Rocznik LXX 2025 Zeszyt 3-4

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POWODZIE WRZEŚNIOWE W KARPATACH W ŚWIETLE ŹRÓDEŁ HISTORYCZNYCH

SEPTEMBER FLOODS IN THE CARPATHIANS IN THE LIGHT OF HISTORICAL DOCUMENTS

Introduction

In the present paper the Carpathians are understood as a part of the European mountain range situated in the south of Poland. It is a geographic unit where the highest precipitation totals in Poland occur. In the annual course, clearly higher precipitation is registered in the summer months (June-August), which in extreme cases reaches 800 mm per month. These pose the most serious flood hazard, especially in July (Niedźwiedź et al. 1999; Cebulak et al. 2011). In September even extremely high rainfall is about two times lower than in summer. Floods in September are an exceptionally rare event (Fig. 1).

Over the last hundred years heavy rainfall in September caused flood only three times: in 1931, 1996 and in 2007. The highest precipitation totals in the years with wet September registered by measurement stations exceeded 440 mm. The lowest monthly

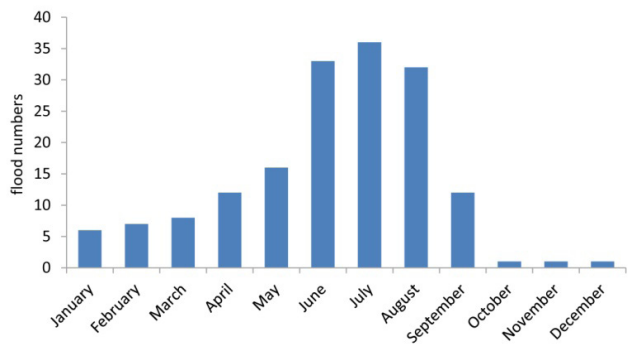

Fig. 1. Information on flood phenomena in respective months for the period 1500-2010 in the Carpathians. Source: own study based on data collected in the project Millennium.

 DOI: 10.32045/PG-2025-056

totals in September were only several millimeters, whereas in 1903 and 1969 some stations did not register any precipitation. Mean monthly total in September for the Carpathians area is about 70 mm. The highest daily precipitation values in September, which occurred during the periods of heavy rainfall and caused floods, exceeded 100 mm. Increases in September precipitation totals have been observed over the whole period of instrumental measurements. A clearly increasing trend was markedly pronounced at the turn of the 20th and 21st century. This trend was affected by very heavy precipitation in 1996 and 2007 (Fig. 4).

A detailed analysis comprised the areas of two catchments – the largest Carpathian tributaries of the Vistula River, i.e., the Dunajec (western part of the Carpathians) and the San (eastern part of the Carpathians) and in the first place, their mountain reaches, before the inflow to the existent artificial water reservoirs (Fig. 2). The catchments of the Dunajec and the San cover almost half of the whole area of the upper Vistula catchment.

Materials and methods

The issue of floods in mountain areas occupies a particular place in meteorological and hydrological research. It has been evidenced not only in Polish literature of the subject. The area of the Carpathians is characterized by diverse physical-geographical conditions, which favor posing the flood hazard. The research covers the spatial extent of floods, associated losses, and their frequency of occurrence. The area of the Carpathians is fed by mountain rivers, where heavy precipitation make their presence apparent immediately as floods (Kaczorowska 1933).

A clear division into the eastern and western part is visible in the Carpathians. The border between these two areas runs along the Biała Tarnowska River. Both areas are characterized by a slightly different water regime and therefore flood hazard. The Dunajec river represents the western part of the Carpathians. It is a Carpathian tributary to the Vistula, the most abundant in water. The catchment area covers mountain groups: the Tatra Mts. (with the highest peak – Rysy 2499 m a.s.l) and the Pieniny and Western Beskidy Mts. The highest precipitation totals are noted in the Tatra Mts. The catchment comprises also mountain basins, the Tatra Valley with Podhale region and Orawa-Nowy Targ Basin. Flowing through the hills of the Uplands, the Dunajec inflows into the Sandomierz Basin.

The San River is the largest tributary to the Vistula in the eastern part of the Carpathians. In its upper course, its catchment is of mountainous in character in the Bieszczady Mts. and there the highest precipitation are registered. In its further course the San flows through Uplands towards the Sandomierz Basin.

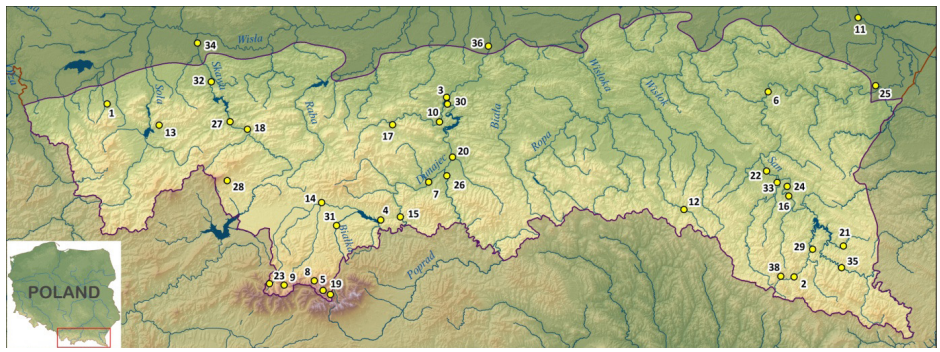

Fig. 2. The Carpathian stations mentioned in the paper.

