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Exceptional floods in the Prut basin, Romania, in the context of heavy rains in the summer of 2010

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Abstract. The year 2010 was characterized by devastating flooding in Central and Eastern Europe, including Romania, the Czech Republic, Slovakia, and Bosnia-Herzegovina. This study focuses on floods that occurred during the summer of 2010 in the Prut River basin, which has a high percentage of hydrotechnical infrastructure. Strong floods occurred in eastern Romania on the Prut River, which borders the Republic of Moldova and Ukraine, and the Siret River. Atmospheric instability from 21 June-1 July 2010 caused significant amounts of rain, with rates of 51.2 mm/50 min and 42.0 mm/30 min. In the middle Prut basin, there are numerous ponds that help mitigate floods as well as provide water for animals, irrigation, and so forth. The peak discharge of the Prut River during the summer of 2010 was 2,310 m^3/s at the Radauti Prut gauging station. High discharges were also recorded on downstream tributaries, including the Baseu, Jijia, Miletin etc. High discharges downstream occurred because of water from the middle basin and the backwater from the Danube (a historic discharge of 16,300 m^3/s). The floods that occurred in the Prut basin in the summer of 2010 could not be controlled completely because the discharges far exceeded foreseen values.

1 Introduction

Catastrophic floods occurred during the summer of 2010 in Central and Eastern Europe. Strong flooding usually occurs at the end of spring and the beginning of summer. Among the most heavily affected countries were Poland, Romania, the Czech Republic, Austria, Germania, Slovakia, Hungary, Ukraine, Serbia, Slovenia, Croatia, Bosnia and Herzegovina, and Montenegro (Bissolli et al., 2011; Szalinska et al., 2014) (Fig. 1). The most devastating floods in Romania occurred in Moldavia (Prut, Siret) and Transylvania (Tisa, Somes, Tarnave, Olt). The most deaths were recorded in Poland (25), Romania (six on the Buhai River, a tributary of the Jijia), Slovakia (three), Serbia (two), Hungary (two), and the Czech Republic (two) (Romanescu and Stoleriu, 2013a,b).

Floods are one of the most important natural hazards on Earth (Merz et al., 2010; Riegger et al., 2009; Thieken et al., 2016). For this reason, they have been subject to intense research, and significant funds have been allocated to mitigating or stopping them. Some of the most interesting studies have investigated catastrophic floods or floods that caused significant damage (Ahilan et al., 2012; Alfieri et al., 2015; Berariu et al., 2015; Blöschl et al., 2013; Bostan et al., 2009; Brilly and Polic, 2005; Cammerer et al., 2012; Detrembleurs et al., 2015; Diakakis, 2011; Feldman et al., 2016; Hufschmidt et al., 2005; Lichter and Klein, 2011; Lóczy and Gyenizse, 2011; Lóczy et al., 2009, 2014; Moel et al., 2009; Parker and Fordham, 1996; Prudhomme and Genevier, 2011; Retsö, 2015; Revuelto et al., 2013; Reza Ghanbarpour et al., 2014; Rufat et al., 2015; Schneider et al., 2013; Strupczewski et al., 2014; Vasileski and Radevski, 2014; Whitfield, 2012). Extreme climatic conditions determine the occurrence of exceptional floods in eastern Romania, as exemplified by the most devastating floods in Romanian history, which occurred on the Prut and Siret Rivers in 2005, 2006, 2008, and

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2010. The heavy rains in eastern and southern Romania led to floods that caused significant damage and loss of life (Iosub et al., 2014; Jora and Romanescu, 2010; Mierla and Romanescu, 2012; Mierla et al., 2015; Mihu-Pintilie and Romanescu, 2011; Podani and Zavoianu, 1992; Reti et al., 2014; Romanescu et al., 2011a,b, 2012, 2013, 2014a,b; Romanescu and Nicu, 2014).

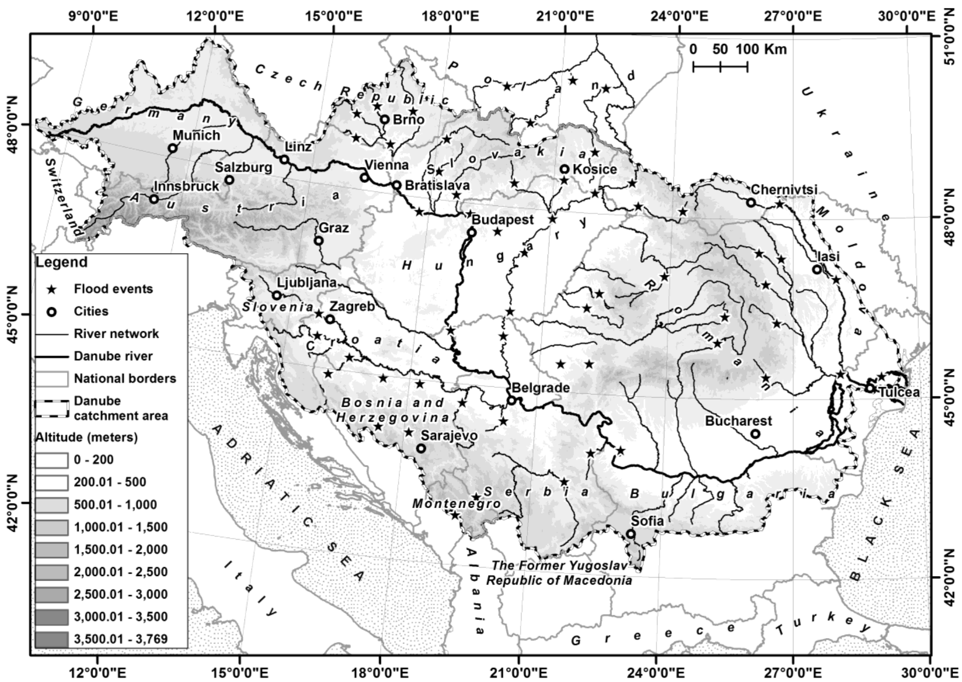

Figure 1. The Danube catchment and the location of the most important floods that occurred from May-June 2010

The Prut catchment basin spans three topographic levels: mountains, plateaus, and plains. The surface and underground water supply to the Prut varies by region and is significantly influenced by climatic conditions. This study underscores the role played by local heavy rains in the occurrence of floods, as well as the importance of ponds, mainly the Stanca-Costesti reservoir, in the mitigation of tidal bores. We also analyse the local contribution of each catchment basin on the right side of the Prut to the occurrence of the exceptional floods in the summer of 2010. Finally, we consider the upstream discharge and its influence on the lower reaches of the Prut.

