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FLOOD EVENTS AS GEOMORPHIC THRESHOLDS FOR CHANNEL BED LEVEL CHANGE

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Abstract: Channel bed levels are highly dynamic in time and across space, constantly adjusting under the influence of natural and anthropogenic controls. The aim of this study was to assess the role of flood events recorded between 1994 and 2018 in the bed elevation changes documented on the major tributaries of Trotuș River (Eastern Carpathians). To this purpose, the data from fifteen gauging stations was used, based on which the evolution trends of channel bed levels were determined for the investigated channel reaches. The role of geomorphic threshold was assigned to stream power. The daily maximum and total values of this parameter were used to explain the bed elevation shifts. The average channel bed deepening rate was 2.2 cm/yr. Depending on the variation trend of channel bed levels, three evolution patterns could be distinguished in relation to the reference year: (i) a category where channel degradation was nearly continuous; (ii) another one where initial aggradation of the channel bed occurred, ensued by continuous degradation, without reverting to the initial state, and (iii) a group with oscillating aggradation-degradation evolution resulting in the eventual recovery of the initial state. The recovery time for changes triggered by major flood events ranged between one and nearly 10 years, whereas in the case of shifts generated by high frequency, low magnitude events, the recovery time was maximum one year. Over short term flood events drive the direction and intensity of channel bed elevation adjustments.

Keywords: Bed elevation; flood; stream power; channel bed level change; recovery time; Eastern Carpathians.

1. INTRODUCTION

The morphology of river channels is highly dynamic in space and time, thus constantly changing under the influence of natural and anthropogenic controls (Grabowski et al., 2014; Wiejaczka & Kijowska-Strugała, 2015; Dewan et al., 2017). Rădoane et al. (2013) have shown that climate changes and related changes in the frequency and amplitude of floods are an essential part of the historic dynamics of river channel, and that human interventions only modulate these dynamics, most often by exacerbating the modifications induced by climate changes. Against this backdrop, episodic, high-magnitude geomorphic events (such as floods) can trigger significant changes in river channels due to the large amount of energy expended during these events (Rusnák & Lehotský, 2014; Nelson & Dubé, 2016). The main geomorphic responses of river channels to such events consist in channel widening, channel deepening and aggrading (Joyce et al., 2018). Channel bed level changes can be determined by certain long or short term shifts of control factors. Thus, the short term variability of these controls can result in reach-scale scour/fill, whereas long term variability leads to channel aggrading or degrading (Slater & Singer, 2013). Such shifts are reported in the literature either as a synchronous response to global climate changes (long term) (e.g. Blum & Törnqvist, 2000; Mol et al., 2000; Marchese et al., 2017), or in relation to the increasing frequency of extreme flood events (short term) (e.g. Knox, 1983; Macklin & Lewin, 1989; Rumsby & Macklin, 1994; Macklin et al., 1998). While the papers reporting channel widening subsequent to flood events are more common, the studies that analyze the correlation between channel elevation changes and certain characteristics of flood events are less numerous (Pfeiffer et al., 2019). Therefore, this study is focused on the short term changes (under the influence of flood events) of channel bed levels.

Geomorphically effective flood events (according to Eisenbies et al., 2007) can be regarded as geomorphic thresholds in the evolution of channels if the channel changes persist for a longer period of time in relation to the frequency of the event (Brunsden & Thornes, 1979; Erskine, 2011). The concept of geomorphic threshold was introduced by Schumm (1973) in the attempt to explain the evolution and the permanent tendency of geomorphic systems to reach a state of dynamic equilibrium (Ichim et al., 1989). Later on, Schumm (1979) defined the geomorphic threshold as "... *a threshold of landform stability that is exceeded either by intrinsic of the landform itself, or by a progressive change of an external variable*". Thresholds hold a particular significance in geomorphology, particularly in fluvial geomorphology (Coates & Vitek, 1980; Chappell, 1983; Schumm, 1991; Church, 2002; Phillips, 2006). Thresholds can be intrinsic (when the force driving the change acts within the system or is a consequence of system evolution) and extrinsic (when the force acts from outside the system) (Schumm, 1973). In fluvial systems extrinsic thresholds can be caused by climate fluctuations, base level changes, land use shifts etc., whereas intrinsic thresholds could originate, for instance, in the increasing sediment amounts, shifts in slope gradients (Ichim et al., 1989). In relation to these thresholds, the resulting changes occurring within river channels can be autogenic or allogenic (Lewin 1977). One of the geomorphic thresholds utilized frequently in fluvial geomorphology is the stream power during flood events (Miller, 1990; Magilligan, 1992, 2015; Erskine, 2011; Thompson & Croke, 2013; Buraas et al., 2014; Marchi et al., 2016; Yochum et al., 2017). In this study the changes in channel bed elevation subsequent to flood events were related to the stream power. This relation has seldom been approached in fluvial geomorphology (Simon & Rinaldi, 2006; Scorpio et al., 2018).

Determining the temporal changes of channel bed levels has been a very common approach since the early 1900s (Juracek & Fitzpatrick, 2009). These analyses were made either based on the relation between the stage and the discharge (if the data used for the study is yielded by gauging stations) (Williams & Wolman, 1984; Juracek & Fitzpatrick, 2009; Rădoane et al., 2010, 2013; Wiejaczka & Kijowska-Strugała, 2015), or on topographic surveys (cross-sections, longitudinal thalweg or water-surface profiles) (Le Coz et al., 2018; Gibson & Shelley, 2020). Both approaches have advantages as well as downsides (Bowen & Juracek, 2011; Pandi & Horváth, 2012).

The temporal changes in channel bed levels originate in the local discrepancies of the sediment flow in relation to the transport capacity of the discharge. When the transport capacity is higher than the sediment flow, the bed is eroded; conversely, if the sediment flow exceeds the transport capacity of the discharge, the sediment is deposited and the channel bed aggrades as a result (Wyżga et al., 2016; Hajdukiewicz et al., 2019; Pfeiffer et al., 2019). The analysis of the double mass curve was used in order to detect the relation between channel bed elevation changes and sediment flow shifts. This application which analyses the role of flood events in changing the channel bed levels by using the double mass curve is novel and has been employed previously solely for other purposes (Gao et al., 2010, 2017; Jiang et al., 2015).

Channel recovery following disturbances can be defined in several ways. Wolman & Gerson (1978) characterize recovery in terms of reestablishing channel form following large storms and climatic variations (Madej & Ozaki, 2009). The recovery time after flood events varies greatly, ranging from several years to hundreds of years, whereas some channels never recover to reach the conditions prior to the flood event (Sloan et al., 2001; Lancaster & Casebeer, 2007; Joyce et al., 2018).

In Romania the temporal changes of channel bed levels have been investigated previously. These studies focused either on rivers from the entire country (Diaconu et al., 1962), from the Eastern Carpathian area (Rădoane et al., 1991, 2010, 2013), or refer to a single river (Popa-Burdulea, 2007; Canciu, 2008; Perșoiu, 2010). However, none of the above mentioned studies approaches the relation between the characteristics of flood events and the shifts in channel bed elevation.

The aim of this study is to identify the role of flood events in the changes of channel bed levels on the most important tributaries of Trotuș River (in the Eastern Carpathians) between 1994 and 2018. In order to attain this goal, the geomorphic effects (short-term change and subsequent recovery) of flood events were assessed based on the data provided by 15 gauging stations. The reason for selecting these particular streams was that all previous studies were focused on major watercourses, despite the fact that small catchments are in fact the fundamental units for interpreting landform dynamics (Rădoane et al., 2006b; Dumitriu, 2007).

The specific objectives of the study focus on: (i) quantifying the temporal changes of channel bed elevation; (ii) assessing the relation between channel bed level changes and the stream power; (iii) identifying the events that generated disturbances in the channel equilibrium using the double mass curve; (iv) determining the recovery time for channels after these events.

2. STUDY AREA

The analysis of channel bed level change was carried out based on the data recorded at gauging stations located on the following tributaries of Trotus River: Valea Rece, Sulța, Ciobănuș, Asău, Uz, Dofteana, Slănic, Oituz, Cașin and Tazlău (Fig. 1). Suspended sediment load measurements are performed only for four tributaries (Asău, Uz, Oituz and Tazlău). The main characteristics of drainage basins upstream of the gauging stations are listed in Table 1. The Dărmănești gauging station are located downstream of Uz reservoir, therefore the flow discharge is controlled by human design and intervention.

Trotuș basin is an upper mesoscale mountainous catchment (i.e. 4350 km^2) located in the central-eastern part of the Eastern Carpathians (Fig. 1). Trotuș River is one of the major tributaries of Siret River, which is, in turn, the largest tributary of the Danube within the Romanian territory (Dumitriu, 2018). The hydrology of Trotuș River basin is regulated by the pluvio-nival regime, with spring flooding occurring typically in April-May as a result of snowmelt, high precipitation or the overlapping of both. In June, July and occasionally extending to August, summer floods can occur as a result of abundant precipitation, reaching very high amplitudes, as was the case with the floods of June-July 2005 (Dumitriu, 2007, 2018).

