

Supplementary file

Extreme floods in the eastern part of Europe: large-scale drivers and associated impacts

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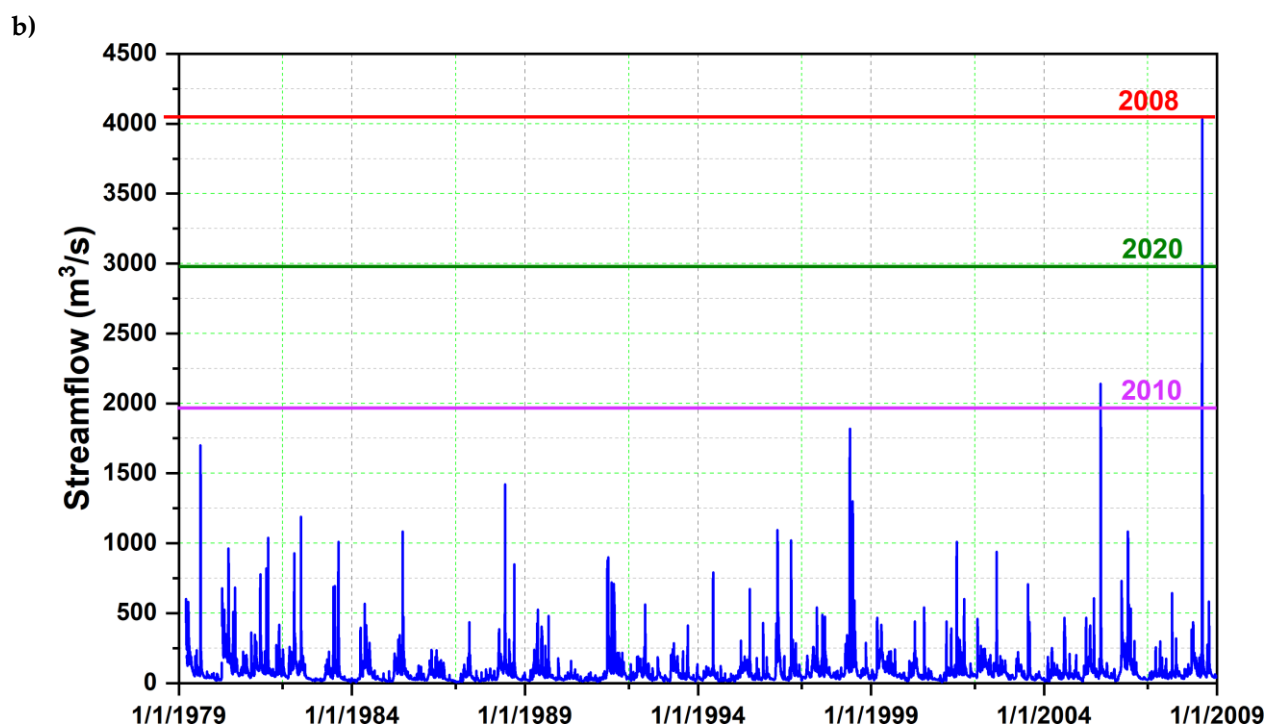
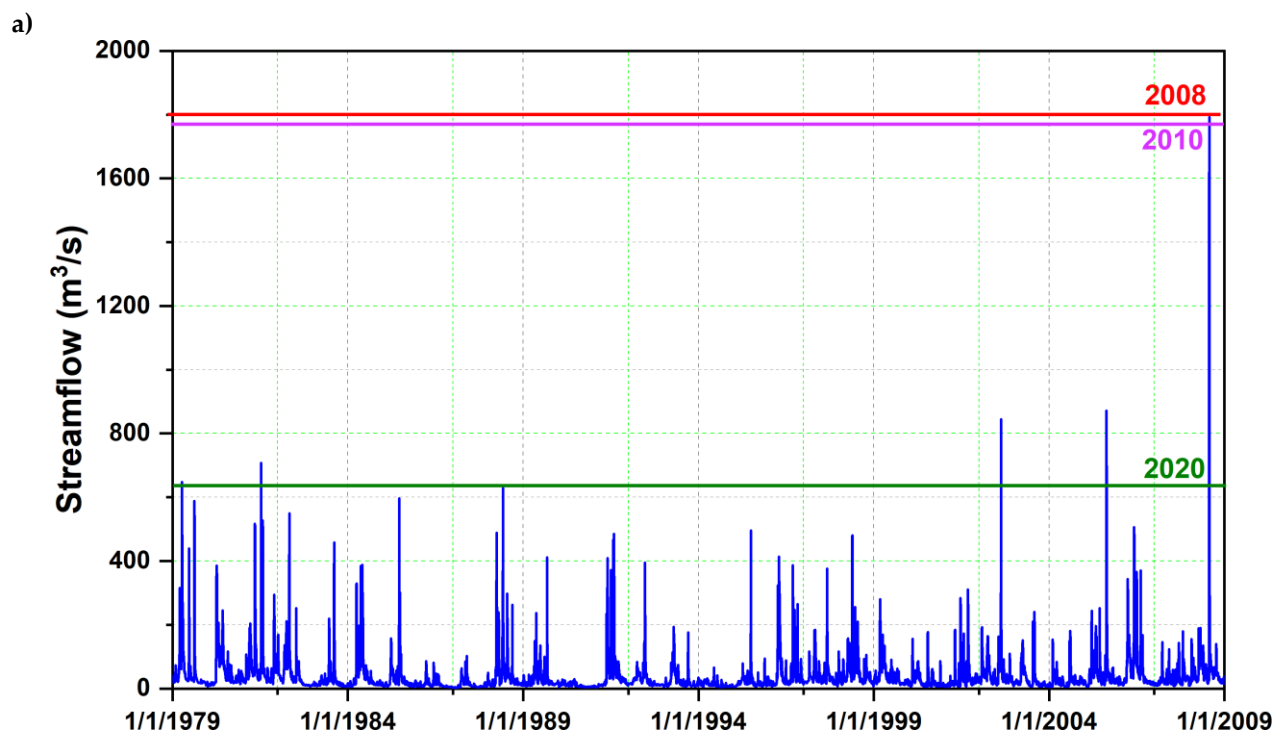
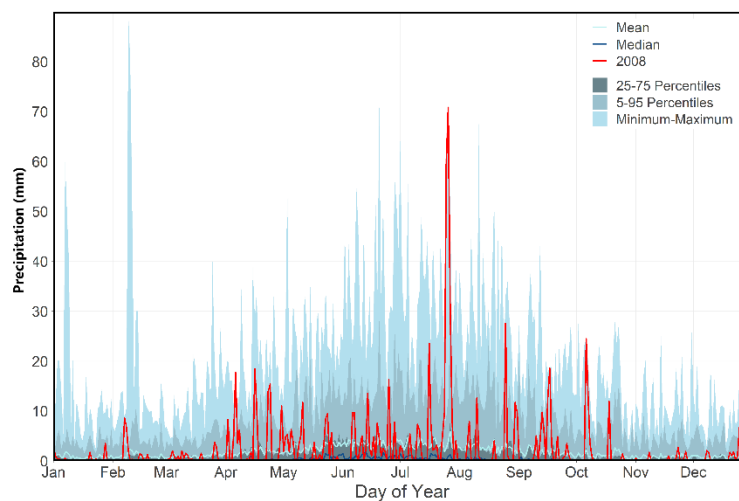
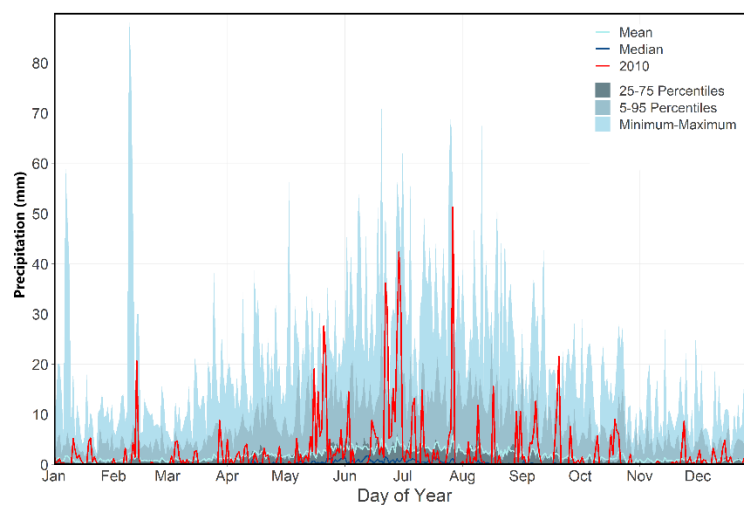


