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IMPACT OF THE CHANNELIZATION-INDUCED INCISION OF THE SKAWA AND WISŁOKA RIVERS, SOUTHERN POLAND, ON THE CONDITIONS OF OVERBANK DEPOSITION

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ABSTRACT

The impact of river incision in response to channelization on the conditions of overbank deposition is shown by the study of two montane rivers from the upper Vistula drainage basin, southern Poland. The Wisłoka River had insufficient energy to destroy the river-control structures and remained laterally stable in the course of the channel downcutting. Under such conditions, the incision has raised the relative elevation of the floodplain above the river bed, thereby reducing considerably the frequency of overbank flows, and increasing concentration of suspended sediment transport within the incised channel. On the high-energy Skawa, the long periods of incision of the channelized river alternated with the shorter periods of lateral channel migration over the twentieth century. This has led to the formation of an incised meander belt, within which flood flows are constricted, and where the high velocities of the floodplain flows inhibit overbank deposition. Field observations confirm an insignificant role played nowadays by floodplain sedimentation in the valleys of both rivers. This study shows that the potential of the floodplains of the Carpathian tributaries to the Vistula for sediment storage has been dramatically reduced over the few past decades as a result of the channelization-induced incision of the rivers. The frequency of overbank flows has decreased considerably on the rivers draining the eastern part of the Polish Carpathians, and the majority of the suspended sediment is routed within the resultant enlarged channels. In the western part of the mountains, high velocities of the floodplain flows restrict overbank deposition on the narrow floodplains developed along incised channels. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: channelization; floodplain; flood flow hydraulics; overbank deposition; river incision; suspended sediment

INTRODUCTION

Rivers transport a majority of their sediment load in suspension, and deposit a proportion of the suspended sediment on their floodplains. The rate of vertical accretion of overbank deposits declines, as the height of river banks and the elevation of the floodplain increase with successive flood events (Wolman and Leopold, 1957). Such a decline should also occur when a river degrades its bed and enlarges the capacity of its channel so that the channel can carry the whole, or a great part, of flood water. As a result of channelization works carried on since the beginning of the twentieth century, Carpathian tributaries to the Vistula have experienced considerable channel degradation in their middle and lower courses (Punzet, 1981; Klimek, 1983; Wyżga, 1991). To date, the rivers have incised by 1.5–3.8 m, with the rates of the downcutting markedly higher in the second half of the century. Indeed, 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).

Three direct reasons for the decreased sediment accumulation in the floodplain areas of a channelized, degrading river may be indicated. First, gradient steepening and channel narrowing in the course of channelization works, and also the increasing concentration of flood flows in a cross-section, with the advancing incision of the channelized river increase mean velocity at a given discharge (Wyżga, 1993a). This facilitates downstream transport of suspended particles and hinders their deposition. Second, as the streambed degradation progresses, a given stage is only attained at increasingly high discharge (Wyżga,

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1991, 1993a); this reduces the frequency of overbank flows. Finally, concentration of suspended grains coarser than fine silt is known to decrease up the water column (Vanoni, 1946). Thus, with increased channel depth, coarser fractions of suspended sediment are conveyed mainly within the channel, and the size of sediment particles which may be introduced into the floodplain areas with flood water must be reduced.

Considerable differences in the course of incision have occurred between rivers draining the western and eastern part of the Polish Carpathians. As a result, a range of factors have also been responsible for the changes in the conditions of overbank sedimentation that followed the river downcutting in these two regions. The purpose of this paper is to demonstrate and explain the influence of the incision of the Carpathian tributaries to the Vistula on the conditions of deposition in their respective floodplain areas. This is achieved by considering representative cross-sections located on the rivers from both regions.

STUDY METHODS

Geomorphological literature abounds with papers describing accelerated floodplain sedimentation, be it historical or present-day (e.g. Knox, 1987; Magilligan, 1992; Gomez *et al*., 1998). However, attempts at documenting recent cases of the slowed down or restrained overbank sediment accretion in response to channel incision face serious methodological problems. Although analytical procedures exist which allow numerical modelling of spatial patterns of floodplain flows (Bates *et al*., 1992) and overbank sedimentation (Nicholas and Walling, 1995), these techniques require a detailed knowledge of floodplain surface morphology. The lack of such data relating to the floodplains from previous decades makes it impossible to use the methods for determining temporal changes in hydraulic and depositional conditions on the floodplains of the Carpathian rivers. A scarcity of suspended sediment gauging stations on the Carpathian tributaries to the Vistula means calculation of the transmission losses of suspended sediment in their reaches occurring in successive time intervals is not possible, in contrast to the Vistula itself, where this method has been successfully applied (Łajczak, 1995, 1997). Furthermore, a lowering of the mean annual flood has taken place on the Carpathian tributaries to the Vistula in the second half of the twentieth century, owing to climatic fluctuations and alterations in basin management (Wyżga, 1991, 1997; cf. Bogdanowicz and Stachý, 1995). Both the lowering of flood peaks and channel incision have decreased the frequency of overbank flows, and thus, it is impossible to discriminate between their effects on the actual rates of floodplain sedimentation on the Carpathian rivers.

To overcome the above-mentioned problems, this study concentrates on changes in depositional conditions, and not on the sedimentation rates themselves. The effect of temporal flow variability on the dataset has been eliminated by comparing stage–discharge curves from different years during the progress of river incision. This has revealed temporal changes in stage attained at discharges of given recurrence intervals, as well as changes in discharge associated with the bankfull stage. Alterations in the elevation over the channel bed of the stage attained at given discharges have also been analysed. This has enabled inferences about the impact of incision on the potential of coarse grains transported in graded suspension to be introduced with flood water onto the floodplains of the rivers considered.

The analysis has been supplemented by examining mean velocity of flows in the channel and floodplain zones of the gauging sections investigated. This has been done using a method which permits mean flow velocity in both zones to be estimated for a given total discharge taken from a stage–discharge curve (Wyżga, 1999). The velocity estimates are used to estimate the potential of transported grains to be deposited (cf. Sundborg, 1967) on the floodplains at given discharges. Furthermore, with the mean velocity in both zones known, the distribution of flow between the channel and floodplain areas can be determined. This allows reconstruction of the temporal changes in the percentage of total flow conveyed in the extra-channel zone of the cross-sections investigated at given discharges.

FIELD SETTING AND HISTORY OF THE TWENTIETH CENTURY CHANNEL AND FLOODPLAIN CHANGES

The study focuses on the Łabuzie gauging station on the Wisłoka River and the Wadowice station on the Skawa River (Figure 1). Both the Wisłoka and Skawa are gravel-bed streams, that drain the northern slopes of the Western Carpathians; however, different morphological characteristics of their catchments are clearly reflected in the diverse channel slope and energy of both rivers (Table I). The catchment of the Wisłoka River to the Łabuzie station comprises low mountains with elevations up to 997 m above sea level (asl), foothills and a small percentage of intramontane depression areas (Figure 1). As a result, the Wisłoka channel has a relatively gentle slope (Table I). The bed material in the vicinity of the station consists of sandy gravel. The Wisłoka is characterized by the occurrence of frequent floods of moderate magnitude, owing to snow melting and of rare, large floods caused by summer rains. The Skawa River drains mountains which range up to 1725 m asl in elevation (Figure 1). Its channel has a relatively steep

