

Causes of spatio-temporal variations in the flood event efficiency index

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Abstract: Spatio-temporal variation of suspended sediment load is a topic of real interest in river geomorphology, especially in the current context of climate change and increasing anthropogenic impacts. In the present study, an attempt was made to argue for these variations based on the correlations between the event efficiency index and the degree of sediment availability in river channel following flood events. Data from four gauging stations along the Trotuș River (Romania) were used to show these types of relationships. The results show that the spatial variations of the event efficiency index are in close correlation with the characteristics of the riverbed in the sectors analysed, and the temporal variations reflect the role of flood events in the modification of river channel and the availability of sediment. Major flood events have caused visible changes in the suspended sediment flux, which is why the analysis of the spatial and temporal variations must necessarily take into account the characteristics of the river channel in terms of sediment sources.

1. Introduction

Suspended sediment transport is considered a very complex nonlinear process (Tao et al., 2021). The most important suspended sediment transport occurs during flood events (Dumitriu, 2020a). Suspended sediment concentration (SSC) varies greatly over time and space, as it is influenced by a range of natural (geological, climatic, hydrological, geomorphological) and anthropogenic controlling factors. The spatio-temporal complexity of these controlling factors induces nonlinear behavior of sediment concentration, hence the difficulty in understanding and predicting these phenomena (Duan et al., 2013).

Spatial variability in suspended sediment transport can be determined by (i) the availability of sediment in the catchment and the transport capacity of the erosive agent; (ii) the degree of connectivity between slopes and river channels in terms of sediment transfer; (iii) the transport capacity of the river (Vercruysse et al., 2017).

Temporal variability in SSC in a given river section may be due to the interlinked action of a number of controlling factors acting at the catchment scale. These can be grouped into four broad categories (Vercruysse et al., 2017): (i) hydro-meteorological factors (precipitation, surface runoff, discharge); (ii) variations in sediment sources as a result of hydro-meteorological events or as a consequence of land cover/land use change (LC/LU); (iii) natural landscape disturbances (mass movements and wildfires); (iv) human interventions (construction of infrastructure or hydro-technical installations, mining, etc.).

In addition to the control factors mentioned above, in the present study, an attempt was made to explain the spatio-temporal variability of suspended sediment transport,

based on the changes in the availability of sediment availability in river channel following flood events.

To date, most studies have addressed the issue of spatio-temporal variation of SSC from the perspective of the discharge (Q)-SSC relationship, such as the sediment rating curve (SRC). However, classical Q-SSC relationships (SRC-type) are considered empirical and usually highly time-varying, which causes, on the one hand, a large scatter of SSC data for the same liquid discharge and, on the other hand, a poor explanation of hysteresis effects (Dai et al., 2016). Because of the drawbacks of the SRC, in a number of studies (Steegen et al. 2000; Vanmaercke et al., 2010, 2014; Obreja, 2013) the event efficiency index (EEI) has been used to determine the variability of suspended sediment transport in different aspects. Two of these studies (Obreja, 2013; Vanmaercke et al., 2014) used EEI to observe the variability of suspended sediment transport in a number of Romanian watersheds. The authors who used this index note that the EEI compensates for the fact that SSC variations are partially controlled by changes in streamflow. In this study, an attempt was made to use EEI from another perspective, namely that of correlation with the availability of sediment sources within the river channel.

The aim of the study is to determine the causes and implications of spatio-temporal variations in suspended sediment transport in the context of changes in river channel following flood events. The objectives of this study were: (i) to quantify the EEI; (ii) to determine the trend of the EEI over the time interval analysed; (iii) to determine the role of previous flood events on alluvial transport variations.

2. Materials and Methods

2.1. Study area

The causal analysis of the spatio-temporal variations of suspended sediment transport was performed for the Trotuș River (Figure 1). Trotuș drainage basin overlies the central areas of the Eastern Carpathians and the Moldavian Subcarpathians (Romania), extending over 4500 km². Trotuș is a gravel bed river along its entire 150 km length (Dumitriu, 2020a). The highest effective erosion and sediment yield rates are documented in the molasse and foreland zones, due to the ample human intervention affecting the hillslopes (Dumitriu, 2014).

