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A review on channel incision in the Polish Carpathian rivers during the 20th century

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Abstract

Rivers draining the Polish Carpathians deeply incised over the 20th century and in many sections, the downcutting was especially rapid in the second half of the century. Incision has resulted from the increase in transport capacity of the rivers caused by their channelization, and the concomitant decrease in sediment supply to the channels. In some of the rivers, in-stream gravel mining has additionally reduced the amount of sediment available for fluvial transport. Where the rivers had insufficient energy to destroy the river-control structures and remained laterally stable following their channelization, bed degradation has proceeded at a relatively steady rate. On the high-energy rivers, the periods of incision of the regulated channel alternated with the periods of lateral channel migration following the destruction of channelization structures. The main phase of incision of the Carpathian rivers occurred progressively later in the upstream direction, this reflecting the variation in timing of the most intense channelization works along their course, the operation of upstream-progressing bed degradation as well as the concentration of the land use changes from the second half of the century in the montane parts of the catchments. A marked increase in flood hazard to downstream reaches and a reduction in the potential of Carpathian floodplains for sediment storage have been the most important detrimental effects of the river incision manifested at the regional scale. Changes in management of the rivers are necessary to reduce their transport capacity and re-establish the conditions for water and sediment storage on the floodplains.

1. Introduction

In alluvial rivers, temporal trends in vertical channel position reflect the mutual relationship between transport capacity of the river and the availability of bed material for fluvial transport. During the 19th century rivers draining the Polish Carpathians showed a marked tendency to aggrade (Wyżga, 1993a). The aggradation of

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the river beds was accompanied by widening of the channels and, at many locations, by the development of multi-thread channel pattern (Fig. 20.1) (Klimek and Trafas, 1972; Szumański, 1986; Wyżga, 1993a). Channel bar deposits from that time consisted of overloose and normally loose gravels (cf. Church, 1978) and lacked armour layers. The aggrading tendency of the channels during the 19th century testifies to an overloading of the Carpathian rivers with sediment, whereas the character of the channel sediments is indicative of high rates of bedload transport and deposition of the materials by flood waves with high peak discharges and short time bases (Wyżga, 1993a, 2001a).

In the 20th century, the Carpathian rivers showed the opposite tendency (Fig. 20.1) (Punzet, 1981; Klimek, 1983; Wyżga, 1991, 2001a). Bed degradation and the resultant channel deepening have significantly altered morphology and functioning of the watercourses, and a variety of detrimental effects of incision have been identified in the channels and on the valley floors of the Carpathian rivers (Froehlich, 1980; Klimek, 1983; Wyżga, 1991, 2001a).

Degradational channel tendency during the 20th century, especially during the last decades, was documented for many rivers of the world. In some cases, it was possible to ascribe channel incision to a single or dominating, disturbing factor such as: gravel mining (Bull and Scott, 1974; Collins and Dunne, 1989; Sear and Archer, 1998), dams (Williams and Wolman, 1984), river channelization (Emerson, 1971; Brookes, 1987; Simon, 1989), catchment reafforestation (Liébault and Piégay, 2001) or cessation of the in-channel deposition of mine tailings (Knighton, 1989). However, much more common are the situations where incision has resulted from a combined impact of two or

Figure 20.1. Structure of a cutbank of the middle Raba at Winiary showing a sedimentary record of the aggradational/degradational tendencies of the river channel from the last two centuries. The shallow braid was eroded in the upper part of the sequence of overbank deposits and filled with massive gravel at about the turn of the 20th century, with the culmination of the aggradational river tendency. A high position of the braid above the low-water level in the contemporary channel testifies to the rapid incision of the Raba over the last century. Marks on the rope stretched along the cutbank are spaced at 1 m intervals.

more disturbances, frequently operating at different temporal and spatial scales (e.g., Bravard et al., 1997; Landon et al., 1998; Rinaldi, 2003; Surian and Rinaldi, 2003).

This paper utilizes data on vertical channel changes from numerous water-gauge stations operating in the rivers draining the Polish Carpathians to conclude about the dimensions and course of incision of the rivers during the 20th century. It also brings together extensive information from previous research on the phenomenon to infer about its causes and their relative importance. Finally, it presents the effects of incision of the Carpathian rivers, especially those apparent at the regional scale. This regional case study may be interesting for the gravel-bed river scientific community because recognition of unfavourable effects of rapid channel downcutting, wherever it occurs, is a pre-requisite to formulating appropriate remedial measures and undertaking actions to restore incised rivers, whereas identification of the causes of incision is essential to succeed in restoration efforts.

2. Physical setting and historical background

Most rivers in the Carpathian part of the upper Vistula River drainage basin rise in the Beskidy Mountains which are underlain by flysch and range up to 1725 m a.s.l. in the western part of the region and to 1346 m a.s.l. in its eastern part. Only the Dunajec River and some of its major tributaries originate in the high-mountain Tatra massif with a considerable proportion of crystalline rocks in its structure and elevations ranging up to 2655 m a.s.l. (Fig. 20.2). There are marked differences between the rivers draining the western and eastern part of the Polish Carpathians (Klimek, 1979), which reflect distinct physiography of the catchments in both areas (Fig. 20.2). Mountain areas predominate in the western part; here, the rivers have steep channel gradients, flow in cobble to pebble gravels and are characterized by high stream power at flood flows. In the eastern part, the main Carpathian rivers have long reaches within the foothill and foreland areas, where they are typified by gentler channel gradients, finer calibre of their bed material and lower stream power values at flood flows.

Within the upper Vistula River drainage basin, annual precipitation totals range from 1200 to 1900 mm in the Tatra massif to 600–700 mm in the Carpathian foreland (Niedźwiedź and Obrębska-Starklowa, 1991), with the respective values of the coefficient of runoff varying from more than 60% in the Tatran watersheds to 20–30% in the foreland area (Dynowska, 1991). In the western part of the drainage basin, with a relatively high frequency of the arrival of oceanic air-masses, floods originate mostly due to summer rains. In the eastern part with more continental climate, the Carpathian rivers are characterized by frequent floods of moderate magnitude following snow melt, and rare, large floods caused by summer rains.

Three economic and demographic factors seem to have exerted a substantial influence on the 20th-century evolution of the Carpathian rivers. First, at the end of the 19th century, the Carpathian part of the upper Vistula drainage basin was a densely populated, agricultural region (Pietrzak, 2005). This situation created a great demand for reclamation of riparian areas and protection of the valley floors from flooding that resulted in undertaking intense river-control works early in the 20th century (Kędzior, 1928). Second, large amounts of aggregate were required with

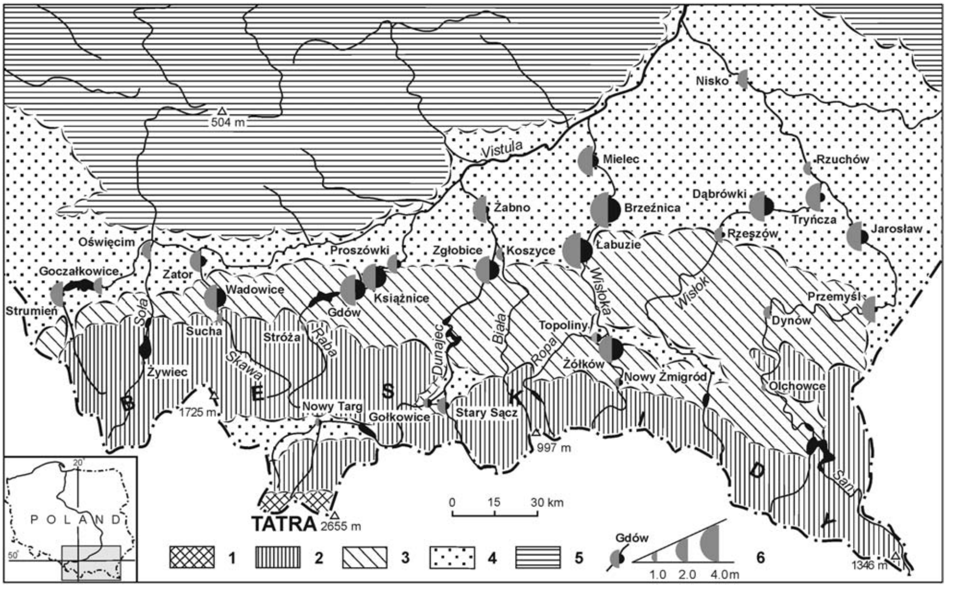

Figure 20.2. Dimensions of channel incision of Carpathian tributaries to the Vistula during the 20th century and in its second half inferred from the lowering of minimum annual water stage at gauging stations on the rivers. (1) High mountains; (2) mountains of intermediate and low height; (3) foothills; (4) intramontane and submontane depressions; (5) uplands; (6) lowering of minimum annual stage at water-gauge stations during the 20th century (grey semicircles) and in its second half (black semicircles).

rapid industrialization and urbanization of southern Poland after the World War II. Since the alluvium of the Carpathian rivers was the only available source of gravel in the region, over at least two post-war decades the need was being satisfied by the sediments mined from the river channels (Rinaldi et al., 2005). Third, the eastern part of the Polish Carpathians was dramatically depopulated in the mid-1940s and reafforested thereafter. This has significantly limited sediment delivery to the river channels in that area (Lach and Wyżga, 2002).

