Flood Risk Management in the Upper Vistula Basin in Perspective: Traditional versus Alternative Measures

Bartłomiej Wyżga, Artur Radecki-Pawlik and Joanna Zawiejska

Abstract Flood-protection works carried out in the Upper Vistula basin since the late nineteenth century have been based on channel regulation and river embankment leading to fast evacuation of floodwater and a significant reduction in floodwater retention on the valley floors. Such a policy of flood-control management stemmed not only from the unfamiliarity with other methods and a generally technocratic approach to nature but also from the need to protect all arable land adjacent to rivers. This last motivation justified the approach in the early part of the period when farming provided for the existence of most of the society, but it progressively declined in significance with increasing urbanization of the region and economic development of the country. Flood-risk management based on the conventional methods has resulted in a severe degradation of the rivers' ecological quality and increased peak discharges of flood waves recorded in the downstream parts of regulated and embanked river reaches. It is thus a priority to decelerate flood runoff and increase floodwater retention in less developed parts of the valleys in order to reduce flood hazard in spatially concentrated, urbanized areas along rivers. This paper presents alternative measures that either aim at reducing flood hazard at various stages of flood-wave passage through the region or serve to diminish flood risk by preventing development of river-adjacent areas, re-construction of bridges and cessation of the detrimental in-channel gravel mining.

B. Wyżga (✉)
Institute of Nature Conservation, Polish Academy of Sciences, al. Mickiewicza 33,
31-120 Kraków, Poland
e-mail: wyzga@iop.krakow.pl

A. Radecki-Pawlik
Department of Hydraulics Engineering and Geotechnique, University of Agriculture,
al. Mickiewicza 24/28, 30-059 Kraków, Poland
e-mail: rmradeck@cyf-kr.edu.pl

J. Zawiejska
Institute of Geography, Pedagogical University of Cracow, ul. Podchorążych 2,
30-084 Kraków, Poland
e-mail: zawiejska.joanna@gmail.com

Z.W. Kundzewicz et al. (eds.), *Flood Risk in the Upper Vistula Basin*,
GeoPlanet: Earth and Planetary Sciences, DOI 10.1007/978-3-319-41923-7_18

Keywords Flood hazard · Flood risk · Flood protection · Flood-control measures · Floodwater retention

1 Introduction

Floods pose a significant threat to human life and property (Merritts 2011). Channelization, bank protection and construction of dam reservoirs were among the measures introduced to limit that threat (Bravard and Petts 1996). A reduction of flood hazard was imperative in mountain and piedmont regions where high precipitation values and considerable slope and channel gradients result in rapid concentration of flood waves and high energy of flood flows, and where settlements are frequently located on valley floors. In the Italian Alps, technical interventions were already introduced in Roman times (Comiti 2012). Large-scale channelization of Carpathian tributaries to the Vistula was initiated in the late nineteenth century in their reaches in the Sandomierz Basin (the San—Szumański 1986; the Dunajec—Zawiejska and Wyżga 2010). In the twentieth century channelization works encompassed almost the whole length of these rivers and a large proportion of the courses of their tributaries.

Flood embankments were constructed in the second half of the nineteenth century along the upper course of the Vistula (Łajczak 1995) and in the 1880s–1890s in the lowest courses of its Carpathian tributaries (Zawiejska and Wyżga 2010). First dam reservoirs on Polish Carpathian rivers were constructed after the catastrophic flood of 1934 (Porąbka Reservoir on the Soła and Rożnów Reservoir on the Dunajec), and several others have been built since the World War II. Until now these interventions (channel regulation, river embankment and dam reservoirs) have been practically the only measures adopted in the Upper Vistula basin to mitigate flood hazard. However, long-term experience in this and other regions has shown that these measures bring a range of adverse effects and they provide only localised protection from flooding, whereas flood risk at the regional scale is not reduced but only transferred downstream (Wyżga and Radecki-Pawlik 2011). In the last decades several methods were indicated that may be more effective in reducing flood hazard and risk at a regional scale than the conventionally used technical measures (European Commission 2003; Wyżga and Radecki-Pawlik 2011).

This paper presents limitations and adverse effects of the "traditional" methods of flood protection and indicates a range of alternative measures which may be more effective in reducing flood hazard and risk at a regional scale.

