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A COMPARATIVE ANALYSIS OF HISTORICAL FLOOD EVENTS (POST-1990) IN THE TREBEŞ-NEGEL REPRESENTATIVE BASIN FOR EASTERN CARPATHIANS AND SUBCARPATHIANS TRANSITION ZONE

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Abstract: The European Network of Experimental and Representative Basins (ENERB) is the results of several experimental projects concerning the hydrological forecasting and flood mitigation effort which have been implemented within states member of European Union. In Romania, the hydrometric activity for ENERB it is currently composed of 14 representative basins (RB) of which the Trebeş-Negel (184 km^2) was selected as RB for Eastern Carpathian and Subcarpathian transition zone. Located in one of the most affected territories by hydrological hazards, the Trebeş-Negel RB reacted as a small-scale flood sensor for the entire region. Using the well-documented discharge and pluviometric database collected at five gauge stations within the study area, we develop the first comparative analysis of historical flood events that occurred in the Trebeş-Negel RB post-1990. Five exceptional floods were selected: flood events from July 2 to July 8, 1991; flood events from June 16 to June 22, 1992; flood events from July 11 to July 14, 2005; flood events from July 26 to July 31, 2010; and flood events from June 28 to July 1, 2018. All flood events envisaged were caused by heavy rains, when significant amounts of precipitations were recorded which sometimes exceeded 100 mm/day.

Keywords: representative river basin, heavy rains, exceptional floods, historical discharge, Trebeş-Negel basin, Eastern Carpathians and Subcarpathians transition zone, NE Romania.

1. INTRODUCTION

Natural disasters, especially those due to climate change and global warming, are increasingly reaching catastrophic scales in the world and in Europe (Blöschl & Montanari, 2010; Blöschl et al., 2017), and the economies of many countries, including Romania (Mihu-Pintilie et al., 2019; Romanescu et al., 2017a, 2018, 2019; Stoleriu et al., 2020), suffer important losses (World Bank, 2014). Among these natural hazards, floods are the most destructive, with the strongest impact on human society from vulnerable territories (Feloni et al., 2020; Kelman et al., 2015; Li et al., 2019). For this reason they have become a growing topic of concern for citizen, authorities and policy-makers within affected countries (ICPDR, 2010). In this context, during the last few decades several experimental projects concerning the hydrological forecasting and flood mitigation effort have been implemented within the member states of the European Union. The results of these projects led to the establishment of an European Network of Experimental and Representative Basins (ENERB) based on which valuable hydrological data (e.g., discharge regime, floods) have been provided (EUROFRIEND, 2020). Over the time, the integrated monitoring databases developed within ENERB contribute substantially for flood hazard documentation, an example from these points of view being the Flood Directive (FD) issued by European Commission in 2007 (EC, 2007; Priest et al., 2016). In the present time, the Experimental and Representative Basins (ERB) network support these catchments through international programs such as Flow Regimes from International Experimental and Network Data (FREND), which is part of the UNESCO program – International Hydrological Program (IHP).

Generally, the activities within ENERB encourage the collaboration and exchange of experiences and techniques between scientists which study the relatively small catchments (cca. 1.00 km^2 – 200 km^2), selected as being typical or representative of a region, in terms of attributes such as geology, slope, vegetation type, hydrological regime, and so on (Gunnell et al., 2019; McNamara et al., 2011; Robinson & Whitehead, 1993). Thereby, the selection of representative basins (RB) was made based on relatively unchanged natural condition for a significant period of time (≥ 30 years) (Toebes & Ouryvaev, 1970). Alternatively, if the natural condition is no longer fulfilled, instead of RB the experimental basins (EB) were instrumented to evaluate the effects on hydrological behavior of changes in land use or land management (Table 1) (Barbet & Givonne, 1993; Robinson & Whitehead, 1993; Toebes & Ouryvaev, 1970). In this framework, the ENERB start with few representative and experimental catchments from 12 European countries (e.g., Austria – 1 basin, Czech Republic – 4 basins, France – 1 basin, Germany – 11 basins, Italy – 7 basin, Luxembourg – 1 basin, Norway – 1 basin, Poland – 4 basins, Romania – 4 basins, Slovakia – 2 basins, Spain – 4 basins, Switzerland – 1 basin) (Barbet & Givonne, 1993), and currently, over 5,000 river gauging stations in 30 countries are used to study natural and manmade changes in hydrological regimes of ERB network (Passarella & Vurro, 2003).

In Romania, the hydrometric activity for ERB began with 1986, when the first four RB were implemented (Barbet & Givonne, 1993; Robinson & Whitehead, 1993; Toebes & Ouryvaev, 1970). After few years (post-1990), their number increased to 14 catchments, and the Trebeş-Negel was selected as RB for Eastern Carpathian and Subcarpathian transition zone (Mătreaţă et al., 2009). Located in one of the most affected territories by hydrological hazards (e.g., floods, flash floods), the Trebeş-Negel RB reacted as a small-scale flood sensor for the entire northeast region of Romania. In this context, based on well-documented discharge and pluviometric database collected at five gauge stations within the study area, we develop the first comparative analysis of historical flood events that occurred in the Trebeş-Negel RB post-1990. Five exceptional floods were selected: flood events from July 2 to July 8, 1991; flood events from June 16 to June 22, 1992; flood events from July 11 to July 14, 2005; flood events from July 26 to July 31, 2010; and flood events from June 28 to July 1, 2018. Our research joins the concerns of the specialists of Siret Water Basin Administration (SWBA) within National Administration Romanian Waters (NARW) about the hydrological risk assessment in the north-eastern Romania (Huţanu et al., 2019; 2020; Paveluc et al., 2019; Urzică et al., 2019). The small-scale

Table 1. Scope and purpose of representative and experimental river basins within ENERB

Representative basins (RB)
(a) Fundamental research: study of all the physical processes of the hydrological cycle or of any specific hydrological characteristics. **(b)** Effects of natural changes: effects on the hydrological regimen of a natural change in climate, vegetation characteristics because of natural growth, in pedagogical characteristics such as erosion, etc. **(c)** Hydrological prediction: development and improvement of methods of hydrological calculation and prediction and for the assessment of water resources in a region or area. This involves a detailed analysis of hydrological phenomena and the direction of research towards solving methodological problems. **(d)** Extension of records: provide a long-term record of basic data to which short-term records observed on roving or investigation stations may be correlated. In some countries (e.g., Romania) the representative basin does serve as the basic network of hydrological stations.
Experimental basins (EB)
(a) Effects of cultural change: study of the effects of cultural change on the hydrological regimen. Cultural changes involve the artificial change of basin characteristics, with a resulting change in some hydrological characteristics and include any changes in land use (such as afforestation) and/or land management and the influence of the use of water resources (e.g., artificial recharge). **(b)** Hydrological prediction and extension of records: experimental basins can be used also for this purpose during their calibration period, provided no direct conflict arises with the principal aim of the manipulation action. Control basins which are left in their natural condition can also be used as representative basins. **(c)** Fundamental research: experimental basins are, like representative basins, ideally suited for fundamental hydrological research and for this reason the extensive instrumentation available in experimental basins provides excellent opportunities for staff training.

analysis of flood patterns and frequency within Trebeş-Negel RB highlights the role played by locally heavy rains at the onset of floods in probably one of the most dynamic RB within the European ERB network, and contributes to a better flood hazard understanding at regional-scale (e.g., Eastern Carpathian and Subcarpathian transition zone).

