A 100-Year History of Floods Determined from Tree Rings in a Small Mountain Stream in the Tatra Mountains, Poland

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1 Introduction

Dendrochronological methods enable the dating of episodes with sudden disturbance events such as forest fires, tree uprooting, rockfall, and snow avalanches in time and space (e.g. Denneler and Schweingruber 1993; Fantucci 1999; Lang et al. 1999; Niklasson and Granström 2000; Storaunet and Rolstad 2004; Stoffel and Perret 2006). Tree rings have also been used to identify floods and raised water levels (Harrison and Reid 1967; Begin and Payette 1988; Hupp 1988; Gottesfeld and Gottesfeld 1990; Tardif and Bergeron 1997; Begin 2001). Information on past activity might be preserved in living trees or dead stumps, thus allowing a long-term reconstruction of past flood events (LePage and Bégin 1996; Yanoski 1999; St George and Nielsen 2003). The time window accessible using tree scars is probably wider than that achieved by dating coarse woody debris accumulated in stream channels. This seems to be especially true for small, steep mountain streams with water flow causing redistribution, fragmentation and abrasion of tree trunks shortly after their delivery to the channel.

Annual rings of various tree species record the occurrence of floods following cambium injury or death in a portion of the circumference due to mechanical abrasion. If the size of the wound is not sufficiently large for the tree to be killed, the injury is often overgrown in the years following the event to form a scar. The identification of overgrown scars can allow for a detection of the exact year of an event that

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caused the injury (Arno and Sneck 1977). Flood scars are wounds on the stems of trees growing on channel banks and in floodplains caused by impacts from objects transported with water (Gottesfeld 1996) such as floating woody debris, ice, stones and boulders. A distribution of scars on calendar-time scale permits the identification of years with flood events (Harrison and Reid 1967). There are, however, only few examples of flood event reconstructions using tree scars in Europe. Historical information about flood events is usually limited to rivers crossing inhabited areas where floods are a serious source of damage. Much less information is available from small forested catchments, such as the one identified for this research. Data generated by such a study might be very important in explaining and understanding fluvial activity of streams, geomorphological dynamics of stream channels, transportation of debris including coarse woody debris or the dynamics of riparian vegetation (McCord 1996).

Floods are among the most dangerous and unpredictable phenomena responsible for enormous losses and constituting a major threat for people. Detailed knowledge of the flood regime in the past, their frequency and intensity is important for the evaluation of potential threats for the future. Because floods are phenomena of cyclic character, it is especially important to obtain the longest possible series of observation. For this purpose, the length of dendrochronological reconstructions may significantly exceed standard series of discharge measurements or climatic records.

This study aims at (i) reconstructing a history of floods in a small mountain stream, (ii) relating these events to meteorological records, and at (iii) indicating possible combinations of extreme weather variables, which may be responsible for the occurrence of floods.

2 Study Site

The study was conducted in the Polish Tatra Mountains in the Western Carpathians and focused on the Potok Waksmundzki mountain stream (Fig. 1). The climate in this area is cool (mean annual temperature: 2–4°C, Hess 1996) and the annual precipitation at elevations of approximately 1,600 m a.s.l. reaches 1,800 mm/year. Common soils in the area are acid podzols formed on granite bedrock (Komornicki and Skiba 1996).

The Potok Waksmundzki stream originates at an elevation of 1,950 m a.s.l. and its outlet into the Białka River is located at approximately 1,000 m a.s.l. The total length of the stream is 6.6 km, the mean slope is 14.6% and the drainage basin area is 5.35 km^2. Bedrock of the valley is dominated by granite and below 1,430 m a.s.l. the stream flows through a forested area. The Waksmundzka Valley belongs to the best preserved areas in the Polish Tatra Range, as the entire valley has been declared a strict reserve in the Tatra National Park for the last 50 years, thus forest management practices and other human activity have been significantly limited.

The study was conducted along a 2.75 km-long section of the stream at an altitudinal range of 1,380–1,080 m a.s.l., where the stream flows through a natural subalpine forest.