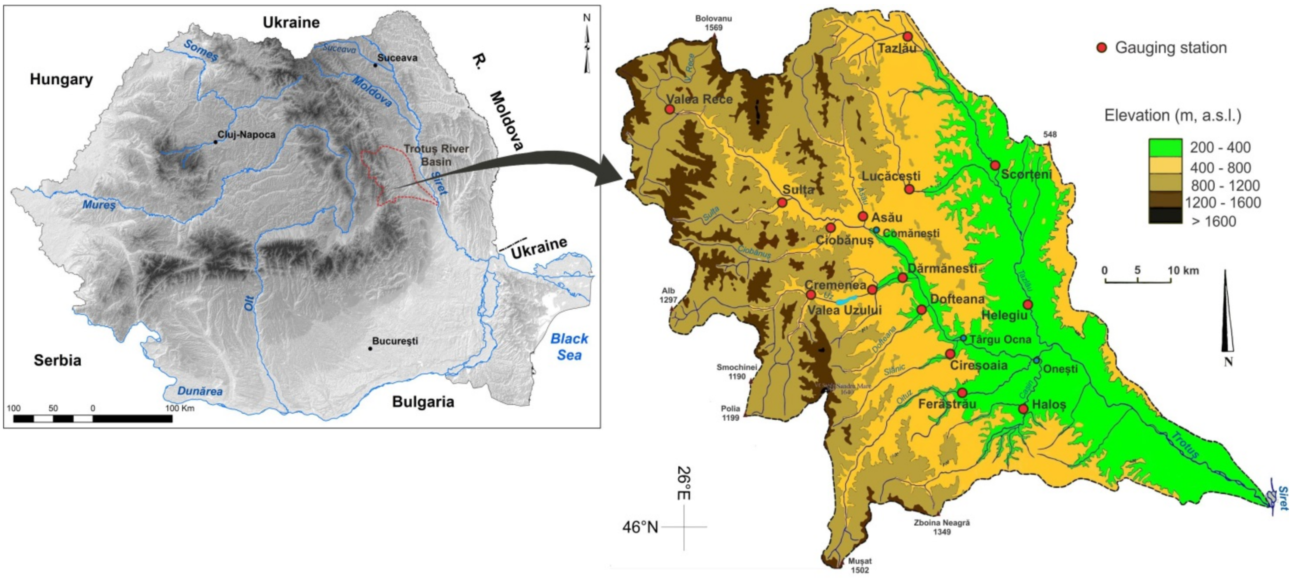

Figure 1. Location of the study area in Romania and the Eastern Carpathians (**a**); Location of analyzed gauging stations within Trotuș drainage basin (**b**).

Table 1. Main characteristics of drainage basin and channel at gauging stations.

No.	River	Gauging station	Distance from river mouth (km)	Data regarding the drainage basin		Gauging station elevation (m)	Gauging station slope (m m^{-1})	Mean multiannual discharge (m^3 s^{-1})
				Area (km^2)	Mean elevation (m)			
1	Valea Rece	Valea Rece	1	120	1145	790	0.019	1.35
2	Sulța	Sulța	1	116	1041	551	0.023	1.06
3	Ciobănuș	Ciobănuș	1	135	1052	475	0.022	0.96
4	Asău	Asău	2	204	951	430	0.012	1.83
5	Uz	Valea Uzului	22	150	1070	628	0.015	1.43
6	Uz	Cremenea	16	337	1070	545	0.012	3.96
7	Uz	Dărmănești	2	470	949	403	0.011	2.86
8	Dofteana	Dofteana	0.4	110	735	301	0.014	0.93
9	Slănic	Cireșoaia	7	105	775	340	0.019	1.10
10	Oituz	Ferăstrău	19	267	810	300	0.008	2.75
11	Cașin	Haloș	18	220	717	298	0.004	2.14
12	Tazlăul Sărat	Lucăcești	18	118	801	425	0.010	1.30
13	Tazlău	Tazlău	72	129	793	435	0.010	1.51
14	Tazlău	Scorțeni	40	412	574	294	0.006	3.00
15	Tazlău	Helegiu	14	998	520	209	0.002	6.50

The resistance to erosion of the geological substrate differs depending on the types of rock outcropping in these basins: thus, erosion resistant rocks are prevalent in basins such as Valea Rece, Sulța, Ciobănuș, Asău, Uz and Oituz (upper and mid basins), and Cașin (upper basin); moderately resistant rocks are dominant in Dofteana and Slănic basins; and rocks with low resistance are prevalent in basins such as Tazlău, Oituz (lower basin) and Cașin (mid and lower basins) (Dumitriu, 2014). Consequently, the most significant sediment yields were documented in basins whereby the rock resistance to erosion is low. These basins are also under the influence of strong anthropogenic intervention (Dumitriu et al., 2017). Gravel bed channels are typical for all 10 investigated streams (Dumitriu, 2007; Rădoane et al., 2006a). With the exception of Tazlău and Valea Rece basins, within the remaining basins the forested area accounts for more than 75% of the total basin area (Dumitriu, 2020).

3. DATA AND METHODS

3.1. Data sources

The data regarding the flow discharge (Q, $m^3 s^{-1}$), the suspended sediment load (SSL, kg s^{-1}), the stage of the stream (above the zero stage of the gage) (S, cm), the maximum depth of the river bed (MD, cm) and the cross-section surveys are provided by the "Romanian Waters" National Administration-Siret Water Branch, which manages the fifteen gauging stations included in this study (Table 1 and Fig. 1). The data analyzed in the study corresponds to the 1994-2018 period, with the exception of Tazlău and Scorțeni gages, which have provided data series covering the 2000-2018 period.

3.2. Methods

3.2.1. Determining the channel bed elevation

The analysis of the vertical dynamics of the channel bed was carried out using "*discharge centralizers*" according to the methodology introduced by Rădoane et al., (2010). Thus, the channel bed elevation (BE) characteristic for a certain time frame is defined as the difference between the water gage height measured above the zero stage of the gage (S) and the maximum water depth (MD). At each gauging station between 3 and 15 S and MD measurements were carried out every month in order to calculate monthly averages. This resulted in two data series for the monthly bed elevation (MBE) and the annual bed elevation (ABE), based on which the dynamics of the monthly and annual average values were derived at the 15 gauging stations. Furthermore, the mean annual values were used to determine the annual bed level change (ABLC). For that purpose, the mean bed elevation in 1994 and 2000 (for Tazlău and Scorțeni gages), respectively, were considered as reference values. The values characteristic for the years 1994 or 2000 were subtracted from all the other values. If the results were positive we considered that during that particular year the channel bed aggraded, whereas negative differences indicated bed degradation. In this context some additional notes are required. During flood events, abrupt processes, such as scouring and filling, occur as short duration hydraulic adjustments of the channel (lasting for hours, days, months, sometimes even 1 year). The two processes alternate in time, creating the appearance of low amplitude, high frequency oscillations. Scour-fill oscillations correspond typically to the rising and falling limbs of flood events (usually, scouring on the rising limb and filling on the falling limb) (Andrews, 1979; Rădoane et al., 1991). Bed elevation changes throughout long periods of time (i.e. years or decades) are called aggradation (bed level increase) and degradation (bed level lowering). Whereas the rhythm of these processes is much slower compared to scouring and filling, their amplitude is considerably larger (Rădoane et al., 2010). Channel bed level variations were also examined using temporal cross sections. These profiles were also provided by the gauging stations.

3.2.2. Stream power

In this study the changes in channel bed elevation were also related to stream power. This parameter was often used to explain channel changes occurring subsequent to flood events (Lea & Legleiter, 2016), despite the fact that it cannot fully account for the response of the river to flood events in all instances (Heritage et al., 2004; Surian et al., 2016; Scorpio et al., 2018).

Specific stream power (SSP, W m^{-2}) is defined as: $SSP = \gamma QS/w$ (1)

where γ is the unit weight of water (9800 N m^{-3}), S is channel bed slope, and w is the channel bankfull width (m) (Bagnold, 1966; Bizzi & Lerner, 2015). The average annual dynamic of bed elevation was correlated with maximum annual stream power (MSP) and to total stream power (TSP). The latter is determined as the sum of daily average stream power values.

3.2.3. Double mass curve

Due to its simplicity, the double mass curve (DMC) was often used to analyze long term trends for hydro-meteorological variables (Gao et al., 2017).

The DMC theory is based on the fact that a plot of two cumulative quantities during the same period exhibits a straight line if the proportionality between the two remains unchanged; the slope of the line represents the proportionality. This method can smooth a time series and suppress random elements in the series; thus, it can show the main trends of the time series (Jiang et al., 2015). In this study DMC (SSL vs Q) was used to correlate channel bed level changes subsequent to flood events with sediment flow shifts generated by the same events. This approach is a novelty for fluvial geomorphology studies.

4. RESULTS

4.1. Monthly bed elevation (MBE) changes

As regards the dynamics of channel bed elevation throughout the entire analyzed period (1994 to 2018 or 2000 to 2018) it was established that channel bed degradation was prevalent, whereas aggradation was documented only at two gauging stations (Valea Rece and Cireşoaia) and channel stability was determined at one station (Valea Uzului) (Fig. 2). Although for the entire analyzed period degradation was dominant, during certain sub-periods the situation was much more complex. The short term succession of stability phases with aggradation/degradation phases was attributed to flood events. High frequency, low magnitude flood events (recurrence intervals of 1-2 years) generate minor disturbances (due to scouring and filling) in terms of channel bed elevation. Therefore, they are less likely to change the general trend of channel aggradation or degradation. Conversely, low frequency, high magnitude events have generated significant changes in channel bed elevation. Such abrupt shifts were documented, either from a state of aggradation (or stability) to degradation, or inversely. At the majority of gauging stations from the study area the flood event of 2005 (12-13 July) stood out as the main threshold in the dynamic of channel bed elevation. Other major changes were generated by the flood events of 1997, 2004, 2010, 2016. Depending on these events which left their mark on the bed elevation, several major intervals were separated in terms of the bed level dynamics.

For the vast majority of analyzed gages, the first homogeneous interval was the one prior to the flood event of 1997. In this period the channel bed was rather stable in seven sections. In three sections (Valea Uzului, Cremenea and Dofteana) the dominant process was aggradation, whereas in the three remaining sections (Valea Rece, Sulţa and Helegiu) channel degradation was prevalent. Aside from these major tendencies, short duration scouring and filling were also documented

The flood event of 1997 had a wide range of effects on channel bed level. Thus, in five sections (Ciobănuş, Asău, Dărmăneşti, Cireşoaia and Lucăceşti) this event resulted in an increase of bed elevation; in six sections (Valea Uzului, Cremenea, Dofteana, Ferăstrău, Haloş and Helegiu) the bed elevation decreased, whereas in the two remaining sections (Valea Rece and Sulţa) both degradation and aggradation ceased and a state of relative stability of the channel bed became prevalent.