The investigations derived from a database on precipitation and floods containing materials for the period 941-2010, originating from published sources and archival materials. All available historical data "natural proxy data" were used for the analysis of hydrological-meteorological events which occurred in 941-1850. Most of them have been collected in the implementation of the international project "The Millennium Project – European Climate of the Last Millennium" (Glaser et al. 2010). Information published in newspapers in Cracow and Lvov since 1846 was used to supplement the data for the early-instrumental period. The other part of the database was composed of measurement and observational data for the South Poland for the period of systematic instrumental observations since the second part of the 19th century. The events of precipitation and floods during this period were analyzed in detail. The characteristics were based on daily values of precipitation, daily water levels and flows obtained from the measurement stations of the Institute of Meteorology and Water Management, National Research Institute. Both their temporal and spatial distribution were presented (Tab. 1).

Despite a considerable number of publications concerning extreme precipitation events both in Poland and in other European countries, there is an urgent need for review papers addressing the cases not analyzed so far. These publications are crucially important in the context of exchanging information about the extreme phenomena, particularly in the border regions and for creating and verification of hydrological forecasting models.

Characteristics of extreme September hydrological-meteorological phenomena until 1850

The first information about heavy precipitation events which occurred in Poland in September have been appearing already since 1221. The sources mention floods in that

Table 1. The stations mentioned in the paper with reference to detailed case analysis (p – precipitation; w – water gauge).

Lp	Station	Type	H (m)	Lat	Lon	Catchment	Lp	Station	type	H(m)	Lat	Lon	catchment
1	Bielsko*	P	335	49°49	36°42′	Wisła	20	Nowy Sącz	PW	292	49°37′	20°42′	Dunajec
2	Cisna	P W	540	49°13′	22°20	San	21	Polana	W	450	49°18′	22°35′	San
3	Czchów	W	325	49°49′	20°40′	Dunajec	22	Olchowce	W	384	49°33′	22°13′	San
4	Czorsztyn	W	496	49°26′	20°19′	Dunajec	23	Polana Chochołowska	P	1147	49°14′	19°47′	Dunajec
5	Dolina Pięciu Stawów Polskich	P	1670	49°13′	20°03′	Dunajec	24	Postołów	W	310	49°29′	22°18′	San
6	Dynów	W	206	49°50′	22°14′	San	25	Przemyśl	P W	279	49°48′	22°46′	San
7	Gołkowice	W	312	49°33′	20°34′	Dunajec	26	Stary Sącz	W	296	49°34′	20°39′	Poprad
8	Hala Gąsienicowa	P	1520	49°15′	20°00′	Dunajec	27	Sucha *	P	337	49°45′	37°16′	Skawa
9	Hala Ornak	P	1109	49°14′	19°52′	Dunajec	28	Śmietanowa	P	785	49°33′	19°35′	Orawa
10	Jakubkowice	W	247	49°44′	20°37′	Łososina	29	Terka	P W	445	49°18′	22°26′	San
11	Jarosław*	PW	204	50°01′	40°21′	San	30	Tropie	W	233	49°47′	20°40′	Dunajec
12	Jaśliska	P	440	49°22′	21°49	Wisłoka	31	Trybsz	W	640	49°25′	20°07′	Dunajec
13	Kocierz Moszczanicki	P	410	49°44′	19°16′	Soła	32	Wadowice*	PW	268	49°53′	37°10′	Skawa
14	Kowaniec	W	640	40°30′	20°02′	Dunajec	33	Zagórz	W	299	49°30′	22°16′	San
15	Krościenko	W	454	49°27′	20°26′	Dunajec	34	Zator	W	221	50°00′	19°26′	Skawa
16	Lesko	PW	315	49°28′	22°19′	San	35	Zatwarnica	W	494	49°14′	22°33′	San
17	Łososina Górna	W	361	49°44	20°24′	Dunajec	36	Zgłobice	W	190	49°58′	20°52′	Dunajec
18	Maków Podhalański	P	360	49°44′	19°41′	Skawa	37	Żabno	W	184	50°08′	20°53′	Dunajec
19	Morskie Oko	P	1408	49°12′	20°05′	Dunajec	38	Żubracze	P	610	49°12′	22°16′	San

*by. zero meridian Fierro.