2 Study area

The Prut River's catchment is situated in the northeastern Danube basin. It is surrounded by several other catchments: the Tisa to the northeast (which spans Ukraine, Romania, and Hungary), the Siret to the west (which is partially in Ukraine), and the Dniestr (in the Republic of Moldova) to the northeast. The Prut catchment occupies eastern Romania and the western part of the Republic of Moldova (Fig. 2). The Prut River begins in the Carpathian Mountains in Ukraine and empties into the Danube near the city of Galati. The catchment

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measures 27,500 km^2, of which 10,967 km^2 lies in Romania (occupying approximately 4.6% of the surface of Romania).

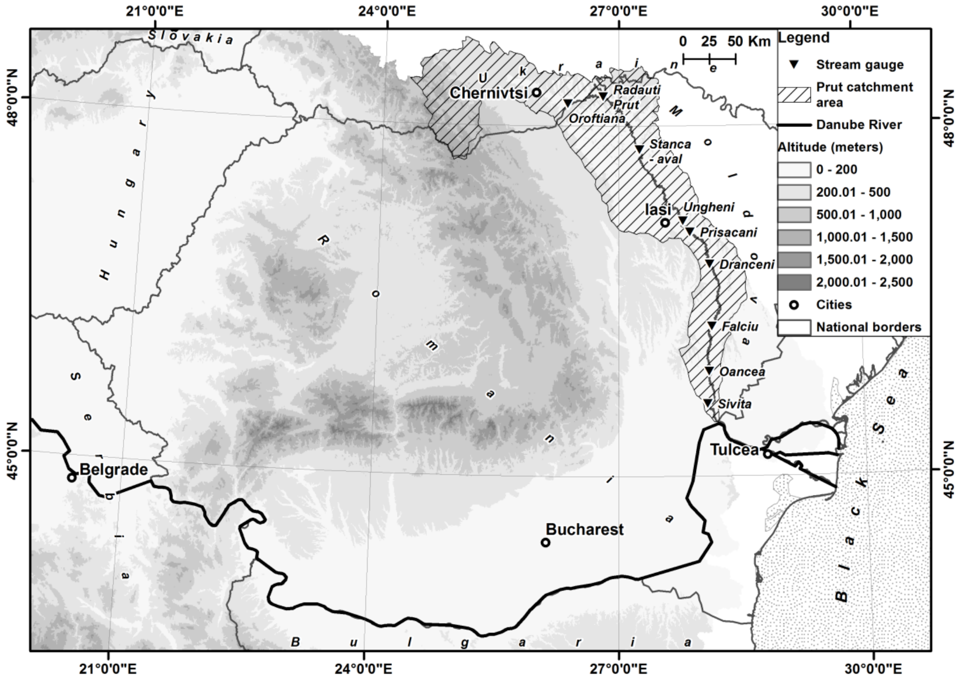

Figure 2. Geographic position of the Prut catchment basin in Romania, Ukraine, and the Republic of Moldova, and distribution of the main gauging stations

The Prut River is the second-longest river in Romania, at 952.9 km in length. It is a cross-border river, with 31 km in Ukraine and 711 km in the Republic of Moldova. The mean altitude of the catchment ranges from 130 m in the centre to 2 m at the confluence. The Prut has 248 tributaries. Its maximum width is 30 km (in the lower reaches) and its average slope is 0.2%. Its hydrographic network measures 11,000 km in total, of which 3,000 km are permanent streams (33%) and 8,000 km are intermittent (67%). The network has the highest density in Romania at 0.41 km/km^2 (the average density is 0.33 km/km^2).

The Prut catchment is relatively symmetrical, but its largest proportion is in Romania. To the west, it has 27 tributaries, including the Poiana, Cornesti, Isnovat, Radauti, Volovat, Baseu, Jijia (with a discharge of 10 m^3/s, the most important), Mosna, Elan, Oancea, Branesti, and Chineja. To the east, it has 32 tributaries, including the Telenaia, Larga, Vilia, Lopatnic, Racovetul, Ciugurlui, Kamenka, Garla Mare, Frasinul, and Mirnova (Romanescu et al., 2011a,b) . The catchment basin has 225 small ponds, counting the Dracsani, which is the largest pond in Romania. The river also has 26 large ponds, of which the most important is the Stanca-Costesti reservoir, which has the largest water volume of the interior rivers in Romania (1,400 million m^3).

The topography of the Prut basin includes the Carpathians in the spring area and the Moldavian Plateau and the Romanian Plain near the river mouth. Arable land occupies 54.7% of the Prut catchment, while forests occupy 21.4%, perennial cultures occupy another 13.3%, and the water surface occupies only 1.19%. The mean annual temperature in the Prut

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catchment is 9°C, and the mean annual precipitation is 550 mm. The mean annual discharge increases downstream, varying from 82 m^3/s at Radauti Prut to 86.7 m^3/s at Ungheni to 93.8 m^3/s at the Oancea gauging station situated near the mouth over the period 1950-2008.

3 Methodology

Diverse methodology has been used to analyse exceptional floods. Hydrological data, including discharge and the water level, were obtained from the Prut-Barlad Water Basin Administration based in Iasi (a branch of the "Romanian Waters" National Administration). For catchment basins that did not have gauging stations or observation points, measurements were taken to estimate the discharge. Most stations within the Romanian portion of the Prut catchment are automatic (Fig. 3). The recording and analysing methodology used is standard or slightly adapted to local conditions (Ali et al., 2012; Delli-Priscoli and Stakhiv, 2015; Demeritt et al., 2013; Fu et al., 2014; Grobicki et al, 2015; Hall et al., 2004, 2014; Hapuarachchi et al., 2011; Jones, 2011; Kappes et al., 2012; Kourgialas et al., 2012; Nguimalet and Ndjendole, 2008; Rusnák and Lehotsky, 2014; Seidu et al., 2012a,b; Serban et al., 2004; Sorocovschi, 2011; Touchart et al., 2012; Verdu et al., 2014; Waylen and Laporte, 1999; Wu et al., 2011).

