Exceptional hydrological phenomena in the Gemenea catchment

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ABSTRACT: Flash floods, accompanied by high waters and regular floods, represent the most dangerous natural hazards in the Gemenea catchment, inducing other risks such as geomorphologic, environmental, social and economical risks. Flash floods occurred during the 1969 to 2014 monitoring interval are characterized by extremely high discharge values, of 68.9 m^3 / s in 2006 and 95.3 m^3 / s in 2008 and a magnitude 2.5 times higher than the average discharge recorded until that timeframe. With an area of 77.7 km^2, the Gemenea catchment falls into the category of small catchments, where the peak discharge during exceptional hydrological phenomena is caused by torrential rainfall. Flash floods of particularly high intensities caused serious damages through: total destruction or damage of the torrent correction works, clogging of culverts on catchment forest roads, failure of river banks and deterioration of the bridges that affected roads and homes in Gemenea, Slătioara and Stulpicani villages. These floods have also caused damage to the forest / agriculture fund through deep and lateral erosion, failure of river banks and landslides. Within this study we aim to emphasize the magnitude, frequency, duration and area of manifestation of such phenomena in the Gemenea catchment. Furthermore, we aim to advance our knowledge of the genesis and specific mechanisms of flash flood occurrence for reducing their negative impacts on the local environment and communities.

KEY WORDS: Risk, torrentiality, time of concentration, frequency, recurrence, flash floods

1. Introduction

Exceptional hydrological phenomena, through the rapidity of occurrence and the effects they produce on the geographical space and the environment, were addressed by researchers from different scientific areas such as geomorphology, hydrology and forestry. These researchers, according to the aims of their studies, sought to understand the genesis and impacts of exceptional hydrological phenomena on the natural and anthropogenic environment and proposed a series of counteractive measures.

A more recent paper on such hydrological phenomena was published by Mustăţea in 2005 and addresses the genesis and effects of exceptional floods manifested on the entire Romanian territory between 1234 and 1996.

The geomorphological effects of floods have been studied in small catchments in the Trotuş valley, by Radoane et.al. (2007). The study showed that after flood occurrence, the accumulation of silt can overcome erosion and that the destructive force of these phenomena in small catchments is enhanced by the transport of sediments and other materials carried away from the riverbed and slopes.

Another study aimed at reducing the flood wave through torrent correction works was published by Ciornei (2014). It showed the importance of enhancement of torrential catchments by applying a series of organizational measures and biological, agrotechnical, forestry and hydrotechnical works, with the primary purpose to diminish peak discharge, soil erosion and sediment transport.

The main aim of this paper is to highlight the torrential character of the Gemenea catchment, where exceptional hydrological phenomena triggered by high intensity precipitation are rapidly formed and propagated downstream. The study focuses on the Gemenea catchment and Slătioara sub-catchment. Gemenea is part of the Suha Bucovineană representative Catchment which was the object of an ample study carried out by the Institute for Hidrotehnical Research and Studies (ISCH) since 1969. As an outcome, the first monitoring and measurement programs for small catchments were developed, and designed to meet the objectives at the basis of the study. The main issues that were studied in the Suha River Catchment were related to the analysis of the conditions of occurrence of liquid and solid flow from the moment precipitation fell on the ground. Research carried out within the catchment was aimed at establishing appropriate methodologies for determining the values of various hydrological parameters necessary for projecting construction and enhancement works.

2. Characterization of the study area

The hydrological characteristics and geographic location within the Carpathian Region place the Gemenea catchment in the Eastern Romanian Carpathians and in the Suha Bucovineană hydrological system.

As regards geomorphological features, our study area is characterized by the presence of Slătioara – Gemenea corridor, by selective erosion landforms and by the presence of river terraces. Under favorable meteorological conditions, convection of air masses generally occurs during summer, with local heavy rains which trigger floods.

Gemenea River is of V order in the Strahler system. It has a length of 15.9 km, and together with its main tributary Slătioara generate an average discharge of 0.911 m^3 / s. Gemenea River collects its waters from an area of 77.7 km^2, which places it into the category of small watersheds (Rădoane, 2002).

In what concerns lithology, the western part of the catchment corresponds to the eastern end of the Rarău marginal syncline and the crystalline-Mesozoic area, whereas the western part belongs to the flysch area, i.e. Ceahlău, Teleajen and Audia nappes. The differences in lithology are observable through higher elevations and slopes in the western half of the catchment and lower, more gently sloping landforms in the east.

Morphometrically, the catchment extends between a maximum elevation of 1628 m (Colţii Rarăului) and a minimum of 590 m (the confluence with Suha Bucovineană) respectively, with an average elevation of 1109 m a.s.l. The average declivity for the entire catchment is 33% and represents a basic morphometric parameter, as it determines the onset and development of torrential phenomena. The morphometric parameters of the Gemenea catchment and of the hydrographic network are shown in Table 1.

