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Floods at the Northern Foothills of the Tatra Mountains – A Polish–Swiss Research Project

Zbigniew W. KUNDZEWICZ[1], Markus STOFFEL[2], Ryszard J. KACZKA[3], Bartłomiej WYŻGA[3,4], Tadeusz NIEDŹWIEDŹ[3], Iwona PIŃSKWAR[1], Virginia RUIZ-VILLANUEVA[2], Ewa ŁUPIKASZA[3], Barbara CZAJKA[3], Juan Antonio BALLESTEROS-CANOVAS[2], Łukasz MAŁARZEWSKI[3], Adam CHORYŃSKI[1], Karolina JANECKA[3], and Paweł MIKUŚ[3,4]

[1]Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Poznań, Poland; e-mail: kundzewicz@yahoo.com

[2]Institute of Geological Sciences, University of Berne, Berne, Switzerland

[3]University of Silesia, Faculty of Earth Sciences, Sosnowiec, Poland

[4]Institute of Nature Conservation, Polish Academy of Sciences, Kraków, Poland

Abstract

The present paper introduces the topical area of the Polish–Swiss research project FLORIST (Flood risk on the northern foothills of the Tatra Mountains), informs on its objectives, and reports on initial results. The Tatra Mountains are the area of the highest precipitation in Poland and largely contribute to flood generation. The project is focused around four competence clusters: observation-based climatology, model-based climate change projections and impact assessment, dendrogeomorphology, and impact of large wood debris on fluvial processes. The knowledge generated in the FLORIST project is likely to have impact on understanding and interpretation of flood risk on the northern foothills of the Tatra Mountains, in the past, present, and future. It can help solving important practical problems related to flood risk reduction strategies and flood preparedness.

Key words: floods, dendrogeomorphology, wood debris transport, climate impact, Tatra Mountains.

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1. INTRODUCTION TO THE PROBLEM AND PROJECT AREA

The costs of extreme weather events have exhibited a rapid upward trend in recent decades, at every spatial scale. In two years (1997 and 2010) of the two last decades, material damage caused by floods in Poland reached or exceeded the level of 1% of natural Polish GDP and dozens of people lost their lives (Kundzewicz *et al.* 2012). Topography and climate of Poland play an important role in the spatial and temporal distribution of flood hazard. The Tatra Mountains are the area of the highest precipitation in the country and largely contribute to flood generation.

The Polish–Swiss research project FLORIST (Flood risk on the northern foothills of the Tatra Mountains) commenced in July 2011 and is planned to last until 2016. It is supported by a grant from the Swiss government through the Swiss Contribution to the enlarged European Union (PSPB No. 153/2010). The FLORIST project deals with the evaluation of flood hazard and risk on the northern foothills of the Tatra Mountains, where considerable flood generation potential exists. The consortium consists of three institutions, namely the Institute for Agricultural and Forest Environment of the Polish Academy of Sciences (Poznań, Poland) – project co-ordinator, the University of Berne (Berne, Switzerland), and the University of Silesia (Sosnowiec, Poland). The present paper introduces the topical area of the project, informs on its objectives, and reports on initial results.

The paper also enriches the existing recent references on various aspects of flood-related studies, such as Alexakis *et al.* (2012), Gąsiorowski (2013), or Hattermann *et al.* (2013), by adding important, area-specific information of relevance to flood risk in Poland.

2. GEOGRAPHY, GEOMORPHOLOGY, AND CLIMATE

Most of the area of Poland is covered by postglacial plains, but the southern part of the country includes mountains (Carpathians and Sudetes) and uplands. The northern foothills of the Tatra Mountains (Fig. 1) belong to the drainage basin of a large river – the Vistula, flowing from the mountains and uplands in the south through lowlands and emptying into the Baltic Sea in the north of Poland.

The Tatra Mountains (“Tatry” in Polish and in Slovak), located in two countries – Slovakia and Poland – are the highest range of the massive arch of the Carpathian Mountains, spreading over a distance of more than 1300 km (Fig. 1) and passing through several Central and Eastern European countries. The Tatra Mountains form part of the main European water divide: the rivers Dunajec and Poprad flow towards the Baltic Sea, whereas the rivers Orava and Vah are tributaries to the Danube and flow towards the Black Sea. The Tatra Mountains occupy an area of 785 km^2, of which about

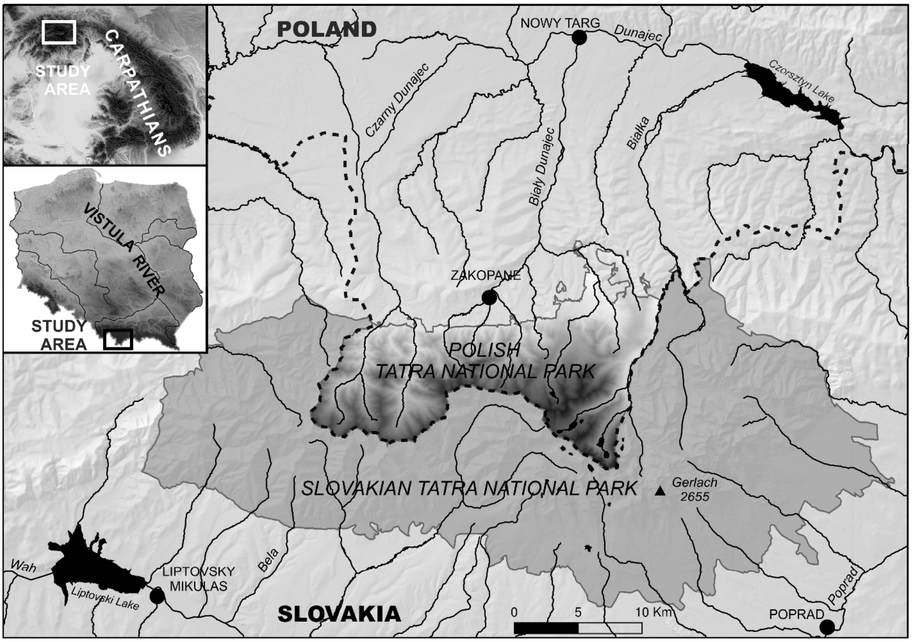

Fig. 1. Map of the study area. For orientation, the study area is also placed on the background of the Carpathian Mountains and Poland.