The state of the channel bed generated by the flood event of 1997 persisted for different periods of time depending of the geomorphic effectiveness of flood events (Dumitriu, 2016): at some stations (Valea Rece, Valea Uzului, Cremenea, Cireşoaia, Lucăceşti) until 2001 or 2002 (Ferăstrău); at others (Ciobănuş, Asău) until 2004 or 2005 (Sulţa, Dărmăneşti, Dofteana, Haloş, Helegiu). At Tazlău gage the bed level was relatively stable between 2000 and 2004, whereas at Scorţeni station the trend indicated a decrease (at these stations the analysis spanned from 2000 to 2018). After the flood events mentioned previously, evident processes of channel bed degradation were documented at all gauging stations. The maximum degree of bed degradation in this period was generated by the succession of several major geomorphically effective flood events (2001, 2002, 2004, 2005). Subsequent to the flood event of 2005 the channel bed had deepened by at least 50 cm in all analyzed sections. The exceptions to this rule were documented at Valea Uzului, Dofteana and Tazlău gauging stations where channel bed deposits are not as thick (Dumitriu, 2007), albeit the deepening reached the bedrock. The only station where aggradation was documented after the flood event of 2005 was Lucăceşti.

Another characteristic phase started in 2005 (after the main peak of the flood event of 12-13 July) and lasted until 2010. However, this phase is not valid for Scorţeni gage, where the maximum degradation in the upstream section extended until 2009. In this time frame a tendency of channel bed aggradation was recorded in late 2005 and early 2006, ensued by a phase of relative stability which lasted until the flood events of 2010. This phase was disturbed only by the scouring generated by the flood event of 2007. However, in Asău section the flood event of 2007 marked the onset of a longer period of lowering of channel bed elevation.

The flood events of 2010 are regarded as the second major threshold in terms of channel bed level dynamics after the events of 2005, although the changes caused by the former were not as persistent as the shifts which occurred after the floods of 2005. Channel bed deepening was slightly prevalent (Sulța, Asău, Cremenea, Dărmănești, Dofteana, Haloș, Lucăcești, Helegiu) compared to aggradation. However, these processes were not exclusive, as it was observed that aggradation and degradation can both occur during the same flood event.

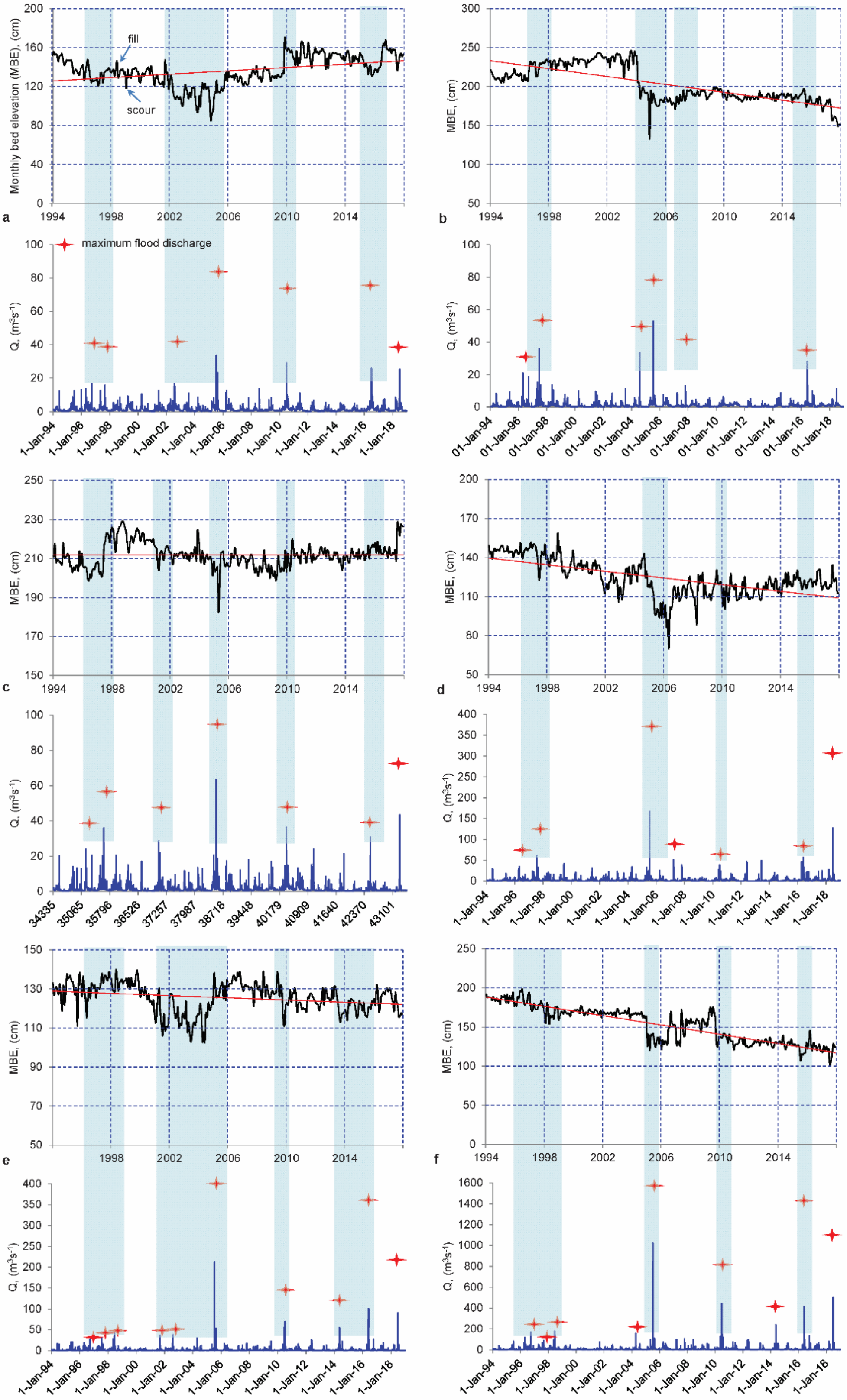

Figure 2. Trend of the monthly average bed elevation in relation to streamflow discharge (**a**) Valea Rece; (**b**) Ciobănuș; (**c**) Valea Uzului; (**d**) Ferăstrău; (**e**) Lucăcești; (**f**) Helegiu.

Between 2010 and 2018 the channel bed level was in a state of relative stability at most of the monitored gauging stations, with the exception of five stations where either degradation (Asău, Dofteana, Scorțeni and Helegiu) or aggradation (Valea Rece) were documented. These general trends were interrupted by short-duration scour-fill processes, such as the ones generated by the flood events of 2012, 2014, 2016 and 2018.

4.2. Annual bed elevation (ABE) changes

By using the annual bed elevation averages the oscillations generated by scour-fill processes are removed, thus preserving only the tendencies induced by aggradation or degradation. The annual bed elevation dynamics was correlated with MSP (Fig. 3). In the vast majority of cases the annual trends of bed level decline were near perfectly correlated with the highest MSP values. However, in certain situations (particularly in the cases of the 1997, 2010 and 2007 flood events) the annual trend of channel bed aggradation corresponded to high MSP values. In the latter instances it was observed that aside from stream power, the duration of the event plays a critical role. When the event duration is significant (more than 15 days) the bed elevation increase becomes prevalent (Dumitriu, 2016). Lower MSP values typically corresponded to either a state of stability of the channel bed or to slight aggradation. Overall, the most significant bed level changes were documented when MSP values exceeded by far the Miller-Magilligan threshold (300 W m^{-2}) (Miller, 1990; Magilligan, 1992), as was the case with the flood events of 1997, 2001, 2002, 2004, 2005, 2007, 2010, 2016. A particular situation occurred at Lucăcești gauging station where the highest MSP values (1998 - 367 W m^{-2}, 2005 – 1733 W m^{-2}, 2010 – 572 W m^{-2}, 2016 – 816 W m^{-2}) coincided with the tendencies of channel bed elevation increase. At this gage it was observed that the MSP values ranging around the Miller-Magilligan threshold correlate with the most significant bed level changes. A conclusive example in this regard is the situation corresponding to the 2001-2004 period (i.e. with MSP values ranging between 200 and 300 W m^{-2}) when the most marked degradation of the channel bed was documented throughout the entire analyzed time frame.

During the years with high magnitude flood events, the abrupt changes of channel bed level were, as previously mentioned, due in part to the very high MSP values. In certain instances, these exceeded by up to 6 times the Miller-Magilligan threshold above which major changes can occur within the channel bed. For example, in 1997 the maximum MSP value was recorded at Ciobănuș and was as high as 845 W m^{-2}. In 2005 the extreme MSP values amounted to 1895 W m^{-2} (Dofteana) and 523 W m^{-2} (Haloș), whereas the average for the 15 gauging stations was 1072 W m^{-2}. In 2010 the MSP values ranged between 827 W m^{-2} (Scorțeni) and 150 W m^{-2} (Ciobănuș), with an average of 405 W m^{-2}. Consequently, the Ciobănuș reach was among the few which underwent small-scale changes subsequent to the 2010 flood events. The flood events of 2016 and 2018 had similarly average MSP values above 300 W m-2 (453 W m^{-2} and 456 W m^{-2}, respectively), although their long term effects are not comprised in this study.