Figure S1. a) Time series of the daily streamflow at Lespezi gauging station (Siret River) and b) Time series of the daily streamflow at Rădăuți-Prut gauging station (Prut River). Analyzed period: 1 January 1978 – 31 December 2008. The horizontal lines indicated the flow peak for the flood events of July 2008 (red line), June 2010 (magenta line) and June 2020 (green line). The magnitude of the flood peaks for these events is given in Table 2.

a)



b)



c)

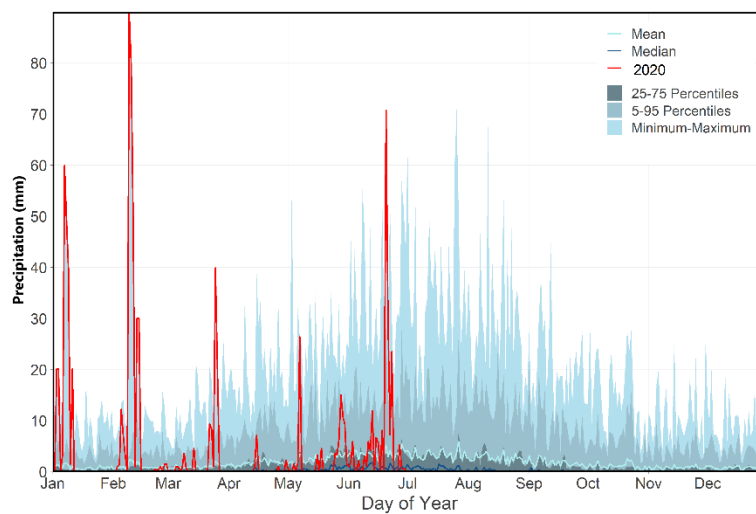
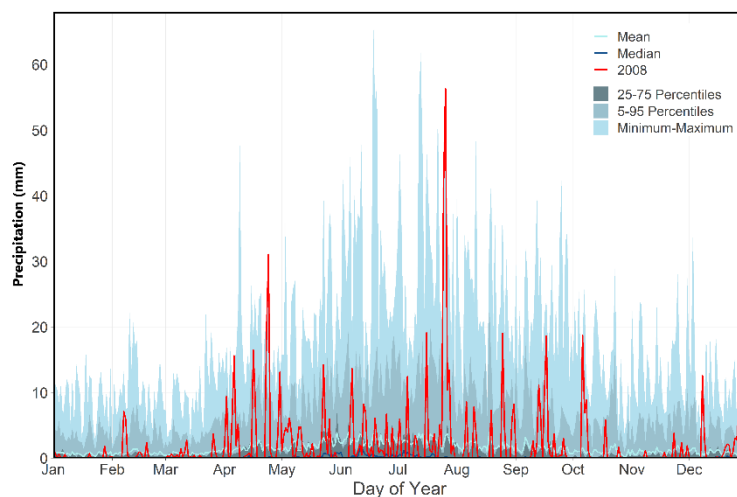
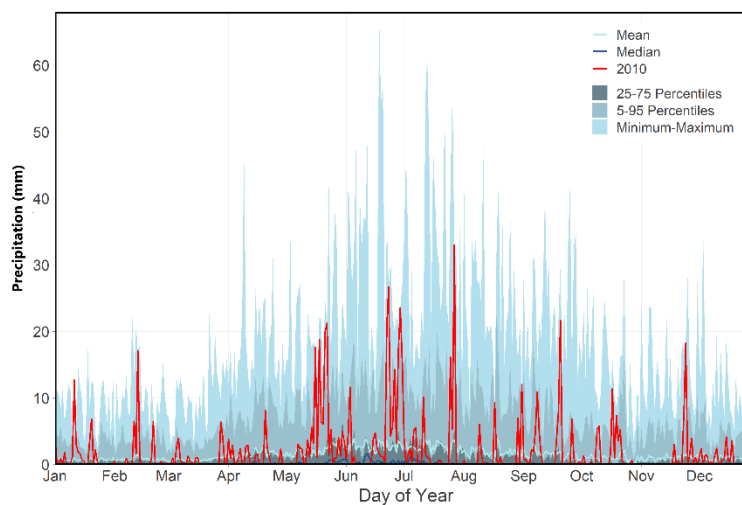


