream of the backwater reach and bank erosion is particularly intensive at a distance of 1.4–2.4 km upstream from the reservoir (Figs. 1A, 2B), where the riparian forest is less dense and the valley floor is wider and unconfined (Liro, 2016). However, in this study we intend to analyse combined direct and indirect effects of the reservoir backwater on the river hydrodynamics, and thus the backwater reach is limited to the river reach with a direct influence of backwater fluctuations.

2.2. Czorsztyn reservoir and its backwater

The Czorsztyn Reservoir has an area of 13.35 km^2 and was created by a 60-m-high dam in 1997. The main purposes of the reservoir are flood control and electricity generation (Sroczyński, 2004). Between mid-May and the end of August, when large floods usually occur on the Dunajec, relatively large flood reserve of the reservoir is maintained to accommodate potential inflow of floodwater (Wyżga et al., 2018); during that time, mean water level of the reservoir in the years 1997–2014 was 527.6 m a.s.l. (Fig. 3). This reservoir stage does not affect the river flow in the backwater reach (Fig. 1A). Using information on daily water stages of the reservoir from the years 1997–2014 and the elevation of the lowest point of successive river cross-sections delimited in the study reach of the Dunajec (see Section 3.1), we determined that the backwater reach was inundated by the reservoir water from 0.8 day per year (0.2% of the time) in its uppermost part to 227 days per year (62.1% of the time) in its lowest part. Regarding the duration of backwater inundation, the studied backwater reach may be divided into two parts: lower (0–0.95 km from the reservoir), where backwater inundation occurs during 143.6 days per year on average (39.3% of the time), and upper (0.95–1.5 km from the reservoir) with backwater inundation occurring during 3.7 days per year on average (1% of the time). This marked difference in the average duration of backwater inundation between both parts of the reach reflects a substantial decrease in channel gradient close to the reservoir. It is important to note that the discharge of a 2-year flood (205 $m^3 s^{-1}$), able to entrain bed material and erode channel banks in the backwater reach of the Dunajec, coincides with full backwater inundation of the lower and upper parts of this reach during 1.7 and 0.33 days per year on average (0.47% and 0.09% of the time), respectively.

3. Methods

3.1. Study design

To evaluate changes in river hydrodynamics resulting from the influence of backwater fluctuations of the reservoir, we analysed the hydrodynamics in the backwater and control reaches of the Dunajec, with the former being affected by both direct and indirect impacts of the reservoir backwater and the latter devoid of these impacts. We defined 6 scenarios with three steady inlet discharges with the recurrence intervals of 1 year (43 $m^3 s^{-1}$, referred here as a small flood), 2 years (205 $m^3 s^{-1}$; medium flood) and 20 years (604 $m^3 s^{-1}$; large flood) and two reservoir levels: 527.5 m a.s.l. (no inundation of the backwater reach by the reservoir water) and 532.35 m a.s.l. (maximum backwater effect) as outlet boundary conditions (Fig. 3). The two-dimensional numerical model *Iber* (Bladé et al., 2014), which solves the full depth-averaged shallow water equations with a non-structured finite volume method explicit in time, was used to compute water depth and elevation, flow velocity and bed shear stress for each scenario. Output raster files for each parameter were then analysed with a GIS software (Quantum GIS) using automatic measurements along 90 cross-sections delimited at 50 m intervals in the whole study section. The cross-sections were divided into channel and floodplain zones, which allowed for separate measurements of the hydraulic parameters in these zones. For a given flood magnitude, average values of an analysed parameter in every cross-section of a given reach constituted statistical samples, which were compared between different reservoir stages to test Hypothesis 1, and between backwater and control reaches to test Hypothesis 2.

During dam operations or during a flood event, the river discharges and water levels in the reservoir are changing. However, to analyse impacts of the reservoir backwater on the river hydrodynamics, we designed the modelling scenarios assuming three flood magnitudes and two water levels of the reservoir. Such an approach was chosen to evaluate effects of flood magnitude on changes in the river hydrodynamics in the backwater reach, to verify whether morphological river changes induced by long-term backwater fluctuations influence river hydrodynamics even in the periods when backwater inundation does not occur, and to identify the largest longitudinal extent of disturbed hydrodynamics along the river profile.

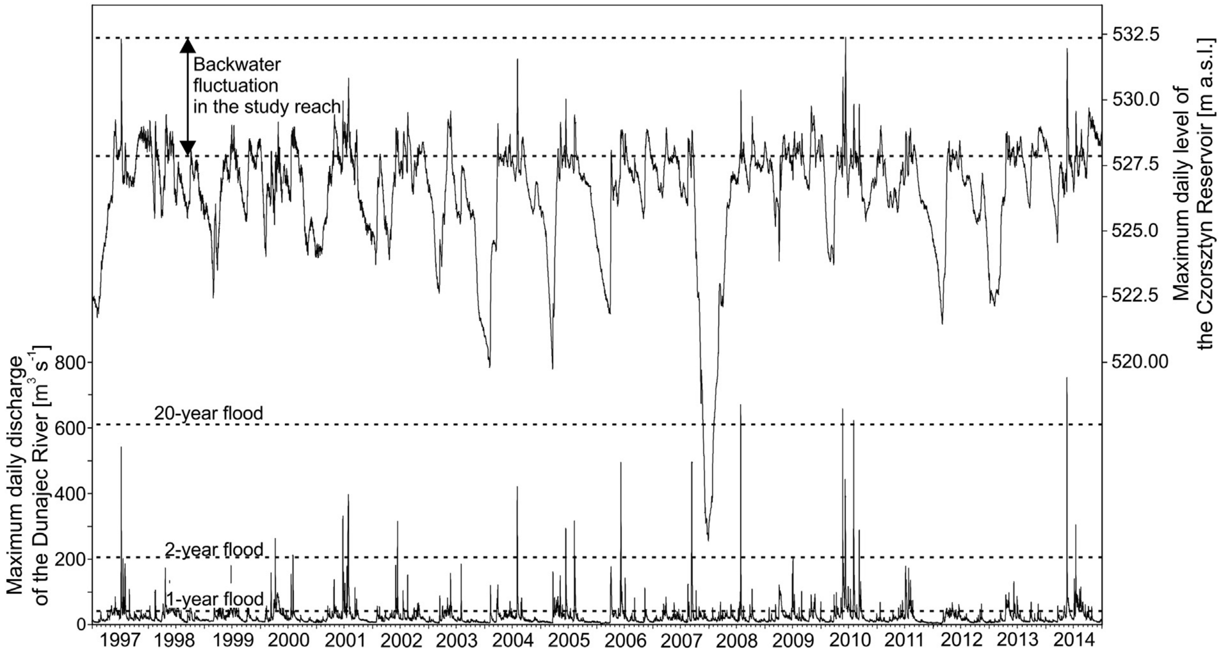

Fig. 3. Maximum daily discharges of the Dunajec River at the Kowaniec gauging station and maximum daily stages of the Czorsztyn Reservoir between 1997 and 2014. The three flood magnitudes and two water stages of the reservoir indicated by dashed lines are used to define the scenarios for hydraulic modelling.

3.2. DEM generation and mesh construction

The *Iber* model performs calculations for a non-structured mesh consisting of triangular or quadrilateral elements (Bladé et al., 2014). A drone survey performed in 2018 and 'Structure-from-Motion' photogrammetry (Westboy et al., 2012) were applied to produce a Digital Elevation Model (DEM) which was subsequently used to obtain a computational mesh representing the geometry of the study river section ~4.5 km in length. The DEM and an orthophoto of the study section were generated using the Agisoft Photoscan software (cf. Rusnák et al., 2018) from 1247 photos taken by a DJI Phantom 4 Advanced Drone on 3 September 2018 at base-flow conditions in the river and with no backwater inundation of the study section (Fig. 1A). The photos were taken from the height of 80–100 m. Their georeferencing was done on the basis of 63 ground control points and 32 check points verifying accuracy assessment, which were evenly distributed in the active river channel and on the floodplain. The position of these points was measured with an RTK GPS receiver (Fig. S1A in the Supplementary material) with horizontal accuracy of 1–2 cm and vertical accuracy of 2.5–3 cm. The automatically generated DEM well reproduced most of the submerged morphology of the river bed because at the base-flow conditions water in low-flow channel(s) was clear and relatively shallow (cf. Javernick et al., 2014). However, where water depth exceeded ~0.5 m (in the lowermost part of the study section and in the central parts of pools on channel bends), the automatically generated DEM indicated the elevation of water surface and elevations of the river bed had to be corrected. At the same hydrological conditions during a few days after the drone flight, water depth was surveyed with a level at 1 m intervals along the 90 river cross-sections running 50 m apart (see Section 3.1), and results of these surveys were subsequently used to manually interpolate bed elevation in the deep parts of low-flow channel(s). The areas with manually corrected elevations constituted ca. 15% of the total area of low-flow channels and less than 10% of the total area of the active river channel in the study river section.

A comparison of xyz coordinates of the DEM with ground control points measured in the field using an RTK GPS receiver indicated that its accuracy ranged from 5.5 to 9.9 cm. The DEM and the orthophoto had a resolution of 9 cm and 4.5 cm, respectively. However, to reduce the computational time of the hydraulic model, the DEM was resampled to 1 m resolution. This resulted in the calculation mesh consisting of 970,935 triangular elements.

3.3. Model calibration

Roughness coefficients were assigned to 5 roughness homogenous units (RHU) delineated in the river and on the floodplain (Table 1; Fig. S2). Each RHU was digitized using a GIS software (ArcGIS) from the orthophoto produced from aerial photos taken by the drone. A possible range of Manning roughness values was then assigned to particular RHU following the criteria of Chow (1959) and applying different empirical equations (Strickler, 1923; Meyer-Peter and Müller, 1948; Bray, 1979) to the size of surface bed material measured in nine channel transects delimited within the entire study section. Three of these transects were located in the control reach, three in the backwater reach and three between these reaches. The grain size of surface bed material within low-flow channels was sampled at 1 m intervals across the low-flow channels, with 15 particles measured at each sampling point. The surface bed material on gravel bars was sampled using the transect pebble-count method (Wolman, 1954), with 400 particles measured across all bars in a transect (Fig. S1B). Median (D_{50}) and D_{90} grain size of the gravel-bar and low-flow channel samples in each transect was determined from their grain-size distribution and used in the above indicated empirical equations.

Following the initial assignment of roughness coefficients for particular RHU, the model was calibrated in terms of roughness values using the information collected during a survey performed after the flood of July 2018. The flood had a peak discharge of 432 m^3 s^{-1} with a 7.3-year recurrence interval. During the post-flood survey, the horizontal extent of the flood was determined at several places on the right river margin or floodplain and we found 43 high-water marks (e.g. mud lines (Fig. S1C), trash lines), which are typically used as evidence of peak flood stage (Bodoque et al., 2015) and hence can be applied in calibration of roughness values for a hydraulic model (e.g. Radecki-Pawlik et al., 2016; Wyżga et al., 2020). The position of the high-water marks was thus measured with an RTK GPS receiver (Fig. S3) and 26 of them

Table 1
Description of roughness homogeneous units (RHU) and the values of Manning's *n* coefficient (in $m^{1/2}\ s^{-1}$) used in the model calibration and final hydraulic simulations.