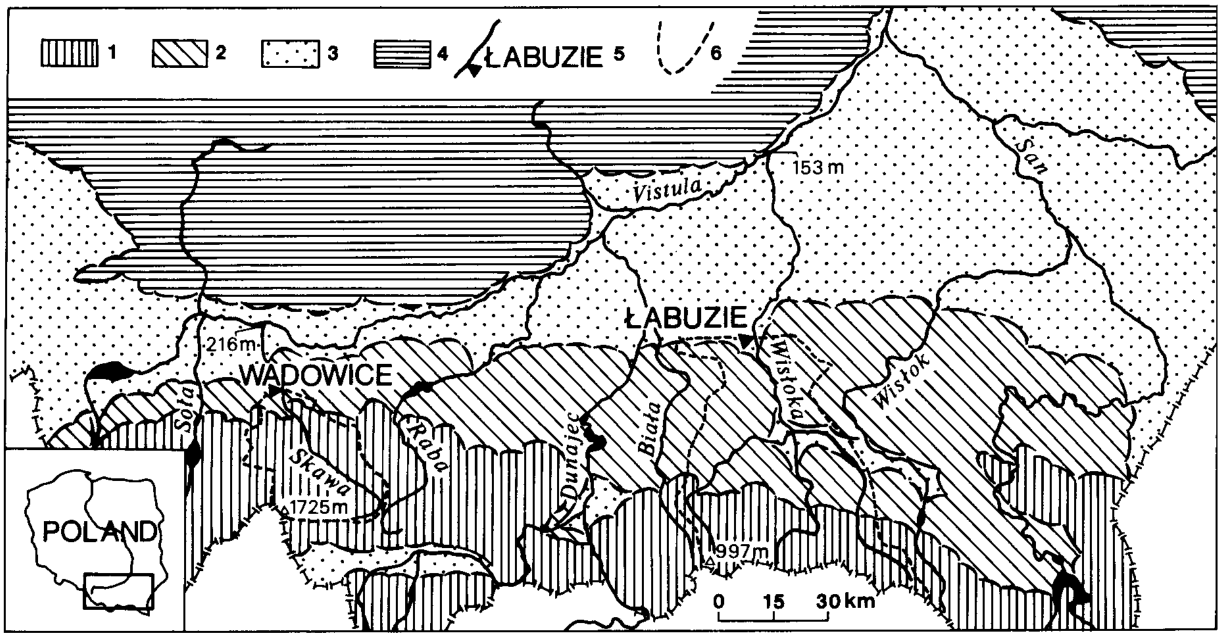


Figure 1. Location of the investigated gauging stations within the upper Vistula River drainage basin. (1) mountains of intermediate and low height; (2) foothills; (3) intramontane and submontane depressions; (4) uplands; (5) gauging stations investigated; (6) boundaries of the catchments of the Skawa and Wisłoka Rivers to the stations investigated

Table I. Hydrological and hydraulic characteristics of the Wisłoka River at the Łabuzie gauging station, and of the Skawa River at the Wadowice station

River	Wisłoka	Skawa
Gauging station	Łabuzie	Wadowice
Drainage area (km^2)	2546	835
Mean annual discharge (1961–1997) (m^3 s^{-1})	26.7	12.7
Mean annual flood (1961–1997) (m^3 s^{-1})	352	242
Ratio Q_{max}:Q_{avg}	13.2	19.0
Channel slope	0.000656	0.0031
Specific stream power at bankfull flow (W m^{-2})	65.5	96.8

Values of channel slope and of specific stream power refer to the 1996 channel of the Wisłoka and to the 1997 channel of the Skawa.

slope (Table I), and the river bed in the vicinity of the Wadowice station is formed from pebble–cobble gravels. Flood flows on the Skawa are more flashy than those on the Wisłoka (Table I), and typically occur in the summer months.

At the end of the nineteenth century, both rivers had wide and shallow channels. By 1904, intensive channelization works had been undertaken (Kędzior, 1928), that caused shortening of the rivers by approximately 15% close to the gauging stations considered, along with some narrowing of their channels. As a result of these works, both rivers started to incise in the 1910s. However, as evidenced by the changes in minimum annual water stage of the rivers (Figure 2), their subsequent evolution has been slightly different in each case.

Owing to the relatively low energy of the Wisłoka, channel regulation structures constructed in the first two decades of the twentieth century remained generally intact through the first half of the century. After the initial rapid downcutting of the river by about 0.6 m in the mid-1910s, slow channel incision occurred at the Łabuzie station, resulting in bed degradation by about 0.4 m between the 1920s and mid-1950s. This is reflected in the minimum annual stage (Figure 2). Training works were undertaken on the Wisłoka in the 1950s, which caused further narrowing of the river. This repeated channelization coincided with a progressive reduction of sediment delivery to the river channel, which occurred as a result of climatic fluctuations and alterations in basin management (Wyżga, 1997). It is probable that the sediment yield of the basin was reduced with the lowering of peak discharges in the second half of the century (cf. Wyżga, 1993b). In the montane section of the Wisłoka basin, much arable land was turned into pasture and meadows, and some areas were afforested just after World War II (Lach, 1975). Finally, intensive exploitation of gravel for building purposes has been carried on in the Wisłoka channel since the 1950s (Osuch, 1968). It can be concluded that an increase in the sediment-transporting ability of the river caused by its repeated

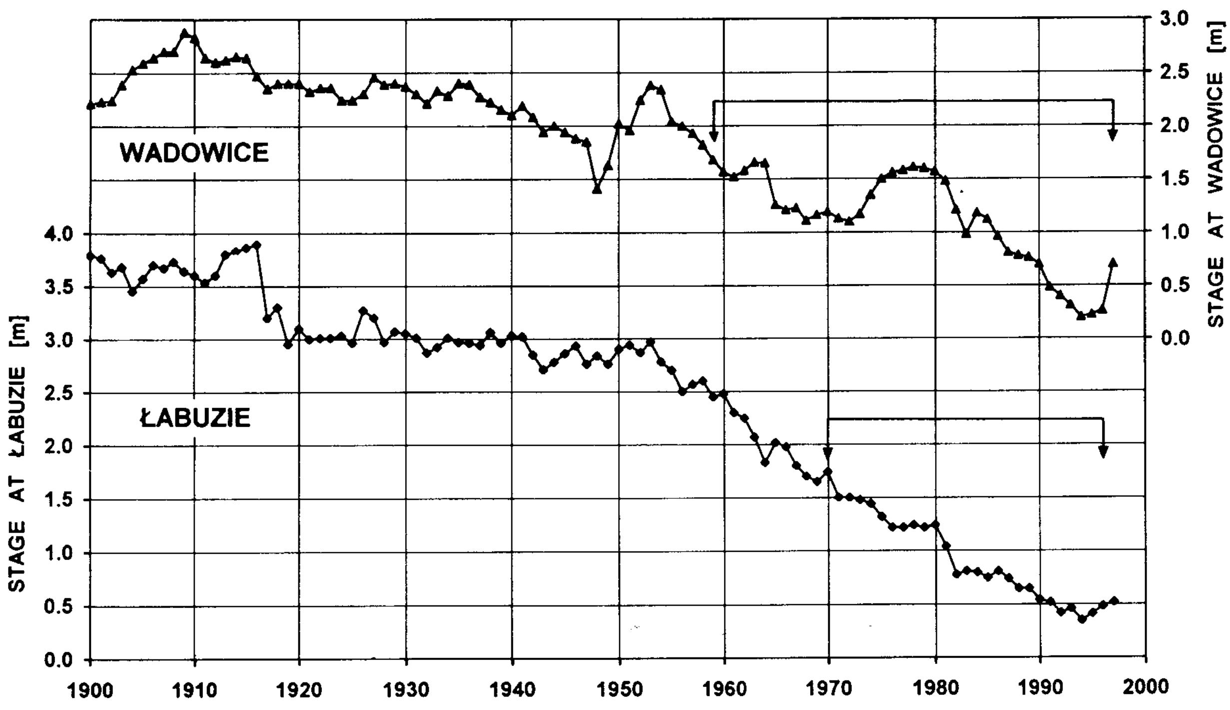


Figure 2. Changes in the lowest annual water stage of the Skawa River at the Wadowice gauging station and of the Wisłoka River at the Łabuzie station since the beginning of the twentieth century. Arrows indicate the years in which the gauging sections shown on Figure 3 were surveyed