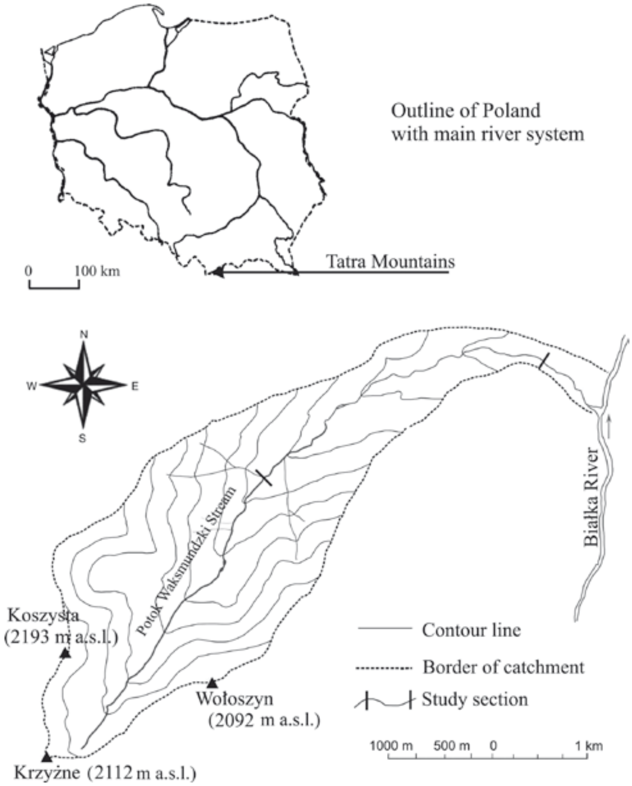

Fig. 1 Map of the study site. The catchment of the Waksmundzki stream and its location on a map of Poland

The stand covering the entire valley including the stream banks is dominated by Norway spruce (*Picea abies*). At higher elevations, dwarf pine (*Pinus mugo*) and individual stone pines (*Pinus cembra*) are present as well. Forest stands in the valley are unevenly-aged and spruces 150–200 years old dominate, however some of the oldest spruces attain up to 350 years at DBH (Zielonka 2006). The bottom of the valley near the channel is usually covered with younger tree cohorts.

3 Material and Methods

Basal parts of trees, both living and dead, were inspected on both banks of the stream for the presence of scars and the other growth anomalies. Only scars closest to the stream channel and facing the stream axis were integrated (Fig. 2). We paid attention to exclude scars formed by other factors such as the fall of neighbors from inside the forest or rot. Scars of doubtful origin were not included in the study.