2 Conventional Methods of Flood Protection

2.1 Channelization Schemes

Natural, vertically stable rivers have channel capacity close to 1.5-year flood flow (Williams 1978). In turn, sizing of regulated channels depends on the character of land use in the adjacent area, with designed flow capacity of the channels ranging from a 2-year flow in forested areas to a 10-year flow in urbanized areas (Hydroprojekt 1987). Channel straightening and narrowing, often to a width significantly smaller than that of the natural channels, resulted in a considerable increase in river transport capacity, while simplification of the natural, morphologically diverse channels reduced their resistance to flow (Wyżga 2001). Consequently, river channelization was followed by channel incision (Fig. 1) (Wyżga 2001; Zawiejska and Wyżga 2010) that further increased flow capacity of the channels. Although the absolute (expressed in metres) amount of the twentieth-century incision of Polish Carpathian rivers was highest in their lower and

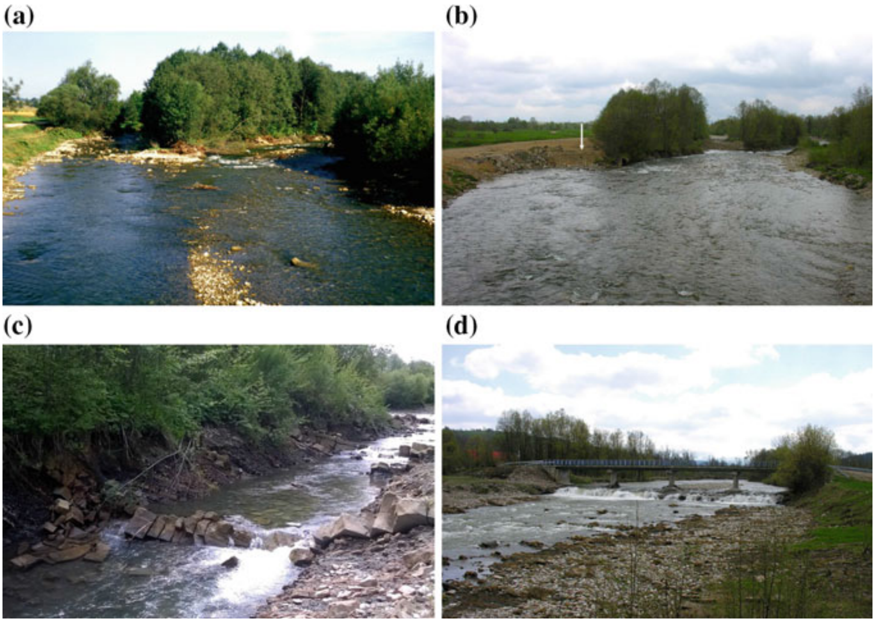

Fig. 1 Example of detrimental effects of inappropriate river management practices on channel stability and valley-floor infrastructure. **a** Downstream view of the Czarny Dunajec from the bridge at Chochołów in 2002. The river flows in two braids and its channel is vertically stable. **b** The same reach in 2005. *Arrow* indicates the position of the former left braid that has been blocked and filled up with earth. **c** Deep incision induced by flow concentration in the single channel downstream of the bridge is visible in 2015. **d** Backward erosion induced by deep incision of the single channel threatens the stability of the bridge

middle courses, the largest increase in channel capacity took place in the headwater reaches where the initial channel capacity was relatively small (Wyżga et al. 2016). By increasing channel capacity for flood flows and accelerating their downstream transfer, channel regulation leads to a substantial reduction in floodplain storage of floodwater (Wyżga 1996). In consequence, river channelization does not reduce flood hazard but only shifts it to downstream river reaches and at the same time, it results in increased peak discharges of flood waves in the reaches located downstream of a channelized reach (Wyżga 1997).

River channelization also resulted in a considerable decrease in habitat diversity and, consequently, a reduction in the abundance and diversity of river biota, including fish and benthic invertebrates (Wyżga et al. 2009, 2011). Rapid channel incision was a cause of considerable economic losses reflecting, among others, the need to reconstruct bridges or bank water intakes (Wyżga 2001). To prevent a loss of vertical channel stability resulting from channel regulation, hydraulic drop structures were constructed in many channelized reaches. This limited an uncontrolled increase in flow capacity of the regulated channels but disrupted river continuity for biota, particularly fish migration.

2.2 Flood Embankments

River embankments provide only localised protection from flooding, while flood hazard is shifted downstream where peak discharges increase as a result of reduced floodwater storage within the constricted floodplain. A reduction in the floodplain width leads to an increase in water stages attained at given discharges within the embanked river section (e.g. Punzet 1985). During large floods such high water stages are in these sections associated with large water depths that enhance failure of the embankments. These are usually destroyed not because of overtopping by floodwater but when their toe is washed away as a result of the increased pore pressure from water seepage. Within the Sandomierz Basin, embankments of the Vistula were breached during the floods of 1934, 1960, 1970, 1997 and 2010, resulting in the inundation of managed areas behind the embankments. In this section of the Vistula, protection from flooding provided by the embankments during minor floods appears problematic during large, catastrophic floods.