2. STUDY AREA

The Trebeş-Negel RB is located in the north-eastern part of Romania (Figure 1a) and belongs to the important basin of Bistriţa River from which it occupies the lower sector, in the Eastern Subcarpathians, also known as Moldavian Subcarpathians (Figure 1b). The total area of the Trebeş-Negel RB is 184 km^2 and the geographic boundaries are: 46°39´N – northern limit, 46°29´N – southern limit, 26°41´ E – western limit, and 26°56´ E – eastern limit. From the morphological point of view, 85% of the analyzed territory overlaps with the eastern slope of the Pietricica Bacaului Peak, which belongs to the southern sector of the Moldavian Subcarpathians, and 15% with the common floodplain with the Bistriţa River (Cojoc et al., 2015; Cozma et al., 2015; Cruceanu et al., 2015).

The general morphostructure of the basin is characteristic of the Molasse unit which consists of a succession of tightly folded deposits made up predominantly of sandstone, marls, clay, and gypsum and salt intercalations of Miocene age. The local geological conditions within the floodplains of the Trebeş and Negel rivers are characterized by the presence of recent alluvial layers accumulated in the Holocene period. The altitude in the studied area varies between 151 m (Trebeş floodplain) and 584.4 m (Căpăţâna Hill) and the dominant altitude class is between 300 m and 350 m (>25%). The asymmetry of the Trebeş-Negel RB (shape ratio 0.54) is a consequence of the development of the Negel River as main tributary in the south part of the basin. The average slope is 9.21° and the dominant slope class is between 10° and 15° (35% of the total area) (Paveluc et al., 2018).

The Trebeş River springs from a relative altitude of 248 m, is 27.35 km long and is one of the main tributary of Bistriţa River, while the Negel River springs from a relative altitude of 371 m and is 12.26 km long. The total length of the hydrographic network within the Trebeş-Negel RB is 128.86 km, with an average density of the 0.7 km/km^2 (Paveluc et al., 2018). Climate conditions control more than 60% of the flow rate, especially during periods with maximum rainfall or in the transition season (spring and autumn). At the regional level (Eastern Carpathians and Subcarpathians), the average air temperature values are between 7.5°C and 11.5°C). The annual average precipitation is between 550 mm

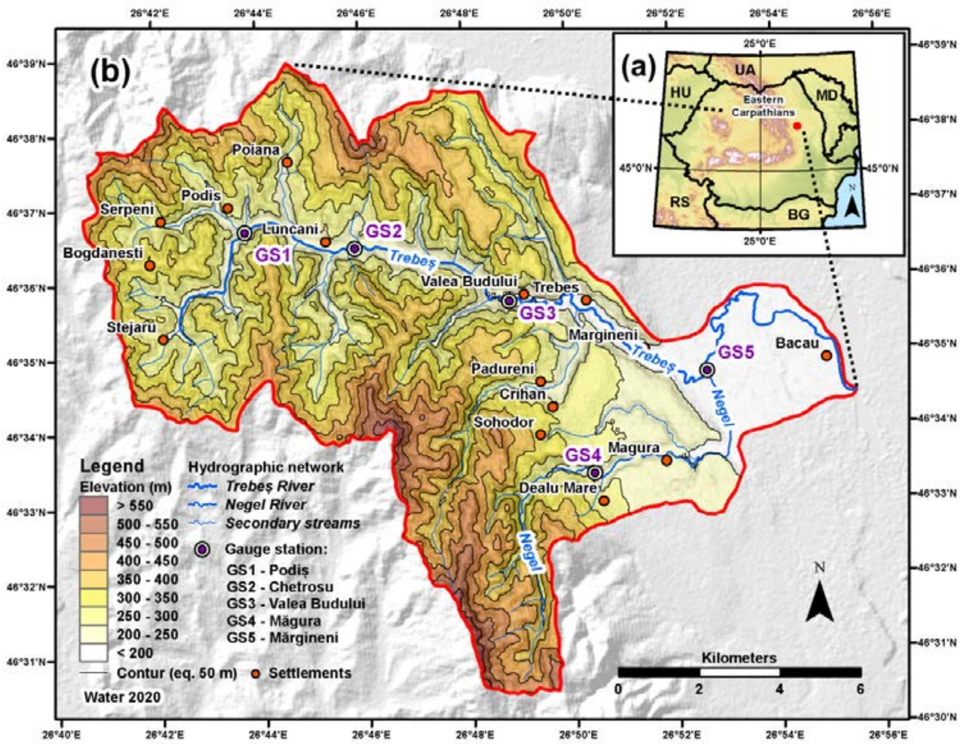

Figure 1. Geographic location of the (a) Trebeş-Negel RB in Romania and (b) elevation and location of the gauge stations within the study area.

and 650 mm, with high values occurring at over 500 m altitude where the maximum daily values of precipitation exceeded sometimes 100 mm/day (e.g., July 27 2010 – 115.2 mm/day) (Romanescu et al., 2015; 2016; 2017b). The groundwater contributes with more than 40% of the average annual flow rate.

Between 1980/1981 and 2018, the multi-annual average flow rates recorded at each gauge station (Figure 1b) within the Trebeş-Negel RB were: GS1 Podiş – 0.099 m^3/s, GS2 Chetrosu – 0.196 m^3/s, GS3 Valea Budului – 0.240 m^3/s, GS4 Măgura – 0.063 m^3/s and GS5 Mărgineni – 0.376 m^3/s. The historical discharge was recorded at GS5 Mărgineni on July 27, 2010, and was 186 m^3/s (Romanescu et al., 2018). Other hydrological events associated with the maximum discharge occurred on: July 3, 1991 at Mărgineni (57 m^3/s) and Valea Budului (49.2 m^3/s); June 18, 1992 at Valea Budului (89 m^3/s), Mărgineni (81.5 m^3/s) and Chetrosu (77.3 m^3/s); July 13, 2005 at Mărgineni (155 m^3/s), Valea Budului (93 m^3/s) and Chetrosu (85 m^3/s); July 27, 2010 at Măgura (96.7 m^3/s), Valea Budului (84 m^3/s) and Chetrosu (73.5 m^3/s); June 30, 2018 at Mărgineni (88 m^3/s) and Valea Budului (49.1 m^3/s) (NARW–SWBA, 1991, 1992, 2005, 2010, 2018).

3. MATERIALS AND METHODS

Worldwide, the assessment of floods phenomena is a very well-documented topic and many methodologies have been developed to better understand the causes and effects of these natural hazards (Allen et al., 2020; Garrote & Bernal, 2020; Jiang et al., 2019; Kvočka et al., 2016; Van Ackere et al., 2019; Van Leeuwen et al., 2016; Wang et al., 2015). In this study, the ENERB available methodological examples for RB assessment were used in order to analyze the flood events which took place in the Trebeş-Negel RB post-1990 (Table 1) (Caloiero et al., 2016; Minea et al., 2016; Mostowik et al., 2018). Thereby, in order to highlight the role played by local and regional heavy rains at the onset of floods, the pluviometric and hydrological data were collected from the SWBA in Bacău Municipality (lower Trebeş-Negel RB).

The daily hydrological measurements program (e.g., water level observations, flow rate) is 2 observations / day, when the flow regime is a normal one, but their frequency increases at 24 observation / day and more (e.g., 20 minutes / hour) when important hydrological events such as flash floods occur. The meteorological data like rainfalls amounts are monitored 24 hours / day according to the Berg intensity scale (Paveluc et al., 2018). All meteorological and hydrological data recorded at pluviometric and hydrometric stations within the study area are transmitted in real time to SWBA where they are centralized in the national monitoring system of Romania for regional hydrological forecasting (Table 2) (NARW–SWBA, 2020). These data are also useful both for practical purposes (e.g., flood hazard management) and for fundamental research (e.g., study of hydrological cycle, physical processes) (INGHA, 2020).

