Flood Generation Mechanisms and Changes in Principal Drivers

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Abstract Mechanisms generating floods are reviewed and next discussed with regard to the Upper Vistula Basin. Here, floods typically result from (i) moderate-intensity rain that lasts a few days over a large area and drives large-scale flooding, or (ii) high-intensity, short-lasting convective rain causing local flash floods. Outside the mountain part of the basin, especially in the San River catchment, floods are also caused by intensive snowmelt. Interpretation of climate track in flood generation is presented, based on the analysis of observation records from the last six decades and projections for the future. Catchment and river changes affecting the conditions of flood generation are next considered for the last 130 years. They comprise changes regulating flood runoff (catchment reforestation and dam reservoirs construction), changes reducing floodwater storage and accelerating flood

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runoff (channel regulation, flood embankments, river incision, and permanent impoundment of the Upper Vistula for navigation purposes), as well as the expansion of riparian forests increasing large wood recruitment to channels during floods.

Keywords Flood hazard · Climate change · Terrestrial drivers · Flood runoff · Upper Vistula Basin

1 Introduction

Changes in flood hazard may be driven by climate changes as well as changes in catchment and river characteristics determining the terrestrial conditions of water runoff (Kundzewicz and Schellnhuber 2004). Potential impacts of climate changes depend largely on flood generation mechanisms, and these mechanisms are subject to review in this chapter, in general terms as well as with respect to flood generation in the Upper Vistula Basin. Interpretation of climate track in flood generation is outlined, based on the analysis of observation records and, albeit highly uncertain, projections for the future. Climate track is typically restricted to the last six decades, for which homogeneous observation records are available. By contrast, changes in terrestrial drivers in the region can be studied over the period exceeding 100 years. We review these drivers, describing catchment and river changes that tended to either regulate or accelerate flood runoff, and changes responsible for the increased flood hazard resulting from large wood delivery to river channels.

2 Climate Track in Flood Generation

There is no doubt that climate is a very important factor driving fluvial flood hazard (cf. Kundzewicz and Stoffel 2016), affected by various characteristics of the climatic/atmospheric systems. Important is the water holding capacity (and the water content) of the atmosphere. Various precipitation characteristics, such as precipitation intensity, duration, total amount, timing, or phase (whether liquid or solid) are virtually essential in shaping flood hazard. Spatial distribution as well as temporal distribution (e.g. measured by the antecedent precipitation index, API) are important (Kundzewicz et al. 2014). Moreover, large-scale circulation patterns as well as temperature patterns (responsible for cold phenomena, such as soil freezing, snow cover, snow and ice melt, and ice jam formation) are of relevance.

The climate change is real and ubiquitous. Significant increases in air temperature have been observed at a range of scales, from local to regional, continental, and global (IPCC 2013). However, changes have not been limited to temperature, but also embraced other variables, of relevance to flood hazard. The effects of climate change on water resources, which vary regionally, largely follow changes in the prime driver—precipitation (additionally, changes in temperature in snow-impacted basins) (Döll et al. 2015).

While observed temperature increases are quite regular, changes in precipitation are not so. Nevertheless, a general large-scale statement can be made that climate variability increases spatially and temporally under climate change, so that wet regions become even wetter and flood hazard is increasing in many locations (Döll et al. 2015). Seneviratne et al. (2012) detected the climate track in some variables affecting floods, including mean precipitation, heavy precipitation, and snow pack, though a direct statistical link between climate change and trends in the magnitude and/or frequency of floods has not been established yet. In climates where seasonal snow storage and melting play a significant role in annual runoff, the hydrological regime is affected by changes in temperature. Changes in the timing (earlier occurrence) of spring peak flows in snowmelt- and glacier-fed rivers have been observed. However, not all such areas are experiencing changes in the magnitude of peak flow (Seneviratne et al. 2012). Intense precipitation has been on the rise and this rhymes with the theoretical Clausius-Clapeyron law, indicating more room for water vapor in the warmer atmosphere (Kundzewicz and Schellnhuber 2004).

Climate-driven changes in flood frequency are complex, depending on whether floods are the result of increasing heavy rainfall (then flood magnitudes are expected to be on the rise) or floods are generated by decreasing spring snowmelt (then flood magnitudes decrease) (cf. Kundzewicz et al. 2014). In some areas, where snowmelt is the principal flood-generating mechanism, the time of the greatest flood risk has shifted from spring to winter (Kundzewicz et al. 2010). A precise understanding of the hydroclimatic characteristics of floods is complicated by a lack of observational data at the spatial and temporal resolution adequate for hydroclimatic research (Kundzewicz et al. 2016). Long time series of good-quality data are not available in many areas. But, even if the data are perfect, it is worthwhile to re-state a tautology: extreme events are rare (Kundzewicz and Schellnhuber 2004). They do not happen frequently, so even where a relatively long time series of instrumental records exists, one still deals with only a small sample of truly extreme and destructive floods (cf. Kundzewicz and Robson 2004).