4.3. Annual bed level change (ABLC)

The annual bed elevation dynamics as observed in 1994 or 2000 illustrates the extent of channel bed degradation or aggradation. This change cannot be correlated with MSP values in all instances, thus we related it to TSP. In some cases, TSP accounted to a higher degree for the rising or lowering tendency of the channel bed. For example, during wet years with numerous low magnitude flood events, while the changes occurring within the channel bed could not be related with the MSP (which had values well below the Miller-Magilligan threshold), they could be explained based on the high TSP annual values (Fig. 4). This situation was documented at various gauging stations: Valea Rece (2001), Ciobănuș (2010-2011), Dofteana (2010), Cireșoaia (2010), Ferăstrău (2001-2002), Tazlău (2008-2009), Scorțeni (2008), Helegiu (1996-1997). However, in the vast majority of cases, high MSP values coincided with the highest TSP values, therefore bed level changes could be attributed to a certain flood event.

Whereas the annual trend of bed elevation change varied at each station, three types of channels can be distinguished in terms of their evolution compared to the reference year: (i) a category wherein channel degradation was nearly continuous; (ii) another one where initial aggradation of the channel bed was documented, ensued by continuous degradation, without recovery of the initial state, and (iii) a group with oscillating aggradation-degradation evolution resulting in the eventual recovery of the initial state. The first class includes five gauging stations (Sulța, Ferăstrău, Tazlău, Scorțeni, Helegiu), where the channel bed underwent a nearly continuous deepening process. The highest degree of degradation compared to the 1994 reference was recorded at Sulța gage and amounted to 104 cm, closely followed by Scorțeni where the channel bed deepened by ca. 100 cm compared to the 2000 reference. The second category includes Ciobănuș, Asău and Dofteana

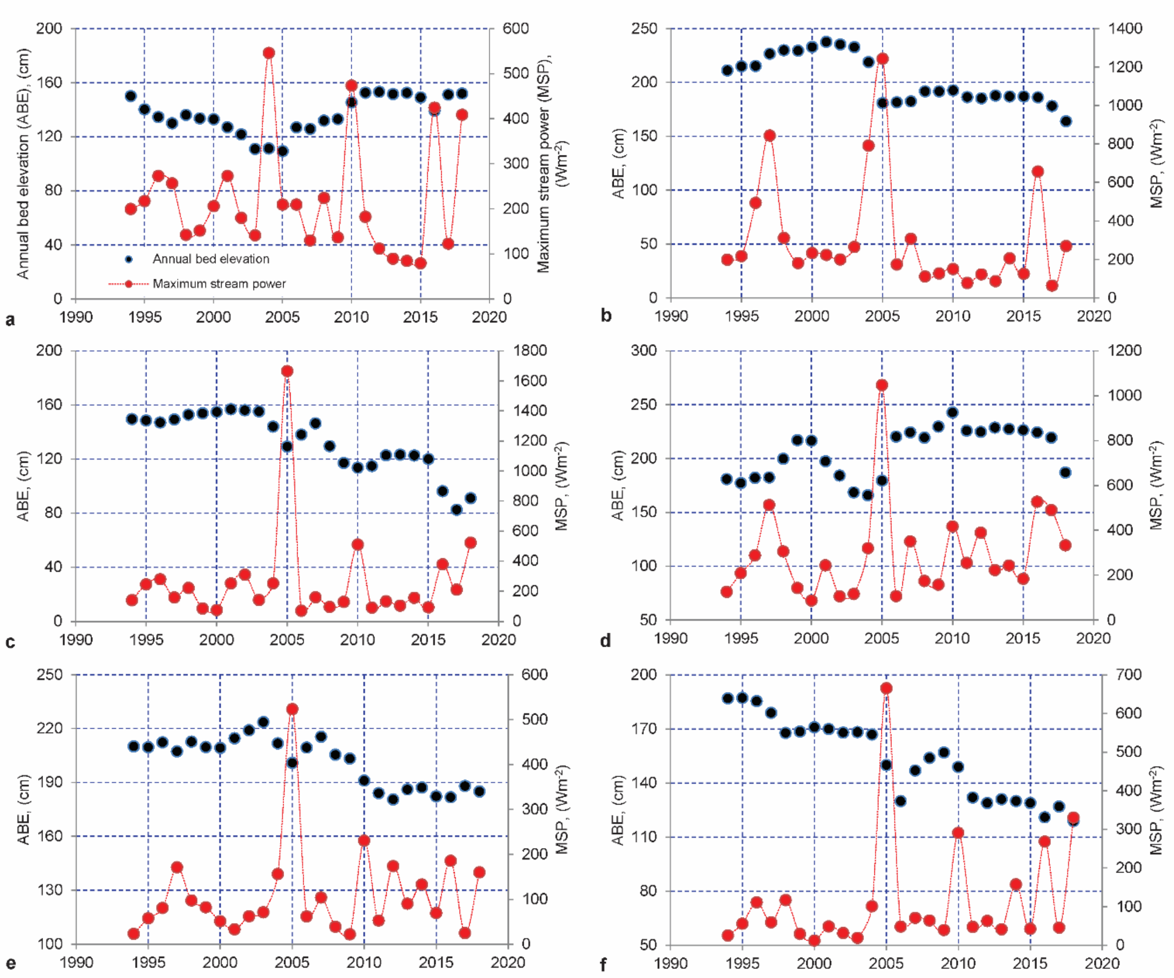

Figure 3. Dynamics of the annual average bed elevation in relation to maximum stream power (MSP) (**a**) Valea Rece; (**b**) Ciobănuş; (**c**) Asău; (**d**) Cireşoaia; (**e**) Haloş; (**f**) Helegiu.

gauging stations. At Ciobănuş, compared to 1994, the channel bed rose by 27 cm and later deepened by 47 cm, whereas at Asău the deepening amounted to 67 cm. The third category comprises the channel reaches at the following stations: Valea Rece (where the bed level recovered the initial state after the flood events of 2010), Valea Uzului (with three recoveries: 1997, 2010 and 2016), Cremenea (2001), Dărmăneşti (2005-2006), Cireşoaia (2005-2006), Caşin (1997, 2005-2006) and Lucăceşti (2005-2006).

4.4. Double mass curve (DMC)

Although this method was used for the first time for the study of channel bed changes after flood events, the results obtained thus far are promising. Any significant changes in the DMC slope indicate variations of the two variables (Q and SSL). The disturbances occurring in the sediment flux during and subsequent to flood events are well reflected the variation of bed levels. Changing points correspond to high magnitude flood events which triggered major changes in channel bed elevation (Fig. 5). The most striking changing point in this case is marked by the flood events of 2005 which generated major changes in terms of the bed level. Additionally, other changing points were triggered by the flood events of 1997, 2010 and 2016. This method clearly highlights the role of flood events as thresholds in the evolution of channel beds.

5. DISCUSSION

5.1. Effectiveness of the method used to determine bed elevation

As regards the method employed for this purpose, the question inevitably arises whether it is effective enough to determine the variation of channel bed levels or if the use of daily data on the stream stage provides sufficient information regarding these changes. Wiejaczka & Kijowska-Strugała (2015) state that this method can be used when other types of data are missing, although the combined use of various methods for more reliable results would be preferable. In this context, we used the information

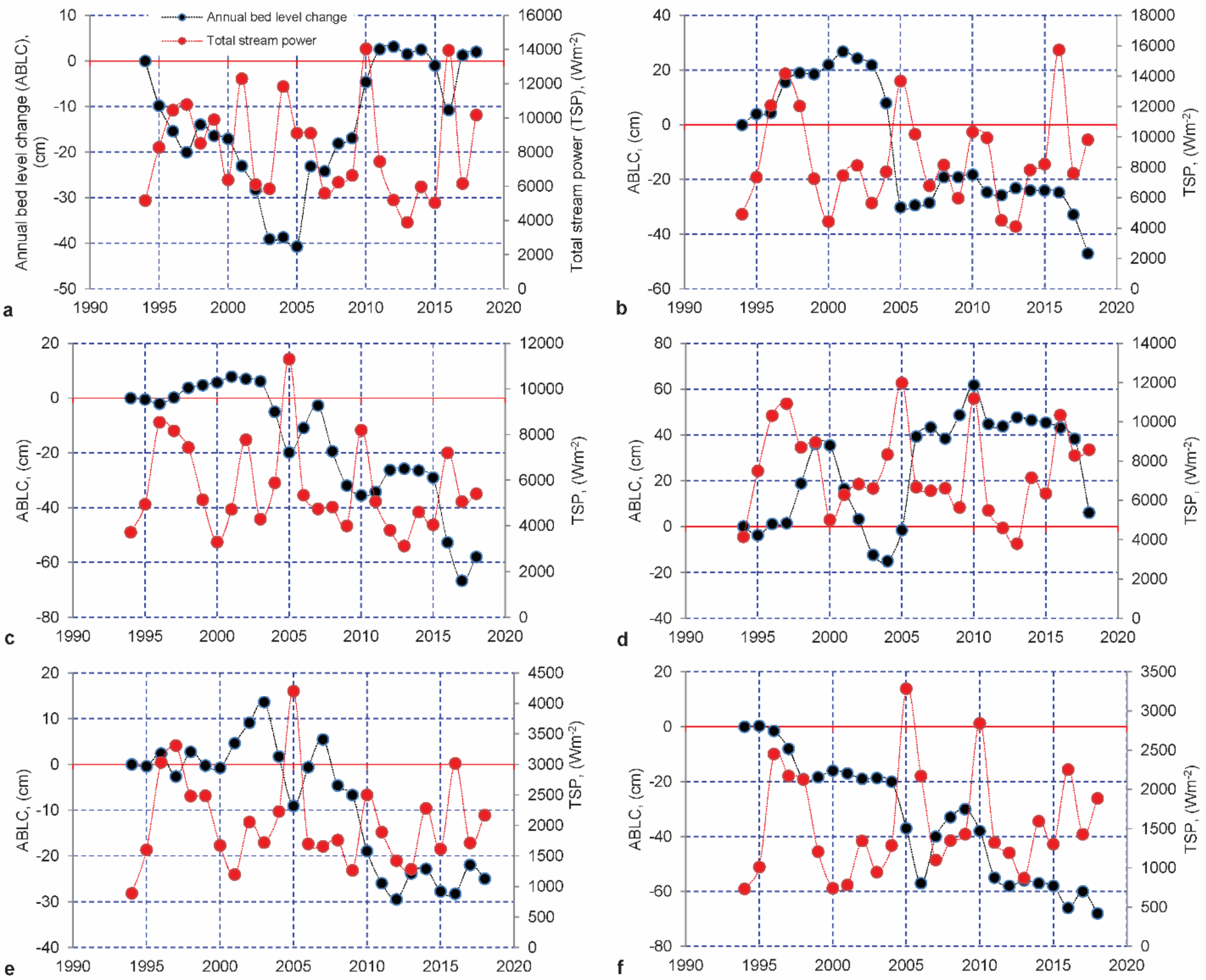

Figure 4. Annual bed level change (ABLC) in relation to total stream power (TSP) (**a**) Valea Rece; (**b**) Ciobănuș; (**c**) Asău; (**d**) Cireșoaia; (**e**) Haloș; (**f**) Helegiu.