As the construction of the embankments along the Upper Vistula and its tributaries in the Oświęcim and the Sandomierz basins encouraged intense development of the adjacent areas, their removal is impossible. However, the above observations question the reasons for raising the existing embankments or constructing new ones in the mountain and foothill reaches of Carpathian rivers. Raising the embankments would increase water pressure during flood events and thus likely increase the probability of the embankments being washed away. New embankments in the mountain and foothill valley sections would prevent flooding of less developed, mostly agricultural areas. With the inevitable increase in flood hazard to downstream river reaches, resulting from the construction of embankments, introduction of these measures to protect agricultural land is not justifiable. In the valleys with gravelly alluvium, typified by high hydraulic conductivity (and thus fast water filtration through sediment), water tables on both sides of the embankments quickly become established at the same level. Under such conditions, not only are the embankments ineffective in providing protection from flooding, but they also create a false sense of security, thus encouraging development of the land adjacent to the embankments.

2.3 Construction of New Dam Reservoirs

With the ability to capture a proportion of the volume of flood waves, dam reservoirs may significantly reduce flood hazard in downstream river reaches. However, this important role of dam reservoirs in flood hazard reduction is limited as a result of the disruption of bed material transfer to the river reaches downstream from the reservoir. This leads to bed degradation (Kondolf 1997) which, in turn, increases channel capacity and reduces floodwater storage on the valley floor. If the channel downstream from a reservoir becomes incised on a considerable distance, the loss of floodplain storage of floodwaters may largely obliterate the flood-control effect of the dam reservoir. This problem could be resolved by coarse sediment augmentation, in this case transferring bedload material deposited at the river's inlet to the reservoir to the river sections below. This solution is now commonly applied in Germany, France or the USA (Kondolf 1997; Rollet et al. 2008).

An important factor to consider before reservoir construction is its useful lifetime, reflecting the rate of silting of the reservoir conditioned by the amount of suspended sediment transported by the river and the rate of water exchange in the reservoir (Łajczak 1994). Longer useful lifetime is typical of deep reservoirs located in the upper reaches of Carpathian rivers, draining largely forested catchments (e.g. the planned Kąty-Myscowa reservoir on the Wisłoka River). In contrast, shallow reservoirs on small watercourses in foothill agricultural catchments with soils developed on loess and loesslike deposits would have very short useful lifetime and their construction is pointless. Recently, construction of a few reservoirs in such locations has been planned; it seems reasonable to abandon such schemes as the reservoirs, built at high cost, will be silted shortly and are most likely to function only as breeding grounds for mosquitoes.

2.4 Conventional Flood Control Methods on the Carpathian Rivers—Examples

Even though it is now evident that the conventional measures of flood control have adversely impacted the environment and shifted flood risk downstream without its

Fig. 2 Rip-rap constructed in 2013 on the concave bank of the Czarny Dunajec at Chochołów protects from erosion a floodplain overgrown with alder and willow shrubs. Buildings that might potentially require protection from erosion are distant from the river bank by more than 100 m, equal to approximately two channel widths at the site

reduction at the regional scale, the already introduced schemes cannot be easily abandoned. However, it is imperative to draw conclusions from the analysis of the past interventions to limit their flood-control use only to the most developed or urbanized valley reaches (Bojarski and Wyżga 2009). Until now the approach to flood protection in the Upper Vistula basin has remained unchanged, with a number of hydrotechnical works done over the last years which were either unnecessary or harmful to the environment and which increased, rather than reduced, flood hazard at the regional and sometimes even local scale (Żelaziński and Wawręty 2005). Below we present examples of such interventions.

Transformation of the multi-thread channel of the Czarny Dunajec at Chochołów into a single-thread one (in 2005) has had no positive economic impact as the cut off and filled side channel was adjacent to fallow land and extensively used meadows. Flow concentration in one of the previous channels induced rapid channel incision and backward erosion that threatens the stability of a nearby bridge (Fig. 1). Reinforcement of the river bank with rip-rap, carried out at Chochołów in 2013, provides protection from erosion to fallow land of no particular economic value (Fig. 2). An incentive to perform these works could have only been the need to spend public funds as there are no structures on the floodplain that require protection from potential bank erosion. At Stróże, a wall constricting the floodplain of the Biała River was erected (2012) in close vicinity of the channel but at a large distance from buildings that may require flood protection. Such a reduction of floodplain width, eliminating floodplain storage of floodwater in this river reach, will inevitably lead to increased peak discharges of flood waves in the downstream reach. At the same time, construction of the wall caused a complete destruction of riparian vegetation and affected riverscape aesthetics (Fig. 3).