Climate projections using multi-model ensembles show ubiquitous warming and increases in globally averaged mean water vapor and precipitation over the 21st century (IPCC 2013). Yet, precipitation scenarios show strong regional differences. This is particularly true for precipitation extremes, of relevance for shaping flood hazard. Seneviratne et al. (2012) assessed that it is *likely* that the frequency of heavy precipitation or the proportion of total rainfall from intense events will increase in the 21st century over many areas of the globe. This would translate into an increase of the magnitude and frequency of floods in some regions, but the projections are largely uncertain (Arnell and Gosling 2014; Kundzewicz et al. 2016).

Climate-related changes in future flood frequency are complex, depending on the flood-generating mechanism. Flood magnitudes typically increase with warming if high flows result from heavy rainfall and decrease where they are generated by spring snowmelt. In some places, rapid snowmelt from rain-on-snow events or warm periods in the middle of winter cause a potential flood threat in a warmer world (Kundzewicz et al. 2010).

Clear temperature increases have been detected in the Upper Vistula Basin (cf. Łupikasza et al. 2016). Precipitation trends are more complex and many trends are not statistically significant, as the natural variability is strong. Niedźwiedź and Łupikasza (2016) spotted changes in flood-prone circulation patterns of importance for the studied region. However, the analysis of data from 14 water-gauge stations within the upper Dunajec Basin indicated that it is difficult to find a statistically significant trend in the records of magnitude of annual maximum floods in the region (Ruiz-Villanueva et al. 2016).

Piniewski et al. (2016) examined climatic and hydrological projections for the Upper Vistula Basin for two future time horizons 2021–2050 (near future) and 2071–2100 (far future). They found model agreement about ubiquitous warming on both seasonal and annual scales, and most models (eight out of nine models for the near future and all nine models for the far future) agreed about an increase in projected mean annual precipitation and total runoff. Projected changes in high-streamflow indicator based on the 90th monthly flow percentile ($Q90$) were found to increase in both future horizons, by a few per cent.

Romanowicz et al. (2016) examined projections of future flood hazard changes in two catchments and found disagreements between particular models and between the two locations. They explain these disagreements by climatic variability and the uncertainty of the results.

3 Flood-Generating Mechanisms—An Overview

Floods, understood as destructive abundance of water, are generated by the interaction of various processes. As Nied et al. (2013) indicated, physical controlling factors include "hydrological pre-conditions (e.g. soil saturation, snow cover), meteorological conditions (e.g. amount, intensity, and spatial and temporal distribution of precipitation), runoff generation processes as well as river routing (e.g. superposition of flood waves in the main river and its tributaries)". The combination of these factors and their spatial distribution at a regional scale may be important, as flooding can affect many sites simultaneously, whereas other sites remain unaffected (Merz and Blöschl 2008; Nied et al. 2013). Across Europe, floods have very different characteristics, depending on geography, climate/weather characteristics, and the human occupancy (FloodSite 2007):

- large, slow rising rivers with floods generated by frontal rainfall and/or snowmelt (e.g. the Rhine, the Thames, the Po, and the Loire);
- summer thunderstorm-type events resulting in flash floods with very short warning lead time, often characteristic of the Mediterranean region (e.g. several flash floods in southern France in the 2010s) and/or mountainous regions (e.g. Ore Mountains in August 2002);

- floods caused by heavy precipitation events in urban areas, falling on inadequate sewer systems which are overloaded and may fail owing to inadequate maintenance or insufficient levels of investment (e.g. heavy rainfalls in July 2002 in Germany);
- ice-dammed rivers, generating floods through the back-up of flows spreading onto wide floodplains (e.g. the Vistula River upstreams of Włoclawek dam in January 1982);
- dam failure, representing a very rare type of events, but posing a potential threat (e.g. toxic spill from a mine into the River Tisza in 2000);
- coastal floods, where embankments may be breached or storm surges overwhelm coastal defences (e.g. the North Sea floods in 1953 and 1962).

The two last mechanisms of flood generation are outside the scope of this book.

Nied et al. (2014) summarized three main approaches to describe flood events in terms of their spatio-temporal physical causes as: (i) flood event description, (ii) classification into flood types, and (iii) linkage of flood occurrence to atmospheric circulation patterns. There are many examples following the first approach where detailed descriptions of flood conditions are provided (Kundzewicz et al. 1999; Ulbrich et al. 2003a, b; Ruiz-Villanueva et al. 2012; Blöschl et al. 2013). Nied et al. (2014) described several flood types to assess the second approach. According to their generating process, Merz and Blöschl (2003) distinguished long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods. Floods can be classified based on storm type, El Niño-Southern Oscillation conditions and decadal-scale climatic variability (Alila and Mtiraoui 2002), or based on precipitation, synoptic weather patterns and snowmelt (Hirschboeck 1987). Finally, the third approach uses statistical or probabilistic links between flood occurrence and atmospheric circulation patterns (e.g. Bárdossy and Filiz 2005; Petrow et al. 2009; Prudhomme and Genevier 2011). Since mechanism generating floods usually depends on the season, the seasonality approach opens the way to studying mixed flood frequency distributions in flood frequency analysis using the information on the seasonality (Sivapalan et al. 2005; Ouarda et al. 2006). In addition to time of the year, the weather circulation patterns associated with floods were used to identify the processes during floods (e.g. Bárdossy and Filiz 2005; Jacobeit et al. 2006; Zehe et al. 2006; Petrow et al. 2009). Most of these studies focused on recognition of flood-triggering circulation patterns to assist in regional flood analyses (Parajka et al. 2010).