610 km² (77.7%) are located in Slovakia and about 175 km² (22.3%) in Poland. The highest peak in the Tatra Mountains, Gerlach (2655 m a.s.l.), is located in Slovakia, near the town of Poprad, while the highest peak on the Polish side is Rysy (2499 m a.s.l.), located near Zakopane. The Tatra Mountains are a young mountain range from the Alpine orogeny. They indeed resemble the Alps landscape-wise, although being significantly smaller. The High Tatras, with over 30 peaks exceeding 2500 m a.s.l., represent the only form of Alpine landscape in the entire arc of the Carpathians.

Human activity in the region has started relatively early and has reached the highest parts of the mountains during the last centuries. Intense farming in the foothills, pasturing and logging in the Tatras have transformed the previously pristine landscape. These processes have resulted in the increase of flood risk, mainly as a result of the considerable reduction of natural retention capacity. Concurrently, the natural and cultural values of the Tatras were appreciated and the necessity of their protection was recognized shortly after the Second World War. Indeed, the National Parks in the Slovakian and Polish Tatras were established in 1949 and 1955, respectively.

Even if only 22% of the Tatra Mountains are located in Poland, the Polish part is recognized as a national jewel with overwhelming tourist attractions. The main resort, Zakopane, is commonly considered the “winter capital of Poland” and famous for Alpine and Nordic skiing.

The Tatra Mountains form an important barrier to the movement of air masses. On the northern slopes of the Tatra Mountains, mean annual temperature ranges from about 6°C at elevations of 600-650 m a.s.l. at the bottom of the Nowy Targ Basin to –4°C on the highest peaks of the Tatra ridge (Niedźwiedź 1992, Niedźwiedź *et al.* 2014). Hess (1974) proposed to divide the region in six vertical climatic belts of 2°K width, based on the mean annual temperature.

The upper tree line (1550 m a.s.l.) is consistent with the annual isotherm of 2°C. The subalpine belt is covered with mountain pine (*Pinus mugo*) and encompasses elevations ranging from 1550 to 1850 m a.s.l., where mean annual temperature drops to 0°C. A belt of Alpine meadows extends from 1850 to 2200 m a.s.l. Above 2200 m (semi-nival belt), bare rock and lichens predominate, and snow precipitation is more frequent than rainfall. Annual snow cover duration at this altitude exceeds 230 days.

Precipitation recorded on the northern slopes of the Tatra Mountains is the highest in Poland. For the period 1951-2012, mean annual precipitation at Kasprowy Wierch (1991 m a.s.l.) was 1765 mm, but the record-high annual maximum precipitation at this station was 2599 mm in 2001 (with monthly maximum of 651 mm in July 2001). Even higher annual precipitation values were recorded in 2001 at other high-elevation locations of the Tatra Mountains, namely 2628 mm at Hala Gąsienicowa and 2770 mm at Dolina Pięciu Stawów.

Whereas the Tatra Mountains are distinctly different from the rest of the Western Carpathians by their high precipitation totals (from daily to annual scales), they also exhibit relatively high water storativity. In the high, crystalline part of the Tatras, thick and highly porous debris cones predominate on slopes and glacial till in the valley floors, both enabling effective infiltration of water. On the northern slopes of the Tatras, limestone and dolomite bedrock favors deep, karstic water circulation. In both areas, lithological conditions slow down runoff and result in a considerable proportion of underground supply of streams draining the mountains.

In the northern foothills of the Tatra Mountains, elevations range from about 600 m a.s.l. in the Orawa–Nowy Targ Basin in the north to 1100-1200 m a.s.l. in the Spisz–Gubałówka Hills close to the Tatra Mountains. Most of this area is underlain by flysch with low water storativity. This setting, together with considerable deforestation of the area (current forest cover is only about 10%), results in greater flashiness of runoff than in other environments of the region. As a result, maximum unit runoff from the flysch area may be similar as in the Tatra Mountains, despite lower precipitation totals (from 800 to 1200 mm annually).

Due to its geographic, geomorphic, and climatic characteristics, the Tatra Mountains and its northern foothills (Podhale) are a distinctive region of Poland. The Tatra Mountains feature highest precipitation in Poland and the specific runoff in both the Tatra Mountains and their northern foothills is high, which translates into flood risk.

3. RIVER FLOW AND FLOODING

It is estimated that most of the national flood damage in Poland occurred in the Upper Vistula Basin (from its source near Barania Góra to the station of Zawichost). During the 20th century, 41 significant floods were caused by abundant rainfall in the Carpathian part of the basin. Events occurred most frequently in July (in 1903, 1934, 1960, 1970, 1997), but also in other months between May and September. During the past two decades, severe floods occurred in July 1997, as well as in May and June 2010. In the upper reaches of the mountainous tributaries of the Vistula (such as the River Dunajec), flood events are typically violent and highly erosive. Later, they transform into huge masses of water propagating downstream through lowland river reaches, causing inundation even at distances of up to 400 km from the Carpathians (Kozak *et al.* 2013).