provided by the temporal cross-sections at all the gages (Fig. 6). From the large amount of data (generated by 2-4 annual cross-sections) only the first and the last ones from the available data series were selected for this study. In all cases, the state of the channel bed as shown in the ABE plots corresponded to the state revealed by the cross-sections. This correspondence provides evidence that the method based on the daily stream stage yields reliable data regarding the direction (i.e. scour-fill or aggradation-degradation) and intensity of processes leading to channel bed change.

5.2. Long-term and short-term in the dynamics of bed elevation

Whereas long-term shifts of environmental controls and anthropogenic activities lead to allogenic changes of channel beds, short-term events, such as floods, can trigger autogenic changes, which include channel bed lifting or deepening, as well (Erskine, 2011). In the case of river reaches analyzed in this study we observed that channel bed degradation is the long-term predominant process. The same observation was made frequently in the Carpathian area (Korpak, 2007; Wyżga, 2008; Rădoane et al., 2010, 2013; Zawiejska & Wyżga, 2010; Wiejaczka & Kijowska-Strugała, 2015; Kidová et al., 2016; Škarpich et al., 2016; Wyżga et al., 2016, 2020) and the surrounding areas (Sipos et al., 2008; Kiss et al., 2011, 2017, 2019). However, if the channel bed stability criterion taken into account is the bed level change threshold below ± 50 cm (Rădoane et al., 2010), only some of the investigated reaches can be regarded as degraded channel beds which underwent a deepening process by more than 50 cm (Fig. 7).

On short-term, the average channel bed deepening rate calculated for three streams (Ropa, Zdynia and Wisłok) from the Polish Carpathians (Wiejaczka & Kijowska-Strugała 2015) of 0.3 cm/yr (between 1997 and 2014), with extreme values ranging between 0.3 and 2.4 cm/yr. The data generated by this study indicate an average rate of

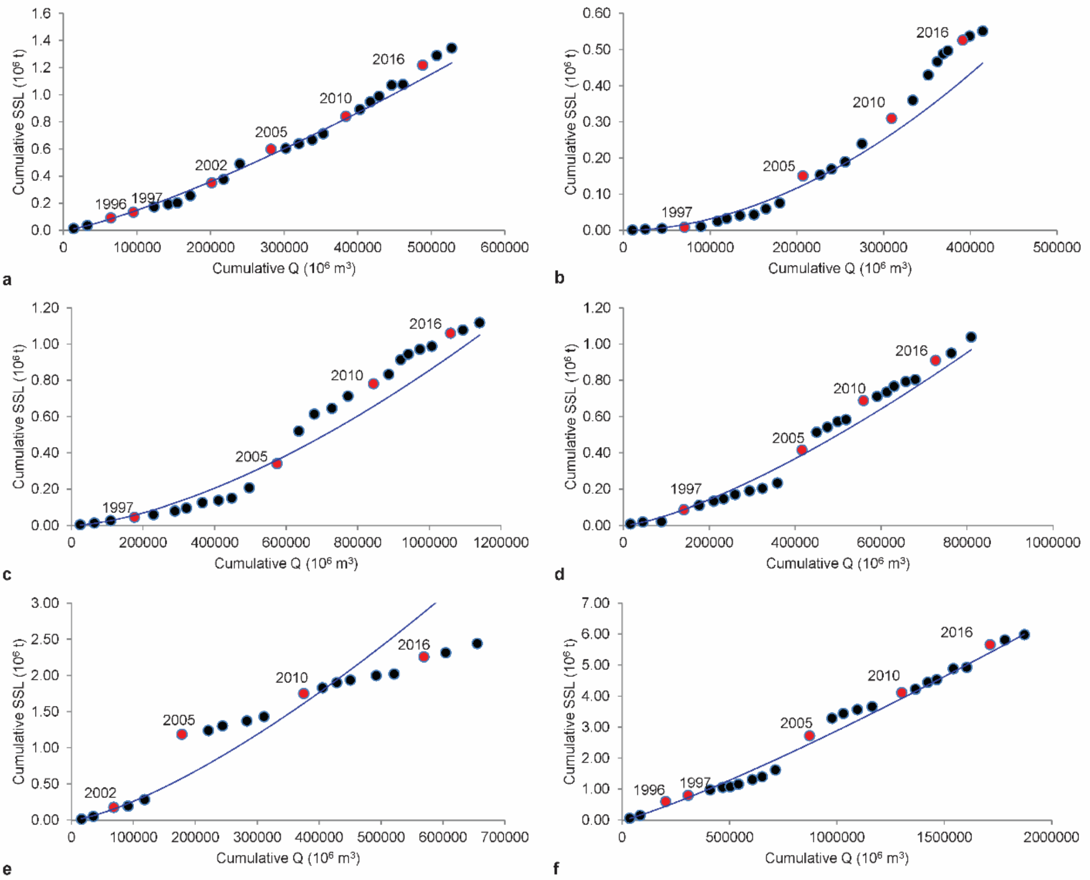

Figure 5. Double mass curve of streamflow versus sediment load highlighting the changing points of channel bed elevation (**a**) Asău; (**b**) Valea Uzului; (**c**) Cremenea; (**d**) Ferăstrău; (**e**) Scorțeni; (**f**) Helegiu.

2.2 cm/yr, with a minimum deepening rate of 0.8 cm/yr (at Valea Uzului) and a maximum value of 5.2 cm/yr (Scorțeni). The strikingly higher values determined for the rivers from the central area of the Romanian Eastern Carpathians can be attributed to two major traits: the peak activity exerted in this area by the retrograde cyclones of the Black Sea which resulted in increasing frequency of flood events; and the relative vicinity of the seismic area of Vrancea which is reflected in the high deepening rates of channel beds on the long-term (Dumitriu, 2020).

Pfeiffer & Finnegan (2018) stated that the sediment input appears to be the main drive of the intensity of changes underwent by channel beds, whereas the temporal dynamics is determined to a large extent by the hydrological regime. In Trotus drainage basin the hydrological regime shifted significantly during the last quarter of a century, as the frequency of high magnitude flood events increased markedly. However, no direct correlation was found between Q and the occurrence of bed level changes, whereas other variables are likely more relevant (such as the duration, flood frequency and power, the availability of sediment sources, the nature of the channel bed etc.) (Rădoane et al., 2010). Pfeiffer et al., (2019) showed that bed elevation variability reflects to a larger degree the sediment supply compared to the peak flow. However, major changes coincided visibly with high magnitude flood events, and in particular with those which exceeded 5 to 10 times the average streamflow discharge (Q_{mean}). In the case of the reaches examined in this study the peak discharge of the most important flood events surpassed Q_{mean} by more than 10 times. For example, in the reaches where the highest rates of channel bed degradation were documented (Scorțeni and Sulța), during the flood event of 2005 the peak discharge exceeded Q_{mean} by 135-fold and 50-fold, respectively, whereas in 2010 Qmean was exceeded 72-fold and 57-fold, respectively. However, the channel bed response to these discharge peaks was inconsistent, with contrasting consequences which were in agreement with the observations made by Pfeiffer et al., (2019), who found that events with equal magnitude triggered different changes in the channel bed levels (lifting, lowering or none of these processes), both in time and across space. For example, whereas after the flood events of 2005 the process of channel bed deepening was nearly ubiquitous, similar discharge peaks recorded during the 2010 flood events led mainly to channel aggradation. Thus, the situation appears to be more complex, as it was observed that in most flood events the rising limb of the event is marked mainly by deepening processes, while the falling limb is associated with channel aggradation (Rădoane et al., 2010). However, channel bed degradation is not limited to major flood events and occurs during high frequency, low magnitude events, as well. This situation was often observed in our study area.