Fig. 3 A concrete wall constructed in 2012 along the Biała River at Stróża under the pretext of preventing the valley floor from flooding. The wall construction resulted in complete eradication of riparian vegetation and separated from the river a wide band of the floodplain that did not require protection from flooding

3 Alternative Methods of Flood Hazard and Risk Reduction

Below we indicate measures which may be significantly more effective than the conventional methods in reducing flood hazard and risk at regional scale—the entire basin of the Upper Vistula River.

3.1 Flood Hazard and Flood Risk Maps as a Basis for Improved Management of Valley Floors

EU Floods Directive (European Commission 2007) indicated the adjustment of valley-floor management to the level of flood hazard and risk as a key measure to control potential flood damage (Santato et al. 2013). Developed valley floors undoubtedly need to be protected from flooding, usually through their separation with flood embankments from artificially constricted floodplains. However, in recent decades the Upper Vistula basin has seen progressive encroachment of development and infrastructure onto riverside land. Such areas are next postulated to be included in flood protection schemes (channel regulation, flood embankment construction). This trend tends to neglect that flood protection of all such areas is from the beginning doomed to fail and the floodwater that was prevented from inundating one valley section will most likely, and uncontrollably (levee breeching), inundate another, downstream valley section resulting in larger flood losses.

It is thus essential to stop the trend and replace it with proactive management of riverside land that is adjusted to the actual level of flood risk (Bobiński and Żelaziński 1996).

A premise for the 2015 Flood Risk Management Plans, the recently prepared maps of flood risk and flood hazard present an opportunity for a change in the management of riparian areas. However, using these maps to improve spatial planning in the valley floors has also certain limitations. First, as a result of high costs of their preparation, in Poland the maps were only made for the valleys of major rivers. Such argumentation entirely neglects the fact that preventing development on the land with high flood risk, based on such maps, is the cheapest method of limiting flood losses. Second, in several places local authorities defy indications derived from these materials, arguing that the maps only present the current level of flood hazard and risk that will be diminished in the upcoming years as a result of engineering works carried out in the catchments. However, it should be emphasized that flood hazard and risk assessments are dynamic in character as in the future both may diminish, thanks to the engineering works improving floodwater retention (e.g. construction of dam reservoirs), or increase as a result of channel regulation or incision and construction of flood embankments in the upstream sections of river valleys or because of climate change. This is why decisions on the management of valley floors must be based on the existing maps presenting current assessment of flood hazard and risk. Third, methodology behind the construction of these maps is based on the assumption that flood damage only results from inundation of valley floors or high flow velocities in these areas. This assumption is not adjusted to the character of floods in mountain regions where a considerable proportion of flood damage is associated with the erosion of riverbanks and abrupt lateral shift of the channels during flood events (cf. Hajdukiewicz et al. 2016).

3.2 Spontaneous or Enhanced Re-Establishment of Small Channel Capacities and Floodplain Retention in Headwater River Reaches

Headwater, first- to third-order (sometimes also fourth-order) river reaches have rarely been of particular interest to river managers as these valley sections are usually undeveloped and do not require construction of hydraulic structures or channel regulation. However, it is here where floods originate and, because these headwater reaches total tens of thousands kilometres of river network in the Upper Vistula River basin, the situation in these reaches will shape the flood conditions in the downstream, developed valley reaches. Over the last few decades a significant improvement of vegetation cover on hillslopes (increase in forest cover, a shift from arable land to grassland) occurred in the Upper Vistula River basin, particularly its Carpathian part. In consequence, the delivery of sediment to the headwater channel