Figure S2. The evolution of the daily precipitation at Rădăuți-Prut meteorological station for a) July 2008 (red line) compared to the daily precipitation pattern on an annual basis (blue shaded area); b) as in a) but for June 2010 and c) as in a) but for June 2020.

a)



b)



c)

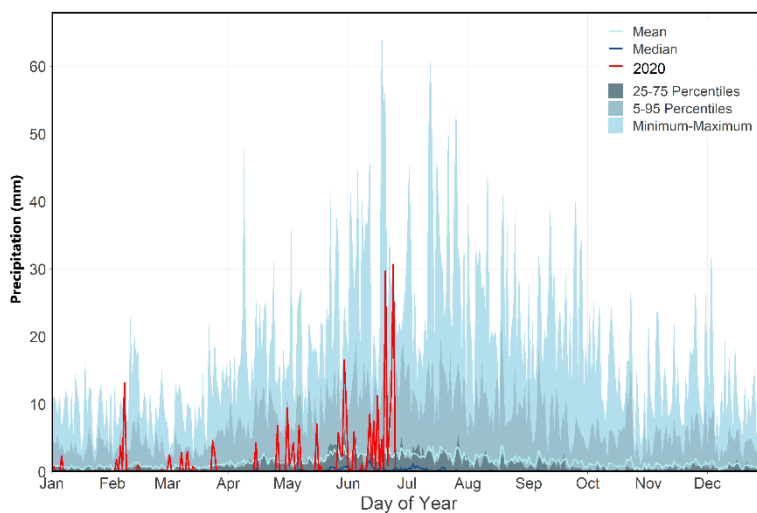


Figure S3. The evolution of the daily precipitation at Darabani meteorological station for a) July 2008 (red line) compared to the daily precipitation pattern on an annual basis (blue shaded area); b) as in a) but for June 2010 and c) as in a) but for June 2020.

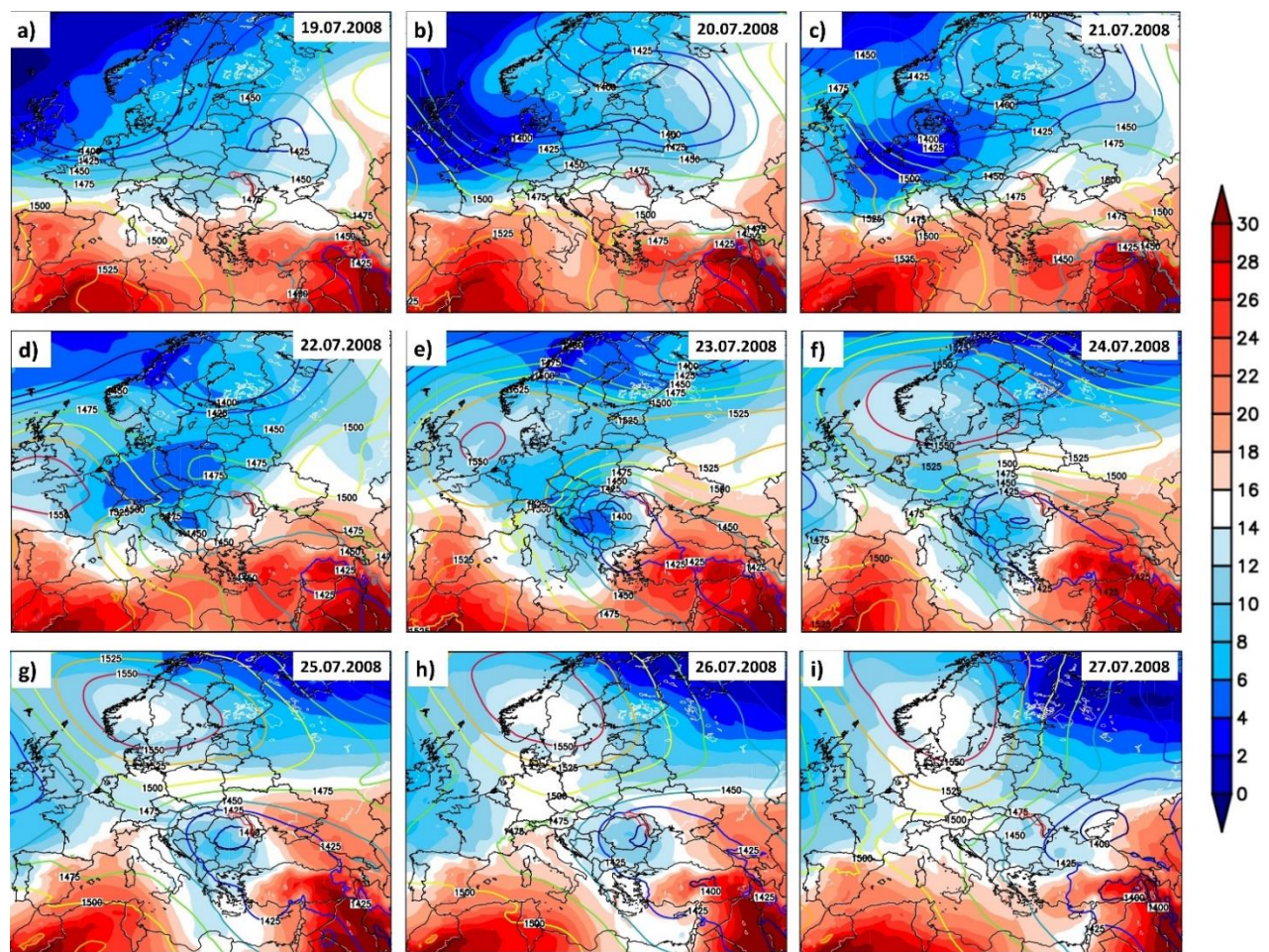


Figure S4. Daily temperature at 850 hPa (TT850) (shaded colors) and daily geopotential height at 850 hPa (Z850) (contour lines) for: a) 19 July 2008; b) 20 July 2008; c) 21 July 2008; d) 22 July 2008; e) 23 July 2008; f) 24 July 2008; g) 25 July 2008; h) 26 July 2008 and i) 27 July 2008. Units: TT850 (°C) and Z500 (m).