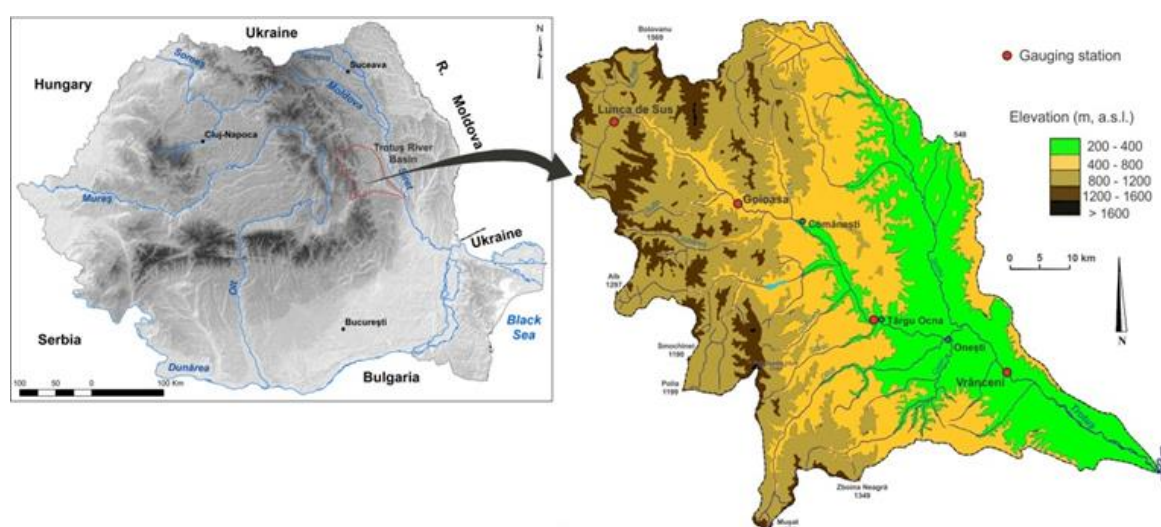


Figure 1. Location of the study area in Romania and location of gauging stations.

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, 2018). Based on the average suspended sediment yield (263 t/km²/an) Trotuş drainage basin ranks among the category of rivers with moderate rates from the Romanian Carpathian area (Dumitriu et al., 2017).

2.2. Data sources

The data regarding Q , suspended sediment load (SSL) and flood events from 2000 to 2020 are provided by the "Romanian Waters" National Administration - Siret Water Branch, which manages the gauging stations included in this study. In the analysed interval 84 flood events were identified, namely: 15 at Lunca de Sus station; 25 at Goioasa; 22 at Târgu Ocna and 22 at Vrânceni.

2.3. Methods

The following variables were determined for all 84 flood events identified in the 2000-2020 timeframe: duration, SSC, EEI and the effect of previous flood events on suspended sediment transport during subsequent events.

The formula proposed by Steegen et al. (2000), modified by Vanmaercke et al. (2014), was used to calculate the Event Efficiency Index (EEI), namely:

$$EEI (g.s/l^2) = \frac{SSC (g/l)}{Q (m^3/s)} \quad (1)$$

For each flood, the average EEI was calculated. The trend of mean EEI values for the 2000-2020 interval was assessed using the Wilcoxon non-parametric test (Wilcoxon, 1945).

Suspended sediment concentration (SSC) was calculated using the following formula (Obreja, 2013):

$$SSC = \frac{SSL (\frac{kg}{s})}{Q} \quad (2)$$

Depending on the characteristics of previous flood events, the SSC on the falling limb of the subsequent event hydrograph may increase or decrease. To capture this effect, current-event peak flow (Q_{max}), the ratio of this to the peak flow of the previous event and the result of the ratio of falling (SSL_F) to rising (SSL_R) sediment load during the current flood event were compared (Haddadchi and Hicks, 2020).