Although many studies emphasize the importance of different flood-controlling processes (e.g., Merz and Blöschl 2003; Sivapalan et al. 2005; Bradshaw et al. 2007; McCabe et al. 2007; Parajka et al. 2010; Freudiger et al. 2014; Slater et al. 2015), understanding of regional differences in the process controls of flooding responses is rather limited (Berghuijs et al. 2016). Moreover, the analysis of flood generating processes is important because flood events may reveal aspects of hydrological behaviour that either were unexpected on the basis of weaker responses or highlight anticipated but previously unobserved behaviour (Borga et al. 2010, and references therein). Hence, improved process understanding is a key element for improving the prediction and interpretation of flood trends, especially under environmental change (Kundzewicz et al. 2014; Hall et al. 2014).

4 Flood Generating Mechanisms in the Upper Vistula Basin

Floods that encompass the largest parts or even the entire Upper Vistula Basin and cause most damage are generated by a few days-long rainfall with average intensity of 8–10 mm h^{-1} and the total sum of precipitation of a few hundred millimetres. Such precipitation has always been linked with cyclones moving along the Vb track (van Bebber 1891) from the Mediterranean region to Central-Eastern Europe and inducing southward movement of air masses on their western side. Depending on the location of the cyclone centre, high precipitation totals may occur (i) on both sides of the Upper Vistula (as in 2001; Sasim and Mierkiewicz 2002), (ii) on the northern slopes of the Western Carpathians and the Sudetes where precipitation is additionally enhanced by orographic effect (as in 1997; Niedźwiedź 1999), or (iii) only in the southernmost parts of the Polish Carpathians (in 2014). Local, heavy downpours, sometimes with intensities typical of torrential rains, with duration of 0.5–2 h and sums of precipitation up to 150 mm, occur in the upland (Cebulak and Niedźwiedź 1998) and the Carpathian parts of the Upper Vistula Basin (Niedźwiedź 1999), and in the lowland Sandomierz Basin (Starkel 2011). They result in local flash floods, especially if linked with specific physiographic catchment features, such as a high proportion of arable lands in the total catchment area, low soil-infiltration rates, and high density of drainage network (Bryndal 2014). Finally, snowmelt floods occur in the catchments with relatively small variation in altitude in which snow pack thawing occurs at the same time catchment-wide. Such floods are thus typical of the left-side tributaries to the Upper Vistula as well as of foothill and foreland reaches of its Carpathian tributaries, although flood magnitudes are usually lower than those of the floods generated by prolonged summer rainfall. Different situation occurs in the catchments of the lower San and its tributaries where snow pack can retain considerable amounts of water as a result of more severe weather conditions during winters. Here, a sudden increase in temperature after long winter conditions with considerable amounts of snowfall may lead to a catastrophic flood as in March 1924 (Punzet 1984). Moreover, the high variability of peak stages of spring floods recorded along the lower San indicates frequent occurrence of ice jams that may locally increase water levels (Punzet 1984).

5 Changes in Terrestrial Drivers of Floods

Over the 20th century catchments and channels of the rivers in the Upper Vistula Basin experienced considerable changes resulting in altered conditions for runoff formation and the passage of flood waves. Below we discuss three groups of such changes with different impacts on flood conditions and the related flood hazard and risk.

5.1 Factors Regulating Flood Runoff

5.1.1 Reforestation of Catchments

Deforestation of catchments in the Polish Carpathians progressed until the early 19th century, and subsequently the forest cover in the region remained at the low level until the 1930s (Kozak 2009). The scarce forest cover facilitated rapid flood runoff and the formation of high, flashy flood waves. The widespread occurrence of braided rivers (Wyżga et al. 2015) and the formation of massive, loosely packed gravels in their channels (Wyżga 1993a; Wyżga et al. 2012) represent morphological and sedimentary records of the rapid flood runoff from the Polish Carpathian catchments during the 19th and an early part of the 20th century. Reconstructions of paleodischarges in the Tatra Mountains streams by means of dendrochronological dating of tree scars and hydraulic modelling evidence higher flood magnitudes in the first half of the 20th century than in its second half (Ballesteros-Cánovas et al. 2016).