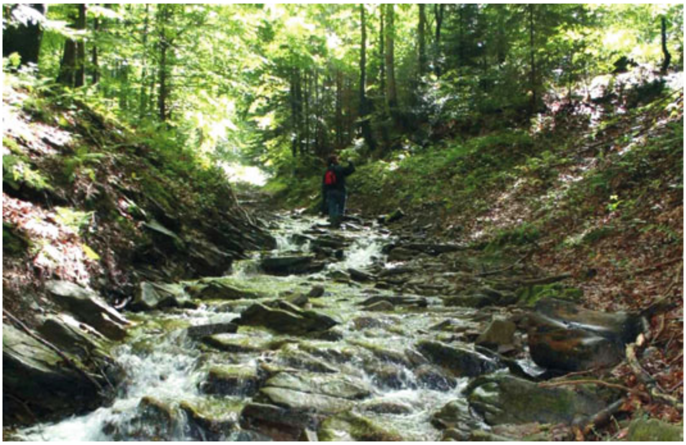

Fig. 4 Deep channels, incised to bedrock, are widespread in headwater reaches of streams in the Polish Carpathians as exemplified by Kryściów Stream in the Low Beskid Mountains (*photo credit* Roman Żurek)

reaches considerably decreased. At the same time, headwater streams continued to be cleaned of fallen trees to maximize the amounts of timber harvested from the forests and use channels as routes for its transport. With the reduced supply of sediment to headwater stream channels and a lack of large wood as a major component of hydraulic roughness, many such channels deepened considerably and incised to bedrock (Fig. 4). As the dimensions of headwater channels are generally small, even low amount of bed degradation, in the range of 0.2–0.4 m, resulted in a manifold increase in their capacities and the resultant loss of floodplain storage of floodwaters (Wyżga et al. 2016).

It is thus necessary to allow accumulation of bed material in these channels to diminish their capacities and re-establish the conditions for floodwater storage in their riparian areas. Accumulation of alluvium can be enhanced by allowing spontaneous formation of wood dams from fallen trees (Fig. 5) or artificial formation of such dams in headwater channel reaches (Bojarski et al. 2005; Wyżga 2007). This requires abandonment of the harvest of riparian trees and of the removal of trees fallen to the channels, that would only slightly decrease the amount of timber harvested from the mountain forests. At the same time, this loss can be compensated with better conditions for tree growth, resulting from slowed drainage of groundwater in near-channel slope sections, particularly beneficial for spruce with its shallow root system. This change in management of riparian forest along headwater stream channels can easily be introduced in the state-owned forests (managed by the State Forests agency). Notably, the limited mobility of large wood in headwater channels means the wood will not pose a flood hazard to downstream, urbanized valley reaches.

Fig. 5 Wood dams, either naturally formed by fallen trees or artificially constructed in headwater channels, facilitate bed material storage, reduce channel capacity and promote maintenance or re-establishment of floodplain retention of floodwaters. Kamienica Stream in the Gorce Mountains

3.3 Storage of Stormwater Runoff from Small Paved Catchments

While in mountain catchments the factors responsible for the formation of surface runoff and rapid concentration of flood waves are steep slopes and channel gradients, in urbanized areas they result mostly from the impervious nature of a large proportion of the catchment surface. During storms, paved surfaces (rooftops, roads, parking lots) prevent infiltration and all rainfall can be transformed into runoff, resulting in the formation of flash floods and inundation of vast urban areas (Radecki-Pawlik 2003). To prevent rapid concentration of flood waves that form in such areas, it is necessary to provide retention for storm runoff from small paved catchments. This can be achieved in dry or wet stormwater management ponds. Dry ponds store runoff only during storms and later slowly drain. Wet ponds do not have outlets and store stormwater that later evaporates or infiltrates into the ground (Fig. 6). Apart from stormwater storage, wet ponds can be used for settling pollutants washed from impervious surfaces, particularly road pavements (Wałęga et al. 2013). Over the last years, a number of wet ponds have been constructed along motorways in southern Poland. Storage ponds for storm runoff from small paved catchments were also constructed in some towns in the Upper Vistula River basin (Fig. 6).

Fig. 6 Wet stormwater pond constructed to collect surface runoff from paved surfaces in a housing estate in Kraków

3.4 Measures Increasing Floodplain Retention of Floodwater

Floodplain retention consists in temporary retention of floodwaters inundating a valley floor or slowing down their flow in comparison with that of floodwaters in the channel. The retention thus increases with the increasing proportion of total flow that is conveyed in the floodplain zone of a cross-section and with increasing difference between flow velocities in the floodplain and channel zones (Wyżga 1999). In the twentieth century, incision was the dominant tendency of Polish Carpathian rivers, increasing flow capacity of their channels and substantially reducing the potential for floodwater retention on their floodplains (Wyżga 2008; Wyżga et al. 2016). It is thus necessary to reduce flow capacity of the channels and re-establish the potential for floodplain retention of floodwaters. This can be achieved by either elevating channel beds or lowering the floodplain surface. The first method, inevitably resulting in increased water stages at particular discharges, may only be applied in relatively undeveloped valley sections.