3. Results and discussion

3.1. EEI - quantification and spatio-temporal variation

Based on equation (1), the average EEI values were calculated for each flood event (Figure 2 and 3). From upstream (Lunca de Sus station) to downstream (Vrânceni station) there is a decrease in the absolute values of the EEI (from about 0.83 g.s/l² at Lunca de Sus to about 0.0027 g.s/l² at Vrânceni) (Figure 3). This demonstrates that the efficiency of flood events, in terms of sediment flux, decreases from the headwaters to the confluences. The causes of this behaviour can be multiple, but all of them are based on changes in: characteristics of sediment sources, degree of slope-channel connectivity, transport capacity or river channel morphology under the influence of flood events (Pagano et al., 2019).

For the whole period analysed (2000-2020), two diametrically opposite situations were observed: at Lunca de Sus and Târgu Ocna stations, an increase in EEI was recorded, while at Goioasa and Vrânceni stations a certain decrease was observed (Figure 2 and 3). A valid observation for all gauging stations studied would be that the

flood events of 2005, 2010, 2016 and 2020 had major contributions to the evident changes in EEI values, a sign that changes in the river channel morphology play an important role in the sediment system.

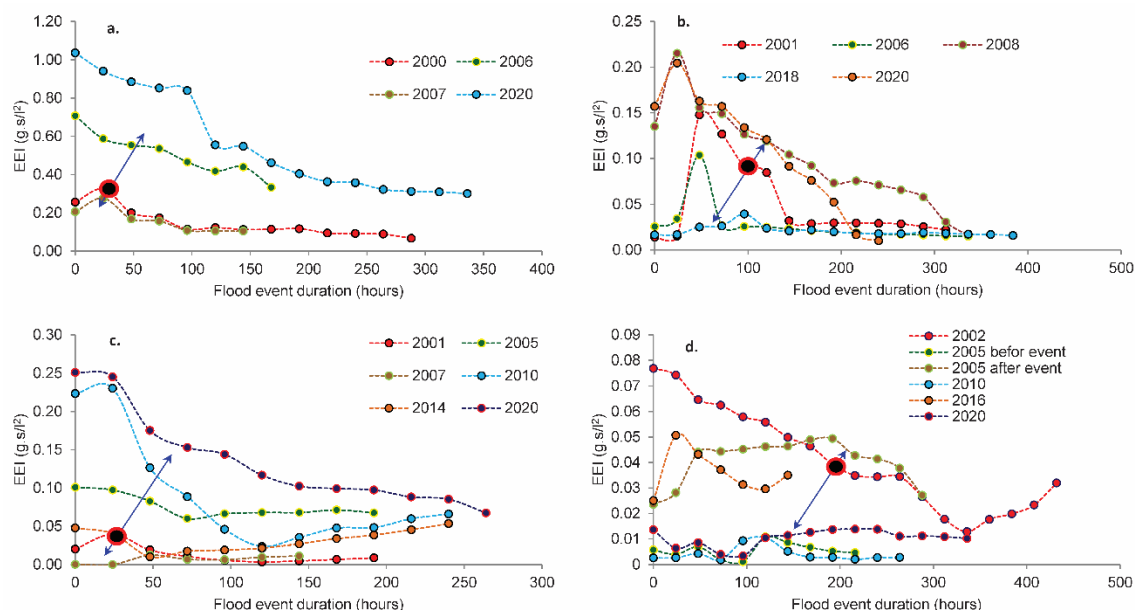


Figure 2. Efficiency index in relation to the duration of flood events: **(a)** Lunca de Sus; **(b)** Goioasa; **(c)** Târgu Ocna; **(d)** Vrânceni.

The long-term EEI behaviour recorded at each gauging station correlates very well with the temporal variation of SRC parameters (Dumitriu, 2020a). Therefore, the main cause could be the same, i.e. the change in sediment availability in the river channel following the main flood events. A certain decrease in EEI was observed where the changes in the river channel morphology were more obvious, a sign that transport capacity of the river decreased.