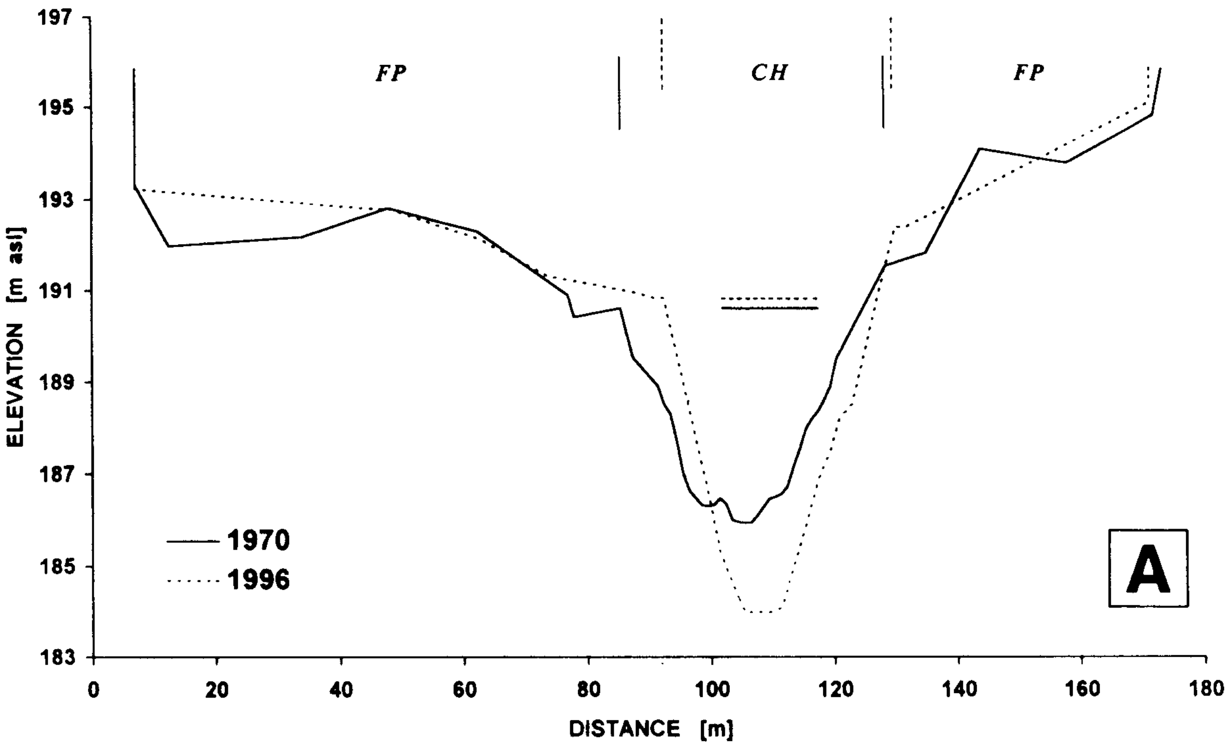
channelization, and a concomitant shrinkage of sediment available for fluvial transport, have brought the Wisłoka into disequilibrium. As a result, rapid streambed degradation has been induced; the minimum annual stages at Łabuzie have lowered by a further 2.5 m since the mid-1950s (Figure 2).

The changes in the Wisłoka channel brought about by this rapid incision are illustrated by the comparison of the river cross-section at Łabuzie taken in 1970 and 1996 (Figure 3(A)). Between these years, the average elevation of the channel bed lowered here by about 2.3 m (Figure 3(A)), which was accompanied by the fall of the minimum annual stage by 1.25 m (Figure 2). This difference is linked with the simultaneous reduction in width of the channel, which partly compensated for the increase in channel capacity resulting from the bed degradation. Owing to these changes, the width/depth ratio of the Wisłoka channel diminished from 8.4 m in 1970 to 5.0 m today (Figure 3(A)). This testifies to the diminishing proportion of bedload in the total load of the river (cf. Schumm, 1969).

The minimum annual water stage of the Skawa River at the Wadowice station has lowered by more than 2 m since the beginning of the 1910s (Figure 2). Three long periods of channel incision, separated by short episodes of bed aggradation, are evident during that time. The amount of bed aggradation in these short episodes has only partly compensated for the incision during the preceding degradational stage, thus, resulting in a progressive lowering of the Skawa channel bed over the twentieth century (Figure 2). Nevertheless, these aggradational episodes are important, as they reflect stages of the destruction of river-control structures, and of widening of the channel. Owing to its high energy, the Skawa was able to destroy the old, weakened structures, through the action of several major floods (cf. Wyżga, 1991). The first such episode was related to the floods of 1948, 1949 and 1951, and the second one followed the floods of 1970 and 1972. Specific stream power of the river must have decreased when the channel widened, and the thalweg became more sinuous, thus allowing bed material to accumulate and the channel bed to aggrade (cf. Wyżga, 1991). Subsequently, the channel was again straightened and narrowed, and the river banks were lined with gabions or rip-rap. Streambed degradation was reactivated with this repeated channelization and, at the same time, a new floodplain originated at a lower position on that part of the formerly wide channel which had been separated from the thalweg by the lining structures.

The comparison of the gauging section at Wadowice surveyed in 1959 and 1997 illustrates the changes in the Skawa River cross-section, resulting from the last cycle of the widening/narrowing of the channel and of the aggradation/degradation of its bed (Figure 3(B)). The left bank retreated here by almost 20 m in the 1970s. As a result of the construction of groynes in around 1980, a gravel bar originated on the left side of the widened channel. Afterwards, overbank deposition was initiated on the surface of this lateral bar, following the commencement of channel incision with repeated straightening and narrowing of the river reach close to the gauging station in the early 1980s. Similarly, a bench in the right part of the 1959 channel has developed into a narrow, right-hand floodplain. Owing to the last degradational stage, the average elevation of the channel bed lowered by slightly more than 1 m between 1959 and 1997 (Figure 3(B)). Since the width/depth ratio of the recent channel (28) is similar to that of the 1959 channel (24.5), the minimum annual stage of the river fell in that period by approximately the same value (Figure 2). As a result of the concentration of flood water in the deepened channel, and over the newly formed floodplain, the floodplain, which was active several decades ago (Figure 3(B)), has been transformed into a terrace (Wyżga, 1999). Thus, the formation of the new, lower floodplain on the Skawa River makes the evolution of its cross-sectional geometry over the few past decades different from that typifying the Wisłoka River, and it will be shown below that the difference has had profound hydraulic consequences.

Although the cross-section at Łabuzie (Figure 3(A)) is situated under a bridge, its general geometry remains typical of the neighbouring reaches of the Wisłoka. Prior to 1959, the gauging station at Wadowice was also located under a bridge where, however, flood flows were constricted by the bridge abutments. Then it was moved to an unconstrained cross-section (Figure 3(B), see also Figure 6, below), the geometry of which is representative of the longer reach of the Skawa. At the same time, a proximity of two bridges allows direct discharge measurements on the river to be performed during flood flows.