In more developed valley sections, a reduction in channel capacities and the resultant increase in floodplain retention of floodwaters can be obtained by removing a proportion of valley-floor sediments and the formation of a new floodplain at lower elevation (Fig. 7). In many river reaches, such a new floodplain can be constructed on the land owned by the state and managed by the Water Authority (Regional Water Management Board). Where the Authority has no rights to such land or where it is too narrow, the purchase of undeveloped riverside land from local owners will be necessary. The cost of floodplain lowering may be significantly decreased if the works are carried out with the use of gravel mined for aggregate from the re-constructed floodplain. Such floodplain reconstruction may

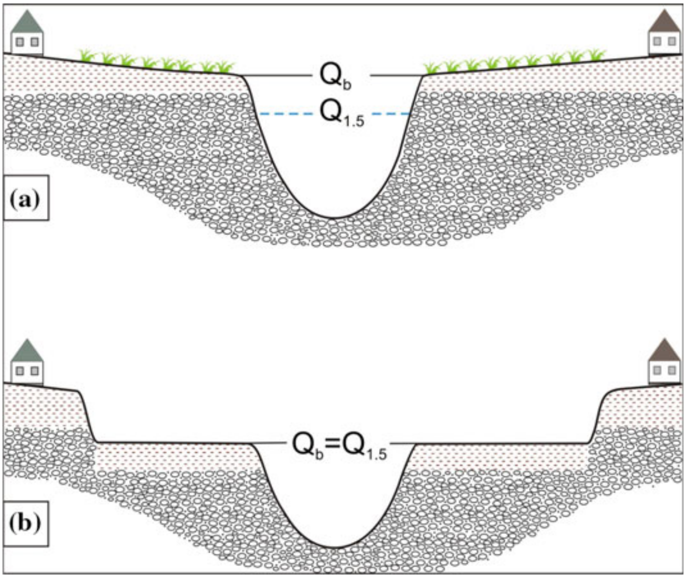

Fig. 7 **a** Incised channel has bankfull capacity (Q_b) larger than that of 1.5-year flow. **b** Re-establishing floodplain retention and channel capacity typical of natural, vertically stable rivers achieved as a result of artificial floodplain excavation at a lower position. In the process, a proportion of the gravelly sediments is removed, while soil fines are replaced over the lowered floodplain

be beneficial not only for flood control but also for the environment as it will enhance re-establishment of riparian habitats, previously lost as a result of channel incision that excessively increased their elevation above the water table.

Establishment of erodible corridors in undeveloped riparian areas can be an efficient way to restore floodplain retention along incised Polish Carpathian rivers (Bojarski et al. 2005). Within the corridors, lowering of the surface of riparian land and the formation of new, low-lying floodplains will be carried out by the laterally migrating rivers. The costs of the functioning of erodible corridors will mainly consist in the purchase of riverside areas from private owners. River restoration projects aimed at the establishment of an erodible river corridor have recently been implemented on the Biała and the Raba rivers (Wyżga and Zawiejska 2012).

3.5 Measures Increasing Channel Storage of Floodwater

In the valley of the Upper Vistula and in the lower courses of its tributaries, an important factor of flood hazard is insufficient width of the inter-embankment zone that results in the formation of high water stages during floods, likely to overflow the embankments. This hazard can be reduced by implementing measures increasing channel storage of floodwaters. Importantly, channel incision that occurred on Polish Carpathian rivers during the twentieth century (Wyżga 2008; Wyżga et al. 2016) did not enlarge channel storage as it can only be increased by a concurrent increase of channel capacity and deceleration of downvalley water flow.

Since the 1990s construction of secondary, side channels along the main regulated channel has been introduced in some EU countries (e.g. Schropp 1995; Hornich and Baumann 2008). At flood conditions these side channels carry a proportion of the total flow and their presence allows a significant decrease in water stages attained at particular discharges. Irrespective of their flood-control function, side channels enrich the array of river habitats, in particular re-establishing slow-velocity habitats previously eliminated as a result of channel regulation. Construction of secondary channels need not be expensive if it follows appropriately designed exploitation of gravel within the valley floor or incorporates disused gravel pits.