Roughness homogenous unit		Roughness coefficient		
Name	Description	Minimum	Maximum	Final
Low-flow channel	Gravelly riverbed submerged at base flow	0.02	0.08	0.03
Gravel bars	Gravel bars without vegetation	0.05	0.09	0.06
Alluvial forest	Dense stand of willows and alder	0.10	0.15	0.12
Sparse woody vegetation	Cleared land with some tree stumps	0.07	0.10	0.09
Agricultural land	Grassland and crops	0.01	0.04	0.02

were used in the model calibration. Final roughness values for all RHU (rather than for each RHU separately; Table 1) were fitted running different Manning's *n* coefficients for the discharge of 432 $m^3\ s^{-1}$ and comparing model results with the observed flood extent and the field measurements of water elevation. The calibration results showed that the flooded area was generally well reproduced (Fig. S3) and that modelled values well fitted the observed ones, with a mean error in the water elevation amounting to 22 cm (median = 18 cm and standard deviation = 16 cm) and a mean Nash–Sutcliffe efficiency (Nash and Sutcliffe, 1970) equal to 0.97 (median = 0.99 and standard deviation = 0.088). Mean modelled water depth in the study section equalled 1.4 m and the maximum one was 4.6 m (Fig. S3). The final values of Manning roughness coefficient for the active river channel ranged from 0.03 to 0.06 and those for the floodplain area from 0.02 to 0.12 (Table 1).

3.4. Data analysis

To evaluate direct effects of backwater fluctuation on river hydrodynamics (Hypothesis 1), differences in water depth, flow velocity and bed shear stress in the backwater reach between the scenarios without backwater inundation and with maximum backwater inundation were examined with a non-parametric Wilcoxon signed-rank test. In turn, to evaluate the effect exerted on river hydrodynamics by morphological changes that had occurred in the backwater reach since the river impoundment by the dam reservoir (indirect effect of backwater fluctuations; Hypothesis 2), differences in the analysed hydraulic parameters between the backwater reach not affected by backwater inundation and the control reach were examined using a non-parametric Mann–Whitney test. Differences were tested for each of the three flood magnitudes considered.

The longitudinal extent of direct and indirect effects of backwater fluctuation on the hydrodynamics of the Dunajec River was determined with a Pettit test (cf. Leviandier et al., 2012). For a given flood magnitude, the values of a given hydraulic parameter under conditions with (H1) and without backwater inundation (H2) calculated for 90 consecutive river cross-sections represented a data series which was analysed with the test to identify the location of a change disrupting its homogeneity. This approach allowed for automatic detection of the location of a change in river hydrodynamics along the longitudinal river profile. This test had been previously used to detect river sections homogeneous with regard to active channel width (Toone et al., 2014), morphological channel changes (Liro, 2015) and in-channel sedimentation (Liro, 2016).

Statistical analyses were performed with Statistica software and iki.dataclim package (Orlowsky, 2014) of R software (R Core Team, 2019). Analysed differences and breaks in data series homogeneity were considered statistically significant if p-value < 0.05.

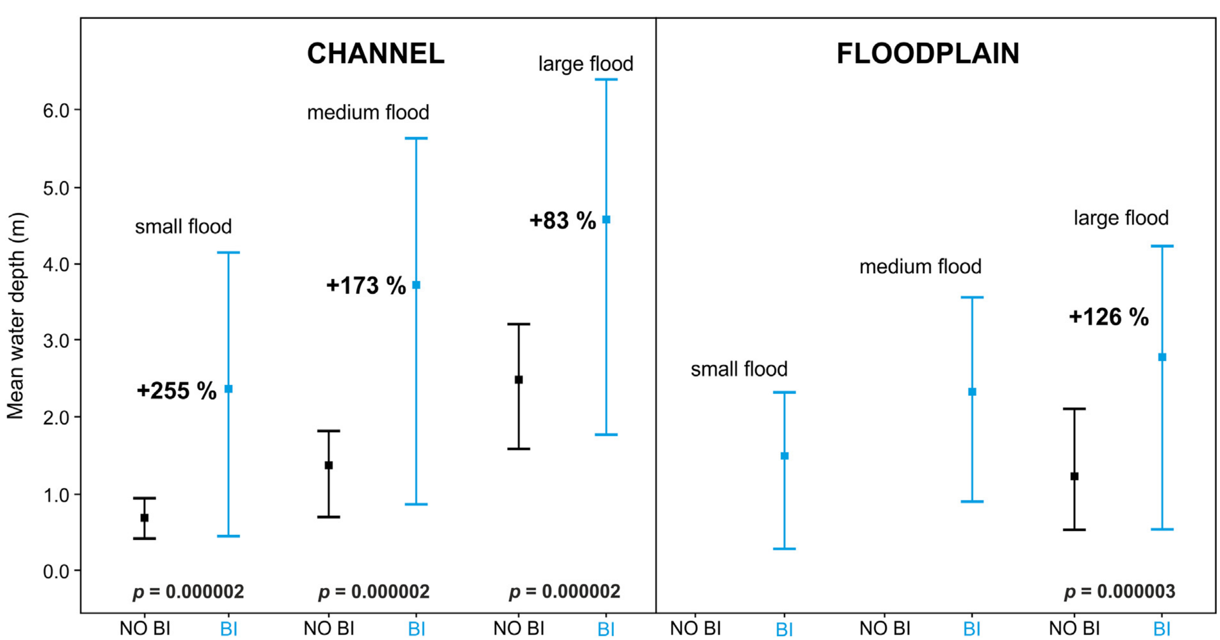

Fig. 4. Comparison of mean water depth in channel and floodplain zones of the Dunajec River in the backwater reach between conditions without backwater inundation (NO BI) and with maximum backwater inundation (BI) during small (1-year), medium (2-year) and large (20-year) floods. Whiskers indicate minimum and maximum values of the parameter among the study cross-sections from this reach and points show the means. Percentage differences of the parameter between the two hydraulic situations are indicated and their statistical significance determined with a Wilcoxon test is shown. p-values < 0.05 are indicated in bold.

4. Results

4.1. Direct effects of backwater fluctuation

A comparison of hydraulic parameters in the backwater reach of the Dunajec between the conditions with its maximum inundation by reservoir water and without inundation indicated that the modelled mean water depth changed significantly as a result of the fluctuation of reservoir level during floods of all considered magnitudes (Fig. 4). During the small flood scenario (43 $m^3 s^{-1}$), mean modelled water depth in the channel zone of 30 analysed river cross-sections was 0.69 m without backwater inundation, while it equalled 2.43 m during the maximum inundation by reservoir water, differing between these two contrasting scenarios by 255% (Wilcoxon test, $p = 0.000002$). Backwater fluctuation changed the range of variation in mean water depth in this zone among the analysed cross-sections from 0.45–0.96 m without backwater inundation to 0.50–4.21 m at the maximum inundation (Fig. 4). The significant increase in mean water depth was associated with significant reductions in mean flow velocity and bed shear stress in the channel zone. For the small flood scenario, we observed that the maximum backwater inundation decreased the average modelled value of mean flow velocity in this zone from 0.68 to 0.19 m s^{-1}—i.e. by 72% ($p = 0.000002$)—in comparison to conditions without backwater inundation, whereas the variation of this parameter among the 30 river cross-sections changed from 0.36–1.16 m s^{-1} to 0.01–0.92 m s^{-1} (Fig. 5). With maximum backwater inundation, average value of modelled bed shear stress in the channel zone was 68% lower ($p = 0.000002$) than without backwater inundation (5 N m^{-2} versus 14 N m^{-2}), and this parameter varied among the cross-sections between 0.5 and 52 N m^{-2} during the former scenario and between 4 and 52 N m^{-2} during the latter one (Fig. 6).

Without backwater inundation, the small flood did not cause floodplain submergence (Figs. 4–6) according to the modelling results. With maximum backwater inundation, modelled mean water depth on the floodplain equalled 1.55 m for the 30 analysed cross-sections and varied between 0.36 and 2.37 m among individual cross-sections (Fig. 4). Mean velocity of the floodplain flow in the 30 cross-sections equalled 0.14 m s^{-1}, with the variation of the parameter among individual cross-sections between 0.01 and 1.14 m s^{-1} (Fig. 5). In turn, modelled bed shear stress in the floodplain zone amounted to 2 N m^{-2} on average, varying among the cross-sections between 0 and 32 N m^{-2} (Fig. 6).

At a medium flood (205 $m^3 s^{-1}$), mean water depth in the channel zone of the backwater reach equalled 1.38 m without its inundation by reservoir water and 3.77 m with its maximum inundation by the reservoir, changing by 173% ($p = 0.000002$) between these scenarios. Backwater fluctuation also considerably changed the range of variation in mean water depth in the channel zone among 30 analysed cross-sections from 0.72–1.80 m without backwater inundation to 0.92–5.64 m at the maximum inundation (Fig. 4). With maximum inundation of the backwater reach by reservoir water, the average value of modelled mean velocity of the channel flow for the 30 cross-sections was 64% lower (0.45 m s^{-1} versus 1.26 m s^{-1}; $p = 0.000002$) than without backwater inundation, and the parameter variation among the cross-sections was reduced to 0.27–0.89 m s^{-1} in comparison to 0.73–1.97 m s^{-1} without backwater inundation (Fig. 5). Notably, as backwater inundation particularly increased submergence of shallow parts of the channel (gravel bars), the highest cross-sectional mean of flow velocity during the medium flood was even lower than during the small flood associated with backwater inundation conditions (0.92 m s^{-1}) (Fig. 5). Maximum backwater inundation at the medium flood was also reflected in 80% lower average value of bed shear stress in the channel zone ($p = 0.000002$) than without backwater inundation (7 N m^{-2} versus 35 N m^{-2}), and this parameter varied among the cross-sections between 0.5 and 60 N m^{-2} during the former scenario and between 11 and 69 N m^{-2} during the latter one (Fig. 6).

Without backwater inundation, a modelled scenario for the medium flood did not produce floodplain submergence in the entire backwater reach (Figs. 4–6). With maximum backwater inundation, mean depth of the floodplain flow in the 30 cross-sections equalled 2.39 m, with the depth varying among individual cross-sections between 0.94 and 3.59 m (Fig. 4). Mean velocity of the floodplain flow in the 30 cross-sections was 0.24 m s^{-1} and the velocity varied among individual cross-sections between 0.07 and 0.92 m s^{-1} (Fig. 5). Modelled bed shear stress on the floodplain equalled 3 N m^{-2} on average and varied between 1 and 28 N m^{-2} among individual cross-sections (Fig. 6).

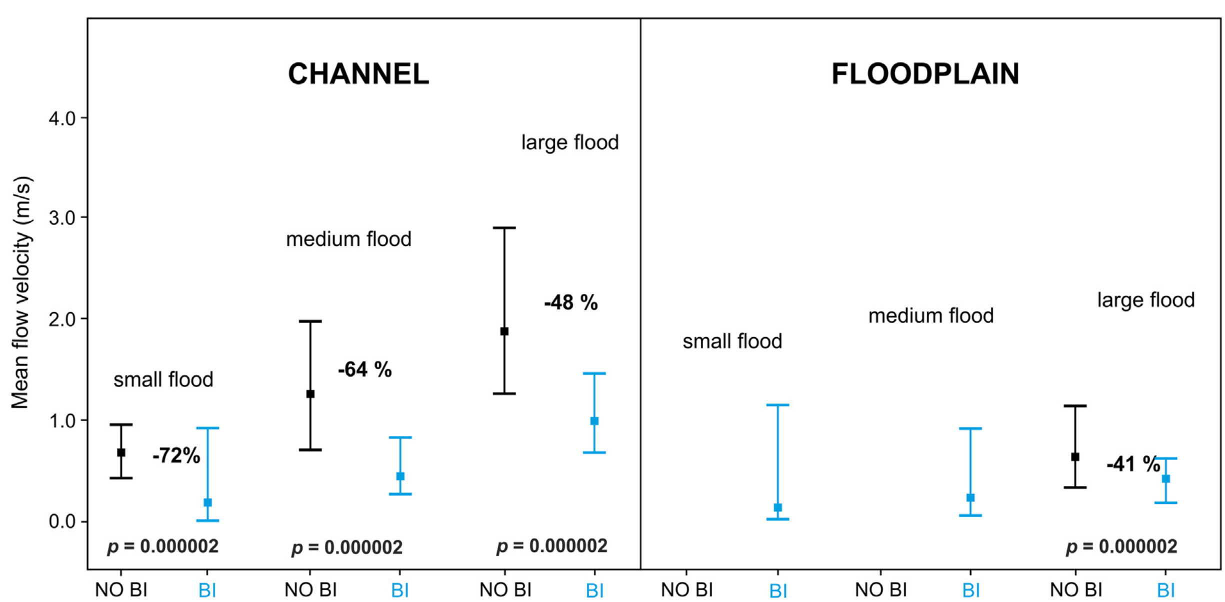

Fig. 5. Comparison of mean flow velocity in channel and floodplain zones of the Dunajec River in the backwater reach between conditions without backwater inundation (NO BI) and with maximum backwater inundation (BI) during small (1-year), medium (2-year) and large (20-year) floods. Whiskers indicate minimum and maximum values of the parameter among the study cross-sections from this reach and points show the means. Percentage differences of the parameter between the two hydraulic situations are indicated and their statistical significance determined with a Wilcoxon test is shown. p-values < 0.05 are indicated in bold.