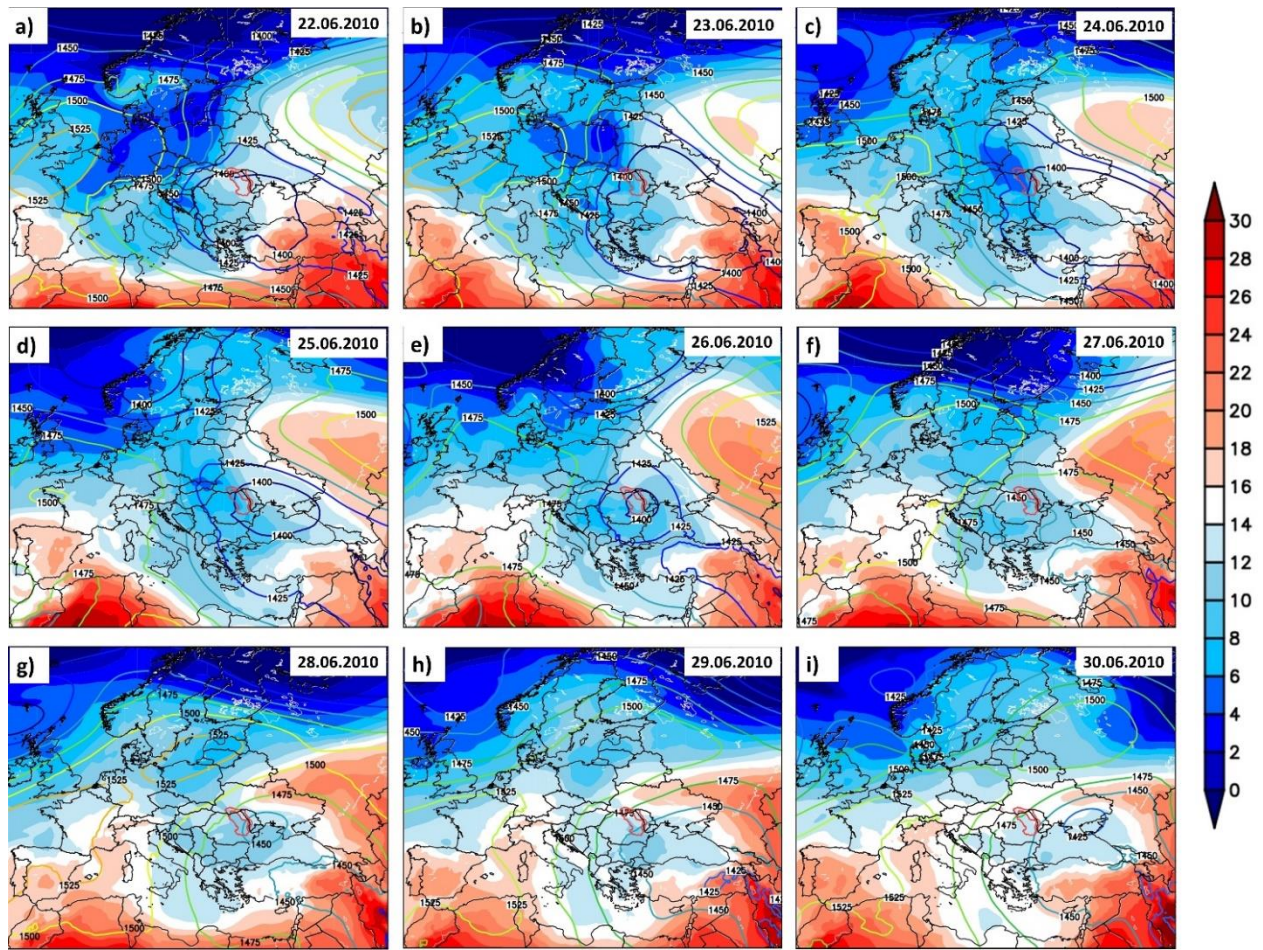


Figure S5. Daily temperature at 850 hPa (TT850) (shaded colors) and daily geopotential height at 850 hPa (Z850) (contour lines) for: a) 22 June 2010; b) 23 June 2010; c) 24 June 2010; d) 25 June 2010; e) 26 June 2010; f) 27 June 2010; g) 28 June 2010; h) 29 June 2010 and i) 30 June 2010. Units: TT850 (°C) and Z500 (m).