In the 20th century and especially in its second half, a considerable increase in forest cover occurred in Polish Carpathian catchments (Kozak 2009). The largest increase typified the eastern part of the Polish Carpathians that was dramatically depopulated in the mid-1940s. For instance, in the upper Wisłoka catchment, the forest cover increased from 26 % in 1900 to 30 % in 1938 and to 67 % in 1995 (Lach and Wyżga 2002). Less intense land use changes occurred in the western part of the Polish Carpathians (Kozak 2009) that remained densely populated and where the changes were conditioned by socio-economic changes (reduced profits from agricultural production, the emergence of new sources of income for the previously purely agricultural community—Kukulak 1994). For instance, in the upper part of the Dunajec catchment, the forest cover increased from 27 % in 1901 to 42 % in 2000 (Wyżga et al. 2012). The increase in forest cover was associated with a reduction in the area of arable land (Munteanu et al. 2014), the scale of which might have been greater than that of the increase in forest cover. In the upper part of the Dunajec catchment, the area of arable land decreased from 42 % in 1901 to 17.5 % in 2000, partly in favour of meadows. The decline in agricultural practices was especially important in the eastern part of the mountains as it has led to the abandonment and overgrowth with bushes of cart tracks that ceased to function as pathways for rapid evacuation of water and sediment from the hillslopes (Lach and Wyżga 2002).

The land use changes led to decreasing flashiness of flood runoff that was clearly reflected in a shift from the formation of loosely packed gravels to normally and closely packed gravels and the onset of the formation of bed armour in channels (Wyżga 1993a; Wyżga et al. 2012), and in the appearance of a tendency of rivers to

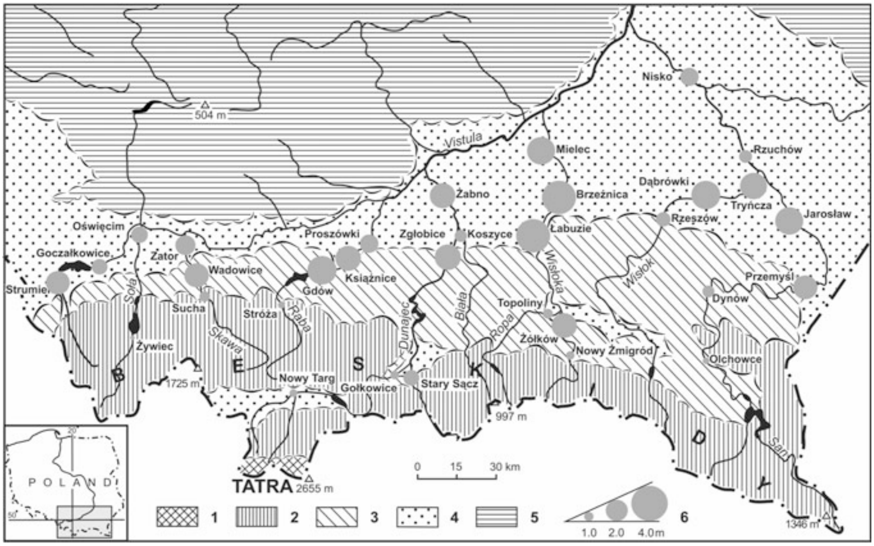

Fig. 1 Dimensions of channel incision of Carpathian tributaries to the Vistula during the 20th century inferred from the lowering of minimum annual water stage at gauging stations on the rivers. *1* high mountains; *2* mountains of intermediate and low height; *3* foothills; *4* intramontane and submontane depressions; *5* uplands; *6* lowering of minimum annual stage at water-gauge stations during the 20th century. After Wyżga (2008), modified, reproduced with permission of Elsevier

meander (Wyżga 2001a; Wyżga et al. 2015). They must have been also reflected in reduced peak flows of flood waves (Ballesteros-Cánovas et al. 2016). Analysis of changes in flood runoff reveals a linkage between the scale of land use change and a reduction in mean annual discharges (Wyżga 2008). At the Wadowice station on the Skawa River draining the western part of the Polish Carpathians (Fig. 1), mean annual flood ($Q_{2.33}$) in the years 1956–2000 was 8 % smaller than that recorded in the years 1921–1955, whereas at the Łabuzie station on the Wisłoka River draining the eastern part of the mountains (Fig. 1) the respective reduction in mean annual flood amounted to 31 %.

5.1.2 Construction of Dam Reservoirs

After the catastrophic flood of 1934, dam reservoirs started to be constructed on Polish Carpathian rivers, with the first two completed (Porąbka Dam on the Soła River—1936; Rożnów Dam on the Dunajec River—1941) within a few years after the works had been initiated. To date, 14 dam reservoirs (including the almost finished Świnna Poręba Dam on the Skawa River) have been constructed in the Upper Vistula Basin, with a total flood capacity of 413 million m^3 during summer (Walczykiewicz and Rataj 2011). If compared with the flow of the Vistula River at the Zawichost gauging station characterizing its whole upper basin, the capacity corresponds to 11 days-long runoff with mean annual discharge or to 14 h of runoff with the peak discharge of 1 % probability of exceedance. Such a capacity must be considered modest as the hydrographs of large floods at the station may last up to 10 days. However, the efficiency of particular dam reservoirs in the reduction of peak flows of flood waves is highly diverse, depending on the location of a given reservoir, its function(s), inflow to and the work of a reservoir during particular flood waves. For instance, during the flood of 2010, small reservoirs located on left-side tributaries to the Upper Vistula reduced the peak flow by 8–75 %. At the same time, large reservoirs located on the Carpathian tributaries to the Upper Vistula exhibited the reduction rate between 11 and 59 % (Walczykiewicz and Rataj 2011) and both these extreme values refer to the same river—the Dunajec; the Rożnów-Czchów reservoirs located in the middle river course could reduce the peak flood flow by only 11 %, despite 59 % reduction of the flood peak by the Czorsztyn-Sromowce reservoirs located in the upper river course.