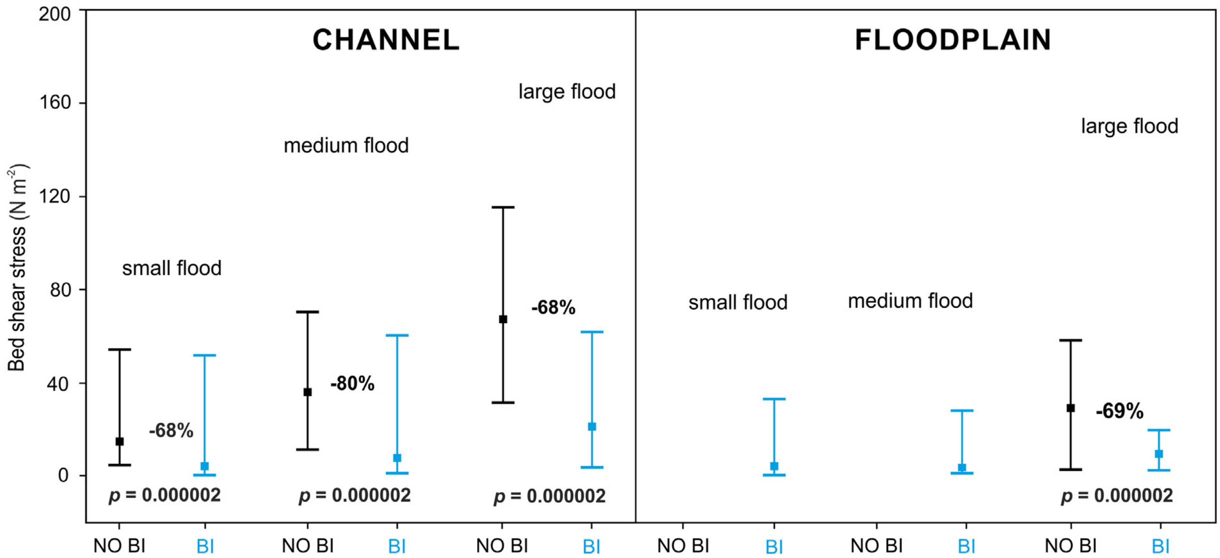

Fig. 6. Comparison of mean bed shear stress in channel and floodplain zones of the Dunajec River in the backwater reach between conditions without backwater inundation (NO BI) and with maximum backwater inundation (BI) during small (1-year), medium (2-year) and large (20-year) floods. Whiskers indicate minimum and maximum values of the parameter among the study cross-sections from this reach and points show the means. Percentage differences of the parameter between the two hydraulic situations are indicated and their statistical significance determined with a Wilcoxon test is shown. *p*-values < 0.05 are indicated in bold.

During a large flood (604 m^3 s^{-1}), modelled mean depth of the channel flow in the backwater reach equalled 2.53 m without backwater inundation and 4.62 m with its maximum inundation by reservoir water, differing by 83% ($p = 0.000002$) between these scenarios. Backwater fluctuation changed the range of variation in modelled mean water depth in the channel zone among 30 analysed cross-sections from 1.61–3.23 m without backwater inundation to 1.8–6.39 m at the maximum backwater inundation, but the relative scale of this change was smaller than during the small and medium floods (Fig. 4). With maximum backwater inundation, the average value of mean flow velocity in the channel zone was 48% lower ($p = 0.000002$) in comparison to conditions without backwater inundation (0.99 m s^{-1} versus 1.90 m s^{-1}), and the range of variation of this parameter among the 30 cross-sections changed from 1.26–2.96 m s^{-1} to 0.67–1.46 m s^{-1} (Fig. 5). Backwater fluctuation reduced the average value of modelled bed shear stress in the channel zone from 67 N m^{-2} without backwater inundation to 22 N m^{-2} at the maximum backwater inundation, i.e. by 68% ($p = 0.000002$), whereas the range of variation of the parameter changed from 31 to 114 N m^{-2} to 3–61 N m^{-2} between these two contrasting scenarios (Fig. 6).

At the peak discharge of the large flood, changes in modelled mean depth of the floodplain flow caused by backwater fluctuation were greater than those in the channel flow—without backwater inundation, mean water depth on the floodplain was 1.25 m, whereas with maximum backwater inundation it was 126% greater ($p = 0.000003$), amounting to 2.83 m. At the same time, the range of variation in the mean depth of the floodplain flow among 30 analysed cross-sections increased from 0.56–2.14 m without backwater inundation to 0.58–4.24 m at the maximum backwater inundation (Fig. 4). The significant increase in mean depth of the floodplain flow was associated with significant reductions in mean velocity and bed shear stress on the floodplain, according to the modelling results. With maximum backwater inundation, the average value of mean velocity of the floodplain flow for the 30 cross-sections was 41% lower (p = 0.000002) than without backwater inundation (0.42 m s^{-1} versus 0.72 m s^{-1}). Backwater fluctuation changed the range of variation of the parameter among the analysed cross-sections from 0.24–1.24 m s^{-1} without backwater inundation to 0.19–0.62 m s^{-1} at the maximum backwater inundation (Fig. 5). Notably, during the large flood the highest cross-sectional mean of flow velocity on the floodplain was lower than during the medium (0.92 m s^{-1}) and the small (1.14 m s^{-1}) floods associated with maximum backwater inundation (Fig. 5); this reflected rapid spreading of water on the floodplain and a substantial increase in the cross-sectional area of floodplain flow with increasing flood magnitude. In turn, the average value of bed shear stress on the floodplain was 69% lower ($p = 0.000002$) with maximum backwater inundation than without backwater inundation (9 N m^{-2} versus 28 N m^{-2}), and the range of variation of the parameter among the cross-sections was reduced to 2–20 N m^{-2} in comparison to 3–56 N m^{-2} without backwater inundation (Fig. 6).

4.2. Indirect effects of backwater fluctuation

To determine how morphological changes in the backwater reach of the Dunajec induced by the fluctuation of reservoir backwater influence the river hydrodynamics (indirect effects of backwater fluctuation), hydraulic conditions for the three scenarios without backwater inundation were compared between the control and backwater reaches. Mean water depth in the channel zone did not differ significantly between the reaches at any of the considered flood magnitude scenarios. Without backwater inundation, the floodplain in both reaches was submerged only during the large flood, when mean depth of the floodplain flow in the backwater reach was 32% larger than in the control reach (Mann–Whitney test, $p = 0.01$) (Table 2; Fig. S4A–C). Morphological changes in the backwater reach had the most pronounced influence on mean velocities of flood flows conveyed in the channel zone. At all considered flood magnitudes, these velocities were significantly lower than in the control reach, with the relative difference between the reaches ranging from 30% for the large flood ($p = 0.000001$) to 34% for the small flood ($p = 0.000004$). However, both reaches did not differ significantly in mean velocity of the floodplain flow during the large flood (Table 2; Fig. S5A–C). During the small and medium floods, no significant differences in bed shear stress in the channel zone were observed between both reaches. During the large flood, this parameter in the backwater reach was significantly lower than in the control reach ($p = 0.03$), differing from the latter by 25%. However, modelled bed shear stress associated with the flow of the large flood in the floodplain

Table 2
Mean values of water depth, flow velocity and bed shear stress in channel and floodplain zones of the control and backwater reaches of the Dunajec River during small (43 $m^3 s^{-1}$), medium (205 $m^3 s^{-1}$) and large floods (604 $m^3 s^{-1}$) and without backwater inundation by reservoir water, and results of a Mann–Whitney test for the significance of difference of these parameters between both reaches. Statistically significant differences are indicated in bold.

Parameter	Flood magnitude	Channel flow				Floodplain flow			
		Control reach	Backwater reach	Relative change	Significance	Control reach	Backwater reach	Relative change	Significance
Water depth (m)	Small	0.77	0.69	−11%	0.47	–	–	–	–
	Medium	1.51	1.38	−9%	0.17	–	–	–	–
	Large	2.52	2.53	0.3%	0.92	0.95	1.25	32%	**0.01**
Flow velocity ($m s^{-1}$)	Small	1.03	0.68	−34%	**0.000004**	–	–	–	–
	Medium	1.89	1.26	−34%	**0.000001**	–	–	–	–
	Large	2.71	1.90	−30%	**0.000001**	0.96	0.72	−25%	0.65
Bed shear stress ($N m^{-2}$)	Small	19.7	14.4	−27%	0.48	–	–	–	–
	Medium	48.4	35.1	−27%	0.18	–	–	–	–
	Large	89.1	66.9	−25%	**0.03**	31.3	27.7	−12%	0.85

zone did not differ significantly between both reaches (Table 2; Fig. S6A–C).

4.3. Longitudinal extent of backwater effects

Homogeneity of the longitudinal series of hydraulic parameters simulated for the conditions with maximum backwater inundation and without backwater inundation was examined with a Pettit test to identify a longitudinal extent of changes in the river hydrodynamics caused by direct and indirect effects of reservoir backwater, respectively. A direct effect of backwater on mean water depth in the channel zone extended to 1.3–1.35 km upstream from the reservoir at all considered flood magnitudes ($p < 0.01$; Figs. 7D–F, S4D–F). The same longitudinal extent was also found for a direct backwater effect on mean depth of the floodplain flow of the large flood ($p < 0.01$; Figs. 7F, S4F). In turn, an indirect effect on mean water depth was found only for the scenario with the large flood, when it extended to 2.5 km from the reservoir for the channel flow ($p < 0.05$) and to 1.35 km from the reservoir for the floodplain flow ($p < 0.01$) (Figs. 7C, S4C). However, no threshold in homogeneity of the series of mean water depth along the study reach was detected for the scenarios simulating indirect effects of backwater during the small and medium floods (Figs. 7A–B, S4 A–B).

An indirect effect of backwater on mean flow velocity in the channel zone reached to 2.05–2.15 km upstream from the reservoir ($p < 0.01$; Figs. 8A–C, S5A–C). Surprisingly, the threshold in homogeneity of the series of mean velocity of the channel flow during maximum backwater inundation had the same position ($p < 0.01$; Figs. 8D–F, S5D–F), hence being located more than 0.5 km upstream from the extent of backwater inundation. The floodplain zone in the study river section was submerged only during the scenarios with the large flood, but no threshold in the values of mean velocity of the floodplain flow could be detected along the section for the scenarios simulating direct (Figs. 7F, S5F) and indirect effects (Figs. 8C, S5C) of reservoir backwater.

