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Paleoflood discharge reconstruction in Tatra Mountain streams

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ABSTRACT

Floods represent a common process in Tatra Mountain streams and may cause flood risk in the valleys of the Tatra foreland. Dealing with the hazards and risks caused by floods requires a detailed analysis of the frequency and magnitude of past and recent events. However, the Polish Tatra region is characterized by a scarcity of data on past floods in general and on systematic peak discharge in particular. In this study, we performed a paleohydrological analyses in four high-gradient mountain streams using scarred trees as paleostage indicators. We couple two-dimensional hydraulic modelling in a highly-resolved topographic environment (LiDAR data) with an important spatiotemporal data set of scars on trees to investigate (i) the magnitude of unrecorded major floods of the twentieth century, (ii) the effect of variability in geomorphic tree positions on the peak discharge reconstruction, and (iii) the impact of reconstructed events on the results of flood frequency analyses. The data set is based on a total of 55 scarred trees and allows peak discharge reconstruction of 16 major floods covering the last 113 years. Results suggest that trees growing in straight stream reaches or in the inner side of channel bends would be better candidates for peak discharge reconstructions than trees located on the outer side of channel bends or growing in overbank sections with dense vegetation cover. The largest reconstructed flood is dated to 1903 with an estimated peak discharge of 115.9 ± 59.2 $m^3 s^{-1}$, and larger-than-today floods are found to have occurred at Strążyska and Łysa Polana in the first half of the twentieth century. The inclusion of our results into the flood frequency analyses suggests that flood hazards might have been underestimated by up to 25.5% in the case of a 100-year flood in Strążyski Stream. In that sense, our findings will be useful for the design of future strategies dealing with flood risks in the foreland of the Polish Tatra Mountains.

1. Introduction

Mountain streams have steep channels and are characterized by recurrent, highly-turbulent and sediment-laden flows (Wohl, 2000, 2006). Their quick hydrological response as well as their considerable power (Borga et al., 2014) make mountain streams highly hazardous and events therein difficult to forecast (Marchi et al., 2010; Borga et al., 2011) such that they cause large amounts of losses and fatalities worldwide. Floods in mountain environments are related to catchment disposition, channel characteristics, and climate triggers (Blöschl et al., 2015), with the last being expected to change in the course of the next few decades with very direct and potentially drastic impacts on precipitation regimes (Kundzewicz et al., 2010).

In view of the ongoing climate changes and expected impacts on process activity, the assessment of flood hazard and risk in mountain areas will require an improved understanding of their spatiotemporal occurrence as well as their links and drivers to climate (Merz et al., 2014). An improved understanding of past and expected states and/or changes of the magnitude (i.e., peak discharge) as well as the return period of flood (Enzel et al., 1993; Lang et al., 1999; Baker, 2008) is not only critically needed for the management of riparian zones downstream of the headwater systems but also the design of reliable mitigation channel infrastructures such as artificial channels or dikes. The main drawback in analysing mountain streams is, however, related to the lack of past observations and measurements. As a consequence, the scarcity of systematic data or the shortness of existing records typically hamper the analysis of reliable and representative flood events, which in turn affects the flood hazard assessment (Sigafoos, 1964; Ballesteros-Cánovas et al., 2013, 2015a; Bodoque et al., 2015).

The Polish Tatra Mountain streams are a paradigm of this problem. In this region, the inhabited valleys in the northern foothills of the Tatras are subjected to frequent floods triggered mainly by intense and long-lasting precipitation during summer (Niedźwiedź et al., 2015). As the network of available gauging stations in the area is not only highly

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discontinuous, but also short operating and not really representative enough for a proper hydrological characterization (Kundzewicz et al., 2014; Ballesteros-Cánovas et al., 2015b,c), we were obliged to carry out alternative and complementary approaches to improve existing understanding of potential flood events in the area (Kundzewicz et al., 2014).

Botanical evidence represents a valuable resource to date and quantifies the magnitude of past flood events in streams with only poorly gauged data (Stoffel and Wilford, 2012; Ballesteros-Cánovas et al., 2015a) and thus allows extension of existing flow records, which may in turn improve the estimation of flood frequency distributions (FFD; O'Connor et al., 1994; O'Connell, 2005). Scars on trees result from the impact of and abrasion by sediment and woody debris transported during floods and have been described as being one of the most useful paleostage indicators (PSI) for peak discharge reconstructions (Yanosky and Jarrett, 2002; Baker, 2008). This scar-based approach is founded on a trial-and-error approximation between scar height and modelled water table profiles as obtained from hydraulic models (Jarrett and England, 2002; Yanosky and Jarrett, 2002; Ballesteros-Cánovas et al., 2015a). The reliability of scar-based peak discharge reconstruction has been proven over the past decades (McCord, 1996; Corriell, 2002; Yanosky and Jarrett, 2002; Ballesteros-Cánovas et al., 2011a,b). For instance, Smith and Reynolds (1983) observed that the average differences between the height of ice-flood scar and punctual flow gauge records along the Red Deer River amounted to 1.37 ± 0.94 m. By estimating the peak discharge of past flood events in two mountain streams in Arizona and Colorado (USA), McCord (1996) compared reconstructions with existing flow records and suggested that scar height could represent minimum flow stages. Observations from Gottesfeld (1996) in the Skeena River (USA) suggest that scar heights were closely related to maximum flood stage (within 20 cm), exhibiting a slope close to the water-surface slope at peak discharge. In the case of high-gradient streams, Yanosky and Jarrett (2002) documented a range of differences between scar heights and high-water marks (HWM) ranging between −0.6 and 1.5 m. Similar ranges of uncertainties have recently been suggested by Ballesteros-Cánovas et al. (2011a; −0.8 to 1.3 m) who also distinguished large from small scars. The same authors also highlighted the need to take critical sections with stable bedrock condition as well as sections with specific hydraulic conditions (i.e., transaction between different hydraulic phases) into account. These discrepancies between maximum flow stage as defined by HWM and scar heights observed in trees have been related to tree position and hydraulic flow conditions (Gottesfeld, 1996; Yanosky and Jarrett, 2002; Ballesteros-Cánovas et al., 2011a,b).

