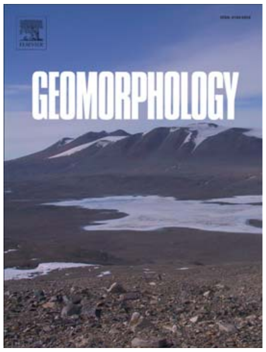

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Floods in mountain environments: a synthesis

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Abstract

Floods are a crucial agent of geomorphic change in the channels and valley floors of mountains watercourses. At the same time, they can be highly damaging to property, infrastructure, and life. Because of their high energy, mountain watercourses are highly vulnerable to environmental changes affecting their catchments and channels. Many factors have modified and frequently still tend to modify the environmental conditions in mountain areas, with impacts on geomorphic processes and the frequency, magnitude, and timing of floods in mountain watercourses. The ongoing climate changes vary between regions but may affect floods in mountain areas in many ways. In many mountain regions of Europe, widespread afforestation took place over the twentieth century, considerably increasing the amounts of large wood delivered to the channels and the likelihood of jamming bridges. At the same time, deforestation continues in other mountain areas, accelerating runoff and amplifying the magnitude and frequency of floods in foreland areas. In many countries, in-channel gravel mining has been a common practice during recent decades; the resultant deficit of bed material in the affected channels may suddenly manifest during flood events, resulting in the failure of scoured bridges or catastrophic channel widening. During the past century many rivers in mountain and foreland areas incised deeply; the resultant loss of floodplain water storage has decreased attenuation of flood waves, hence increasing flood hazard to downstream river reaches. On the other hand, a large amount of recent river restoration activities worldwide may provide examples of beneficial changes to flood risk, attained as a result of increased channel storage or reestablished floodplain water storage. Relations between geomorphic processes and floods operate in both directions, which means that changes in flood probability or the character of floods (e.g., increased wood load) may significantly modify the morphology of mountain rivers, but morphological changes of rivers can also affect hydrological properties of floods and the associated risk for societies. This paper provides a review of research in the field of floods in mountain environments and puts the papers of this special issue dedicated to the same topic into context. It also provides insight into innovative studies, methods, or emerging aspects of the relations between environmental changes, geomorphic processes, and the occurrence of floods in mountain rivers.

Keywords: flood; mountain river; environmental change; geomorphic change

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1. Introduction

Mountain environments cover roughly 25% of the land surface and are often referred to as 'natural water reservoirs' as a substantial amount of water surplus is usually transported from mountain areas to adjacent lowlands in some of the largest river systems on Earth (Viviroli et al., 2003). Mountain regions cover 52% of Asia, 36% of North America, 25% of Europe, 22% of South America, 17% of Australia, and 3% of Africa, as well as substantial areas of islands including Japan, New Guinea, and New Zealand (Bridges, 1990). Mountain rivers are defined here as having a mean elevation above sea level ≥ 1000 m (Viviroli et al., 2003). Despite the fact of being widespread, mountain rivers and river floods have not been studied in detail in the past and have only seen increased attention over the past decade (Wohl, 2010). Increased attention has been directed to maintenance or restoration of rivers and as critical areas of water supply in mountain environments, where human pressure typically is smaller than in the adjacent lowlands. In addition, steep and coarse-grained mountain rivers with poorly sorted beds and limited sediment supply are more poorly described by empirical equations for hydraulics and sediment dynamics, which renders them an ideal field for research and a challenge for river managers.

The hydrological response of mountain river catchments is driven by many factors including temperature, precipitation, soil, lithology, vegetation or slope, just to name a few. Floods in mountain rivers will be favoured by the typically steep channel gradients and can be generated by various types of rainfall, rain-on-snow, snowmelt, or the failure of either natural or artificial dams (Weingartner et al., 2003). As a result, floods in mountain rivers often differ from those in lowland environments because of the close coupling between the channel and adjacent hillslopes (Wohl, 2010).

This contribution does not aim at providing a complete review of literature on floods in mountain rivers and their histories, drivers, and changes but merely tries to summarize some of the key issues in the research field and to put the contributions of the special issue *Floods in Mountain Environments* into perspective. Most of the contributions of this chapter have in fact been presented during the International Geographical Union (IGU) Regional Conference in Kraków, Poland, between August 18 and 22, 2014 (www.geo.uj.edu.pl/konferencja/igu2014/).

