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Flash floods in the Tatra Mountain streams: Frequency and triggers

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HIGHLIGHTS

- Flash floods represent a common natural hazard in the Tatra Mountains.
- Tree ring analysis is the most suitable approach in mountain forested areas.
- We report a flash flood chronology from 4 ungauged catchments covering the last 148 years.
- We identify the common meteorological conditions acting as triggers of flash flood events.

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ABSTRACT

Flash floods represent a frequently recurring natural phenomenon in the Tatra Mountains. On the northern slopes of the mountain chain, located in Poland, ongoing and expected future changes in climate are thought to further increase the adverse impacts of flash floods. Despite the repeat occurrence of major floods in the densely populated foothills of the Polish Tatras, the headwaters have been characterized by a surprising lack of data, such that any analysis of process variability or hydrometeorological triggers has been largely hampered so far. In this study, dendrogeomorphic techniques have been employed in four poorly-gauged torrential streams of the northern slope of the Tatra Mountains to reconstruct temporal and spatial patterns of past events. Using more than 1100 increment cores of trees injured by past flash floods, we reconstruct 47 events covering the last 148 years and discuss synoptic situations leading to the triggering of flash floods with the existing meteorological and flow gauge data. Tree-ring analyses have allowed highlighting the seasonality of events, providing new insights about potential hydrometeorological triggers as well as a differentiating flash flood activity between catchments. Results of this study could be useful to design future strategies to deal with flash flood risks at the foothills of the Polish Tatras and in the Vistula River catchment.

1. Introduction

Flash floods in mountain catchments are typically localized but highly variable hydrological processes characterized by a large water-sediment discharge in a short time period causing large economic losses and fatalities (Borga et al., 2008, 2014). Their spatio-temporal analysis requires, hence, an accurate definition of rainfall and discharge variables (Tarolli et al., 2012; Viglione et al., 2010). However, the scarcity of instrumental data and basic environmental information in these environments typically leads to considerable uncertainties (Brázdil et al., 2006), hampering our understanding of climate–process linkages and consequently the assessment of existing hazards (de Jong et al., 2009; Merz et al., 2014).

The most accurate alternative to overcome this lack of data in forested mountain catchment is the paleohydrology analysis based on tree-ring data (i.e., dendrogeomorphic methods, Stoffel et al., 2010; Ballesteros-Cánovas et al., in review). Highly-resolved tree-ring records from trees affected by flash floods allow tracking of past process activity with high spatial and temporal accuracy (Stoffel et al., 2006; Schneuwly-Bollschweiler et al., 2012). Over the last decades, the application of dendrogeomorphic analysis in paleohydrology studies has primarily focused on the analysis of flash flood histories at the level of specific catchment (e.g., Astrade and Bégin, 1997; St. George and Nielsen, 2003; Zielonka et al., 2008; Ruiz-Villanueva et al., 2010; Ballesteros-Cánovas et al., in press; Šilhan, 2014), and, in combination with hydraulic models, for the estimation of peak discharge (Yanosky and Jarrett, 2002; Ballesteros-Cánovas et al., 2011a,b). Dendrogeomorphic investigations are also of value at larger scales (Procter et al., 2011; Šilhán, in review), even more so as it is generally recognized that catchments located within homogenous regions may lead to varied hydrological responses. Such

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physical differences in soil and geomorphology may hinder the transferring of knowledge from one catchment to another even within the same region (Merz and Blöschl, 2005; Blöschl, 2006), thereby limiting the specific understanding of flash flood processes. Beyond the interest of tree-ring analysis in comparative hydrology (Blöschl, 2006), flash flood studies at regional scales also allow a better understanding of the mechanisms that determine the long-term history of these processes in terms of magnitude, frequency, and seasonality — as well as climate–flood linkages at the regional scale (Merz et al., 2014).

Based on the above considerations, we here present a spatio-temporal reconstruction of past flash flood activity in four selected, poorly gauged mountain streams located on the northern slope of the Tatra Mountains (South Poland). Based on the analysis and dating of flood damage in *Picea abies* (L.) Karst. and *Abies alba* Mill.,we reconstruct flash flood occurrence during the last 148 years and provide frequencies of events. Based on the analysis of local meteorological data, we also determine hydrometeorological threshold related with the reconstructed flash flood and discuss the hydrologic behavior of this region during intense rainfall events.

2. Study area

The study was conducted in four streams draining the northern slope of the Tatra Mountains (Tatras), the highest massif of Carpathian arc (max. elevation 2655 m a.s.l.; Fig. 1). The Tatras have a crystalline and metamorphic core covered by nappes of Mesozoic sedimentary rocks. During the Pleistocene, the Tatras underwent at least three glaciations, which strongly reshaped the region, left conspicuous relief forms and typical moraine deposits.

Climate of the Tatras is influenced by regional air mass oscillations and local topography, with a predominance of polar marine (65% of annual incidents) and polar continental airmasses (25%; Niedźwiedź et al., 2014). The Tatras also form a considerable barrier for air mass movements resulting in heavy rainfall events with 24-h sums of up to 300 mm (30 June 1973; Niedźwiedź, 2003). Annual precipitation varies from 1100 mm at the foothills (Zakopane, 844 m a.s.l.) to 1660 mm at timberline (Hala Gąsienicowa, 1550 m a.s.l.) and 1721 mm on the summits (Lomnicky stit, 2635 m a.s.l.). The most effective precipitation events that result in flash floods are largely concentrated to the summer months as shown in Fig. 2.