Table 1 Morphometric parameters of the Gemenea catchment

No.	**Morphometric parameters of the catchment**	M.U.	Catchment 1	Catchment 2	Total catchment
			Gemenea*	Slătioara	Gemenea
1	Area: ***S***	ha	3138,10	3711,65	7776,42
2	Perimeter: ***Pb***	km	27,28	28,04	44,80
3	Gravelius coeficient		1,37	1,30	1,43
4	Elevation				
	minimum: ***Hmin***	m	650	650	590
	maximum: ***Hmax***	m	1430	1600	1600
	average: ***Hmed***	m	1040	1125	1095
5	Height				
	maximum: ***Rmax***	m	780	950	1010
	average: ***Rmed***	m	390	475	505
9	Average catchment declivity	%	20	32,94	33,4
10	Average slope length	m	220,75	337,93	321,6
	Morphometric parameters of the hydrographic network	U.M.	Gemenea*	Slătioara	Gemenea
1	Length of hydrographic network, Total: ***Lr***	km	78,26	80,05	177,99
2	Length of main riverbed: ***La***	km	11,67	9,82	15,97
3	Density of hydrographic network	m/ha	25	21	22
4	Average gradient of main riverbed ***Ia***	%	54,4	57,5	26,0
	Time of flow concentration, Tc	min	37,63	33,95	64,16

*Gemenea catchment to the confluence with Slătioara

Another relevant issue in the formation of flash floods is the catchment shape coefficient (Gravelius coefficient). This parameter equals 1.43, which indicates for our catchment a hypothetically circular shape that allows concentration of flow from secondary river network and slopes in the main river over a short time, thus favoring the formation of the flash flood wave.

Gemenea catchment has a temperate continental climate with moderate, mountain influences. The average annual temperature is 6,9°C and the average annual precipitation ranges between 778.0 l / sqm (at Gemenea 2 gauging station) and 813.7l / sqm (at Gemenea 5 gauging station). The largest precipitation amounts originate from torrential frontal or local rains. According to the divisions constructed for Romania based on rainfall amounts, our catchment falls in the M5 rainfall zone, where the maximum amount of precipitation in 24 hours can exceed 100 l, with intensities ranging between 0.91 and 1.41 l/min.

Major vegetation types, i.e. forests and meadows, are represented in the general landscape by dense, sometimes old-growth spruce, fir and beech forests, interspersed with meadows of complex floristic composition. The general forest cover coefficient is rather high for almost the entire catchment area, with 76% for Gemenea and 86% for Slătioara (Ciornei, 2014). This coefficient is very important because it ensures a certain regularization of flash floods, given the high declivity values. Floods are nevertheless common, not mainly because of torrential rains, but mostly as a result of the significant reduction of river bed capacities through high inputs of silts.

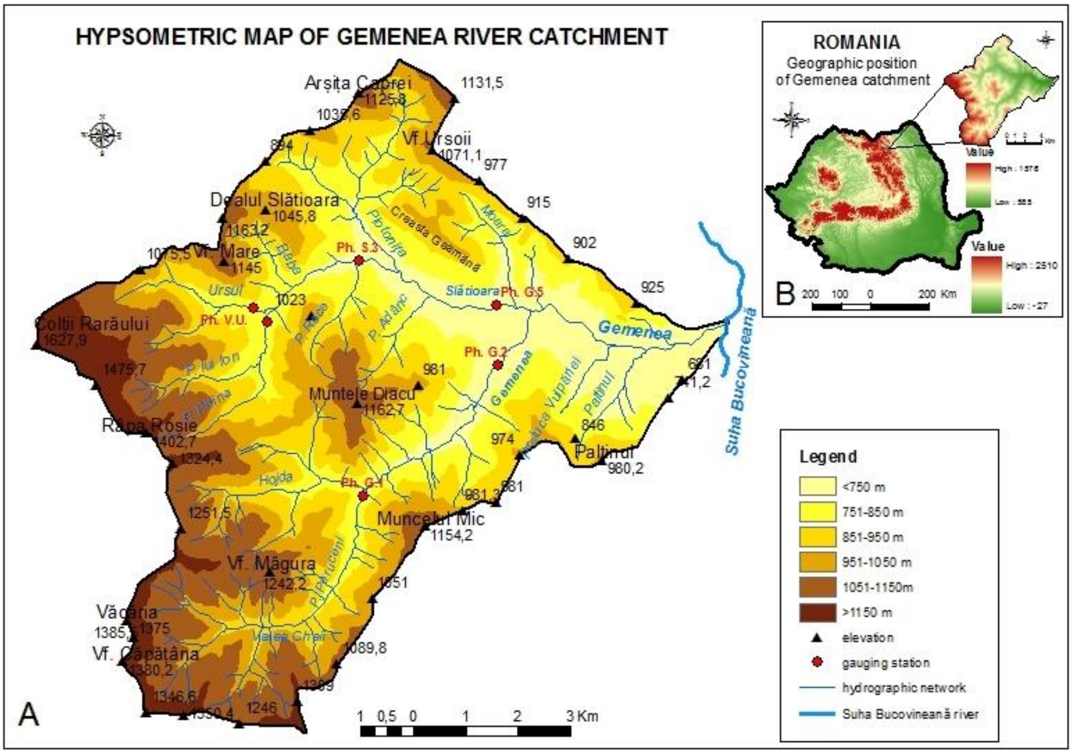

Figure 1 Position of the studied catchment.