2. Channel incision processes in mountain streams

In the last century a tendency to channel incision appeared so common worldwide that causes, controls, course, and effects of the phenomenon became a focus of international scientific debate (Darby and Simon, 1999); and incised rivers are now considered to represent typical *Anthropocene* landscapes (Florsheim et al., 2013). While bed degradation of alluvial rivers induced by tectonic uplift or climate change has mostly initiated the formation of new valley floors at lower positions, contemporary incised rivers are the effect of human-induced rapid rates of bed degradation usually coupled with constraints on lateral river migration. Opposite evolutionary tendencies of European mountain rivers in the eighteenth–nineteenth centuries and in the twentieth century (Kondolf et al., 2002; Rinaldi et al., 2013) indicate that floods are only a mechanism entraining and transporting bed material in incising rivers, whereas river incision itself has been caused by the lack of equilibrium between a river's transport capacity and the amount of sediment available for fluvial transport (Simon and Rinaldi, 2006). Sometimes incision can be ascribed to a single type of disturbance or environmental change such as channel regulation (Simon, 1989), catchment reforestation (Liébault and Piégay, 2001), or cessation of in-channel deposition of mine tailings (James, 1991). However, more frequent are situations when the tendency has resulted from a complex interplay of factors that either restricted availability of bed material for fluvial transport or increased transport capacity of the river (e.g., Bravard et al., 1997; Surian and Rinaldi, 2003; Wyżga, 2008).

Channel incision decreases local frequencies of overbank flows and—as a result of increased channel conveyance—affects downstream flow patterns. By comparing peak discharges of flood flows recorded upstream and downstream of incising reaches of two rivers in the Polish Carpathians, Wyżga (1997) demonstrated high temporal consistency of changes in vertical channel position of the analysed rivers and of the increase in flood peaks recorded downstream. This increase in flood hazard to downstream river reaches was attributed to increased concentration of flood flows in the deepened channel that reduced floodplain storage of floodwater and increased relative smoothness (ratio of water depth to the height of protrusion of bed material particles to the flow) of channel flows, hence accelerating the passage of flood waves (Wyżga, 1996). Costa and de Almeida Prado Bacellar (2007) found that gullying of catchments in southeastern Brazil results in decreased base flow and increased occurrence of high but short-lasting storm flows and explained the change in flow pattern by increased rates of regolith drainage after rainfall events.

In this issue, Wyżga et al. consider impacts of channel incision on the hydraulics of flood flows using examples from Polish Carpathian rivers. They first indicate that in the literature, channel deepening is frequently ascribed to channel incision; but it may also result from river metamorphosis changing a wide and shallow channel to a narrow and deep one. In contrast to channel incision, this process does not lead to increased channel capacity; consequently, a lowering of water stage associated with a given discharge rather than a lowering of river bed should be used as a diagnostic feature of channel incision. The authors next discuss suitability of a lowering of minimum annual stage at gauging stations as a metric used to assess the hydraulic importance of channel incision and to compare it along a given river or within a particular region. In Polish Carpathian rivers, absolute amounts of incision are greater in the middle and lower courses. However, the relative increase in channel conveyance resulting from incision is greatest in their upper courses, where the initial channel capacity was relatively low. As the loss of floodplain storage of floodwater caused by channel incision tends to be largest in upper river courses, this is where special efforts should be made to arrest, limit, or prevent river incision. Finally, the authors demonstrate that hydraulic effects of channel incision depend on lateral stability of an incising river. Where the incising rivers remained laterally stable, incision has mostly reduced water stages associated with low flood discharges and considerably decreased flow velocities over the floodplains. In contrast, the formation of incised meander belts caused by lateral migration of incising rivers has substantially lowered stages for all flood discharges and increased flow velocities over the newly formed, low-lying floodplains.

3. Riparian forest development and increased wood delivery to watercourses

Mountain and piedmont areas in Europe experienced remarkable expansion of riparian forest cover over the last century (e.g., Kondolf et al., 2007; Wyżga et al., 2012). One of the effects of riparian forest development was the intensification of large wood recruitment and increased flood hazard resulting from wood transport and deposition during flood events. This is reflected in increased frequency of clogging by wood in critical river sections such as those with bridges (e.g., Ruiz-Villanueva et al., 2013; Lucia et al., 2015). Effective prevention of flood hazard related to large wood in mountain watercourses may require structures that trap wood from floodwaters (Comiti et al., 2012), but better recognizing wood dynamics during floods is crucial. Research of wood dynamics in mountain watercourses is thus an important element of projects aimed to improve the recognition of flood hazard and risk in mountain areas (Kundzewicz et al., 2014).

Use of innovative techniques of the monitoring of large wood recruitment, transport, and deposition during flood events improved insight into the wood dynamics in watercourses. MacVicar et al. (2009) indicated a possibility of recording the transfer of large wood pieces during floods with a video camera. Results of such a study of wood transport by floods in the Ain River, France, were first presented by MacVicar and Piégay (2012). It indicated that wood starts to be transported at approximately two-thirds of the bankfull discharge and that transport rates are a few times higher on the rising limb of the hydrograph than on the falling limb.