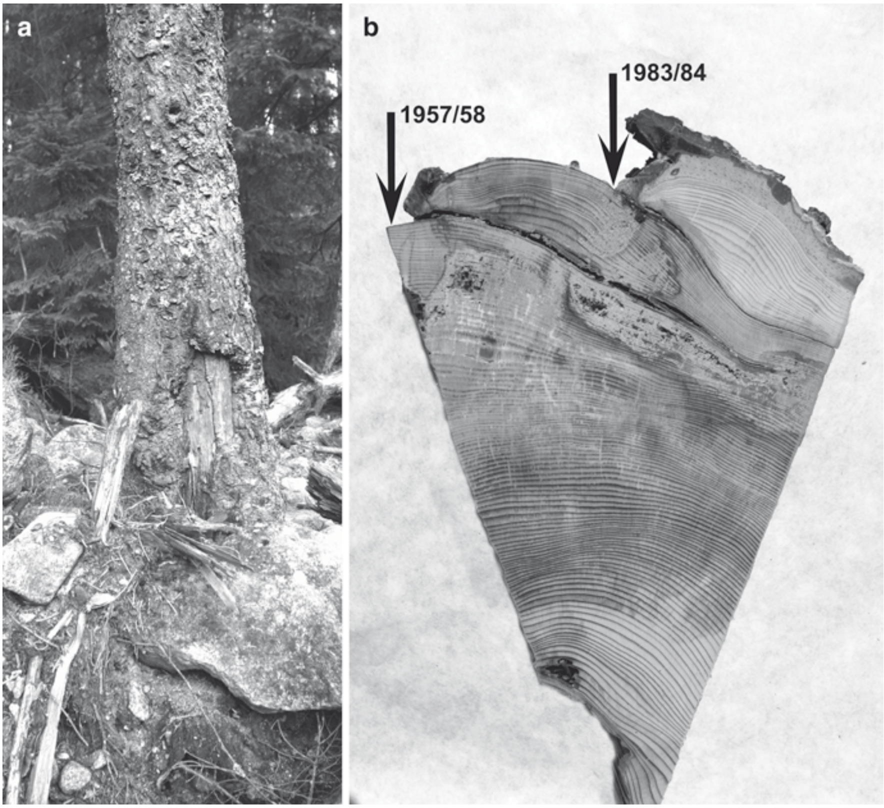

Fig. 2 A typical flood scar in a base of a spruce stem from the stream bank formed by debris transportation during a flood event (**a**). Cross-section extracted from the stem exhibits two flood scars. Dendrochronological cross-dating indicates that both scars were formed during the dormant season, namely in 1957/1958 and 1983/1984 (**b**)

In total, 48 wood samples containing scars were extracted with a saw from dead and living trees, with trees being evenly distributed along the 2.75 km-long section of the stream. While whole cross-sections were collected from dead stumps, sampling of living trees was restricted to the extraction of wedges from the scars (Arno and Sneck 1977). In the lab, samples were dried and polished with a belt sander. For the construction of a local reference chronology, 30 living spruces were chosen in the forest surrounding the stream within an altitudinal gradient between 1,100 and 1,300 m a.s.l. Selected trees belonged to the dominant layer and were free from visual signs of mechanical disturbance like broken tops or damaged branches. Each tree was cored twice perpendicular to the slope direction. Cores were glued to wooden sticks, dried and polished. Ring widths of wood samples and cores were then measured with a resolution of 0.01 mm using the LINTAB measurement devices (Rinn 1996). Before constructing the reference chronology, the validity of tree-ring measurements was checked with COFECHA (Holmes 1983) and two measurements of each tree were averaged. So as to eliminate long-term variability, time series were indexed using a five-point moving average (Baillie and Pilcher 1973). Wood samples with scars were then cross-dated against the reference chronology using standard parameters provided by the TSAP software (Rinn 1996), before the validity of the cross-dating was verified with the sequence of pointer years (Schweingruber et al. 1990). The calendar year of scar formation was then determined (Fig. 2). We compared the years of scar formation with available climatic data recorded at the meteorological station in Zakopane, located approximately 10 km from the study area at an elevation of 820 m a.s.l. Climatic records are available for the station since AD 1900. The following weather parameters were taken into consideration: average monthly precipitation for the April-September period, average winter precipitation (December–March), the highest 24-h precipitation in a year, and the difference between average April and May temperatures (as a snow melting indicator). Variance analyses were used to test the significance of the relationship between the years of scar formation and weather parameters. As the time of scar formation was determined with yearly resolution, we assumed that weather parameters responsible for spring and early summer floods are linked with scars formed in the previous calendar year during the dormant season.

4 Results

Most of the cross-dated tree-ring series covered the entire twentieth century (Fig. 3). The oldest ring identified in the trees growing along the channel was cross-dated to 1841. In 14 samples, the first rings were formed in the nineteenth century.

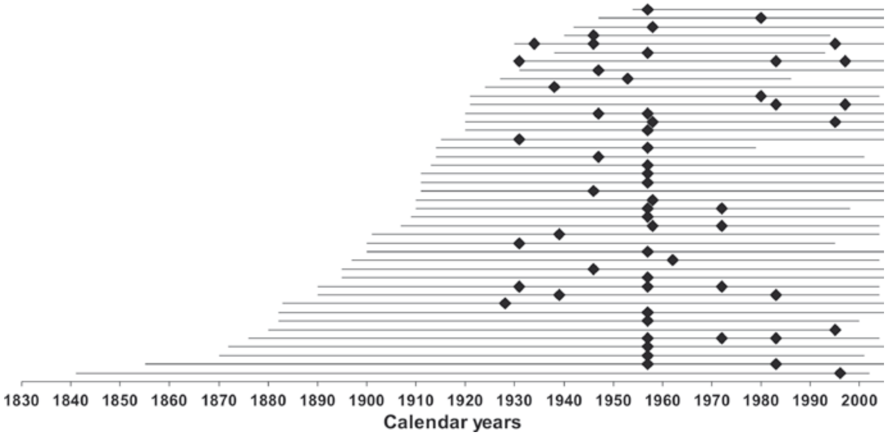

Fig. 3 Distribution of flood scars in time. *Horizontal lines* show the time span of each tree, *dots* indicate the year of scar formation in the trees sampled

However, in some cases, it was not possible to cross-date the pith due to rot in the central part of the stem.