In this paper, we present a scar-based paleoflood discharge reconstruction for four poorly or ungauged mountain streams in the Tatra Mountains (Poland). Based on a comparably large number of scarred trees, two-dimensional hydraulic model and highly-resolved LiDAR data, we focus on (i) the quantification of past flood magnitudes, (ii) the definition of the most suitable geomorphic locations from which trees should be sampled for peak discharge reconstruction based on PSI (i.e., scar heights), and (iii) the comparison of existing flow discharge series for the region with the reconstructed events.

2. Study area

The peak discharge reconstruction was conducted in four different mountain streams draining the northern slopes of the Polish Tatra Mountains (Fig. 1; Table 1). Catchments and stream reaches were selected according to (i) their spatial and hydrogeomorphic representativeness of the region, (ii) the availability of flow gauge records, and (iii) their potential for dendrogeomorphic studies (i.e., presence of trees with PSI and limited human disturbance in the form of path networks or forestry). All the catchments contribute to the main foreland rivers for which a long record of flood damage exists for the last two centuries (Kotarba, 2004; Kundzewicz et al., 2014; Ballesteros-Cánovas et al., 2015b).

Catchment geology consists of a crystalline and metamorphic core overlain by Mesozoic sedimentary rocks. Characteristic geomorphic features of the area comprise — but are not limited to — Pleistocene glacial and Holocene mass-movement forms and deposits including glacier abrasion, glacier lakes, moraine deposits, and alluvial/colluvial fans. Vegetation is mainly characterized by five climatic-vegetation zones (Niedzwiedz, 1992), with timberline being located at around 1420 m asl. The high-elevation study reaches Rybi Potok (RP), Roztoka (DR), and Chochołowski Potok (DCH) are located in the cool temperate belts characterized by the presence of Norway spruce (*Picea abies* (L.) Karst.), whereas the low-elevation reach of Strążyski Potok (ST) is located in a cool temperate belt characterized by a mixed forest of *P. abies* and Silver fir (*Abies alba* Mill.). The channels of RP, DR, and DCH have been formed in granitic and pegmatitic bedrock (Bac-Moszaszwili et al., 1979) covered by gravel and loamy moraine deposits. By contrast, ST flows on sedimentary rocks. All four reaches have a straight and/or braided channel pattern and a channel bed composed of pebble-cobble material with sporadic boulders. Lateral gravel bars as well as woody debris are common in all reaches, whereas mid-channel bars were limited to DCH. Abundant bank undercuts and secondary channels testify to the presence of past fluvial activity and related flood events. Table 1 summarizes the main characteristics of the analysed stream reaches.

A limited number of hydroclimatic series exist in the study area. The oldest instrumental data date back to the end of the nineteenth century, when gauges were, however, frequently moved or working for only a few years. The two world wars during the twentieth century caused yet another gap in measurements. Table 1 provides information on available data and the length of records.

From a climatic perspective, the Tatra Mountains form a barrier for air mass movement and in particular for polar marine air masses (65%) and polar continental air masses (25%) that make up 90% of the events being blocked by the chain (Niedźwiedź et al., 2015). The blocking effect often results in heavy rainfall events with 24-h precipitation sums of up to 300 mm (30 June 1973; Niedźwiedź et al., 2015). Annual precipitation, therefore, varies from 1100 mm at the foothills (Zakopane, 844 m asl) to 1660 mm at timberline (Hala Gąsienicowa, 1550 m asl) and 1721 mm on the summits (Lomnicky, 2635 m asl). The most effective precipitation events resulting in floods are concentrated in the summer season (Niedźwiedź et al., 2015; Ruiz-Villanueva et al., 2014; Ballesteros-Cánovas et al., 2015b), with maximum recorded peak discharges of up to 144 $m^3 s^{-1}$ downstream RP and DR, 88 $m^3 s^{-1}$ at DCH, and 6 $m^3 s^{-1}$ at ST.

Over the last three centuries, the study region was affected by intense human activity in the form of pasturing and intense logging in the eighteenth and nineteenth centuries. Grazing pressure in the upper parts of the catchments has been particularly intense during the nineteenth and mid-twentieth centuries. Both impacts have altered soil and vegetation characteristics, resulting in increased flooding. The Tatra National Park was enacted in 1954, also to reduce the negative effect that altered soils and vegetation had on floods, but pasturing locally continued until 1978 and logging also remains permitted under certain conditions.

3. Methodology

3.1. Scarred trees analysis

All *P. abies* and *A. alba* trees presenting visible flood scars or evidence of internal tree damage were sampled and dated following the standard dendrogeomorphic sampling procedures as described by Stoffel and Corona (2014). These procedures consisted of (i) sampling of injured trees using an increment borer, (ii) sample preparation in the lab (mounting, sanding), (iii) tree-ring dating, (iv) detection of growth