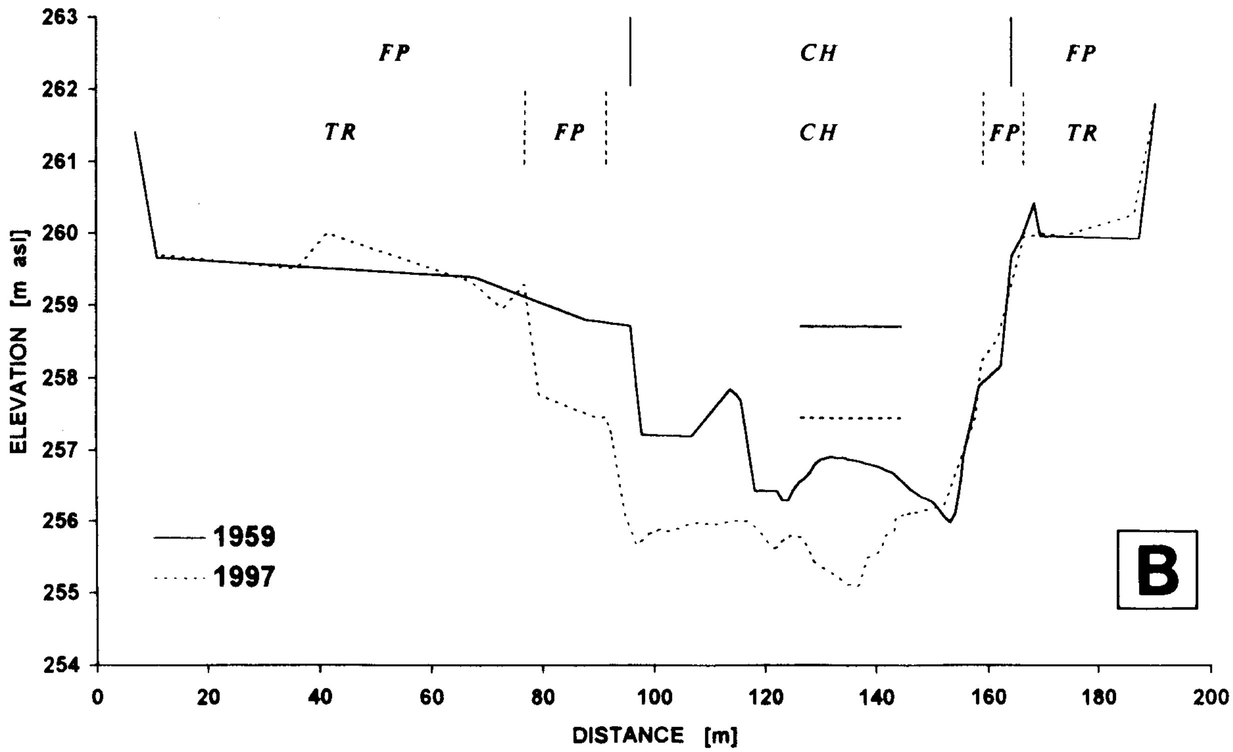


Figure 3. Downstream view of the cross-sections of (A) the Wisłoka River at the Łabuzie gauging station in 1970 and 1996, and (B) the Skawa River at the Wadowice station in 1959 and 1997. Elevation of bankfull stage is also marked. Morphological zones of the cross-section: *(CH)* channel; *(FP)* floodplain; *(TR)* terrace

CHANGES IN THE HYDRAULIC AND DEPOSITIONAL CONDITIONS ON THE FLOODPLAINS OF THE WISŁOKA AND SKAWA RIVERS SUBSEQUENT TO THEIR INCISION

Owing to the streambed degradation and a small rise in the bank top elevation (Figure 3(A)), bankfull discharge of the Wisłoka River at Łabuzie increased between 1970 and 1996 from 167 to 354 $m^3 s^{-1}$, with a corresponding change in its recurrence interval, determined by an annual maximum series method, from 1.03 to 2.35 years (Figure 4). Because mountain rivers with a high variability of discharge are characterized by a pronounced discrepancy in the range of low magnitude floods between the annual maximum series and the partial duration series (Wyżga, 1995), a partial duration series method has also been applied for evaluating the recurrence interval of the discharges attained at bankfull stage in 1970 and 1996. It increased from 0.32 to 1.71 years in that period, which implies that the frequency of overbank flows on the Wisłoka is now more than five times lower than it was in 1970.

The frequency of inundating a given level on the floor of the Wisłoka valley also decreased in the period considered (Table II). The level, which had been inundated in 1970 by a 5-year flood, in 1996 could only be submerged by a flood with a 7.8-year return period. Similarly, the discharge of a 27.5-year recurrence interval was associated in 1996 with the stage attained previously by a 20-year flood. At the same time, a lowering of the stage attained at a given discharge took place, amounting to 69 cm for a 5-year flood, 44 cm for a 10-year flood, and 28 cm for the flow of the 20-year return period (Table III).

As a result of the changed morphology of the Wisłoka, considerable alterations in flow velocity occurred, both with regard to its absolute values, and also to its pattern in the river cross-section (Figure 4). Mean flow velocity at bankfull discharge markedly increased from 1.44 m s^{-1} in 1970 to 2.44 m s^{-1} in 1996 (although this rise resulted partly from the increased discharge at the bankfull condition). Under out-of-bank conditions, mean velocity in the total cross-section is now higher than it was in 1970, exceeding the respective values by 32% at the 5-year flood, and by 12% at the flow of the 20-year recurrence interval. However, this rise of the mean velocity in total cross-section was the effect of two opposed tendencies. With increased concentration of flow in the deepened channel, mean velocity in the channel zone increased and this increase amounted to 15% for the 5-year flood, and to 12% for the discharge with the 20-year return period. On the other hand, mean velocity in the floodplain zone decreased considerably, owing to the reduced depth of the floodplain flows; this decrease amounted to 43% for the 5-year flood, and to 26% for the flow of 20-year frequency. At the present time, mean velocity in the channel zone equals 2.78 m s^{-1}, and that over the floodplain 0.27 m s^{-1} for the 5-year flood, whereas the values at the discharge of the 20-year recurrence interval amount to 3.17 and 0.54 m s^{-1}, respectively. Thus, the present Wisłoka River is characterized by a marked contrast in the mean velocity of flow in its channel and floodplain areas. The enlarged capacity of the river channel, and the increased velocity of flow in the channel zone, resulted in a significant reduction of the amount of flood water carried on the floodplain (Table IV). This diminished from 7.3% of the total flow in 1970 to merely 1.2% in 1996 at the 5-year flood. At the discharge with the 20-year recurrence interval, 17.4% of the total flow was conveyed in the floodplain zone in 1970, but in 1996 this would have been only 10.3%. It is just this considerable reduction in the proportion of the total flow carried on the floodplain which explains why mean velocity in total cross-section increased more than that in the channel zone, despite the concomitant fall of velocity in the floodplain zone.

Another effect of the incision of the Wisłoka River was a considerable increase of the relative elevation of flood stages above the channel bed (Table III). Between 1970 and 1996, the relative elevation of the stage associated with the 5-year flood increased by 1.61 m, whereas at the discharges of the 10-year and 20-year return period, this increase in the relative elevation of the river stage amounted to 1.86 m and 2.02 m, respectively. With the decreased depth of floodplain inundation at particular discharges (Table III), this marked enlargement of the vertical distance between the river bed and the water surface means that, at present, the river banks can be overtopped only by the uppermost parts of