A direct effect of backwater on bed shear stress in the channel zone extended to 1.4–1.45 km from the reservoir at all considered flood magnitudes ($p < 0.01$; Figs. 9D–F, S6D–F). The threshold in homogeneity of the series of bed shear stress in the floodplain zone during maximum backwater inundation was detected only for the large flood, when it was positioned 2.85 km upstream from the reservoir ($p < 0.01$; Figs. 9F, S6F), again far upstream from the extent of backwater inundation. An indirect effect of backwater on bed shear stress was detected only in the channel zone for the large flood scenario, extending to 0.85 km from the reservoir ($p < 0.05$; Figs. 9C, S6C), whereas no threshold in the series homogeneity was found for the scenarios representing indirect effects of backwater on bed shear stress in the channel zone during the small and medium floods (Figs. 9A–B, S6A–B) and on bed shear stress in the floodplain zone during the large flood (Figs. 9C, S6C).

5. Discussion

5.1. General pattern of backwater-caused changes in the river hydrodynamics

Using the example of the gravel-bed Dunajec River upstream from the Czorsztyn Reservoir, this study shed light on how dam reservoirs modify the hydrodynamics of mountain rivers upstream from these reservoirs. The simulation of different flood conditions with a two-dimensional hydraulic model allowed us to identify changes in key hydraulic parameters (i.e., water depth, flow velocity, bed shear stress) in the channel and floodplain zones of the study river. The study demonstrated that backwater inundation significantly increased water depth and decreased flow velocity and bed shear stress in the channel zone of the backwater reach. However, the relative changes in water depth and flow velocity caused by backwater inundation diminished with increasing flood magnitude (Figs. 4, 5). This reflected a progressively lower impact exerted by backwater inundation on the cross-sectional area of flood flows with increasing flood discharge. In contrast, we observed no consistent change of backwater inundation-caused decrease in bed shear stress in the channel zone with increasing flood magnitude (Fig. 6). This seems to reflect the opposite effects of backwater inundation on water depth and energy gradient of flood flows—the inundation increased water depth and decreased the energy gradient of flood flows in the backwater reach, but both these impacts decreased in importance with increasing flood discharge.

In the floodplain zone of the backwater reach, the most important change resulting from backwater inundation took place during the small and medium floods, turning the emerged floodplain surface into a submerged one. Because of the incised nature of the Dunajec River, overbank flow would not occur during these floods (Wyżga et al., 2016b) unless the backwater effect of the reservoir occurred. Floodplain inundation by reservoir backwater thus re-established hydrological connectivity between the river channel and floodplain during such floods. During the large flood, backwater inundation significantly increased modelled mean water depth and decreased modelled flow velocity and bed shear stress on the floodplain.

The obtained results indicated that inundation of the backwater river reach driven by reservoir water increases channel–floodplain connectivity and remarkably decreases transport capacity of flood flows (because of reduced flow velocity) and their potential for sediment mobilization (because of reduced bed shear stress), hence stimulating accumulation of sediment in the channel and on the floodplain. According to the Hjulström–Sundborg diagram (Sundborg, 1956), settling velocity separating transport and depositional conditions for the particles with 70 mm diameter—the median grain size of surface bed material in the reach—is 0.82 $m s^{-1}$. During the medium flood, for instance, mean velocity of the channel flow would exceed this value in

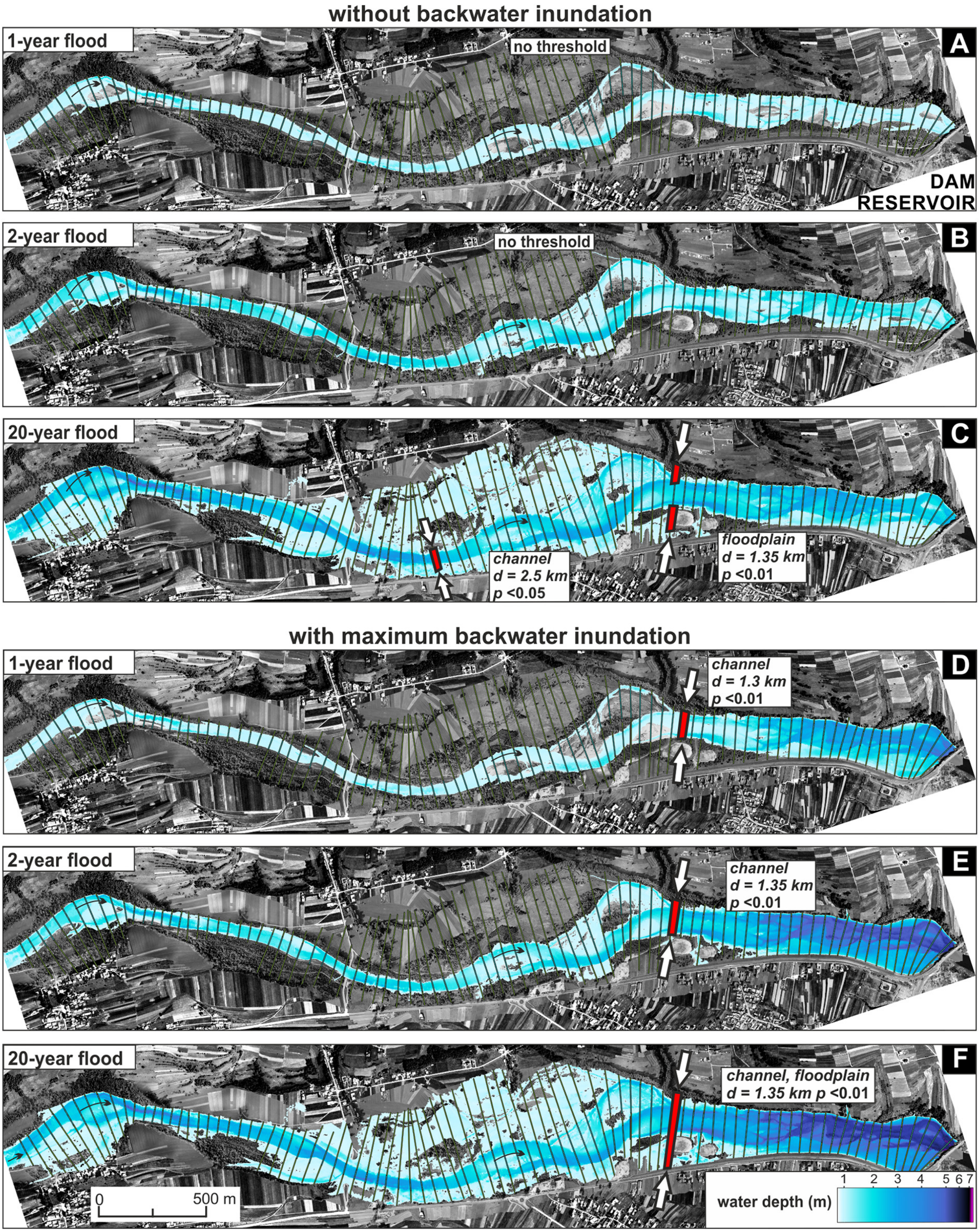

Fig. 7. Spatial pattern of water depth in the channel and on the floodplain in the study section of the Dunajec River during small (A, D), medium (B, E) and large (C, F) floods without backwater inundation (A–C) and with maximum backwater inundation (D–F). *d*-values indicate the length of the river reach upstream of the Czorsztyn Reservoir with significantly different mean depth of channel and floodplain flows than in the upstream part of the study section not affected by direct and indirect effects of reservoir backwater. Location of the threshold between the two parts of the study river section with homogenous longitudinal distributions of the mean depth of channel and floodplain flows, indicated by the Pettit test, is shown. *p*-values indicate significance of the Pettit test.

28 out of 30 study cross-sections without backwater inundation of the reach, but only in 2 cross-sections with its maximum backwater inundation. With a standard value of the Shields parameter ($\theta = 0.056$; Shields, 1936), shear stress of 63.5 N m^{-2} is needed to entrain particles with the median grain size in the reach. However, during the medium flood mean bed shear stress in the reach would represent 55% of the critical shear stress without backwater effect and only 11% with maximum backwater inundation. The changes in the hydrodynamics identified

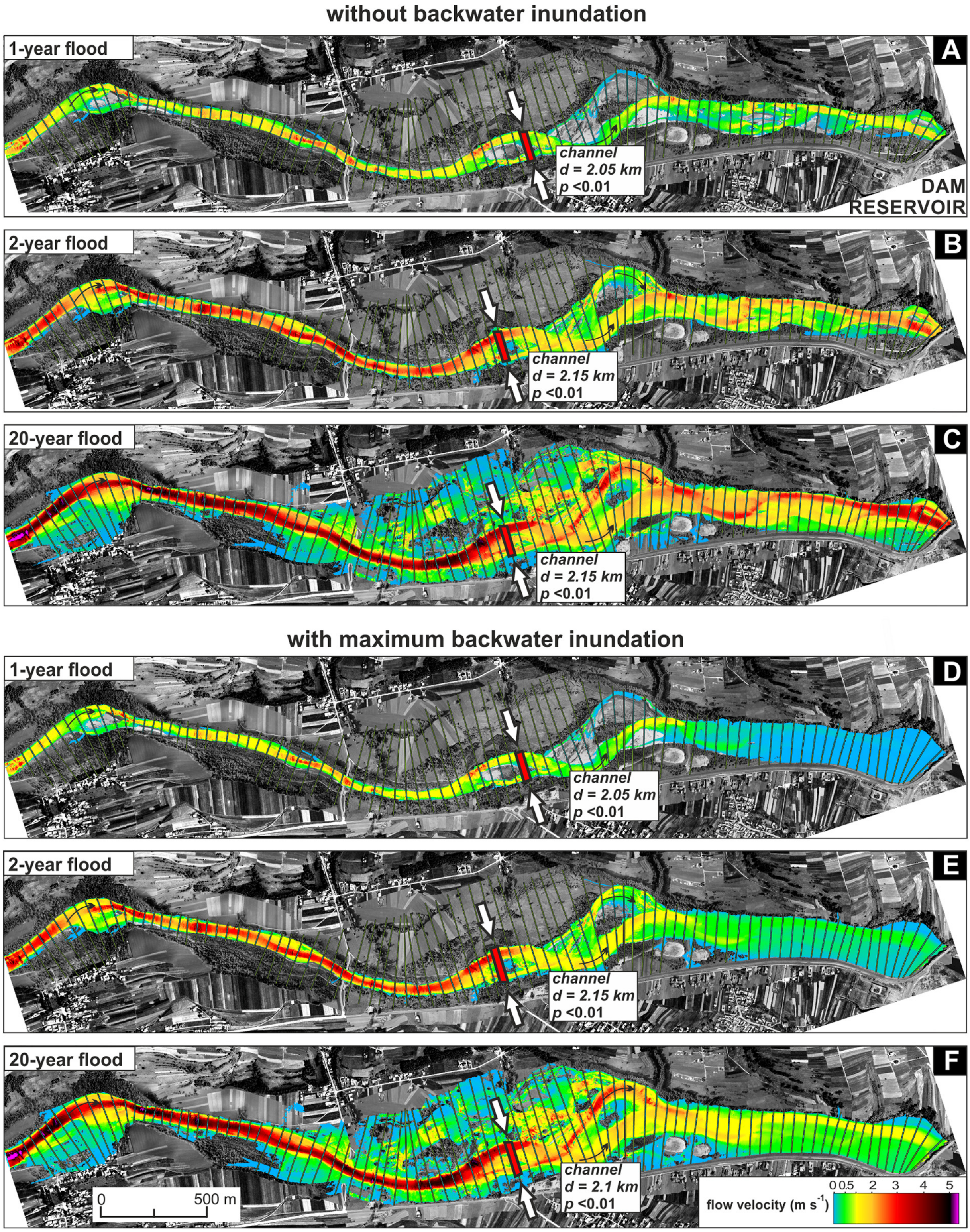

Fig. 8. Spatial pattern of flow velocity in the channel and on the floodplain in the study section of the Dunajec River during small (A, D), medium (B, E) and large (C, F) floods without backwater inundation (A–C) and with maximum backwater inundation (D–F). *d*-values indicate the length of the river reach upstream of the Czorsztyn Reservoir with significantly different mean velocity of channel and floodplain flows than in the upstream part of the study section not affected by direct and indirect effects of reservoir backwater. Location of the threshold between the two parts of the study river section with homogenous longitudinal distributions of the mean velocity of channel and floodplain flows, indicated by the Pettit test, is shown. *p*-values indicate significance of the Pettit test.

upstream from the Czorsztyn Reservoir are thus opposite to those commonly observed downstream from dam reservoirs, where they result in increased erosional potential of flood flows, bed degradation and floodplain disconnection from the channel (cf. Petts, 1979; Brandt, 2000; Graf, 2006; Grant, 2012; Hanks, 2020; Kondolf et al., 2019). This aspect is further discussed in the following section.