3. Study methods

In the foothill and foreland reaches of Carpathian tributaries to the Vistula, a number of water-gauge stations have been operating since the last decades of the 19th century (Fig. 20.2). The amount and timing of 20th-century changes in vertical channel position in the reaches were reconstructed by examining the record of the lowest annual water stages at the stations (Punzet, 1981; Klimek, 1983; Wyżga, 1991, 2001a). Because the observed variation of the lowest flows of the rivers has been shown to explain some deviations from general trends of the lowest stages only, not the trends themselves (Wyżga, 1997), multi-year variations of minimum annual water stages can reasonably be considered as reflecting erosional or aggradational tendencies of the river channels.

In the montane reaches of Carpathian rivers, a small number of gauging stations operated throughout the 20th century (Fig. 20.2) and this makes dating the onset of channel incision and establishing its total extent more difficult than in the foothill and foreland river reaches. Scarce hydrometric data from the montane reaches were supplemented by information obtained from examination of the difference in elevation between the beds of cartographically dated paleochannels and contemporary river beds as well as between the tops of older and contemporary gravel bars (Zawiejska and Wyżga, 2005).

Planar and cross-sectional channel changes of Carpathian rivers during the 20th century were documented in a number of studies (e.g., Krzemień, 1981; Szumański, 1986; Klimek, 1987; Wyżga, 1991, 1993a–c, 2001a) which utilized information from historical maps, aerial photos and channel regulation plans as well as from repeated channel cross-section surveys at water-gauge stations performed by the Hydrologic Survey.

Facies patterns of channel sediments of the middle Raba River dated on the basis of cartographic data were studied in river cutbanks and walls of gravel pits, and compared with those of contemporary gravel-bar sediments to infer about depositional conditions during the passage of flood waves (Wyżga, 1993a–c, 2001a). Samples were collected from a short valley reach to avoid distortion of temporal sediment-change patterns by downstream trends. Temporal trends in channel sedimentation similar to those described from the middle Raba were also observed in other rivers of the Polish Carpathians (e.g., Lach and Wyżga, 2002).

The location and timing of large-scale, in-stream gravel mining, the volumes of extracted material as well as the post-mining channel adjustments were documented for two Carpathian rivers in which such activity was especially pronounced (Augustowski, 1968; Osuch, 1968; Rinaldi et al., 2005).

The effect of channel incision upon flood flows was investigated using a set of procedures which analyse temporal trends in the relationship between inflow and outflow peak discharges of flood waves passing the modified reach, and relate them to alterations in vertical channel position (Wyżga, 1996, 1997). In the present article, a simple comparison of the magnitude of floods of given recurrence intervals at two gauging stations on the Wisłoka River is presented for the record periods characterized, respectively, by small and high degree of channel incision between the stations.

Finally, the impact of channel incision on the potential of Carpathian floodplains for sediment storage was studied by analysing temporal changes in flow characteristics at representative gauge cross-sections located on the rivers from the western and eastern part of the Polish Carpathians. The analysed parameters comprised: (i) percentage of the total flow conveyed in the extra-channel zone of the cross-sections at particular flood discharges; (ii) frequency of the valley floor inundation at given discharges; (iii) relative elevation of flood stages above the channel bed; and (iv) flow-velocity in the extra-channel zone (Wyżga, 2001b; Lach and Wyżga, 2002).

4. Amount of the 20th-century incision of the Polish Carpathian rivers

In the middle and lower courses of Carpathian tributaries to the Vistula, the onset of channel downcutting typically occurred around the turn of the 20th century

(Punzet, 1981; Wyżga, 1991) and to date, the rivers have incised by 1.3–3.8 m as shown by the lowering of their minimum annual stages at water-gauge stations (Fig. 20.2). Sections with about 3 m of channel downcutting accomplished over the century occur on most of the rivers and the greatest extent of incision is observed at the Łabuzie and Brzeźnica stations on the Wisłoka River. In many sections the downcutting was especially rapid in the second half of the century (Fig. 20.2).

During the second half of the century, channel downcutting was also recorded in the upper course of some Carpathian tributaries to the Vistula (Lach and Wyżga, 2002; Krzemień, 2003; Kukulak, 2003) and in their mountain tributaries (Soja, 1977; Froehlich, 1982; Rinaldi et al., 2005). Here, at most of the stations for which a stage record from the whole 20th century is available, the main degradational phase took place during the second half of the century. In the extreme case, 2.8 m of the total channel downcutting accomplished at the Żółków station on the upper Wisłoka River over the 20th century, about 2.3 m occurred between 1964 and the early 1980s, with the average rate of incision in that period exceeding 10 cm/year (Fig. 20.2, see also Fig. 20.7 below) (Lach and Wyżga, 2002). The hydrometric data from gauging stations (Fig. 20.2) as well as field evidence indicate that 0.5–3.5 m of bed degradation has occurred in the montane river reaches, its intensity having been highly varied spatially. There also occur few unregulated or bedrock-controlled channel sections that remained vertically stable over recent decades (Zawiejska and Wyżga, 2005). At many locations in the upper course of main Carpathian rivers and along their mountain tributaries, incision has resulted in dissection of the whole thickness of alluvium and transformation of the former alluvial channels into bedrock ones (Lach and Wyżga, 2002; Krzemień, 2003; Rinaldi et al., 2005). Where the rivers are underlain by sandstones, bed lowering has ceased following the change to bedrock boundary conditions. However, incision has continued in channel sections underlain by less resistant lithologies and up to 3.5 m of bed lowering was recorded in the section of the Czarny Dunajec River where the bedrock consists of unconsolidated Pliocene clays (Zawiejska and Wyżga, 2005).

5. Causes of the channel incision

Rapid incision of the rivers draining the Polish Carpathians indicates that in the 20th century their transport capacity must have greatly exceeded sediment delivery to the channels. A few factors have contributed to this situation, different from that prevalent during the 19th century.

5.1. Increase in transport capacity of the rivers due to channelization works

Although early localized attempts to channelize main rivers of the Polish Carpathians were undertaken already in the second half of the 19th century, intensive and widespread channelization works on the rivers began in 1904 and were continued through the 1930s (Kędzior, 1928). In that period, works were concentrated in the middle and lower courses of Carpathian tributaries to the Vistula River. They consisted of channel straightening through meander cut-offs, channel narrowing by groynes and the lining of concave banks by gabions and rip-rap; moreover, channel stretches where the flow diverged among mid-channel bars or islands were replaced by a single, artificial channel. In the foreland river reaches, the channelization works either immediately succeeded or were concurrent with the construction of flood-protection embankments. The first phase of channelization had the greatest impact on the foreland river reaches. For example, the foreland reach of the Dunajec River was shortened by about 10% and channel width was here reduced by one third (Zawiejska and Wyżga, 2005). In the foreland reach of the Raba, the channel was shortened by 15% and also considerably narrowed; in the foothill reach, little change in the width and length of the channel took place although the works helped to train the thalweg and led to the formation of a single-thread channel by 1932 (Wyżga, 1991, 1993a).

After a break in channelization works during and immediately after the World War II, the works were resumed late in the 1950s. In the second half of the century, they were concentrated in the middle and upper courses of main rivers of the Polish Carpathians and in their mountain tributaries. In the foothill reaches of the Carpathian tributaries to the Vistula River, the second phase of channelization caused considerable narrowing of the channels and shortened their length. For example, between 1955 and 1987, the Dobczyce-Gdów reach of the Raba River was shortened by 15% and the average channel width was here reduced from 140 to 60 m (Wyżga, 2001a). If the pre-regulation and regulated channels in this reach had the same flow capacity, the changes would have increased unit stream power at bankfull flow by about 170%. In fact, the increase in unit stream power must have been even greater as flow capacity of regulated Carpathian channels was typically increased in comparison with the pre-regulation conditions (with regulated channels designed to convey 2- to 5-year flows in rural areas and 10-year flows in urban areas (Raczyński, 1989)). In the montane reaches of the Carpathian rivers, the channels were narrowed and most multi-thread river sections were replaced by a single, artificial channel (Krzemień, 1981; Zawiejska and Krzemień, 2004; Zawiejska and Wyżga, 2005).

The shortening and narrowing of the channels in the course of channelization have increased unit stream power of the rivers. At the same time, the concentration of flow which was previously divided between separate braids or channels in multi-thread river reaches must have reduced channel-form resistance (cf. Bathurst, 1982), thus increasing a portion of the total flow energy available for sediment transport. The combined effect of the changes has been the increase in mean velocity at a given flow (Wyżga, 1993b, 2001a) and therefore in transport capacity of the rivers.