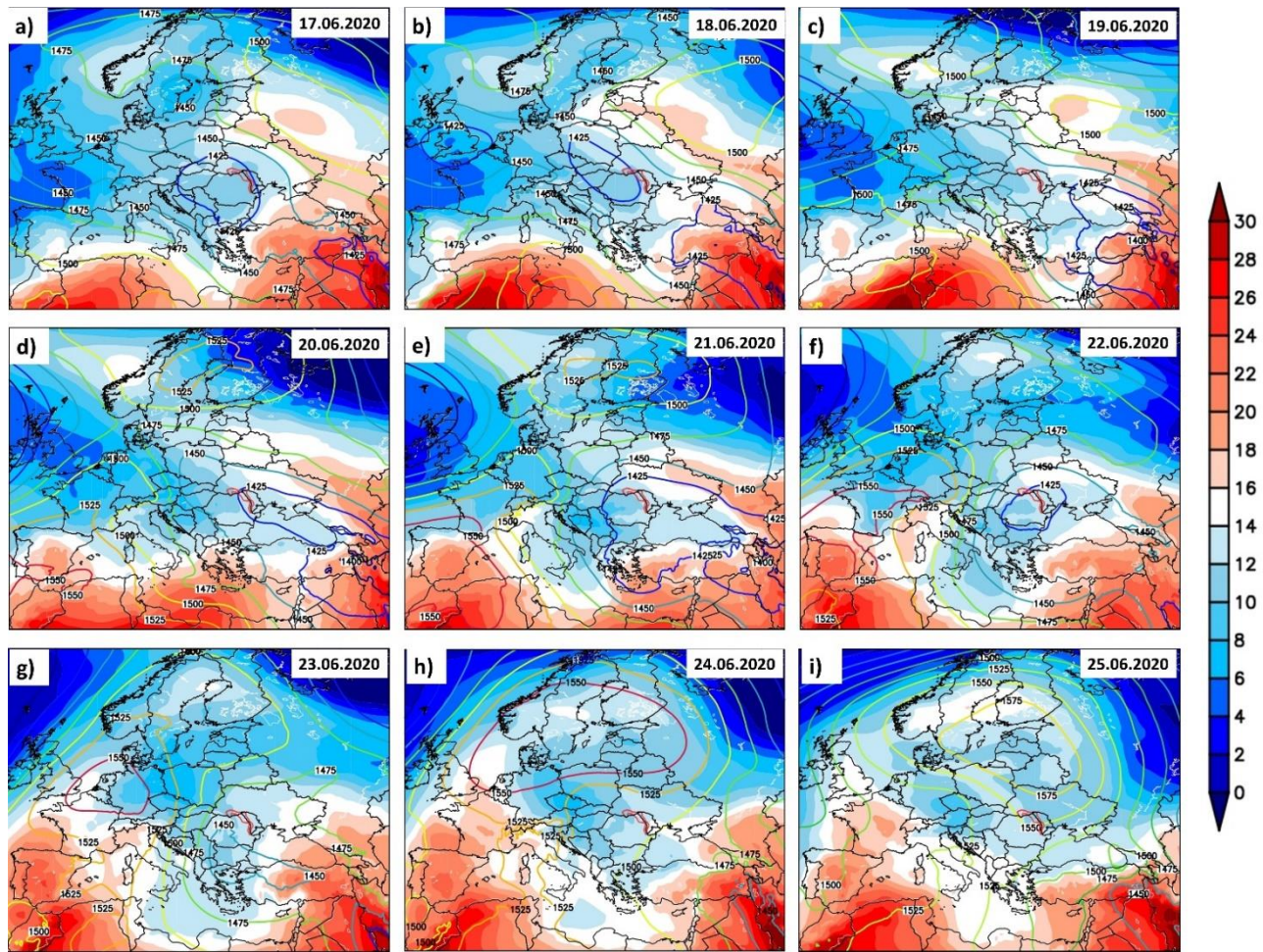


Figure S6. Daily temperature at 850 hPa (TT850) (shaded colors) and daily geopotential height at 850 hPa (Z850) (contour lines) for: a) 17 June 2020; b) 18 June 2020; c) 19 June 2020; d) 20 June 2020; e) 21 June 2020; f) 22 June 2020; g) 23 June 2020; h) 24 June 2020 and i) 25 June 2020. Units: TT850 (°C) and Z500 (m).

Projected change in maximum 100-year daily river discharge for two global warming levels

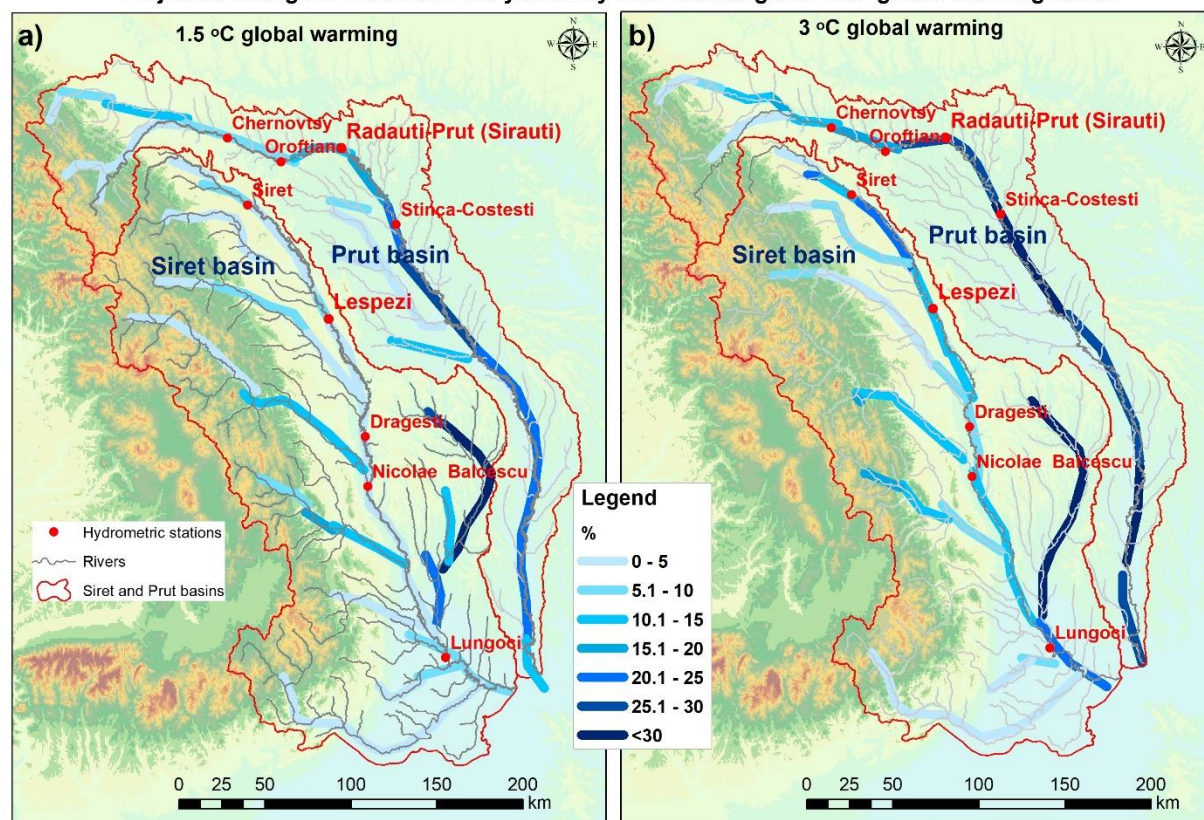


Figure S7. Projected changes in the maximum 100-year daily river discharge for two global warming levels: a) 1.5°C and b) 3°C. The projections were downloaded from the Joint Research center website <https://ec.europa.eu/jrc/en>

Table S1. Daily precipitation totals recorded over the period 1 July – 31 July2008 at different meteorological stations situated in the catchment area of Siret and Prut Rivers.