In terms of soil distribution, the largest area is covered by eutricambosoils, with a share of 55%, which are part of Group C with slightly above average potential for runoff. Prepodzols and districambosoils characterize a smaller area, namely 20%. These soil types belong to the Hydrological Group B, with a close to average potential for runoff. The remaining 5% of the catchment area is covered by other types of soils, such as rendzinas and aluvisoils.

3. Materials and methods

The study of exceptional phenomena was based on morphometric parameters of the catchment and river network. Rainfall and evolution of mean annual discharge and peak discharge were analyzed based on observations from gauging stations in the catchment over a period of 46 years (1969-2014) (Table2). Processing of cartographic material, fieldwork data and results syntheses were performed using ArcGIS, Global Mapper and Mapsys software.

Table 2 Characteristic discharge values on Gemenea River

Gauging station	E	DRM	BA	MAD	PD	YMD
Valea Ursului	795	10,469	6,45	0,092	20,5	2008
Valea lui Ion	780	10,554	6,59	0,086	17,8	2008
Gemenea 1	750	9,625	13,88	0,184	17,4	2008
Slătioara3	730	8,082	19,13	0,270	63,6	2008
Gemenea 2	680	5,573	30,27	0,450	68,9	2006
Gemenea 5	650	4,995	34,19	0,461	95,3	2008

E= elevation (m); DRM = distance to the river mouth (km); BA = basin area (km^2); MAD = mean annual discarge (m^{3}s^{-1}); PD = peak discharge(m^{3}s^{-1}); YMD = year of maximum discharge.

To understand the speed of flash flood occurrence, the time of flow concentration (TC, minutes) was computed (Eq.1). This parameter indicates the amount of time needed by the water flow to cover the distance between the most remote hydrological point of the catchment and the monitored section. According to torrent planning regulations, the time of flow concentration (TC, minutes) is estimated through the formula:

$$T_c = 0,5\sqrt{\frac{L_v}{I_b^{0,5}}} + K\,\frac{L_a}{I_a^{0,5}} \qquad \text{(Eq.1)}$$

where: Lv- slope length; La- length of main river bed; Ib (Iv) - average declivity of slopes; Ia - mean gradient of the main riverbed; K- erodibility coefficient.

The recurrence interval (T) of flash floods was estimated by the relationship:

$$T = (n+1)/m \qquad \text{(Eq.2)}$$

where: n = number of records, and m = magnitude of flash floods in descending order

The probability of exceeding the peak discharge or ensuring the maximum flow is the ratio, expressed as a percentage, of the number of years ***n*** in which a certain value of this discharge was exceeded and the total number of considered years ***N***. The parameter was calculated according to the formula:

$$\text{p}\% = \frac{n}{N}100 \qquad \text{(Eq.3)}$$

4. Results and discussion

4.1. Precipitation and mean annual discharge

Precipitation, together with other natural and anthropogenic factors, dictate the magnitude and duration of extreme hydrological phenomena during peak discharge. The geographic location of our study catchment results in a mountain climate with high amounts of precipitation. Records of rainfall at gauging stations in the catchment indicate that 1991, 2001, 2006 and 2008 were years in which excessive rainfall amounts were recorded, of 1232, 9 l / m^2 at Gemenea 1 and 1138.8 l / m^2 at Valea lui Ion and Valea Ursului gauging stations respectively (Figure 2).

The location of the stations along the main rivers highlights upstream to downstream precipitation distribution, namely the reduction of amounts at lower elevations which correspond to stations located at the end point of the catchments. However there are some exceptions in 1995, 1997, 1998 at Gemenea 2 gauging station, and 1995, 1996, 1997, 1998, 2002, 2006 and

2007 at Gemenea 5, when precipitation records at these stations surpassed the amounts recorded at the upstream stations.

