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Hydraulic controls on the entrapment of heavy metal-polluted sediments on a floodplain of variable width, the upper Vistula River, southern Poland

Bartłomiej Wyżga *, Dariusz Ciszewski

Institute of Nature Conservation, Polish Academy of Sciences, al. Mickiewicza 33, 31-120 Kraków, Poland

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A B S T R A C T

Distribution of heavy metal-polluted overbank sediments deposited by a major flood in July 2001 in three gauging sections of different width on the Vistula River, southern Poland, was investigated and related to reconstructed pattern of flow velocity during the event. The mean velocity of the flow over the floodplain was low and showed a marked contrast with mean velocity in the channel zone in the Smolice and the Sierosławice cross-sections, 4.5 and 9 times wider than the respective channel widths. High rates of lateral thinning and fining of overbank deposits were observed. At Sierosławice, the heavy metal concentrations first rapidly increased with distance from the channel, and then remained high over most of the floodplain, At Smolice, concentrations were relatively low within the levee deposits and high over the rest of the floodplain. In both cross-sections the loads of heavy metals were highest close to the channel margins, and decreased exponentially with increasing distance from the channel due to the rapid lateral thinning of the flood deposits. The mean velocity of the flow over the floodplain was high in the Bielany cross-section, only 2.6 times wider than the channel width. Sediments deposited on the narrow floodplain were mostly sand, slowly thinning laterally. While the concentrations of various heavy metals increased gradually with increasing distance from the channel, their loads varied across the floodplain. The highest load of some metals occurred near the channel margin and that of others away from the channel. This study indicates that floodplain width and the resultant flow hydraulics exert a significant influence on the lateral distribution of floodplain sediments and entrapped heavy metals. In wider floodplain sections, the largest amounts of heavy metals accumulate near the channel margin and may be remobilized in the future due to bank erosion.

1. Introduction

Heavy metals have been recognised as principal contaminants in many fluvial systems in the last three decades. A number of studies indicated that as much as 90% of heavy metal loads can be associated with fine-grained sediment, generally 0.2–20 µm in diameter (Förstner and Wittman, 1983). Pathways of heavy metal dispersal in a river catchment are essentially the same as those of suspended sediment, and are largely controlled by physical processes and geomorphic features of the catchment. Apart from the concentration of pollutants and the size of suspended sediment particles, flood flow hydraulics and floodplain topography are considered as the main controls of the conveyance losses of sediment-associated heavy metals passing the river system (Lewin and Macklin, 1987; Walling et al., 2003). Increased awareness of the role of suspended sediment in transporting contaminants as well as of the significance of floodplains as overbank sediment sinks has recently raised interest in spatial dispersion of pollutants within valley floors (Stewart et al., 1998; Lecce and Pavlovsky, 2001; Walling et al., 2003), drawing attention to the earlier studies of sediment dispersal mechanisms (James, 1985; Pizzuto, 1987; Marriott, 1992; Magilligan, 1992a).

During overbank flooding sediments are usually transferred from a channel to the floodplain by diffusion (Pizzuto, 1987). Turbulent eddies develop in the contact zone between the channel and floodplain, (Knight and Shiono, 1996), transferring solid particles as well as momentum from the deeper and faster flow in the channel to the shallower and slower flow over the floodplain. As turbulent mixing and flow velocity decline with distance from the channel, the resultant overbank deposits exhibit an exponential decrease in grain size and thickness in the distal direction (James, 1985; Pizzuto, 1987), reported in many field studies (Marriott, 1992; Guccione, 1993; Marriott, 1996; Middelkoop and Asselman, 1998). Sediment transfer by convection may also occur at locations where the channel is inclined to the direction of flow on the floodplain (James, 1985), and coarser particles falling out from suspension may be transferred across floodplains by tractive movements, making less regular the lateral changes in the thickness and grain size of deposited sediment (Marriott, 1996).

* Corresponding author.
E-mail address: wyzga@iop.krakow.pl (B. Wyżga).

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Some studies indicate that heavy metal concentrations attain their maximum close to the channel and decrease toward floodplain margins (Macklin, 1996; Ciszewski, 2003). Especially large differences (2–3 orders of magnitude) in metal concentrations between a natural levee and the distal floodplain areas typify rivers draining former mining areas. Such differences are related to the rapid deposition close to the channel of high-density, fine ore particles (Marron, 1989, 1992). Overbank sediments, however, displayed no apparent trend in metal concentrations away from the channel for the Derwent, UK. This was explained by the uniform deposition of silty-clayey sediment across the floodplain (Bradley and Cox, 1990). Relatively high concentrations of heavy metals typify sediments stored in floodplain depressions, which are characterised by a high content of silt and clay fractions. In closed depressions, where flood water is ponded, all particles present in the water column settle out (Asselman and Middelkoop, 1995).

The load of heavy metals accumulated on a floodplain is related to the thickness of deposited sediment, usually being the highest along channel margins (Middelkoop, 2000). Floodplain depressions are also characterised by increased sediment accretion rates (Asselman and Middelkoop, 1995; Walling et al., 1996). Their role in storing pollutants has been taken into account in numerical models constructed to predict entrapment of polluted sediments on floodplains (Stewart et al., 1998).