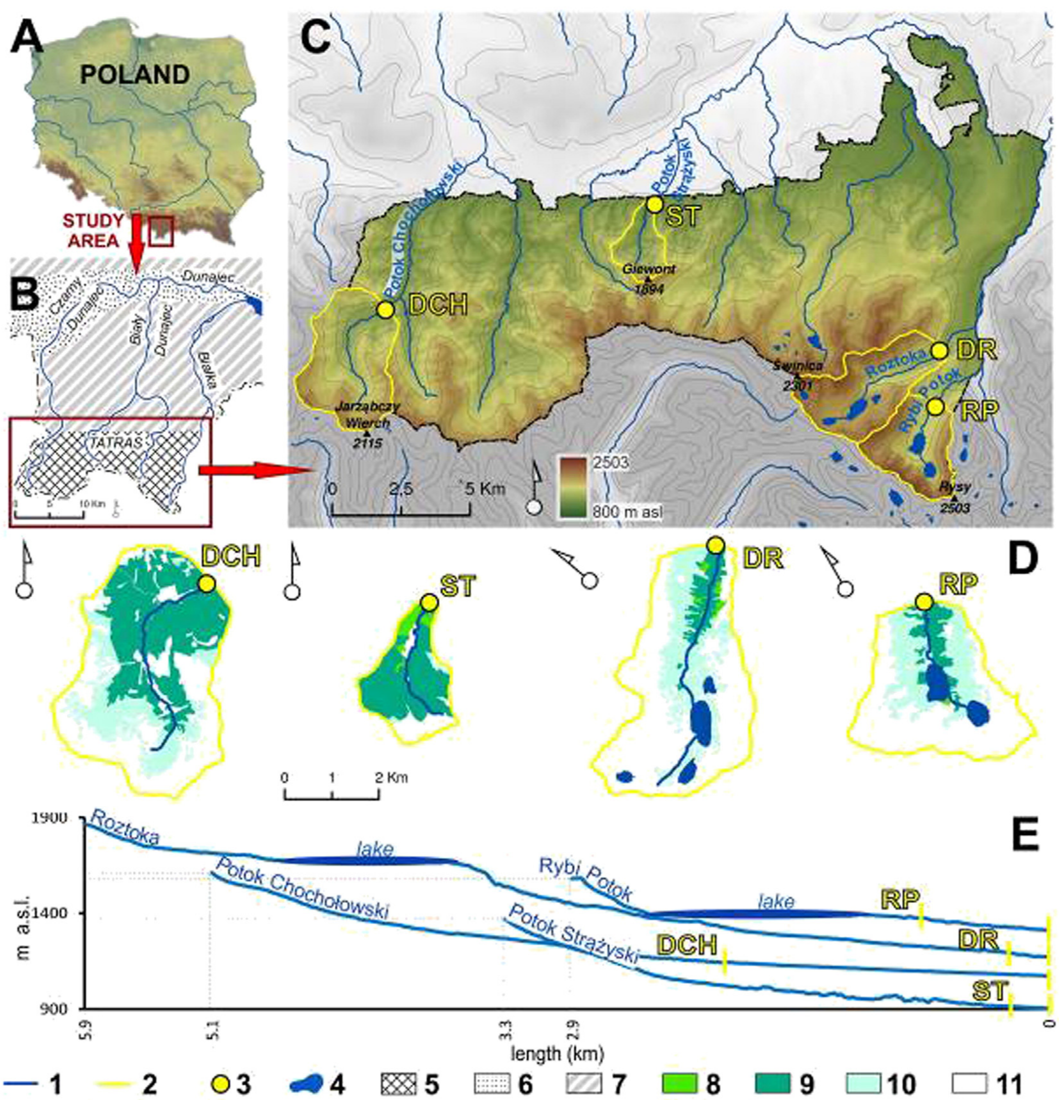

Fig. 1. (A) Location of the study site in Poland. (B) Overview of main rivers draining the Tatra Mountains. (C) Location of the investigated catchments and (D) their land-use characteristics. (E) Altitudinal profiles of the studied streams. Legend: 1 — streams; 2 — investigated catchments; 3 — dendrogeomorphic study sites (RP = Rybi Potok, DR = Dolina Roztoki; DCH = Dolina Chochołowska, ST = Strążyski Potok); 4 — lakes (WSP — Wielki Staw Polski Lake, MO — Morskie Oko Lake); 5 — high mountains; 6 — intramontane and submontane depressions; 7 — mountains of intermediate and low height; 8 — deciduous forest; 9 — coniferous forest; 10 — dwarf pine; 11 — low vegetation.

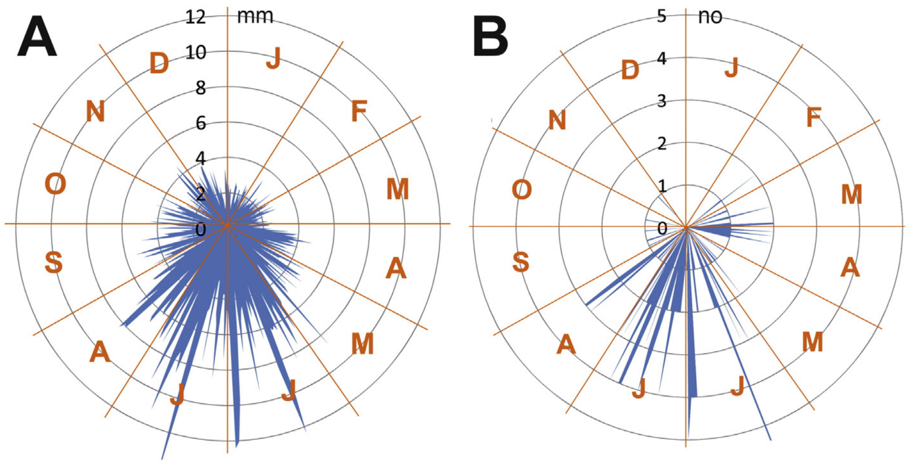

Fig. 2. Hydrometeorological situation at the northern foothills of the Tatra Mountains: (A) average precipitation (cm) from 19 meteorological stations (28 years: 1954–1982); (B) number of water stage larger than 1.5 times averages in each day of the year as measured at Nowy Targ water gauge for the period 1898–1983.

Vegetation is composed by a sequence of five climatic vegetation belts, with timberline located up to ~2200 m a.s.l., as the most distinct natural boundary (Hess, 1965; Niedźwiedź, 1992). The study reaches within the four streams are located in cool (Rybi Potok, Roztoka, Chochołowski Potok) and temperate cool belts (Strążyski Potok) with mean annual temperatures of 2–4 °C, and 4–6 °C, respectively (Hess, 1974). The subalpine forests of the three higher sites are dominated by Norway spruce (*Picea abies* (L.) Karst.), whereas the banks of Strążyski Potok comprise of mixed forest with large contribution of *P. abies*, and Silver fir (*Abies alba* Mill.). The main characteristic of the study reaches is summarized in Table 1. Noteworthy, the sector investigated at Rybi Potok is located 1.5 km below the Morskie Oko Lake, a 9,935,000 m^3 volume glacial lake. The channel is formed in gravel loamy moraine deposits, which cover granititic and pegmatitic bedrock (Bac-Moszaszwili et al., 1979). Roztoka stream also originates from a lake of slightly bigger size and shows comparable geology (Wielki Staw Polski Lake, 12,967,000 m^3), but the study reach is located at 3.3 km from the water body. The study reach of Strążyski Potok stream is located close to Zakopane City. The catchment area is considerably smaller and built by sedimentary, mainly carbonatic, rocks. The study reach at Chochołowski Potok stream is located in the westernmost part of the Polish Tatras and characterized by crystalline metamorphic and granitic rocks covered by moraine deposits.