Since 1980, on the Trebeş-Negel RB territory eleven gauge stations and five pluviometric stations placed at different key points along the two rivers work partially or completely until now (Paveluc et al., 2018). In this study, because not all gauge stations have permanently work during the analyzed period (post-1990), we selected the pluviometric and discharge data recorded at five gauge station according to full-time operating criteria: Podiş, Chetrosu, Valea Budului, Măgura and Mărgineni (Table 2). According to the multi-annual flow rates data recorded at each gauge station the average discharge between 1980 and 2018 was: Podiş – 0.099 m^3/s, Chetrosu – 0.196 m^3/s, Valea Budului – 0.240 m^3/s, Măgura – 0.063 m^3/s and Mărgineni – 0.376 m^3/s (Table 3).

Thereby, based on annual maximum discharge data from SWBA hydrological archive, five exceptional flood events were selected: flood events from July 2 to July 8, 1991; flood events from June 16 to June 22, 1992; flood events from July 11 to July 14, 2005; flood events from July 26 to July 31,

Table 2. The main characteristics of the gauge stations within the Trebeş-Negel RB

River	Gauge station	Inauguration year	[1] Latitude	[1] Longitude	Altitude (m)	Area (km^2)
Trebeş	Podiş	1981	569,405.915	632,351.357	225.73	9.60
Trebeş	Chetrosu	1981	569,012.656	634,879.392	213.87	48.4
Trebeş	Valea Budului	1981	567,721.886	638,593.001	197.31	66.1
Negel	Măgura	1981	563,400.970	641,124.925	227.4	13.8
Trebeş-Negel	Mărgineni	1980	566268.240	643906.371	177.52	124

[1] Projection Double Stereographic 1970 (Geographic Coordinate System of Romania)

Table 3. Average monthly and multi-annual discharge (m^3/s) recorded between 1980 and 2018 at each gauge station within the Trebeş-Negel RB

River	Gauge station	Month												Avg.
		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Trebeş	Podiş	0.04	0.08	0.19	0.23	0.15	0.18	0.12	0.05	0.02	0.03	0.03	0.04	0.099
Trebeş	Chetrosu	0.10	0.14	0.37	0.46	0.36	0.36	0.30	0.16	0.07	0.07	0.08	0.09	0.196
Trebeş	Valea Budului	0.11	0.17	0.40	0.56	0.43	0.45	0.41	0.15	0.11	0.10	0.10	0.12	0.24
Negel	Măgura	0.02	0.04	0.06	0.11	0.11	0.09	0.15	0.03	0.02	0.01	0.01	0.01	0.063
Trebeş-Negel	Mărgineni	0.23	0.29	0.86	0.78	0.59	0.68	0.80	0.37	0.16	0.18	0.17	0.19	0.376

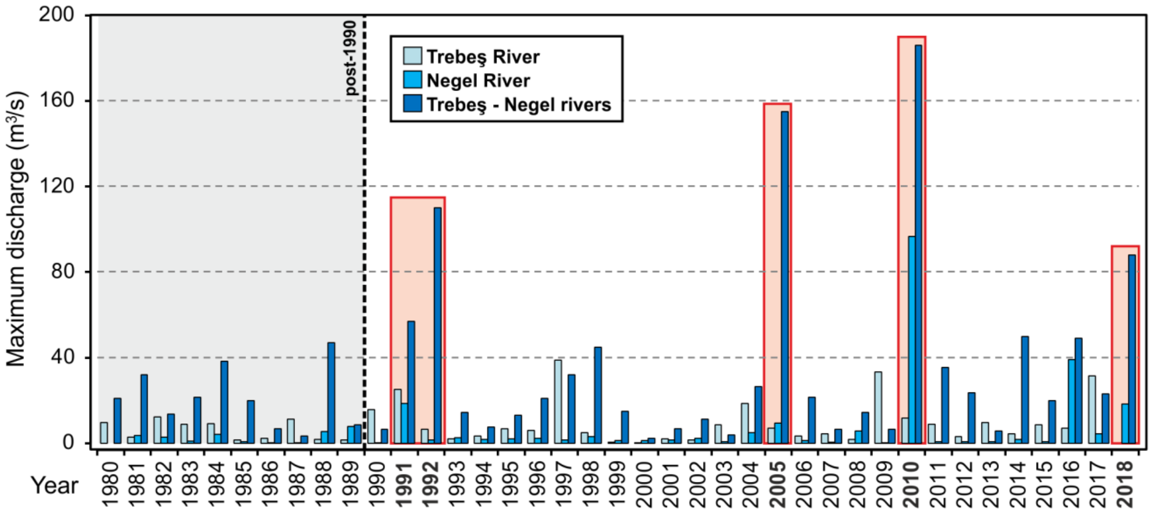

Figure 2. The maximum annual discharge (m^3/s) recorded between 1980 and 2018 at the Podiş gauge station on the Trebeş River, Măgura gauge station on the Negel River and Mărgineni gauge station located downstream of the confluence of the rivers Trebeş and Negel. The red squares highlight the years (post-1990) when exceptional flood events occur in the Trebeş-Negel RB

2010; and flood events from June 28 to July 1, 2018 (Figure 2). Each of the selected flood events was permanently monitored by competent personnel of SWBA (e.g., hydrologists, emergency situations authorities), using modern tools and technologies (Mihu-Pintilie et al., 2014, 2019).

The field observations and measurements were made by the staff of Bacău gauge station both during the floods and after them for flow rate reconstruction purpose. The daily water levels and flow rates were collected starting with the hydrometric data recorded at main gauge stations that are included in national gauge stations list and provided daily hydrological data at standard hours (07:00 AM and 5:00 PM), respectively from upstream to downstream (along the Trebeş River: Podiş – Chetrosu – Valea Budului – Mărgineni; along the Negel River: Măgura – Mărgineni). The damage assessments caused by the analyzed flood events are based on the summary reports provided by the Inspectorate for Emergency Situations in the Bacău County (IESBC) and by delegates for emergency situations within SWBA. Also, valuable data related to the impact and magnitude of the recent flood events (e.g., flood events from July 11 to July 14, 2005; flood events from July 26 to July 31, 2010; flood events from June 28 to July 1, 2018) were obtained directly on the field or by consulting the locals. Concerning the roads and railways affected by floods, documentation provided by the Ministry of Transport and Communication of Romania (MTCR) and commune halls (e.g., Măgura, Mărgineni) were consulted.

4. RESULTS

4.1. Flood events from July 2 to July 8, 1991

The flood event of 1991 started on July 2 and lasted seven days (Figure 3). The bimodal flood wave was induced by torrential precipitations recorded in the upper sector of the Trebeş-Negel RB. The first flood peak recorded on July 3 was determined by high intensity of precipitation cumulated during the night between July 2 and July 3 (cumulative rainfalls – 62.2 mm) and in the morning of the July 3 (cumulative rainfalls – 143 mm) (Table 4). The maximum discharge of 57 m^3/s was recorded at Mărgineni gauge station at 2:20 PM where the caution level was exceeded with +80 cm and the flood level was reached (Table 5). The second flood peak was recorded on July 4 due to the torrential activity caused by the heavy rains (cumulative rainfalls – 136.2 mm). Overall, during the flood events from July 2 to July 8, the flood level was reached at all gauge stations (Podiş +53 cm; Chetrosu +95 cm; Valea Budului +20 cm; Măgura +30 cm; Mărgineni +95 cm) (NARW–SWBA, 1991).