Analyses allowed for a cross-dating of 58 scars (Fig. 3). The oldest recorded wound was induced in AD 1928. Four wood samples contained three scars, six samples contained two scars, and the rest of the trees bore just one scar (Fig. 3). For the period between AD 1928 and 2005, 17 years with scars were identified. On average, scars occurred every 4–5 years. The highest number of scars (33% of all recorded) was observed in the dormant season of 1957/1958. Numbers of scarred trees in the remaining years were much lower and did not exceed six scarred trees per year (1946/1947).

Monthly precipitation averages distinguished by both high values as well as peaks in the twentieth century overlapped with the years of scar formation (Fig. 4). This is especially true for the summer months, when precipitation was generally highest. Peaks in precipitation of July overlapped with scar formation in AD 1934, 1938, 1980 and 1997 (Fig. 4). The highest precipitation in the century occurred in June (over 300 mm in 1948, 1959 and 1972) and might be responsible for scar formation in the dormant season before cambial activity or in the beginning of cambial activity in these years. Similarly, the second highest level of precipitation during the last century, in May 1940 might have resulted in scars in the dormant season of 1939/1940. Unusually high precipitation in August 1938 (305 mm) and August 1972 (323 mm) might also have resulted in late summer floods which were responsible for scar formation. In September, which usually is much dryer than the summer months, high values of 272 mm were recorded in 1931 and 247 mm in 1996 when scars were formed. The relationship between years of scar formation and snow accumulation in winter (precipitation December–March) was not statistically significant, and no years with high winter precipitation coincides with years of scar formation (Fig. 4).

The maximal 24-h precipitation recorded in individual years does not seem to be strongly related with years of scar formation. In AD 1934, when the highest 24-h precipitation was observed (172 mm), only one scar was found in the trees (Fig. 5). During an important 24-h precipitation event in 1983 (109 mm), however, we identified five scars in the selected trees (Fig. 5).

The best explanation as to why the highest percentage of scars appeared in 1957/1958 (33%) was the extraordinary value of snow melting indicator (Fig. 6). The difference between the mean temperatures of April and May 1958 was more then twice higher than the average for the century and totaled 12.2°C (Fig. 6). This was the result of exceptionally low temperatures in April (mean 1.4°C) followed by a very warm May (mean 13.6°C) (Fig. 7). A similar situation may have occurred in 1929, when a difference between May and April temperature of 10.6°C was noted and the oldest scar found in AD 1928/1929. However, an ANOVA test for the entire series of scarred years did not confirm the significance of this relationship. In the case of the event year 1946/1947 showing the second highest number of scars, none of the analyzed parameters indicated abnormal precipitation or temperature distributions.