The study region has a long history of land use, starting with Medieval ore mining, through pasturing to intense logging in the 18th and 19th centuries. Although the alpine pastures were usually separated from timberline by a *Pinus mugo* belt, the forest has been used intensively for grazing, with peaks in grazing pressure during the 19th and mid-20th century. The abundance of livestock, mainly sheep and cattle (up to 40,000) has changed the characteristics of soil, vegetation, and forest and has ultimately led to an increase in flood risk. In addition, the region has been affected by intensive logging associated with steel industry in the second half of the 18th century. Most beech forests of the montane zone has been harvested during this period and was replaced by spruce, subsequently the subalpine forest supplied the charcoal production necessary for blast furnaces. The Tatra National Park was enacted in 1954 but pasturing locally continues until 1978 and logging is also recently partially permitted. The long history of wood exploitation – as a fuel for the local industry and building material – has substantially changed the character of forests in the study region. The use of the valley floor and stream channels as transportation routes furthermore intensified this process.

Table 1
Main catchment characteristics.

Aspect		DCH	ST	DR	RP
		NNW	NNW	NW	NW
Area (km^2)		13.84	3.69	11.79	8.64
Perimeter (km)		15.53	8.77	16.60	12.81
Gravelius index		1.17	1.28	1.35	1.22
Catchment length (km)		4.70	3.00	5.45	3.70
Concentration time (h)		0.43	0.26	–	–
Total relief (m)		997	990	1048	1280
Relief ratio		0.20	0.30	0.18	0.44
Land cover	Forested	5.51 (40%)	2.89 (79%)	1.02 (9%)	0.88 (10%)
(km^2, %)	Un-forested	5.64 (40%)	0.71 (21%)	7.37 (62%)	4.68 (55%)
	Dwarf pine zone	2.74 (20%)		2.80 (24%)	2.52 (29%)
	Glacier lakes			0.63 (5%)	0.52 (6%)
Geological characteristics		Crystalline (80%), moraine deposits	Carbonates (100%)	Crystalline (70%), moraine deposits (30%)	Crystalline (80%), moraine deposits (20%)
Stream length (km)		5.1	3.3	5.9	2.9
Slope (%)		11	14	12	9
Highest point (m a.s.l.)		2115	1894	2301	2499
Length of the sector (m)		1890	215	175	830
Drained density		0.36	0.89	0.50	0.33

3. Methodology

3.1. Sampling procedure

The analysis of flash floods focused on representative upstream sectors of those rivers draining the northern foothills of the Tatra Mountains. Study site selection was based on the dendrogeomorphic potential of river reaches and limited to areas in which signs of human activity or geomorphic processes other than flash floods (e.g., landslides, snow avalanches) were minimal. Based on these criteria, 6 river reaches were selected in the Chochołowski Potok (DCH sector), Strążyski Potok (ST), Roztoka (DR), and Rybi Potok (RP) streams.

In these reaches, all trees presenting visible flood damage were sampled following standard dendrogeomorphic sampling procedures (Stoffel and Corona, 2014). A minimum of two increment cores was extracted per tree, one next to the overgrowing callus pad and one in the opposite direction (Schneuwly et al., 2009a). Additional cores, wedges or even cross-sections were occasionally taken from dead trees. Undisturbed specimens of *P. abies* and *A. alba* were also sampled to build 5 references chronologies. Finally, for each tree, reference parameters such as tree height, remarkable growth characteristics, diameter at breast height (DBH), photographs and tree locations (GPS) were also collected in the field.

3.2. Analyses of samples

Samples were mounted on woody supports before they were sanded and polished (Stoffel and Bollschweiler, 2009). All samples were scanned with a resolution of 3200dpi and ring widths recorded with the imagery analysis software CooRecorder and CDendro (Cybis Elektronik & Data AB; Larsson, 2003a,b). The reference cores were cross-dated against site chronologies employing both visual and statistical techniques. Mistakes and grow discrepancies (i.e., missing, wedging, and false rings) were identified and corrected. The same approach was used to cross-date cores of disturbed trees.

Growth disturbances (GD) were analyzed and dated under a stereomicroscope following Stoffel et al. (2006), with a focus on injuries induced by flash floods as well as on the intensity (i.e., strong, medium and weak; Stoffel and Corona, 2014) of related tangential rows of traumatic resin ducts (TRD; see Bollschweiler et al., 2008; Stoffel and Hitz, 2008; Schneuwly et al., 2009a,b for details). Other GD such as abrupt growth suppression or release as well as the occurrence of compression wood was only used to support the interpretation of events. For each year, the number of GD, their nature and intensity as well as the age of trees was displayed in ArcGIS.

The definition of flash flood events was based on the weighted index as defined by Kogelnig-Mayer et al. (2011). This index considers the number of GD and the intensity of TRDs observed in a specific year and the total number of trees available for the reconstruction. The threshold needed to distinguish flash flood signals from noise was set to $Wit \geq 0.5$ and $GD \geq 2$, as suggested in previous work for hydrogeomorphic processes (Schneuwly-Bollschweiler et al., 2013).

3.3. Hydrometeorological analysis

Precipitation data from the closest meteorological stations of each river reach (Fig. 3) was then analyzed to identify potential hydrometeorological triggers of past flash floods.

Analysis included a total of 38 stream gauges and 21 meteorological stations, as shown in Fig. 4. As the nearest stations yielded the most valuable results, we primarily focused analysis on Polana Chochołowska (49.2° N., 19.8° E.; 1150 m a.s.l.; time series: 1971–1984); Dolina Chochołowska (49.3° N., 19.8° E.; 920 m a.s.l.; time series: 1954–1966, 1968–1969); Morskie Oko (49.2° N., 20.1° E.; 1400 m a.s.l.; time series: 1954–2004); and Zakopane (49.3° N., 20.0° E.; 857 m a.s.l.; time series: 1954–2011).