The Dunajec is the principal river of the northern foothills of the Tatra Mountains (Fig. 2) and is a merger of two smaller tributaries joining in Nowy Targ, namely the Czarny (Black) Dunajec and Biały (White) Dunajec. The Dunajec is 250 km long and its basin area is 6804 km^2, of which 4854 km^2 are located in Poland and 1950 km^2 in Slovakia. The following tributaries deliver their waters to the River Dunajec (ordered from upstream to downstream): Białka, Grajcarek, Ochotnica, Kamienica (Gorczańska), Poprad, Kamienica Nawojo-wska, Łososina, and Biała. The basin of the River Dunajec has the highest flood-generation potential in Poland and has contributed significantly to the disastrous floods of 1934 and 1970. This reflects the high potential of the Tatra Mountains for generating floods due to abundant rainfall in the area.

Stage observations on the rivers of the Upper Vistula Basin were initiated in the second half of the 19th century and document numerous floods, on the Vistula itself and in the catchments of its tributaries. The largest flood of the first half of the 20th century in the Vistula Basin occurred in July 1934, with inundations covering record-large areas in Poland. The track of the northern foothills of the Tatra Mountains in this disastrous flood event was strong. The flood, caused by intense rainfall, started in the mountain valleys of the Dunajec catchment and propagated downstream along the Vistula. During the dramatic July 1934 flood, peak discharge of the Vistula upstream of the mouth of the River Dunajec was 3100 m^3 s^{-1}, whereas the Dunajec added further 4500 m^3 s^{-1}. Flood waters inundated an area of 1260 km^2 and

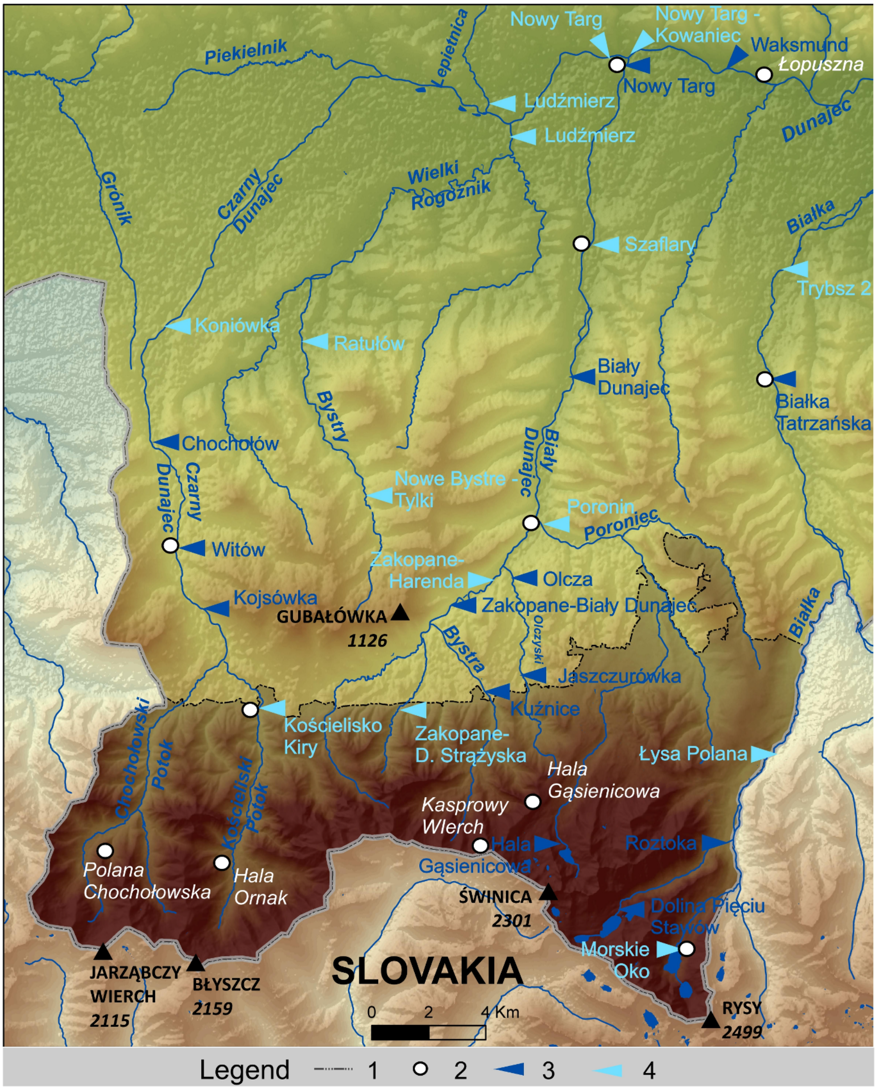

Fig. 2. River network in the study area and the location of stream and river gauges as well as precipitation and meteorological stations. Legend: 1 – Tatra National Park, 2 – precipitation or meteorological stations, 3 – historical water gauges, and 4 – operating water gauges.

caused 55 fatalities, destroyed 78 bridges and 22 000 buildings. As a consequence of the 1934 flood, intense flood control work was undertaken on the highland tributaries to the Vistula, such as flood protection reservoirs at

Porąbka (River Soła, terminated in 1936) and Rożnów (River Dunajec, completed in 1941). Half a century later, despite considerable opposition of environmentalists and part of the population, another reservoir was constructed at Czorsztyn (River Dunajec). Figure 3 illustrates a streamflow series of the Białka (gauge Łysa Polana), Cicha Woda (gauge Zakopane–Harenda), and Czarny Dunajec (gauge Nowy Targ) rivers for the period 1961-2011. This figure demonstrates strong variability of maximum monthly discharge of the rivers, whereas Table 1 compiles the five highest annual maximum discharge events of the three rivers presented in Fig. 3.