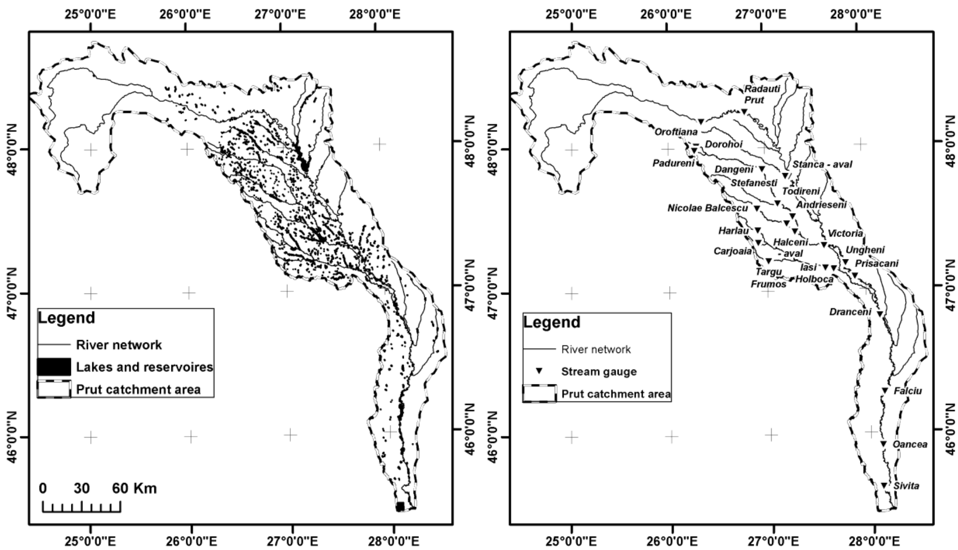

Figure 3. Main tributaries, reservoirs (left), and gauging stations (right) in the Prut River basin

All areas with gauging stations had automatic rain gauges (Anghel et al., 2011; Tirnovan et al., 2014a,b) (Fig. 3, Table 1). The heavy rains that cause flooding are recorded hourly over the course of 24 hours according to the Berg intensity scale. In the areas lacking gauging stations, data were collected from the closest meteorological stations, which are automatic and form part of the national monitoring system. The water level and discharge were analysed throughout the entire flood period. For comparison, the mean monthly and annual data for the water level and discharge were also analysed. The processed data were portrayed as histograms that illustrate the evolution of water levels during the floods, including the CA, CI, and CP flood threshold levels before and after the flood, the daily and

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monthly runoff, and the hourly variations of runoff during the tidal bore. For an exact assessment of the damage and the flooded surface area, observations and field measurements were conducted on the major floodplains of the Volovat, Baseu, Jijia, Sitna, Miletin, Bahluet, Bahlui, Elan, and Chineja Rivers (Romanescu and Stoleriu, 2013b).

Nine gauging stations exist in Romanian sections of the Prut River: Oroftiana (near the entry, only including water level measurements), Radauti Prut, Stanca Aval (downstream), Ungheni, Prisacani, Dranceni, Falciu, Oancea, and Sivita (which is directly influenced by the Danube, so no data were collected from this station) (Fig. 3, Table 1). The first gauging station was installed at Ungheni in 1915, and the newest station is Sivita, which was installed in 1978. Much older water level and discharge data are available from stations in other places.

Table 1. Morphometric data for the gauging stations on the Prut River (Romania)

Gauging station	Inauguration year	Geographic coordinates		River length from the confluence	Data on the catchment basin		“0 mira” level
		Latitude	Longitude	km	Surface km^2	Altitude m	mrBS
Oroftiana	1976	48°11'12"	26°21'04"	714	8020	579	123.47
Radauti Prut	1976	48°14'55"	26°48'14"	652	9074	529	101.87
Stanca Downstream	1978	47°47'00"	27°16'00"	554	12000	480	62.00
Ungheni	1914	47°11'04"	27°48'28"	387	15620	361	31.41
Prisacani	1976	47°05'19"	27°53'38"	357	21300	374	28.08
Dranceni	1915	46°48'45"	28°08'04"	284	22367	310	18.65
Falciu	1927	46°18'52"	28°09'13"	212	25095	290	10.04
Oancea	1928	45°53'37"	28°03'04"	88	26874	279	6.30
Sivita	1978	45°37'10"	28°05'23"	30	27268	275	1.66

Flood damage reports were collected from city halls in the Prut catchment and the Inspectorate for emergencies in Botosani, Iasi, Vaslui, and Galati. In isolated areas, we conducted our own field research. We note that some of the reports from city halls seem exaggerated.

4 Results

Tidal bores in the upper basins of the Prut and Siret (in northeast Romania) recorded during the summer of 2010 were caused by atmospheric instability from 21 June-1 July 2010. At this time, the flood danger level (CP) was exceeded on the Prut and Jijia Rivers. High amounts of rain fell during three periods: 21-24 June 2010, 26-27 June 2010, and 28 June-1 July 2010. Precipitation exceeding 100 mm was recorded from 21-24 June (105 mm, at the Oroftiana station) and from 28 June-1 July 2010 (206 mm at Padureni and 110 mm at Pomarla on the Buhai River). Very high rainfall rates occurred within a brief timeframe: 51.5 mm/50 min. was recorded at Oroftiana station on the Prut River and 42.0 mm/30 min. at Padureni on the Buhai River (Romanescu and Stoleriu, 2013a,b; Tirnovan et al., 2014b) (Fig. 4).

Precipitation in the Carpathian Mountains in Ukraine initiated a series of floods in the upper Prut basin. Among the five flood peaks recorded by the Cernauti gauging station, we noted one with a discharge of 2,070 m^3/s recorded on 9 July 2010 at 12:00. In comparison, another flood recorded in May was not very significant (308 m^3/s). In the mountainous sector, the flood warning level (CA) was exceeded only twice, with water levels of 523 cm (+25 cm CA) and 645 cm (+145 cm CA) (Fig. 5).

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At the Oroftiana gauging station, where only the water levels are measured, the flood danger level (CP) was exceeded four times, with levels of 716 cm (+66 cm CP), 743 cm (+93 cm CP), 736 cm (+86 cm CP), and 797 cm (+147 cm CP, on 9 July 2010 at 12:00). The flood warning level (CA) was exceeded throughout the entire flooding period (May-July 2010). In the month of May, the flood levels (CI) were not exceeded (Fig. 5).