In addition to this general long-term behaviour, a number of secondary EEI trends have also been observed. These change points reflect changes water and/or sediment supply in the catchment (Vercruysse et al., 2017). Change points indicate a sudden alteration of the sediment regime, which in turn can be caused by a drastic change in one or more sediment system control factors (Wohl, 2015).

In the case of the Trotuş River the secondary EEI trends can be correlated, quite well, with the geomorphic effectiveness (the one that expresses the degree of change of the river channel) of the analyzed flood events. The most stable river channel are characteristic of the upper course, where few flood events have managed to change the overall trend of the EEI. For example, in the case of the Lunca de Sus section, only the flood events of 2005–2006 caused an obvious decrease in the EEI, a sign that a number of changes in the sediment regime occurred then (Figure 3a). However, the changes in the riverbed in this section during 2005–2006 were not significant, as the trend prior to these events returned relatively quickly. It appears that in this section the slopes are the main sediment source.

In the next section, Goioasa, the number of flood events causing short-term disruptions in the general trend of the EEI increased. As in the previous section, flood events in 2005 led to a sharp decrease in the EEI, indicating that much larger quantities of sediment were made available, exceeding the transport capacity of the river. The situation changed dramatically during the 2007–2008 flood events, when there was a significant increase in the EEI (Figure 3b). Flood events in 2007–2008 were characterized by rapid increases in flow and short duration, which did not allow for an obvious connection to the channel of the sediment sources on the slopes. In this case, the increased streamflows led to an increased transport capacity of sediment made available

by the 2005 flood events. The flood events of 2010, through their long period of occurrence, contributed to an increase in the amount of sediment available from the river channel, so that there is a further marked downward trend in the EEI. This trend has been halted by the 2018 flood events, which like the 2007–2008 flood events, contributed to the increase in sediment flux. The maximum sediment transport efficiency was recorded during the 2008 and 2020 events.