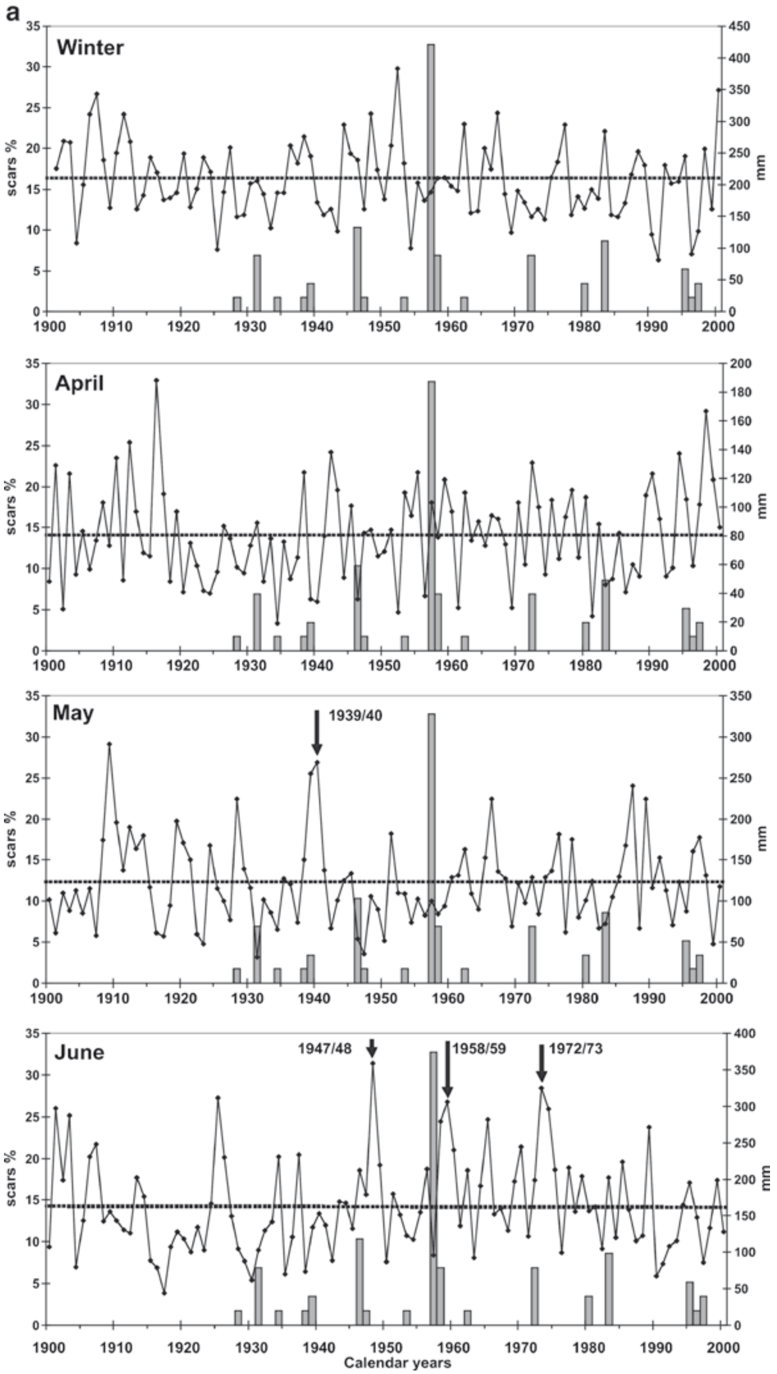

Fig. 4 Percentage of formed scars and the distribution of monthly precipitation in the twentieth century. Winter precipitation comprises precipitation in January, February, March as well as December of the previous year. *Dashed lines* show the average value for the century. *Arrows* indicate years with the highest precipitation which might be responsible for scarring