Based on existing data on the seasonality of (flash) floods in the wider study region (Parajka et al., 2010; Niedźwiedź et al., 2014;

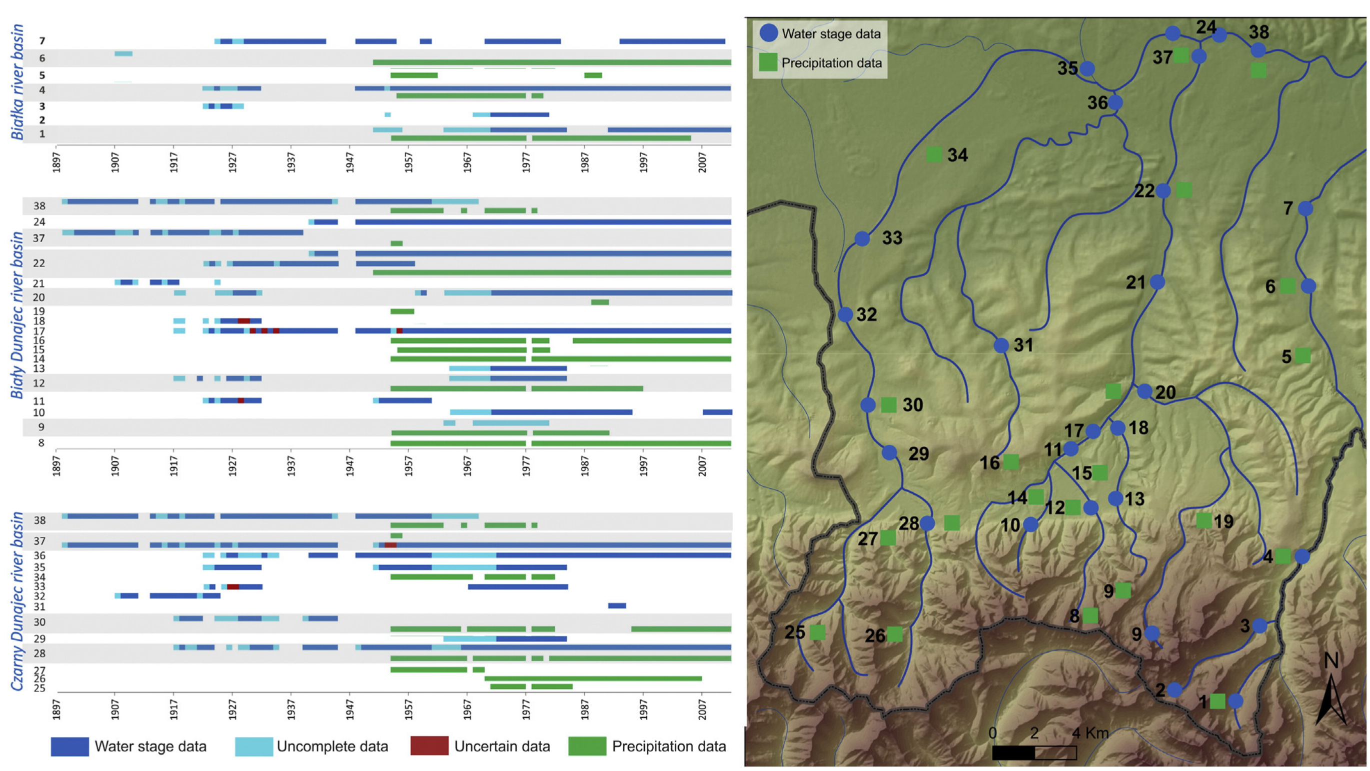

Fig. 3. Spatial and temporal distribution of meteorological and flow gauge dataset on the northern slope and foothills of the Polish Tatra Mountains.

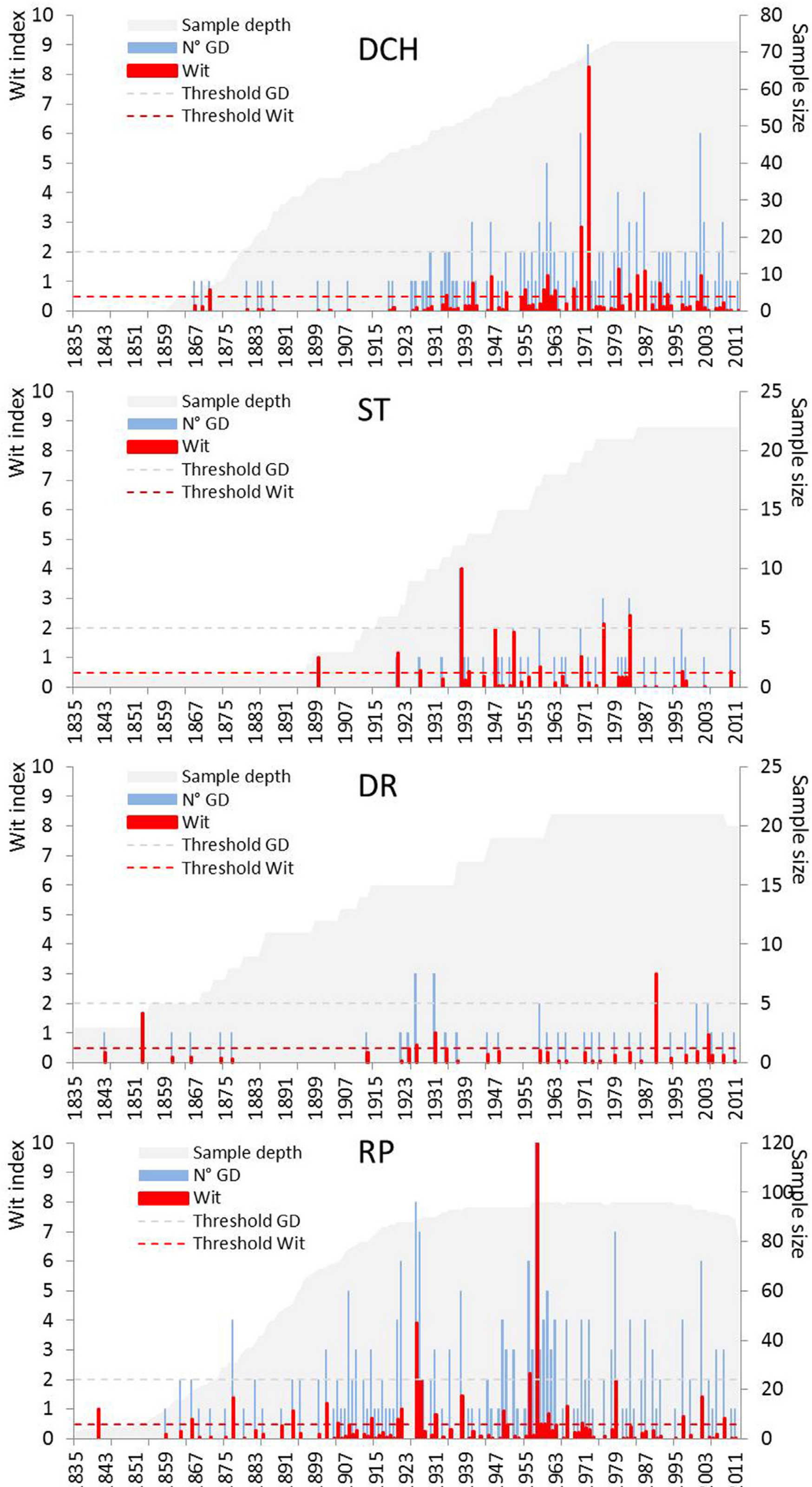

Fig. 4. Growth disturbances in trees observed at the different river reaches are presented with a weighted index, the number of growth disturbances and the sampled size (i.e., the number of trees living in each year of the reconstruction).