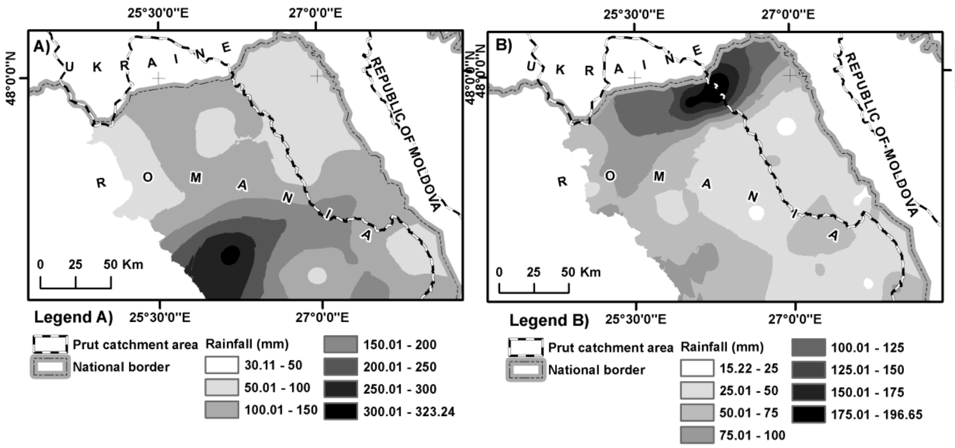

Figure 4. Cumulative precipitation amounts from 21-27 June 2010 (left) and 28 June-1 July 2010 (right)

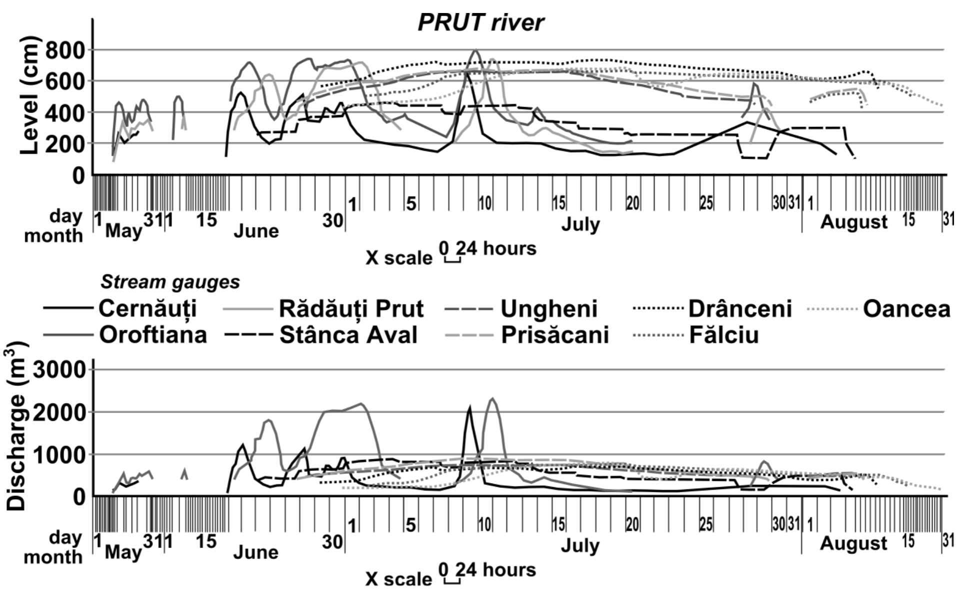

Figure 5. Water levels and discharge on the Prut River at the gauging stations of Cernauti, Oroftiana, Radauti Prut, Stanca Aval (downstream), Ungheni, Prisacani, Dranceni, Falciu, and Oancea during the summer of 2010

At the Radauti Prut gauging station, three important peaks were recorded on 26 June, 29 June-2 July 2010, and 10-11 July 2010. A maximum discharge of 2,310 m^3/s was

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registered on 10 July 2010 at 9 pm. The flood danger level (CP) was exceeded at four times, with water levels of 643 cm (+43 cm CP, on 25 June 2010), 685 cm (+85 cm CP, on 29 June 2010), 721 cm (+121 cm CP, on 29 June-2 July 2010), and 744 cm (+144 cm CP, on 10-11 July 2010) (Fig. 5).

The Stanca Aval (downstream) gauging station is controlled by overflow from the Stanca-Costesti reservoir. This control mitigates the flood hydrographs. The maximum discharge value at this station was 885 m^3/s on 3 July 2010. The flood level (CI) was exceeded from the beginning to the end of the flooding period. The flood danger level (CP) was exceeded from 1-13 July 2010, reaching a maximum water level of 460 cm (+85 cm CP, on 3 July 2010) (Fig. 5).

At the Ungheni gauging station, floods were recorded throughout the entire month of July. The maximum discharge was 673 m^3/s on 8 July 2010. Flooding continued until 5 August 2010. The flood danger level (CP) was exceeded during the 12-day period from 6-17 July 2010. The maximum water level was 661 cm (+1 cm CP) (Fig. 5).

Floods were also recorded throughout July at the Prisacani gauging station. The maximum discharge was 886 m^3/s on 9 July 2010. Flooding continued until 5 August 2010. The flood danger level (CP) was exceeded during the 16-day period from 4-19 July 2010. The maximum water level was 673 cm (+73 cm CP) (Fig. 5).

At the Dranceni gauging station, floods were recorded over a long period from the end of June until the beginning of August. The maximum discharge was 718 m^3/s on 17 July 2010. The flood danger level (CP) was reached or exceeded during the 18-day period from 4-22 July 2010. The maximum water level was 729 cm (+29 cm CP) (Fig. 5).

At the Falciu gauging station, floods occurred throughout July and during the first half of August. The maximum discharge was 722 m^3/s on 19 July 2010. The flood danger level (CP) was reached or exceeded during the 35-day period from 6 July-2 August 2010. The maximum water level was 655 cm (+55 cm CP) (Fig. 5).

At the Oancea gauging station, two tidal bores were recorded in July and August. The first tidal bore on 19 July 2010 had a peak discharge of 697 m^3/s and the second on 27 July 2010 had a peak discharge of 581 m^3/s. Both tidal bores exceeded the flood danger level (CP) throughout the month of July. The maximum water level of the first bore was 683 cm (+83 cm CP), and the maximum for the second was 646 cm (+46 cm CP) (Fig. 5).

The western tributaries of the Prut (within the Moldavian Plain) are numerous, but they have only modest mean annual discharges. They are periodically affected by floods following heavy summer rains. At the Stefanesti gauging station, within the downstream sector of the Baseu River, floods were recorded from 1-4 July 2010. The maximum discharge was 107 m^3/s on 6 July 2010. The flood level (CI) was reached or exceeded for two days. The maximum level was 355 cm (+5 cm CI) (Fig. 6).