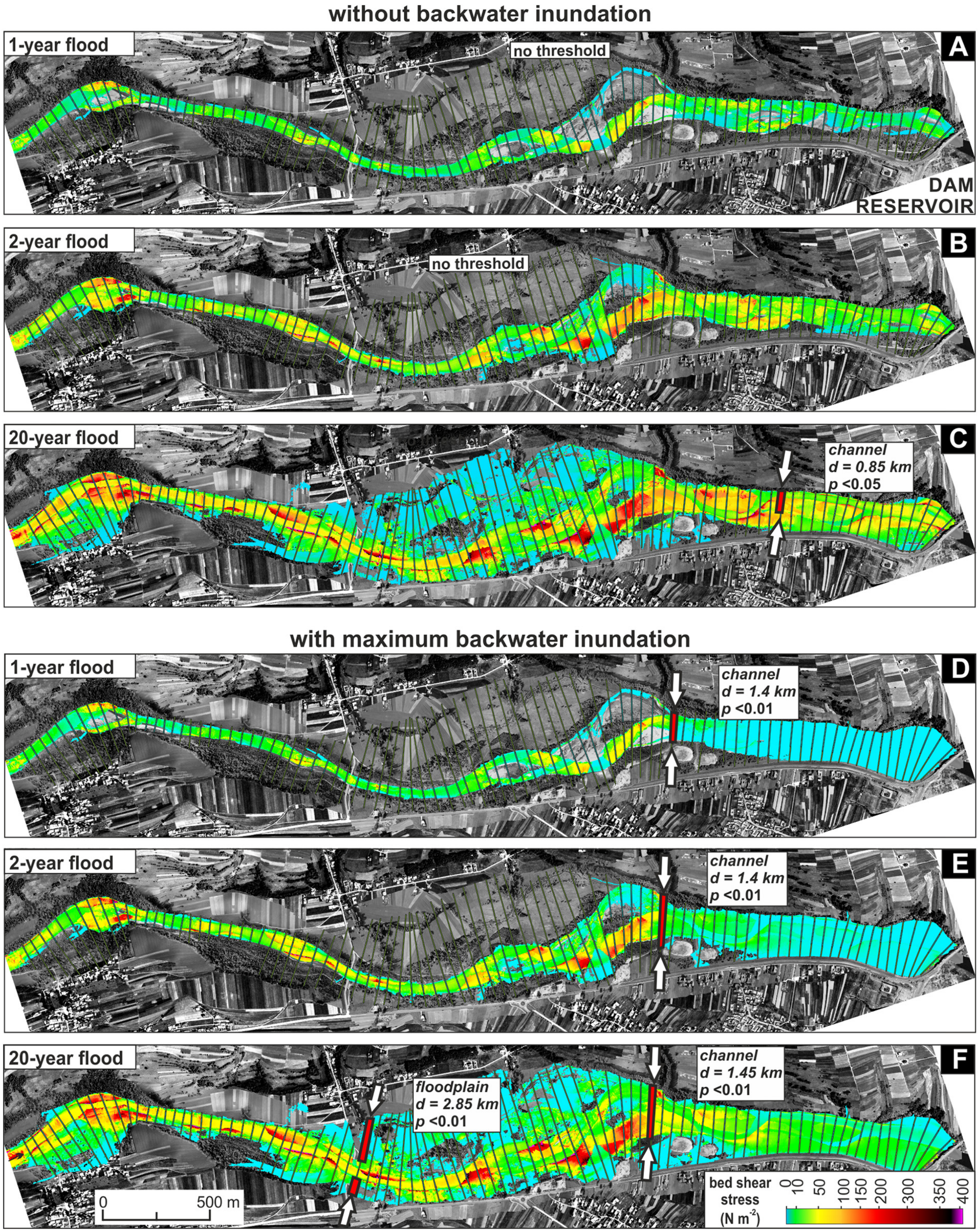

Fig. 9. Spatial pattern of bed shear stress in the channel and on the floodplain in the study section of the Dunajec River during small (A, D), medium (B, E) and large (C, F) floods without backwater inundation (A–C) and with maximum backwater inundation (D–F). *d*-values indicate the length of the river reach upstream of the Czorsztyn Reservoir with significantly different mean bed shear stress in the channel and on the floodplain than in the upstream part of the study section not affected by direct and indirect effects of reservoir backwater. Location of the threshold between the two parts of the study river section with homogenous longitudinal distributions of the mean bed shear stress in the channel and on the floodplain, indicated by the Pettit test, is shown. *p*-values indicate significance of the Pettit test.

Considerable channel widening and the development of large gravel bars induced by intense in-channel sedimentation after the reservoir construction were documented in the backwater reach and along a few hundred metres of channel length upstream from it (Liro, 2015, 2016). Hydraulic simulations performed in the present study demonstrated that these morphological changes induced by backwater effect trigger a positive feedback with changes in hydrodynamics, significantly decreasing mean velocity in the channel zone of the backwater reach at all considered flood magnitudes, and during the large flood significantly decreasing bed shear stress in the channel zone and increasing mean water depth on the floodplain of that reach in comparison to the control reach (Table 2).

Changes in the river hydrodynamics caused by the indirect and direct influence of reservoir backwater differed with respect to their longitudinal extent and longitudinal variation of hydraulic parameters. Changes of flood flows in the channel zone caused by the indirect influence of backwater typically reached farther upstream than the maximum extent of backwater inundation. They mostly referred to mean flow velocity which showed no longitudinal tendency of the modified values (Fig. S5A–C). In the lowest part of the backwater reach, the reduction in flow velocity was driven by a considerable reduction in channel gradient, whereas farther upstream it must have reflected a considerable increase in channel width after the reservoir construction (Liro, 2016) and increased resistance to flow of the channel with numerous mid-channel and lateral bars (cf. Bathurst, 1982). In turn, the observed variation in channel width upstream from the reservoir (Fig. 2B, C) reflects differences in the thickness of fine sediments on the floodplain and in the degree of valley-floor confinement at different distances from the reservoir (Liro, 2016). Close to the reservoir, the river banks are composed of fine-grained, cohesive sediments, which makes them relatively resistant to erosion and inhibits channel widening (cf. Xu, 1990, 2001a, 2001b). Farther upstream, presence of only a thin layer of fine sediments on the floodplain and the lack of valley confinement facilitate bank erosion and channel widening (Liro, 2016).

The direct effects of reservoir backwater on water depth and bed shear stress in the channel zone extended nearly to the beginning of the backwater reach. Under the conditions of maximum backwater inundation, clear longitudinal tendencies of the parameter values were observed, with mean water depth progressively increasing (Fig. S4D–F) and bed shear stress decreasing (Fig. S6D–F) towards the dam reservoir. A similar longitudinal extent typified also the direct impact of reservoir backwater on mean depth of the floodplain flow during the large flood, with its values increasing towards the reservoir (Fig. S4D–F). The Pettit test also indicated that with maximum backwater inundation, reduced values of mean flow velocity in the channel zone at all considered flood magnitudes and of bed shear stress on the floodplain during the large flood extended far upstream from the beginning of the backwater reach. However, it could be noticed that the reduced values of the parameters could be grouped into two subseries: one with the values progressively decreasing downstream along the backwater reach, and another without such a tendency upstream from this reach (Figs. S5D–F, S6F). The Pettit test apparently separated values of these parameters modified as a result of direct and indirect impacts of reservoir backwater from unmodified parameter values upstream. The above observations indicate that the occurrence of a longitudinal tendency in a hydraulic parameter upstream from a dam reservoir is a diagnostic feature of direct effects of backwater because the influence of backwater inundation on the cross-sectional area of flood flows progressively changes with increasing distance from the reservoir. In the case of indirect effects of backwater, no longitudinal tendency of parameter values is observed.

5.2. River adjustments downstream and upstream from dam reservoirs

Reservoir backwater-induced changes in the mountain river hydrodynamics revealed by the present study, together with morphological and sedimentary changes of mountain rivers upstream from dam reservoirs described in previous works (Liro, 2015, 2016; Luo et al., 2018; Masselli et al., 2018; Hosseiny and Smith, 2019), differ from river adjustments occurring downstream from dams, for which extensive literature exists (e.g., Petts and Gurnell, 2005; Grant, 2012). We summarize these differences in a conceptual model (Fig. 10).

Although dam reservoirs typically reduce peak discharges of flood waves (Graf, 2006), the most important driver of river changes in the downstream reaches is the release of waters underloaded with sediment (Fig. 10), particularly bedload (Kondolf, 1997; Kondolf et al., 2019). For instance, deep dam reservoirs constructed on Polish Carpathian rivers trap all the bedload and most of the suspended-sediment load delivered from the upstream (Łajczak, 1996). To re-establish the equilibrium between their transport capacity and sediment load, rivers mobilize bed material and transfer it downstream, but its loss is not compensated for by transport from the upstream (*hungry water* effect; Kondolf, 1997). This leads to channel incision (Fig. 10) which in gravel-bed rivers continues until the coarsening of bed material and the development of bed armour will radically decrease sediment mobility (Gaeuman et al., 2005; Grant, 2012). Up to 7.5 m of channel incision was documented immediately below dams, and the amount of incision gradually decreases downstream on a distance reaching up to 100–140 km from dams (Williams and Wolman, 1984; Grant, 2012). Flow concentration in the deepening channel decreases the frequency of disturbance of marginal parts of the former active channel, which leads to their stabilization by vegetation and the narrowing of active channel (Fig. 10); downstream from dams, channel narrowing up to about half of the pre-dam width was observed (Graf, 2006). Incision and the associated channel narrowing increase flow velocity and unit stream power at given flood discharges, which activates a positive feedback increasing sediment deficit and retarding the re-establishment of equilibrium conditions (Fig. 10; Wyżga, 1993). This feedback is particularly intense during large floods, as their peak discharges are typically less reduced by upstream dam reservoir than those of small and medium floods (Petts and Gurnell, 205). Flushing out of bed material from the reach located immediately below a reservoir temporarily maintains equilibrium conditions downstream, but once the sediment flux declines, sediment deficit is shifted downstream. Over time, this results in downstream propagation of river adjustments, including channel incision and narrowing, on a distance that ranges from several to hundreds of kilometres, depending on river size and the possibility of sediment replenishment through bank erosion and input by tributaries (Fig. 10; Petts, 1979, 1980; Williams and Wolman, 1984; Brandt, 2000; Petts and Gurnell, 2005; Grant, 2012; Skalak et al., 2013). However, the relative scale of these adjustments decreases with an increasing distance from a dam as the scale of disturbance to the sediment balance and the natural flow regime of the river caused by dam reservoir diminishes (Fig. 10; Williams and Wolman, 1984).