2008	Rădăuți	Roman	Suceava	Tg. Neamt	Darabani	Iasi	Botosani	Negresti	Ceahlau	Cernauti
1-Jul-08	2.2	1.9	1.9	0.1	6.0	4.8	5.2	0.1	0.3	0.0
2-Jul-08	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.7	0.0
3-Jul-08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4-Jul-08	0.6	0.2	0.2	0.5	0.0	0.0	0.0	0.0	3.1	7.0
5-Jul-08	5.4	12.9	16.0	5.4	12.4	11.3	17.9	6.4	4.2	0.7
6-Jul-08	0.7	0.0	0.2	0.2	0.2	0.0	0.1	0.1	3.0	0.0
7-Jul-08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7
8-Jul-08	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.4	4.0
9-Jul-08	7.3	4.3	4.9	3.2	3.5	0.7	3.4	1.6	7.7	6.0
10-Jul-08	6.1	1.5	3.9	3.6	2.6	0.6	2.3	0.4	2.3	1.0
11-Jul-08	1.2	0.0	1.5	0.1	0.0	0.0	0.1	0.0	0.2	0.0
12-Jul-08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13-Jul-08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14-Jul-08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
15-Jul-08	23.6	26.8	20.3	24.5	19.1	18.5	19.4	24.4	20.2	26.0
16-Jul-08	7.3	0.5	4.7	4.9	2.8	0.6	3.5	0.1	8.4	7.0
17-Jul-08	2.1	1.5	0.5	1.2	1.1	0.5	0.6	1.0	5.0	0.0
18-Jul-08	2.5	0.2	4.5	0.9	1.0	0.0	2.4	0.1	0.3	11.0
19-Jul-08	3.2	8.9	6.8	4.1	3.7	9.8	5.6	8.4	6.3	0.0
20-Jul-08	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
21-Jul-08	0.4	0.0	0.2	0.4	0.0	0.0	0.0	0.0	2.2	Tr
22-Jul-08	5.2	10.7	5.7	12.1	5.1	7.0	5.3	10.5	14.5	9.0
23-Jul-08	9.5	0.8	9.1	4.1	1.7	1.4	3.5	0.4	9.3	4.6
24-Jul-08	59.5	38.5	52.3	37.4	41.3	33.5	45.2	32.7	42.9	37.0
25-Jul-08	70.8	15.4	66.3	14.8	56.3	46.1	60.2	10.1	8.0	41.0
26-Jul-08	31.5	11.1	13.7	16.1	10.4	1.7	7.3	5.1	32.8	3.3
27-Jul-08	8.3	23.8	17.3	20.8	13.4	13.0	18.8	13.5	17.2	0.0
28-Jul-08	0.2	5.2	0.3	5.6	0.7	0.9	0.2	3.3	5.3	3.0
29-Jul-08	4.0	2.6	10.9	5.7	2.0	0.3	6.7	1.0	6.5	0.0
30-Jul-08	0.2	0.0	0.1	1.3	0.0	0.0	0.0	0.0	7.5	0.0
31-Jul-08	0.0	0.1	0.0	0.6	0.0	0.0	0.0	0.2	3.6	0.0
SUM	252.4	167.2	241.3	167.5	183.4	150.8	207.7	119.5	211.7	164.3

Table S2. Daily precipitation totals recorded over the period 1 June – 30 June 2010 at different meteorological stations situated in the catchment area of Siret and Prut Rivers.

2010	Rădăuți	Roman	Suceava	Tg. Neamt	Darabani	Iasi	Botosani	Negresti	Ceahlau	Cernauti
1-Jun-10	2.2	0.5	1.2	1.6	0.8	0.0	0.7	0.0	2.4	1.0
2-Jun-10	5.9	5.9	4.9	4.7	4.7	2.9	5.2	4.1	2.1	22.0
3-Jun-10	14.5	8.5	16.5	7.1	11.6	5.8	15.1	5.2	4.4	4.3
4-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9
5-Jun-10	3.0	0.3	1.8	1.0	1.1	0.1	0.8	0.1	2.5	0.0
6-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0
9-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12-Jun-10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13-Jun-10	0.5	0.1	0.4	0.6	0.1	0.0	0.1	0.0	2.6	3.0
14-Jun-10	2.1	1.0	1.9	0.8	0.6	0.9	0.6	0.7	4.3	6.6
15-Jun-10	8.9	1.2	4.0	1.0	3.7	0.5	1.7	0.5	6.3	0.0
16-Jun-10	7.1	4.4	7.9	5.4	4.8	2.7	6.1	2.4	8.4	8.0
17-Jun-10	5.5	1.5	4.2	4.1	2.5	0.8	2.4	1.8	5.5	0.6
18-Jun-10	5.3	1.2	1.1	1.5	1.6	0.2	0.4	0.6	3.6	7.0
19-Jun-10	2.0	7.1	1.4	13.9	1.2	0.5	1.3	2.9	16.3	0.3
20-Jun-10	3.6	0.9	2.8	3.8	1.2	0.0	1.8	0.5	7.8	0.4
21-Jun-10	1.5	0.0	0.4	0.1	0.4	0.0	0.1	0.0	0.4	
22-Jun-10	36.2	43.6	40.4	53.6	21.0	27.8	28.4	34.8	64.0	52.0
23-Jun-10	30.4	21.2	27.8	22.8	26.7	26.6	29.0	17.9	39.5	16.0
24-Jun-10	5.2	6.7	3.2	2.6	4.3	14.9	3.0	9.9	10.0	0.3
25-Jun-10	5.7	5.7	4.6	5.0	5.6	4.8	6.5	9.8	12.8	19.0
26-Jun-10	15.2	27.5	13.4	33.5	14.3	16.5	15.7	33.2	55.5	25.0
27-Jun-10	8.6	3.3	11.7	7.6	3.2	0.5	7.1	2.2	18.3	1.2
28-Jun-10	25.1	18.4	9.7	23.1	16.9	18.7	12.9	11.5	19.4	31.0
29-Jun-10	42.4	2.8	35.2	5.7	23.6	2.9	19.2	2.3	11.1	24.0
30-Jun-10	30.3	2.1	18.1	7.5	15.3	4.1	13.1	3.2	15.7	0.0
SUM	261.1	163.4	212.4	206.9	165.2	131.2	171.0	143.4	313.5	222.6

Table S3. Daily precipitation totals recorded over the period 1 June – 30 June 2020 at different meteorological stations situated in the catchment area of Siret and Prut Rivers.