Ruiz-Villanueva et al., 2014), we based our assessment on the assumption that past flash floods have been triggered by intense prolonged orographic precipitation events. Consequently, the focus of the meteorological data was on 1-, 3-, and 5-day accumulated precipitation totals (with positive temperatures in the source areas of flash floods) and for the months comprised between April and October. In addition, to detect spatial patterns of triggering rainfalls, we calculated coefficients of variation (CV) from all available rainfall datasets from the study regions as well as plotted differences in 3-day precipitation events higher than 100 mm combined with water stage values higher than 150% of the average.

4. Results

4.1. Disturbed and undisturbed trees

The 1111 increment cores sampled from 218 *P. abies* and *A. alba* trees affected by past flash flood activity, have a mean age of 110 ± 26 years, with the oldest tree reaching back to A.D. 1829 and the youngest tree attaining sampling height in A.D. 1986. Generally, trees were older in DCH01 sector, whereas the youngest specimens were found in DCH02. Statistics of the trees sampled in the different catchments is provided in Table 2.

Dendrogeomorphic analysis of the affected trees yielded 480 GD induced by past flash flood activity. As can be seen in Table 2, one in four (120; 25%) GD were injuries whereas the remaining 361 GD (75%) were TRDs, of which 73 (20%) were strong, 83 (23%) medium and 205 (57%) weak. The sector presenting the largest number of GD was RP01, with 41 injuries and 145 TRDs, whereas the smallest number of GD was found in DR01 with only 10 injuries and 32 TRDs.

4.2. Flash floods chronologies

The spatio-temporal analysis of the 480 GD allowed definition of 47 flash flood events between A.D. 1866 and 2012. The weighted index (W_{it}) and sample size are presented in Fig. 4 for each year of the reconstruction and for each river segment, whereas Table 3 summarizes those years where the threshold defined for events ($W_{it} \geq 0.5$ and $GD \geq 2$). The catchment presenting the largest number of flash floods is RP with 23 reconstructed events since A.D. 1866 (0.15 events yr^{-1} with sample size = 97), whereas the smallest number of events was observed at DR with 4 reconstructed flash floods since A.D. 1926 (0.04 events yr^{-1} with sample size = 21). Trees sampled in the other two streams, DCH and ST, allowed reconstruction of 19 (0.24 events yr^{-1} with sample size = 73) and 9 (0.12 events yr^{-1} with sample size = 22) since AD 1934 and 1938, respectively. At the regional scale, the most replicated events — defined as having a $W_{it} > 5$, were recorded in 1958 ($W_{it} = 32.2$) and 1972 ($W_{it} = 8.2$) in catchments RP and DCH. A total of 27 reconstructed flash floods had a W_{it} ranging between 1 and 5, whereas 28 flash floods were exhibited a W_{it} ranging between 0.5 and 1.

Inter-catchment comparison reveals that a large majority of dated events (82%) was limited to individual catchments, and no years can be finding with reconstructed flash floods in all catchment. The flash flood with the largest spatial replication took place in 1970 and was documented in DCH, ST, and RP. In addition, in ten years flash floods occurred in two catchments (Table 3).

During the time period covered by the reconstruction, one can distinguish at least three periods with enhanced flash flood activity. As shown in Fig. 5 enhanced activity occurred between 1946–1949 (5-yr average: 0.8 events yr^{-1}), 1955–1963 (5-yr average: 0.7 events yr^{-1}), and 1979–1987 (5-yr average: 0.6 events yr^{-1}).

Table 2
Characteristics of growth disturbances (GD) induced by past flash flood events.

Catchment	River reach	Injury	TRD		
			S	M	W
DCH	DCH01	26	19	10	27
DCH	DCH02	8	5	14	29
DR	DR01	10	7	5	20
RP	RP01	41	24	25	96
RP	RP02	15	11	17	20
ST	ST	19	7	12	13
	Σ sum	119	73	83	205

Table 3
Overview of sample size (n), growth disturbances (GD; n) and weighted index (W_{it}) for each year of the time series and for the four streams analyzed. Years highlighted in gray contain to reconstructed flash flood events.

	RP			DR			DCH			ST		
Year	Sample size	N° GD	Wit	Sample size	N° GD	Wit	Sample size	N° GD	Wit	Sample size	N° GD	Wit
1866	20	2	0.66									
1877	31	4	1.39									
1893	55	2	0.94									
1902	70	3	1.21									
1905	72	2	0.52									
1914	82	3	0.68									
1921	88	4	0.66									
1922	88	6	1.00									
1926	*89*	*8*	*3.93*	*15*	*3*	*0.60*						
1927	89	7	1.96									
1931	*90*	*3*	*0.82*	*15*	*3*	*1.00*						
1934							50	2	0.54			
1938	*93*	*5*	*1.46*							*12*	*4*	*4.00*
1941							53	3	0.94			
1946							55	3	1.17			
1947										14	2	2.00
1949	94	4	0.96									
1950							58	2	0.63			
1952										15	2	1.87
1955							61	2	0.74			
1956	94	6	2.22									
1958	96	22	32.2									
1959	*96*	*3*	*0.51*							*17*	*2*	*0.71*
1960							63	2	0.74			
1961	*96*	*5*	*0.84*				*63*	*5*	*1.19*			
1962							65	3	0.51			
1963							65	2	0.70			
1966	96	4	1.09									
1968							67	2	0.77			
1970	*96*	*4*	*0.55*				*68*	*6*	*2.86*	*19*	*2*	*1.05*
1972							70	9	8.26			
1976										21	3	2.14
1979	96	7	1.98									
1980							73	4	1.42			
1983							*73*	*3*	*0.56*	*21*	*3*	*2.43*
1985							73	3	1.19			
1987							73	4	1.36			
1990				21	3	3.00						
1991							73	2	0.93			
1993							73	2	0.56			
1997	*95*	*4*	*0.75*							*22*	*3*	*0.75*
1997												
2002	*93*	*6*	*1.43*				*73*	*6*	*1.20*			
2004				21	2	0.95						
2008	91	3	0.71									
2010										22	2	0.55

4.3. Hydrometeorological triggers of reconstructed flash flood events

Table 4 and Fig. 6 illustrate the relationships between reconstructed flash flood events and maximum 1-, 3- and 5-day April–October rainfalls in the northern slopes and foothills of the Tatra mountains. We describe 26 flash floods with hydrometeorological parameters, 9 each in DCH and RP, 6 in ST, and 2 in DR.