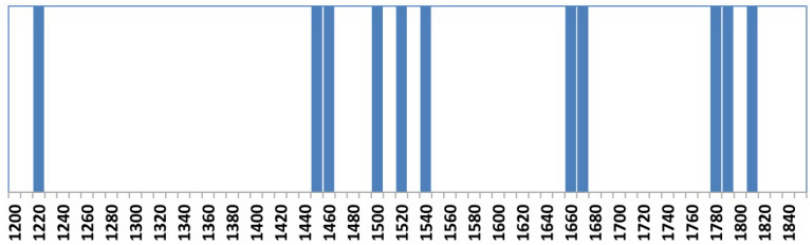

Fig. 3. Information about heavy precipitation or floods in September over the pre-instrumental period 1200-1850 in the Carpathians. Source: own study based on data collected in the project Millennium.

year caused by precipitation occurring since Easter until autumn (Girguś, Strupczewski 1965). The subsequent notices refer to a rainy autumn in 1451. Information about rains and flood in the Krakow environs concerns the period of summer and autumn 1468. September 1505 was described as wet, with rainfall occurring daily from April "…*Estas Nubium pluviosa fuit, ab Aprili ad Septemtrionem inclusive, fere quottidie pluens* (Girguś, Strupczewski 1965). In 1515 the chronicles recorded the Vistula overflow in Krakow, also in September "*„…bis circa festum S. Michaelis (29 September)"* (Girguś, Strupczewski 1965). Historical sources also provide information about a flood of 1541, which happened from 8-15 September on the Vistula and other rivers and were caused by heavy rains (Walawender 1932). The flood which occurred in Krakow in September 1661 is mentioned by Namaczyńska (1937), who quotes information from a manuscript by Marcin Goliński, a town councilor: "*16 Septembris in the morning high water came, overturned the ferry, overflew the banks and people were transported only by boats*". On the basis of the same source, previous information refers to the "high water (in Krakow)" on 20 and 26 August of the same year (Namaczyńska 1937). In September 1675 flood caused by downpours covered the western part of the Carpathian catchment of the Upper Vistula. According to the description recorded by the Bernardine order in Alwernia, the Vistula and the Skawa overflew the banks and destroyed the environs of Zator and Spytkowice, but also Krakow and its environs. "Heavy rainfalls in 1675 had fatal results for agriculture in Poland. Rains, like the previous year, falling almost every day during summer, but particularly in autumn brought damage to cereals causing crop failure…" (Namaczyńska 1937). Downpours on 1 and 2 September 1785 in the San catchment destroyed the Dukla road, which was under construction at that time (Szewczuk 1939). The next year, 1786 rainfall lasted from spring to autumn and "*Galicia was threatened with poverty due to constant rains making impossible harvest, damaging cereals in the field and animal feed …*" (Szewczuk 1939). Subsequent information concerns flood in September 1813. Constant downpours lasting from 15 June to mid-September caused a catastrophic flood in South Poland already by the end

of August. All Carpathian tributaries of the Vistula River overflowed (Szewczuk 1939). In 1932 the flood of 1813 was reported as follows: "… *the most severe known summer flood in the whole Vistula catchment happened by the end of August and beginning of September 1813*" (Szewczuk 1939).

The accumulated "proxy" data derived from the available historical sources show that the most numerous descriptions of heavy rainfalls, which occurred in September in the Carpathians, come from the years 1450-1550, i.e., from the period preceding "Little Ice Age" (Fig. 3), (Limanówka 1999, 2001; Bokwa et al. 2001).

Characteristics of extreme September hydrological-meteorological phenomena for the period of instrumental measurements and observations conducted in 1851-2010

Information about rainfall in September comes from the period of systematically conducted instrumental observations. The highest mean monthly precipitation exceeding 170 mm (mean for the Carpathians area) occurred in the years of 1876, 1931, 1996, 2007 and as extreme events, they were subjected to a detailed analysis in the presented paper.

The lowest September precipitation in the years 1903, 1959, 1961 and 1969, whose value did not exceed 20 mm are in contrast to them.

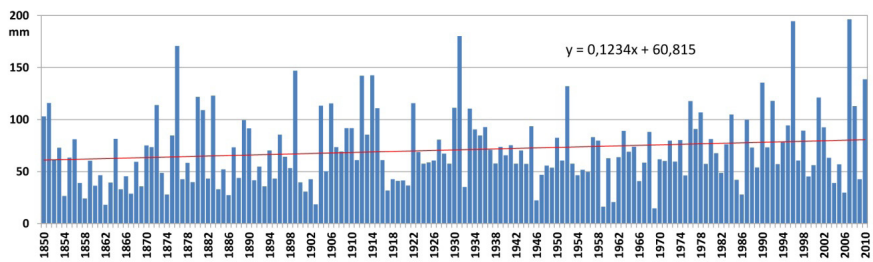

Fig. 4. Course of September totals in the Carpathians over the period of instrumental measurements 1850-2010 and the trendline with equation. Source: own study based on data collected in the project Millennium and archive data IMGW-PIB.