At the Padureni gauging station on the Buhai River, two tidal bores were recorded in June and a secondary tidal bore in May. The maximum discharge was 470 m^3/s on 28 June 2010. The flood danger level was exceeded during both bores, with water levels of 470 cm (+120 cm CP, on 28 June 2010) and 440 cm (+90 cm CP, on 29 June 2010) (Figs. 3, 6).

At the Todireni gauging station on the Sitna River (a tributary of the Jijia), floods occurred from 1-4 July 2010. The maximum discharge was 19 m^3/s on 1, 2, and 4 July 2010. The flood level (CI) was exceeded on 1 and 2 July 2010. The maximum water level was 387 cm on 1 July 2010. The flood warning level (CA) was exceeded on 4 July 2010 (Figs. 3, 6).

At the Nicolae Balcescu gauging station on the Miletin River (a tributary of the Jijia), floods were recorded from 26-29 June 2010. The maximum discharge was 60 m^3/s on 6 June 2010. The flood level (CI) was exceeded just once, on 28 June 2010. The maximum level was

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444 cm (+22 cm CI). The warning level (CA) was exceeded throughout the flooding period (Figs. 3, 6).

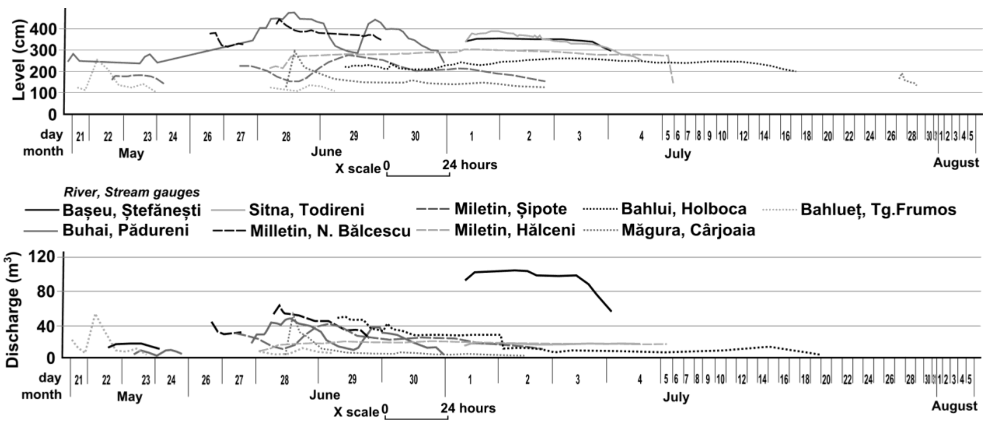

Figure 6. Water levels and discharge on the main Prut tributaries during the summer of 2010: the Baseu, Buhai, Sitna, Miletin, Bahlui, Magura, and Bahluiet Rivers

At the Sipote gauging station on the Miletin, four tidal bores were recorded from 22 June-2 July 2010. The maximum discharge was 45 m^3/s on 29 June 2010. The flood level (CI) was exceeded from 29-30 June 2010. The maximum water level was 269 cm (+19 cm CI). The warning level (CA) was exceeded throughout the flooding period (Figs. 3, 6).

At the Halceni gauging station on the Miletin, floods were recorded from 28 June-5 July 2010. The maximum discharge was 32 m^3/s on 1-2 July 2010. The flood danger level (CP) was exceeded during the peak discharge period, with a water level of 302 cm (+2 cm CP). The flood level (CI) was exceeded throughout the flooding period (Figs. 3, 6).

The Carjoaia gauging station on the Magura River (a tributary of the Bahlui), one major tidal bore was recorded. The maximum discharge was 73.5 m^3/s on 28 June 2010. The flood level (CI) was exceeded on 28 June 2010. The maximum water level was 280 cm (+90 cm CI) (Figs. 3, 6).

At the Targu Frumos gauging station on the Bahluet (atributary of the Bahlui), one major tidal bore was recorded on 22 May 2010, with a maximum discharge of 48 m^3/s. The flood danger level (CP) was reached on the same day and the maximum water level was 250 cm (0 cm CP). The flood warning level (CA) was exceeded throughout the flooding period (Figs. 3, 6).

At the Harlau gauging station on the Bahlui (a tributary of the Jijia), successive and increasing tidal bores were recorded from 22 May-1 July 2010. The maximum discharge was 32 m^3/s on 29 June 2010. The flood level (CI) was exceeded throughout the flooding period. The maximum water level was 552 cm (+132 cm CI) (Figs. 3, 6).

At the Iasi gauging station on the Bahlui, floods occurred from 24 June-4 July 2010. The maximum discharge was 44 m^3/s on 1 July 2010. The flood warning level (CA) was exceeded throughout the flood. The maximum water level was 286 cm (+86 cm CA) (Figs. 3, 6).

At the Holboca gauging station on the Bahlui, floods were recorded from 29 June-17 July 2010. The maximum discharge was 50 m^3/s on 29 June 2010. The warning level (CA) was reached or exceeded throughout the flooding period. The maximum water level was 259 cm (+59 cm CA) (Figs. 3, 6).

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At the Dorohoi gauging station on the Jijia, several tidal bores were recorded from 21 May-7 July 2010. The maximum discharge was 119 m^3/s on 29 June 2010. The flood danger level (CP) was exceeded from 29-30 June 2010. The maximum water level was 760 cm (+160 cm CP). The flood warning level (CA) was exceeded throughout the flooding period (Figs. 3, 7).