The rainfall totals for 1-day events ranged from 28.8 to 168.4 mm (mean 80.2 ± 34.3 mm), whereas the 3- and 5-day precipitation sums ranged between 50.3 and 247.7 mm (mean 130.4 ± 51.3 mm) and 65.2 and 258.1 mm (mean 149.4 ± 53.5 mm), respectively. The non-parametric Friedman test confirms the presence of non-significant differences (at 95% ICL) of rainfall threshold values between catchments, neither for 1- ($\chi^2(3) = 2.400$, $p = 0.494$), 3- ($\chi^2(3) = 1.800$, $p = 0.615$) nor 5-day ($\chi^2(3) = 1.800$, $p = 0.615$) events. The most intense rainfall event was recorded in Dolina Chochołowska with a daily precipitation total of 333.5 mm (24 July 1980) and has reportedly triggered a flash flood in the DCH catchment. The most replicated event (ST, RP, DCH) occurred in 1970 and has not only been confirmed by flood records in Zakopane, but also corresponds to the second largest, recorded rainfall in the Tatra mountains on 20 July 1970, when the 1-, 3-, and 5-day rainfall totals were 150.1, 206.4, 243.2 mm, respectively. The CV analysis of precipitation records (Fig. 7) as well as their spatial

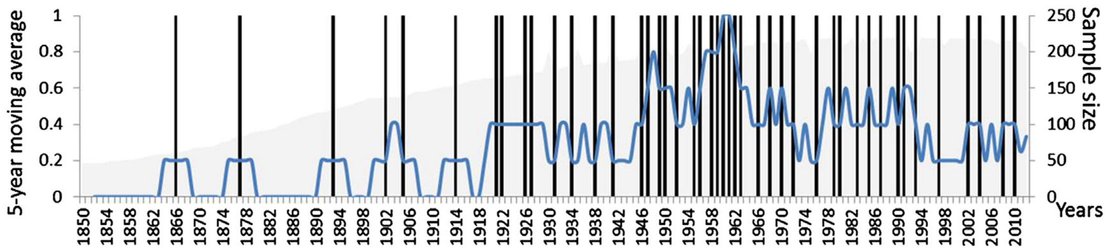

Fig. 5. Reconstructed flash flood chronology for the northern slopes of the Tatra mountains and 5-yr moving average of process activity highlighting periods of enhanced and limited flash flood activity.

fingerprint indicates that past rainfall events leading to flash floods commonly (74% of all cases) affected the entire northern slope of the Tatra mountains (e.g., 1970; Fig. 68). Hoverer, we found moderate variations in measured rainfall intensities along the mountain range (e.g., 1972; Fig. 8).

5. Discussion and conclusions

In this study we present the first systematic flash flood reconstruction of the Polish Tatra Mountains. In the analysis of 218 trees injured by past flash floods in six river reaches of four headwater catchments of the northern slopes of the mountain chain, we were able to identify 47 flash floods covering the period A.D. 1866–2012. Moreover, we illustrate that differences exist between catchments insofar their triggering is concerned, and illustrate precipitation and flow gauge records related with the release of reconstructed events.

The flash flood chronologies presented in this study were obtained through the dendrogeomorphic analysis of injuries in trees, an indicator that has been considered the most reliable source of evidence for process reconstructions (Stoffel and Corona, 2014). Scars in the selected stream sections were inflicted by logs and boulders transported downstream during flash floods of moderate to high hydraulic power, which is in agreement with previous observations made in the same environment (Zielonka et al., 2008) and congruent with data from other high gradient streams in other geographic contexts (Gottesfeld, 1996; Ballesteros-Cánovas et al., 2011a,b). The tree species analyzed in this study (i.e., *P. abies* and *A. alba*) are renowned for the occurrence of TRD (Stoffel, 2008; Stoffel and Hitz, 2008) and callus tissue (Schneuwly et al., 2009a) being formed next to the scars (Stoffel, 2008) and on up to one-fourth of the circumference remaining vital after wood-penetrating impacts (Schneuwly et al., 2009b), thus reducing the risk of missing events in the tree-ring-record. The W_{it} threshold used in this study was also defined as a result of the significant noise in the tree-ring records which is related to intense forest management practices in the wider study region (Jahn, 1979) since the 18th century and until the proclamation of the national park in 1955. Forestry remains an important source of noise in the western part of the Tatras Mountains where extraction is still possible today.

Despite this possible drawback of potential noise in the records, the reliability of the reconstructed flash-flood series is very well supported by several major floods measured in the flow gauge records of the foothills (i.e., 1955, 1958, 1960, 1970, 1983, 1997, 2008, and 2010; Kundzewicz et al., 2014; Niedźwiedź et al., 2014; Ruiz-Villanueva et al., 2014) and/or recorded in historical archives (1866, 1893, 1902, and 1934; Kotarba, 2004). Moreover, our flash flood chronology also matches with results from an existing, localized case study realized in the eastern Tatra mountains (Zielonka et al., 2008). When put into a much larger context, we realize that our flash flood record suggests

Table 4
Precipitation records (1-, 3- and 5-day totals) associated with dated flash flood events. Values given in italics represent years for which the largest amount of rainfall has been recorded at the second nearest precipitation station. (*) represent years with a CV larger than 0.35, which indicate a larger variability in the measured precipitation over the northern Tatra Mountains.