Tagging trees along channel banks or wood pieces already present in a channel was used to determine their transport distance during individual floods or a sequence of flood pulses. In streams where large wood typically moves relatively short distances, wood pieces were tagged with metal plates that subsequently could be found with a metal detector (Warren and Kraft, 2008). In rivers with larger channel dimensions and longer average lengths of wood displacement during floods, tracking signals emitted by electronic devices previously installed in growing trees or wood pieces had to be used to effectively locate displaced pieces (MacVicar et al., 2009; Schenk et al., 2014; Ravazzolo et al., 2015). Based on test applications, MacVicar et al. (2009) presented advantages and disadvantages of the use of passive and active RFID transponders and radio transmitters in such experiments. Ravazzolo et al. (2015) used active RFID and GPS tracker devices to monitor the entrainment and movement of logs during flood events of different magnitudes in the Tagliamento River, Italy. Their observations indicated that logs are preferentially entrained during the rising limb of floods and deposition begins already at the flood peak.

Still another approach to determine wood dynamics during floods is based on one- or two-dimensional hydraulic modelling. Early attempts in this field first calculated flow hydraulics, and the results were subsequently employed to determine mobilization and deposition of wood pieces (Merten et al., 2010). Mazzorana et al. (2011) estimated potential volumes of wood recruited from different sources to a mountain river and simulated wood transport under unsteady flow conditions using results from a two-dimensional simulation of hydrodynamics. Ruiz-Villanueva et al. (2014a) developed a two-dimensional hydrodynamic model that couples the simulation of wood transport and hydrodynamics. The model was next applied to study wood dynamics in several rivers, particularly in the context of flood hazard assessment (Ruiz-Villanueva et al., 2014b).

In this issue, Ruiz-Villanueva et al. use two-dimensional numerical modeling coupled with direct field observations to determine the conditions of large-wood transport in the Czarny Dunajec River in southern Poland. Through the modelling of wood transport in two river reaches with contrasting, single- and multithread morphologies under different flood scenarios, they reveal relationships between the rate of wood transport and discharge, wood size, and river morphology. The results indicate that the length of wood pieces has a stronger influence on the rates of wood transport in single-thread river reaches, whereas log diameter exerts a stronger control in the multithread channel. The threshold discharge, above which wood transport commences during a passage of flood waves is higher in the multithread channel than in the single-thread one. Moreover, the results demonstrate nonlinearity in the rates of wood transport between in-channel and overbank flows, with wood transport rate decreasing or increasing more slowly after overtopping of river banks; however, the two river reaches differ in the threshold discharge because of differences in their flow capacities.

4. River restoration and environment-friendly river management

In the latest historical time and especially in the twentieth century, mountain streams and rivers experienced extensive human impacts (Wohl, 2006) that adversely affected the integrity of their riverine and riparian ecosystems. Changes in catchment land use and the morphological structure of river channels and floodplains, as well as direct modifications of flow regime altered key attributes of river flow: magnitude, frequency, duration, timing, and rate of change (Beechie et al., 2013). Recognition of numerous adverse effects of human impacts on rivers has initiated diverse activities aiming to improve their degraded attributes that collectively are called *river restoration*; improvement of the ecological integrity of rivers is one of the most important but not sole goals of the activities (Wohl et al., 2015). A wide range of flood flows is important for various processes in riverine and riparian ecosystems (Bertoldi et al., 2009), but it was most evidently disturbed by flow regulation by dams. Efforts to reestablish the natural flow regime in the impacted rivers range from release of environmental flows from dams to dam removal. Releasing flushing flows from dams improves the quality of spawning grounds (Ortlepp and Mürle, 2003), whereas reestablishing more natural magnitudes and timing of flood flows improves channel–floodplain connectivity and promotes recruitment of trees on the floodplains (Hughes and Rood, 2003). However, these environmental flows typically are too low to reestablish the morphological dynamics of the rivers; only exceptional magnitudes of these controlled floods are sufficient to allow considerable scouring of the riverbed and deposition of the mobilized sediment on bars, hence increasing channel relief (Mueller et al., 2014).

In contrast to the regulation of flood flows by dams, river channelization and embanking reduce channel and floodplain storage of floodwater and in consequence increase peak flows of floods in the downstream reaches. A reduction of this increased flood hazard is thus indicated either as a primary goal of river restoration activities or as a valuable byproduct of the activities aimed to improve the ecological conditions in impacted rivers. The removal or relocation of flood embankments farther away from the channel, in lowland river valleys frequently applied to increase water storage on floodplains, is also used in mountain areas (Jäggi and Zarn, 1999; Habersack and Piégay, 2008) but less often because of space constraints. At the same time, Konrad et al. (2008) demonstrated its beneficial influence on the amount and distribution of riparian and aquatic habitats. Secondary channels are reconstructed along channelized rivers or reconnected with them (Hornich and Baumann, 2008), resulting in increased channel storage of floodwater and reduced bed shear stress of flood flows. Finally, establishing an erodible river corridor—a part of a valley floor where the river can develop its channel freely (Piégay et al., 2005)—is increasingly applied in mountain and piedmont areas (e.g., Nieznański et al., 2008; Rinaldi et al., 2009).