5.2. Reduction in sediment delivery to the rivers

Contemporary channel bar deposits of the rivers draining the Polish Carpathians are coarser-grained and better sorted than their 19th-century counterparts; moreover, contemporary bar surfaces are typically armoured, in contrast to the 19th-century bar sediments lacking armour layers (Wyżga, 1993a–c, 2001a). However, it might be argued that the altered mode of channel sedimentation reflects channelization-induced changes in hydraulic conditions in the rivers, rather than changes in sediment supply to their channels. Undoubtedly, the latter must have also contributed to the sedimentary change and their influence can be demonstrated by comparing channel geometry and sediments of different age that originated under free channel development conditions. Such data were presented (Wyżga, 2001a) with respect to the middle Raba for the second half of the 19th century, before the initiation of channelization works, and for the mid-20th century, when the river destroyed the regulation structures and formed a natural channel in its middle course during the break in channelization works.

In the second half of the 19th century, the middle Raba was a wide and shallow river. In the Dobczyce-Gdów reach, it flowed in a straight or braided channel (sinuosity index SI = 1.12). In contrast, the unregulated channel from the mid-20th century showed a conspicuous tendency to meander. Between 1932 and 1955 the river increased its length in the reach by 22% with the resultant increase in sinuosity (to SI = 1.31) and reduction in gradient, and the changes were accompanied by the increase in channel depth compensating for the decrease in river gradient. The average distance between successive points of flow inflection in the 1955 channel was reduced by almost half in comparison with that typifying the pre-regulation channel from 1878. The changes in river planform were accompanied by alterations in cross-sectional channel geometry; at the Gdów gauging station, the width/depth ratio of the Raba channel diminished from 40 in 1928 to 32 in 1963 (Wyżga, 1993a).

According to Schumm (1969), changes in water and/or sediment discharge of a river can be inferred from changes in the morphology of its channel. The increase in sinuosity and depth of the Raba River channel and the reduction in its gradient and meander wavelength clearly testify to the decrease in sediment load of the river over the first half of the 20th century (Wyżga, 2001a). At the same time, the decrease in the width/depth ratio of the channel indicates a reduction in the percentage of bedload in the total river load during that period (Wyżga, 1993a).

The channel bars of the 19th-century Raba River were formed by bimodal, normally loose and overloose gravels (Fig. 20.3a). These channel sediments were massive and very poorly sorted and no armour layers have been observed within them. Such sediments must have been deposited by flood waves with high peak discharges and short time bases that carried huge volumes of bed-material load (Wyżga, 1993a). The river, heavily overloaded with sediment, transported not only gravel particles but also much sand as bedload. After a peak of such a flood wave, the sediment was deposited rapidly and subjected to little or no reworking.

The point bar deposits of the sinuous river from the 1950s were characterized by a highly variable texture. However, overloose gravels now decreased in significance in favour of filled underloose gravels and openwork gravels (Fig. 20.3b) that were lacking in the 19th-century channel. These younger sediments were typified by a lower content of sand and improved sorting, and their tighter packing was accompanied by the occurrence of armour layers and imbricated gravels. The changes in channel sedimentation that occurred over the first half of the 20th century indicate a reduction in the sediment load of the Raba River and a decreasing flashiness of its flood flows during that period.

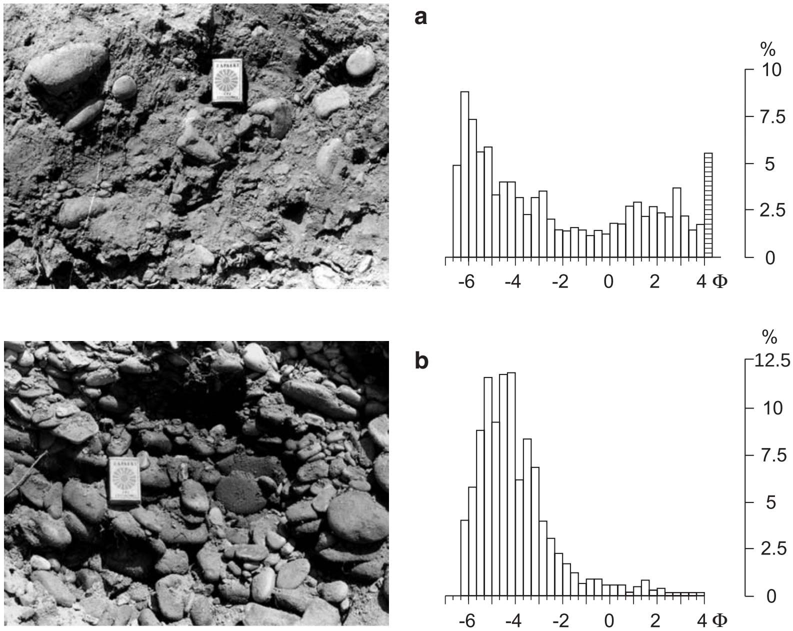

Figure 20.3. Bar gravels of the middle Raba River and histograms of their grain-size distribution (in weight frequency per cent): (a) massive, underloose gravels from the second half of the 20th century showing bimodal grain-size distribution; (b) unimodal, openwork gravels from the 1950s. Sediment size is expressed in Φ units. Hatched area in the histogram of sample A represents percentage of undivided fines.

While the channelization of the middle Raba between 1955 and 1987 significantly changed hydraulic conditions in its channel, the tendency to decrease the percentage of sand in the bar deposits continued through the second half of the century and caused a marked reorganization of the facies pattern (Wyżga, 1993a,b, 2001a). By 1987 overloose gravels ceased to originate in the channel. Instead, deposition of underloose gravels increased in significance, accompanied by the formation of bed armouring and numerous pebble clusters on the bed surface.

Also in other Carpathian valleys there were observed similar changes in the mode of channel sedimentation leading to a progressive coarsening of bed material, formation of a tightly packed texture and development of bed armouring during the 20th century (cf. Lach and Wyżga, 2002). Such changes follow a restriction of sediment delivery to channels (e.g., Dietrich et al., 1989; Lisle et al., 1993) and they are typical of rivers recovering from a phase of intense sediment supply (cf. Knighton, 1989; Madej and Ozaki, 1996).

A number of alterations in catchment management must have contributed to the reduction in sediment delivery to the Raba and other rivers of the Polish Carpathians during the 20th century (Wyżga, 1991, 1993a, 2001a). Ploughing along slopes was increasingly replaced by contour ploughing and terracing of cultivated slopes was introduced. The grazing of forest areas, common in the 19th century, ceased after the World War II. The eastern montane section of the Polish Carpathians (upper parts of the catchments of the Biała, Wisłoka, Wisłok and San rivers) was dramatically depopulated in the mid-1940s and much arable land was here turned into pasture and meadows or afforested after the World War II (Lach, 1975). For example, in the upper part of the Wisłoka catchment, the forest cover increased from 30% in 1938 to 67% in 1995 (Lach and Wyżga, 2002) whereas in the upper San catchment, it increased from 48 to 77% between 1937 and 1997 (Kukulak, 2004). The sediment yield of the catchments must have decreased not only due to the change of vegetation cover on hillslopes but also to a general reduction in human activity in the area since the mid-1940s. For example, as cart tracks were abandoned and became overgrown with grass or bushes, they have progressively ceased to function as pathways for rapid evacuation of water and sediment from the hillslopes (Lach and Wyżga, 2002).

Direct human interventions in the Carpathian river beds also were a reason for the reduced delivery of sediment to their channels in the 20th century (Klimek, 1987; Wyżga, 2001a). The channel regulation paths for the Carpathian tributaries to the Vistula were designed so as to avoid undercutting by the rivers of valley slopes, terraces and fans of tributaries (Kędzior, 1928); this, together with the stabilization of the channel banks, must have reduced the amount of sediment supplied by lateral erosion. Lining of the banks of mountain streams and construction of check dams in the headwaters, especially intensive in the western part of the Polish Carpathians, must have reduced the delivery of sediment from montane parts of the catchments. Moreover, a few dam reservoirs have been constructed on the Carpathian rivers starting in 1936 (Fig. 20.2). The reservoirs have trapped all the bedload and most of the suspended-sediment load carried from upstream (Łajczak, 1994), thus interrupting the continuity of sediment transport in the rivers and releasing underloaded water to their downstream reaches (cf. Kondolf, 1997).