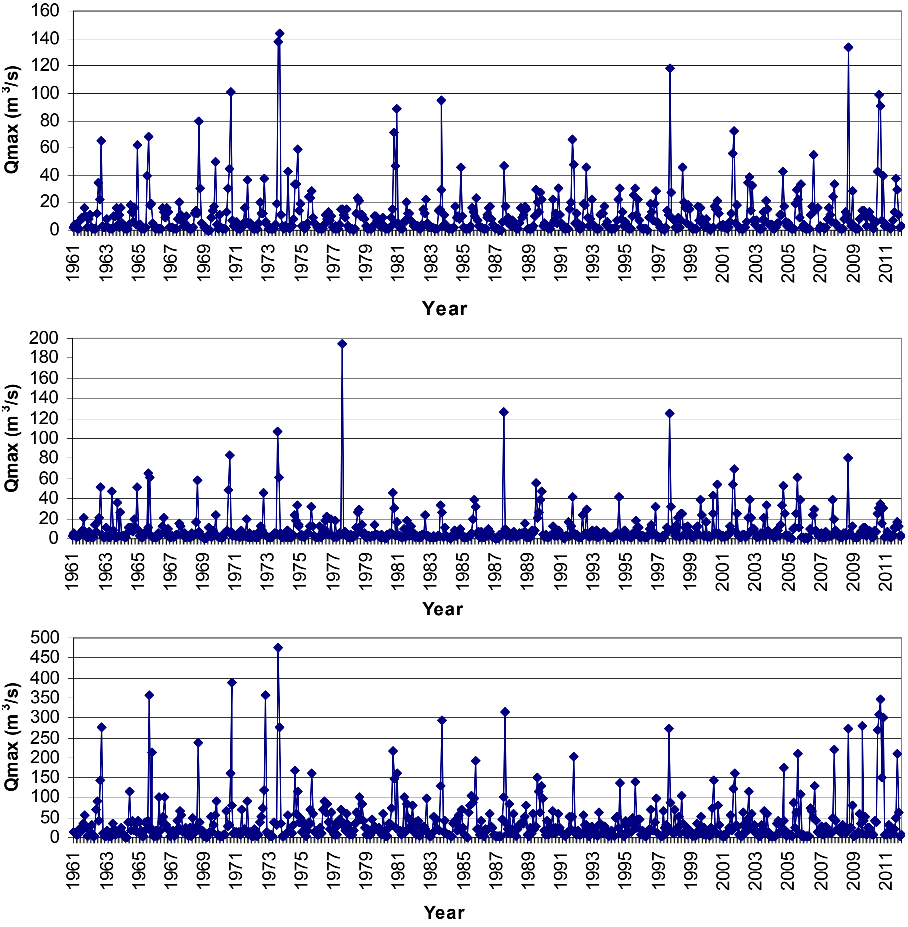

Fig. 3. Time series of maximum monthly discharge of the Białka (gauge Łysa Polana, upper diagram), Cicha Woda (gauge Zakopane–Harenda, middle diagram), and Czarny Dunajec (gauge Nowy Targ, lower diagram) rivers for the period 1961-2011 (data provided by IMGW-PIB, used with permission).

Table 1

Five months with highest annual maximum discharge
of the Białka (gauge Łysa Polana), Cicha Woda (gauge Zakopane–Harenda),
and Czarny Dunajec (gauge Nowy Targ) rivers for the period 1961-2011
(data provided by IMGW-PIB, used with permission)

Rank	Highest maximum discharge [$m^3 s^{-1}$]								
	River Białka Gauge Łysa Polana			River Cicha Woda Gauge Zakopane–Harenda			River Czarny Dunajec Gauge Nowy Targ		
	$Q_{\max}$	Year	Month	$Q_{\max}$	Year	Month	$Q_{\max}$	Year	Month
1	144	1973	07	195	1977	06	474	**1973**	**06**
2	138	**1973**	**06**	126	1987	05	387	**1970**	**07**
3	134	2008	07	125	1997	07	356	1965	06
4	118	1997	07	107	**1973**	**06**	356	1972	08
5	101	**1970**	**07**	84	**1970**	**07**	346	2010	07

River flow of the northern foothills of the Tatra Mountains considerably varies in time. For the Białka (gauge Łysa Polana), the lowest discharge recorded between 1961 and 2011 is 0.36 $m^3 s^{-1}$, whereas the highest discharge is 144 $m^3 s^{-1}$, *i.e.*, 400 times more. For the Cicha Woda (gauge Zakopane–Harenda), the lowest value is 0.46 $m^3 s^{-1}$, whereas the highest value is 195 $m^3 s^{-1}$, *i.e.*, over 423 times more. For the Czarny Dunajec (gauge Nowy Targ), the lowest value is 0.85 $m^3 s^{-1}$, whereas the highest value is 474 $m^3 s^{-1}$, *i.e.*, over 557 times more. As a general rule, values of the coefficient of runoff irregularity increase downstream in rivers originating in the Tatras, due to the increasing proportion of flysch environments and more rapid runoff delivery (Wyżga *et al.* 2012).

Table 1 also illustrates quite clearly the apparent lack of synchronicity of record-high values between the three basins, with the exception of July 1970 and June 1973 (entries shown in bold) that belong to the top five discharge events at all the gauges.