Flood in September 1876

In 1876 precipitation was registered in South Poland by a dozen or so operating stations. September precipitation totals in the western part of the Carpathians reached

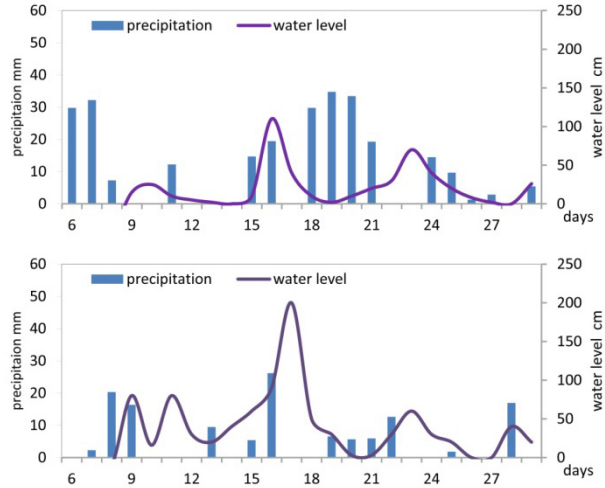

Fig. 5. Course of daily precipitation registered by Wadowice station and water levels (Zator) (top); course of daily precipitation registered by Sucha station and water levels (Wadowice) (bottom) on the Skawa River (western part of the Carpathians) in September 1876. Source: data from publication Physiographic Commission reports in 1876, Galicia Climatographic materials.

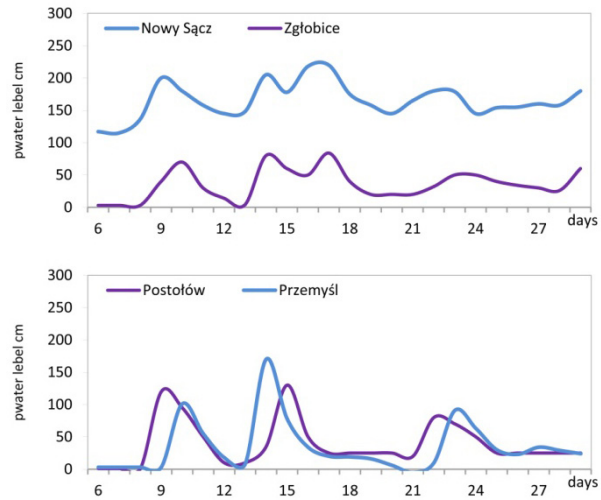

Fig. 6. Hydrograph of daily water levels in the Nowy Sącz and Zgłobice profiles on the Dunajec and in Postołów and Przemyśl profiles on the San in September 1876. Source: as in figure 5.

300 mm (294 mm in Wadowice). Precipitation occurred intermittently during the period from 6 to 29 September (Fig. 5). Maximum daily rainfall in this month exceeded 40 mm. The highest daily rainfall 43.4 mm was noted on 16 September in Bielsko.

High rainfall caused elevated water level in rivers. Increases in water levels in the eastern part of the Carpathians occurred on 14 and 15 September. Two considerable flood wave peaks occurred in the San upper course after heavy rainfalls on 9 and 14 September. In the western part, higher water levels were noted on 16 and 17 September. Water levels measured on the Dunajec, by the water gauge in Nowy Sącz on 17 September exceeded 200 cm (Fig. 6).

Flood in September 1931

The flood which occurred in September 1931 was directly caused by precipitation which occurred on 18-25 September, exceeding 250 mm in the western part of the Carpathians and even 300 mm in the Tatra Mts. They were preceded by long-term rainfall, particularly in the second and third decade of August (Langer 1952). Over 500 mm of rain fell in the Carpathians in August and September, exceeding 600 mm in the high mountain areas and locally even over 700 mm. Precipitation total registered in August and September on the Hala Gąsienicowa in the Tatra Mts. was 776.9 mm (Fig. 8).

The period of heaviest rainfall started on 11 September. After a two-day break on 15 and 16, strong rains lasted until the end of the month.

The most intensive precipitation occurred on 23 and 24 September causing a rapid elevation of the water levels (Fig. 7). The flood culmination was noted on 25 September. On the Carpathian tributaries of the Vistula in the western part of the Carpathians, including the Dunajec, water level approached the highest values (Fig. 9). The water gauge Żabno on the Dunajec river showed the highest water level 550 cm on 26 September 1931, at the absolute maximum of that time – 550 cm, registered on 6 May 1909. The San

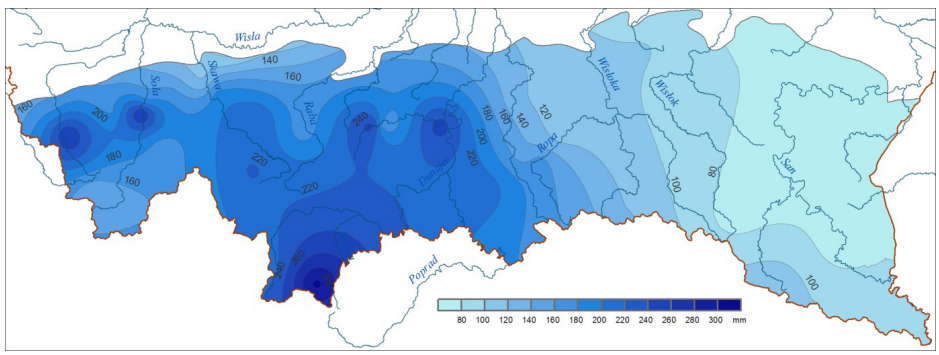

Fig. 7. Precipitation totals on 18-25 September 1931 in the Carpathians. Map based on 73 rainfall stations in the Upper Vistula basin. Source: own study based on archival data IMGW-PIB.