The influence of floodplain width on the dispersal of sediment-associated heavy metals has received limited interest so far. A few studies indicated the role of flood embankments and narrowing of natural valley floors in restricting the zone of overbank sediment accumulation (e.g. Łajczak, 1995) and also in decreasing the storage volume of contaminated sediments (Miller et al., 1999; Walling et al., 2003).

This paper demonstrates patterns of flow velocity in river cross-sections of different width during a single flood event, and relates them to the observed patterns of overbank deposition and heavy metal distribution. This is achieved by considering three cross-sections located in the piedmont reach of the Vistula River, southern.

2. Field setting and the flood of July 2001

The study focuses on the Smolice, Bielany and Sierosławice gauging stations on the upper Vistula River (Fig. 1A). The upper Vistula is among the most heavily metal-polluted rivers in Poland. A high content of zinc in the river water (Buszewski et al., 2005) is accompanied by elevated concentrations of zinc, cadmium and lead in the bottom sediments (Helios-Rybicka, 1986). The content of cadmium in the overbank sediments is among the highest in European rivers, whereas that of lead and zinc is moderate (Macklin and Klimek, 1992). The considerable contamination of the 20th-century channel and overbank sediments of the river is related to a manifold increase in lead and zinc production and discharging waters from non-ferrous ore mines located in the catchments of left-side tributaries of the upper Vistula (Macklin and Klimek, 1992; Ciszewski, 1997, 1998). Pollution in the river rose substantially during and after the World War II accompanying the rapid industrialization and urbanization in the Upper Silesia Mining District and the growth of the town of Cracow (Helios-Rybicka, 1996).

The three investigated cross-sections are located in a 107 km long but hydrologically homogeneous reach of the upper Vistula between its two Carpathian tributaries, the Skawa and the Raba (Fig. 1A). In the reach, the Vistula flows parallel to the Carpathians through an elongated depression, which is a morphological expression of the Carpathian Foredeep. Suspended sediment is mostly delivered to the upper Vistula by its Carpathian tributaries, and thus, the river reach between Smolice and Sierosławice is characterised by net deposition of the suspended load (Łajczak, 2003). With a 12% increase in drainage