As specified in this section, the Tatra Mountains and their northern foothills have been the contributing areas to several large floods in the last century. Within the area, the River Dunajec played a particular role. However, natural, year-to-year variability of maximum monthly discharge of the examined rivers is strong, with erratic occurrence of the highest peaks that do not coincide for different streams and gauges.

4. FLOOD GENERATION PROCESSES – HEAVY, LONG-LASTING PRECIPITATION AND/OR SNOWMELT

Economic losses (in inflation-adjusted currency units) from large events have typically increased during recent decades at every spatial scale, from point to global scale (Kundzewicz *et al.* 2013). A part of the observed upward trend is linked to socio-economic factors, such as an increase in population and in wealth gathered in vulnerable areas (Kundzewicz 2012). However, these factors alone cannot generally explain the observed growth of damage in its entirety, and a part of the increase is typically linked to climatic effects (change in intensity and frequency of heavy precipitation and snowmelt) and terrestrial effects (urbanization, increase in impervious areas, and loss of flood water storage in floodplain areas caused by river channelization and incision and flood embankment construction), *cf.* Kundzewicz and Schellnhuber 2004).

The two principal types of disastrous floods prevailing in Poland (Kundzewicz *et al.* 2012) have been identified as: (i) summer floods caused by intense rainfall, and (ii) winter-spring floods (freshets) caused by snowmelt. “Rain-induced floods” can be sub-divided into those generated by convective rains, occurring locally over small areas, typically in summer, and those generated by frontal precipitation, that can cover large areas. Local, but intense “flash floods” associated with torrential rain of short duration, also called “cloudbursts”, are generated by thunderstorm cells in an air mass or frontal convection, being the result of free convection or of a convective system generated by frontal raising motion, with maximum precipitation intensity reaching high values of up to 150 mm in 2 hours (Niedźwiedź 1999).

The Polish (as well as the Western Carpathian) record of 24-hr precipitation is 300 mm and was observed on 30 June 1973 at Hala Gąsienicowa during a northern cyclonic situation Nc (as compared to the 100-yr 24-hr value of 242 mm). On 16 July 1934, precipitation of 172 mm was observed in Zakopane. In the Tatra Mountains, the most damaging floods are normally a result of precipitation lasting incessantly for three or more days. For example, on 16-18 July 1934, the highest 3-day total of precipitation at Hala Gąsienicowa reached 422 mm (Niedźwiedź 2003), whereas the monthly total for July 1934 was 684 mm. An increase in several annual indices of intense precipitation has been observed for the stations at Kasprowy Wierch and Zakopane, but trends typically are not statistically significant (Pińskwar 2010). Significant upward trends in some extreme precipitation indices have been observed at the seasonal scale and for the period 1951-2007. An increase of several indices relating to the frequency and magnitude of intense precipitation has been found for autumn and winter for the meteorological stations of Kasprowy Wierch and Zakopane, respectively (Łupikasza 2010, Niedźwiedź *et al.* 2014).

The highest precipitation leading to floods usually occurs between May and October. In Zakopane, precipitation totals for this period ranged from 532 mm in 1993 to 1285 mm in 2010. Values for the summit station Kasprowy Wierch are much higher, and varied between 698 mm (1993) and

1765 mm (2001). A clear positive trend in precipitation totals is found and amounts to +10 mm 10 yr^{-1}. After a relatively dry period before 1957, two periods characterized by higher precipitation were 1961-1981 and 1996-2010.

As for the seasonal distribution of intense precipitation, highest rainfall totals tend to occur between June and August. Summer totals ranged from 265 mm (1990) to 769 mm (2001) in Zakopane and from 300 mm (1990) to 1254 mm (2001) at Kasprowy Wierch. No significant trends were observed in the long-term course of summer precipitation, while fluctuations are similar to those of warm half-year totals.

The average annual maximum 24 h precipitation total in Zakopane was 63.9 mm for the period 1951-2012 (Niedźwiedź *et al.* 2014), whereas it ranged from 29.8 mm in 1993 to 138.9 mm in 1970 and 1973.

A statistically insignificant downward trend in maximum daily precipitation totals for 1951-2012 was observed in Zakopane (–2.1 mm 10 yr^{-1}, Niedźwiedź *et al.* 2014); however, a significant downward tendency can be found for the shorter period 1973-1993 (–21.8 mm 10 yr^{-1}).

Long-term changes in the frequency of the circulation types characterized by the highest likelihood of extreme precipitation (Nc + NEc + Bc) provide hints as to possible future changes in the frequency of extreme precipitation. The observed, statistically significant, increasing trend in the number of days with the Nc + NEc + Bc circulation types (of the order of 3 days per 10 years) may lead to an increase in the number of extreme precipitation events. It is also worth mentioning that the highest number of days with these circulation types, which occurred in 2010 (84 days), was accompanied by the highest annual and warm half-year (May to October) precipitation totals.

The number of days with snow cover in the Tatra Mountains increases with the altitude at a rate of 9 days/100 m and ranges from less than 120 days at the mountain base to about 220-290 days on the highest peaks. In Zakopane, during 85 winter seasons (1914/1915-1998/1999), the average duration of snow cover was 126 days (minimum 84, maximum 170 days). A statistically significant decreasing trend of snow cover duration (–8 days/ 10 years) and maximum snow cover depth (–9 cm/10 years) in Zakopane can be identified for the period 1961-1990 (Falarz 2002). However, on longer time scales (1915-1999), statistically significant trends could not be detected.