River (eastern part of the Carpathians) had a much smaller contribution to the flood. On 27 September in Przemyśl the water level was 172 cm at the absolute maximum of 500 cm of 3 August 1913.

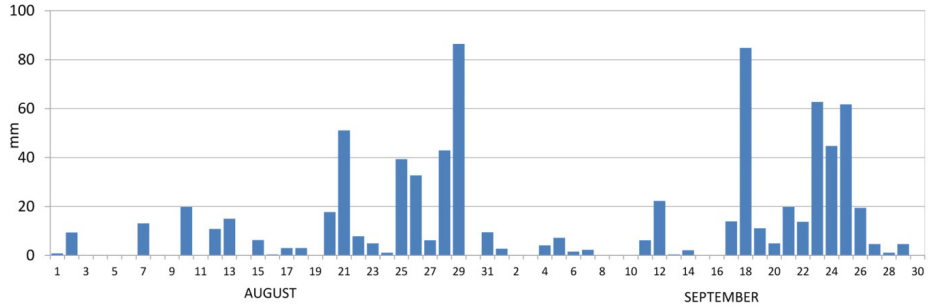

Fig. 8. Course of daily precipitation in August and September 1931 registered at the Hala Gąsienicowa station. Source: own study based on archival data IMGW-PIB.

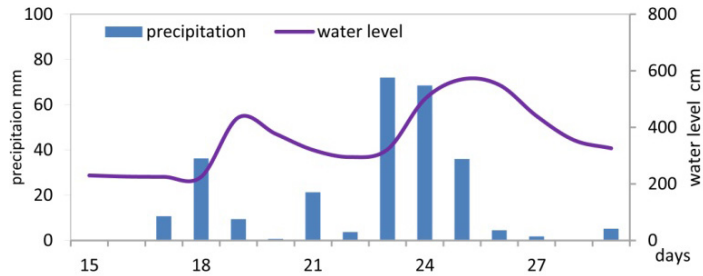

Fig. 9. Daily precipitation course at the Łososina Górna station and hydrograph of water levels in the Tropie profile on the Dunajec (The Dunajec catchment). Source: Hydrographic Yearbook 1931, Vistula Basin.

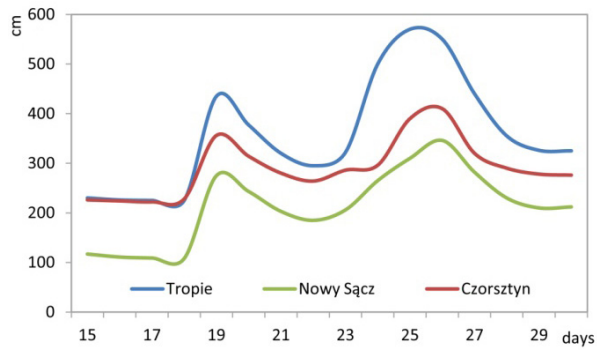

Fig. 10. Hydrographs of daily water levels in the Czorsztyn, Nowy Sącz and Tropie profiles on the Dunajec in September 1931. Source: Hydrographic Yearbook 1931, Vistula Basin.

Flow volumes measured on the Dunajec in Nowy Sącz on 28 September and 30 September 1931 were respectively 256.30 m^3/s at the water level 218 cm and 218.40 m^3/s at the water level 210 cm (Fig. 10).

Exceptionally high-water levels in September 1931 caused a flood with disastrous results. Floods on the rivers Soła, Skawa and Dunajec in the western part of the Carpathians were exceptionally dangerous and violent (Ilustrowany… 1931). The water levels exceeded average values for September, reaching the ones hardly ever noticed in this month.

Flood in September 1996

The subsequent September flood occurred only 65 years later, in 1996. Monthly precipitation totals in September 1996 in the Tatra Mts. reached 400 mm (445 mm on the Polana Chochołowska) whereas in the Soła and Skawa catchments exceeded 300 mm. Throughout the area of the Carpathians they considerable exceeded mean multi-annual values (Cebulak, Niedźwiedź 1998).

Precipitation started already at the turn of August and September, then returned on 6 and 7 of September and covered the whole Carpathians. Daily totals in September 1996 on many stations exceeded 100 mm and reached the highest values for that month registered during the period of instrumental measurements. On 6 September high daily precipitation occurred in the eastern part, where they exceeded 80 mm whereas locally even 100 mm of rain fell (Jaśliska 105.7 mm, Cisna 102.0 mm).