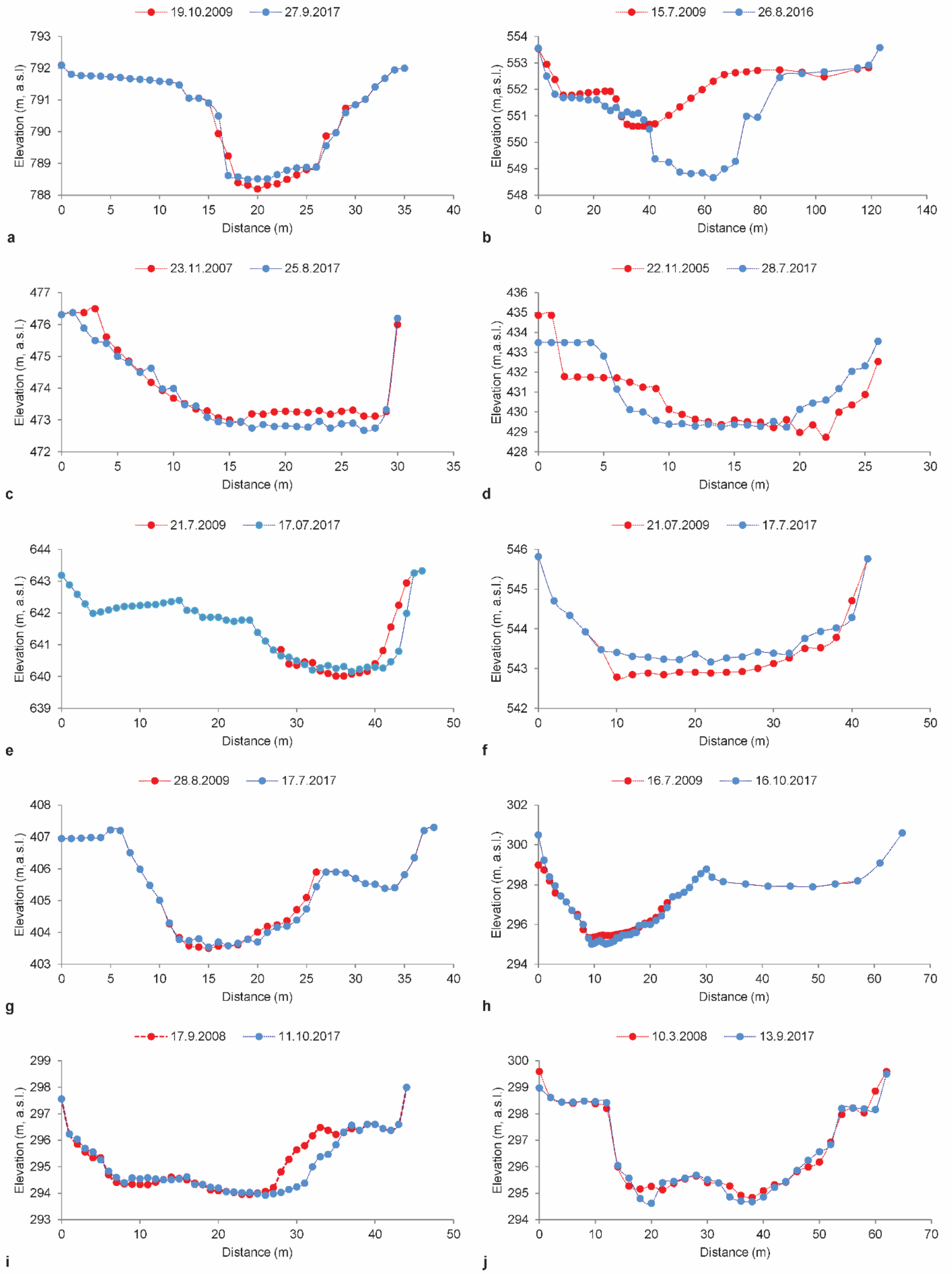

Figure 6. Cross-sections highlighting channel bed aggrading or degrading processes at several analyzed reaches (**a**) Valea Rece; (**b**) Sulța; (**c**) Ciobănuș; (**d**) Asău; (**e**) Valea Uzului; (**f**) Cremenea; (**g**) Dărmănești; (**h**) Dofteana; (**i**) Ferăstrău; (**j**) Haloș.

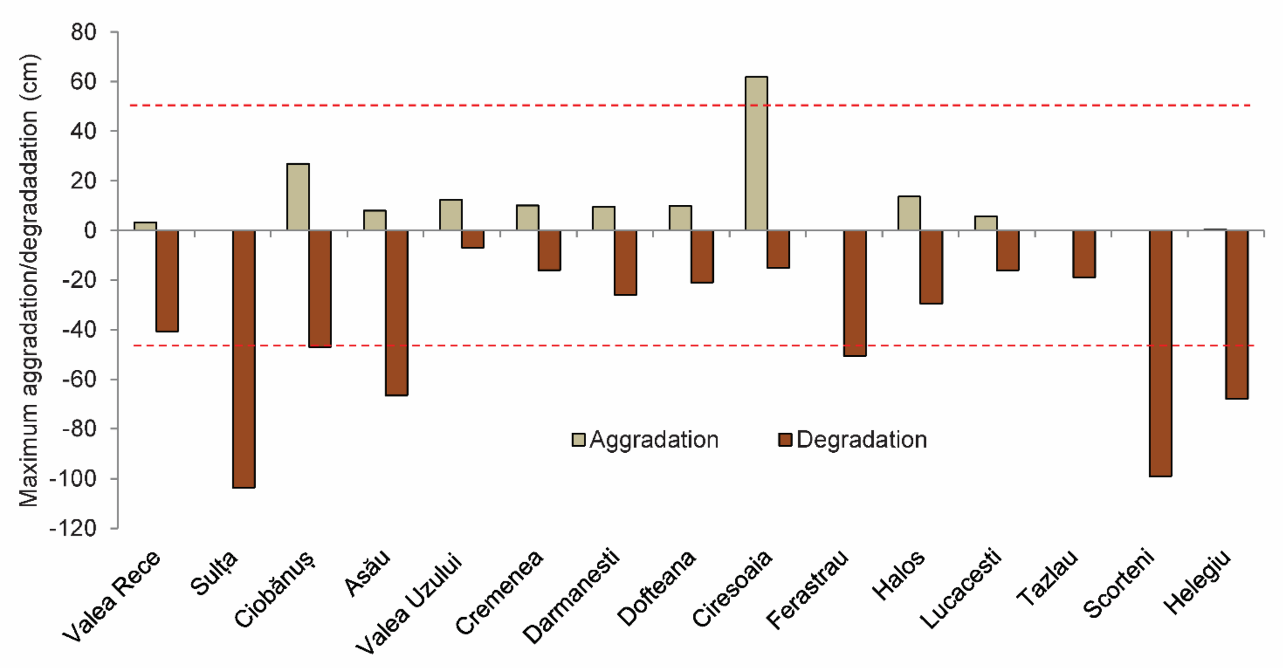

Figure 7. Channel bed dynamics at analysed reaches.

Channel bed changes which occur during major flood events are regarded as "acute" flood disturbance, whereas the others are ranked as "chronic" incision between floods (Gibson & Shelley, 2020).

The effects of these flood events cannot be fully addressed by global laws (Phillips, 2006) and no single standard pattern for channel bed evolution exists (Rădoane et al., 2010). However, the fact that certain thresholds manifest during flood events which often trigger irreversible channel bed changes is undisputed (Joyce et al., 2018). In this study, the geomorphic threshold introduced by flood events was related to stream power. Once the Miller-Magilligan threshold is exceeded, various changes occur in terms of bed elevation, although the intensity and direction of these shifts is just as inconsistent as in the case of the peak discharge. In our study, the most visible discrepancies (particularly in the case of the 2010 flood events) were attributed to flood duration (Dumitriu, 2016, 2018). This approach is in agreement with the findings of Costa & O'Connor (1995) and Magilligan et al., (2015) who suggested that in order to better explain these changes, event duration must be taken into account along with stream power.

5.3. Recovery time

Recovery time can be generally defined as the time required to transition from a „*degraded*" state to a state resembling a „*reference*" condition (Beechie et al., 1996, 2008). In this study, the recovery time refers to the time required for the channel bed level to revert to the state of reference (in our case, the state specific to the years 1994 and 2000). In our case, the analysis of bed level adjustments was focused on the short term, therefore the recovery times subsequent to major changes amounted to a few years. However, in some situations the channel bed never reverts to its reference state. This was the case with certain reaches comprised in our study, such as Sulța, Ferăstrău, Tazlău, Scorțeni and Helegiu. Overall, it was observed that in the case of "*acute*" changes the recovery time ranges between 1 year and nearly 10 years, whereas for "*chronic*" shifts (generated by scour-fill) the recovery time was a year at most. Moreover, "*chronic*" shifts can be ranked as "river behavior", while "*acute*" shifts are regarded as "*river change*" (Khan & Fryirs, 2020). In the reaches analyzed in this study the channel "*sensitivity*" (according to Fryirs, 2017) to bed level adjustments also depended of the characteristics of channel deposits and the availability of sediment sources. For example, at Valea Uzului and Dofteana the thickness of alluvial deposits is rather reduced compared to deposits from other reaches, therefore the amplitude of bed elevation changes in the former is low, and they recover at a much faster rate. At Scorțeni și Helegiu the significant thickness of alluvial deposits and the high availability and capacity for sediment transport resulted in high amplitude adjustments of the channel bed level which in turn led to a much longer recovery time.

Another aspect refers to the recovery of the channel bed elevation subsequent to each flood event, without taking into account the 1994 and 2000 reference points. In this case, after major flood events (particularly those recorded between 2001 and 2005, which triggered the most significant channel bed deepening processes), the channel recovery to the pre-flood bed elevation required nine years at Lucăcești, eight years at Valea Rece, seven years at Cireșoaia, six years at Ferăstrău, four years at Asău and Haloș, three years at Valea Uzului and one year at Dofteana. In the other channel reaches the recovery process is still ongoing and the bed level has not reached to date the state prior to the events of 2001-2005. In fact, in some instances the channel bed recovery stopped the deepening process and the onset of a state of stability or slow aggradation (Sulța, Ciobănuș).

6. CONCLUSIONS

The analysis of the temporal change of channel bed levels at fifteen gauging stations located in Trotuș drainage (the Eastern Carpathians) revealed that over short term, major flood events act as geomorphic thresholds. For the purpose of this study, the geomorphic threshold was represented by stream power during the flood events. In the majority of investigated reaches, a direct correlation was found between the annual trend of bed level elevation lowering and the highest MSP values. Furthermore, in many of the cases where a direct correlation between ABE and MSP could not be established, the annual bed elevation change could be explained to a satisfactory degree by the TSP values. Whereas the behavior of channel bed level change varied at each station, three evolution patterns could be distinguished depending on the reference year: (i) a category where channel degradation was nearly continuous; (ii) another one where initial aggradation of the channel bed occurred, ensued by continuous degradation, without recovery of the initial state, and (iii) a group with oscillating aggradation-degradation evolution resulting in the eventual recovery of the initial state.