In the course of the 20th century, considerable environmental changes have occurred in the catchments and within the rivers on the northern foothills of the Tatra Mountains, and these changes have affected flood risk in the area in different ways. After the creation of the Tatra National Park in 1955, the previously intense pasture and forest grazing ceased as a result of the national park regulations and the state of Tatra forests improved considerably (Jahn 1979). The percentage of arable land in the Upper Dunajec Basin (to the mouth of Ochotnica Stream) decreased from 42.0% in 1901 to

17.5% in 2000 and forest cover increased from 27.3 to 42.0% (Wyżga *et al.* 2012). With these changes, runoff from the catchments has slowed down and sediment delivery to the rivers has been reduced. At the same time, rapid incision of the rivers has been induced as a result of widespread channel regulation, intense in-channel gravel mining and the concomitant reduction in catchment sediment supply, leading to the incision of river beds by 1-3.5 m over the second half of the 20th century (Zawiejska and Wyżga 2010). Bed degradation increased the flow capacity of the river channels, which in turn led to a reduction in the frequency and lateral extent of floodplain inundation. As a consequence of the lowered potential for flood water retention on the valley floors, higher peak discharges must be currently expected in downstream river reaches with given magnitudes of the floods originating in the upstream reaches (Wyżga 1997, 2008).

Another environmental change affecting flood risk in the valleys of Polish Carpathian rivers was the expansion of riparian forest during the 20th century (Wyżga *et al.* 2012), stimulated by a reduction in pastoral and agricultural pressure on the riparian areas and by river narrowing (due to reduced river dynamics and channelization of many river sections), which in turn left the abandoned portion of the channel beds for forest development. With the forest currently growing along river banks and on islands, large amounts of woody material are delivered to the rivers during floods. Moreover, as the harvesting of larger trees in the riparian forests and the extraction of larger wood pieces from the channels for firewood are common (Fig. 4), the woody

Fig. 4. Removal of the larger wood pieces (logs) deposited in river channels for firewood leaves relatively small, highly mobile wood debris that can pose significant flood risk if transferred to urbanized valley sections.

debris remaining in the rivers is relatively small and highly mobile (Wyżga and Zawiejska 2010). The debris can thus be readily transported by higher water flow to urbanized valley sections, where it can damage bridges and obstruct flow.

Processes driving changes in flood risk at the northern foothills of the Tatra Mountains include climatic and terrestrial mechanisms. The most damaging floods result from intense precipitation lasting incessantly for at least three days. Yet, some floods have been caused by torrential rains of short duration and by snowmelt. Trends in climatic variables of relevance to flood generation are typically weak, *i.e.*, statistically insignificant, superimposed on strong natural variability. Among environmental changes with impact on flood risk are: land use and land cover changes (including changes in the extent of pastures and forests, expansion of riparian forests and changes in logging patterns).

5. FLORIST PROJECT OBJECTIVES

The principal objectives of the FLORIST project are as follows:

- ☐ Creation of a data base on past torrential disasters and floods on the northern foothills of the Tatra Mountains, including information on the frequency and magnitude, generating mechanisms, triggers and impacts of past events. This includes the creation of a flood information catalogue, based on sources such as routine observations of the hydrometeorological service, references, and archives; as well as the creation of dendrogeomorphic input to flood information (via flood scar analysis using trees impacted by past events) generated within the project.
- ☐ Estimation of flood risk generated by woody debris on mountain rivers. This will include tracking experiments with radio transmitters installed in trees growing along the study river and in logs in its channel; analysis of wood storage patterns in mountain watercourses narrower and wider than the riparian tree height, modelling of transport and retention of large woody debris under various discharge, wood amount and recruitment rate scenarios; analysis of potential bridge clogging with woody debris; and issuing recommendations concerning management of the flood risk related to woody debris in mountain rivers.
- ☐ Change detection in flood-generating climate events through the construction of a climatological data base and examination of the climatology of past flood events. The analysis will be strived to detect change in intense precipitation and in circulation patterns. Also seasonality aspects will be considered and probability analyses will be performed.
- ☐ Examination of changes in mean and extreme precipitation events in the study area, based on projections with the help of a downscaled ensemble of Regional Climate Model (RCM) data.

- Analysis of projected changes in the frequency and magnitude of intense precipitation and river floods in a future greenhouse climate by 2050 and 2100. This will include comparison of intense precipitation in the control period and in the projection horizon. Frequency and magnitude analysis and change detection will be undertaken.
- Performance of retrospective and scenario-defined modelling of selected torrential disasters and river floods and an assessment of possible future risks. Climatic variables will be linked with torrential disasters and river floods for the control period and selected events will be modelled.

In more generic terms, the project is focused around four competence clusters, namely: observation-based climatology; model-based climate change projections and impact assessment; dendrogeomorphology; and impact of large wood on fluvial processes. Each of the three institutions in the consortium belongs to several of the above clusters.

The FLORIST project, being a challenging interdisciplinary endeavour, is highly innovative in terms of research objectives and approaches. Changes in flood generation processes and flood risk on the northern foothills of the Tatra Mountains have never been studied in such a comprehensive way, accounting past observations and model-based projections for the future.

The primary areas of major innovation in the FLORIST project are as follows:

- generation of comprehensive and unique database on past episodes of intense precipitation and flooding for the Polish Tatra Mountains and their foothills, based on multiple sources, including dendrogeomorphology and flood scar analysis conducted within this project;
- analysis of change in intense precipitation, weather circulation patterns, and flood flow in the study area;
- assessment of flood risk due to wood debris transport in mountainous rivers, including innovative concepts of field experiment, building upon the pioneering results by Wyżga and Zawiejska (2005, 2010), and numerical modelling of wood transport and potential bridge clogging, with the approach recently proposed by Ruiz-Villanueva *et al.* (2013);
- development of spatial downscaling of RCMs in data-scarce situation;
- analysis of projections of climatic and river flow characteristics for the future, using state-of-the-art regional model results.