3.6 Dry Reservoirs

In the upper river reaches, dry reservoirs can play a significant role in the attenuation of flood waves. Dry dams have spillways of relatively small conveyance, which allows undisturbed passage of water at low to medium flows and causes the reservoir to fill at higher flows. Dry reservoirs have some undeniable advantages:

– unlike typical dam reservoirs, their full storage capacity is used to hold floodwater and thus dry reservoirs are very effective in capping large flood waves;
– the bottom of such reservoirs can be used for agriculture as it is inundated only once in a few years during a larger flood;
– they do not disrupt bedload transfer and longitudinal connectivity of the watercourse for biota.

Dry reservoirs were constructed on the streams and rivers draining the Sudetes (Lower Silesia region) in the first half of the twentieth century, especially after the catastrophic flood of 1897 (Lenar-Matyas et al. 2009). Currently, a large dry reservoir is under construction on the Oder River in Racibórz. So far, no such structures have been constructed in the Upper Vistula River drainage basin.

3.7 Polders

In the lower river courses where valleys are wide, floodwater should be effectively stored in polders (detention basins): undeveloped areas within valley floors that can be inundated during larger floods. Separation of a polder from the river by a flood embankment allows its inundation during a flood peak and thus efficient attenuation of the flood wave (Huang et al. 2007). Polders with a single connection to the river are filled with water during the rising limb of a flood wave or at flood peak; the water gradually drains back into the river during flood recession. Elongated polders typically have two connections with the river: that located in the upper section of the valley enables inflow of floodwater which subsequently returns to the river through the connection in the lower section of the valley.

Polders can be constructed in undeveloped portions of valley floors, cut off river bends and large gravel pits. To date, the practice of flood control in the Upper Vistula River drainage basin has not involved construction of polders. The 2015 Flood Risk Management Plan prepared for this area includes construction of polders in the Upper Vistula valley. A study by a pro-environmental organization indicated a potential for construction of nine polders upstream of Kraków with a total volume of 59.3 million m^3, comparable to the flood-control capacity of a large dam reservoir on the Skawa River at Świnna Poręba (Ciężak et al. 2014).

3.8 Compensating the Loss of Floodplain Water Storage Resulting from Channel Regulation or the Construction of Flood Embankments

Formation of a channel with flow capacity larger than that of natural, vertically stable rivers, i.e. 1.5-year flow (Williams 1978) (Fig. 8a, b), and construction of flood embankments—necessary in urbanized valley sections—accelerate evacuation of floodwaters from such a valley section and reduce its storage on the valley floor resulting in increased flood peaks downstream (Wyżga 1997). Therefore, the loss of floodplain water storage resulting from flood protection of developed riparian areas should be compensated for with increased floodwater storage in either upstream or downstream, undeveloped valley sections (Fig. 8c) (Bojarski and Wyżga 2009).

It seems advisable to implement the approach of balancing the loss of floodplain storage of floodwater by the measures re-establishing such storage; each action reducing floodwater storage as a result of channel regulation or the construction of flood embankments must be accompanied by other activities increasing the lost storage potential in other valley sections, including purchase of riparian land. Only then the decrease in floodplain water storage will not result in increased flood hazard at a regional level; at the same time, decisions about channel regulation or valley-floor embanking will have to incorporate not only the costs of such works but also of re-establishment of floodwater storage in other parts of the valley.

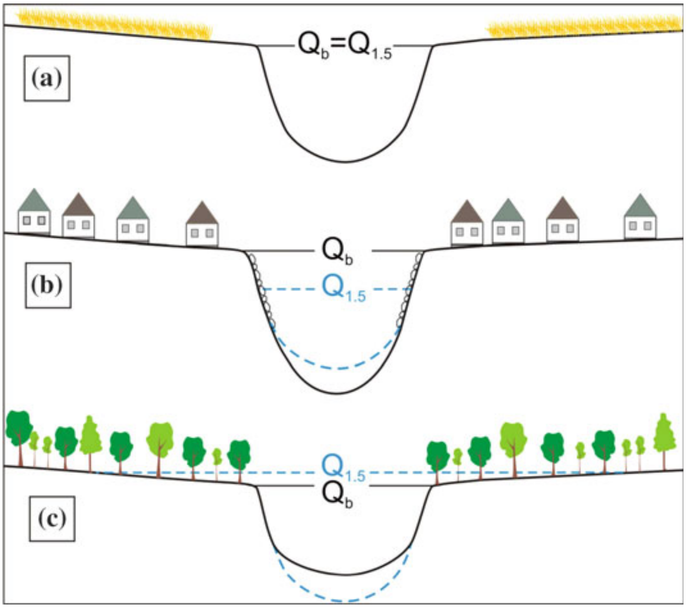

Fig. 8 Flow capacity (Q_b) typifying channels of natural, vertically stable rivers (**a**) and regulated channels formed in highly developed valley sections (**b**), and postulated flow capacity of river channels in undeveloped valley sections (**c**). In the two last situations, the stage attained at a discharge of 1.5-year recurrence interval and the location of the bed of vertically stable channel are indicated by dashed line. Modified after Bojarski and Wyżga (2009)