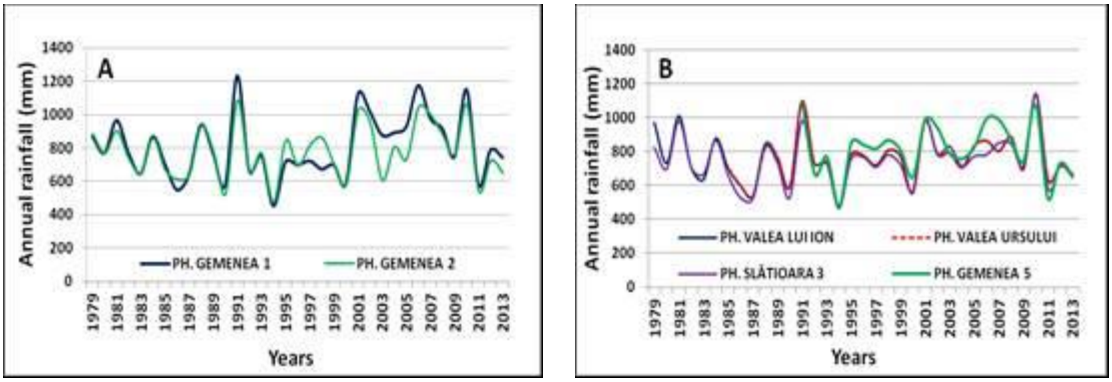

Figure 2 Annual precipitation recorded at the gauging stations in the Gemenea (A) and Slătioara (B) catchments.

Multi-annual average of annual precipitation sums amounts to 803.6 l / m^2 at Gemenea 1 and decreases to 778.8 l / m^2 at Gemenea 2, located downstream on the Gemenea River. The situation appears different at the gauging stations located in the Slătioara sub/catchment: upstream, multi- annual average precipitation is 768.4 l / m^2 at Valea lui Ion, 743.4 l / m^2 at Slătioara 3 and 813.7 l / m^2 at Gemenea 5. Although Gemenea 2 and Gemenea 5 gauging stations are located close to one another, there is a difference of 34 l / m^2 between the two records. This difference is also reflected in the liquid discharge of the rivers.

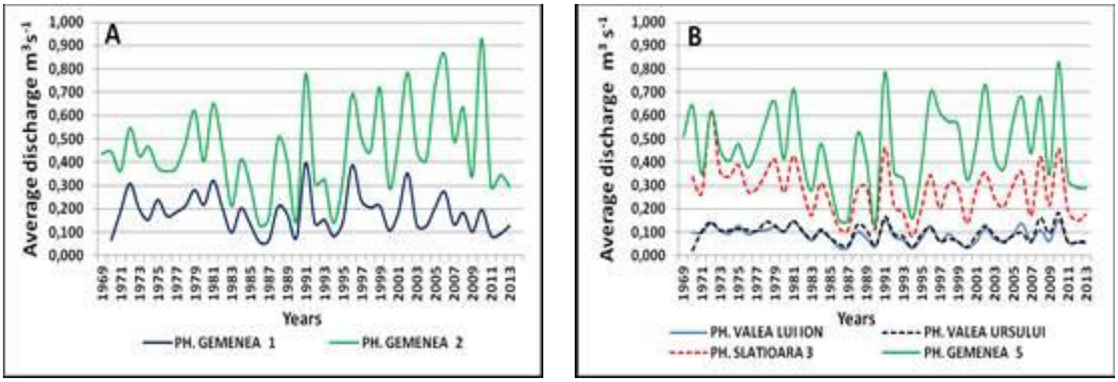

Figure 3 Mean annual discharge recorded at gauging stations in the Gemenea (A) and Slătioara (B) catchments.

A first analysis of the mean annual discharge values in Figure 3 reveals a similarity between the two catchments, namely the increase of liquid discharge with increasing catchment area. By comparing variations of the mean annual discharge values recorded at the upstream stations in both catchments, one may observe large variations at Gemenea 1 (750 m a.s.l.), as opposed to Valea lui Ion (780 m a.s.l.) and Valea Ursului (795 m a.s.l.). Low mean annual discharge values and reduced variation are caused by the small size of river catchments and by the fact that Valea lui Ion and Valea Ursului catchments partly overlap the Slătioara Centennial Forest (Codrul Secular Slătioara) Nature Reserve. Slătioara forest covers an area of 1064.20 ha, and has a very dense crown cover and retention capacity superior compared to the rest of the forest, which implies that a significant amount of precipitation is retained by trees and litter, thus helping reduce discharge values.

The research carried out in our country during the 1960 - 1974 timeframe showed that litter retention varies between 5% and 30% of the fallen precipitation, which confirms the hydrologic and anti-erosion role of litter. Canopy retention is on average 32% of precipitation in 50 years old spruce stands, and 30% in beech forests over 100 years old (Arghiriade et al., 1960).

Records at the Slătioara 3 gauging station, located at an elevation of 730 m a.s.l. and 10 km distance from the upstream stations, show that the mean annual discharge increase and their annual variation is larger compared with discharge values recorded at Valea lui Ion and Valea Ursului. The increase and varation of discharge occur due to the increase in the catchment area, proportionally to the reduction in forest cover which is replaced by grasslands and pastures.