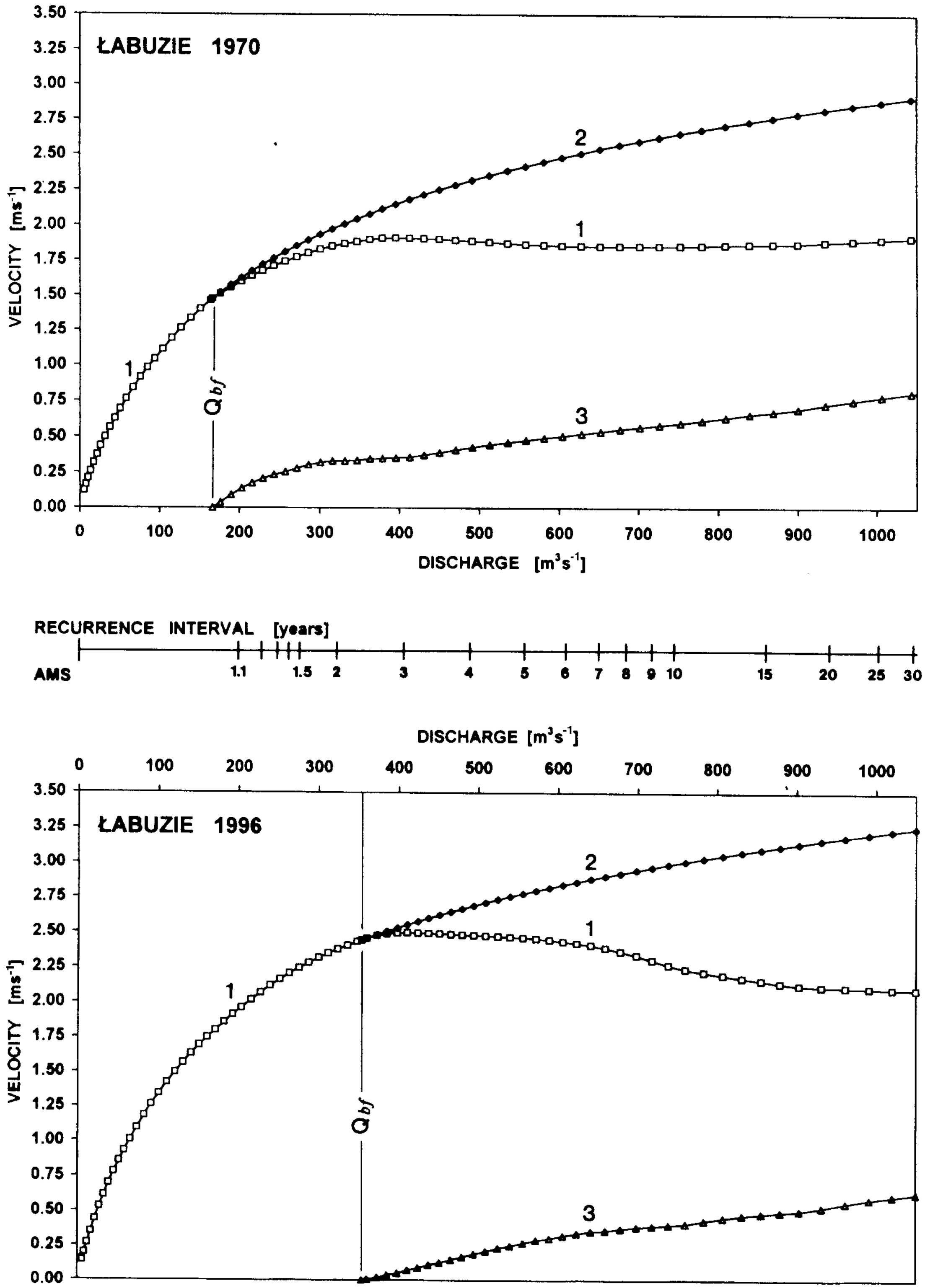


Figure 4. Relationship between the mean flow velocity in total cross-section (1), in channel zone (2) and in floodplain zone (3) of the cross-section, and discharge for the Łabuzie gauging station on the Wisłoka River in 1970 and 1996. Points represent conditions for stage changing at 10 cm intervals. $\mathbf{Q}_{bf}$ denotes bankfull discharge. Discharges in Figures 4 and 5 are referred to their recurrence interval determined by the annual maximum series method from the years 1961–1997

Table II. Changes in discharge and its recurrence interval associated with the same stages of the Wisłoka River at the Łabuzie gauging station, and of the Skawa River at the Wadowice station, recorded before and after the period of rapid incision of the rivers

Wisłoka River at Łabuzie				Skawa River at Wadowice			
1970		1996		1959		1997	
Discharge of given recurrence interval ($m^3 s^{-1}$)		Discharge at the same stage ($m^3 s^{-1}$)	Recurrence interval (years)	Discharge of given recurrence interval ($m^3 s^{-1}$)		Discharge at the same stage ($m^3 s^{-1}$)	Recurrence interval (years)
Q_3	407	551	4.9	Q_3	288	639	17.9
Q_5	558	678	7.8	Q_5	393	751	33.5
Q_{10}	745	848	14.5	Q_{10}	530	886	68.0
Q_{15}	860	952	21.0	Q_{15}	605	?	?
Q_{20}	940	1025	27.5	Q_{20}	660	?	?

Q_X denotes discharge of given recurrence interval.

Table III. Elevation above channel bed of the water stage of the Wisłoka River at the Łabuzie gauging station attained at discharges of given recurrence intervals in 1970 and 1996 and its change between these years

Recurrence interval (years)	Discharge ($m^3 s^{-1}$)	1970		1996		1970–1996
		Stage (m asl)	Elevation above channel bed (m)	Stage (m asl)	Elevation above channel bed (m)	Increase in elevation above channel bed (m)
3	407	192.27	5.97	191.27	7.27	1.30
5	558	193.00	6.70	192.31	8.31	1.61
10	745	193.77	7.47	193.33	9.33	1.86
15	860	194.17	7.87	193.82	9.82	1.95
20	940	194.41	8.11	194.13	10.13	2.02
25	1000	194.58	8.28	194.33	10.33	2.05

Table IV. 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
Q_{25}	18.9	12.0	20.8	7.5

Q_X denotes discharge of given recurrence interval.

flood water. Furthermore, 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 should reduce the amount of coarse particles introduced with flood water onto the floodplain, unless it were counterbalanced by a concurrent, substantial increase in average concentrations of suspended sediment at the same discharges. However, no data exist to support the assumption about the increased average sediment concentrations, as a clear trend towards decreasing annual loads of suspended sediment has been observed over the few past decades at the Mielec gauging station (Łajczak, 1995), located several tens of kilometres down the Wisłoka River. Therefore, it seems justified to assume that the sedimentation rate of coarse sediment particles on the floodplain decreased as a result of the increased channel depth (Figure 3(A)), and the reduced percentage of total flow conveyed on the floodplain (Table IV). The rate of deposition of fine sediment particles, transported in uniform suspension, is known to be proportional to the water depth at a given location on a floodplain (Walling and He, 1998). Thus, it is probable that the sedimentation rate of fine sediment on the Wisłoka floodplain also decreased with the decreased water depth and the resulting shortened time of the floodplain submergence at a given discharge.

Between 1959 and 1997, bankfull discharge of the Skawa River at Wadowice increased from 159 to 211 $m^3 s^{-1}$ (Figure 5). At the same time, the recurrence interval corresponding with the discharge attained at bankfull stage in these years changed from a 1.50 to a 1.97-year period, when determined by the annual maximum series method (Figure 5), and from a 0.87 to a 1.29-year period, when evaluated by the partial duration series method. This decrease in the frequency of overbank flows on the Skawa was considerably lower than that which occurred on the Wisłoka in the years of 1970–1996, with a similar fall of minimum annual stage of both rivers in the periods considered, and the difference is, apparently, related to the formation of the new floodplain at a lower position on the Skawa.

The concentration of flood water in the deepened channel, and over the low-lying floodplain, caused a dramatic lowering of the stage attained at given discharges; in the years of 1959–1997, it amounted to 139 cm for a 5-year flood, 118 cm for a 10-year flood, and 94 cm for the discharge with a 20-year return period. On the other hand, the stages associated previously with the 5-year and 10-year floods now could be attained at the discharges with a 33.5-year and 68-year recurrence interval, respectively (Table II). Owing to the fall of high 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 (Figure 3(B)).