The flood events between July 2 and July 8, 1991, caused significant damage to settlements located along the Trebeş and Negel rivers of which the village of Mărgineni was the most affected (Romanescu et al., 2017a). According to the summary report on the evolution and effects of dangerous hydro-meteorological phenomena provided by SWBA for this flood event (NARW–SWBA, 1991), more than 31 buildings were flooded out of which 3 houses were completely destroyed, and more than 33 ha of agricultural land were flooded out of which 15 ha were completely compromised.

4.2. Flood events from June 16 to June 22, 1992

The next major flood event that occurred post-1990 in the Trebeş-Negel RB started on June 16, 1992, and lasted seven days (Figure 4) (NARW–SWBA, 1992). Similar to the flood event from 1991,

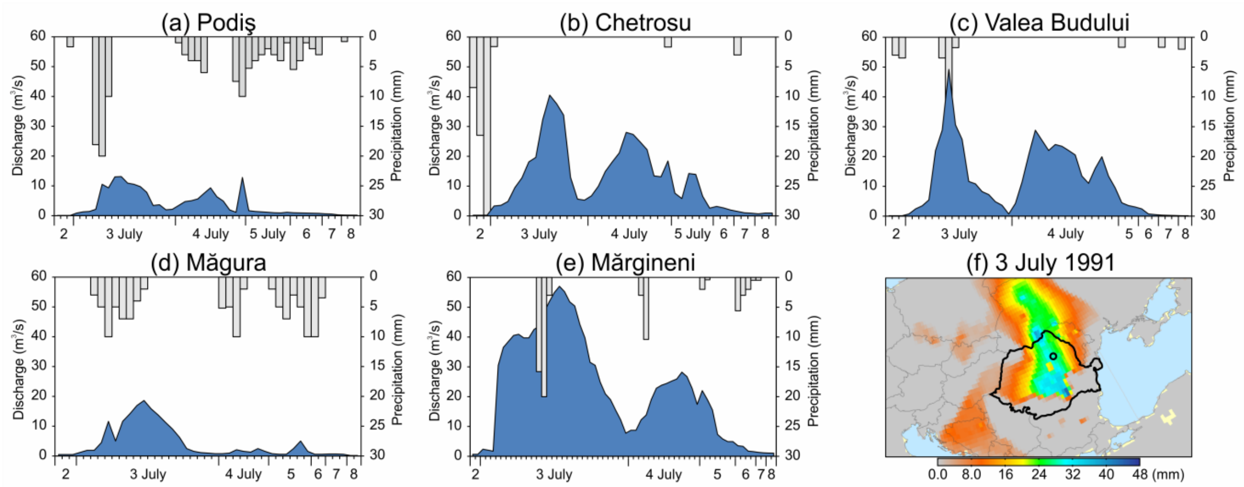

Figure 3. Correlations between hydrographs (m^3/s) and daily precipitations intensity (mm) recorded during the flood events between July 2 and July 8, 1991, at: (a) Podiş, (b) Chetrosu, (c) Valea Budului, (d) Măgura and (e) Mărgineni gauge stations on the Trebeş-Negel RB; (f) E-OBS v 20.0e daily rainfall amounts (mm) map in Eastern Europe on July 3, 1991.

Table 4. Daily rainfall recorded at the Podiş, Chetrosu, Valea Budului, Măgura and Mărgineni pluviometric stations during the period between July 2 and July 8, 1991, in the Trebeş-Negel RB

River	Pluviometric station	Daily rainfall amounts (mm)							
		2nd	3rd	4th	5th	6th	7th	8th	Total
Trebeş	Podiş	1.7	58.1	37.5	22.3	15.5	-	0.8	135.9
Trebeş	Chetrosu	6.5	5.0	-	1.7	-	1.0	2.0	16.2
Trebeş	Valea Budului	54.0	1.6	-	1.7	-	3.0	-	60.3
Negel	Măgura	-	43.0	25.2	32.0	13.5	-	-	113.7
Trebeş	Mărgineni	-	35.8	13.4	2.4	11.6	-	-	63.2

Table 5. Correlations between the maximum levels, caution levels and discharges recorded at the Podiş, Chetrosu, Valea Budului, Măgura and Mărgineni gauge stations during the period between July 2 and July 8, 1991, in the Trebeş-Negel RB

River	Gauge station	[1] $H_{max.}$ (cm)	[2] Compared to caution levels (cm)	[3] $Q_{max.}$ (m^3/s)	Date and hour occurrence of $H_{max.}$ and $Q_{max.}$
Trebeş	Podiş	403	+53 *Fl*	13.1	3 July 1991 – 12:00 PM
Trebeş	Chetrosu	595	+95 *Fl*	40.5	3 July 1991 – 12:30 PM
Trebeş	Valea Budului	420	+20*Fl*	49.2	3 July 1991 – 1:00 PM
Negel	Măgura	280	+30*Fl*	18.6	3 July 1991 – 10:35 AM
Trebeş	Mărgineni	580	+80 *Fl*	57	3 July 1991 – 2:20 PM

[1]$H_{max.}$: Height; [2]Caution level abbreviations: *Wl*: Warning level; *Dl*: Danger level; *Fl*: Flood level; [3]$Q_{max.}$: Flow rate.

the bimodal flood wave was induced by heavy rains (cumulative rainfall between 16 and 22 June – 384.8 mm) (Table 6), but the propagation time and flood manifestation were different (flash flood in this case) (Romanescu et al., 2017a). Thereby, the first and most intense flood peak was recorded on the morning of June 18 when high values of the discharge were recorded at each gauge station located on the Trebeş River: Podiş – 25.1 m^3/s (1:00 AM); Chetrosu – 77.3 m^3/s (1:30 AM); Valea Budului – 89.0 m^3/s (2:00 AM); Mărgineni – 81.5 m^3/s (5:40 AM) (Table 6). The second flood peak occurred on June 20 but its intensity was much lower than the previous one. However, during the flood events from June 16 to June 22, the flood level was reached at all gauge stations: Podiş +82 cm; Chetrosu +123 cm; Valea Budului +105 cm; Mărgineni +130 cm (Table 7) (NARW–SWBA, 1992).

The flood events between June 16 and June 22, 1992, caused significant damage to settlements located along the Trebeş River out of which the village of Mărgineni and the Bacău Municipality were the most affected (NARW–SWBA, 1992). Thus, in the village of Mărgineni 26 houses were affected and 39 ha of agricultural land were flooded and agricultural crops completely compromised. On the Bacău Municipality territory, 30 buildings were flooded out of which 8 houses were completely destroyed, and more than 10 ha of agricultural land were flooded.