Although the Slătioara sub-catchment has a large forest cover coefficient, of 86%, and a large amount of rainfall retained in the canopy and litter compared to the Gemenea catchment (to the confluence with Slătioara) which has a coefficient of 76%, the mean discharge of Slătioara River is higher than the mean discharge of Gemenea River. In the closing sections of the catchments, we note that the discharge is 0,561 m^3 / s at the Gemenea 5 station (650 m a.s.l.), higher by 0.011 m^3/s compared to the 0.450 m^3 / s recorded at Gemenea 2 (680 m a.s.l.).

4.2. Annual peak discharge

Similarly, for peak discharges higher values are recorded at Gemenea 5 compared to those obtained at Gemenea 2 (Figure 4). The fact that the historical peak discharge occurred in different years is due to the local climate. Namely, convection of air masses occurs during the summer, superimposed on high evaporation, giving rise to local torrential rainfalls which produce flooding.

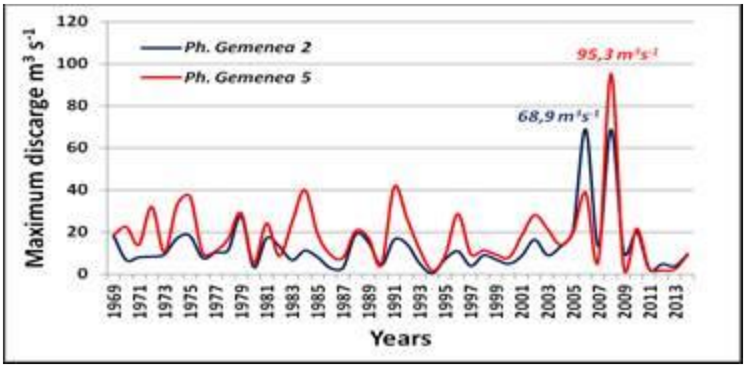

Figure 4 Peak discharge values for Gemenea catchment at the two gauging stations.

The maintaining of high discharge results from the important contribution of the Plutoniţa brook left tributary, which feeds the Slătioara River downstream of the Slătioara 3 gauging station, and of the Pârâul Adânc brook right tributary. The discharge is also maintained by the catchment area of 3711.65 ha, higher with 573.55 ha compared to the Gemenea catchment, which in turn covers an area of 3138.10 ha. To this, other catchment and river network morphometric characteristics are added, that are different from those of Gemenea catchment: a circularity coefficient of 1.30 for Slătioara catchment and of 1.37 for Gemenea catchment; the average catchment declivity of 32.9% for Slătioara and of 20% for Gemenea; mean gradient of main riverbed of 57.5 for Slătioara River and of 54.4 for Gemenea River; maximum height of catchment equals to 950m for Slătioara and 780 m for Gemenes; short runoff concentration time of 33.9 minutes for Slătioara and 37.6 minutes for Gemenea, etc. (Table 1).

The peak discharge recorded during the 1969-2005 interval at Gemenea 2 gauging station was 27.6 m^3 /s and occurred in 1979. This threshold has been exceeded on 27.06.2006 when the historical peak discharge, of 68.9 m^3 / s, occurred, and on 24.07.2008 when the same discharge was recorded, which is 2.5 times the maximum discharge recorded in 1979. After 2008, the peak discharge underwent a pronounced decrease compared to the rest of the period, without recording considerable values, with fluctuations similar to the period 1969-2005. The probability of exceedance of the 68.9 m^3 / s peak discharge is 4%.

At Gemenea 5 gauging station, the peak discharge evolution is similar to that recorded at the Gemenea 2 station, however with much higher values. The peak discharge in the period 1969 - 2007 was 41.5 m^3/ s and occurred in 1991. This value was exceeded in 2008, when the historical peak discharge of 95.3 m^3 / s was recorded, with a probability of exceedance equal to 2%.

4.3. Exceptional hydrological phenomena in the Gemenea catchment

Annual peak discharge values were frequently recorded over the monitoring period. However, the flash floods occurred in 2006 (Figure 5) in the Gemenea catchment and 2008 (Figure 6, 7) in the Slătioara catchment displayed historical discharge.

Based on the hydrograph shape, the flash flood that occurred in 26-30.06.2006 at Gemenea 1 and 2 stations is complex, with two discharge peaks caused by consecutive high rainfall intervals.

At Gemenea 1 station, between 16 and 17.06.06, a total amount of 28.9 l / m^2 were recorded, which generated the first flood peak at 18:20, with a very small concentration time, of only 1h 20'. The second peak occurred the next day, on 27.06.2006, at 16:30 and reached a maximum discharge of 32 m^3 / s. The rain that caused this discharge peak occurred between 17:50 to 18:30, amounting to 43.2 l / m^2.