Site	Year	Likely event date	Precipitation station	1-day (mm)	3-day (mm)	5 − day (mm)
DCH	1934	19.07	Historic event (no data)	N/A	N/A	N/A
DCH	1955	5.08	Dolina Chochołowska	66.4	85.2	112.2
RP	1956 (*)	19.06	Morskie Oko	37.4	50.3	65.2
RP	1958	29.06	Morskie Oko	168.4	238.2	248.4
RP	1959	30.06	Morskie Oko	83.4	148.9	156.2
ST	1959 (*)	1.06	Dolina Chochołowska	93.4	133.0	134.1
DCH	1960	13.07	Dolina Chochołowska	110.6	113.6	153.0
DCH	1961	30.07	Dolina Chochołowska	45.7	115.5	115.5
DCH	1962	18.07	Dolina Chochołowska	97.4	128.2	132.0
DCH	1963	5.10	Dolina Chochołowska	53.4	89.8	96.6
RP	1966	25.06	Morskie Oko	47.3	52.0	91.4
DCH	1968	18.07	Dolina Chochołowska	74.9	90.5	99.7
DCH	1970	18.07	Historic event (no data)	N/A	N/A	N/A
ST	1970	18.07	Zakopane	138.7	192.1	218.8
RP	1970	18.07	Morskie Oko	150.1	206.4	243.2
DCH	1972 (*)	21.08	Polana Chochołowska	92.1	187.6	214.5
ST	1976	17.09	Zakopane	41.3	72.3	85.6
RP	1979 (*)	27.06	Morskie Oko	28.8	86.3	88.5
DCH	1980	24.07	Polana Chochołowska	84.5	247.7	258.1
ST	1983	14.07	Zakopane	109.2	179.3	190.2
DCH	1983	14.07	Polana Chochołowska	84.7	118.9	134.7
DR	1990 (*)	25.05	Morskie Oko	59.0	73.0	87.4
ST	1997	08.07	Zakopane	104.0	166.0	205.3
RP	1997	08.07	Morskie Oko	84.0	134.1	153.0
RP	2002	14.08	Morskie Oko	58.0	89.8	107.2
DR	2004	28.07	Morskie Oko	72.2	150.1	168.2
RP	2008	23.07	Zakopane	113.5	155.0	185.2
ST	2010	27.07	Zakopane	68.1	119.1	151.6

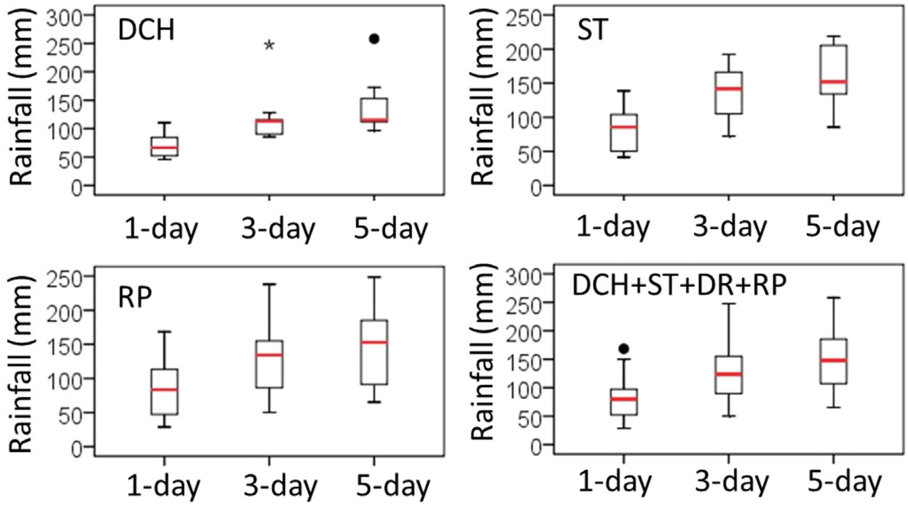

Fig. 6. Illustration of 1-, 3- and 5-day average rainfall thresholds related to the occurrence of reconstructed flash flood events for individual catchments and for the entire Tatra Mountains. The limited number of events reconstructed in DR has prevented the plotting of rainfall thresholds.

slightly lower activity (0.32 events yr^{-1}) than in the Western Carpathians, where Šilhan (2014) reconstructed 0.55 events yr^{-1}. By contrast, our record of significant changes in flash flood activity – with enhanced number of events between 1958 and 1963 and much lower activity after the 1980s and during the 1990s is in nice agreement with positive (1958–1980) and negative (1981–1996) trends in extreme rainfalls as observed by Niedźwiedź et al. (2014). We believe that our flash flood chronology is representative for the region and that it extends the time period covered by systematic records (Fig. 2) in a quite considerable way, while also providing evidence for behavioral differences between the catchments. The most noticeable difference in flash flood activity was found between catchments DR and RP. Our findings indicate that despite their spatial proximity, flash floods occurred much less frequently in DR (only 4 dated events) than in RP (23 dated events). Despite the number of catchments analyzed prevents to perform any reliable statistical analysis of potential controls, the qualitative assessment of the main catchment characteristics (Table 1) does not point to substantial differences in geologic and geomorphic characteristics. One could thus assume that this striking difference in reconstructed flash flood activity is reflective of differences in sample size (21 disturbed trees in DR whereas 96 in RP), which have been shown to affect the reliability of reconstructed chronologies (Corona et al., 2012). However, all trees affected by flash floods have been sampled at the six field sites, such that the low amount of disturbed trees in DR could possibly also be indicative of a hydrological system less prone to intense rainfalls and/or flooding. This explanation can possibly be

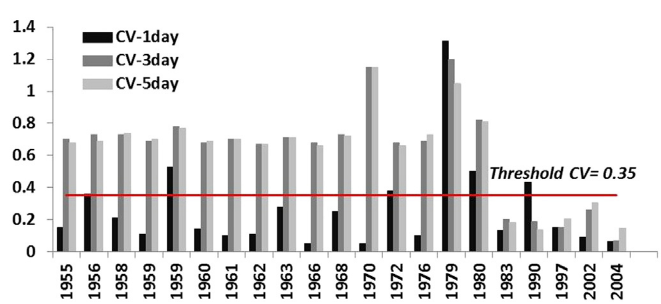

Fig. 7. Coefficient of variation for 1-, 3- and 5-day precipitation totals as measured in Polana Chochołowska, Dolina Chochołowska, Zakopane, and Morskie Oko stations during flash floods. The 1-day CV showed much larger variability than the 3- and 5-day values. Lower CV values since 1983 are related with the dysfunction of the Polana Chochołowska and Dolina Chochołowska stations.

supported by the fact that the DR catchment, unlike the other sites, could be somewhat in the shadow of orographic rainfalls (Keef et al., 2009), which are primarily advected by air masses flowing from N and/or NW directions (Niedźwiedź et al., 2014).