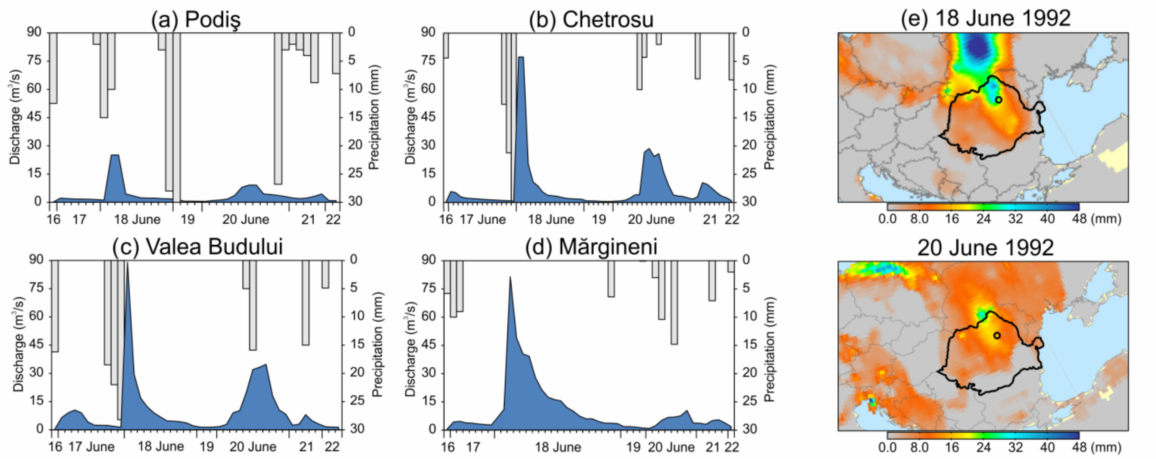

Figure 4. Correlations between hydrographs (m^3/s) and daily precipitations intensity (mm) recorded during the flood events between June 16 and June 22, 1992, at: (a) Podiş, (b) Chetrosu, (c) Valea Budului and (d) Mărgineni gauge stations on the Trebeş-Negel RB; (e) E-OBS v 20.0e daily rainfall amounts (mm) maps in the Eastern Europe on June 18 and June 20, 1992.

Table 6. Daily rainfall recorded at Podiş, Chetrosu, Valea Budului and Mărgineni pluviometric stations during the period between June 16 and June 22, 1992, in the Trebeş-Negel RB

River	**Pluviometric station**	**Daily rainfall amounts (mm)**							
		16th	**17th**	**18th**	**19th**	**20th**	**21st**	**22nd**	**Total**
Trebeş	Podiş	9.5	17.0	61.0	-	26.8	8.8	7.2	130.3
Trebeş	Chetrosu	0.6	12.6	51.2	-	14.3	8.1	8.3	95.1
Trebeş	Valea Budului	0.5	18.5	50.2	-	20.9	15.0	4.9	110
Trebeş	Mărgineni	-	19.0	6.4	0.1	14.8	7.1	2.0	49.4

Table 7. Correlations between the maximum levels, caution levels and discharges recorded at the Podiş, Chetrosu, Valea Budului and Mărgineni gauge stations during the period between June 16 and June 22, 1992, in the Trebeş-Negel RB

River	**Gauge station**	**[1] $H_{max.}$ (cm)**	**[2] Compared to caution levels (cm)**	**[3] $Q_{max.}$ (m^3/s)**	**Date and hour occurrence of $H_{max.}$ and $Q_{max.}$**
Trebeş	Podiş	432	+82 *Fl*	25.1	18 June 1992 – 1:00 AM
Trebeş	Chetrosu	623	+123 *Fl*	77.3	18 June 1992 – 1:30 AM
Trebeş	Valea Budului	505	+105 *Fl*	89	18 June 1992 – 2:00 AM
Trebeş	Mărgineni	630	+130 *Fl*	81.5	18 June 1992 – 5:40 AM

[1]$H_{max.}$: Height; [2]Caution level abbreviations: *Wl*: Warning level; *Dl*: Danger level; *Fl*: Flood level; [3]$Q_{max.}$: Flow rate.

4.3. Flood events from July 11 to July 14, 2005

The summer of 2005 was one of the most catastrophic period in term of flood events and hazard manifestation in the north-eastern Romania (Mihu-Pintilie et al., 2019; Romanescu et al., 2017a). In the Trebeş-Negel RB the second most intense flood events were recorded between 11 and 14 July (Figure 5) (NARW-SWBA, 2005; Paveluc et al., 2018; Romanescu et al., 2017a).

The flood peak recorded on the morning of July 13 was determined by high intensity of precipitation cumulated during the previous two days (cumulative rainfalls – 295 mm) with precipitation which occurred in the first part of the day 13 July (cumulative rainfalls – 259.1 mm) (Table 8). At each of the gauge stations located on the river Trebeş river the following maximum discharge values were recorded: Podiş – 18.3 m^3/s (6:30 AM); Chetrosu – 85.0 m^3/s (7:00 AM); Valea Budului – 93 m^3/s (8:00 AM); Mărgineni – 155 m^3/s (9:00 AM) (Table 8). Accordingly, the flood level has been reached at all analyzed gauge stations: Podiş +49 cm; Chetrosu +8 cm; Valea Budului +37 cm; Mărgineni +248 cm (Table 9) (NARW-SWBA, 2005; Romanescu et al., 2017a).

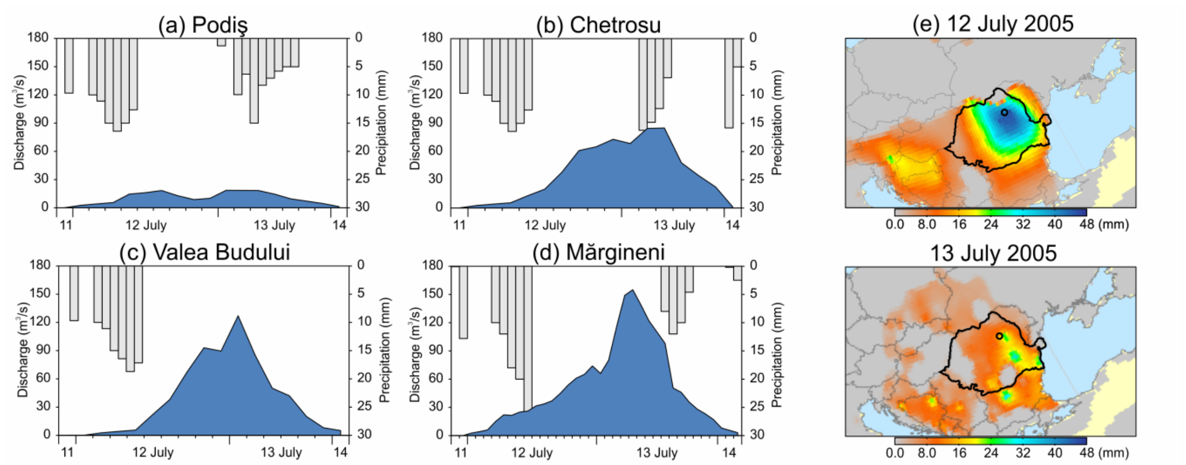

Figure 5. Correlations between hydrographs (m^3/s) and daily precipitations intensity (mm) recorded during the flood events between July 11 and July 14, 2005, at: (a) Podiş, (b) Chetrosu, (c) Valea Budului and (d) Mărgineni gauge stations on the Trebeş-Negel RB; (e) E-OBS v 20.0e daily rainfall amounts (mm) maps in the Eastern Europe on July 12 and July 13, 2005.