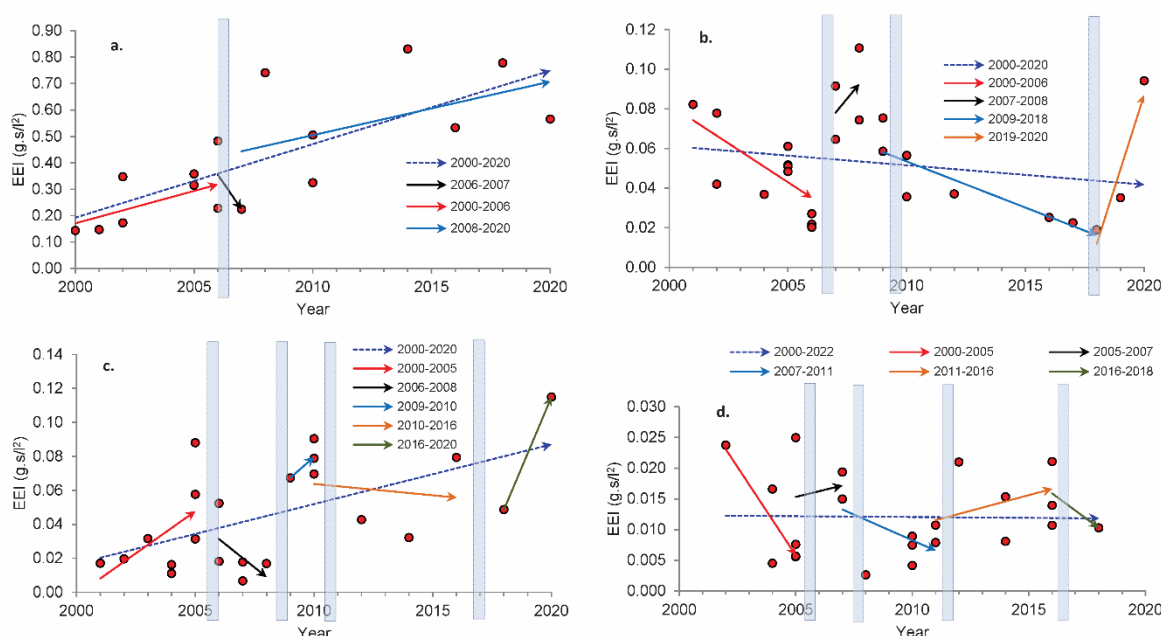


Figure 3. Flood event efficiency index trends from 2000–2020: **(a)** Lunca de Sus; **(b)** Goioasa; **(c)** Târgu Ocna; **(d)** Vrânceni.

In the case of the Târgu Ocna section, the general trend is somewhat similar to that of the Lunca de Sus station, except that in addition to the 2005 flood events, a clear decrease in EEI was also recorded during the 2010 events (Figure 3c). Again, the 2020 flood event scores with the highest suspended sediment transport efficiency.

In the last section, Vrânceni, although a slight decreasing trend of EEI is observed in the long time, in the short time the situation is more complicated and different compared to the other stations. This can be explained by the fact that in the lower course all the changes in the basin are accumulated. The 2005 flood events also marked in this section a drastic reduction of the EEI, with a period of recovery and slight increase until the 2007 events (Figure 3d). The large amounts of sediment accumulated in the river channel following the 2008 and 2010 flood events led to a further period of decreasing EEI. The efficiency of flood events in transporting suspended sediment began to increase slightly from 2011 to 2016, amid lower sediment inputs from other sources outside the river channel. In the Vrânceni section, it appears that the 2016 flood event had the same effect in terms of sediment export as the 2005 and 2010 flood events in terms of a decrease in the EEI.

Obreja (2013) suggested that EEI values indicate a range of information about the amounts of sediment available in the river channel prior to a flood event. In the literature, temporal changes in EEI (especially increases) have been mainly attributed to hydro-climatic or anthropogenic control factors. However, the situation presented in the case of the Trotuș River may argue for the inclusion in this set of EEI control factors also of the geomorphic effectiveness of floods (Dumitriu, 2016). The degree of river channel modification following flood events is in close correlation with the availability of sediment sources and transport capacity and consequently also with the EEI.

Important information on the susceptibility of the river channel to changes following flood events and which can be very well correlated with the EEI is provided by the values of the D_{s50}/D_{sub50} called armoring ratio (Dumitriu, 2007; Dumitriu et al., 2017). D_{s50} represents the median diameter of the materials within the surface layer and D_{sub50} the median diameter of the materials in the subsurface layers. This ratio primarily provides information on the presence or absence of armor layer (or river-bed armour) or on the sediment entrainment and transport capacity (Dietrich et al., 1989). If $D_{s50}/D_{sub50} > 1$ at the bed-bed surface where the armor layer or hydraulic pavement develops. Low values of this ratio (< 1.3) indicate a weakly developed hydraulic pavement, while high values (> 4) a strongly developed river-bed armour. In the case of the sections with a well-developed armor layer (Lunca de Sus and Târgu Ocna) (Figure 4) during major flood events there was no destruction of the armor layer, but only a total "flushing" of the finer sediments, so that post-event a decreasing trend of EEI was observed. The lower resistance of the hydraulic pavement in the Goioasa and Vrânceni sections led to its destruction during the main events, which resulted in availability of the finer sediments and thus an increasing trend of post-event EEI.