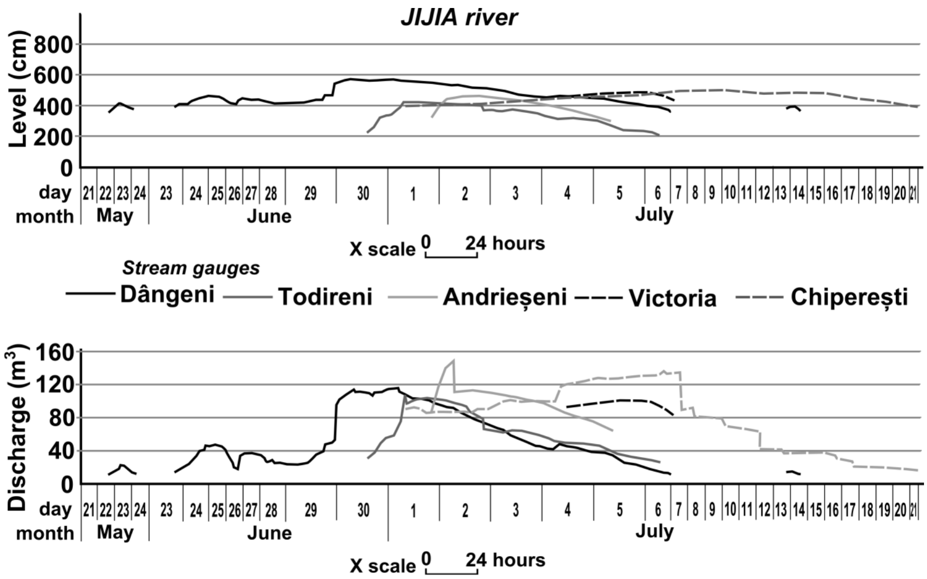

Figure 7. Water levels and discharge on the Jijia River at the gauging stations of Dangeni, Todireni, Andrieseni, Victoria, and Chiperesti during the summer of 2010

At the Dangeni gauging station on the Jijia, several tidal bores were recorded from 22 May-28 July 2010. The maximum discharge was 116 m^3/s on 1 July 2010. The flood level (CI) was exceeded from 30 June-3 July 2010. The maximum water level was 578 cm (+108 cm CI). The flood warning level (CA) was exceeded throughout the flooding period (Figs. 3, 7).

At the Todireni gauging station on the Jijia, flooding occurred from 30 June-6 July 2010. The maximum discharge was 104 cm on 1 July 2010. The flood levels (CI) were exceeded from 1-4 July 2010. The maximum water level was 417 cm (+47 cm CI). The flood warning level (CA) was exceeded throughout the flooding period (Figs. 3, 7).

At the Andrieseni gauging station on the Jijia, flooding was recorded from 1-4 July 2010. The maximum discharge was 148 m^3/s on 2 July 2010. The flood danger level (CP) was exceeded on 2 and 3 July 2010. The maximum water level was 461 cm (+11 cm CP). The flood warning level (CA) was exceeded throughout the flooding period (Figs. 3, 7).

At the Chiperesti gauging station on the Jijia, successive and increasing tidal bores were recorded from1-19 July 2010. The maximum discharge was 136 m^3/s on 6 July 2010. The flood warning level (CA) was exceeded throughout the flooding period. The maximum water level was 497 cm (+97 cm CA) (Figs. 3, 7).

At the Victoria gauging station on the Jijia, flooding occurred from 4-7 July 2010. The peak discharge was 100 m^3/s on 5 July 2010. The flood warning level (CA) was exceeded throughout the flooding period. The maximum water level was 485 cm (+35 cm CA) (Figs. 3, 7).

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At the Capitanie A.F.D.J. gauging station on the Danube, record floods occurred. The maximum discharge was 16,300 m^3/s on 5-6 July 2010, which is a historic discharge for the Galati station. The flood level (CI) was exceeded from 26 June-14 July 2010 (Fig. 8).

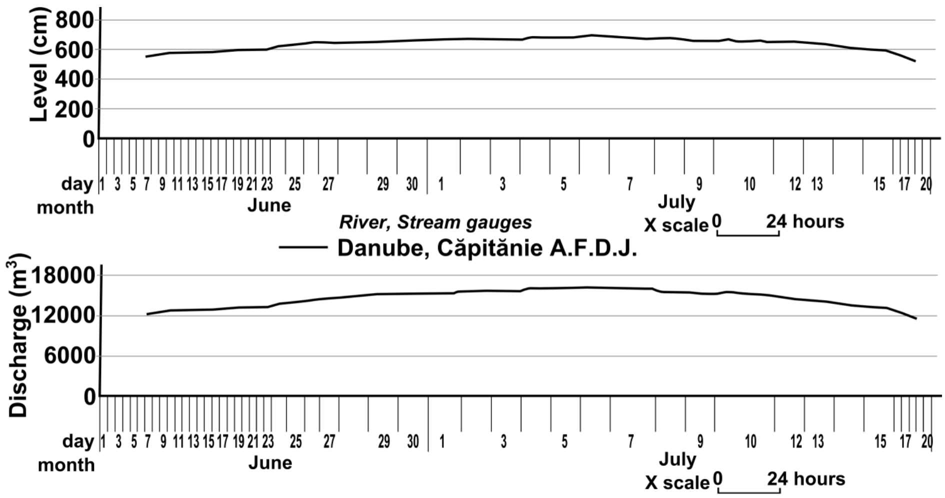

Figure 8. Water levels and discharge on the Danube at the Capitanie A.F.D.J. gauging station in the summer of 2010

5 Discussion

Cumulative heavy rains from 21-24 June, 26-27 June, and 28 June-1 July 2010 caused water levels to exceed the flood danger level (CP) by 40-150 cm on the Prut in the Oroftiana-Radauti Prut sector and by 30-150 cm in the upper basin of the Jijia. The flood level (CI) was exceeded by 80-110 cm in the middle basin of the Jijia and in its tributaries (Sitna, Miletin, and Buhai). Discharges within the lower Jijia basin were controlled by upstream reservoirs and downstream polders in the lower reaches of the Jijia.

The Oroftiana gauging station only records water level measurements. The Radauti Prut gauging station may be influenced by the water stored in the Stanca-Costesti reservoir (which occurred during the historic flood of 2008) (Romanescu et al., 2011a,b). The Stanca downstream gauging station may be influenced by overflow from the Stanca-Costesti reservoir. The Oancea gauging station, situated near the mouth of the Prut, may be influenced by waters from the Danube.

High discharge and water levels of 2,310 m^3/s and 744 cm (+144 cm CP), respectively, were recorded at the Radauti Prut gauging station. The 2010 values are significantly lower than the maximum values recorded in 2008 of 7,140 m^3/s and 1,130 cm (+530 cm CP) (the highest value for Romanian rivers). This value was recalculated after two years, resulting in a discharge of 4,240 m^3/s, which is the second highest value in Romania (after the historic discharge of 4,650 m^3/s on the Siret in 2005) (Romanescu et al., 2011a,b). The existence of five tidal bore peaks (with the second and third tidal bores being weaker) clearly indicates that they were caused by heavy rains in the Carpathian Mountains in Ukraine.