3.9 Solution to River–Bridge Conflict: Bridge Reconstruction

A large proportion of flood losses result from the destruction of bridges with insufficient conveyance and excessively concentrated flow energy (Jeleński 2004), caused by undermining of their piers, or from damage to bridge construction and elevation of local water level by wood clogging under bridges (Fig. 9a), especially with insufficient span between bridge piers (Wyżga 2007; Hajdukiewicz et al. 2016). Preventing or limiting such losses does not require interventions frequently undertaken in or along the river, such as channel regulation or clearing of riparian forest, but rather bridge reconstruction to accommodate more flow, including an increase in the span between piers or placing the piers outside the channel (Fig. 9b) (Wyżga 2007). Numerical modelling may help to predict the probability of clogging particular bridges with wood and thus to identify bridges that are most vulnerable to clogging and should be rebuilt (Ruiz-Villanueva et al. 2016). Unfortunately, destroyed bridges are still being rebuilt without modifications to significantly improve their functioning under flood conditions. This was the case with the bridge over the Białka River destroyed by the flood in July 2008 and subsequently rebuilt without an increase of its span.

Fig. 9 **a** Bridge on the Czarny Dunajec River at Chochołów before 2005, with its piers based on the channel bed. During the flood of 2001 wood jams were deposited on the upstream side of the piers, reducing cross-sectional area of the flow. **b** The bridge at Chochołów rebuilt in 2005. The arch supporting the new bridge is based outside the river channel, which excludes a possibility of channel obstruction by deposited woody debris. After Wyżga and Radecki-Pawlik (2011)

3.10 Introduction and Effective Enforcement of the Ban on in-channel Sediment Mining

In-channel sediment mining leads to sediment deficit in the channels and the destruction of bed armour that prevents entrainment of the underlying bed material (Rinaldi et al. 2005; Wyżga et al. 2010). As a consequence, it results in degradation of channel beds and undermining bridge piers and channel regulation structures (Korpak et al. 2009). The condition of river channels is also essential in reducing flood damages. Undisturbed, long-term development of river channel leads to the stabilization of its vertical position and flow capacity. Such a channel becomes less vulnerable to erosion caused by flood flows. Stability of the banks and bed of mountain streams and rivers is one of the key factors determining flood losses. In-channel gravel mining, especially if uncontrolled, destroys that stability leading to an increase in channel dimensions and the resultant reduction in floodplain storage of floodwaters as well as the change from alluvial channel boundary conditions to bedrock ones (Rinaldi et al. 2005; Wyżga et al. 2010). Ecological consequences of such activities include elimination of river biota caused by the destruction of habitats for benthic invertebrates and disappearance of spawning grounds of lithophilic fish. To reconstruct damaged road infrastructure after floods, large volumes of sediment are mined from Carpathian rivers under the pretext of increasing channel capacities for floodwaters and preventing erosion of concave banks positioned against channel bars. In the light of its negative consequences, sediment exploitation from river channels should be forbidden and the ban should be effectively enforced. Improving the conditions for floodwater transfer and protecting riverbanks from erosion should instead be obtained by bulldozing channel sediment towards the concave banks and concurrent straightening of the thalweg. In case some of the sediment needs to be removed from the channel, the material should be put into the river in another reach to prevent sediment deficit and channel incision.

4 Conclusions

Since the late nineteenth century flood-control measures introduced in the Upper Vistula basin were based on the notion of fast evacuation of floodwater that was associated with a significant reduction in floodwater retention on the valley floors. Such a policy of flood-control management stemmed not only from the unfamiliarity with other methods and a generally technocratic approach to nature (Wyżga 2007) but also from the need to protect all arable land adjacent to rivers as at the time farming provided for the existence of most of the society (Wyżga 2008). At present the negative effects of the conventional methods of flood control are evident and agriculture contributes only a fraction of gross national product. It is thus now a priority to decelerate flood runoff and increase floodwater retention in less developed parts of the valleys in order to reduce flood risk to spatially concentrated, urbanized areas. This paper has presented a catalogue of environment-friendly measures that comply with the best practices of flood protection recommended by the European Commission (2003) and are aimed at such a change in the flood-control policy in the Upper Vistula basin.

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