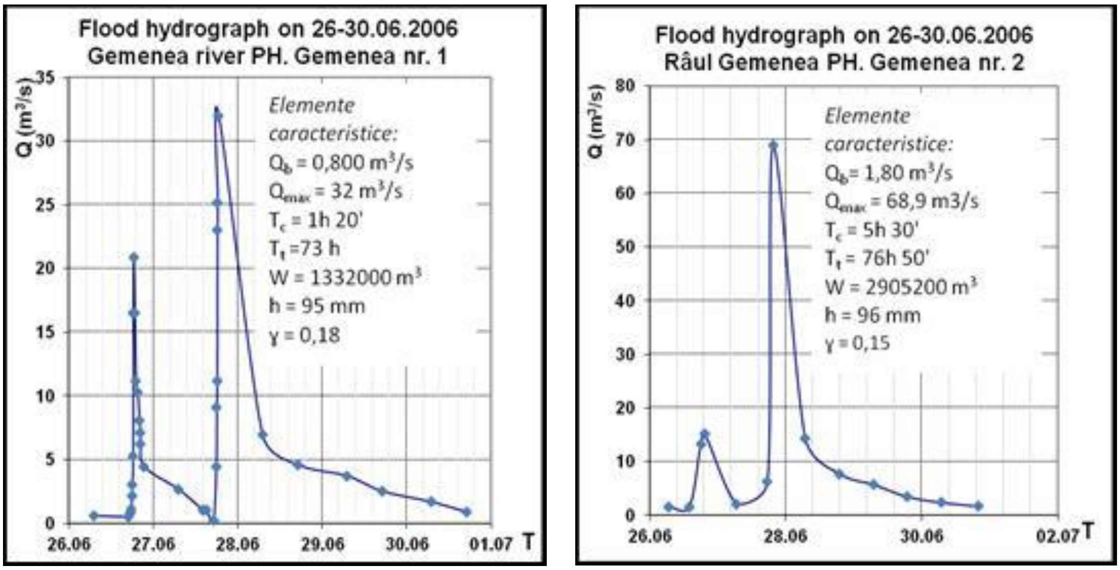

Figure 5 Historical flash floods in the Gemenea catchment at Gemenea 1 and 2 gauging stations.

Downstream propagation of the flash flood wave to Gemenea 2 station was achieved in a short time of 1h 10 'for the first peak which decreased to 15.1 m^3 / s. 1 hour was the propagation time for the second peak of 68.9 m^3 / s which doubled its values compared to the discharge recorded upstream. The flash flood manifested over 76h 30 ', during which time a volume of 2905200 m^3 were recorded, equivalent to a 96 mm layer from the surface of the 30.27 km^2 catchment.

Rainfall which occurred during the flash floods downstream at Gemenea 2 station was lower compared to the amounts recorded at Gemenea 1, namely 7.4 l / m^2 between 17.00 and 18.00, on 26.06.2006 and 23 l / m^2 between 18.00 and 19.00 on 27.06.2006.

In the Slătioara sub-catchment, the records from the four gauging stations located along the river reflect better discharge variation in relation to rainfall intensity. Historical peak discharge was recorded during the flash flood manifested between 23 and 26.07.2008.

Similar to the 2006 historical flash flood in the Gemenea catchment, the flash flood recorded at the gauging stations along the Slătioara River is complex and reflects the torrential and successive character of rainfall intervals.

Concerning the upstream - downstream flash flood propagation, a total of 29.4 l / m^2 were recorded at Valea lui Ion station on 23-24.07.2008, between 23:50 and 1:30. The event generated a flood wave of 17.8 m^3 / s in 1h 30', corresponding to a 58 mm thick layer from the surface of the 6.6 km^2 catchment. The large amount of rainfall fallen over a small area in a short time exceeded the retention and infiltration capacity of the forest. Rainfall rapidly concentrated in torrents which generated increased river discharge simultaneously with the increase in rainfall intensity. Rainfall recorded between 01:30 and 02:20 amounted to 50.6 l / m^2 in only 50 minutes, much higher than the rainfall which generated the flood wave. Given that no discharge measurements were carried out between 01: 30 and 06:30 on 24.07.2008, corroborated with the extremely high precipitation intensity between 01:30 and 02:20 on the same day, we suggest that the flash flood wave had a much larger discharge than 17,8m^3 / s.