As a result of heavy precipitation all rivers swelled. In the eastern part of the Carpathians flood warning points were exceeded and, on some watercourses, even the danger points. The areas of communes situated on the San River were flooded.

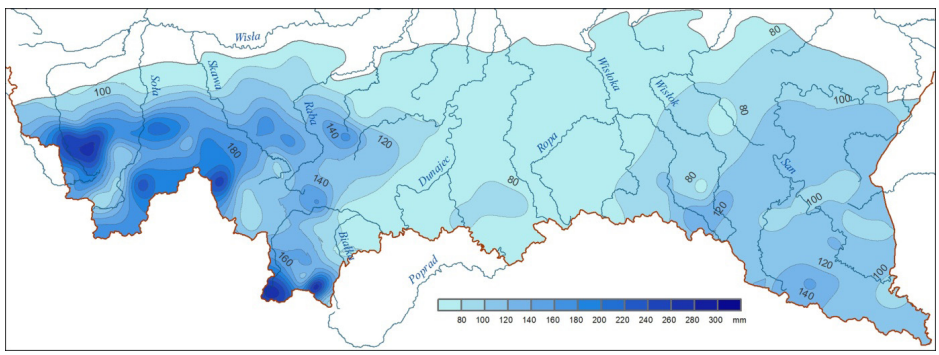

Fig. 11. Precipitation totals on 4-9 September 1996 in the Carpathians. Map based on 294 rainfall stations in the Upper Vistula basin. Source: own study based on archival data IMGW-PIB.

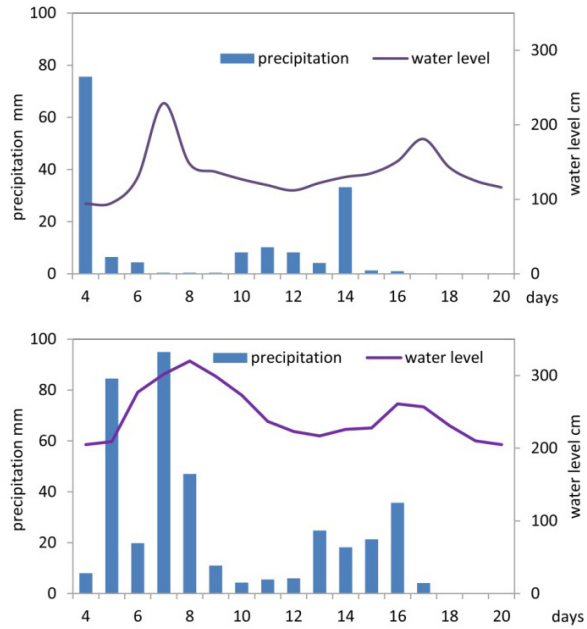

Fig. 12. Course of daily precipitation and hydrograph of daily water levels at Terka station and in the Terka profile on the San – September 1996 (top). Course of daily precipitation in September 1996 on the Polana Chochołowska in the Tatra Mts, and a hydrograph of daily water levels in the Kowaniec profile on the Dunajec – September 1996 (bottom). Source: own study based on archival data IMGW-PIB.

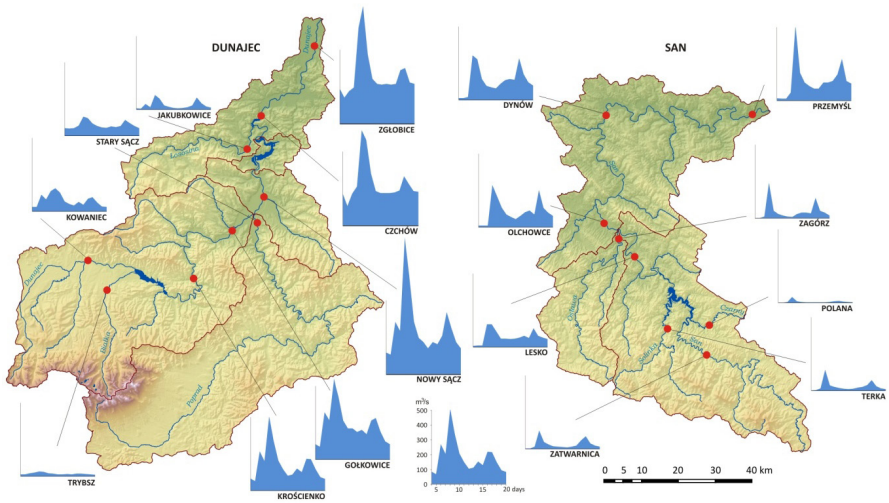

Fig. 13. Hydrographs of flows in the gauging profiles on the Dunajec (left) and on the San (right) in September 1996. Source: own study based on archival data IMGW-PIB.

On 7 September 1996 the zone of heavy rains moved to the west, where the heaviest daily rainfalls in many places exceeded 100 mm (Śmietanowa 143.5 mm, Kocierz Moszczaniecki 129.2 mm).