The first-time use (according to our knowledge) of the DCM method to assess the role of flood events in terms of channel bed level change has yielded conclusive results. Thus, the changing points of the DCM curve correspond to high magnitude flood events which triggered significant bed elevation shifts.

The short-term average deepening rate for analyzed channel beds was 2.2 cm/yr, comparatively much higher than the rates determined elsewhere in the Carpathians. The elevated values documented for the rivers from the central area of the Eastern Carpathians can be attributed to two major traits: the peak activity exerted in this area by the retrograde cyclones of the Black Sea which resulted in a higher flood event frequency and the relative vicinity of the seismic area of Vrancea which is reflected in the high deepening rates of channel beds on the long-term (Dumitriu, 2019).

Channel bed level changes were ranked in two categories (acute and chronic), depending on which the recovery time varied in relation to these shifts. Thus, the recovery time for "*acute*" changes ranged between one and nearly 10 years, whereas in the case of "*chronic*" changes the recovery time was one year at most.

While over long term the evolution trend of channel level is highly sensitive to environmental controls shifts and anthropogenic influence, on short term flood events drive the direction and intensity of bed elevation adjustments.

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REFERENCES

Andrews, E.D., 1979. *Scour and fill in a stream channel. East Fork River*. Western Wyoming. U.S. Geol. Surv. Prof. Pap., 1117.

Bagnold, R.A., 1966. *An approach to the sediment transport problem from general physics*. U.S. Geol. Surv. Prof. Pap., 422-I.

Beechie, T.J., Beamer, E., Collins, B. & Benda, L., 1996. *Restoration of habitat-forming processes in Pacific Northwest watersheds: a locally adaptable approach to salmonid habitat restoration*. In: Peterson DL, Klimas CV (eds) The role of restoration in ecosystem management, Society for Ecological Restoration, Madison, pp. 48-67.

Beechie, T.J., Pollock, M.M. & Baker, S., 2008. *Channel incision, evolution and potential recovery in the Walla Walla and Tucannon River basins, northwestern USA*. Earth Surf. Proc. Land., 33, 784-800.

Bizzi S., & Lerner D.N., 2015. *The use of stream power as an indicator of channel sensitivity to erosion and deposition processes*. River Res. Appl., 31, 16-27.

Blum, M.D., & Törnqvist, T.E., 2000. *Fluvial responses to climate and sea-level change: a review and look forward*. Sedimentology, 47, 2-48.

Bowen, M.W., & Juracek, K.E., 2011. *Assessment of the geomorphic effects of large floods using streamgage data: the 1951 floods in eastern Kansas, USA*. Phys. Geogr., 32, 52-77.

Brunsden, D. & Thornes, J.B., 1979.*Landscape sensitivity and change*. Trans. Inst. Br. Geogr. N.S., 4, 463-484.

Buraas, E.M., Renshaw, C.E., Magilligan, F.J. & Dade, W.B., 2014. *Impact of reach geometry on stream channel sensitivity to extreme floods*. Earth Surf. Proc. Land., 39, 1778-1789.

Canciu, C., 2008. *Danube valley between Brăila and*

Pătlăgeanca - geomorphological study. PhD thesis, University of Bucharest (in Romanian, with English summary).
Chappell, J., 1983. *Thresholds and lags in geomorphologic changes*. Aust. Geog., 15, 358-366.
Church, M., 2002. *Geomorphic thresholds in riverine landscapes*. Freshwater Biol., 47,541-557.
Coates, D.R., & Vitek, J.V., 1980. *Thresholds in geomorphology*. George Allen & Unwin, London.
Costa, J.E., & O'Connor, J.E., 1995. *Geomorphically effective floods*. In: Costa JE, Miller AJ, Potter KP, Wilcock PR (eds), Natural and anthropogenic influences in fluvial geomorphology. Am. Geophys. Union, Monograph 89, Washington, pp. 45-56.
Dewan, A., Corner, R., Saleem, A., Rahman, M.M., Haider, M.R., Rahman, M.M. & Sarker, M.H., 2017. *Assessing channel changes of the Ganges Padma River system in Bangladesh using Landsat and hydrological data*. Geomorphology, 276, 257-279.
Diaconu, C., Ciobanu, S., Avădanei, A., Motea, I. & Stănescu, S., 1962. *On the stability of river channels in Romania during the last 30–40 years*. Studii de hidrologie, 63(III), 53–63 (in Romanian, with English summary).
Dumitriu, D., 2007. *Sediment system of the Trotuş drainage basin*. Editura Universităţii, Suceava (in Romanian, with English summary).
Dumitriu, D., 2014. *Source area lithological control on sediment delivery ratio in Trotuş drainage basin (Eastern Carpathians)*. Geogr. Fis. Din. Quat., 37, 91-100.
Dumitriu, D., 2016. *Geomorphic effectiveness of floods on Trotuş River channel (Romania) between 2000 and 2012*. Carpath. J. Earth. Env., 11, 181-196.
Dumitriu, D., 2018. *Sub-bankfull flow frequency versus magnitude of flood events in outlining effective discharges. Case Study: Trotuș River (Romania)*. Water, 10, 1292.
Dumitriu, D., 2020. *Sediment flux during flood events along the Trotuș River channel: hydrogeomorphological approach*. J. Soils Sediments, 20, 4083–410.
Dumitriu, D., Rădoane, M. & Rădoane, N., 2017. *Sediment sources and delivery*. In: Rădoane M, Vespremeanu-Stroe A (eds), Landform dynamics and evolution in Romania, Springer, Cham, pp. 629-654.
Eisenbies, M.H., Aust, W.M., Burger, J.A. & Adams, M.B., 2007. *Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians - A review*. For. Ecol. Manage, 242, 77-98.
Erskine, W.D., 2011. *Geomorphic controls on historical channel planform changes onthe lower Pages River, Hunter Valley, Australia*. Aust. Geog., 42, 289-307.
Fryirs, K.A, 2017. *River sensitivity: A lost foundation concept in fluvial geomorphology*. Earth Surf. Proc. Land., 42, 55-70.
Gao, P., Zhang, X., Mu, X., Wang, F., Li, R. & Zhang, X., 2010. *Trend and change-point analyses of streamflow and sediment discharge in the Yellow River during 1950-2005*. Hydrol. Sci. J., 55, 275-285.
Gao, P., Li, P.F., Zha,o B.L., Xu, R.R., Zhao, G.J., Sun, W.Y. & Mu, X.M., 2017. *Use of double mass curves in hydrologic benefit evaluations*. Hydrol. Process., 31, 4639-4646.
Gibson, S. & Shelley, J., 2020. *Flood disturbance, recovery, and inter-flood incision on a large sand-bed river*. Geomorphology, 351, 106973.
Grabowski, R.C., Surian, N. & Gurnell, A.M., 2014. *Characterizing geomorphological change to support sustainable river restoration and management: Characterizing geomorphological change in rivers*. Wiley Interdiscip. Rev. Water, 1(5), 483-512.
Hajdukiewicz, M., Wyżga, B., Hajdukiewicz, H. & Mikuś, P., 2019. *Photogrammetric reconstruction of changes in vertical river position using archival aerial photos: case study of the Czarny Dunajec River, Polish Carpathians*. Acta Geophys., 67, 1205-1221.
Heritage, G.L., Large, A.R.G., Moon, B.P. & Jewitt, G., 2004. *Channel hydraulics and geomorphic effects of an extreme flood event on the Sabie River, South Africa*. Catena, 58,151-181.
Ichim, I., Bătucă, D., Rădoane, M. & Duma, D., 1989. *Morphology and dynamics of riverbeds*. Editura Tehnică, București (in Romanian, with English summary).
Jiang, C., Zhang, L., Li, D. & Li, F., 2015. *Water discharge and sediment load changes in China: change patterns, causes, and implications*. Water, 7, 5849-5875.
Joyce, H.M., Hardy, R.J., Warburton, J. & Large, A.R., 2018. *Sediment continuity through the upland sediment cascade: Geomorphic response of an upland river to an extreme flood event*. Geomorphology, 317, 45-61.
Juracek, K.E., & Fitzpatrick, F.A., 2009. *Geomorphic applications of stream-gage information*. River Res. Appl., 25, 329-347.
Khan, S., & Fryirs, K., 2020. *An approach for assessing geomorphic river sensitivity across a catchment based on analysis of historical capacity for adjustment*. Geomorphology, 359, 107135.
Kidová, A., Lehotský, M. & Rusnák, M., 2016. *Geomorphic diversity in the braided–wandering Belá River, Slovak Carpathians, as a response to flood variability and environmental changes*. Geomorphology, 272, 137-149.
Kiss, T., Andrási, G. & Hernesz, P. 2011. *Morphological alternation of the Dráva as the result of human impact*. AGD Landscape & Environment, 5(2), 58-75.
Kiss, T., Nagy, Z. & Balogh, M., 2017. *Floodplain level*

development induced by humanactivity–case study in the Lower Maros/Mures River, Romania and Hungary. Carpathian Journal Earth and Environmental Sciences, 12 (1), 83-93.

Kiss, T., Fiala, K., Sipos, G. & Szatmári, G., 2019. *Long-term hydrological changes after various river regulation measures: Are we responsible for flow extremes?* Hydrology Research, 50(2), 417-430.

Knox, J.C., 1983. *Responses of river systems to Holocene climates*. In: Wright HE (ed), Late Quaternary environments of the United States, Vol. 2, The Holocene, University of Minnesota Press, Minneapolis, pp. 26-41.