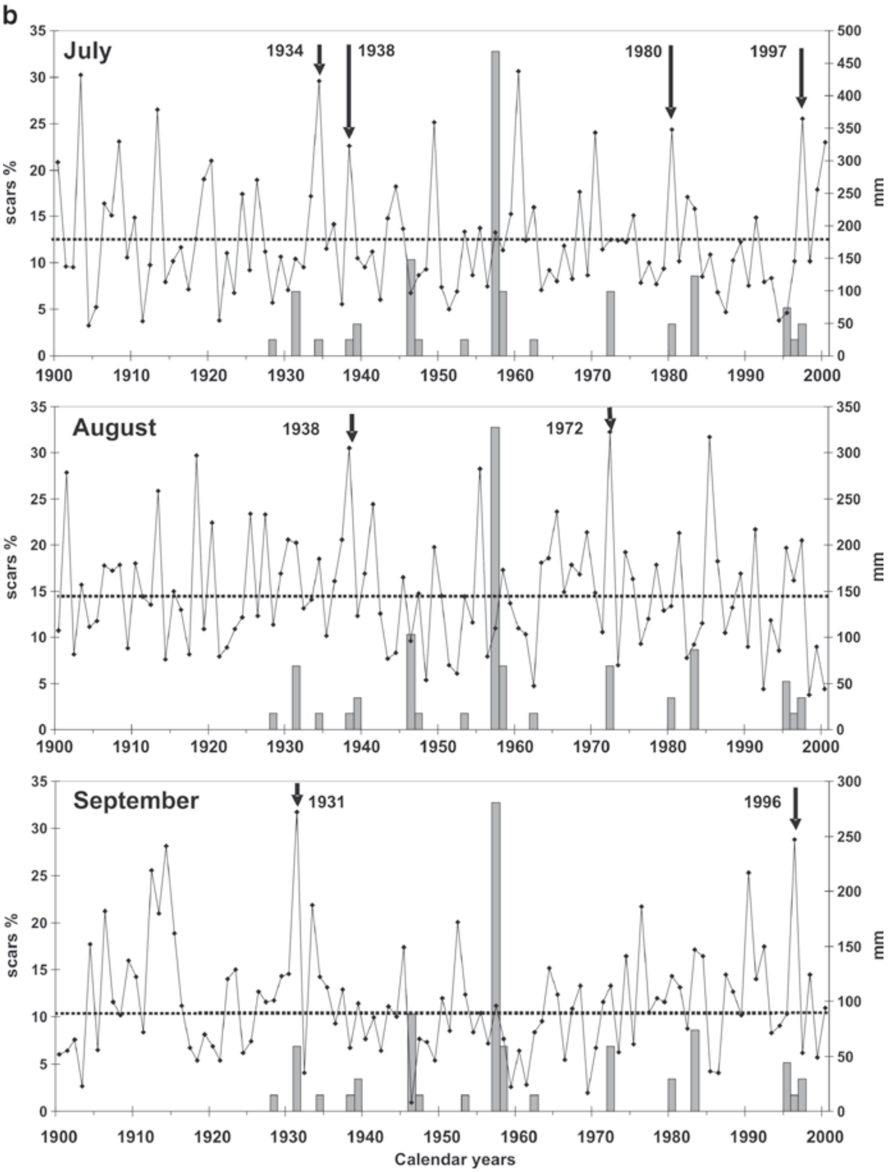

Fig. 4 (continued)

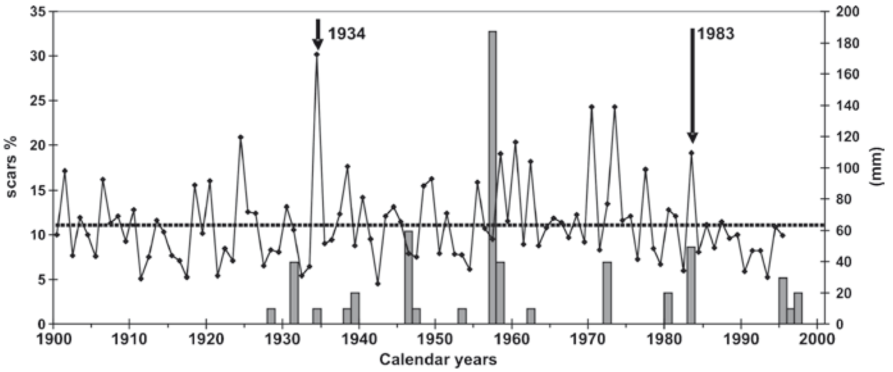

Fig. 5 Percentage of scars and the maximal 24-h precipitation recorded during a year. The *dashed line* shows the average value for the century. *Arrows* indicate years with the highest precipitation which might be responsible for scarring

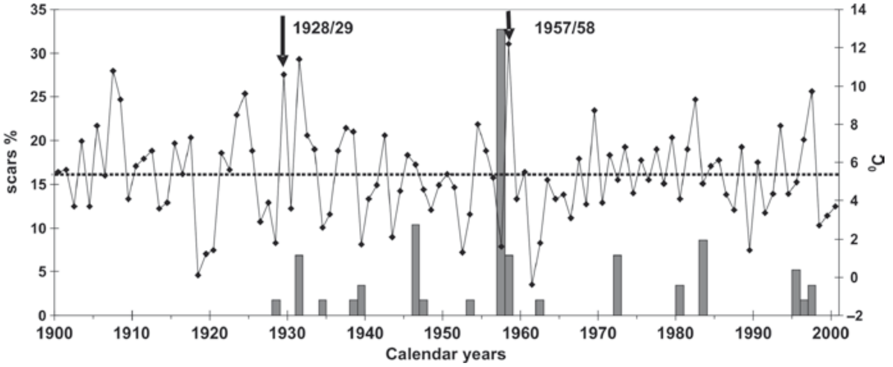

Fig. 6 Percentage of scars and snowmelt (difference between the average temperatures of April and May). The *dashed line* shows the average value for the century. *Arrows* indicate years with the highest values of the melting factor which might be responsible for scarring