The hydrometeorological characterization of reconstructed flash flood event suggests rainfall thresholds beyond 50 mm day^{-1}, a value, which has been considered previously as a high daily precipitation causing floods in the Tatra Mountains (Niedźwiedź et al., 2014). Our hypothesis that flash floods are caused by heavy rainfalls occurring between May and October is in agreement with local observations and previous studies (Fig. 3, Kotarba, 2004; Niedźwiedź et al., 2014), but not in line with the hypothesis of Zielonka et al. (2008) who stressed the potential role of snowmelt processes on flood generation in 1958 using monthly meteorological records. As our study uses daily data, we have good reasons to believe that the most plausible explanation for the 1958 flash flood was indeed a large and prolonged rainfall which occurred on 1 July 1958; it resulted in a daily rainfall of 158.4 mm and accumulated rainfall totals of 238.2 mm (Morskie Oko station) and 248.4 mm, respectively, if the 3- and 5-day antecedent precipitation events are taken into account as well. Based on a visual assessment of synoptic maps, we furthermore agree with Niedźwiedź (1972) and Niedźwiedź et al. (2014) that prolonged rainfalls related with North cyclonic circulations (Nc) are the first and foremost driver of flash flood triggering in the region. This observation also explains the generalized and widespread occurrence of heavy rainfalls (Fig. 8) in situations with flash floods such as the well-replicated event of 1970, for which we observe the highest daily rainfall sum in all meteorological stations. Nevertheless, we also see changes in rainfall intensity along the Tatra Mountains because of local effects, which in turn may partially explain the differences observed in catchment responses in 24% of the cases. An example for such different response is 1972 (CV:0.38), when prolonged rainfalls mostly affected the Central and Western parts of the Tatra Mountains with a maximum 3-day precipitation recorded at Hala Gąsienicowa station (218.1 mm) and reconstructed flash floods at DCH and ST. We therefore support the idea that the lack of spatial replication of flash floods (18% cases) could also be related with the orographic effect of precipitation (Borga et al., 2002), as has been suggested for the wider study region (Niedźwiedź et al., 2014). This effect has been well described in other mountain areas (Buytaert et al., 2006), where even larger discrepancies in rainfall intensity has been observed within shorter distances. Therefore, despite the fact that data from more catchment and more time series would be desirable, our study highlights, at least to some degree, the space-time variability in catchment response (Viglione et al., 2010).

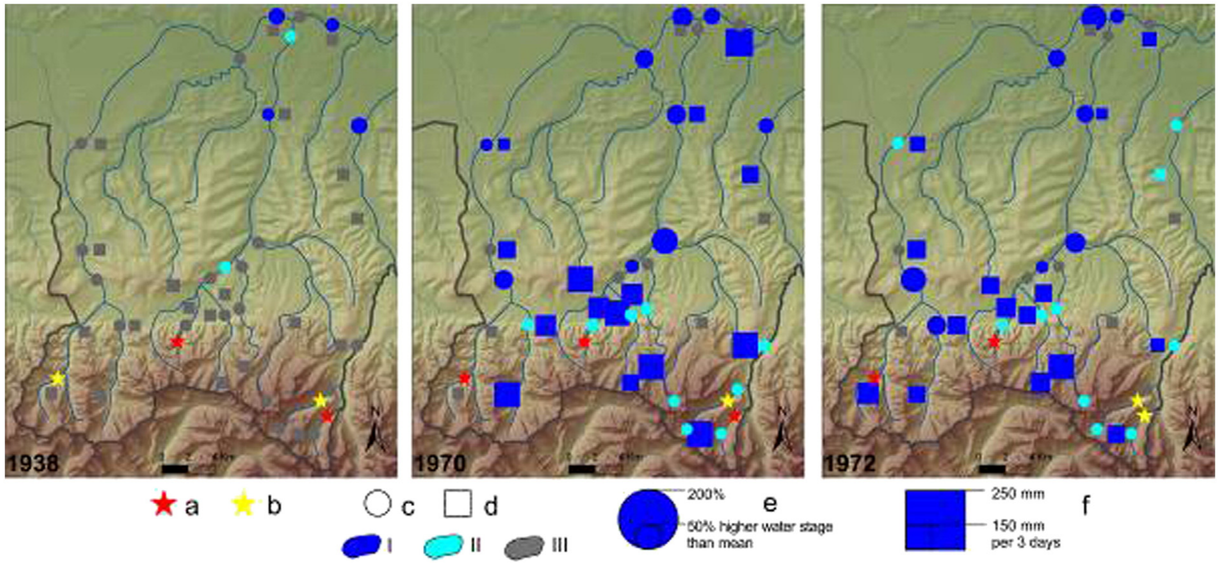

Fig. 8. Selected examples of observed spatial pattern of flash floods and their relation with rainfall and flow discharge at the study site. The flash flood reconstructed in 1938 points to the huge scarcity of data available at this time, the 1970 event illustrates the effects of a generalized rainfall event (CV = 0.05) whereas the 1972 flash floods occurred during a less generalized precipitation (CV = 0.38) event and fewer high water stages, but more pronounced signals in tree-ring records (scars and TRD). Legend: a — sectors affected by flash floods; b — sectors not affected by flash floods; c — water stage data; d — precipitation data; I — high water stage/large precipitation event; II — low water stage/limited precipitation event; III — lack of data; e and f — runoff and rainfall values associated with the event.

Our results are also useful in the design of future strategies to deal with flood risks in the region, as the quantitative rainfall thresholds reported represent the longest record of potential daily hydrometeorological triggers for flash flood in the Polish Tatras. Based on regional climate model (RCMs) and downscaling, the expected future frequency of intense precipitation could be compared with our data to provide changes in hazard and risks over the next few decades. Previous studies suggest that an increase in the duration, severity, and frequency of intense precipitation events could lead to an increase in flash flood event (IPCC, 2012). Despite the fact that many uncertainties remain about quantitative future changes in precipitation rates along the Tatra Mountains (Kundzewicz et al., 2006; Niedźwiedź et al., 2014), some evidence exists for cyclonic circulation types responsible of flash floods to increase in the long term (Niedźwiedź et al., 2014). This evolution clearly could lead to an increase in flash flood activity which in turn could impact infrastructures and properties, thereby also restricting the future development of the region.

We conclude that the dendrogeomorphic approaches presented in this study are indeed a reliable tool for the reconstruction of flash flood histories on the northern slopes of the Tatra Mountains. The tree-ring records have allowed substantial extension and improvement of the existing historical and systematic records of past flash flood activity in frequently visited recreational zones and densely inhabited foothills and also highlight the past activity of hydrometeorological extremes and their impacts as well as variations thereof in time. Despite the limitations encountered at some sites with regard to sample size, this study clearly supports existing knowledge on the seasonality of flash floods and provides new insights into potential rainfall thresholds leading to the release of events. As a consequence, we are confident that the results of this work can be used to improve understanding of the potentiality of each catchment to flash flood processes and as an excellent basis for future regional flash flood frequency estimations. We are also convinced that the results obtained for the headwaters draining the northern Tatra Mountains can be used to improve the understanding of the hydrological behavior between headwaters and lowland rivers, and consequently improve our apprehension of current and possible future flood risk in the foothill areas of the Polish Tatras and even in the Vistula River catchment.

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