2020	Rădăuți	Roman	Suceava	Tg. Neamt	Darabani	Iasi	Botosani	Negresti	Ceahlau	Cernauti
1-Jun-20	1.0	4.3	0.8	2.6	0.0	4.5	0.2	4.7	4.1	5.2
2-Jun-20	1.9	2.2	2.3	3.6	0.4	0.0	3.2	0.0	2.0	1.1
3-Jun-20	5.9	0.8	0.1	0.2	0.0	0.5	1.6	0.0	1.0	6.6
4-Jun-20	0.0	0.0	0.0	0.0	5.9	0.0	0.0	0.0	1.0	3.6
5-Jun-20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.6
6-Jun-20	2.2	0.0		0.0	0.0	0.0	0.0	0.0	2.6	0.0
7-Jun-20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	2.0
8-Jun-20	0.0	0.0	0.5	0.0	1.2	0.1	0.0	0.1	1.2	0.0
9-Jun-20	3.1	0.0	1.1	0.0	0.0	0.0	0.0	1.2	9.2	0.3
10-Jun-20	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.8	2.3	0.3
11-Jun-20	5.9	29.7	4.7	12.0	3.0	0.2	7.6	2.1	25.4	3.6
12-Jun-20	4.1	3.3	7.7	6.6	8.5	2.5	26.3	3.4	5.5	4.0
13-Jun-20	11.9	4.1	39.3	1.0	1.0	0.0	0.0	0.5	5.9	8.0
14-Jun-20	0.0	33.9	0.0	7.2	7.5	28.7	8.1	8.5	6.4	10.0
15-Jun-20	6.7	0.5	1.7	0.8	0.2	0.5	0.0	0.3	5.1	4.0
16-Jun-20	5.7	4.5	21.4	4.4	11.3	12.5	28.8	12.2	0.9	28.0
17-Jun-20	0.2	8.8	4.1	3.2	0.0	14.5	7.5	2.7	5.1	0.0
18-Jun-20	8.1	2.4	7.5	9.2	4.8	6.9	2.2	0.1	5.6	0.6
19-Jun-20	0.5	25.7	0.0	2.8	0.0	0.1	0.0	0.3	4.1	24.0
20-Jun-20	70.8	0.0	24.2	5.2	29.7	0.4	71.0	10.9	2.1	1.0
21-Jun-20	29.9	1.7	12.9	1.6	0.9	0.6	0.5	14.3	41.7	34.0
22-Jun-20	7.2	4.5	9.4	54.8	7.1	18.6	2.9	0.0	60.1	12.0
23-Jun-20	23.5	9.4	0.4	0.0	11.5	7.6	0.0	47.3	0.6	6.3
24-Jun-20	0.0	0.5	0.5	0.0	30.7	0.2	35.7	0.0	0.3	14.0
25-Jun-20	0.0	0.3	0.0	0.0	0.0	0.0	0.7	0.0	4.7	14.0
26-Jun-20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27-Jun-20	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28-Jun-20	0.6	0.0	0.0	0.8	0.0	0.0	3.7	0.0	0.3	0.0
29-Jun-20	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.0
30-Jun-20	0.3	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.6
SUM	196.6	137.1	138.9	116.0	123.7	98.4	200.0	109.5	200.9	193.8

Table S4. Hydrometeorological situation, socio-economic impact and management policy for the three extreme flood events analyzed in this study: July 2008, June 2010 and June 2020.

		2008	2010	2020
Hydrometeorological situation	Precipitation preconditions	<ul style="list-style-type: none"> • Precipitation amounts twice and a half more than the norm was recorded, half of which was recorded during two days: 24 and 25 July; • The July rainfall amount at Rădăuți and Darabani meteorological stations were 252mm and 183mm, while the norm for this month is 103mm and 84mm respectively; 	<ul style="list-style-type: none"> • The precipitation amount that fell during 21.06 – 02.07.2010 period was 50-80% of the annual norm, exceeding 1.5-2 times the multiannual average; • At the Rădăuți (Darabani) meteorological stations, over the May-June 2010 a rainfall amount of 403 mm (301 mm) was recorded, while the annual norm for these months is 180 mm (144 mm); • Locally, heavy and very heavy torrential rain exceeded 40 mm of precipitation in just a few hours; 	<ul style="list-style-type: none"> • At Rădăuți meteorological station, a rainfall amount of ~55 mm/day was recorded on the 22nd of June, which is half of the monthly average; • The precipitation falling over the western part of Ukraine and the Republic of Moldova in June 2020 was up to six-time higher than the monthly average;
	Hydrometric characteristics	<ul style="list-style-type: none"> • At Lespezi hydrometric station (Siret river) the streamflow started to rise on the 24th of July and reached the maximum flood peak on the 27th July, when a streamflow of 1793 m³/s was recorded. After the maximum of the flood peak, the streamflow started to decrease, reaching again a level below the danger limit on the 30th of July; • At Rădăuți-Prut hydrometric station (Prut river), on the 24th of July a streamflow of 217 m³/s has recorded, three times higher than the day before, and continued to rise until 28th of July, when the maximum peak of the flood (~4033 m³/s) was recorded, after which the streamflow started to decrease, reaching a value of 349 m³/s on August 1st; 	<ul style="list-style-type: none"> • At Lespezi hydrometric station, on the 29th of June 2010, an exceptional high streamflow was recorded (1205 m³/s) and continued to grow until the 1st of July 2010, when a flood peak of 1719 m³/s was recorded. After this flood peak the streamflow started to decrease, reaching again an average streamflow for this period on the 3rd of July 2010; • At Șirăuți hydrometric station the streamflow reached a value of ~1400 m³/s on the 26th of June. The second flood wave at Șirăuți was recorded between 29th of June and 3rd of July 2010, with a maximum peak of 1930 m³/s on the 2nd of July 2010, after which the streamflow decreased up to ~ 450 m³/s on the 5th of July; 	<ul style="list-style-type: none"> • At Lespezi hydrometric station (Siret River), the streamflow started to rise slowly on the 15th of June. From 21st of June the streamflow started to rise very fast, until the 24th of June, when a flood peak of 640 m³/s was recorded; • The first flood wave at Rădăuți-Prut hydrometric station occurred between 14th and 21st of June 2020 (766 m³/s); • Station the second flood wave began on the 22nd of June, with a rapid, exponential increase of the streamflow, which reached the maximum flood peak (2920 m³/s) four days later, on 26th of June;