The increased concentration of flow in the river cross-section, and the steepening of the channel gradient in the course of channelization, resulted in the higher velocity of flow on the Skawa (Figure 5). Mean velocity at bankfull discharge increased from 1.36 $m s^{-1}$ in 1959 to 2.06 $m s^{-1}$ in 1997, although, again, the rise was partly related to the increased discharge at the bankfull condition. At out-of-bank flows, the present velocities are higher, not only in the channel zone, but over the floodplain as well; as a result, the mean velocity for the total cross-section also exceeds that of the 1959 river by about 20–30%. During the flood of July 1997, mean velocity in the channel zone amounted to 2.35 $m s^{-1}$ at the flow of 5-year frequency and to 2.65 $m s^{-1}$ at a peak discharge of 725 $m^3 s^{-1}$ which has a 29-year recurrence interval. At the same time, mean velocity on the floodplain equalled 0.64 $m s^{-1}$ at the discharge of 5-year frequency and 1.68 $m s^{-1}$ at the flood peak. In 1997, mean velocity in that zone attained 1 $m s^{-1}$ at the discharge with a 8.5-year return period, whereas, in 1959, this value would have been reached at the flow of a 12.5-year recurrence interval. At such a velocity, clasts as coarse as fine pebble may be transported in traction, and fractions up to medium-grained sand may be maintained permanently in suspension (Sundborg, 1967). This shows that now, during major floods carrying large sediment loads, the flow over the narrow floodplains of the Skawa is too fast to allow deposition of sediment transported in suspension by the river.

The inundation of the terrace on the left side of the present river (*TR* in Figure 3(B)) caused the pattern of flow velocity in 1997 to deviate significantly from that in 1959 (Figure 5). Mean velocity of flow on the terrace (not shown on Figure 5) was low, reaching about 0.3 $m s^{-1}$ at the maximum discharge of the July 1997 flood. With water spreading onto the terrace, mean velocity in the total extra-channel zone grew at a slower rate than that over the floodplain itself, attaining a maximum value of 1.37 $m s^{-1}$ at a discharge of 685 $m^3 s^{-1}$, and, finally, decreasing to 1.31 $m s^{-1}$ at the peak flow of the 1997 flood.

Finally, also on the Skawa, the amount of flood water conveyed in the extra-channel zone was reduced with the river incision (Table IV). Between 1959 and 1997, the amount decreased from 5.5 to 1.6% of the total flow at the 5-year flood and from 19.0 to 6.7% at the discharge of 20-year frequency. For major floods, the scale of the reduction was apparently greater on the Skawa than on the Wisłoka River (Table

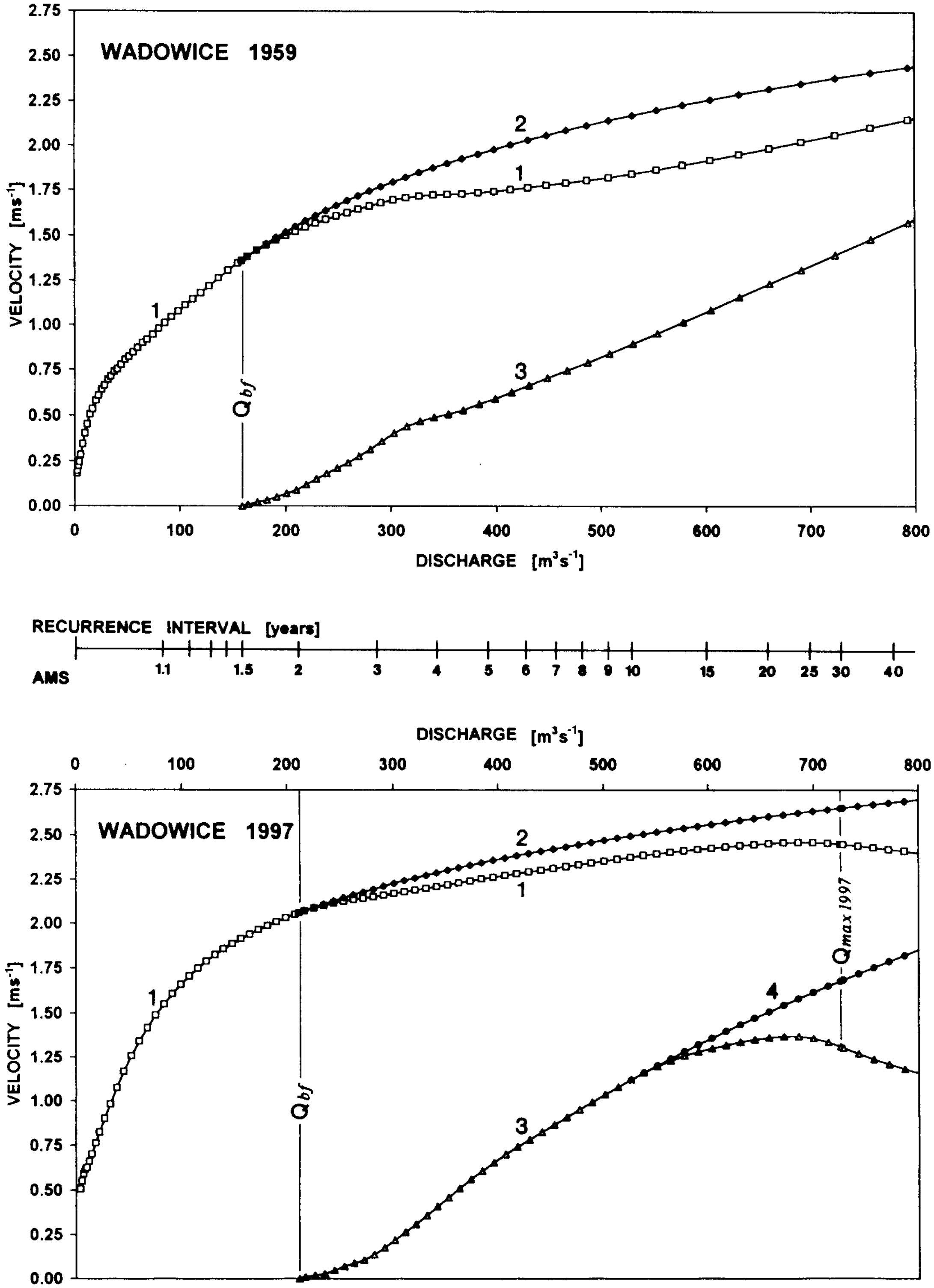


Figure 5. Relationship between the mean flow velocity in total cross-section (1), in channel zone (2) and in extra-channel zone (3) of the cross-section, and discharge for the Wadowice gauging station on the Skawa River in 1959 and 1997. Signature (4) depicts velocities over the floodplain itself after the start of inundation of the terrace in the 1997 cross-section. Points represent conditions for stage changing at 5 cm intervals. $\mathbf{Q}_{bf}$ denotes bankfull discharge

IV). It may be attributed to the retained channel width with the progress of river incision, and to the constriction of both channel and floodplain flows in the river cross-section (Figure 3(B)).

In summary, the amount of sediment carried in suspension by the Wisłoka and Skawa with potential for being deposited on their floodplains has been reduced considerably in the few past decades, as a result of the changes in the hydraulics of flood flows on the rivers (conditioned by their incision). As a significantly lower percentage of total flows is conveyed nowadays in the extra-channel zone of these rivers (Table IV), lower amounts of suspended sediment can be introduced into their floodplain areas with flood water. On the Wisłoka, it has been accompanied by the considerably reduced frequency of overbank flows, and by the increased concentration of the transport of coarser fractions of the suspended load within the channel itself, with the raised relative elevation of the floodplain surface above the river bed. On the Skawa, the lateral extent of inundation has shrunk significantly with the dramatic fall of flood stages. At the same time, high velocities over the narrow, low-lying floodplains inhibit deposition of suspended sediment during major floods.