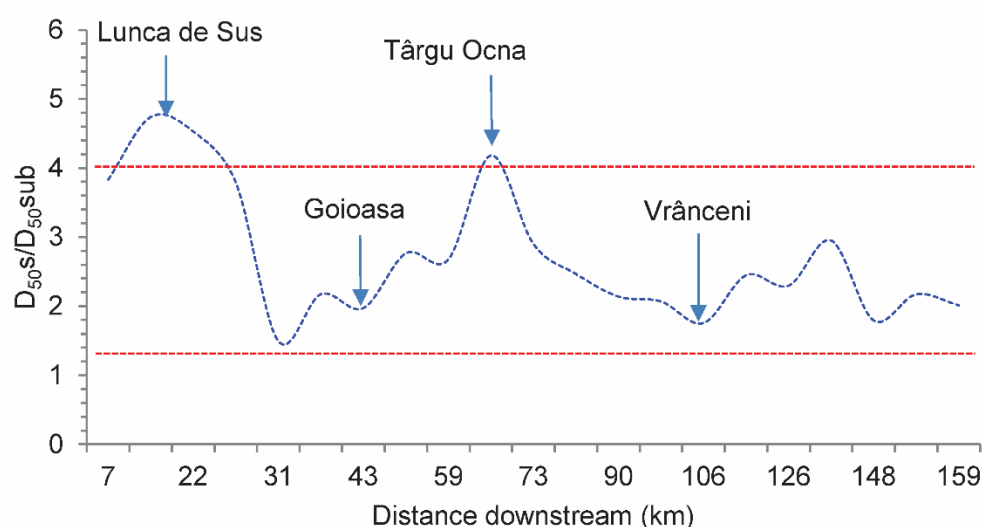


Figure 4. Variation of the armoring ratio along the Trotuș River: (a) Lunca de Sus; (b) Goioasa; (c) Târgu Ocna; (d) Vrânceni.

3.2. Inter-event variation of EEI

Certainly, the degree of river channel modification following flood events has an impact on the availability of sediment sources within the river channel (Dumitriu, 2020b, 2021). Therefore, the geomorphic effectiveness of previous flood events influences the EEI trends. Comparing the ratio of previous to current flow peaks against current flow peaks and proportion of the load carried after the flood peak (following the method proposed by Haddadchi and Hicks, 2020) indicated that in all four sections, previous major flood events had some influence on sediment flux during subsequent flood events (Figure 5). This influence was reflected in the fact that during flood events of reduced magnitude and duration, significant sediment flux was observed throughout the duration of the event, indicating that sufficient sediment was available in the river channel. In the case of the Trotuș River, it was observed (Figure 5) that the effect of previous flood events on sediment transit is more evident in the Goioasa and Vrânceni sections, where the most important changes in river channel morphology actually occurred. In the Lunca de Sus section only the 2005 and 2010 flood events influenced the sediment transit of subsequent events (Figure 5a). At Goioasa station, an increase in sediment transport efficiency was observed for the flood events following the 2005, 2007, 2009 and 2020 flood events (Figure 5b). At Târgu Ocna, only after the major event in 2005, an

increasing trend of alluvial transit was observed during subsequent events (Figure 5c), while at Vrânceni, those immediately following the events in 2005, 2010 and 2016 were observed (Figure 5d).