Table 8. Daily rainfall recorded at Podiş, Chetrosu, Valea Budului and Mărgineni pluviometric stations during the period between July 11 and July 14, 2005, in the Trebeş-Negel RB

River	Pluviometric station	Daily rainfall amounts (mm)				
		11th	12th	13th	14th	Total
Trebeş	Podiş	2.2	75.3	91.8	-	169.3
Trebeş	Chetrosu	1.8	58.1	72	-	131.9
Trebeş	Valea Budului	2.1	56.3	60.7	-	119.1
Trebeş	Mărgineni	12.80	86.40	34.60	0.20	134

Table 9. Correlations between the maximum levels, caution levels and discharges recorded at Podiş, Chetrosu, Valea Budului and Mărgineni gauge stations during the period between July 11 and July 14, 2005, in the Trebeş-Negel RB

River	Gauge station	[1] $H_{max.}$ (cm)	[2] Compared to caution levels (cm)	[3] $Q_{max.}$ (m^3/s)	Date and hour occurrence of $H_{max.}$ and $Q_{max.}$
Trebeş	Podiş	399	+49 *Fl*	18.3	13 July 2005 – 6:30 AM
Trebeş	Chetrosu	508	+8 *Fl*	85	13 July 2005 – 7:00 AM
Trebeş	Valea Budului	437	+37 *Fl*	93	13 July 2005 – 8:00 AM
Trebeş	Mărgineni	748	+248 *Fl*	155	13 July 2005 – 9:00 AM

[1]$H_{max.}$: Height; [2]Caution level abbreviations: *Wl*: Warning level; *Dl*: Danger level; *Fl*: Flood level; [3]$Q_{max.}$: Flow rate.

The flood events that occurred between July 11 and 14, 2005, were among the most destructive hydrological phenomena recorded in the Trebeş-Negel RB and caused significant damage to settlements located along the Trebeş River. Thereby, 105 buildings were flooded in the territory of Mărgineni settlement of which 17 houses were completely destroyed, and 69 attachment buildings were flooded of which more than 50% were completely destroyed. Also, 11.4 km of county roads were damaged by floods and 13 bridges were completely destroyed. In the Bacău Municipality, from 386 buildings affected by floods, 12 houses were completely destroyed, 42 basements of apartment buildings were flooded, and more than 0.5 km of hydrotechnical work (e.g., water supply network, heating pipes) was damaged (NARW-SWBA, 2005).

4.4. Flood events from July 26 to July 31, 2010

The period July-August 2010 was characterized by intense hydrological activity, with floods considered among the most powerful in the Romanian territory (Cojoc et al., 2015; Paveluc et al., 2018; Romanescu et al., 2017a, 2018). In the Trebeş-Negel RB the most intense flood events were recorded between July 26 and July 31 (Figure 6) (NARW-SWBA, 2010). The peak of the flood was reached on the morning of July 27 at the gauge stations in the upper basin (Podiş – 33 m^3/s; Chetrosu – 73.5 m^3/s; Valea Budului – 84.5 m^3/s; Măgura – 96.7 m^3/s) and at noon at the Mărgineni hydrometric station (historic discharge – 186 m^3/s) in the lower basin. This situation was determined by high intensity of precipitation during the previous day (cumulative rainfall – 397.1 mm) (Table 10). As opposed to previous flood events that occurred in the Trebeş-Negel RB, in this case the maximum discharge was recorded both on the Trebeş and Negel rivers (Table 11). However, the flood level was reached at all gauge stations (Podiş +25 cm; Valea Budului +26 cm; Măgura +25; Mărgineni +225 cm) except for Chetrosu gauge station where only the danger level was reached (+95 cm) (Table 11) (NARW-SWBA, 2010).

Due to rainfall manifestation on the entire area of the Trebeş-Negel RB, the flood extent affected all settlements located along the Trebeş and Negel rivers. Thereby, within Măgura settlement (Negel River) 37 houses and attachment buildings were affected (12 houses completely destroyed), 7.1 km of rods were damaged (more than 50%), 3 bridges and 0.655 km of protection dams were completely destroyed, and 73 ha of agricultural land were flooded and agricultural crops completely compromised. In the Mărgineni settlement (Trebeş River), 152 houses and attachment buildings were affected (37 houses completely destroyed), 107.8 km of rods were damaged (more than 50%), 49 bridges and 0.5 km of protection dams were completely destroyed, and 112 ha of agricultural land were flooded and agricultural crops completely compromised. Also, in the Bacău Municipality major damage were reported: 31 houses and attachment buildings were affected (13 houses completely destroyed), 0.5 km of urban streets were damaged, 3.5 km of sewerage network were affected and more than 5 ha of built-up area were flooded (NARW-SWBA, 2010).

4.5. Flood events from June 28 to July 1, 2018

The last flood events analyzed in this study took place between June 28 and July 1, 2018, and affected the entire area of Trebeş-Negel RB (Figure 7) (NARW-SWBA, 2018). The peak of the flood,

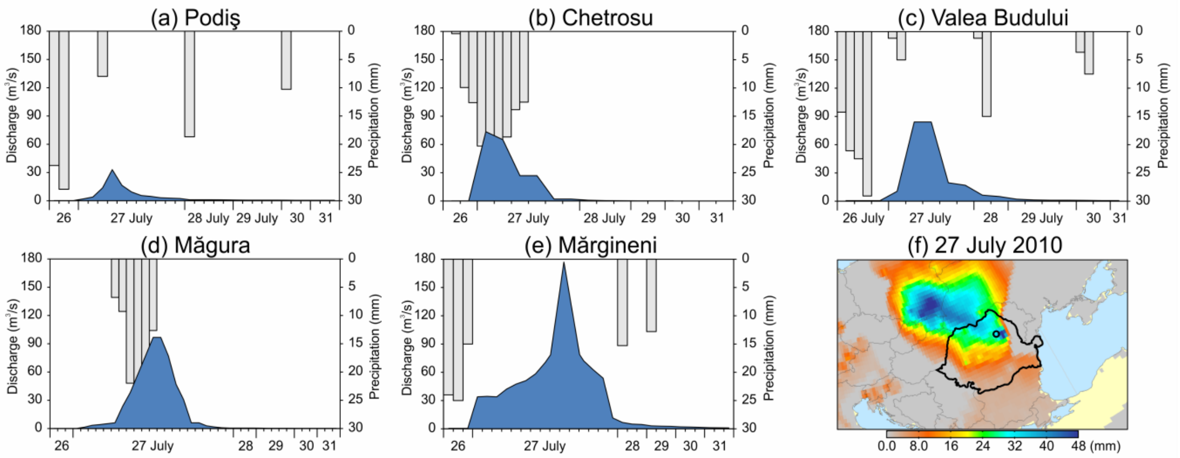

Figure 6. Correlations between hydrographs (m^3/s) and daily precipitations intensity (mm) recorded during the flood events between July 26 and July 31, 2010, at: (a) Podiş, (b) Chetrosu, (c) Valea Budului, (d) Măgura and (e) Mărgineni gauge stations on the Trebeş-Negel RB; (f) E-OBS v 20.0e daily rainfalls amounts (mm) map in the Eastern Europe on July 27, 2010.