The other tributaries of the Vistula also swelled. Both warning states and danger points were exceeded. The Dunajec reached the highest water level along the reach from its headwater to Krościenko. On 8 September the highest water level in the Kowaniec profile was 320 cm, in the Nowy Sącz profile was 332 cm and in the Zgłobice profile 410 cm.

The totals for the period of heavy rainfall on 4-9 September 1996 in the western part of the Carpathians exceeded 200 mm. On the Polana Chochołowska in the Tatra Mts, 263.5 mm was registered. In the eastern part of the Carpathians, in the San catchment precipitation totals were lower. They exceeded 100 mm at a majority of measurement stations in this region and locally reached even 140 mm (Cisna 142 mm).

Flood in September 2007

In September 2007, precipitation totals in the Carpathians considerably exceeded the standard. The highest monthly totals in September 2007 of over 300 mm occurred in the Tatra Mts. (342.2 mm on the Polana Chochołowska, 338.4 mm on the Hala Ornak, 354 mm on the Hala Gąsienicowa, 314.4 mm in Morskie Oko) and the maximum total 405.4 mm was noted in the Dolina Pięciu Stawów Polskich.

Particularly heavy downpours on 4-12 September, with daily total exceeding 60 mm caused a rapid increase in water levels in the mountain tributaries to the Vistula River. Like in 1996, the zone of heavy rains was moving from the east to the west. On 4 September the heaviest precipitation covered the eastern part of the Carpathians, reaching the maximum of 72.8 mm at the Żubracze station in the Bieszczady Mts.

Over the next days the heavy rainfall zone moved to the west reaching the maximum – 90.4 mm on 6 September in Maków Podhalański and 89.3 mm on 7 September in Kocierz Moszczanicki. In the Tatra Mts. the highest value, over 60 mm was registered on 7 September.

The totals for the period of heavy rainfall on 4-12 September 2007 in the Dunajec catchment reached 300 mm (the Tatra Mts.), on many stations in the San catchment exceeded 200 mm (Fig. 15).

Following the heavy rainfalls, water level in rivers raised considerably. Warning states and danger points were exceeded. Houses were inundated, roads and farms were flooded. On the San, in the eastern part of the Carpathians, water levels and flows increased considerably following the rainfall of 11 September 2007. They were higher than

the first culmination of 5 September. Water levels in the Dunajec exceeded the danger points, were increasing slightly slower than on the San but since 5 September maintained high values for a longer period (Fig. 16).

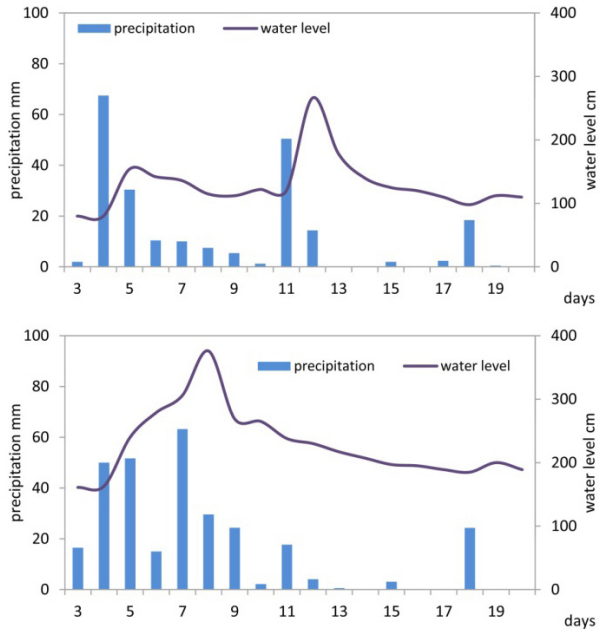

Fig. 14. Course of daily precipitation and hydrograph of every day water levels at the Terka station (eastern part of the Carpathians) in September 2007 (up). Course of daily precipitation registered at the Hala Gąsienicowa station and hydrograph of everyday water levels in the Nowy Targ profile (western part of the Carpathians) in September 2007 (bottom). Source: own study based on archival data IMGW-PIB.

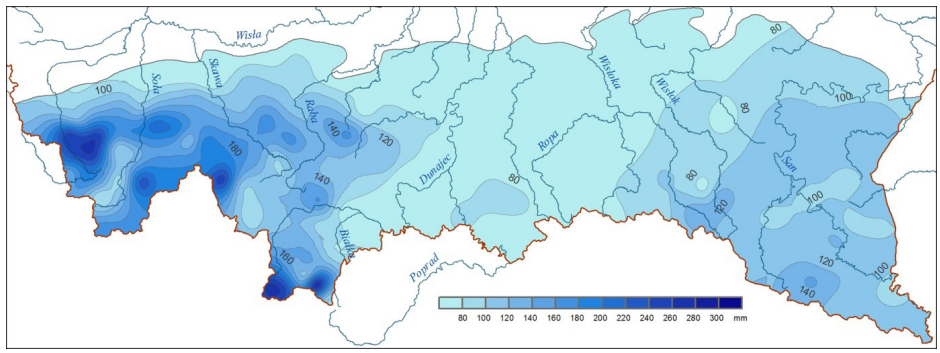

Fig. 15. Atmospheric precipitation totals on 4-12 September 2007 in the Carpathians. Map based on 195 rainfall stations in the Upper Vistula basin. Source: own study; archival data from IMGW-PIB.