Upstream from a dam reservoir, a primary driver of changes is inundation of the river valley by reservoir water (Liro, 2019). The backwater effect reduces flow velocity and bed shear stress in the channel and on the floodplain (Fig. 10), which leads to in-channel deposition of bedload (Leopold et al., 1964; Łajczak, 2006; Skalak et al., 2013; Liro, 2016; Volke et al., 2019) and settling of fine particles transported in suspension on the floodplain (Klimek et al., 1990; Xu and Shi, 1997; Skalak et al., 2013; Volke et al., 2019). These sediment surplus conditions cause aggradation of the channel bed and the floodplain surface (Fig. 10; Skalak et al., 2013; Volke et al., 2019), with aggradation in the channel being more intense and hence resulting in shallowing of the channel (Luo et al., 2018). Intense formation of channel bars shifts a thalweg towards one (in case of lateral bars) or both channel banks (in case of mid-channel bars), which stimulates bank erosion and channel widening (Fig. 10; Liro, 2016). The depositional and morphological changes are initiated at the downstream end of the backwater reach—where the largest increase in water depth caused by backwater inundation leads to the largest decreases in flow velocity and bed shear stress at flood flows—and gradually propagate in the upstream direction (Leopold et al., 1964; Łajczak, 1996; Liro, 2015, 2016). In mountain rivers, a longitudinal extent of direct changes induced by backwater effect is relatively small because of steep channel gradient limiting backwater inundation to a short river reach (Fig. 10; Liro, 2014). However, channel widening and the reduction in channel gradient caused by bed aggradation additionally reduce velocities of channel flows even without inundation of the backwater reach by reservoir water and cause that indirect changes

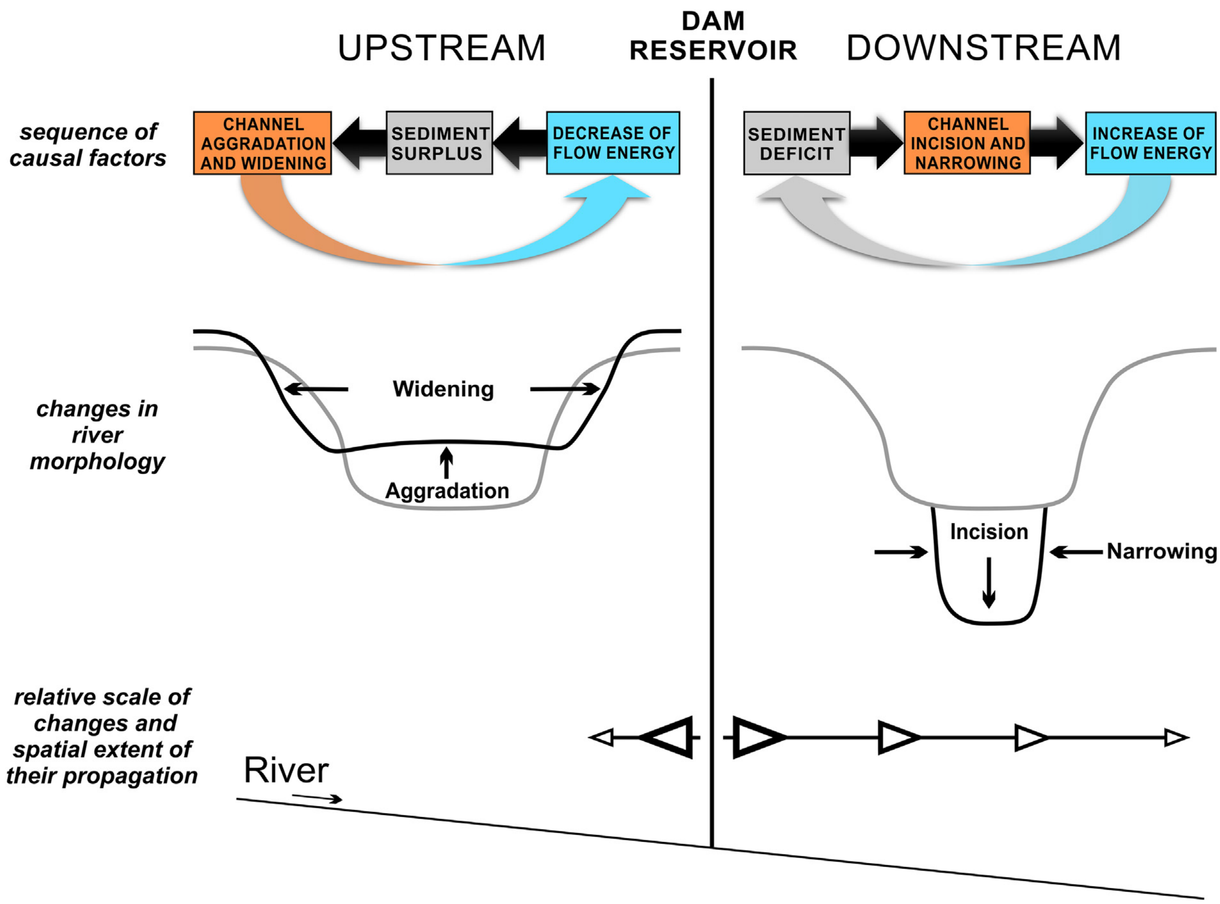

Fig. 10. Conceptual model comparing the sequence of causal factors (with black arrows indicating direct effects of dam reservoir and colour, curved arrows depicting indirect effects), changes in river morphology, and the relative scale of changes and the spatial extent of their propagation upstream and downstream from a dam reservoir on a mountain river.

in the river hydrodynamics may propagate backward behind the beginning of the backwater reach (Fig. 10; Leopold et al., 1964; Liro, 2016).

5.3. Implications of reservoir backwater-induced changes in the river hydrodynamics for the riverine and riparian ecosystems

Changes in the river hydrodynamics caused by direct and indirect impacts of reservoir backwater may have important implications for hydromorphological quality and the condition of riverine and riparian communities of channelized gravel-bed rivers such as the Dunajec. In most European mountain rivers, their high ecological potential, mainly conditioned by a braided channel pattern and the associated diverse hydromorphological characteristics (Tockner et al., 2006; Hauer et al., 2016), was lost in the last century or so as a result of channelization and related channel incision (e.g. Wyżga et al., 2012; Hajdukiewicz et al., 2019). Channel narrowing increased velocities of flood flows and simplification of the flow pattern of the rivers eliminated flow refugia that previously allowed fish and benthic invertebrates to escape high shear forces during floods (Wyżga et al., 2009, 2011). Floods may cause severe mortality or flushing out to downstream reaches of benthic invertebrates and juvenile fishes (Augustyn et al., 2006; Death, 2008; Hajdukiewicz et al., 2018). Channelization and incision of mountain rivers must have increased detrimental effects of floods on riverine biota and this—together with reduced complexity of habitats at base-flow conditions—was reflected in significant decreases in the abundance and taxonomic richness of riverine communities in human-modified river reaches (Wyżga et al., 2009, 2011).

As a result of backwater inundation and morphological river adjustments induced by backwater fluctuations, during floods the river reach located immediately upstream from a dam reservoir is typified by relatively low values of flow velocity and bed shear stress in the channel, facilitating persistence of riverine biota (cf. Negishi et al., 2002). With significantly increased water depth, gravel bars are here submerged even during small floods and become the zones of especially low flow velocity and bed shear stress, hence providing flow refugia for biota (cf. Rempel et al., 1999). All that might make the channel reach immediately upstream from a reservoir a large flow refugium during floods. It seems to be especially crucial for benthic invertebrates which need a stable gravelly substrate to hide during floods (Brunke and Gonser, 1997; Effenberger et al., 2006). Reduced transport capacity of flood flows in the backwater reach facilitates deposition of fine sediments on the channel bed. It may cause clogging of gravel interstices that prevents spawning of lithophilic fish and reduces available habitat for rheophilic benthic invertebrates (Wood and Armitage, 1997). However, it may also increase heterogeneity of substrate types, providing suitable conditions for eurytopic and limnophilic invertebrate taxa and thus increasing the diversity of benthic invertebrate communities (e.g. Wyżga et al., 2011).

River channelization and incision disconnect floodplain from the channel, as it is visible in the control reach of the Dunajec, where the floodplain is not submerged during small and medium floods. Disconnection decreases diversity of invertebrate (Skalski et al., 2016) and plant communities (Cordes et al., 1997; Škarpich et al., 2016) in the riparian and floodplain areas, with vegetation in these areas suffering from reduced frequency of erosional and depositional disturbances (Hupp and Bornette, 2003), reduced delivery of seeds by hydrochory (Cordes et al., 1997) and reduced water availability in the ground (Scott et al., 1999).

Morphological, hydraulic and sedimentary changes recorded in the backwater reach of the Dunajec reduce the floodplain disconnection and may mitigate its negative impacts on riparian and floodplain communities. Backwater-induced aggradation of the channel bed reduces a relative elevation of the floodplain (Fig. 10). This, together with episodes of floodplain inundation by reservoir water, increases soil water availability for floodplain vegetation, which may improve the condition and growth rates of floodplain trees (cf. Allen et al., 2016). The increased frequency and spatial extent of floodplain submergence resulting from fluctuations of reservoir level may improve conditions for the delivery and dispersal of seeds of herbal and tree species by floodwaters (cf. Hayashi et al., 2012). Finally, a thick cover of overbank sediments formed on the floodplain of the backwater reach provides more suitable conditions for plant growth (cf. Bätz et al., 2014) than a relatively thin layer of such sediments overlying gravels on the floodplain along the regulated, incised river channel.

Bed aggradation and considerable channel widening immediately upstream from the beginning of the backwater reach enhance development of highly elevated bars, the surface of which is relatively rarely disturbed by flood flows and may provide edaphic conditions for plant growth (Francis et al., 2009; Bätz et al., 2014). Consequently, wooded islands establish and develop on these bars (Fig. 2B) similarly as in passively restored mountain rivers (Mikuś et al., 2019).

6. Conclusions

This study has demonstrated direct and indirect changes in the hydrodynamics of the Dunajec River upstream from the Czorsztyn Reservoir that were induced by fluctuations of the reservoir backwater. Direct changes of hydraulic parameters of flood flows were limited to a relatively short river reach influenced by backwater inundation during floods and comprised a significant increase in water depth and significant decreases in flow velocity and bed shear stress in the channel and on the floodplain. The modified values of water depth gradually increased and those of flow velocity and bed shear stress decreased towards the reservoir. Moreover, backwater inundation re-established hydrological connectivity between the channel and floodplain during small and medium floods, that was previously disrupted by channel incision. Indirect changes in the river hydrodynamics reflected adjustments in river morphology induced by backwater fluctuations since the beginning of reservoir operation. They comprised significant changes in only some of the modelled hydraulic parameters—mostly reduced velocity of flood flows in the channel zone—but were observed on a longer distance upstream from the reservoir than the backwater reach itself. Such changes influence river hydrodynamics even when backwater inundation does not occur; they must operate, for instance, in early phases of the flood waves entering the reservoir with a large flood reserve and, hence, a relatively low water level.

Changes in river morphology, the sequence of causal factors of environmental changes upstream from dam reservoirs on mountain rivers, and the relative scale and spatial extent of propagation of these changes differ from those occurring downstream from such reservoirs. Upstream from dam reservoirs, environmental changes are driven by modified hydrodynamics and they result in channel widening and bed aggradation. These changes propagate upstream, but their impact is limited to a relatively short river reach.

Changes in hydromorphological characteristics of mountain rivers recorded upstream from dam reservoirs may mitigate negative impacts that riverine and riparian ecosystems of these rivers experienced as a result of channelization and channel incision. These changes include considerably reduced flow velocity and bed shear stress during floods, facilitating finding of flow refugia by riverine biota, better conditions for seeds dispersal and growth of vegetation on the floodplain, and development of wooded islands within the active river zone. However, enhanced deposition of fine sediments on the channel bed may increase the heterogeneity of habitat conditions for benthic invertebrates on one hand and worsen spawning conditions for lithophilic fish on the other hand.

About 14% of dam reservoirs in the world were constructed on mountain rivers (ICOLD, 2019) and findings from this study may be useful for their management.