Modifications of flood flows generated by the montane and foothill parts of Carpathian catchments must have also influenced the amount of sediment delivered to the rivers and the conditions of its downstream transfer. The existing record of annual maximum discharges of Carpathian rivers since 1921 shows a reduction in peak flows during the last 80 years and such data are presented for the Wisłoka and Skawa Rivers draining, respectively, the eastern and western part of the Polish Carpathians. At the Łabuzie station on the Wisłoka, the mean annual flood ($Q_{2.33}$) from the years 1956 to 2000 decreased by 31% in comparison with the period 1921–1955 (Table 20.1) whereas at the Wadowice station on the Skawa, the respective reduction in mean annual flood amounted to 8%. With little change in forest cover of the Skawa catchment during the 20th century, the reduction in peak flows of this river most likely reflected a change in precipitation pattern induced by modifications to the atmospheric circulation above central Europe (cf. Kaszewski and Filipiuk, 2003). It has been shown previously (Wyżga, 2001a) from the analysis of flood discharges of the Raba that a marked reduction in peak flows over the years 1951–1980 was accompanied by an increase in the duration of low flood discharges, the changes reflecting a shift from high flash floods at the beginning of this period to flattened and more prolonged flood waves at its end. The considerably greater reduction in peak flows of the Wisłoka must have reflected both the regulatory effect of the reafforestation of the montane part of its catchment, and the change in precipitation pattern (cf. Wyżga, 1997). With the reduction in flood discharges of

Table 20.1. Estimations of the magnitude of floods (in m^3/s) of given recurrence intervals at the Łabuzie and Brzeźnica stations on the Wisłoka River 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

Note: Q_X denotes discharge of given recurrence interval. Recurrence intervals of flood discharges were determined from frequency curves graphically fitted to the points plotted on a logarithmic graph paper.

Carpathian rivers, the bed-material yield of their catchments must have been reduced. At the same time, the longer duration of low flood flows facilitated outwashing of finer grains from the channel beds and their downstream transfer. The latter effect must have been especially pronounced below dam reservoirs constructed on the rivers.

5.3. *In-stream gravel mining*

Gravel exploitation from the channels of the Carpathian rivers has been a common practice since the 1950s. Especially large amounts of sediment were mined in the first two decades after the World War II from the Wisłoka and its tributary, the Ropa (Augustowski, 1968; Osuch, 1968; Rinaldi et al., 2005), which had relatively fine-grained bed material, suitable for concrete production. Between 1941 and 1966, at least 1 million m^3 of gravel were mined from a few kilometre-long section of the Ropa in its lower course and the exploitation ended with the complete exhaustion of the gravel resources in the channel in the mid-1960s (Augustowski, 1968). In the years 1955–1964, 2.1 million m^3 of sediment were extracted from the channel of the Wisłoka River in its lower and middle course (Osuch, 1968). From that volume, about 1.5 million m^3 of sediment were mined from a 30 km-long river reach located where the Wisłoka flows from the Carpathian Foothills onto the foreland basin.

The volumes of sediment taken from both rivers were large in comparison to the amounts of bed material stored in the channels and their extraction have exerted a considerable impact on the rivers. The volume of sediment mined from the Ropa was equivalent to a 1 m-thick layer of material that would be removed from the 25 km-long section of its channel of 40 m width. The extraction of such a volume of sediment from the relatively short channel stretch must have been possible due to an increase in bedload transport rate in the river caused by steepening of the channel bed upstream of the mining site (cf. Kondolf, 1997). The exploitation lowered the channel bed at the mining site by about 1.5 m and in 1966 the river was incised to bedrock here (Augustowski, 1968). Bed degradation was progressing upstream and downstream from the mining site, resulting in transformation of a few tens of kilometres-long reach of the Ropa to bedrock boundary conditions by the early 1980s (Rinaldi et al., 2005).

Estimation of the sediment transport rate in the Wisłoka indicated that it would take about 500 years to fully replenish the volume of sediment extracted from its channel (Osuch, 1968). In the 30 km-long river reach with the most intensive exploitation, the amount of mined sediment was equivalent to a 0.68 m-thick layer of bed material removed over the pre-mining, bankfull width of the channel (Osuch, 1968). Rapid degradation of the river bed began concurrently with the onset of the sediment mining and about 2.5 m of channel incision occurred in the middle course of the Wisłoka over the second half of the century (Rinaldi et al., 2005). The incision must have reflected a variety of causative factors, including an increase in transport capacity of the river caused by the narrowing of its channel by training structures (Wyżga, 1997, 2001b) as well as the reduction in bed-material delivery from upstream resulting from the land-use changes in the montane part of the catchment (Lach and Wyżga, 2002) and the gravel mining in the Ropa (Rinaldi et al., 2005). However, two facts emphasize the importance of the sediment mining as a cause of incision of the Wisłoka channel. The greatest extent of incision on the river, both over the whole 20th century and in the second half of that century was concentrated just in the channel section with the most intensive sediment mining (Fig. 20.2 – the Łabuzie and Brzeźnica stations). Moreover, the Wisłoka is characterized by the greatest extent of the 20th-century channel incision among the main rivers of the Polish Carpathians (Fig. 20.2) although all the rivers were similarly channelized in the century and in many of them, excluding the Wisłoka, continuity of sediment transport from the montane parts of their catchments was interrupted by dam reservoirs.

Although large-scale gravel mining from the channels of Carpathian rivers has been prohibited since the 1970s, minor amounts of sediment have still been extracted from the rivers in the recent decades. Removing the whole volume of channel bars positioned against undercut concave banks (Fig. 20.4) has repeatedly been undertaken by river engineers in order to keep the rivers on their designed channelization paths (Wyżga, 2001a). Moreover, illegal extraction of bed material from some mountain watercourses has been a common practice, especially in the western part of the Polish Carpathians (Radecki-Pawlik, 2002). Owing to their repeated occurrence, such activities must have considerably contributed to the sediment deficit in the rivers, although their impact has been dispersed along the length of the channels.

5.4. Increase in sediment mobility caused by in-channel human disturbances

Contemporary rivers of the Polish Carpathians are characterized by the occurrence of armour and numerous pebble clusters on the bed surface as well as the predominance of close packing of subarmour material. These features reduce sediment mobility (Laronne and Carson, 1976; Reid et al., 1985; Richards and Clifford, 1991) and their undisturbed occurrence in the channels is crucial for protecting bed-material particles from entrainment. However, both bed armouring and internal structure of the channel sediments in the rivers have been repeatedly destroyed in the

Figure 20.4. Skimming of the gravel bar positioned against an undercut concave bank in the channel of the middle Raba River undertaken in order to eliminate flow confinement and move the thalweg away from the bank.

course of channelization and gravel mining practices undertaken in the last few decades (Wyżga, 1991, 2001a). The channelization has involved formation of channels with a smooth bed gradient and trapezoid cross-section, with large volumes of bed material being pushed across the channels by bulldozers. With the present-day tendency of Carpathian tributaries to the Vistula to meander, such a channel form is unstable and the practice has been periodically repeated by river engineers to prevent thalweg meandering and to protect concave banks of the regulated channels from erosion. Illegal exploitation of gravel has been typically associated with crossing the channel by vehicles that destroys close packing of channel sediments and exposes finer grains to flow. Exploitation of cobbles from a bar surface, that removes the protective bed armouring and reduces mean size of channel sediments, has been especially common in the rivers originating in the Tatra massif (Dudziak, 1965). All these factors have facilitated erosion and transportation of bed material, thus increasing its loss to the downstream river reaches and strengthening the tendency to channel incision.

6. Spatial variation in the course and timing of channel incision

Considerable differences in the course and timing of channel incision during the 20th century can be identified among the Carpathian tributaries to the Vistula as well as between their different sections and three aspects of the variation are considered below. First, the course of bed degradation varied along a river channel (Wyżga, 1991, 1993b). It can be demonstrated by a comparison between changes in minimum annual stage of the Raba at the Proszówki gauging station and those at the Gdów