Discharges in the downstream reaches of the Prut are controlled by the Stanca-Costesti reservoir. In the Romanian Register of Large Dams, the Stanca-Costesti dam ranks 49th out of 246 dams in terms of height, but 2nd in terms of active reservoir volume (1,400 million m^3,

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after the Iron Gates I, with a volume of 2,100 million m^3). It has a surface area of 5,900 ha during a normal retention level (NRL). After construction of the Stanca-Costesti reservoir, floods on the Romanian parts of the Prut diminished considerably. Because the Prut has higher banks in the Republic of Moldova, this area was not affected by dam construction. The reservoir was constructed with a mitigation level of 550 million.m^3, allowing the mitigation of a 1% tidal bore from 2,940 to 700 m^3/s. The damming infrastructure constructed downstream from the hydrotechnical nodes prevents the flooding of approximately 100,000 ha of floodplain area (Romanescu et al., 2011a,b).

The flood hydrographs recorded at the Stanca Aval (downstream) gauging station features flattened and relatively uniform tidal bores, mostly in the central part of the river. This behaviour is due to the influence of Stanca-Costesti reservoir, which significantly reduced the maximum discharge at Stanca Aval (885 m^3/s) compared to the Radauti Prut gauging station upstream of the reservoir. The water level was maintained within the upper limit recorded by longitudinal protection dams.

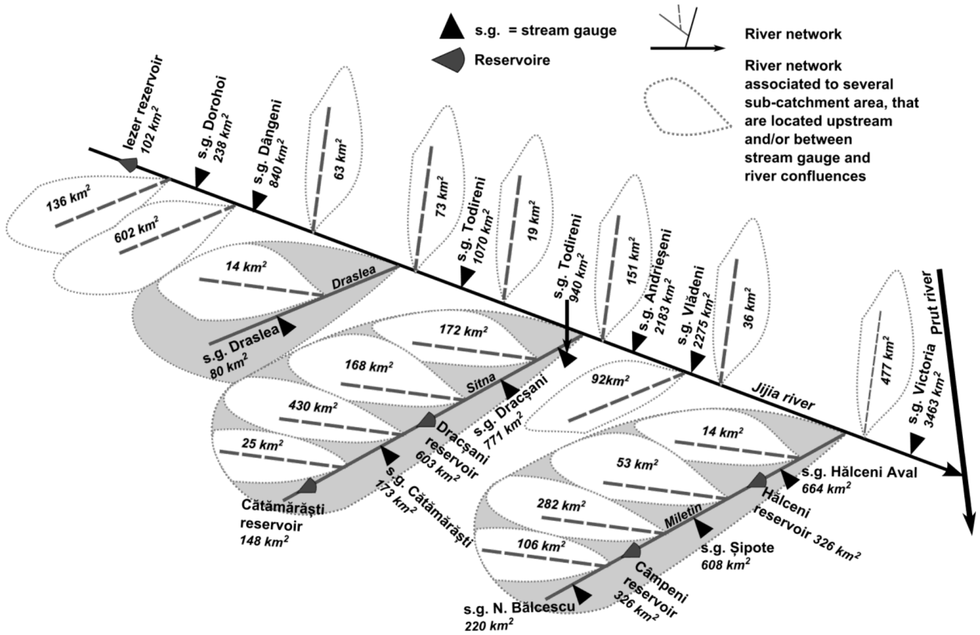

Figure 9. Distribution of sub-basins within the Jijia catchment and placement of the main ponds

The Ungheni, Prisacani, Dranceni, and Falciu gauging stations had a flattened and uniform tidal bore, which signifies upstream control, including some of the tributaries. The flood danger level (CP) was exceeded by a few centimetres and the floodplain was partially flooded in these areas. The high discharges recorded at the Prisacani station occurred because of waters in the upper Prut basin, including controlled spills from the Stanca-Costesti reservoir. Downstream of the Prisacani station, the influence of the Jijia becomes obvious: it increases the water level and lengthens the duration of floods.

Stronger floods within the middle reaches of the Prut occur because of its tributaries. Flooding on the Baseu, Sitna, Miletin, Jijia, Bahluet, and Bahlui Rivers was strong, but it was mitigated for the most part by the existence of ponds (Fig. 9). Therefore, the excess water

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entering Romania from Ukraine entered the Stanca-Costesti reservoir. The excess water downstream of the Stanca-Costesti reservoir came from tributaries. Discharge from the tributaries is controlled by hydrotechnical works within each tributary's catchment. The Jijia and Bahlui catchments are 80% developed. The water levels downstream of these tributaries, in the lower reaches of the Prut, are mitigated by the extreme width of the Prut floodplain (the most important wetland of the interior Romanian rivers).

The system of polders in the lower reaches of the Jijia served as an effective trap for surplus water. High discharges on the Danube, which reached a historic maximum of 16,300 m^3/s at Galati, would have flooded the city centre without the precincts constructed on the Jijia that stopped a portion of the floodwaters. When the floods on the Danube ceased, the water was gradually eliminated from the polders was eliminated gradually, which explains why high water levels persisted in the lower Prut for a long time (Fig. 10).

Figure 10. Polders on the Jijia and the floods recorded in the summer of 2010: storage of excess water (left) and its elimination (right)

Discharge at the Oancea gauging station increased dramatically from 4-5 July 2010, coinciding with the increased discharge on the Danube at Galati. The tidal bore at Oancea was also enhanced by backwater from the Danube. The second tidal bore was caused by upstream contributions. The flood danger level (CP) at Oancea was exceeded by +83 cm (CP) during the first tidal bore and by +46 cm (CP) during the second tidal bore (Table 2).

Table 2. Values of CA, CI, and CP for the Oancea (Prut) and Galati (Danube) gauging stations.

Gauging station	CA (Warning level)	CI (Flood level)	CP (Danger level)
Oancea (Prut)	440	550	600
Galati (Danube)	560	600	660

The city of Galati is situated at the confluence of the Prut and the Danube Rivers. Thus, water at the Oancea station may be influenced by the Danube and the Prut. In the summer of 2010, the highest values of discharge and water level at Galati were recorded (Tables 3, 4). The control of flooding on the Prut meant that floodwaters in Galati reached the sector of banks where flood infrastructure had been developed (the sea-cliff) as well as the lower areas of the city (Fig. 11).

Table 3. Maximum water levels during flooding in the summer of 2010 for the Danube compared to values from other flood years.