Authors' contribution

All co-authors contributed to the realization of the study and writing of the paper.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140555.

References

Allen, S.T., Krauss, K.W., Cochran, J.W., King, S.L., Keim, R.F., 2016. Wetland tree transpiration modified by river–floodplain connectivity. J. Geophys. Res. Biogeosci. 121, 753–766. https://doi.org/10.1002/2015JG003208.

Augustyn, L., Bartel, R., Epler, P., 2006. Effects of catastrophic floods on post-stocking survival of reared fry of the brown trout (*Salmo trutta* m. *fario* L.). Acta Scient. Pol. Piscaria 5, 3–16.

Bao, Y., Gao, P., He, X., 2015. The water-level fluctuation zone of Three Gorges Reservoir — a unique geomorphological unit. Earth Sci. Rev. 150, 14–24. https://doi.org/10.1016/j.earscirev.2015.07.005.

Bathurst, J.C., 1982. Theoretical aspects of flow resistance. In: Hey, R.D., Bathurst, J.C., Thorne, C.R. (Eds.), Gravel-bed Rivers. Wiley, Chichester, pp. 83–108.

Bätz, N., Verrecchia, E.P., Lane, S.N., 2014. The role of soil in vegetated gravelly river braid plains: more than just a passive response? Earth Surf. Process. Landf. 40, 143–156. https://doi.org/10.1002/esp.3631.

Best, J., 2019. Anthropogenic stresses on the world's big rivers. Nat. Geosci. 12, 7–21. https://doi.org/10.1038/s41561-018-0262-x.

Bladé, E., Cea, L., Corestein, G., Escolano, E., Puertas, J., Vázquez-Cendón, E., Dolz, J., Coll, A., 2014. Iber: herramienta de simulación numérica del flujo en ríos. Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería 30, 1–10. https://doi.org/10.1016/j.rimni.2012.07.004.

Bodoque, J.M., Díez-Herrero, A., Eguibar, M.A., Benito, G., Ruiz-Villanueva, V., 2015. Challenges in paleoflood hydrology applied to risk analysis in mountainous watersheds – a review. J. Hydrol. 529, 449–467. https://doi.org/10.1016/j.jhydrol.2014.12.004.

Brandt, S.A., 2000. Classification of geomorphological effects downstream of dams. Catena 40, 375–401. https://doi.org/10.1016/S0341-8162(00)00093-X.

Bray, D.J., 1979. Estimating average velocity in gravel-bed rivers. J. Hydraul. Div. ASCE 105 (HY9), 1103–1122.

Brunke, M., Gonser, T., 1997. The ecological significance of exchange processes between rivers and groundwater. Freshw. Biol. 37, 1–33. https://doi.org/10.1046/j.1365-2427.1997.00143.x.

Chow, V.T., 1959. Open-channel Hydraulics. McGraw-Hill, New York (770 pp.).

Cordes, L.D., Hughes, F.M.R., Getty, M., 1997. Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: the Red Deer River, Alberta, Canada. J. Biogeogr. 24, 675–695. https://doi.org/10.1111/j.1365-2699.1997.tb00077.x.

Death, R.G., 2008. The effect of floods on aquatic invertebrate communities. In: Lancaster, J., Briers, R.A. (Eds.), Aquatic Insects: Challenges to Populations. CAB International, Wallingford, pp. 103–121 https://doi.org/10.1079/9781845933968.0103.

Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266, 753–762. https://doi.org/10.1126/science.266.5186.753.

Effenberger, M., Sailer, G., Townsend, C., Matthaei, C.D., 2006. Local disturbance history and habitat parameters influence the microdistribution of stream invertebrates. Freshw. Biol. 51, 312–332. https://doi.org/10.1111/j.1365-2427.2005.01502.x.
Evans, J.E., Huxley, J.M., Vincent, R.K., 2007. Upstream channel changes following dam construction and removal using a GIS/remote sensing approach. J. Am. Water Resour. Assoc. 43, 683–697. https://doi.org/10.1111/j.1752-1688.2007.00055.x.
Francis, R.A., Corenblit, D., Edwards, P., 2009. Perspectives on biogeomorphology, ecosystem engineering and self-organisation in island-braided fluvial ecosystems. Aquat. Sci. 71, 290–304. https://doi.org/10.1007/s00027-009-9182-6.
Gaeuman, D.A., Schmidt, J.C., Wilcock, P.R., 2005. Complex channel responses to changes in stream flow and sediment supply on the lower Duchesne River, Utah. Geomorphology 64, 185–206. https://doi.org/10.1016/j.geomorph.2004.06.007.
Graf, W., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79, 336–360. https://doi.org/10.1016/j.geomorph.2006.06.022.
Grant, G.E., 2012. The geomorphic response of gravel-bed rivers to dams: perspectives and prospects. In: Church, M., Biron, P.M., Roy, A. (Eds.), Gravel-Bed Rivers: Processes, Tools, Environments. Wiley, Chichester, pp. 165–181 https://doi.org/10.1002/9781119952497.ch15.
Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R.M., Goichot Higgins, J., Hogan, Z., Lip, B., McClain, M.E., et al., 2019. Mapping the world's free-flowing rivers. Nature 569, 215–221. https://doi.org/10.1038/s41586-019-1111-9.
Hajdukiewicz, H., Wyżga, B., Amirowicz, A., Oglęcki, P., Radecki-Pawlik, A., Zawiejska, J., Mikuś, P., 2018. Ecological state of a mountain river before and after a large flood: implications for river status assessment. Sci. Total Environ. 610-611, 244–257. https://doi.org/10.1016/j.scitotenv.2017.07.162.
Hajdukiewicz, H., Wyżga, B., Zawiejska, J., 2019. Twentieth-century hydromorphological degradation of Polish Carpathian rivers. Quat. Int. 504, 181–194. https://doi.org/10.1016/j.quaint.2017.12.011.
Hanks, R.D., 2020. Dams: Anthrome Enablers. Reference Module in Earth Systems and Environmental Sciences. https://doi.org/10.1016/b978-0-12-409548-9.12035-4.
Hauer, F.R., Locke, H., Dreitz, V.J., Hebblewhite, M., Lowe, W.H., Muhlfeld, C.C., Nelson, C.R., Proctor, M.F., Rood, S.B., 2016. Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. Sci. Adv. 2, 1–13. https://doi.org/10.1126/sciadv.1600026.
Hayashi, H., Shimatani, Y., Shigematsu, K., Nishihiro, J., Ikematsu, S., Kawaguchi, Y., 2012. A study of seed dispersal by flood flow in an artificially restored floodplain. Landsc. Ecol. Eng. 8, 129–143. https://doi.org/10.1007/s11355-011-0154-3.
Hosseiny, H., Smith, V., 2019. Two dimensional model for backwater geomorphology: Darby Creek, PA. Water 11, 2204. https://doi.org/10.3390/w11112204.
Hupp, C.R., Bornette, G., 2003. Vegetation as a tool in the interpretation of fluvial geomorphic processes and landforms in humid temperate areas. In: Kondolf, G.M., Piégay, H. (Eds.), Tools in Fluvial Geomorphology. Wiley, Chichester, pp. 269–288 https://doi.org/10.1002/0470868333.ch10.
ICOLD, 2019. World Register of Dams. ICOLD—International Commission of Large Dams.
Javernick, L., Brasington, J., Caruso, B., 2014. Modeling the topography of shallow braided rivers using structure-from-motion photogrammetry. Geomorphology 213, 166–182. https://doi.org/10.1016/j.geomorph.2014.01.006.
Klimek, K., Łajczak, A., Zawilińska, L., 1990. Sedimentary environment of the modern Dunajec delta in the artificial Rożnów Lake, Carpathian Mts. Quaest. Geogr. 11/12, 81–92.
Knighton, D., 1998. Fluvial Forms and Processes. A New Perspectives. Arnold, New York (383 pp.).
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, M., Loire, R., Piégay, H., Malavoi, J.R., 2019. Dams and channel morphology. In: Williams, J.G., Moyle, P.B., Webb, A., Kondolf, G.M. (Eds.), Environmental Flow Assessment: Methods and Applications. Wiley, Chichester, pp. 143–213 https://doi.org/10.1002/9781119217374.ch8.
Krzemień, K., 1981. Zmienność subsystemu korytowego Czarnego Dunajca (The changeability of the Czarny Dunajec channel subsystem) Zesz. Nauk. Uniw. Jagiel., Pr. Geogr. 53, 123–137 (in Polish, with English summary).
Książek, L., 2006. Morfologia koryta rzeki Skawy w zasięgu cofki zbiornika Świnna Poręba. Infrastruktura i Ekologia Terenów Wiejskich 4, 249–267 (in Polish, with English summary).
Kundzewicz, Z.W., Stoffel, M., Kaczka, R.J., Wyżga, B., Niedźwiedź, T., Pińskwar, I., Ruiz Villanueva, V., Łupikasza, E., Czajka, B., Ballesteros-Canovas, J.A., Małarzewski, Ł., Choryński, A., Janecka, K., Mikuś, P., 2014. Floods at the northern foothills of the Tatra Mountains — a Polish–Swiss research project. Acta Geophys 62, 620–641. https://doi.org/10.2478/s11600-013-0192-3.
Łajczak, A., 1996. Modelling the long-term course of non-flushed dam reservoir sedimentation and estimating the life of dams. Earth Surf. Process. Landf. 21, 1091–1107.
Łajczak, A., 2006. Deltas in dam-retained lakes in the Carpathian part of the Vistula drainage basin. Pr. Geol. 116, 99–109.
Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco (522 pp.).
Leviandier, T., Alber, A., Le Ber, F., Piégay, H., 2012. Comparison of statistical algorithms for detecting homogeneous river reaches along a longitudinal continuum. Geomorphology 138, 130–144. https://doi.org/10.1016/j.geomorph.2011.08.031.
Li, Y., Shang, Q., Jiang, J., Da, B., Gao, Y., 2019. Study on processes of Changshou waterway after 175 m experimental impoundment of the Three Gorges Reservoir. IOP Conf. Ser.: Earth Environ. Sci. 304, 022025. https://doi.org/10.1088/1755-1315/304/2/022025.
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.
Liro, M., 2014. Conceptual model for assessing the channel changes upstream from dam reservoir. Quaest. Geogr. 33, 61–74. https://doi.org/10.2478/quageo-2014-0007.
Liro, M., 2015. Gravel-bed channel changes upstream of a reservoir: the case of the Dunajec River upstream of the Czorsztyn Reservoir, southern Poland. Geomorphology 228, 694–702. https://doi.org/10.1016/j.geomorph.2014.10.030.
Liro, M., 2016. Development of sediment slug upstream from the Czorsztyn Reservoir (southern Poland) and its interaction with river morphology. Geomorphology 253, 225–238. https://doi.org/10.1016/j.geomorph.2015.09.018.
Liro, M., 2017. Dam-induced base-level rise effects on the gravel-bed channel planform. Catena 153, 143–156. https://doi.org/10.1016/j.catena.2017.02.005.
Liro, M., 2019. Dam reservoir backwater as a field-scale laboratory of human-induced changes in river biogeomorphology: a review focused on gravel-bed rivers. Sci. Total Environ. 651, 899–2912. https://doi.org/10.1016/j.scitotenv.2018.10.138.
Luo, M., Yu, H., Huang, E., Ding, R., Lu, X., 2018. Two-dimensional numerical simulation study on bed-load transport in the fluctuating backwater area: a case-study reservoir in China. Water 10, 1425. https://doi.org/10.3390/w10101425.
Malmqvist, B., Rundle, S., 2002. Threats to the running water ecosystems of the world. Environ. Conserv. 29, 134–153. https://doi.org/10.1017/S037689202000097.
Masselli, V., Pellegrini, C., Del Bianco, F., Mercorella, A., Nones, M., Crose, L., Guerrero, M., Nittrouer, J., 2018. River morphodynamic evolution under dam-induced backwater: an example from the Po River (Italy). J. Sed. Res. 88, 1190–1204. https://doi.org/10.2110/jsr.2018.61.
Meyer-Peter, E., Müller, R., 1948. Formulas for bed-load transport. Proceedings 2nd Meeting International Association of Hydraulic Research, Stockholm, Sweden, pp. 39–64.
Mikuś, P., Wyżga, B., Walusiak, E., Radecki-Pawlik, A., Liro, M., Hajdukiewicz, H., Zawiejska, J., 2019. Island development in a mountain river subjected to passive restoration: the Raba River, Polish Carpathians. Sci. Total Environ. 660, 406–420. https://doi.org/10.1016/j.scitotenv.2018.12.475.
Muhar, S., Jungwirth, M., 1998. Habitat integrity of running waters – assessment criteria and their biological relevance. Hydrobiologia 386, 195–202. https://doi.org/10.1023/A:1003588631679.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — a discussion of principles. J. Hydrol. 10, 282–290. https://doi.org/10.1016/0022-1694(70)90255-6.
Negishi, J.N., Inoue, M., Nunokawa, M., 2002. Effects of channelisation on stream habitat in relation to a spate and flow refugia for macroinvertebrates in northern Japan. Freshw. Biol. 47, 1515–1529. https://doi.org/10.1046/j.1365-2427.2002.00877.x.
Niedźwiedź, T., Obrębska-Starklowa, B., 1991. Klimat (Climate). In: Dynowska, I., Maciejewski, M. (Eds.), Dorzecze górnej Wisły. PWN, Warszawa-Kraków, pp. 68–84.
Orlowsky, B., 2014. iki.dataclim. R package, version 1.0. Available at: https://cran.r-project.org/web/packages/iki.dataclim/iki.dataclim.pdf.
Petts, G.E., 1979. Complex response of river channel morphology subsequent to reservoir construction. Prog. Phys. Geogr. 3, 329–362.
Petts, G.E., 1980. Long-term consequences of upstream impoundment. Environ. Conserv. 7, 325–332.
Petts, G.E., Gurnell, A.M., 2005. Dams and geomorphology: research progress and future directions. Geomorphology 71, 27–47. https://doi.org/10.1016/j.geomorph.2004.02.015.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. Bioscience 47, 769–784. https://doi.org/10.2307/1313099.
R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna https://www.R-project.org.
Radecki-Pawlik, A., Wyżga, B., Czech, W., Mikuś, P., Zawiejska, J., Ruiz-Villanueva, V., 2016. Modelling hydraulic parameters of flood flows for a Polish Carpathian river subjected to variable human impacts. In: Kundzewicz, Z.W., Stoffel, M., Niedźwiedź, T., Wyżga, B. (Eds.), Flood Risk in the Upper Vistula Basin. Springer, Cham, pp. 127–151 https://doi.org/10.1007/978-3-319-41923-7_7.
Rempel, L.L., Richardson, J.S., Healey, M.C., 1999. Flow refugia for benthic macroinvertebrates during flooding of a large river. J. N. Am. Benthol. Soc. 18, 34–48. https://doi.org/10.2307/1468007.
Rinaldi, M., Wyżga, B., Dufour, S., Bertoldi, W., Gurnell, A., 2013. River processes and implications for fluvial ecogeomorphology: A European perspective. In: Shroder, J., Butler, D., Hupp, C.R. (Eds.), Treatise on Geomorphology. Ecogeomorphology. vol. 12. Academic Press, San Diego, pp. 37–52. https://doi.org/10.1016/B978-0-12-374739-6.00321-3.
Rusnák, M., Sládek, J., Kidová, A., Lehotský, M., 2018. Template for high-resolution river landscape mapping using UAV technology. Measurement 115, 139–151. https://doi.org/10.1016/j.measurement.2017.10.023.
Scott, M.L., Shafroth, P.B., Auble, G.T., 1999. Responses of riparian cottonwood to alluvial water table declines. Environ. Manag. 23, 347–358. https://doi.org/10.1007/s002679900191.
Shields, A., 1936. Application of Similarity Principles and Turbulence Research to Bed-Load Movement. vol. 26. Mitteilungen der preussischen Versuchsanalt fürWasserbau und Schiffbau, Berlin (524 pp.).
Skalak, K.J., Benthem, A.J., Schenk, E.R., Hupp, C.R., Galloway, J.M., Nustad, A.R., Wiche, W.J., 2013. Large dams and alluvial rivers in the Anthropocene: the impacts of the Garrison and Oahe Dams on the Upper Missouri River. Anthropocene 2, 51–64. https://doi.org/10.1016/j.ancene.2013.10.002.
Skalski, T., Kędzior, R., Wyżga, B., Radecki-Pawlik, A., Plesiński, K., Zawiejska, J., 2016. Impact of incision of gravel-bed rivers on ground beetle assemblages. River Res. Appl. 32, 1968–1977. https://doi.org/10.1002/rra.3027.