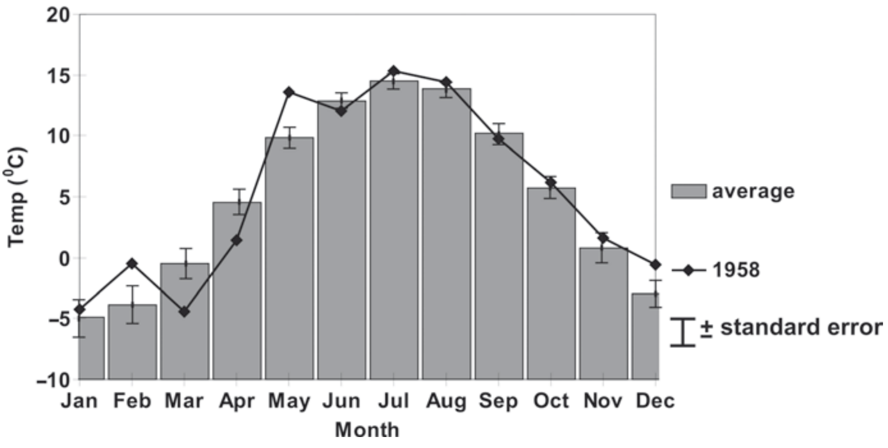

Fig. 7 Distribution of monthly temperatures, average for the whole century and for AD 1958

5 Discussion

In the Waksmundzki Potok stream, scars on trees are most likely caused by transported logs and probably also rocks and boulders. Logs of different stages of decay and various dimensions were present along the whole study section of the stream. Also, scars might be caused by granite boulders, which fill the stream channel. During fieldwork, boulders of different dimension were identified on the banks among ground vegetation, and this indicates that granite debris can be transported from and to the channel banks during floods. In contrast, floating ice, which can also be responsible for tree injuries (Begin 2001), is nonexistent in the studied stream due to the high relief and high decline of the stream channel.

According to Gottesfeld's (1996) observations, scars are easily formed on the stems of living trees by rubbing of transported logs during floods. Woody debris may hit partially submerged trees forming a wound, then rotate and continue movement downstream. Other stems may remain anchored against trees and start to rub the bark according to changes of the water level. Such a rubbing cycle may last from 10 s to several minutes with vertical movement ranging from 10 to 30 cm (Gottesfeld 1996). These mechanisms may also explain the occurrence of several scars in the same tree. After causing the first wound, a log remaining caught at the base of a living tree may cause further scars during the next flood event, thus resulting in a series of partially healed wounds (Fig. 2). On the other hand, successive and partially healed scars occurring at the same position of the tree trunk may also result from frequent impacts of debris.

The average time interval between subsequent flood events calculated for the period AD 1928–2005 was 4.5 years and shows that the Waksmundzki stream discharge can be highly variable and flood events appear very frequently. The lack of scars before AD 1928 could be caused by at least two factors. Most of the trees growing on the banks were rather young. Flow activity of the stream as a disturbance factor probably resulted in the lack or regular removal of old trees on the banks. It can also be expected that a minimal diameter is required for a tree to sustain an injury and survive. Trees of small diameters could easily be devastated by floating objects, or wounds might be too extensive to enable further growth. We can also presume that the channel was located at some distance from the present course of the stream before the late 1920s. Old, inactive channels, overgrown by vegetation and spruce regeneration were observed in the field in some flat fragments of the valley bottom.