6. INFORMATION DATA BASE

The FLORIST project will extend the pool of information on floods and flood-generating processes in the study area. Information on past torrential and flood disasters is being collected from multiple sources: observation networks, references, archive records, and field studies conducted within the

Fig. 5. Information on flood scars on trees may offer additional insights on high flows and floods to be accommodated in the data base.

project. Field experiments have been carried out and further ones are planned, aimed at improving the understanding of flood risk. They deal with dendrogeomorphology and thereby focus on the analysis of flood scars (Fig. 5). The existing instrumental data and historical information are relatively short and unevenly distributed within the studied region. The oldest hydrological measurements have started in the second part of the 19th century. These data are incomplete and suffer from significant uncertainty (Fig. 3). In addition, the number of water gauges located within the Tatra Mountains is insufficient to trace floods in the headwater parts of the catchments. It is expected that tree-ring reconstructions will help to overcome this lack of information and that they will yield valuable information about the frequency of past flood disasters. The magnitude of past flood events will be assessed through the analysis of tree disturbances, such as scars (indicative of the energy of the water and of physical impacts by materials transported by the flow; Johnson *et al.* 2000) and coupled to hydraulic approaches (*e.g.*, empirical equations, 1D and 2D models). Based on this data on flash flood frequency (Ruiz-Villanueva *et al.* 2010) and the vertical distribution of impact scars on the stem surface (Ballesteros *et al.* 2011), an accurate reproduction of flow heights can be obtained, which in turn will allow deriving data on stream power, flow velocity and discharge of past flood events. Several streams along the Tatra Mountains will be investigated with dendrogeomorphic techniques to compile the most exhaustive database of past events. This will allow instrumental record data series to be extended, complemented or possibly verified using proxy data, and incorporating this information in the flood frequency analysis, uncertainty in the quantile estimation may be reduced.

On the basis of this database, characteristics of past flood disasters will be reconstructed and interpreted. The project will study flood generating events and their variability and tendencies during last decades by analysing meteorological conditions, weather and circulation patterns involved in the triggering of intense precipitation and torrential disasters as well as hydrological conditions (via stream discharge records). The project also makes use of hydrometeorological data provided by the Institute of Meteorology and Water Management – State Research Institute (IMGW-PIB).

The collaborative FLORIST project is expected to improve our understanding and reduce uncertainty in the interpretation of past and expected future changes in the frequency and magnitude of torrential processes and river floods in mountainous watersheds. Examination of available data gives conflicting evidence for an increase in the frequency and intensity of heavy precipitation events (Kundzewicz *et al.* 2006). There is no ubiquitous finding that severe floods are becoming significantly more frequent and more intense in the warming world (Kundzewicz *et al.* 2005). Whereas some authors detect a significant increase in the number of torrential disasters, others report decreasing numbers of events or do not observe any significant trends at all. The fact that results are contradictory and that they differ between study regions clearly highlights the necessity to continue efforts to solve this problem of vast practical relevance and to launch projects at the local and regional scales.

7. PROCESSES OF FLOODING AND WOOD DEBRIS TRANSPORT

Work also addresses flood risk related to the presence of woody debris in mountain watercourses. Tracking experiments with tagged wood will be performed during flood events in a reach of the River Czarny Dunajec, aimed at providing quantitative data on the transport of woody debris and on the potential to retain large wood in river sections of distinct morphology and channel management. Radio transmitters have been installed in trees growing along the river banks prone to erosion and in logs already occurring in the river prior to the passage of a flood wave. Both variants of the tracking experiment have definite advantages and deficiencies. We tend to install radio transmitters in the logs of similar dimensions, especially length, that can be found in the river close to the beginning of its incised, channelized, and multi-thread sections.

Data from wood inventories in the watercourses narrower and wider than the height of riparian trees will be compared to determine how the pattern of wood storage in these watercourses varies with channel width. A number of studies performed in relatively small mountain streams have indicated that the amount of wood retained on unit channel area decreases with increasing channel width (Kaczka 2005). At the same time, the opposite trend was recorded during the wood inventory performed in the Czarny Dunajec (Wyżga and Zawiejska 2005, 2010). This suggests that the locations at which woody debris can be transported downstream or preferentially retained can differ significantly between watercourses narrower and wider than the riparian tree height, with contrasting effects on flood risks related to either the transported debris or to flow obstructions in the two types of watercourses.

These studies will be complemented with 2D hydrodynamic wood transport modelling. The model recently developed by Ruiz-Villanueva (2012) will be used to run several scenarios including different hydrodynamic regimes and wood recruitment rates. The model is a 2D hydrodynamic simulation solved with the finite volume method and incorporates a Lagrangian module which calculates the position and velocity of logs with different sizes based on the balance of forces involved in wood motion. A significant contribution of this model is that hydrodynamics and wood transport are computed in two ways; therefore, the hydrodynamics influences the wood transport, but the presence of wood also influences the hydrodynamics. The modelling will allow reproduction of the patterns of wood accumulations, but it also may be used to test some other features of wood transport and storage in mountain rivers (Gurnell *et al.* 2000, Wyżga and Zawiejska 2005). From a flood risk perspective, wood may increase significantly the impacts of floods, particularly in critical sections such as bridges (Ruiz-Villanueva *et al.* 2013). The bridge at Długopole is the narrowest one on the River Czarny Dunajec and thus potentially at risk of wood clogging, with the resultant flood damage to nearby settlements. The mobilization of woody material in rivers has been considered in the past, but very few studies have included this phenomenon in flood hazard and risk analysis (Diehl 1997, Lyn *et al.* 2007, Mao and Comiti 2010). The feasibility to pass large wood (Schmocker and Hager 2011, Lassettre and Kondolf 2012) will be tested in the Czarny Dunajec by means of modelling and scenario-based approaches. This shall allow analysis of the influence of wood transport and accumulations on flood risk and an evaluation and assessment of possible prevention and mitigation tools.