Table 10. Daily rainfall recorded at Podiş, Chetrosu, Valea Budului, Măgura and Mărgineni pluviometric stations during the period between July 26 and July 31, 2010, in the Trebeş-Negel RB

River	**Pluviometric station**	**Daily rainfall amounts (mm)**						
		26th	**27th**	**28th**	**29th**	**30th**	**31st**	**Total**
Trebeş	Podiş	51.1	8	18.7	-	10.3	-	88.1
Trebeş	Chetrosu	0.4	115.2	-	-	-	-	115.6
Trebeş	Valea Budului	51.1	8	17.3	-	10.2	-	86.6
Negel	Măgura	-	99.3	-	-	-	-	99.3
Trebeş	Mărgineni	64	-	15.3	12.8	-	-	92.1

Table 11. Correlations between the maximum levels, caution levels and discharges recorded at Podiş, Chetrosu, Valea Budului, Măgura and Mărgineni gauge stations during the period between July 26 and July 31, 2010, in the Trebeş-Negel RB

River	**Gauge station**	**[1]$H_{max.}$ (cm)**	**[2]Compared to caution levels (cm)**	**[3] $Q_{max.}$ (m^3/s)**	**Date and hour occurrence of $H_{max.}$ and $Q_{max.}$**
Trebeş	Podiş	375	+25 *Fl*	33	27 July 2010 – 7:50 AM
Trebeş	Chetrosu	495	+95 *Dl*	73.5	27 July 2010 – 7:00 AM
Trebeş	Valea Budului	426	+26 *Fl*	84	27 July 2010 – 8:00 AM
Negel	Măgura	275	+25 *Fl*	96.7	27 July 2010 – 8:50 AM
Trebeş	Mărgineni	726	+225 *Fl*	186	27 July 2010 – 12:00 PM

[1]$H_{max.}$: Height; [2]Caution level abbreviations: *Wl*: Warning level; *Dl*: Danger level; *Fl*: Flood level; [3]$Q_{max.}$: Flow rate.

recorded on June 30 at all gauge stations between 5:30 AM and 10:00 AM, was determined by high intensity of precipitation cumulated during the previous two days (cumulative rainfalls – 301.8 mm) with precipitation which occurred in the first part of the day 30 June (cumulative rainfalls – 361 mm) (Table 12) (Paveluc et al., 2018, 2019). The maximum discharge values recorded at each gauge station located on the Trebeş River were: Podiş – 18.4 m^3/s (9:15 AM); Chetrosu – 34 m^3/s (10:00 AM); Valea Budului – 49 m^3/s (10:00 AM); Măgura – 31.4 m^3/s (5:30 AM); Mărgineni – 88 m^3/s (10:00 AM) (Table 13). The danger level was reached at four gauge stations: Chetrosu +1cm; Valea Budului +80 cm; Măgura +30; Mărgineni +80 cm (Table 13) (NARW-SWBA, 2018).

As in the case of the flood events of 2010, all settlements located along the Trebeş and Negel rivers were affected during the flood events from June 28 to July 1, 2018. Thus, in the village of Mărgineni (Trebeş River) 6 houses were completely destroyed, 10 km of rods and 3 bridges were affected, and 4 ha of agricultural land were flooded and agricultural crops completely compromised. On the territory of Măgura (Negel River), 11 km of rods were affected and 3 bridges were completely destroyed. In the Bacău Municipality, along with other significant damage to the sewerage network, 13 houses and 1 administrative building were completely destroyed (NARW-SWBA, 2018).

5. DISCUSSION

The increasing scales and frequency of natural disasters in the last decades in Europe can be associated to the climate change and global warming (Bergholt & Lujala, 2012; Halgamuge & Nirmalathas, 2017; Hoeppe, 2016; IPCC, 2012; Mertz et al., 2009; Simić et al., 2014; Türk et al., 2016; Petrović et al., 2015; Dragićević et al., 2013; 2016). On the Romanian territory an increase of +0.8°C of the air temperature and a slightly increase from 630 mm/year to 640 mm/year of the average amounts of precipitations was recorded (Dumitriu, 2016; Romanescu et al., 2020). This trend similar to that of central and south-eastern Europe is less significant in the western and north-western regions of Romania, but is notable in the north-east of the country (e.g., Eastern Carpathian and Subcarpathian transition zone, Eastern Carpathians lowland) (Mihu-Pintilie et al., 2019; Romanescu et al., 2018).

In the Trebeş-Negel RB the repartition of precipitations per month post-1990 underscores the extreme values recorded in the June-August interval and the heavy rains characteristics were highlighted by the precipitation amounts in 24 h (>100 mm/day). Thereby, all five exceptional flood events analyzed in this study were caused by heavy rainfalls that exceed this threshold: flood events from July 2 to July 8, 1991 (July 3 – 143 mm; cumulative rainfalls – 389.3 mm), flood events from June 16 to June 22, 1992 (June 17 – 168.8 mm; cumulative rainfalls – 384.8 mm), flood events from July 11 to July 14,

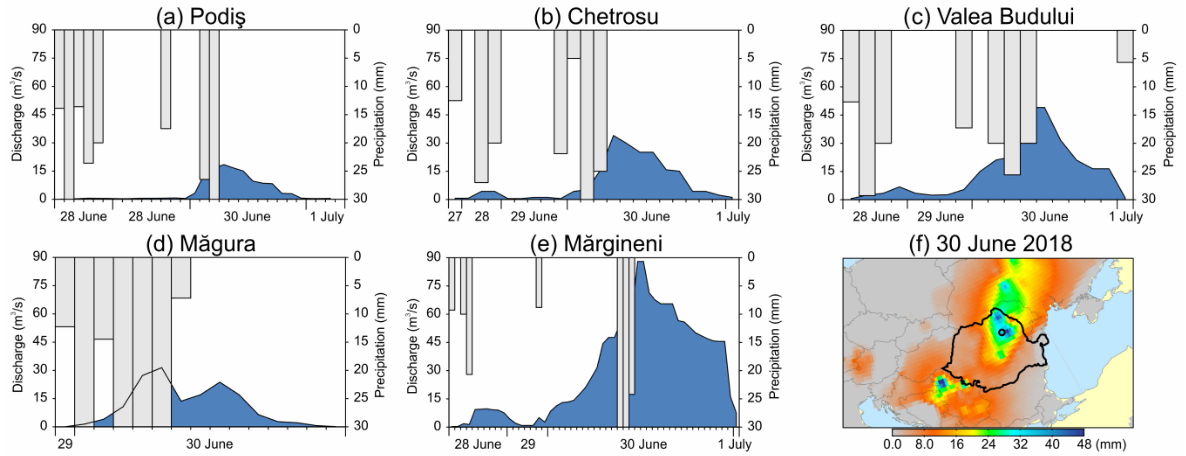

Figure 7. Correlations between hydrographs (m^3/s) and daily precipitations intensity (mm) recorded during the flood events between June 28 and July 1, 2018, recorded at: (a) Podiş, (b) Chetrosu, (c) Valea Budului, (d) Măgura and (e) Mărgineni gauge stations on the Trebeş-Negel RB; (f) E-OBS v 20.0e daily rainfall amounts (mm) map in the Eastern Europe on June 30, 2018.

Table 12. Daily rainfall recorded at Podiş, Chetrosu, Valea Budului, Măgura and Mărgineni pluviometric stations during the period between June 28 and July 1, 2018, in the Trebeş-Negel RB

River	**Pluviometric station**	**Daily rainfall amounts (mm)**				
		28th	**29th**	**30th**	**1st**	**Total**
Trebeş	Podiş	43.6	17.5	56.5	4	121.6
Trebeş	Chetrosu	47	21.9	60	4.7	133.6
Trebeş	Valea Budului	49.3	17.3	65.6	4.7	136.9
Negel	Măgura	51.2	14.5	94.7	2.5	162.9
Trebeş	Mărgineni	30.7	8.8	84.2	10.1	133.8

Table 13. Correlations between the maximum levels, caution levels and discharges recorded at Podiş, Chetrosu, Valea Budului, Măgura and Mărgineni gauge stations during the period between June 28 and July 1, 2018, in the Trebeş-Negel RB

River	**Gauge station**	[1] $H_{max.}$ **(cm)**	[2]**Compared to caution levels (cm)**	[3] $Q_{max.}$ **(m^3/s)**	**Date and hour occurrence of $H_{max.}$ and $Q_{max.}$**
Trebeş	Podiş	299	+49 *Wl*	18.4	30 June 2018 – 9:15 AM
Trebeş	Chetrosu	400	+1*Dl*	34	30 June 2018 – 10:00 AM
Trebeş	Valea Budului	380	+80 *Dl*	49	30 June 2018 – 10:00 AM
Negel	Măgura	180	+30 *Dl*	31.4	30 June 2018 – 5:30 AM
Trebeş	Mărgineni	580	+80 *Dl*	88	30 June 2018 – 10:40 AM

[1] $H_{max.}$: Height; [2]Caution level abbreviations: *Wl*: Warning level; *Dl*: Danger level; *Fl*: Flood level; [3] $Q_{max.}$: Flow rate.