A few factors limit the efficiency of the dam reservoirs in the Upper Vistula Basin in reducing flood peaks. First, apart from protection from flooding, the dams play also other roles, mainly hydropower production or water supply, which require the maintenance of relatively high water level in the reservoirs. Second, reliable forecasts of rainfall and thus also of water inflow to the reservoirs are available shortly before an event, which limits the time span required to considerably increase their flood capacities. Third, a full flood capacity of the reservoirs is typically kept during summer months, whereas in the remaining part of a year higher water level is maintained. Therefore, floods occurring outside the "usual period" (e.g. in mid-May 2010) are likely to coincide with reservoir capacities lower than the maximal ones. Fourth, dam reservoirs disrupt the continuity of bed material transport in the rivers, inducing or strengthening the tendency to channel incision in the downstream reaches. The resultant loss of floodwater storage in floodplain areas partly counteracts the effect of dam reservoirs on flood peaks. In several countries, river reaches downstream of dam reservoirs are fed with gravel to prevent sediment starvation of the rivers (Kondolf 1997), but so far this solution has not been implemented in Poland.

5.2 *Factors Accelerating Flood Runoff*

5.2.1 Construction of Flood Embankments and Channel Regulation

Channelization works in the Upper Vistula River began in the mid-19th-century and were continued to the second half of the 20th century (Łajczak 1995). In the late 19th century channelization works were also initiated in the lower courses of Carpathian tributaries to the Vistula (Szumański 1986; Zawiejska and Wyżga 2010). In both cases the works consisted in channel narrowing and straightening through meander cutoffs. In the first half of the 20th century channelization works encompassed also middle courses of Carpathian tributaries to the Vistula, whereas in the second half of the century they were conducted in the middle and upper courses of the rivers (Wyżga 2001a; Zawiejska and Wyżga 2010). In these river reaches, the works resulted in considerable channel narrowing and replacement of the multi-thread channel by a single, regulated channel. As a result of the works, mean velocity at given discharges increased (Wyżga 1993b) and bed degradation was initiated leading to deep channel incision over several decades (Łajczak 1995; Wyżga 2001a, 2008).

In the 1890s–1900s flood embankments were constructed along the Upper Vistula and lower courses of its main tributaries (Łajczak 1995; Zawiejska and Wyżga 2010). Over the 20th century, flood embankments were also constructed along short reaches of the middle and upper courses of Carpathian tributaries to the Vistula. Since their construction, many reaches of the embankments have been modified by increasing the height or straightening some sections, especially along the Upper Vistula where several river meanders were cut off during the past century. A reduction in floodplain width caused by the construction of embankments increased water stages attained at particular flood discharges and this effect must have been particularly important on the Upper Vistula where the ratio of channel width to inter-embankment zone width was especially high. A combination of channelization works and flood embankment construction increased the frequency of high flood stages and discharges resulting in non-stationarity of flow record—according to Punzet (1972), flood flows from the periods before and after 1920 represent different populations, although at particular water-gauge stations the change might have occurred at somewhat different time. The non-stationarity of the record of maximum annual water stages can be shown on the example of the Żabno station located in the lowest course of the Dunajec River. Since around 1930 peak stages of large floods have started to reach about 1 m higher than previously, and this effect has been persistent despite the operation of the large Rożnów reservoir (located upstream) since the early 1940s and continuing channel incision at the gauge cross-section (apparent in the progressive lowering of minimum annual stages) (Fig. 2). The timing of the change at the station allows to attribute it to the channel narrowing and straightening in the course of channelization works conducted in the lower and middle course of the Dunajec in the first three decades of the 20th century rather than to the construction of embankments along the lower river course in the 1890s–1900s (Zawiejska and Wyżga 2010).

Still another effect of the channelization works, especially channel straightening through meander cutoffs, was a shortening of the travel time of flood waves. For instance, the travel time of flood waves on the Vistula River between its tributaries the Skawa and the Raba was shortened by half from 44 h at the beginning of the 20th century to 22 h in the 1980s (Punzet 1985). This has increased synchronicity of the flood waves on the Vistula and on its mountain tributaries, especially the Dunajec, with the resultant increased peak discharges of the flood waves in the downstream course of the Vistula.