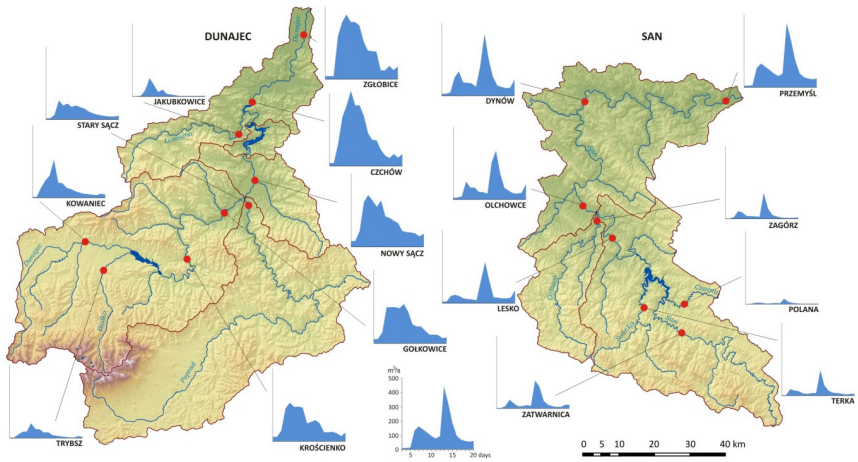

Fig. 16. Hydrographs of flows in gauging profiles on the Dunajec (left) and on the San (right) in September 2007. Source: own study based on archival data IMGW-PIB.

Conclusion

Analysis of the accumulated data for the pre-instrumental period and for the time of systematic measurements revealed a clear increasing trend of precipitation in the Carpathians in September, particularly visible at the turn of the 19th and 20th century. The increasing trend of September precipitation is significant on $\alpha = 0.05$ level. A majority of information about September floods classifies them genetically as autumn floods originating due to long-term rainfall. The floods in 1996 and 2007 break this pattern because they occurred in the atmospheric pressure systems characteristic for the summer period. Heavy summer rainfalls in the Carpathians are caused by low-pressure centers moving from above the Mediterranean and northern Italy along Vb tract (according to Van Bebber nomenclature), over Italy, Hungary and Poland towards north-east, sometimes over the Black Sea. Such system of atmospheric pressure leads to an advection of humid air masses from the north and occurrence of heavy several-day long rains in the Carpathians, intensified by the orography and usually causing disastrous floods. In the years 1996 and 2007 precipitation in South Poland occurred in a typical summer situation connected with low barometric pressure above the Ukraine and Belarus. Intensive inflow of cool and humid arctic air and cumulation of air masses on the northern slopes of the Carpathians caused a long-term orographic rainfall. Heavy downpours in September were particularly significant over the last years in the eastern part of the Carpathians, indicating a low increasing trend of precipitation totals in this part the Carpathian Vistula catchment.

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S t r e s z c z e n i e

Wrześniowe opady atmosferyczne w regionie Karpat, położonym w południowej Polsce, charakteryzowały się dużą zmiennością w czasie. Analiza danych z okresu przedinstrumentalnego oraz z późniejszych, systematycznych obserwacji meteorologicznych wykazała dodatni trend sum opadów we wrześniu, najbardziej wyraźny na przełomie XX i XXI wieku. Większość informacji dotyczących powodzi wrześniowych pozwala na ich genetyczną klasyfikację jako powodzi jesiennych, powstałych w wyniku długotrwałych opadów atmosferycznych. Powodzie z września 1996 i września 2007 roku stanowiły odstępstwo od tego schematu, gdyż były związane z układami barycznymi typowymi dla okresu letniego. Najwyższe średnie miesięczne sumy opadów wystąpiły w latach 1876, 1931, 1996 oraz 2007 i jako przypadki ekstremalne w niniejszej pracy zostały poddane szczegółowej analizie.

Słowa kluczowe: opady atmosferyczne, Karpaty, powodzie, historyczne dane klimatyczne.

S u m m a r y

September rainfalls in the Carpathians region located in the South Poland were characterized by a high variability in time. Analysis of the data collected from the pre-instrumental period, and systematic measurements showed positive trend of rainfalls in September, most visible at the turn of the 20th and 21st century. Most of the information about the September floods genetically classifies them as autumn floods, as a result of long-term rainfalls. Floods in September 1996 and September 2007 were breaking this pattern, since it occurred at atmospheric pressure systems typical of the summer

period. The highest monthly mean precipitation occurred in the years: 1876, 1931, 1996, 2007 and as extreme cases were subject to detailed analysis in this paper.

Key words: precipitation, Carpathians, floods, historical climate data.