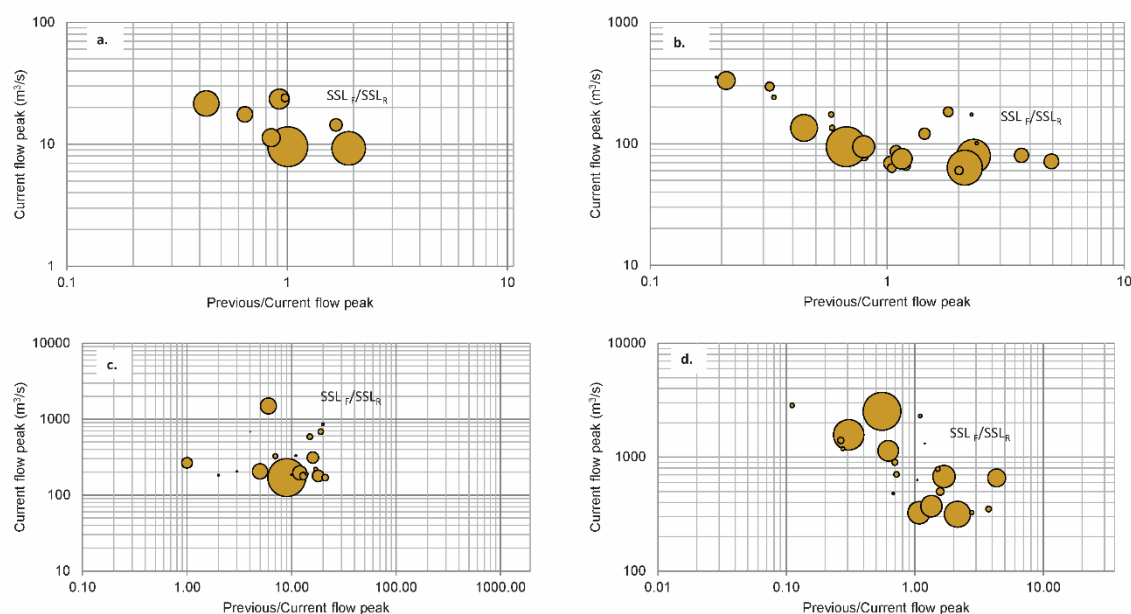


Figure 5. Ratio of previous to current flow peak versus current peak flow and proportion of sediment load during recession and rising of the hydrograph. Circle size indicates the proportion of the sediment load carried during falling to rising stage of hydrograph. Circle size scale is different on each plot and the range of SSL_F/SSL_R shown within the plots: **(a)** Lunca de Sus; **(b)** Goioasa; **(c)** Târgu Ocna; **(d)** Vrânceni.

This behaviour can be explained by the fact that during major long-lasting flood events, the degree of sediment transfer from slopes to river channel increases. Under these conditions, significant amounts of sediment from slopes will be stored in river channel. In addition to this, there will be additional sediment made available by erosion processes within the river channel. As a result, during future flood events of lower magnitude, there will be an increase in sediment flux. In these situations, the effect of previous events is highlighted by the fact that, due to the lower streamflows of subsequent events, the maximum sediment transit will occur on the falling limb. If future flood events have a higher magnitude than previous ones, the reverse situation is often observed, i.e. a lower suspended sediment transport on the falling limb. In this context, river channel can be considered important sources of sediment (Harvey et al. 2012; Piqué et al. 2014; Haddadchi and Hicks, 2020), and the analysis of spatio-temporal trends in sediment transit and IEE must necessarily take this into account.

4. Conclusions

The main aim of this study was to highlight that the spatio-temporal variations in suspended sediment flux can be influenced to a large extent by changes in river channel following flood events. For the argumentation, an attempt was made to use the EEI from another perspective, namely that of correlation with the availability of sediment sources within the river channel. Regarding the spatial and temporal variation of the EEI, two diametrically opposite situations were observed: at the Lunca de Sus and Târgu Ocna stations an increase of the EEI was recorded, while at the Goioasa and Vrânceni stations a certain decrease was observed. Spatially, these trends were correlated with the characteristics of the armor layer. Thus, it was observed that in the sections with a well-developed armor layer (Lunca de Sus and Târgu Ocna) there was a decreasing trend in

the EEI after major events, and in the sections with a lower resistance of the hydraulic pavement (Goioasa and Vrânceni) an increasing trend in the EEI in the same situations. From a temporal point of view, it was observed that in addition to the general long-term behaviour, there are also a number of secondary trends in EEI. The points of change in the EEI trend reflect changes in the availability of sediment sources, especially in the river channel. On the other hand, the close correlation between the geomorphic effectiveness of previous flood events and the EEI trends was observed. In this sense, during flood events of lower magnitude and duration compared to previous ones, increased sediment flux was observed, indicating that previous events made significant amounts of sediment available in the river channel. Consequently, if several flood events with a long recurrence interval (more than 50 years) occur in a short period of time (10 years), then the recovery time of the river channel is prolonged. Under these conditions, river channel become important sources of sediment, which is why the analysis of spatio-temporal trends in sediment flux and EEI must necessarily take this into account.

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