The increase in water stages of embanked rivers, resulting from floodplain constriction by embankments and the increase in flood discharges induced by

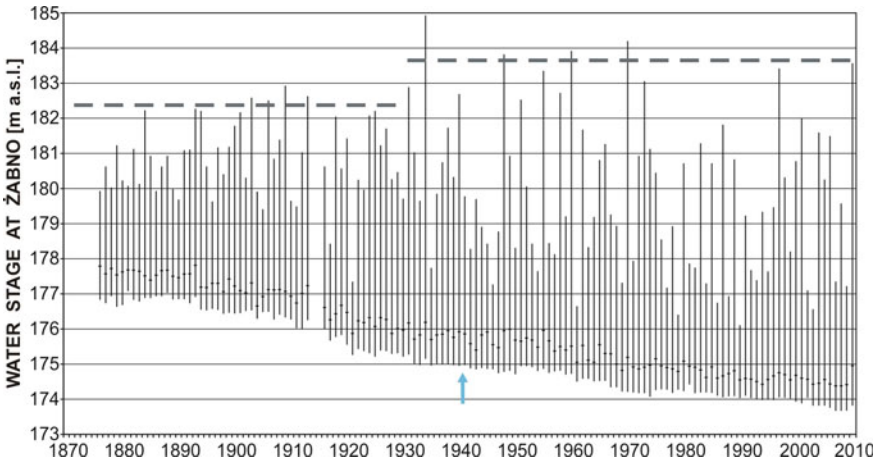

Fig. 2 Amplitude of water stages (*vertical lines*) and mean annual stages (*points*) at the Żabno gauging station in the lowest course of the Dunajec River since 1876. *Dashed lines in the left and right parts* of the diagram indicate approximate maximum stage of the large floods occurring before and after channelization of the river in its lower and middle courses. The *arrow* indicates the onset of the operation of the Rożnów dam reservoir in the middle river course

channel change in the upstream reaches, facilitated failure or overtopping of the embankments during large floods. The embankments along the Upper Vistula and the lower courses of its Carpathian tributaries within the Sandomierz Basin were breached/overtopped during floods in 1903, 1925, 1934, 1960, 1970, 1997, and 2010. The failure of the embankments resulted in storage of up to 400 million m^3 of water (in 1934) outside the embankments, and this prevented or slowed down the increase in peak discharges of the flood waves in the downstream reaches of the Vistula. However, it was also the reason for enormous flood damage as the inundated area outside the embankments reached up to 1000 km^2 (in 1934).

5.2.2 Channel Incision

Rivers draining the Polish Carpathians incised by 0.5–3.8 m over the 20th century (Fig. 1). In many river reaches, incision resulted in the dissection of the whole thickness of alluvium on the valley floor and transformation of the alluvial channels into bedrock ones (Hajdukiewicz and Wyżga 2013). Incision has been caused by the channelization-induced increase in transport capacity of the rivers caused by their channelization, the concomitant decrease in sediment supply to the channels and in-channel gravel mining (Wyżga 2008). The term *channel incision* describes bed degradation or channel deepening that leads to the increase in channel capacity (Wyżga et al. 2016). Absolute (expressed in metres) amounts of channel incision in Polish Carpathian rivers are typically greater in their lower and middle courses than in the upper course (Fig. 1). However, Wyżga et al. (2016) examined incision-caused changes in channel conveyance and the frequency of valley-floor inundation at water-gauge cross-sections along the Dunajec River and found the increasing impact of incision with decreasing river size. They concluded that as channel dimensions decrease and channel slope increases in the upstream direction, the influence of a given absolute amount of river incision on channel conveyance and on the resultant loss of floodwater storage on floodplains will also increase toward the upper reaches of a river network.

Rivers draining the eastern part of the Polish Carpathians exhibit somewhat greater absolute amounts of incision than rivers draining the western part of the mountains (Fig. 1). Also in this case a different impact of incision on the loss of floodwater storage in floodplain areas was demonstrated by Wyżga (2001b) who compared changes in the percentage of total flood flows conveyed on the valley floor between the Łabuzie gauge cross-section on the Wisłoka River and the Wadowice gauge cross-section on the Skawa River. Despite similar absolute amounts of incision recorded at both gauging stations during analysed periods, in the Skawa a reduction in the amount of floodwater conveyed on the valley floor was considerably greater, especially at low-frequency, high-magnitude flood flows.