Škarpich, V., Horáček, M., Galia, T., Kapustová, V., Šala, V., 2016. The effects of river patterns on riparian vegetation: a comparison of anabranching and single-thread incised channels. Morav. Geogr. Rep. 24 (3), 24–31. https://doi.org/10.1515/mgr-2016-0014.
Sroczyński, W., 2004. Jeziora zaporowe w krajobrazie Karpat (barrier lakes in the Carpathians — Selected problems in spatial organization). In: Myga-Piątek, U. (Ed.), Przemiany Krajobrazu Kulturowego Karpat. Wybrane aspekty. Komisja Krajobrazu Kulturowego PTG, Sosnowiec, pp. 87–98 (in Polish, with English summary).
Strickler, A., 1923. Beiträge zur Frage der Geschwindigkeitsformelund der Rauhigkeitszahlen fur Ströme, Kanäle und Geschlossene Leitungen (Bern (77 pp.).
Sundborg, A., 1956. The river Klarälven: a study of fluvial processes. Geogr. Ann. 38A, 127–316.
Tockner, K., Paetzold, A., Kraus, U., Claret, C., Zettel, J., 2006. Ecology of braided rivers. In: Sambrook Smith, G., Best, J.L., Bristow, C.S., Petts, G.E. (Eds.), Braided Rivers: Process, Deposits, Ecology and Management. Blackwell, London, pp. 339–359 https://doi.org/10.1002/9781444304374.ch17.
Toone, J., Rice, S.P., Piégay, H., 2014. Spatial discontinuity and temporal evolution of channel morphology along a mixed bedrock-alluvial river, upper Drôme River, Southeast France: contingent responses to external and internal controls. Geomorphology 205, 5–16. https://doi.org/10.1016/j.geomorph.2012.05.033.
Volke, M.A., Scott, M.L., Johnson, W.C., Dixon, M.D., 2015. The ecological significance of emerging deltas in regulated rivers. BioScience 20, 1–14. https://doi.org/10.1093/biosci/biv040.
Volke, M.A., Johnson, W.C., Dixon, M.D., Scott, M.L., 2019. Emerging reservoir delta backwaters: biophysical dynamics and riparian biodiversity. Ecol. Monogr. 89, e01363. https://doi.org/10.1002/ecm.1363.
Westboy, M.J., Brasington, N.F., Glasser, M.J., Hambrey, J.M., Reynolds, J.M., 2012. 'Structure-from-motion' photogrammetry: a low-cost, effective tool for geosciences applications. Geomorphology 179, 300–314. https://doi.org/10.1016/j.geomorph.2012.08.021.
Wiejaczka, Ł., Kiszka, K., Bochenek, W., 2014. Changes of the morphology of the Ropa River — upstream and downstream of the Klimkowka water reservoir. Stud. Geomorph. Carp.–Balcan. 48, 61–76. https://doi.org/10.1515/sgcb-2015-0005.
Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. Geol. Surv. Prof. Paper 1286, 1–83. https://doi.org/10.3133/pp1286.
Wohl, E., 2006. Human impacts to mountain streams. Geomorphology 79, 217–248. https://doi.org/10.1016/j.geomorph.2006.06.020.
Wolman, M.G., 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union 35, 951–956.
Wood, P.J., Armitage, P.D., 1997. Biological effects of fine sediment in the lotic environment. Environ. Manag. 21, 203–217. https://doi.org/10.1007/s002679900019.
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., Amirowicz, A., Radecki-Pawlik, A., Zawiejska, J., 2009. Hydromorphological conditions, potential fish habitats and the fish community in a mountain river subjected to variable human impacts, the Czarny Dunajec, Polish Carpathians. River Res. Appl. 25, 517–536. https://doi.org/10.1002/rra.1237.
Wyżga, B., Oglęcki, P., Radecki-Pawlik, A., Zawiejska, J., 2011. Diversity of macroinvertebrate communitites as a reflection of habitat heterogeneity in a mountain river subjected to variable human impacts. In: Simon, A., Bennett, S.J., Castro, J.M. (Eds.), Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses and Tools. American Geophysical Union, Washington, pp. 189–207 https://doi.org/10.1029/2010GM000983.
Wyżga, B., Zawiejska, J., Radecki-Pawlik, A., Hajdukiewicz, H., 2012. Environmental change, hydromorphological reference conditions and the restoration of Polish Carpathian rivers. Earth Surf. Process. Landf. 37, 1213–1226. https://doi.org/10.1002/esp.3273.
Wyżga, B., Zawiejska, J., Hajdukiewicz, H., 2016a. Multi-thread rivers in the Polish Carpathians: occurrence, decline and possibilities of restoration. Quatern. Int. 415, 344–356. https://doi.org/10.1016/j.quaint.2015.05.015.
Wyżga, B., Zawiejska, J., Radecki-Pawlik, A., 2016b. Impact of channel incision on the hydraulics of flood flows: examples from Polish Carpathian rivers. Geomorphology 272, 10–20. https://doi.org/10.1016/j.geomorph.2015.05.017.
Wyżga, B., Kundzewicz, Z.W., Konieczny, R., Piniewski, M., Zawiejska, J., Radecki -Pawlik, A., 2018. Comprehensive approach to the reduction of river flood risk: case study of the upper Vistula Basin. Sci. Total Environ. 631–632, 1251–1267. https://doi.org/10.1016/j.scitotenv.2018.03.015.
Wyżga, B., Radecki-Pawlik, A., Galia, T., Plesiński, K., Škarpich, V., Dušek, R., 2020. Use of high-water marks and effective discharge calculation to optimize the height of bank revetments in an incised river channel. Geomorphology 356, 107098. https://doi.org/10.1016/j.geomorph.2020.107098.
Xiao, Y., Yang, F.S., Su, L., Li, J.W., 2015. Fluvial sedimentation of the permanent backwater zone in the Three Gorges Reservoir, China. Lake Reserv. Manag. 31, 324–338. https://doi.org/10.1080/10402381.2015.1085115.
Xu, J., 1990. Complex response in adjustment of Weihe channel to the construction of the Sanmenxia reservoir. Z. Geomorphol. 34, 233–245. https://doi.org/10.11821/yj1989020009.
Xu, J., 2001a. Modified conceptual model for predicting the tendency of alluvial channel adjustment induced by human activities. Chin. Sci. Bull. 46, 51–56. https://doi.org/10.1007/BF03187236.
Xu, J., 2001b. Adjustment of mainstream — tributary relation upstream from a reservoir: an example from the Laohahe River, China. Z. Geomorphol. 45, 359–372.
Xu, J., Shi, C., 1997. The river channel pattern change as influenced by the floodplain geoecosystem: an example from the Hongshan Reservoir. Z. Geomorphol. 41, 97–113. https://doi.org/10.1360/sb1994-39-7-560.
Zawiejska, J., Krzemień, K., 2004. Human impact on the dynamics of the upper Dunajec River channel: a case study. Geogr. Čas. 56, 111–124.
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.