8. MODELLING OF CLIMATE-RELATED IMPACTS – HINDCASTS AND PROJECTIONS

The FLORIST project will document and quantify the impacts that climatic changes are expected to have on the occurrence (frequency), size (magnitude), duration, and spatial extent characteristics of projected future intense precipitation and river floods. Analyses will first focus on the impact of climate change on the occurrence of events by comparing the occurrence probabilities of disasters under current conditions with those expected to prevail under future climatic conditions. On the ground of model-based projections of future precipitation, intense precipitation, and river discharge, one can assess future changes in flood risk.

Climate models predict increased duration, severity and frequency of intense precipitation over some areas and this may translate into increased climate-related flood risk in the future. However, in the existing studies related to mountainous and piedmont areas (*e.g.*, Zimmermann and Haeberli 1992, Stoffel *et al.* 2008, Stoffel 2010), the findings are study- and site-specific. Expected changes in torrential activity exhibit different patterns depending on the model used and study region and generalized conclusions are not possible.

The frequency and size of future torrential disasters will not only depend on climatic parameters like precipitation and temperature, but also on system-intrinsic factors such as sediment and wood debris availability. A realistic evaluation of future torrential disasters and river floods will therefore need to take account of sediment and wood debris sources and climate model output data downscaled to the level of torrential catchments. The flood risk depends also on other factors, such as land use, land-surface properties, and water storage in the catchment.

Significant effort has been made over the past few years towards a characterization of future climatic changes and the estimation of related impacts using different greenhouse gas emission scenarios. In the Polish Tatra Mountains, according to different RCMs, a warming climate will presumably result in seasonal shifts and higher inter-annual variability of precipitation (extremes getting more extreme), and induce an increase in extreme precipitation events (*e.g.*, Christensen and Christensen 2004). However, no study on future projections in this important, flood-triggering area has been conducted to date.

The likelihood of the occurrence of changes in the frequency and magnitude of intense precipitation, torrential disasters, and flooding by 2050 and 2100 will therefore be analysed in the FLORIST project. In a first step, retrospective modelling of past torrential disasters and floods will be performed. Based on this experience, scenario-defined modelling of extreme future events will be done, which will allow quantification of risks of past and potential future events.

Study of future change in extreme precipitation events will be conducted based on downscaled RCM ensemble projections. The project will derive scenarios of climatic events triggering flooding disasters and quantify uncertainties. Uncertainties will be addressed and the probability of events of a specific size will be quantified. Sources of uncertainty in future climates will deal with predicted emissions scenarios, imperfect parameterisations of many components of the climate system, and with sensitivity to initial state uncertainties. It has become a widely accepted practice to quantify these uncertainties using ensembles of multiple GCM runs for each of the three factors mentioned.

Solid time series on past and contemporary events without significant gaps are among the primary pre-conditions for a realistic determination of potential future torrential hazards and risks. Such data is often missing, or records are not readily accessible. Modelling of torrential disasters and river floods can only be performed realistically if models are tested against reality, meaning that data from past events must be obtained to calibrate the model and to assess its accuracy before scenario-defined events can be realistically represented and the vulnerability of objects at risk evaluated for future projections. These issues are highly critical for realistic and credible assessment of future hazards, but to date they have not been addressed in research on torrential processes in Poland in general and in the northern foothills of the Tatra Mountains in particular. Even more critically, such analyses have been performed only exceptionally in other mountainous settings around the globe. The climate track will be studied based on observations and projections, with the use of the state-of-the-art climate model results available from the ENSEMBLES pan-European multi-partner project of the European Union Sixth Framework Programme (http://ensembles-eu.metoffice.com), where several FLORIST scientists were collaborating.

9. CONCLUDING REMARKS

Stationarity is "dead" (Milly *et al.* 2008), *i.e.*, the past is not really a key to the future, as we are entering a situation with no analogy in past records and this general finding is of vast importance also for flood preparedness systems and design rules. What used to be a 100-year river discharge (with exceedance probability of 0.01 in any one year) is projected to be exceeded less frequently over some areas and more frequently over other areas. In the areas of increasing flood risk, where the level of past 100-year flood is projected to be exceeded more frequently, there will be a need to strengthen the existing flood preparedness system, in order to maintain the same protection level. Multiple flood protection measures are needed, of both structural and non-structural type, also adjusting the management of the valley floors. In order to adapt to changes, better understanding and more reliable and accurate information is needed.

The knowledge generated in the FLORIST project is likely to have impact on understanding and interpretation of flood risk on the northern foothills of the Tatra Mountains, in the past, present and future. It can help solving important practical problems related to flood risk reduction strategies and flood preparedness. Hence the FLORIST project will not only be of considerable scientific interest, but also of social and practical relevance. Last but not least, research that may quantify changes in flood risk in the area where destructive floods are endemic can be of value for implementation of the EU Floods Directive.

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