2005 (July 12 – 276.1 mm; cumulative rainfalls – 554.3 mm), flood events from July 26 to July 31, 2010 (July 27 – 230.5 mm; cumulative rainfalls – 481.7 mm), flood events from June 28 to July 1, 2018 (June 30 – 361 mm; cumulative rainfalls – 688.8 mm) (NARW–SWBA, 1991, 1992, 2005, 2010, 2018). The degree of availability and accuracy of data has increased due to the multiplication of hydrometric and pluviometric stations together with the designation of the Trebeş-Negel basin as RB within ENREB, as well as multiplication from one hydrometric station in the Bacău Municipality before 1980 to five permanent hydrometric and pluviometric stations at present (Paveluc et al., 2018).

Regarding the manifestation of flood waves associated to maximum discharge within the Trebeş-Negel RB, the flood hydrographs are either simple, with one flood peak (e.g., 2005, 2008 and 2010 flood events), or bimodal, with two flood cycles (e.g., 1991 and 1992 flood events). The shape of flood hydrographs is different along the Trebeş River, Negel River and downstream of their confluence because it depends on the amount of precipitation and their space and time distribution. In this context, the most catastrophic flood events recorded post-1990 in the Trebeş-Negel RB occurred in 2005 and 2010

(Figure 8). Therefore, the flood event that took place between July 11 and July 14, 2005, was triggered by the highest amount of precipitation recorded in one day post-1990 (July 12 – 276.1 mm) and generated a flood wave with 155m3/s maximum discharge recorded on July 13 at the Mărgineni gauge station (Figure 8a). The flood event that took place from July 26 to July 31, 2010, was generated by a lower precipitation amount compared to 2005, but it produced the maximum discharge ever recorded in the Trebeş-Negel RB (historic discharge – 186 m3/s) on 27 July at 12:00 PM (Figure 8b). The flood event from June 28 to July 1, 2018, was relatively similar to the flood from 2010, but this time the magnitude was lower than the previous one. Regarding the consecutive flood events recorded in 1991 and 1992, because the heavy rainfall occurred in short and repeated stages over two or three days, the shapes of the flood hydrographs were bimodal and the impact of flood waves was double. All these facts highlight the role played by rainfall in term of distribution in space and time in the occurrence and manifestation of floods within the middle and small scale catchments like Trebeş-Negel RB.

Regarding the assessment of floods impact within the Trebeş-Negel RB, the summary reports and hydrological archive provided by IESBC, MTCR and SWBA show that, even the floods magnitude has increased from 1990 to the present, the damage they produced remain proportionally constant or even slightly decrease. This fact is due to the recent hydro-technical works and active land planning that have been put into operation in order to reduce the flood hazard and vulnerability. As already mentioned, because the Trebeş-Negel catchment was well equipped with hydrometric and pluviometric stations, all data derived from the monitoring activity were constantly used within local and regional flood mitigation strategy. Also, compared with other river basins with relatively the same size (≤ 200 km^2) and importance (e.g., Bistriţa tributary) in the Eastern Carpathian and Subcarpathian region, the Trebeş-Negel RB is one of the few catchments where flood hazard maps based on different recurrence interval probabilities (e.g., 10 years, 20 years, 100 years and 1,000 years) were possible to achieve (NARW, 2020). Based on this advantage, the measures taken by the authorities to reduce the flood impact during the emergency situations became more efficient.

Due to the fact that the Trebeş-Negel RB reacted as a small-scale flood sensor for the entire region, several data obtained from monitoring activity (e.g., floods frequency, heavy rains intensity) can be extrapolated to other basins for different purpose (e.g., discharge reconstruction during the floods). However, from this point of view several limitations must be taken into account (e.g., hydrological and geomorphological framework, afforestation degree, hydro-technical works that modified the natural flow) which are specific to each new catchment for which the extrapolation data is made.

6. CONCLUSIONS

The ENERB is a scientific entity which encourages collaboration and exchange of experience and techniques between scientists which study the relatively small catchments (cca. 1.00 km^2 – 200 km^2). Within the ENERB the RB's are selected as being typical or representative of a

Figure 8. Settlements, arable land and transport infrastructure affected by the flood events that occurred (a) from July 11 to July 14, 2005, and (b) from July 26 to July 31, 2010.

region in terms of their attributes (e.g., hydrological regime, vegetation type, geology), and provide a long-term record of basic data to which short-term records observed on roving or investigation stations may be correlated. The Trebeş-Negel RB (184 km^2) was selected as being representative for the Eastern Carpathian and Subcarpathian transition zone (north-eastern Romania). Based on a well–documented discharge and pluviometric database we developed within this study the first comparative analysis of five historical flood evens which occurred in the Trebeş-Negel RB post-1990. Accordingly, the following concluding remarks can be summarized:

• The bimodal flood events that occurred in 1991 (from July 2 to July 8) and 1992 (from June 16 to June 22) were caused by consecutive heavy rains and the impact of flood waves was double per each event. The damage to settlements located along the Trebeş and Negel Rivers were significant: year 1991 – 31 buildings were flooded of which 3 houses were completely destroyed; year 1992 – 56 buildings were flooded of which 8 houses were completely destroyed.

• The flood event that occurred from July 11 to July 14, 2005, was triggered by the highest amount of precipitation recorded in one day (July 12 – 276.1 mm) within the Trebeş-Negel RB and the second most intense flood event (maximum discharge – 155 m^3/s). During that period, 391 buildings were flooded of which 29 houses were completely destroyed.

• The flood event that took place from July 26 to July 31, 2010, even if caused by a lower precipitation amount than that from 2005, resulted in the recording of the maximum discharge ever recorded in the Trebeş-Negel RB (historic discharge – 186 m^3/s) on July 27 at 12:00 PM. Thereby, 139 houses and attachment buildings were affected (49 houses completely destroyed) and more than 115 km of local and national roads were affected.

• The flood event from June 28 to July 1, 2018, was relatively similar to the flood from 2010, but this time the magnitude was lower than the previous one (20 houses and one administrative building were completely destroyed). This fact is due to the recent hydro-technical works and active land planning that have been put into operation in order to reduce the flood hazard and vulnerability.

Overall, each flood events that occurred post-1990 was determined by heavy rains, when significant amounts of precipitations (>100 mm/day) were recorded. From this point of view the Trebeş-Negel RB reacted as a small-scale flood sensor for the entire region. The results highlight the role played by locally heavy rains at the onset of floods and contributes to a better flood hazard knowledge at regional-scale (e.g., Eastern Carpathian and Subcarpathian transition zone) based on small-scale analysis.

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