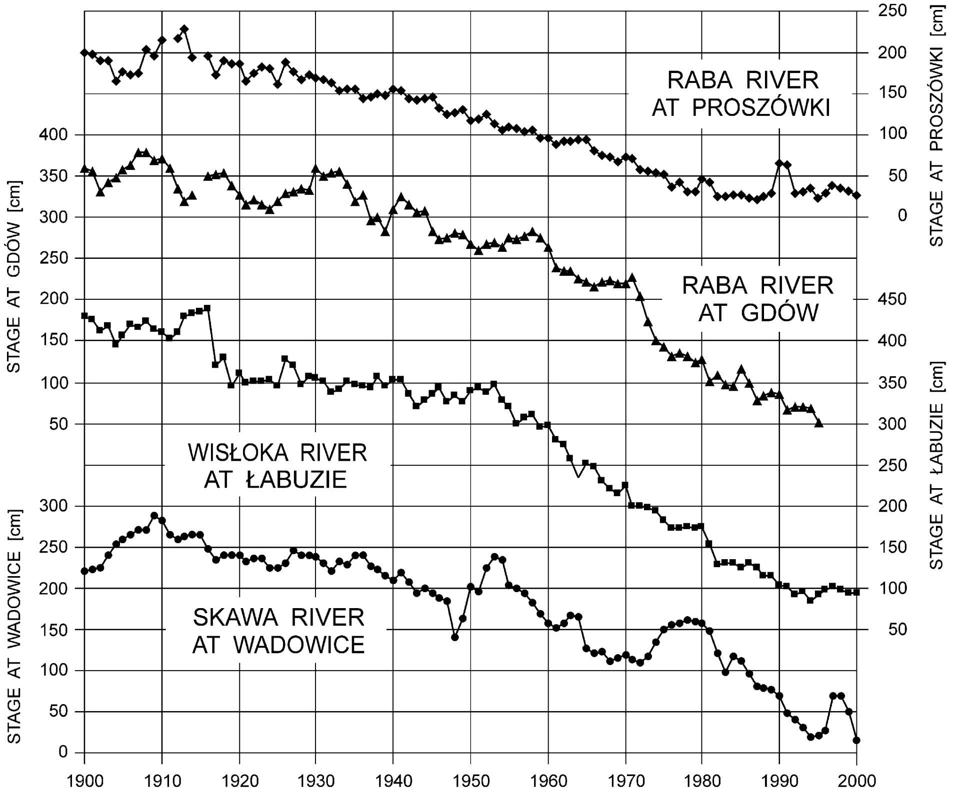

Figure 20.5. Changes in minimum annual stage of the Raba River at the Proszówki and Gdów gauging stations, the Wisłoka River at the Łabuzie station and the Skawa River at the Wadowice station since the beginning of the 20th century. The variation of the changes in minimum annual stage among the stations illustrates differences in the course of channel incision between the low-energy (the Wisłoka at Łabuzie) and high-energy (the Skawa at Wadowice) Carpathian rivers as well as between the low-energy (the Raba at Proszówki) and high-energy (the Raba at Gdów) sections of a given river.

station located, respectively, in the lower and middle course of the river (Fig. 20.5). In the lower river course, the channel bed degraded at a relatively steady rate. In contrast, in the middle course, channel incision was a result of the series of separate degradation events alternating with periods of vertical stability or aggradation of the channel bed. A similar difference in the course of bed degradation was also recognized between rivers draining the eastern and western part of the Polish Carpathians (Wyżga, 2001b) and it is shown here for the Łabuzie station on the Wisłoka and the Wadowice station on the Skawa (Fig. 20.5), both gauging stations being located at about one third of the total length of each river upstream of its mouth to the Vistula (Fig. 20.2). At Łabuzie downcutting of the Wisłoka channel proceeded in the second half of the 20th century at a practically constant rate whereas at Wadowice, three long periods of incision of the Skawa channel, separated by short episodes of bed aggradation, are evident over the century.

The mentioned variation in the course of channel incision most likely reflects differences in channel gradient and, hence, the energy of flood flows between particular rivers or between particular reaches of a given river. In the lower, foreland reaches, Carpathian rivers have more gentle channel gradient and are typified by lower values of unit stream power at flood flows of a given frequency than in their middle, foothill reaches. Considerable differences in channel gradient and flow energy exist also between the rivers draining the eastern and western part of the Polish Carpathians (Klimek, 1979; Wyżga, 2001b), conditioned by the differences in the orography of the catchments in both regions, and in the distance between the river headwaters and their recipient, the Vistula, flowing obliquely to the mountains (Fig. 20.2). In their lower reaches as well as in the eastern region, Carpathian rivers have had insufficient energy to destroy the river-control structures and have generally remained laterally stable following their channelization. Under such conditions, the excess energy of the straightened and narrowed rivers has been dissipated by the scouring of their channel beds, this leading to the formation of deep channels bounded by the highly elevated floodplains as at the Łabuzie station on the Wisłoka (Fig. 20.6a) and the Proszówki station on the Raba. In the higher river reaches and in the rivers from the western part of the Polish Carpathians, the relatively high energy of flood flows has facilitated exceedance of the threshold of stability of the channelization structures. With the increase in channel width and sinuosity following a destruction of bank-protection structures, transport capacity of the rivers had been reduced and degradation of their beds had been arrested until the next channelization that again straightened and narrowed the channels. Such alternating periods of incision of the channelized rivers and of lateral channel migration have led to the development of incised meander belts with progressively lower floodplain levels formed along the incised channels, and to the transformation of the former floodplains into terraces as at the Wadowice station on the Skawa (Fig. 20.6b) and the Gdów station on the Raba.

Second, the main phase of incision of Carpathian rivers occurred progressively later in the upstream direction. It is demonstrated by changes in minimum annual stage of the Wisłoka at the Mielec and Żółków gauging stations located, respectively, in the lower and upper course of the river (Fig. 20.2). At Mielec about two thirds of the total bed degradation were accomplished over the first half of the 20th century whereas at Żółków, the major phase of channel incision took place in the 1960s–1980s (Fig. 20.7). Several factors must have contributed to the variation in timing of the main phase of channel incision observed along the course of Carpathian rivers. Time-shifting of the most intense channelization works for different river reaches caused that the resultant increase in transport capacity of the watercourses occurred first in their foreland reaches and later in the foothill and montane reaches (Wyżga, 2001a; Zawiejska and Wyżga, 2005). Moreover, steepening of the channel gradient immediately above already incised reaches has induced upstream-progressing bed degradation (Galay, 1983; Wyżga, 1993b). With the channel width and sinuosity of Carpathian rivers fixed by channelization structures, the increase in channel depth and gradient flattening, occasioned by backward erosion, have been important mechanisms of re-attaining equilibrium conditions in the rivers disturbed by channelization (Wyżga, 1993b). Finally, in the second half of the 20th century,

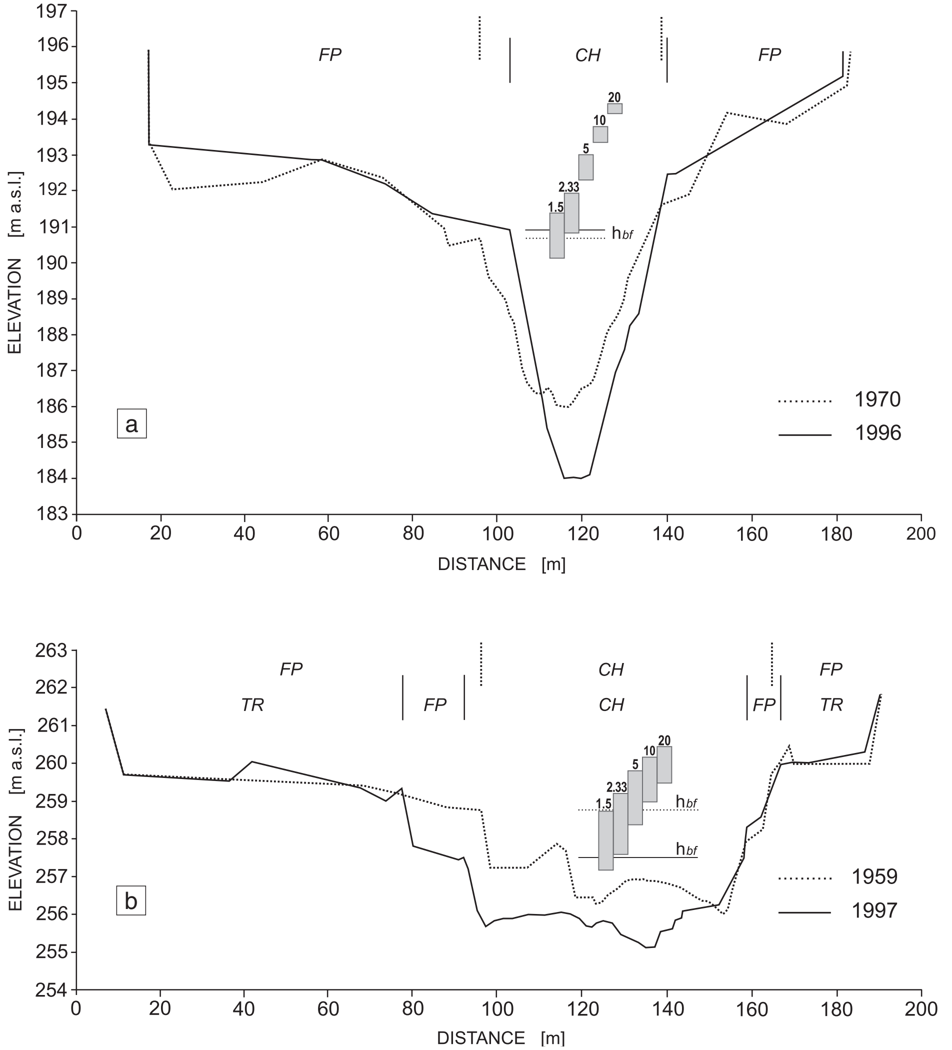

Figure 20.6. Downstream view of the cross-sections of (a) the Wisłoka River at the Łabuzie gauging station in 1970 and 1996, and (b) the Skawa River at the Wadowice station in 1959 and 1997. Grey-shaded columns indicate a lowering of the stage attained at the flood discharges of given recurrence intervals, that accompanied incision of the channels between the years considered. Elevation of the bankfull stage, h_{bf}, is also marked. Morphological zones of the cross-section: (CH) channel; (FP) floodplain; (TR) terrace.

montane reaches of the rivers, especially those draining the eastern part of the Polish Carpathians, experienced considerable reduction in sediment delivery in response to the land-use changes in the catchments (Lach and Wyżga, 2002; Kukulak, 2003).