FIELD OBSERVATIONS AND THEIR MEANING

The flood in July 1997 on the Skawa River provided an opportunity to compare the theoretically predicted hydraulic conditions in the extra-channel zone of the Wadowice gauging section with the pattern of overbank sedimentation resulting from the event, and, thus, observations were undertaken at this site a few days after the flood. The considerable damage to floodplain vegetation was apparent, confirming high velocities of flow over the floodplain; not only herbaceous plants, but also osiers growing upstream from the gauging section were bent down and aligned parallel with the current (Figure 6). Four sediment

Figure 6. Downstream view of the Skawa River and its left-hand floodplain at Wadowice. White arrows indicate the location of the gauging section on the floodplain and of the most proximal and most distal of the four sediment samples taken here. Note osiers bent down to the ground on the floodplain immediately upstream of the gauging section

samples were collected across the left-hand side of the floodplain (Figure 6), and they reveal two important features of the floodplain sedimentation on the river. First, the sediments were relatively fine-grained, ranging from silty sands on the bank top to silts 4 m from the bank, and to muds at two distal locations. Second, 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, amounting from 6–7 cm near the bank, to about 1.5 cm near the slope of the terrace. At the same time, conspicuous levee sediments, consisting of medium-grained sands, and 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 (Wyżga, 1999). The channel slope of the Skawa River at Wadowice is about 20 times steeper than that of the Vistula below the mouth of the Skawa. Thus, grains at least as coarse as those deposited on the Vistula floodplain must have been transported in suspension over the Skawa floodplain, and the low thickness and fine-grained nature of the overbank sedimentation on that river cannot be attributed to the low competence of its floodplain flows. Instead, the thin overbank sediments seem to reflect the conditions of no deposition at the flood crest when the flow over the floodplain was very fast. Such a lack of deposition during high out-of-bank flows is typical of the floodplains of mountain rivers (Teisseyre, 1989); on the Skawa, this phenomenon must have been strengthened as a result of the increased concentration of flood flows in the river cross-section with the advancing incision. The deposition had been most likely limited to the early phase of the flood here, with the floodplain vegetation acting as a sediment trap until it became bent down to the ground by the current. At the same time, only a film of sediment on grass blades could be observed on the terrace on the left side of the river. As the velocity of flow over the terrace was very low, this fact should be attributed to the evidently low concentration of suspended sediment in the uppermost part of the water column, and to the short submergence of the terrace.

No major flood has occurred on the Wisłoka in the last few years. Although this fact has made it impossible to identify and analyse the sediments from the last depositional event(s), some conclusions could be drawn from an inspection of the river floodplain. With a marked contrast in mean velocity between the channel and floodplain flows of a river, large amounts of the coarser sediment carried in suspension into the floodplain area should be deposited on the natural levees, and, indeed, such a deposition during the July 1997 flood was documented on the Vistula (Wyżga, 1999). However, no prominent levees have been observed on the Wisłoka, both in the cross-section studied (Figure 3(A)) and in the neighbouring river reaches, although they could have been formed during the major floods of 1987 and 1989, which had recurrence intervals of 35 and 18 years, respectively. The explanation for this is that little sediment is carried by the upper parts of the water column, even at such high floods, whereas the transport of coarser fractions of the suspended load takes place almost entirely within the incised channel. Under such conditions, these fractions are laid down on the convex bank of the river, forming steeply inclined beds typical of the so-called inner accretionary bank (Bluck, 1971). Just such a depositional style has been responsible for the narrowing of the Wisłoka River channel after 1970 (Figure 3(A)).

REGIONAL DIFFERENTIATION OF THE IMPACT OF RIVER INCISION ON THE CONDITIONS OF FLOODPLAIN SEDIMENTATION

It follows from the discussion above that different factors have played a dominant role on the Wisłoka and Skawa Rivers in reducing the depositional potential of their floodplain flows in the few past decades. It is interesting to consider the reasons for this differentiation, and a wider significance of two cases investigated.

The changes in the hydraulics of flood flows of the Wisłoka have resulted from the incision of its channel, accompanied by increase in planform stability. A few factors have contributed to the lacking or insignificant migration of the Wisłoka channel in the few past decades. First, with channel slope much gentler, and discharges less flashy than those on the Skawa (Table I), the Wisłoka is characterized by lower stream power at flood flows. Thus, more flood events must occur on this river before it could destroy the lining structures on its banks. Second, the banks of the Wisłoka are considerably higher than those of the Skawa (Figure 3), and their height increased further with channel incision between 1970 and 1996. Therefore, a greater amount of sediment needs to be eroded and carried away here, with a given retreat of the river bank. Earlier observations on the Wisłoka actually documented (Klimek, 1974) that the rate of retreat of its banks had been inversely related to the bank height. Finally, with the streambed degradation during the twentieth century exceeding 3 m in the lower course of the Wisłoka, the river has dissected at many locations the cover of Quaternary alluvium and cut into Miocene claystones and mudstones (Alexandrowicz *et al.*, 1981). These Miocene sediments are relatively resistant to erosion, hence, strengthening the lateral stability of the river.

Conversely to the situation on the Wisłoka, the changes in the hydraulics of flood flows of the Skawa have been caused by the river incision alternating with the channel widening and thalweg meandering. Obviously, the energy of the Skawa has been sufficient for the destruction of channelization structures, whereas the low height of the river banks has facilitated their retreat. As the river has been channelized again, the final effect of its lateral erosion is the formation of an incised meander belt, within which both channel and floodplain flows are constricted.

The evolutionary histories of the Skawa and Wisłoka during the twentieth century illustrate the differences between the rivers from the western and eastern part of the Polish Carpathians in the course of their incision in response to channelization. These differences reflect distinct physiography of the catchments in both regions (Klimek, 1979). Mountain areas predominate in the western part (Figure 1); the rivers draining that region have steep channel gradients, and are characterized by high stream power at flood flows. This facilitates exceedance of the threshold of stability of the channelization structures. Once the structures become destroyed, lateral channel migration begins, reducing the river gradient already oversteepened by channelization. This leads to the formation of an incised meander belt, within which flood flows are constricted and sediment may be easily routed downstream (cf. Knox, 1987; Lecce, 1997). Indeed, investigations carried out by the present author in the Raba valley indicate (Wyżga, 1991) that the alternating episodes of streambed degradation and of lateral channel shifting during the twentieth century have resulted in the formation of progressively lower steps on the valley floor, with lacking or thin cover of fine-grained overbank sediments.

In contrast, in the eastern region, the main Carpathian rivers have long reaches within the foothill and foreland areas (Figure 1), where they are typified by gentler channel gradients and lower stream power values at flood flows than the rivers from the western region. Once straightened and narrowed during the channelization works, these rivers have generally remained laterally stable, and their excess energy has been dissipated by the scouring of their channel beds. The incision has enlarged considerably channel capacity of the rivers, thereby increasing concentration of water and sediment transport in their channel zone.

FINAL REMARKS

The energy of the rivers draining the Polish Carpathians has been sufficient to allow channel adjustment following their channelization during the twentieth century (cf. Brookes, 1987). The cases of the Skawa and Wisłoka considered in this paper illustrate the processes which have operated on the rivers, draining the western and eastern part of the mountains, respectively, in reducing the deposition in the floodplain areas of these streams as a result of incision induced by channelization. The distinct evolution of the rivers from these two regions has reflected their different energetics (cf. Lecce, 1997), 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 (Figure 1). In the western region, the high-energy rivers have formed incised meander belts, within which flood flows are constricted, and where the high velocities of the floodplain flows inhibit overbank deposition. In contrast, the rivers from the eastern region have had insufficient energy to destroy the river-control structures, and remained laterally stable during the channel downcutting; the incision has reduced considerably the frequency of overbank flows on these rivers, and increased concentration of suspended sediment transport within the incised channels.

Following the incision, a very low percentage of the total volume of flood water is conveyed in the extra-channel zone of the Carpathian tributaries to the Vistula (Table IV) and, because the concentration of suspended sediment decreases up the water column, the percentage of the total suspended load of the rivers being introduced into their floodplain areas must be even lower. Therefore, the channelization has caused that the floodplains of the Carpathian rivers in their middle and lower courses have lost their potential for sediment storage, the role they have played continuously since the Late Glacial (Klimek and Starkel, 1974), and the sediment may, nowadays, be routed through these reaches directly to the Vistula. In fact, as the streambeds have been degraded and the incised meander belts formed in the twentieth century, a net loss of sediment storage has taken place in the Carpathian valleys during that time, this being indicative of the situation when the carrying capacity of streams exceeds their sediment supply (Trimble, 1983).