	Atmospheric conditions	<ul style="list-style-type: none"> • The days with extreme precipitation events were associated with inter water vapor transport (WVT); • The days before the flood peak from July 2008 in the Siret and Prut river basins, were associated with high PV values over the eastern part of Europe; • Three particular weather regimes prevailing the days prior to the flood peak: WZ (West cyclonic), TRM (trough over central Europe) and HNFZ (High Pressure over Fennoscandia); 	<ul style="list-style-type: none"> • The days with extreme precipitation events were associated with intense water vapor transport towards the catchment area of both Prut and Siret Rivers; • The heavy rainfall events in June 2010 were triggered by strong high PV anomalies over the analyzed region and several pivoting low-pressure systems, which developed in cycles of two or three days; • One of the preferred weather regimes prior to the flood peaks was the BM (High Pressure over Central Europe); 	<ul style="list-style-type: none"> • The days with extreme precipitation events were associated with intense water vapor transport over Ukraine and the northern part of Romania; • The heavy rainfall events in June 2020 were triggered, by strong high PV anomalies extending from the North Atlantic basin towards the eastern part of Europe and several low-pressure systems, which developed in cycles of two or three days; • One of the preferred weather regimes prior to the flood peaks was the BM (High Pressure over Central Europe);
Socio-economic impact	Number of fatalities	<ul style="list-style-type: none"> • In Romania 7 deceased persons; • In Republic of Moldova 3 deceased persons; • In western Ukraine 37 deceased persons; 	<ul style="list-style-type: none"> • In Romania 24 deceased persons; • In Republic of Moldova 2 deceased persons; 	<ul style="list-style-type: none"> • In Romania 3 deceased persons; • In Ukraine 3 deceased persons;
	Number of affected peoples	<ul style="list-style-type: none"> • In Romania over 30 000 affected people; • In Republic of Moldova ~ thousands; 	<ul style="list-style-type: none"> • In Romania more than 17 000 people were evacuated; • In Republic of Moldova more than 13 000 people were affected and more; than 4000 were evacuated; 	<ul style="list-style-type: none"> • In Romania ~300 peoples were evacuated; • In Republic of Moldova dozens of households were evacuated; • In Ukraine ~300 people were evacuated;
	Direct economic impact	<ul style="list-style-type: none"> • In Romania ~2 billion Euro; • In Republic of Moldova ~101 million Euro; • In western Ukraine ~548-733 million Euro; 	<ul style="list-style-type: none"> • In Romania ~1 billion Euro; • In Republic of Moldova ~35.19 million Euro; • In Ukraine ~1 million €; 	<ul style="list-style-type: none"> • In Romania ~290 million Euro; • In Republic of Moldova more than 2 million Euro; • In Ukraine ~90-120 million Euro;
	Indirect impacts	<ul style="list-style-type: none"> • In Romania over 150 damaged localities, 67 500 damaged or destroyed houses, 313 damaged annexes and 24 socio-economic objectives, 1246 bridges and footbridges damaged or destroyed, ~1900 km of national 	<ul style="list-style-type: none"> • In Romania, the flood has affected 426 localities in various degrees, more than 3936 households (out of which 863 were completely destroyed), ~110 000 ha agricultural land, 707 bridges and 2729 small bridges, 31 km of water 	<ul style="list-style-type: none"> • In Romania, the floods affected 161 localities in 29 counties, nearly 400 households and 600 courtyards were flooded, while many bridges and footbridges, several kilometers of national roads, railways (between Gura-

		<p>and country roads and 345 of railway road affected. Other damaged goods include: 49 km of canals, 355 km of dikes, 94.13 km of bank defenses and dams, 55.4 km of drainage channels, 110 km of anti-erosion works, 5 dams, 10 micro hydropower plants, 27 hydrometric stations, more than 49 000 ha of agricultural land, 1.68 km of water supply networks, 37.2 km of sewerage networks, 234.8 km of electricity networks, 1.6 km of natural gas supply networks, 6.1 km of riverbed clogging and erosions, 30 km of water supply pipes destroyed and 1.500 flooded fountains;</p> <ul style="list-style-type: none"> • In Republic of Moldova 8473 ha of agricultural land and 1183 houses were damaged, 3000 fountains were flooded, and more than 3000 domestic animals died; • In western Ukraine over 45 000 houses from 784 localities, 30 000 hectares of agricultural land, 700 km of roads, and over 350 bridges were damaged; 	<p>supply, 147 social and economic objects (out of which 87 schools, 3 hospitals and 33 churches) and over 5200 km of national and regional roads, 14 000 wells;</p> <ul style="list-style-type: none"> • In Republic of Moldova were damaged 1105 households and 4308 ha of farmlands, 4800 ha of pastures, and 930 ha of forests. Also the anti-flood dam from Nemneti broke on the 6th of July 2010, flooding more than 3800 ha and the a controlled break of the dam from the confluence with the Nirnava river was performed in order to avoid a possible accidental break; • In Ukraine more than 750 households, 12 000 ha of agricultural land, and numerous roads and infrastructure facilities were affected; 	<p>Humorului and Frasin), county roads, and streets were damaged;</p> <ul style="list-style-type: none"> • In Republic of Moldova the most affected areas were on the sector from the entrance of the Prut River on the territory of the Republic of Moldova to the Stânca-Costești accumulation lake, especially Edineț and Briceni; • In Ukraine more than 11 000 households were flooded, ~90 bridges destroyed, and more than 400 km of national and local roads were damaged (including a highways section). The railway was damaged, and many trains were canceled on the route Ivano-Frankivsk – Vorokhta;
<p>Management – policy and vulnerability aspects</p>	<p>Drought risk management aspects</p>	<ul style="list-style-type: none"> • Lack of proper management and awareness tools; 	<ul style="list-style-type: none"> • In Romania the implementation of the European Flood Management Directive in Romania started in 2009; 	<ul style="list-style-type: none"> • A better implementation of the European Flood Management Directive in Romania; • Ukraine and the Republic of Moldova started the work to implement also the European Directive for Flood Management in a national framework;
	<p>Awareness</p>	<ul style="list-style-type: none"> • Warning codes for flood risk were issued; 	<ul style="list-style-type: none"> • Multiple warning codes for flood risk were issued; 	<ul style="list-style-type: none"> • In Romania the population from the risk areas was alerted via the RO-alert program (55 alerts);

				<ul style="list-style-type: none"> • Multiple warning codes for flood risk were issued;
	Preparedness	<ul style="list-style-type: none"> • Lack of proper measures for preparedness; 	<ul style="list-style-type: none"> • Lack of proper measures for preparedness; 	<ul style="list-style-type: none"> • Water evacuation from the Stânca-Costești accumulation lake weeks before the occurrence flood event; • Portions of the Prut river bank were consolidated with sandbags (20 000) and mobile panels (500 linear meters);