Third, with rapid incision of a major tributary, the cessation or slowing down of bed degradation in the stem river was observed (Wyżga, 1993c). Such a situation occurred in the lower section of the San where rapid channel incision, recorded in the first half of the 20th century, has ceased since the 1950s with the onset of intensive

Figure 20.7. Changes in minimum annual stage of the Wisłoka at the Mielec gauging station in the lower course of the river and at the Żółków station in its upper course since 1890.

downcutting of the Wisłok channel (Fig. 20.2 – see the Nisko and Rzuchów stations). At the same time, in the reach of the San located upstream of the Wisłok mouth, rapid channel incision continued in the second half of the century (Fig. 20.2 – see the Jarosław station). Apparently, a plentiful supply of bed material having been flushed out from the deepening Wisłok channel must have largely promoted the vertical stabilization of the lower San bed. The different tendencies of the vertical position of the San channel observed in the second half of the century downstream and upstream of the tributary indicate that with transport capacity of this and other Carpathian rivers considerably increased owing to their channelization, stabilization of vertical position of the river beds was only possible with an abundant delivery of bed material.

7. Importance of the main incision drivers

A comparison of the amount and timing of incision of Carpathian rivers with the location and time of occurrence of its major drivers enables determining the relative importance of particular factors for producing bed degradation in the watercourses. At the regional scale, river channelization was undoubtedly the most important reason for the channel incision. It disturbed vertical stability of the rivers by increasing considerably their transport capacity, reducing sediment delivery to the channels through their disconnection from valley slopes and bed material stored on the valley floors and increasing susceptibility of bed-material particles to entrainment due to a frequent disturbance of the channel beds in the course of repeated river-control works. The commencement of bed degradation in the Carpathian rivers almost concurrently with the beginning of major regulation works in their channels in 1904 (Wyżga, 1991, 2001a), the progressive shifting in the upstream direction of both the most intensive changes to river planform and the main phase of channel incision (Wyżga, 2001a; Zawiejska and Wyżga, 2005) as well as a clear relation between the degree of channel narrowing and the amount of bed degradation along a river course (Wyżga, 1993b) point to channelization works as the principal cause of the degradational tendency of Carpathian rivers during the 20th century. The increase in transport capacity of the rivers caused by their channelization was so large that even with a delivery of bed material flushed out from the deepening upstream reaches, the channels have not been able to recover to their pre-disturbance vertical position.

Large-scale gravel mining carried out in some Carpathian rivers during the 1940s–1960s greatly increased sediment deficit as well as the resultant rates and total extent of bed degradation in their channels. In the river reaches subject to such activity, either the greatest channel incision among the Carpathian rivers (3.8 m in the lower course of the Wisłoka and up to 3.5 m in the Czarny Dunajec) or transformation from alluvial to bedrock boundary conditions (the Ropa River) were recorded (Rinaldi et al., 2005; Zawiejska and Wyżga, 2005).

Among direct interventions in the Carpathian rivers, construction of dam reservoirs appears to have exerted the least influence on the hitherto accomplished incision of their channels. This situation reflects a small number of the reservoirs, their construction relatively late in the 20th century (e.g., compare the impoundment of the Raba River at Dobczyce in 1987 with the course of channel incision at the downstream located Gdów gauging station – Fig. 20.5) and/or location of some of them in the upper river reaches (the reservoirs on the San, Wisłok and Ropa Rivers) where they have trapped sediment delivered from only a small proportion of the total area of the catchments. Only the Porąbka Dam on the Soła and the Rożnów Dam on the Dunajec, constructed in the late 1930s at the half-length of the river courses (Fig. 20.2), must have significantly affected degradational processes in the downstream reaches of these rivers.

The land use changes that occurred in the eastern montane part of the Polish Carpathians during the second half of the 20th century must have substantially and persistently reduced sediment delivery to the rivers draining that area. This is shown by the widespread transformation of the former alluvial channels into bedrock ones over recent decades (Lach and Wyżga, 2002; Kukulak, 2003), also in the river reaches within forested corridors where their channels have not been regulated. In valley sections underlain by a thick cover of alluvium, a combined operation of the increase in transport capacity of the rivers caused by their channelization and the reduction in sediment supply following the catchment reafforestation has led to deep, rapid channel incision (see the Żółków station – Figs. 20.7 and 20.8a) (Lach and Wyżga, 2002). However, it should be noted that with little proportion of mountain areas in the catchments of the rivers draining the eastern part of the Polish Carpathians (Fig. 20.2), the impact of the hillslope reafforestation must have progressively declined in the downstream direction. In the western part of the Polish Carpathians, land-use changes took place gradually since the last decades of the 19th century and were mostly represented by alterations in some agricultural practices (Wyżga, 1991, 2001a), with little modification to forest cover of the area. Although the resultant reduction in sediment yield of the catchments must have been considerably lower than in the eastern part of the mountains, its impact on the river channels is shown by the transformation of the braided channel of the 19th-century middle Raba into the sinuous channel in the mid-20th century. With the decreased sediment delivery from the catchments, channelization works carried out in the second half of the 20th century caused a greater disturbance to vertical stability of the rivers than the works from the early decades of the century (Wyżga, 2001a).

8. Effects of the channel incision

The deep incision of the rivers of the Polish Carpathians during the 20th century resulted in unintentional effects in their channels and on the valley floors, which are unfavourable for the natural environment and the economy (Froehlich, 1980; Klimek, 1983; Wyżga, 1991, 2001a). The undermining of bridge piers and regulation structures is the reason for expensive repairs. With water stage in the rivers lowered below the level of water intakes, the construction of weirs is necessary to enable their further operation. The lowering of water table on the valley floors, which follows a fall of medium and low stages in the rivers, causes several detrimental effects. These include: (i) a loss of groundwater resources; (i) drying of the soil of cultivated land on the valley floors, reducing root-crop yields; and (iii) drying up of oxbow lakes and the impoverishment of plant and animal communities of riverside ecosystems. Finally, the lowering of water level in the rivers below a dense network of roots of riparian vegetation facilitates undermining and fast retreat of the channel banks.

Such adverse effects are apparent at a local scale, but of primary significance seems to be that the potential of the floodplains of the Carpathian rivers for water and sediment storage has been dramatically reduced with the progress of channel incision. A considerable increase in the flood hazard to downstream reaches of the Carpathian rivers has been recorded following their channelization and subsequent incision (Wyżga, 1996, 1997). It is shown by a comparison of the magnitude of floods of given recurrence intervals at the Łabuzie and Brzeźnica stations on the Wisłoka, estimated for the record periods 1921–1955 and 1956–2000 characterized, respectively, by small and high degree of incision of the river channel (Table 20.1). With its length of 21 km, the Łabuzie-Brzeźnica reach is long enough to allow significant flood wave transformation. As the catchment area increases along the reach by only 12%, recorded trends of flood magnitude cannot be attributed to changed inflow from tributaries. At both stations, in the second period flood magnitudes decreased in comparison with those recorded in the first period (Table 20.1) in response to reafforestation of the montane part of the catchment (Lach, Wyżga, 2002) and, probably, also to some change in precipitation pattern (see Part 5.2). However, a scale of the reduction at both stations was distinct, with mean annual flood lowered by 31% at Łabuzie and 19% at Brzeźnica, and the difference can be attributed to changed conditions of flood wave transformation between the stations. While in the years 1921–1955 the magnitude of all considered index floods ($Q_{1.5}$–Q_{20}) slightly decreased in the reach, after 1955 the increase in peak discharges of the flood waves passing the reach was apparent, reaching from 5% for a 20-year flood to 14% for mean annual flood (Table 20.1).

Also for the Gdów-Proszówki reach of the Raba River, a considerable increase over time of the peak discharges recorded at its downstream end has been recognized by comparing the annual maximum discharges from both stations as well as the inflow and outflow peak discharges for all flood waves from particular decades (Wyżga, 1996, 1997). A remarkable coincidence of the channel incision in the Łabuzie-Brzeźnica reach of the Wisłoka, the Gdów-Proszówki reach of the Raba and in some other reaches of Carpathian rivers, and of the increase in peak discharges recorded at their downstream ends indicates a link between the two phenomena (Wyżga, 1996, 1997). As flood flows were increasingly concentrated in the deepened channels with the advancing incision, water retention in the floodplain areas was progressively reduced. Moreover, flows conveyed in the progressively deeper channels were characterized by increasingly high relative smoothness of flow (ratio of water depth to the height of protrusion of bed-material particles to the flow). This, together with the reduction in channel-form resistance resulting from the channelization, must have also decreased attenuation of in-channel flood waves.