Improved understanding of geomorphological processes is important for environment-friendly river management that adjusts a degree of intervention to the level of flood risk in particular river reaches. Successful mitigation of flood hazard in this approach will greatly depend on recognition of the trajectories of river adjustment to contemporary and likely future flux boundary conditions (Brierley and Fryirs, 2016).

In this issue, Czech et al. analyse the effect of free channel development in an erodible corridor of the Biała River, Polish Carpathians, on the hydraulic conditions of flood flows. They compare a number of closely located channelized and unmanaged cross sections to determine how the river restoration influenced (i) large tractive forces associated with the concentration of flood flows in the narrowed and incised channels, and (ii) the potential for floodwater retention in floodplain areas. Results of the analysis indicate that after a relatively short period of free channel development, the unmanaged cross sections are typified by significantly lower unit stream power and shear forces exerted on the bed and banks of the channel than the channelized cross sections. However, as the hitherto accomplished channel change in the unmanaged river sections mostly consisted in channel widening, it has not yet increased floodwater retention in the floodplain areas. It will be possible in further stages of the river recovery because, with the preserved continuity of bedload transfer in the river, the reduction of shear forces should be followed by bed aggradation reducing channel capacity.

In turn, Mikuś et al. consider management options that reduce the erosional hazard to a local road caused by the laterally migrating channel of a multithread river in the Polish Carpathians. Channelization of the river reach was initially planned by water authorities, but this would deteriorate its ecological status and would eliminate functioning of the multithread channel as a natural trap for large wood. The analysis of geomorphic processes in the reach revealed different channel tendencies in the periods with low and high flood flows and showed the hazard could be mitigated by reactivating flow in side braids located by the neck of the main-channel bend threatening the road. This environment-friendly solution was implemented, allowing relocation of most flow to the braid most distant from the local road without negative effects on physical habitat conditions and river biota; the solution was significantly less expensive than the traditional, hard-engineering solution, and maintained the role of the reach as a natural wood trap. However, avulsion of the main channel in an upstream-located river bend during a major flood in 2014 again caused erosional risk to the road, although at another location. Considering the highly unstable, multithread channel pattern in the reach, the authors proposed a better management approach involving free channel migration within the floodplain area with local reinforcement of the channel bank where the migrating channel is close to the valley-floor infrastructure.

5. **Extreme floods in mountain rivers**

Among various processes contributing to the generation of floods on mountain rivers, three seem to be especially effective in producing large/extreme flood events: high-intensity convective rainfall (Gutiérrez et al., 1998; Hicks et al., 2005), extensive deep cyclones generating a few days-long, orographic rainfall (Sturdevant-Rees et al., 2001), and outburst floods resulting from the failure of either natural or artificial dams (Cenderelli, 2011). These processes may generate peak discharges greatly exceeding average flood discharges. For instance, glacial-lake outburst floods in Nepal had discharges up to 60 times greater than normal floods generated by snowmelt runoff, glacier melting, and monsoonal precipitation (Cenderelli and Wohl, 2003).

Large floods may be especially effective in creating channel form in steep channels, in which large forces are required to mobilize coarse sediment grades (Lenzi et al., 2006). A number of studies analysed controls on the geomorphic effectiveness of large floods. Costa and O’Connor (1995) indicated that the most geomorphologically effective floods combine high peak discharge and long duration, whereas flash floods may produce little geomorphic change despite high peak discharges. Using evidence from two gravel-bed rivers affected by a tropical storm, Magilligan et al. (2015) demonstrated that short-duration, high peak discharge floods may have important sedimentological effects, encompassing entrainment, transport, and deposition of coarse sediment grades but produce little morphological change of the channels. Aiming to explain morphological changes of mountain rivers caused by large flood events, some studies focused on hydraulic variables such as unit stream power or shear stress (e.g., Cenderelli and Wohl, 2003; Krapesch et al., 2011). However, other studies have shown that the variability in hydraulic parameters alone may not be sufficient to explain geomorphic effects of such floods (e.g., Nardi and Rinaldi, 2015), and other factors such as lateral channel confinement (Fuller, 2008), channelization structures (Arnaud-Fassetta et al., 2005; Langhammer, 2010), or bedload supply and deposition of sediment slug (Nelson and Dubé, 2016) must also be taken into account.

Extreme floods can be disastrous, resulting in substantial material losses and/or large numbers of fatalities, if they affect managed valley sections and inhabited valley floors. Examples can be an outburst flood caused by a landslide entering the Vaiont reservoir, Italian Alps, with 2600 deaths (Semenza and Ghirotti, 2000) or a flash flood in the Arás basin, Spanish Pyrenees, resulting in 87 fatalities (Gutiérrez et al., 1998). A decisive role in the origin of the disasters must be attributed to inappropriate management decisions, unadjusted to the actual hazard, rather than to the course of natural phenomena. Such was the situation with the Vaiont flood, where water was stored in the reservoir despite the identification of a giant landslide on the valley side above the reservoir (Semenza and Ghirotti, 2000) or with the flood on the Arás that destroyed a camp site located on an alluvial fan (Gutiérrez et al., 1998). More frequent are less dramatic situations when flood damages are enhanced by structures that reduce channel conveyance (e.g., Arnaud-Fassetta et al., 2005).