Our results show that most probably there are two weather factors responsible for floods in the studied stream: violent mid-summer rainfall and heavy snow melting in spring. In the Tatras, the highest precipitation amounts occur in the summer months. The average July precipitation for the twentieth century was 177 mm. Rainfall in this month might be responsible for scar formation in AD 1934, 1938, 1980 and 1997. During these years, July rainfall varied from 323 to 423 mm and was more than twice as high as the mean precipitation for July. For example, at the beginning of July 1997, a large flood was recorded throughout southern Poland,

and much flood damage was reported along streams and rivers in the nearby area. August is characterized by lower average precipitation (147 mm), however, the rainfall can still be substantial in this month. In 1972, when four flood scars were formed, the highest August rainfall in the twentieth century was recorded (323 mm). Also, in AD 1938, a very wet July was followed by a rainy August.

The amount of snow fall during winter does not seem to influence the occurrence of spring floods. Irrespective of precipitation in winter, the depth of the snow cover is 0.5–1.5 m but locally may exceed 3 m in the higher elevations (Łajczak 1996). The rate of snow melting which most likely induces high water flows is more important. Many scars formed in the dormant season of 1957/1958 were most likely the result of such an intense snowmelt event in late spring of 1958. Climatic records also indicate that an unusual increase of the temperature in May occurred during this year. The monthly temperature of April was 3.1°C below average while the temperature of May was 3.8°C above average. The snow melting period, which normally lasts from April to May was limited to May in 1958. Also, the average precipitation in June 1958 exceeded considerably the average for the century. This may indicate that flooding in 1958 was a result of a coincidence of intensive snowmelt due to warm spring temperatures and high precipitation amounts in June. Such a combination of extremes, when snowmelt adds to the catchment discharge from the rainfall may cause flooding (Benestad and Haugen 2007). The flood in 1958 was also recorded in nearby Tatranská Lomnica (Slovakia), located on the other side of the mountain range (Koreň2005). Historical information also confirms a large flood in 1958 in southern Poland, described as "the largest since the Second World War" (Fal 1997). The oldest scar from 1928/1929 might also be a result of such an anomaly in AD 1929, when one of the highest differences between April and May temperatures was recorded.

The high precipitation in May and June reinforcing discharge normally caused by snowmelt may explain scar formation in 1939/1940, 1947/1948, 1958/1959 and 1972/1973, when the highest values of precipitation (>300 mm) were recorded.

The relatively small dataset collected in this study of the formation of scars during floods is to some extent accidental. The formation of a flood scar requires high flow, the presence of debris in the channel and finally an abrasive process in stems of trees growing on the bank. Thus, the flood scar indicates a flood event, but a period without scars does not have to be a period without floods. In the small scale of this study (2.75 km along a stream), a flood event may happen without leaving scars due to the lack of transported objects and therefore result in the absence of injured trees. Also scarred trees might have already disappeared from the banks. This means that the series of reconstructed flood events cannot be treated as a complete dataset. A similar problem concerns the intensity of the flood events. A high number of scars formed in the dormant season of 1957/1958 may indicate an event of relatively high intensity. In the case of the rest of the flood years when the number of scarred trees varied from one to six, the intensity of the flood can hardly be estimated. Available climatic records from Zakopane may not precisely reflect the weather conditions in the study area, where elevation is significantly higher. The use of monthly precipitation and temperature is a simplification as well, as it might be too long a period to detect weather anomalies. For instance, the presence of six scars identified in 1946/1947 could not be explained with climatic data. This shows that stream flow in small catchments extending across wide altitudinal ranges and different hydrological zones may react very violently to abrupt local weather change, which might not be recognized with basic weather records.

6 Conclusions

Our study shows that it is possible to reconstruct flood events in the fine scale of a small mountain stream over almost one century. It is hard to point out one weather factor, which is responsible for these flood events. In the mountain area, a flood is usually linked with complex extreme meteorological events like violent rainfall and rapid snowmelt due to high spring temperatures. Small catchments of high relief and varied physiography may react very suddenly to weather extremes. Flood-scar evidence proves that the Waksmundzki Stream discharge can be highly variable. Cross-dated scars also enabled detection of past floods, which hardly could be reconstructed only with basic climatic data. The reconstruction of the flood history based on tree rings may substantially improve our understanding of this phenomenon, especially in different spatial scales when direct discharge records are lacking.

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