River	Gauging station	Maximum levels in the year (cm)

		2010	2006	2005	1981	1970
Danube	Galati	678	661	600	580	595
	Isaccea	537	524	481	490	507
	Tulcea	439	437	399	415	429

Table 4. Maximum discharges during flooding in the summer of 2010 for the Danube compared to the maximum values from 2006.

River	Gauging station	Maximum discharges in the year (m^3/s)	
		2010	2006
Danube	Galati	16300	14220
	Isaccea	16240	14325
	Tulcea	6117	5768

Discharges and water levels in the middle sector of the Prut River (recorded at the Oroftiana, Radauti Prut, and Stanca Aval stations) rank third in the hierarchy of floods (after 2008 and 2005). Values for the tributaries (particularly the Jijia, Buhai, Miletin, and Sitna) rank first in the hierarchy of floods (Table 5).

Table 5. Maximum water levels during flooding in the summer of 2010 compared to 2008 and 2005.

River	Gauging station	Maximum level cm	Day	Hour	Difference from the three levels of danger Cm	Maximum level 2008 cm	Maximum level 2005 cm
Prut	Oroftiana	717	24.06	11	+67 CP	867	703
		744	28.06	11-12	+94 CP	-	-
		737	1.07	04	+87 CP	-	-
		797	9.07	17-18	+147 CP	-	-
		425	13.07	20	+75 CA	-	-
Prut	Radauti Prut	643	25.06	18-19	+43 CP	1130	680
		686	29.06	17	+86 CP	-	-
		722	1.07	23	+122 CP	-	-
		744	10.07	19-20	+144 CP	-	-
Prut	Stanca Downstream	461	3.07	15-22	+86 CP	512	331
Jijia	Dorohoi	750	29.06	09	+150 CP	558	646
		722	30.06	05	+122 CP	-	-
		630	30.06	17	+30 CP	-	-
Jijia	Dangeni	575	30.06	08	+105 CI	449	512
		579	1.07	05	+109 CI	-	-
Jijia	Todireni	417	1.07	08	+77 CI	123	420
Buhai	Padureni	470	28.06	19-20	+120 CP	292	-
Miletin	Nicolae Balcescu	444	28.06	15	+24 CI	286	334
Miletin	Sipote	226	27.06	12	+76 CA	198	236
		269	29.06	18	+19 CI	-	-
Miletin	Halceni	302	1.07	15-18	+2 CP	226	238
Sitna	Todireni	378	1.07	17	+28 CI	-	-

The floods recorded in the summer of 2010 in the Buhai catchment (a tributary of the Jijia, which is a tributary of the Prut) caused backwaters to emerge at the mouth of the river. The manifestation of this backwater phenomenon is unique because the floodwaters of the

Buhai River climbed the Ezer dam (on the Jijia River) and flooded its lacustrine cuvette. The phenomenon was named "spider flow" (Romanescu and Stoleriu, 2013a,b) (Fig. 12).

Figure 11. Flooding of the sea-cliff and the NAVROM headquarters in Galati

6 Conclusions

In the summer of 2010, significant precipitation occurred in Central and Eastern Europe. Heavy rains in northeast Romania caused devastating floods in the Prut and Siret basins. Romania incurred huge economic damages. The flooding in 2010 was comparable with previous strong flood years in 2005, 2006, and 2008 in Romania. The greatest damage occurred in, and the most arable area was destroyed in, the middle Prut basin in the Jijia-Bahlui Depression of the Moldavian Plain.

Discharge in the downstream sector of the Prut was controlled by the Stanca-Costesti reservoir, which ranks 2nd in Romania in terms of active reservoir volume (1,400 million m^3, after the Iron Gates I, with 2,100 million m^3). It has a surface area of 5,900 ha for a normal retention level (NRL). Under normal circumstances, the Stanca-Costesti reservoir can retain enough water to control the downstream discharge and water level.

Discharges downstream of the Stanca-Costesti reservoir are controlled by reservoirs and retention systems constructed on the main tributaries of the Prut. We emphasize that the Jijia and Bahlui catchments have hydrotechnical works on 80% of their surface areas. The system of polders in the downstream sector of the Jijia River was used extensively to mitigate discharge and prevent the city of Galati from flooding (Galati is the largest Danubian port, situated at the confluence of the Prut and the Danube Rivers).

The gauging stations in the lower sector of the Prut recorded high discharges and water levels because of excess water coming from upstream (the middle sector of the Prut). At the Oancea gauging station, however, which is situated near the discharge of the Prut into the Danube, there is a significant backwater influence. The Danube had historic discharge at Galati, which affected the water level at Oancea station on the Prut.

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Floods during the summer of 2010 in northeast Romania rank third among hydrological disasters in Romanian history after the floods of 2005 and 2008, which also occurred in the Siret and Prut catchments. The 2010 floods caused grave economic damage (almost one billion Euros in just the Prut catchment) and greatly affected agriculture. Furthermore, six people died in Dorohoi, on the Buhai River.

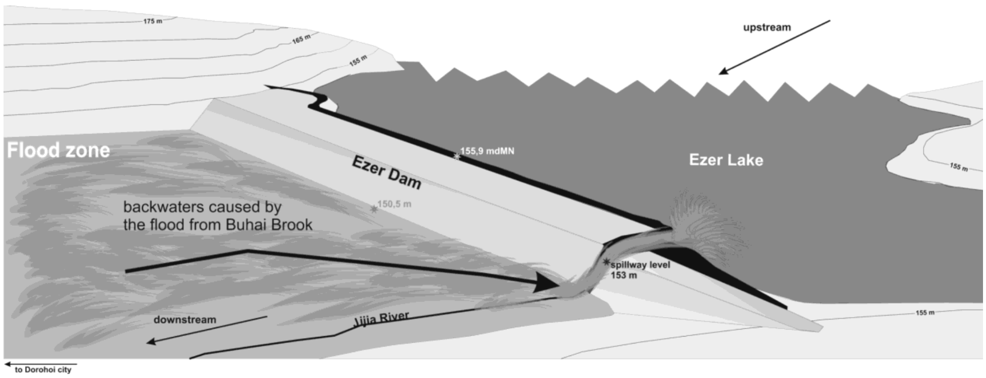

Figure 12. The "spider flow" phenomenon in which the Buhai waters climbed the Ezer dam on the Jijia, in the area of confluence of the two rivers

The 2010 floods caused a unique backwater phenomenon at the mouth of the Buhai River. Floodwaters from the Buhai climbed the Ezer dam (situated on the Jijia River) and flooded its lacustrine cuvette. The phenomenon was called "spider flow".

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