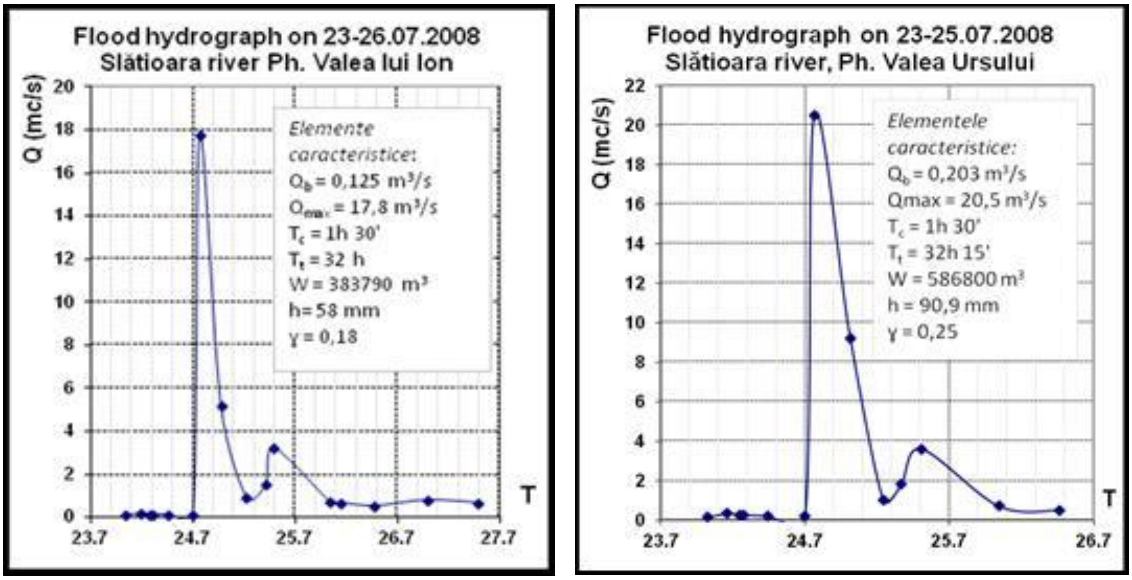

Figure 6 Historical flash floods in the Slătioara catchment, at Valea lui Ion and Valea Ursului gauging stations.

A similar phenomenon is observable as well at the nearest gauging station, i.e. Valea Ursului, on the homonymous creek, in the near vicinity of the Valea lui Ion creek, left tributary of the river Slătioara. The flood wave occurred during the same day, same hours, with the same concentration time, reaching a peak discharge of 20.5 m3 / s, equivalent to a 90.9 mm thick layer from the surface of the 6.4 km^2-catchment.

The second flood wave, much lower than the first one, occurred during the same day at both stations, at 19:00 and 19:20 , with discharge rates of 3.20 m^3 / s and 3.60 m^3 / s respectively.

From the upstream gauging stations, the flash flood wave propagated downstream in 2h 15 'at Slătioara 3 and in 2 h 30 'at Gemenea 5. On 24.07.2008 at 02:15, the peak discharge reached 63.6 m^3 / s, equivalent to a 75 mm layer at Slătioara 3 station and 95.3 m^3 / s (historical peak discharge) at Gemenea 5 around 02:30. In only 15 minutes, between these two gauging stations, the river discharge increased dramatically.

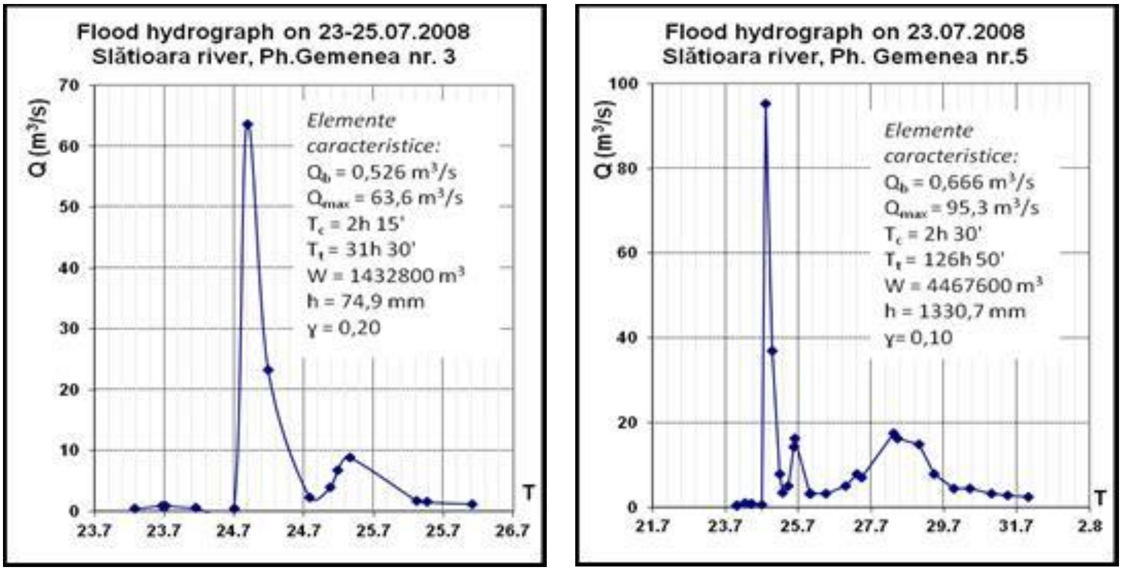

Figure 7 Historical flash floods in the Slătioara catchment, at Slătioara 3 and Gemenea 5 gauging stations.