A reduction of flood hazard was one of the main aims of the channelization of Carpathian rivers; however, it had an opposite effect. Although flood stages lowered in the upper parts of the incised river reaches, the danger has been merely shifted downstream and, at the same time, magnified there owing to the increasingly peaked nature of flood waves passing the incised reaches. The increase in the flood hazard to downstream river reaches has been commonly overlooked by river managers owing to the simultaneous reduction in flood flows generated by the montane parts of the Carpathian catchments. However, future consequences of the increase are likely to be diverse in the rivers draining the eastern and western part of the Polish Carpathians (Wyżga, 1997). In the rivers from the eastern part, the lowering of floods formed in the past few decades in the montane parts of their catchments has mainly resulted from the reafforestation of these areas and, thus, is likely to continue in the future. The magnification of peak flows in the incised reaches of these rivers will simply mean the lost chance for permanent reduction of flood hazard on the watercourses that could be achieved as a result of the land-use change. On the contrary, the occurrence of meteorologic conditions that in the past few decades favoured the formation of lower flood flows on the rivers in the western part of the mountains seems temporary. Here, the recovery of heavy rains in subsequent years would suddenly manifest the potential flood hazard resulting from the channel incision.

Incision of the Carpathian rivers has also considerably decreased the potential of their floodplains for sediment storage (Wyżga, 2001b). However, different factors have played a dominant role in reducing the depositional potential of the floodplain flows in the valley reaches with an incised channel, typical of the Carpathian rivers with lower energy, and in those with an incised meander belt, characteristic of the high-energy rivers. This was shown by analysing the changes in flow characteristics of the Wisłoka River at the Łabuzie station between 1970 and 1996, as well as the Skawa River at the Wadowice station between 1959 and 1997, with minimum annual stage of both rivers lowered during the periods by a similar value of 1–1.2 m (Wyżga, 2001b). At Łabuzie, substantial lowering of stages for low flood discharges contrasted with markedly smaller one for high-magnitude floods. For instance, the stage associated with mean annual flood lowered in the years 1970–1996 by 110 cm whereas that attained at a 20-year flood fell by 28 cm (Fig. 20.6a). At Wadowice, the concentration of flood water in the deepened channel and over the new, low-lying floodplain caused a substantial lowering of stage both for low and high flood discharges. In the years 1959–1997 it amounted to 160 cm for mean annual flood and 94 cm for the discharge with a 20-year return period (Fig. 20.6b). With this large fall of flood stages of the river, its former floodplain has become transformed into a terrace, and the lateral extent of flood water on the valley floor has shrunk considerably (Fig. 20.6b). Linked with the reduced vertical and lateral extent of flood water in the river cross-sections was also a reduction in the frequency and duration of submergence of particular levels on the valley floors at given flood discharges. On the Skawa River, the reduction was considerably greater than on the Wisłoka (Wyżga, 2001b).

The amount of flood water conveyed in the extra-channel zone of the rivers was reduced with the increased concentration of flood flows in the river cross-sections (Table 20.2). For major floods, the scale of the reduction was apparently greater on the Skawa than on the Wisłoka River (Table 20.2). This may be explained by the retained channel width of the Skawa with the progress of river incision and the constriction of both channel and floodplain flows in the river cross-section (Fig. 20.6b).

Where bed degradation was associated with lateral channel stability, it has increased the relative elevation of flood stages above the channel bed (Wyżga, 2001b). At Łabuzie on the Wisłoka River, the elevation above the mean bed level of the stage attained at the 5-year flood increased from 6.7 m in 1970 to 8.31 m in 1996 and that of the stage of the 20-year flood increased from 8.11 to 10.13 m. With the increased distance between river bed and water surface and the decreased depth of floodplain inundation at particular discharges (Fig. 20.6a), at present, the river banks can be overtopped only by the uppermost parts of flood water. Moreover, vertical differentiation of the size and concentration of sediment particles transported in graded suspension must have increased with the greater depth of the water column. The operation of these factors tended to reduce the amount of coarse sediment particles

Table 20.2. Percentage of the total flow of the Wisłoka River at the Łabuzie station, and of the Skawa River at the Wadowice station, conveyed in the extra-channel zone of the gauging sections before and after the period of rapid incision of both rivers.

	Wisłoka River at Łabuzie		Skawa River at Wadowice	
	1970	1996	1959	1997
Q_3	2.7	0.1	1.3	0.2
Q_5	7.3	1.2	5.5	1.6
Q_{10}	12.3	5.2	12.5	4.2
Q_{15}	15.3	8.2	16.3	5.7
Q_{20}	17.4	10.3	19.0	6.7

Note: Q_X denotes discharge of given recurrence interval. On the Wisłoka, the extra-channel zone is equivalent to the floodplain but on the Skawa, it comprises the floodplain and the lower terraces.

introduced with flood water onto the floodplain, thus increasing concentration of suspended-sediment transport within the incised channel.

Changes in flow velocity have been another effect of incision of the Carpathian rivers that must have affected overbank deposition on the valley floors. Mean velocity in channel zone typically increased with the progress of bed degradation but the direction of change of the velocity in extra-channel zone differed between the valley reaches with an incised channel and those with an incised meander belt (Wyżga, 2001b). At Łabuzie on the Wisłoka River, mean velocity in the floodplain zone decreased between 1970 and 1996 with the reduced depth of floodplain submergence at particular discharges. At Wadowice on the Skawa, in 1997 mean velocity over the low-lying floodplain was 20–30% higher than velocity typifying the floodplain flows in 1959. Still greater increase in flow velocity accompanied the formation of an incised meander belt of the upper Wisłoka River at Żółków, which originated through dissection of the former, wider channel bed by about 2.5 m (Fig. 20.8a) (Lach and Wyżga, 2002). Here, mean velocity in the channel zone increased between 1963 and 1991 by 35–45% but mean velocity in the extra-channel zone is now three to four times faster than before channel incision (Fig. 20.8b).

Investigations carried out in the Raba valley have identified a dramatic reduction in the rate of overbank sediment accretion that followed channelization and the subsequent incision of this river (Wyżga, 1991). Field observations on the Skawa and Wisłoka Rivers confirm an insignificant role played nowadays by floodplain sedimentation in the valleys of Carpathian rivers. At the peak discharge of the flood of July 1997 on the Skawa River at Wadowice, which had a 29-year recurrence interval, mean velocity of flow over the narrow, low-lying floodplain attained 1.68 m/s. Although bankfull stage was exceeded for more than 2 days in this section and the floodplain was covered by about 2 m of water at the flood peak, the thickness of floodplain deposition was relatively low, varying from 1.5 to 7 cm. At the same time, conspicuous levee sediments ranging up to 30 cm in thickness were deposited during the flood on the Vistula River floodplain immediately downstream of the junction with the Skawa. Here, the Vistula is not incised and mean velocity of the floodplain flow at the flood peak was estimated at 0.3 m/s (Wyżga, 1999). These contrasting hydraulic and depositional patterns show that at present, during major floods carrying large sediment loads, flows over the narrow floodplains formed along the incised channels of Carpathian rivers are too fast to allow significant overbank deposition (Wyżga, 2001b). In turn, with the contrast in mean velocity between the channel and floodplain flows of the Wisłoka River at Łabuzie increased owing to channel incision, large amounts of the coarser sediment carried in suspension into the floodplain area should be deposited on the natural levees. However, despite the occurrence of two major floods in 1987 and 1989, which had recurrence intervals of 35 and 18 years, respectively, no prominent levees have been observed along the incised channel of this river. Apparently, little sediment is carried by the upper parts of the water column overtopping the river banks, even at such high floods, whereas the transport of coarser fractions of the suspended load takes place almost entirely within the incised channel (Wyżga, 2001b).