Extreme floods are generally considered as threats for aquatic ecosystems (Wydoski and Wick, 2011) that may dramatically though temporarily reduce the abundance of riverine biota such as fish or benthic macroinvertebrates. Because such events cannot be predicted, very few papers compared pre- and post-flood conditions of river biocoenosis in mountain rivers. While the existing studies analysed direct action of floodwaters on biota (e.g., the effect of the extreme flood of 1997 on the Oder River, Czech Republic, on fish fauna; Lojkasek et al., 2005), no papers have described more prolonged effects of extreme flood events on the physical structure of mountain river habitats.

In this issue, impacts of recent extreme flood events on mountain rivers are analysed in three papers. Hajdukiewicz et al. use the case of an 80-year flood on the Biała River, Polish Carpathians, to consider the flood impact on river habitats, channel morphology, and valley infrastructure. They compare physical habitat conditions surveyed in 10 pairs of closely located unmanaged and channelized cross sections before and after the flood, finding that the event obliterated the previous differences in sediment size and in the lateral variability of flow velocity between the river reaches with a different style of channel management. A comparison of channel planform determined before and after the flood indicated larger width increase in the unmanaged cross sections than in the channelized cross sections, but damage to valley-floor infrastructure was practically limited to the channelized river reaches with reinforced banks. This allows the authors to ascribe the economic losses caused by the flood to incompetent management of riparian areas rather than to the degree of river widening during the flood. The authors also demonstrate that intense channel incision typical of downstream sections of the river was a factor limiting its widening by the flood.

In turn, Marchi et al. analyse controls on maximum stream power in the fluvial systems from different hydroclimatic regions of central and southern Europe that were affected by recent flash floods. They base their analysis on post-flood surveys of 110 river cross sections characterizing catchments from 0.5 to 1981 km^2 in area. The authors demonstrate that the highest values of cross-sectional stream power and of unit stream power occur in Mediterranean regions, which can be attributed to the larger peak discharges associated with flash floods in these regions. The variability of unit stream power with catchment area can be described by a log-quadratic relation; however, considerable variation exists in the catchment area at which maximum values of unit stream power were attained during particular flash floods, reflecting differences in the spatial scale of the events. Morphological changes caused by these large floods were found to depend on cross section characteristics, with bedrock and artificially reinforced channel banks showing negligible erosion and alluvial channels being subjected to significant widening.

Finally, Surian et al. use the flood in the Magra River catchment (northern Appennines, Italy) with estimated recurrence interval > 100 years to explore relationships between flood-caused channel widening and controlling factors. Results of their analysis indicate that hydraulic variables such as cross-sectional stream power or unit stream power are not sufficient to explain satisfactorily the degree of channel widening during extreme floods, and other factors such as lateral channel confinement or the hillslope area supplying sediment to the channels must be taken into account to increase explanation of the morphological change. The degree of channel widening is more strongly related to unit stream power calculated on the basis of pre-flood than post-flood channel width, which may suggest that most width changes occurred after the flood peak. The authors also demonstrate that a set of explanatory variables differ between steep reaches with channel slope $\geq 4\%$ and those with slope □ 4% and that channel widening must be a more complex phenomenon in the less steep reaches as more variables are necessary to explain its variability.

6. Paleoflood reconstructions in mountain streams

Data on paleofloods typically is scarce in mountain environments and often censored toward extremes (Mayer et al., 2010). As a result of their quick hydrological response of catchments as well as the considerable power of floods (Borga et al., 2014), the latter represent a high hazard in mountain streams but remain very difficult to be forecasted (Marchi et al., 2010; Borga et al., 2011). Floods in mountain environments are related to catchment disposition, channel characteristics, and climate triggers (Blöschl et al., 2015), with the latter being expected to change in the course of the next few decades with very direct and potentially drastic impacts on precipitation regimes. In regions like the northern foothills of the Tatras, southern Poland, inhabited valleys and their inhabitants 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 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; Ruiz-Villanueva et al., 2016b), the authors were to find alternatives 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; Stoffel and Corona, 2014; 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 (Stoffel and Bollschweiler, 2008) 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; Ballesteros-Cánovas et al., 2015a). The reliability of scar-based peak discharge reconstructions has been proven over the past decades (McCord, 1996; Corriell, 2002; Ballesteros-Cánovas et al., 2011a, b).

In their paper, Ballesteros-Canovas et al. (this issue) present a paleohydrological reconstruction for four high-gradient mountain streams in the Tatra Mountains and use scars in trees to assess paleostage levels. The authors then couple a two-dimensional hydraulic modeling approach 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 twentieth-century floods, (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 was based on a total of 55 scarred trees and allowed 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 these 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, these findings will be useful for the design of future strategies dealing with flood risks in the foreland of the Polish Tatra Mountains.