A recurrence interval of 1.5 years, determined on annual maximum series, is known to approximate the frequency of bankfull flow established in relation to the active floodplain of vertically stable streams (Williams, 1978). The deviation from this value may be thought of as indicative of the degree of river incision and, thus, the Wisłoka seems more incised than the Skawa (Figures 4 and 5). On the other hand, a noticeably lower percentage of the total flow is conveyed at high discharges outside the channel zone on the Skawa than on the Wisłoka (Table IV), owing to the constriction of both the channel and floodplain flows within the incised meander belt on this river. It shows that the frequency of the bankfull flow alone cannot characterize satisfactorily the impact of channel incision on the hydraulics of flood flows and, at the same time, it proves the usefulness of the recently developed method of estimating mean flow velocity in channel and floodplain zones of a river (Wyżga, 1999).

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REFERENCES

Alexandrowicz SW, Klimek K, Kowalkowski A, Mamakowa K, Niedziałkowska E, Pazdur M, Starkel L. 1981. The evolution of the Wisłoka Valley near Dębica during the Late Glacial and Holocene. *Folia Quaternaria* **53**: 1–91.

Bates PD, Anderson MG, Baird L, Walling DE, Simm D. 1992. Modelling floodplain flows using a two-dimensional finite element model. *Earth Surface Processes and Landforms* **17**: 575–588.

Bluck BJ. 1971. Sedimentation in the meandering River Endrick. *Scottish Journal of Geology* **7**(2): 93–138.

Bogdanowicz E, Stachý J. 1995. Zmiany reżymu wezbraniowego w Polsce. Domysły czy prawda? (Changes in the regime of floods in Poland. True or false?), in Polish, with English summary. *Wiadomości Instytutu Meteorologii i Gospodarki Wodnej* **18**(2): 3–21.

Brookes A. 1987. River channel adjustment downstream from channelization works in England and Wales. *Earth Surface Processes and Landforms* **12**: 337–351.

Gomez B, Eden DN, Peacock DH, Pinkney EJ. 1998. Floodplain construction by recent, rapid vertical accretion: Waipaoa River, New Zealand. *Earth Surface Processes and Landforms* **23**: 405–413.

Kędzior A. 1928. Roboty wodne i melioracyjne w Południowej Małopolsce wykonane z inicjatywy Sejmu i Wydziału Krajowego. Lwów (in Polish).

Klimek K. 1974. The retreat of alluvial river banks in the Wisłoka Valley (South Poland). *Geographia Polonica* **28**: 59–75.

Klimek K. 1979. Geomorfologiczne zróżnicowania koryt karpackich dopływów Wisły (Morphodynamic channel types of the Carpathian tributaries to the Vistula). *Folia Geographia*, *Series Geographia Physica* **12**: 35–47.

Klimek K. 1983. Erozja wgłębna dopływów Wisły na przedpolu Karpat (Vertical erosion of Vistula tributaries on the Carpathian foreland), in Polish, with English summary. In *Ekologiczne podstawy zagospodarowania Wisły i jej dorzecza*, Kajak Z (ed.). PWN: Warszawa-Łódź; 97–108.

Klimek K, Starkel L. 1974. History and actual tendency of flood-plain development at the border of the Polish Carpathians. *Abhandlungen der Akademie der Wissenschaften in Göttingen* **29**: 185–196.

Knox JC. 1987. Historical valley floor sedimentation in the Upper Mississippi Valley. *Annals of the Association of American Geographers* **77**: 224–244.

Lach J. 1975. Ewolucja i typologia krajobrazu Beskidu Niskiego z uwzględnieniem gospodarczej działalności człowieka (Evolution and typology of the landscape in the Low Beskid Mts with special consideration of the economic activity of man), in Polish, with English summary. *Prace Monograficzne Wyższej Szkoły Pedagogicznej w Krakowie* **16**: 5–72.

Lecce SA. 1997. Spatial patterns of historical overbank sedimentation and floodplain evolution, Blue River, Wisconsin. *Geomorphology* **18**: 265–277.

Łajczak A. 1995. Potential rates of the present-day overbank sedimentation in the Vistula valley at the Carpathian foreland, southern Poland. *Quaestiones Geographicae* **17/18**: 41–53.

Łajczak A. 1997. Anthropogenic changes in the suspended load transportation by and sedimentation rates of the River Vistula, Poland. *Geographia Polonica* **68**: 7–30.

Magilligan FJ. 1992. Sedimentology of a fine-grained aggrading floodplain. *Geomorphology* **4**: 393–408.

Nicholas AP, Walling DE. 1995. Modelling contemporary overbank sedimentation on floodplains: some preliminary results. In *River Geomorphology*, Hickin EJ (ed.). Wiley: Chichester; 131–153.

Osuch B. 1968. Problemy wynikające z nadmiernej eksploatacji kruszywa rzecznego na przykładzie rzeki Wisłoki. *Zeszyty Naukowe Akademii Górniczo-Hutniczej* **219**: 283–301.

Punzet J. 1981. Zmiany w przebiegu stanów wody w dorzeczu górnej Wisły na przestrzeni 100 lat (1871–1970) (Changes in the course of water stages in the Upper Vistula River basin over a century 1871–1970), in Polish, with English summary. *Folia Geographia*, *Series Geographia Physica* **14**: 5–28.

Schumm SA. 1969. River metamorphosis. *Journal of the Hydraulic Division of the American Society of Civil Engineers* **95**: 255–273.

Sundborg A. 1967. Some aspects on fluvial sediments and fluvial morphology: I. General views and graphic methods. *Geografiska Annaler* **49A**: 333–343.

Teisseyre AK. 1989. Mady dolin sudeckich. Część III: Subaeralnie i subakwalnie deponowane osady pozakorytowe w świetle eksperymentu terenowego (1977–1979) (Recent overbank deposits of the Sudetic valleys, SW Poland. Part III: Subaerially and subaqueously deposited overbank sediments in the light of field experiment (1977–1979)). *Geologia Sudetica* **23**(2): 1–81.

Trimble SW. 1983. A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853–1977. *American Journal of Science* **283**: 454–474.

Vanoni VA. 1946. Transportation of suspended sediment by water. *Transactions of the American Society of Civil Engineers* **111**: 67–133.

Walling DE, He Q. 1998. The spatial variability of overbank sedimentation on river floodplains. *Geomorphology* **24**: 209–223.

Williams GP. 1978. Bank-full discharge of rivers. *Water Resources Research* **14**: 1141–1154.

Wolman MG, Leopold LB. 1957. River flood plains: some observations on their formation. *US Geological Survey Professional Paper* **282-C**: 87–109.

Wyżga B. 1991. Present-day downcutting of the Raba River channel (Western Carpathians, Poland) and its environmental effects. *Catena* **18**: 551–566.

Wyżga B. 1993a. River response to channel regulation: case study of the Raba River, Carpathians, Poland. *Earth Surface Processes and Landforms* **18**: 541–556.

Wyżga B. 1993b. Present-day changes in the hydrologic regime of the Raba River (Carpathians, Poland) as inferred from facies pattern and channel geometry. In *Alluvial Sedimentation*, Special Publication of the International Association of Sedimentologists: 17, Marzo M, Puigdefábregas C (eds). Blackwell: Oxford; 305–316.

Wyżga B. 1995. Evaluating the occurrence of low magnitude floods: a study of the reliability of the annual maximum series method. *Geografiska Annaler* **77A**: 23–33.

Wyżga B. 1997. Methods for studying the response of flood flows to channel change. *Journal of Hydrology* **198**: 271–288.

Wyżga B. 1999. Estimating mean flow velocity in channel and floodplain areas and its use for explaining the pattern of overbank deposition and floodplain retention. *Geomorphology* **28**: 281–297.