The impact of channel incision on the flood hazard to downstream river reaches was analysed by comparing inflow and outflow peak discharges of flood waves passing the modified river reaches (Wyżga 1997). The analysis focused on relatively long river reaches, along which the catchment area increases relatively little; such reaches thus provide good conditions for flood-wave transformation, but the recorded changes in flood flows cannot be attributed to changed inflow from tributaries. Analysis of annual maximum discharges, peak discharges of ten largest flood waves and of all flood waves from particular decades consistently indicated a shift toward higher values of flood discharges recorded at the downstream end of such reaches with the progress in channel incision (Wyżga 1997). This can be illustrated by a comparison of the magnitude of floods of given recurrence intervals at the Łabuzie and Brzeźnica stations on the Wisłoka (Fig. 1), estimated for the record periods 1921–1955 and 1956–2000 typified, respectively, by small and high degree of channel incision (Table 1). As a result of reforestation of the montane part of the Wisłoka catchment, flood magnitudes recorded at both stations were lower in the second period than in the first one. However, the stations differed in the scale of the reduction, which amounted to 31 % at the upstream located Łabuzie station and to 19 % at the downstream located Brzeźnica station, and the difference can be ascribed to changed conditions of flood-wave transformation between the stations. In the years 1921–1955 all considered index floods ($Q_{1.5}$–Q_{20}) slightly decreased in magnitude in the Łabuzie-Brzeźnica reach, with mean annual flood ($Q_{2.33}$) decreasing by 4 %. After 1955, peak discharges of flood waves increased between the stations, and the increase varied between 5 % for a 20-year flood and 14 % for mean annual flood (Table 1).

The changes in flood flows recorded downstream of the river reaches modified by channel incision can be explained by increased concentration of flood flows in

Table 1 Flood flows (in $m^3 s^{-1}$) of given recurrence intervals at the Łabuzie and Brzeźnica stations on the Wisłoka River estimated for the record periods 1921–1955 and 1956–2000

	Łabuzie		Brzeźnica	
	1921–1955	1956–2000	1921–1955	1956–2000
$Q_{1.5}$	385	272	370	295
$Q_{2.33}$	525	360	505	410
Q_5	720	575	690	630
Q_{10}	880	745	850	800
Q_{20}	1035	910	990	960

After Wyżga (2008), reproduced with permission of Elsevier
Q_x denotes discharge of given recurrence interval

the deepened channels. It reduced floodplain retention of floodwater and increased relative smoothness (ratio of water depth to the height of protrusion of bed-material particles to the flow) of flood flows, resulting in decreased attenuation and faster propagation of flood waves.

5.2.3 Loss of Channel Storage in the Impounded Reach of the Upper Vistula River

Between 1949 and 2003, six barrages were constructed on the Upper Vistula with the aim to increase water depth in the river for navigation purposes. Their construction changed the river into a sequence of shallow water reservoirs on the distance of 86 km. Because the river was impounded for navigation, the barrages maintain the same water level except at high flows. This distinguishes these shallow reservoirs from typical dam reservoirs, from which a considerable proportion of stored water can be released before the flood in order to increase their flood capacity.

Channel storage is the volume of water that can be temporarily retained in a channel up to the bankfull stage (Fig. 3). In the shallow reservoirs formed upstream of the barrages, a considerable proportion of channel storage is exhausted as a result of the permanent river impoundment (Fig. 3). When discussing a possible

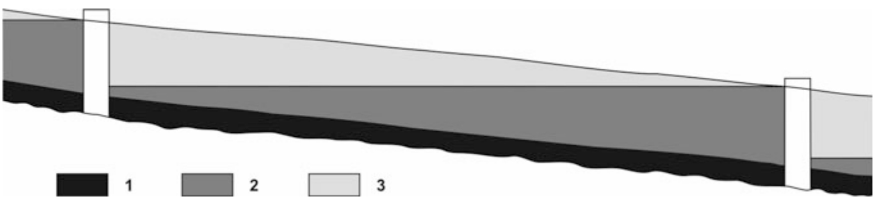

Fig. 3 Elements of the total channel volume upstream of a barrage constructed for navigation purposes: *1* permanently filled with water at base-flow conditions before the barrage construction, *2* permanently filled with water after the barrage construction, *3* filled with water during floods. Available channel storage of floodwater encompasses parts 2 and 3 before, while only part 3 after the barrage construction

construction of a new barrage downstream, Wyżga et al. (2014) indicated that its construction would permanently exhaust 2.4 million m^3 of channel storage (189 m^3 per 1 m of river length, on average), i.e., 57 % of the volume hitherto available along the planned reservoir. In turn, the amount of channel storage that was already lost as a result of the construction of the six barrages can be estimated at ~12 million m^3 (with an average of 139 m^3/1 m of river length). This lost storage volume is rather large as it corresponds to one-fifth of the flood capacity of the large dam reservoir constructed in past years at Świnna Poręba on the Skawa River.

5.3 Expansion of Riparian Forests Increasing Large Wood Recruitment to River Channels

Topographic maps of the Polish Carpathians prepared in the late 18th to the late 19th centuries indicate a lack or only a scarce occurrence of riparian forests in the river valleys (Wyżga et al. 2012, 2015). This situation was typical of European mountain areas of that time (Kondolf et al. 2002; Rinaldi et al. 2013) and reflected high intensity of grazing or cultivation of riparian areas (preventing development of riparian forests) combined with high dynamics of the rivers draining highly deforested catchments, that facilitated rapid turnover of their active zones. During the 20th century riparian forests developed in the valleys of Polish Carpathian rivers (Wyżga et al. 2012). For instance, in the middle course of the Czarny Dunajec, the riparian area in the late 19th century was devoid of forest; at the mid-20th century forest expanded to ca. 40 % of the reach length, whereas at present it grows along the entire reach (Wyżga 2007). The expansion of riparian forests was stimulated by a reduction in agricultural and pastoral activities in the riparian area and by river narrowing caused by reduced river dynamics and channelization of many river sections.