Working in a completely different environment shaped by river erosion (and not by glaciations), repeated earthquake activity and recurrent and extremely intense rainfalls (related to typhoons), Imaizumi et al. (this issue) draw 'a biographical sketch of a giant' by documenting and reconstructing past debris-flow activity for Ohya landslide. Field monitoring has been demonstrated to be one of the best ways to document the timing and flow characteristics of debris flows. Detailed field monitoring has been undertaken in many regions including Europe (Berger et al., 2011; Arattano et al., 2012) or East Asia (Hu et al., 2011; Suwa et al., 2011), mostly in torrents with high debris-flow activity. The fact that recurrence intervals of debris flows are often > 10 years (e.g., Van Steijn, 1996; Imaizumi and Sidle, 2007) limits the choice of suitable torrents and methods. For a better understanding of debris-flow characteristics and process dynamics at a given site, one needs to select the best and most appropriate methods, taking into account debris-flow frequency, flow characteristics, and available data. Advantages and limitations of each method should be known before an appropriate approach is being defined. In the past, however, most research focused just on the evaluation of errors and the description of limitations of single approaches (Brardinoni et al., 2003; Bremer and Sass, 2012). By contrast, a comparison and/or combination of different approaches has not been realized in sufficient detail so far.

The purpose of the paper by Imaizumi et al. (this issue) therefore is to compare characteristics, advantages, and limitations of different assessment methods to study debris flows and to apply them to a specific case where process activity has been very high in the recent past. The authors investigated the debris-flow history out of the Ohya landslide, central Japan, by using field monitoring, airborne LiDAR DEMs, orthophoto interpretation, and tree-ring assessments. Ohya landslide is one of the largest landslide bodies in Japan and seems very appropriate for such a comparison because of the very high debris-flow frequency (with 3–4 events per year; Imaizumi et al., 2005). In addition, various monitoring techniques and surveys have aimed at mitigating disasters in this area. The authors conclude that the different methods showed agreement on the larger depositional patterns in general but also unveiled considerable mismatches among approaches. The authors state that orthophoto interpretation usually underestimates areas affected by individual debris flows as it ignores small changes in topography. In addition, debris-flow paths in shady and/or tree-crowned areas cannot be identified in the photographs either and are thus affecting underestimation of orthophoto assessments as well. Airborne LiDAR assessments have some advantage in the interpretation of debris flows in the area with incised topography or vegetation cover. On the other hand, limitations in airborne LiDAR interpretation are related to their difficulty in distinguishing between local topographic changes and noise.

A combination of multiple methods may overcome the weaknesses of each single approach. For example, the combination of airborne LiDAR and orthophoto interpretation can improve the spatial resolution and delineation of areas affected by debris flows. In addition, tree-ring analyses may help to improve temporal resolution in case that the area under investigation supports trees. Accordingly, the combination of these methods permits assessment of the debris-flow history with high spatial and temporal resolution.

Galia and Škarpich (this issue) analyze hydraulic and sedimentary trends recorded along three fluvially dominated headwater streams and a stream influenced by debris flows in the flysch Carpathians, Czech Republic. The streams shaped exclusively by fluvial processes exhibit direct relations between the coarsest sediment size and unit stream power, especially its values calculated for a recent 20-year flood. In these streams, incised reaches were typified by increased values of unit stream power and the downstream coarsening of bed material, and the competence of the 20-year flood flow clearly exceeded that required to entrain the largest bed particles. In turn, aggraded reaches supported finer grades of the coarsest bed particles and led to the disconnectivity of transport of the coarsest bed material even during the 20-year flood. By contrast, in the stream influenced by past debris flow activity, calculated values of unit stream power and contemporary trends in vertical channel position were not clearly reflected in boulder size because the significantly greater presence of debris-flow-derived boulders prevented the full adjustment of the coarse material on the channel bed to contemporary erosional or depositional trends of the channel.

In a study presented by Van den Heuvel et al. (this issue), data from reconstructed debris-flow histories derived from dendrogeomorphic records of conifer trees growing on depositional cones (Stoffel et al., 2005, 2008; Bollschweiler and Stoffel, 2010a, b, c; Stoffel, 2010) have been used to investigate the types of large-scale meteorological situations that have been conducive to the precipitation and temperature conditions most likely to trigger debris flows, under current and future climates. Although many site-specific factors may influence debris-flow triggering, rainfall quantities and intensity as well as rising mean and extreme air temperatures have been identified as the most prominent triggers in various debris-flow catchments in the Swiss Alps (Stoffel et al., 2011, 2014a, b; Schneuwly-Bollschweiler and Stoffel, 2012). Soil saturation leads to increased shear forces as well as surface water flow that in turn leads to erosion and debris-flow triggering, especially when pore saturation happens at potential rupture surfaces (Sassa, 1984; Iverson et al., 1997). This is particularly the case for the study area, where scree slopes can hold very little quantities of water (Lugon and Stoffel, 2010; Stoffel and Huggel, 2012). Furthermore, Schneuwly-Bollschweiler and Stoffel (2012) found that high temperatures are significantly correlated with debris-flow occurrence. The reason for this is that higher temperatures may lead to rainfall instead of snowfall as warmer air can contain more water vapour, according to the Clausius–Clapeyron equation, and ensuing condensed moisture would ultimately be transferred into the ground. These findings are confirmed by observations during the twentieth century, and climate model simulations of future climate change indicate that important changes in these variables may be expected (Pall et al., 2007; Gobiet et al., 2014).