Rainfall amounts recorded on 24- 25 July, between 24.00 and 02:30 at Slătioara 3 station equaled 69 l / m. At Gemenea 5 station, the flash flood lasted for 126h 50 ' and had three peaks, reflecting the successive episodes of rain. During this time, a 4467600 m^3 volume was recorded, equivalent to a layer of 130.7 mm thickness.

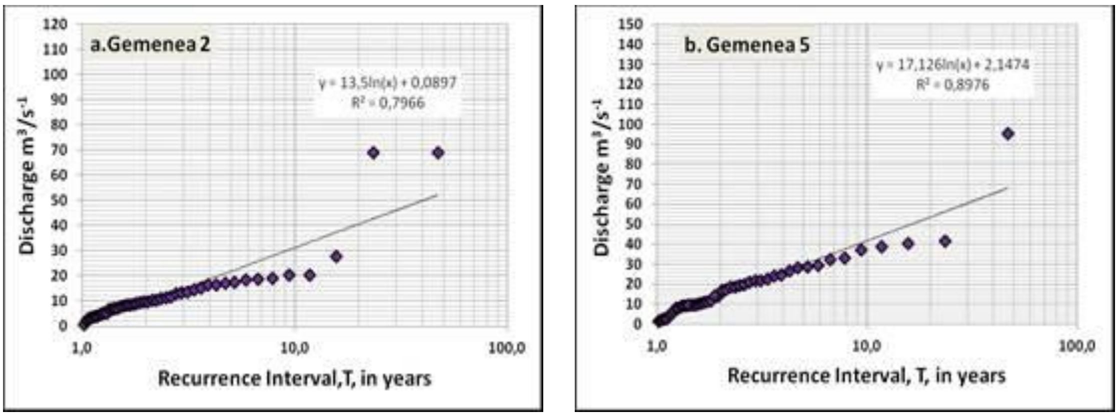

Figure 8 The recurrence interval of flash floods at Gemenea 2 and Gemenea 5 gauging stations.

The flash floods recorded in the two catchments, which occur more frequently (84.8% of the cases), have a recurrence period of 1 to 7 years, with flow rates ranging from 0.540 m^3 / s to 18.6 m^3 / s (Figure 8). The flash floods manifested in 2006 and 2008 have a recurrence period of 47 years and as a result their frequency is very low (2.2% at Gemenea 5 and 4.3% at Gemenea 2). However, on occurrence, they have a high geomorphological impact on the river bed.

During the 2006 flash flood, the anti-erosion dam located on the Gemenea River, upstream of the confluence with Slătioara, was destroyed. Dam failure had significant consequences on the riverbed, as sediments from the embankment were deposited downstream, thus reducing riverbed flow capacity, causing further floods and the destruction of the only access road to the Gemenea locality. After the water retreat, sediments brought by the flood were removed from the riverbed and used to rise and consolidate banks (Figs 9a,b). Upstream, the process was reversed, i.e. the main riverbed and torrents were emptied of sediments (river bed degradation).

Figure 9a. Strengthening of river banks with sediment from embankment, **b.** The anti-erosion dam which was destroyed during the 2006 flash floods.

5. Conclusions

The main drivers of the formation of flow and flash floods in the Gemenea catchment result from the geographical location of the river catchment, the geology and morphology of the territory, climate, vegetation and soil types, as well as size and complexity of human impact.

Based on the 46 years of data (1969 to 2014), the flash floods occurred in 2006 and 2008 were characterized by historical peak discharges and very high magnitudes. The magnitude of the floods was caused by high rainfall amounts fallen over a short period of time, but also by irrational cutting of trees, which do not extend on large areas but considerably influence water regime.

In order to reduce the magnitude and negative effects of extreme hydrological events, in 2010 certain measures were taken to prevent floods and consolidate banks by damming the riverbed sectors with risk of flooding with concrete dams and gabions. However, afforestation of cleared areas was not considered. In recent years, the recorded floods had reduced discharges, mainly because precipitation amounts were also lower.

Although river discharge is low, during floods, it undergoes significant increases from the average flow rate of 0,459 m^3 / s to a peak discharge of 68,9m^3 / s recorded in 2006 at the Gemenea 2 gauging point, and from 0.461 m^3 / s to a peak discharge of 95.3 m^3 / s in 2008 at Gemenea 5. The increases were 150 times and 206 times larger respectively than the average discharge, which indicates the torrential character and aggressiveness of these extreme phenomena.

As a result of the geomorphological processes and landform dynamics, presently there is a pronounced aggradation of riverbeds with sediments brought during flash floods. This geomorphological process increasingly extends downstream, where the slope gradients are reduced and water transport capacity is low. Upstream, the process is reversed, i.e. degradation of the riverbed occurs.

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