Table 20.3 summarizes major factors which have affected overbank deposition on the rivers of the Polish Carpathians in response to their incision, operating in the

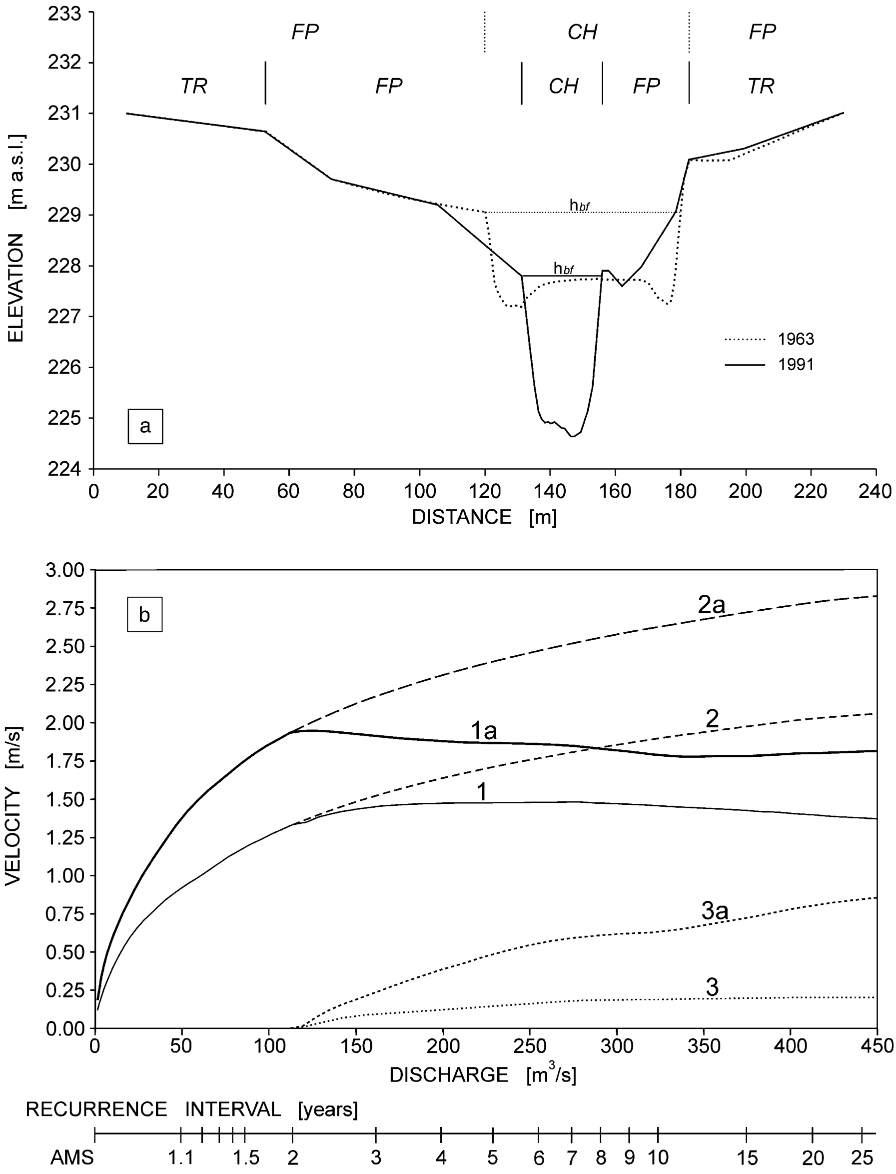

Figure 20.8. (a) Downstream view of the cross-section of the Wisłoka River at the Żółków gauging station in 1963 and 1991. Morphological zones of the cross-section: (CH) channel; (FP) floodplain; (TR) terrace. Elevation of the bankfull stage, h_{bf}, in 1963 and 1991 is also marked. (b) Relationship between the mean flow velocity in total cross-section (1, 1a), in channel zone (2, 2a) and in extra-channel zone (3, 3a) of the cross-section, and discharge for the Żółków station on the Wisłoka River in 1963 (1–3) and 1991 (1a–3a). Discharges are referred to their recurrence interval determined by the annual maximum series method from the years 1951 to 2000.

valley reaches with an incised channel and in those with an incised meander belt. Despite the different combination of the factors in both valley types, their overall result has been a considerable reduction of the potential of the Carpathian floodplains for sediment storage during the past few decades (Wyżga, 2001b). Consequently, the majority of the suspended load of the rivers may now be routed through their incised reaches directly to the Vistula, contributing to the rapid channel and floodplain aggradation in the middle course of that river (Łajczak, 1997).

9. Concluding remarks

Up to 3.8 m of channel incision occurred over the 20th century in the rivers of the Polish Carpathians. With its extent and rate, the incision has undoubtedly been a spectacular phenomenon in the Holocene history of the rivers. It resulted from a combination of factors which increased transport capacity of the rivers while reducing availability of bed-material calibre sediments for fluvial transport. The earlier occurrence of a main phase of channel incision in the lower sections of Carpathian rivers and later in their higher sections indicates the channelization-induced increase in transport capacity of the watercourses as the principal cause of bed degradation at the regional scale, with the reduction in catchment sediment supply being a less important or later operating factor. In some of the rivers, in-stream gravel mining has additionally increased the deficit of sediment available for fluvial transport.

A similar history of channel changes has also been recorded for mountain and piedmont rivers of western (Bravard et al., 1997; Landon et al., 1998) and southern Europe (Rinaldi, 2003; Surian and Rinaldi, 2003). The tendency towards channel aggradation that typified the rivers from these regions during the Little Ice Age, has been reversed since around the beginning of the 20th century as a result of river-control works and land use changes in the catchments. In-stream gravel mining and construction of dam reservoirs have dramatically increased bed degradation on the rivers since about the mid-20th century. Hydroclimatic changes after the end of the Little Ice Age have been reported as one of the reasons for the reduced sediment supply to the rivers of western Europe (Bravard et al., 1997) and the existing evidence for the modified pattern of atmospheric circulation over central Europe allows also to invoke changes in precipitation pattern as a cause of the reduced sediment yield of the Carpathian catchments during the 20th century. However, the distant location of the regions, with their mountain ranges differently oriented in relation to the general directions of atmospheric circulation over the northern hemisphere, casts doubt on the climatic changes as a major causative factor in reducing sediment yield of the mountain catchments in Europe. Rather, the equivalent evolution of the rivers from different regions reflects a similar history of the changes in channel and catchment management.

With a variety of the identified detrimental effects of channel incision, changes in management of the Carpathian rivers and the degrading rivers of the mentioned regions are necessary to arrest degradation of their beds and re-establish the conditions for water and sediment storage on the floodplains. Any human activities in channels, that cause the removal of bed material from the rivers or facilitate its loss to downstream reaches, should be stopped (Wyżga, 2001a; Bojarski et al., 2005;

Table 20.3. Factors affecting overbank deposition on the rivers of the Polish Carpathians in response to channel incision, shown for the valley reaches with an incised river channel and those with an incised meander belt.

	Valley reaches with an incised river channel	Valley reaches with an incised meander belt
Frequency and duration of the valley floor submergence at a given flood discharge	Decreased	Slightly decreased for the new, low-lying floodplain but considerably decreased for the former floodplain
Percentage of the total flow conveyed in the extra-channel zone	Decreased both for low and high-flood discharges	Decreased for low flood discharges, considerably decreased for high-flood discharges
Relative elevation of flood stages above the channel bed (affecting concentration of suspended sediment transport within the channel)	Increased	Unchanged or slightly decreased
Flow velocity in the extra-channel zone	Decreased	Increased over the new, low-lying floodplain but considerably decreased over the former floodplain

Rinaldi et al., 2005). Thus, extracting gravel from channels, practiced by river engineers to keep the rivers on their channelization paths, must be abandoned and uncontrolled sediment mining should be rigorously forbidden. River-control works must be carried on in such a way that minimizes or eliminates the destruction of bed armouring and the internal structure of channel sediments.

Most importantly, a reduction in transport capacity of the rivers is necessary to compensate for their present-day decreased sediment loads (Wyżga, 2001a). In mountain valleys, it could be achieved with some widening of the river channels but in foothill and foreland reaches, where the tendency to river meandering reappeared in the 20th century, an increase in channel sinuosity should be allowed wherever it is possible without an erosional threat to property and infrastructure. The active meandering would reduce channel gradient and, hence, transport capacity of the rivers, whereas the input of material from lateral erosion would help to increase sediment loads not only in the reaches where active meandering is allowed but also in those in which channelization schemes are maintained.

Recently, a proposal for a new management policy of the streams and rivers from the Carpathian part of the upper Vistula drainage basin has been formulated (Bojarski et al., 2005), in which various methods of restoring the disturbed equilibrium conditions in mountain watercourses are presented and discussed in terms of their usefulness under different styles of valley floor management. For narrow streams in forested corridors, it is suggested to allow spontaneous formation of wood dams from fallen trees. As wood dams facilitate dissipation of the energy of flood flows and force in-channel sediment storage, mountain streams with abundant wood accumulations can maintain their alluvial beds even under relatively steep valley gradients (Montgomery et al., 1996). For wider watercourses flowing far from settlements and infrastructure, free channel migration within erodible river corridors should be allowed (cf. Piégay et al., 2005), with anti-erosion revetments located at the boundaries of the floodplain area. Where planform stability of the channelized stream or river in an urbanized area must be preserved, construction of artificially elevated riffles made of layers of compacted boulders is recommended to reduce the excessive flow capacity of the incised channel.

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Discussion by R.J. Batalla and A. Rovira

Gravel mining appears to explain an important part of the incision phenomena observed in many European rivers throughout the second half of the 20th century, besides other human impacts, such as river embankment, dams and land-use change. However, there is still no general concept foreseeing the recovery in time and place of the river channel's original equilibrium after mining ceases.