Currently, large amounts of woody material are recruited during floods from the forested channel banks and islands to the channels of Polish Carpathian watercourses and may cause flood damage if deposited at vulnerable sites such as bridges or urban reaches. Negative impacts of wood debris during floods are mainly related to the clogging of narrow river sections and bridges, which causes a quick succession of backwater effects as a result of the reduction of cross-sectional area. Such clogging can trigger bed aggradation, channel avulsion, and local scouring processes, which can ultimately lead to floodplain inundation and bridge collapse (Comiti et al. 2012). As a result, the nearby area may be flooded more frequently (Ruiz-Villanueva et al. 2013), increasing flood risk (Ruiz-Villanueva et al. 2014). Impacts of bridge clogging were observed during the large flood of 2010 on the Biała River when deposition of wood debris under a bridge (Fig. 4) directed flood flow onto the adjacent valley floor, resulting in flood damage to the nearby houses and infrastructure (Hajdukiewicz et al. 2016).

Fig. 4 Partial clogging of the bridge at Jankowa on the Biała River with large woody debris trapped on the bridge pillar during the flood of June 2010. The bridge clogging directed the flood flow onto the adjacent valley floor, causing flood damage to the nearby houses and infrastructure

As demonstrated by Mikuś et al. (2016, in this volume), large wood is particularly mobile in larger rivers where it can be transported long distances along single-thread, channelized and incised reaches, which are currently common in the rivers (Wyżga et al. 2015). As a result, during floods substantial amounts of wood can be delivered to and deposited at vulnerable sites located within or downstream of such reaches irrespective of preventive measures (e.g. riparian forest clearing) undertaken in the vicinity of these sites.

6 Concluding Remarks

Floods in the Upper Vistula Basin are generated by three principal mechanisms: (i) a few days-long rainfall of moderate intensity, (ii) short-duration, high-intensity rainfall, and (iii) snowmelt, locally linked with ice jam formation. During the last century, changes in climatic and terrestrial drivers of floods have affected the flood hazard in the region, although both the changes themselves and their impacts on flood hazard are better documented for terrestrial drivers. An increase in temperature, already recorded over the past century and forecast to continue during the 21st century, tends to reduce the magnitudes of snowmelt floods and to increase the frequency of occurrence of local flash floods generated by high-intensity, convective rainfall. However, the ongoing climate changes may have no significant influence on the frequencies and magnitudes of floods caused by the rainfall generated by widespread cyclones as the Upper Vistula Basin is located between the Southern Europe, where precipitation totals are forecast to decrease, and Northern Europe, where they are expected to increase (European Commission 2005).

The increase in forest cover in the Polish Carpathians had an apparent regulating effect on the flood runoff from the mountain catchments, and the construction of dam reservoirs allowed for some reduction in peak discharges of flood waves, although multiple functions of the reservoirs limit their efficiency in reducing flood discharges. In turn, widespread channel regulation and river incision tended to reduce floodwater retention in floodplain areas and to accelerate the passage of flood waves, with the resultant increase in flood hazard in downstream river reaches. Construction of flood embankments considerably limited the lateral extent of active floodplains, stimulating enhanced management of the river valleys. However, as water stages of flood flows on the embanked rivers increased, flood embankments—especially in river reaches within the Sandomierz Basin—have been repeatedly breached/overtopped, resulting in the inundation of managed areas outside the embankments and considerable material damage. Shallow water reservoirs constructed for navigation purposes on the Upper Vistula substantially reduced channel storage of floodwater in that river because of the specific mode of functioning of these reservoirs. Finally, increased delivery of large wood to river channels following the 20th-century expansion of riparian forests in the valleys of Polish Carpathian rivers currently makes wood jamming during floods an important factor of flood hazard in vulnerable river reaches/cross-sections.

Analyses of long-term records of flood discharges at numerous gauging stations indicated no systematic increase in the magnitudes of floods on the rivers of the region (Soja 2002; Ruiz-Villanueva et al. 2016), and this can be explained by the counteracting operation of different drivers. However, this seemingly optimistic conclusion can be reformulated into a less optimistic one. The lack of common and significant decreasing trends in flood magnitudes indicates a lost opportunity for permanent reduction of flood hazard on the rivers in the region, that could have been achieved as a result of the reforestation of catchments (cf. Wyżga 1997) and the construction of dam reservoirs. Moreover, it should be remembered that the lack of increase in flood hazard over the few past decades does not translate to the same situation in flood risk because of the increased exposure and vulnerability of the valley communities to floods, caused by the enhanced management of the valley floors and the increased wealth of the communities.

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