To test the future incidence of synoptic situations leading to the release of debris flows, Van den Heuvel et al. (this issue) apply a two-dimensional Bayesian probability calculation to take account of uncertainties in debris-flow triggering. Precipitation quantities exceeding the 95th percentile of daily precipitation amounts were found to have a significantly higher probability to coincide with observed debris flows. It was also found that a different relationship exists for extreme temperatures, however. Southerly air flows, weak horizontal pressure gradients over Europe, and westerly flows are mostly associated with observed debris flows and 95th precipitation percentile exceedances. The authors also found that these principal flow directions are well represented in the regional climate model (RCM) control simulations for events exceeding the 95th precipitation and the 30th temperature percentiles. Under the IPCC A2 emission scenario, westerly and southerly flows are mostly responsible for these precipitation and temperature conditions under the hypothesis of slow adaptation to climate change. Under the hypothesis of rapid adaptation to climate change, however, southerly flows and weak horizontal pressure gradients are likely to gain in importance. In both future scenarios, southeasterly flows are among the principal flow directions responsible for the joint exceedance of the 95th precipitation and the 30th temperature percentiles, while these were absent in observations and the control simulation.

7. Impacts of changes in flood flows on river morphology

Many studies have described changes in morphology of mountain rivers resulting from the alterations in flood regime and sediment supply to channels induced by various types of human impacts. In mountain areas of Europe, deforestation and agricultural and pastoral activities on hillslopes progressed through historical time, culminating in the nineteenth century (Gurnell et al., 2009; Comiti, 2012; Rinaldi et al., 2013). All these changes tended to accelerate water runoff and to increase flood peaks and sediment delivery to channels, but an especially large intensification of these processes was caused by the development of potato cultivation on hillslopes (Klimek, 1987). The environmental changes resulted in widespread channel aggradation and downstream-progressing transformation of single-thread to braided channels in mountain and piedmont valley reaches (e.g., Gurnell et al., 2009; Wyżga et al., 2015). These channel changes were accompanied by the onset of the formation of poorly sorted, loosely packed gravels that were deposited by flash floods transporting large amounts of bedload (Wyżga, 1993). The widespread occurrence of braided morphology of mountain rivers was facilitated by the increased humidity of the Little Ice Age (Rumsby and Macklin, 1996); however, the asynchronous onset of the river transformation in various regions (seventeenth century in the foreland of the Massif Central, France: Arnaud-Fassetta and Provansal, 1999; nineteenth century in the Polish Carpathians: Wyżga et al., 2015) indicates human modification of the mountain environment to be the principal cause of this change.

In contrast to other parts of the world subjected to continued clearance of forests on hillslopes and valley floors, mountain and piedmont areas in Europe experienced an increase in forest cover over the last century (e.g., Kondolf et al., 2002; Lach and Wyżga, 2002; Gurnell et al., 2009; Rinaldi et al., 2013), with profound effects on hydrology, morphology, and functioning of the watercourses in these areas. One of the effects was the regulation of flood runoff from reforested catchments, with lower peak discharges recorded in the second half of the century than in its first half (e.g., Lach and Wyżga, 2002; Piégay et al., 2004; Wyżga et al., 2012). The lowering of peak discharges was associated with a change in the shape of flood hydrographs as flashy, high flood waves generated in deforested catchments were replaced by lower flood waves of longer duration (Wyżga, 2001; Piégay et al., 2004). A reduction in peak discharges of flood flows over the twentieth century is also demonstrated by a paleohydrological reconstruction performed by Ballesteros-Canovas et al. (this issue) for streams draining the high-mountain Tatra massif in southern Poland. A reduction in peak discharges and in sediment delivery from hillslopes resulted in decreased intensity of floodplain reworking, the replacement of braided channel pattern by a wandering or single-thread one, channel narrowing, and the expansion of riparian forest on the abandoned parts of the former channel beds (e.g., Marston et al., 1995; Kondolf et al., 2007; Wyżga et al., 2012). If a river could adjust its sinuosity to the diminishing sediment load, the vertical stability of its channel was maintained (Wyżga, 2001); however, much more common were situations where river constriction by channelization structures or valley sides prevented an increase in channel sinuosity, forcing the river to incise (e.g., Bravard et al., 1997; Wyżga, 2008).