Korpak, J., 2007. *The influence of river training on mountain channel changes (Polish Carpathian Mountains)*. Geomorphology, 92, 166-191.

Lancaster, S.T. & Casebeer, N.E., 2007. *Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes*. Geology, 35, 1027-1030.

Lea, D.M. & Legleiter, C.J., 2016. *Mapping spatial patterns of stream power and channel change along a gravel-bed river in northern Yellowstone*. Geomorphology, 252, 66-79.

Le Coz, J., Smart, G., Hicks, M., Mansanarez, V., Renard, B., Camenen, B. & Lang, M., 2018. *Estimating the long-term evolution of river bed levels using hydrometric data*. River Flow 2018: 9th International Conference on Fluvial Hydraulics, Sep. 2018, Lyon, France.

Lewin, J., 1977. *Channel pattern changes*. In: Gregory KJ (ed), River channel changes, Wiley, Chichester, pp. 167-184.

Macklin, M.G., & Lewin, J., 1989. *Sediment transfer and transformation of an alluvial valley floor: the River South Tyne, Northumbria, U.K.* Earth Surf. Proc. Land., 14, 233-246.

Macklin, M.G., Passmore, D.G. &Newson, M.D., 1998. *Controls of short and long term river instability: processes and patterns in gravel-bed rivers, the Tyne basin, northern England*. In: Klingemann PE, Beschta RL, Bradley J, Komar PD (eds), Gravel bed rivers in the environment, Water Resources Publications, LLC Colorado, pp.257-278.

Madej, M.A., & Ozaki, V., 2009. *Persistence of effects of high sediment loading in a salmon-bearing river, northern California*. In: James LA, Rathburn SL, Whittecar GR (eds), Management and restoration of fluvial systems with broad historical changes and human impacts. Geol. Soc. Am. Spec. Pap., 451, Boulder, CO, pp. 43–55.

Magilligan, F.J., 1992. *Thresholds and the spatial variability of flood power during extreme floods*. Geomorphology, 5, 373-390.

Magilligan, F.J., Buraas, E.M. & Renshaw, C.E., 2015. *The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding*. Geomorphology, 228,175-188.

Marchese, E., Scorpio, V., Fuller, I., McColl, S. & Comiti, F., 2017. *Morphological changes in Alpine rivers following the end of the Little Ice Age*. Geomorphology, 295, 811-826.

Marchi, L., Cavalli, M., Amponsah, W. & Borga, M., Crema, S., 2016. *Upper limits of flash flood stream power in Europe*. Geomorphology, 272,68-77.

Miller, A.J., 1990. *Flood hydrology and geomorphic effectiveness in the central Appalachians*. Earth Surf. Proc. Land., 15, 119-134.

Mol, J., Vandenberghe, J. & Kasse, C., 2000. *River response to variations of periglacial climate in mid-latitude Europe*. Geomorphology, 33, 131-148.

Nelson, A. & Dubé, K., 2016. *Channel response to an extreme flood and sediment pulse in a mixed bedrock and gravel-bed river*. Earth Surf. Proc. Land., 41, 178-195.

Pandi, G., & Horváth, C., 2012. *Mureş river middle course riverbed dynamics between the Arieş and Strei confluences*. In: Air and water components of the environment, Presa Universitară Clujeană, Cluj-Napoca, pp. 49-56.

Perşoiu, I., 2010. *Reconstruction of Holocene geomorphological evolution of Someşu Mic Valley*. Ph.D. thesis "Al. I. Cuza" University, Iaşi (in Romanian, with English summary).

Pfeiffer, A.M., & Finnegan, N.J., 2018. *Regional variation in gravel riverbed mobility, controlled by hydrologic regime and sediment supply*. Geophys. Res. Lett., 45,3097-3106.

Pfeiffer, A.M., Collins, B.D., Anderson, S.W., Montgomery, D.R. & Istanbulluoglu, E., 2019. *River bed elevation variability reflects sediment supply, rather than peak flows, in the Uplands of Washington State*. Water Resour. Res., 55, 6795-6810.

Phillips, J.D., 2006. *Evolutionary geomorphology: thresholds and nonlinearity in landform response to environmental change*. Hydrol. Earth Syst. Sc., 10, 731-742.

Popa-Burdulea, A., 2007. *Geomorphology of channel of the Siret River on the Romania territory*. Ph.D. thesis "Al. I. Cuza" University, Iaşi (in Romanian, with English summary).

Rădoane, M., Ichim, I. & Pandi, G., 1991. *Current trends in river bed dynamics in the Eastern Carpathians*. St. Cerc. Geol. Geofiz. Geogr., 38, 21-31 (in Romanian, with English summary).

Rădoane, M., Rădoane, N., Dumitriu, D. & Miclăuş, C., 2006a. *Bimodality origin of fluvial bed sediments. Study case: East Carpathian rivers*. Carpathian Journal Earth and Environmental Sciences, 1 (2), 13-38.

Rădoane, N., Rădoane, M., Olariu, P. & Dumitriu, D., 2006b. *Efectele geomorfologice ale inundaţiilor din 28-29 iulie 2004 în bazine hidrografice mici din Valea Trotuşului*. In: Geografia în contextul dezvoltării durabile, Presa Universitară Clujeană, Cluj Napoca, pp. 43-52.

Rădoane, M., Pandi, G. & Rădoane, N., 2010. *Contemporary bed elevation changes from the Eastern Carpathians*. Carpathian Journal Earth and

Environmental Sciences, 5(2), 49-60.
Rădoane, M., Obreja, F., Cristea, I. & Mihailă, D., 2013. *Changes in the channel-bed level of the eastern Carpathian rivers: climatic vs. human control over the last 50 years*. Geomorphology, 193, 91-111.
Rumsby, B.T., & Macklin, M.G., 1994. *Channel and floodplain response to recent abrupt climate change; the Tyne basin, northern England*. Earth Surf. Proc. Land., 19, 499-515.
Rusnák, M., & Lehotský, M., 2014. *Time-focused investigation of river channel morphological changes due to extreme floods*. Z. Geomorphol., 58, 251-266.
Schumm, S.A., 1973. *Geomorphic thresholds and complex response of drainage system*. In: Morisawa M (ed), Fluvial geomorphology, Proc. 4th Annual Geomorph Symp, Binghampton, NY, pp.299-310.
Schumm, S.A., 1979. *Geomorphic thresholds: the concept and its applications*. Trans. Inst. Br. Geogr., NS4, 485-515.
Schumm, S.A., 1991. *To interpret the Earth. Ten ways to be wrong*. Cambridge University Press, New York.
Scorpio, V., Crema, S., Marra, F., Righini, M., Ciccarese, G., Borga, M., Cavalli, M., Corsini, A., Marchi, L., Surian, N. & Comiti, F., 2018. *Basin-scale analysis of the geomorphic effectiveness of flash floods: a study in the northern Apennines (Italy)*. Sci. Total Environ., 640, 337-351.
Simon, A. & Rinaldi, M., 2006. *Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response*. Geomorphology, 79, 361-383.
Sipos, G., Kiss, T. & Fiala, K., 2008. *Changes of cross-sectional morphology and channel capacity during an extreme flood event, Lower Tisza and Maros Rivers, Hungary*. Journal of Environmental Geography, 1(1), 41-51.
Škarpich, V., Galia, T. & Hradecký, J., 2016. *Channel bed adjustment to over bankfull discharge magnitudes of the flysch gravel-bed stream-case study from the channelized reach of Olše River (Czech Republic)*. Z. Geomorphol., 60, 327-341.
Slater, L.J. & Singer, M.B., 2013. *Imprint of climate and climate change in alluvial riverbeds: continental United States, 1950–2011*. Geology, 41, 595-598.
Sloan, J., Miller, J.R. & Lancaster, N., 2001. *Response and recovery ofthe Eel River, California, and its tributaries to floods in 1955, 1964 and 1997*. Geomorphology, 36, 129–154.
Surian, N., Righini, M., Lucía, A., Nardi, L., Amponsah, W., Benvenuti, M., Borga, M., Cavalli, M., Comiti, F., Marchi, L., Rinaldi, M. & Viero, A., 2016. *Channel response to extreme floods: insights on controlling factors from six mountain rivers in northern Apennines, Italy*. Geomorphology, 272, 78-91.
Thompson, C., & Croke, J., 2013. *Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, southeast Queensland, Australia*. Geomorphology, 197, 156-169.
Wiejaczka, Ł., & Kijowska-Strugała, M., 2015. *Dynamics of the channel beds level in mountain rivers in the light of the minimum water stages analysis*. Carpathian Journal Earth and Environmental Sciences, 10 (4), 105-112.
Williams, G.P., & Wolman, M.G., 1984. *Downstream effects of dams on alluvial rivers*. U.S. Geol. Surv. Prof. Pap., 1286.
Wolman, M.G., & Gerson, R., 1978. *Relative scales of time and effectiveness of climate in watershed geomorphology*. Earth Surf. Proc. Land., 3, 189-208.
Wyżga, B., 2008. *A review on channel incision in the Polish Carpathian rivers during the 20th century*. In: Habersack H, Piégay H, Rinaldi M (eds), Gravel-bed rivers (VI): from process understanding to river restoration, Elsevier, Amsterdam, pp.525-556.
Wyżga, B., Zawiejska, J. & Radecki-Pawlik, A., 2016. *Impact of channel incision on the hydraulics of flood flows: examples from Polish Carpathian rivers.* Geomorphology, 272,10-20.
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.
Yochum, S.E., Sholtes, J.S., Scott, J.A. & Bledsoe, B.P., 2017. *Stream power framework for predicting geomorphic change: The 2013 Colorado Front Range flood*. Geomorphology, 292, 178-192.
Zawiejska, J. & Wyżga, B., 2010. *Twentieth-century channel change on the Dunajec River, southern Poland: patterns, causes and controls*. Geomorphology, 117, 234-246.

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