With the increasing proportion of human population living in towns, urbanization is among the most common catchment changes that may have an important impact especially on relatively small rivers. As the increase in impervious surface area and the installation of storm sewers increase flood magnitudes in urban catchments, channels enlarge from 2-3 to as much as 15 times their size before urbanization (Chin, 2006). These increased flows can mobilize greater amounts of bedload, and thus urban channels are wider and have lower sinuosity than their rural counterparts (Pizzuto et al., 2000).

Construction of dam reservoirs has been the direct human impact on rivers leading to a reduction of peak flood flows and flow variability. Many dams have been constructed on mountain rivers because of their high flow variability, the abundance of water, relatively easy damming of narrow valleys, and high water heads of the dams reflecting steep valley gradients, advantageous for hydropower production. Impacts of dams on river morphology were described in a number of case studies (e.g., Surian, 1999) and several review papers (e.g., Williams and Wolman, 1984). By comparing regulated and unregulated reaches of American rivers with large dams, Graf (2006) indicated that with annual peak discharges reduced by 67% on average, the regulated reaches have 50% smaller high-flow channels and 79% less active floodplain area and exhibit substantially less geomorphic complexity. Sediment entrapment by reservoirs and releasing underloaded waters from the dams typically lead to bed degradation and channel incision (Williams and Wolman, 1984; Kondolf, 1997), although this vertical channel tendency may change downstream from steep tributaries that deliver coarse bed material, while slightly increasing the transport capacity of flows in the main river (Grant, 2012). However, in gravel-bed rivers typical of mountain areas, relatively small amounts of channel incision are observed as the coarsening of bed material and bed armouring limit bed degradation (Grant, 2012).

Schumm's (1969) concept of river metamorphosis assumed that rivers respond to increases in formative discharges by increasing the size of their channels, without a change in channel shape. However, results from a cellular river basin evolution model indicated that climatically conditioned increases in flood magnitude and frequency over relatively long periods (> 10 years) induce substantial increases in the amount of sediment delivered by floods of a given size and thus result in a changed relationship between water and sediment discharges (Coulthard et al., 2008). This explains why the prolonged period of increased frequency/magnitude of floods and enhanced fluvial activity during the Little Ice Age (Rumsby and Macklin, 1996) contributed to the widespread occurrence of braided river morphology in mountain areas at that time (e.g., Wyżga et al., 2015) and why the occurrence of major floods is necessary to sustain such morphology in mountain and piedmont rivers (Belletti et al., 2014). Major floods are also responsible for erosion and resetting the formation of islands in mountain rivers (Comiti et al., 2011; Mikuś et al., 2013). Predicting effects of the ongoing climate change on river morphology is, however, difficult because of a number of involved processes. Considering potential impacts of climate change on Canadian rivers, Ashmore and Church (2001) indicated that potential changes will include increased precipitation, the proportion falling as rain, shifts in cyclonic storm tracks, increased intense rain, reduction in snow accumulation, reduction of glacier mass, permafrost thawing, and changes to the dominant flood-generating processes. Impacts of these changes on river morphology may thus vary depending on latitudinal and altitudinal position and catchment size of rivers. For instance, rivers draining small catchments may be most sensitive to increased magnitude and frequency of local, convective storms, whereas those draining larger catchments will predominantly respond to changes in cyclonic storms and/or snow accumulation.

In this issue, Kidová et al. demonstrate and explain morphological evolution of the gravel-bed Belá River, Slovak Carpathians, over the last 60 years through the analysis of archival aerial photos, annual maximum discharges, and changes to forest cover in the catchment and to channel boundary conditions. The authors identify six periods with differing flood characteristics and analyse the morphological river pattern at the end of every period using GIS methods. A general decrease in flood magnitudes over the study period coupled with increased forest cover in the high-mountain part of the catchment and direct human impacts on the river has resulted in channel narrowing, straightening and incision, decreased area and number of channel bars in favour of islands, and decreased diversity of fluvial forms within the braidplain. However, these general trends of morphological changes varied between particular river reaches, mostly reflecting spatially diverse human impacts, and between periods with different flood magnitudes. The authors conclude that with sediment supply reduced as a result of the land use changes in the catchment and with accomplished changes in channel boundary conditions, several large floods in a relatively short time would be needed to return the river to its braided pattern that existed just a few decades ago.

8. Final remarks

In this paper, we set the stage for the special issue dedicated to *Floods in Mountain Environments* and provide a review on some of the most recent research papers on the topic. Although we reference almost 140 manuscripts, mostly published over the past decade or so, including the papers published in this special issue, we are well aware that only a subset of the litertaure and some aspects related to floods in mountain environments could be covered in this contribution. This explosion of literature related to floods in mountain environments (i) points to the importance of the subject and reflects the continually increasing impact that floods in mountain areas have on human interests, (ii) hightlights a variety of environmental changes that are currently affecting the relations between geomorphology of mountain river systems and floods, and (iii) underlines rapidly developing tools of studying relations between environmental changes, geomorphology, and floods (e.g., numerical models, technical development in measurement techniques, etc.).

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