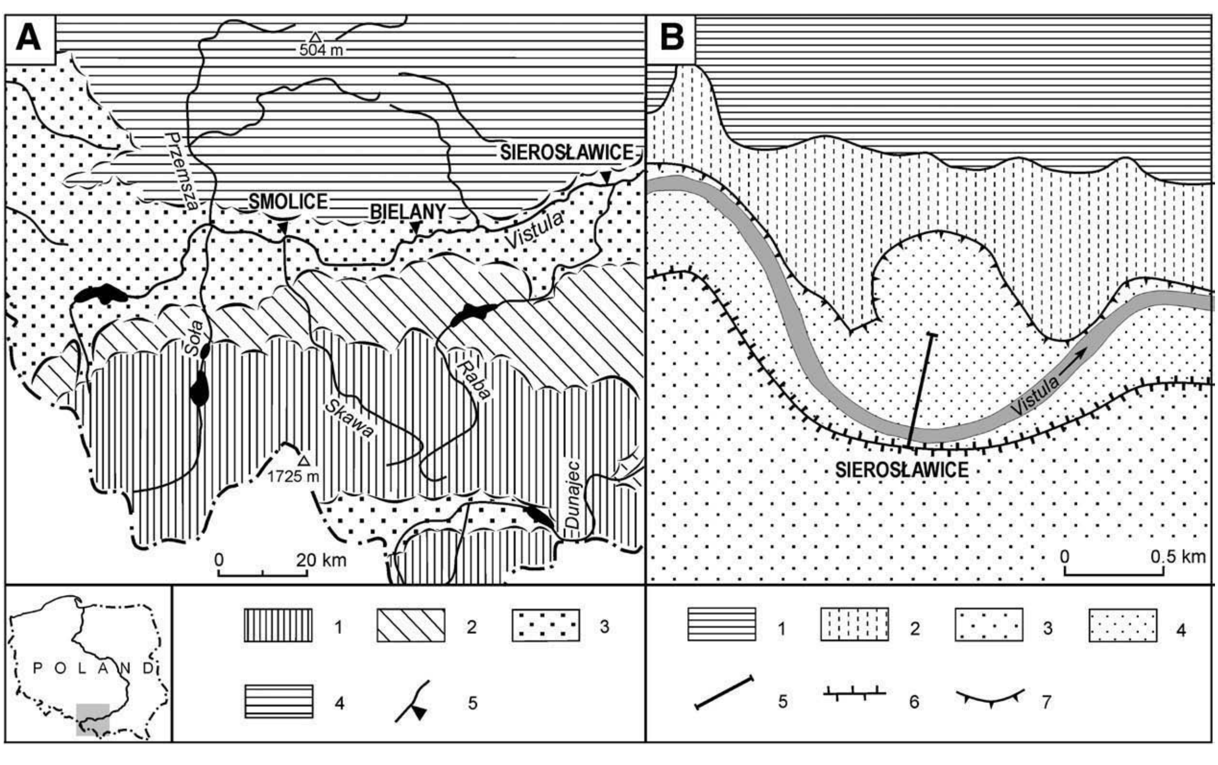

Fig. 1. (A) Location of the Smolice, Bielany and Sierosławice water-gauge stations in relation to physiogeographic regions of the upper Vistula River drainage basin. 1 — mountains of intermediate and low height; 2 — foothills; 3 — submontane and intramontane depressions; 4 — uplands; 5 — water-gauge stations. (B) Details of the location of the Sierosławice gauging section. 1 — upland; 2 — Pleistocene terrace; 3 — the Vistula valley floor outside the flood embankment; 4 — contemporary floodplain; 5 — active gauge cross-section; 6 — flood embankment; 7 — terrace riser.

area between Smolice and Bielany, mean annual flood has the same value at both stations. Between Bielany and Sierosławice, the drainage area increases by 18%, with an accompanying increase in mean annual flood by 9% (Table 1).

Despite the similarity in hydrological characteristics of the river at the investigated stations, the cross-sections differ markedly with respect to their morphology. At the beginning of the twentieth century, flood protection dikes were constructed along the reach, considerably narrowing an active floodplain of the river (Łajczak, 1995). At Smolice, their spacing was 4.5 times broader than the present-day bankfull width of the river. Repeated channelization works carried out at the end of the 1980s resulted in the formation of a channel with relatively high conveyance (Table 1) and of a floodplain with a smooth surface that sloped toward the channel and almost lacked natural levees (Fig. 2A). In the vicinity of Smolice, the Vistula now flows in gentle bends (sinuosity 1.10) across two-thirds of the inter-dike width, forming a typical quasi-natural compound channel (see Sellin and Willetts, 1996).

At Bielany, the span between flood protection dikes is similar to that at Smolice. This cross-section is located immediately upstream of the town of Cracow and channelization works carried out in the river reach within the town have resulted in about 2.5 m of channel incision since the beginning of the twentieth century (Łajczak, 1995). As a result, the floodplain, which was active before channel incision, has been transformed into a terrace, and a new floodplain developed over parts of the former channel bed. The extent of this new floodplain is 2.6 times greater than the bankfull width of the river (Fig. 3A). In the vicinity of Bielany, the Vistula exhibits a nearly straight course (sinuosity 1.03), and with the floodplain margin and the dikes running parallel to the channel, water on the floodplain flows parallel to river banks in a manner typical of quasi-straight compound channels (see Sellin and Willetts, 1996).

At Sierosławice, the river floodplain is constricted by a Pleistocene terrace on its left side and by a flood protection dike on the right (Fig. 1B). Flowing across almost the whole width of its artificially confined floodplain in moderately curved bends (sinuosity 1.19), the Vistula forms a typical quasi-natural compound channel (see Sellin and Willetts, 1996) in the vicinity of the station. Adjacent to the gauge cross-section there is a floodplain "embayment" eroded into the Pleistocene terrace (Fig. 1B), in which a large anticlockwise vortex forms under flood conditions. This part of the floodplain represents a dead flow zone, whereas the extent of the active floodplain is 9 times greater than the bankfull width of the river (Fig. 4A). The floodplain surface is irregular, with the lowest level occurring next to the channel, at the place of a silted inter-groyne basin that was formed in the course of channelization works in the first half of the 20th century (Łajczak, 1995).

Floods on the upper Vistula typically occur during the summer. The first two decades of July 2001 were moderately rainy in southern Poland. With soil retention in the region exhausted by the preceding precipitation, heavy rain that fell in the third decade of the month caused a flood in the upper Vistula catchment (Sasim and Mierkiewicz, 2002). A characteristic feature of this flood was the high run-off from both sides of the catchment, reflecting similar monthly totals of precipitation (200–300 mm) in the Polish Carpathians to the south and the Mid-Polish Uplands to the north.

Recurrence intervals of the peak discharges of the July 2001 flood at the investigated gauging stations have been evaluated using data from the record period of 1951–2001. At Smolice, the flood had a maximum discharge of 1650 $m^3 s^{-1}$ with a recurrence interval of 17 years, and the floodplain was inundated for 6.5 days. The peak flow of 1740 $m^3 s^{-1}$ attained at Bielany had a recurrence interval of 15.5 years, and the bankfull stage was exceeded for 14 days. At Sierosławice, the Vistula peaked at a discharge of 1840 $m^3 s^{-1}$, which has an 18-year recurrence interval, and the river overtopped its banks for 15.5 days.

Table 1
Hydrological and morphological characteristics of the Vistula River at the Smolice, Bielany and Sierosławice stations and the river length between the stations.

Gauging station	Smolice		Bielany		Sierosławice
River length between stations (km)		45.6		61.3	
Drainage area (km^2)	6796		7634		8999
Mean annual discharge (1951–2001) ($m^3 s^{-1}$)	80.9		87.5		99.2
Mean annual flood (1951–2001) ($m^3 s^{-1}$)	620		620		675
Channel slope	0.00016		0.00013		0.00025
Floodplain slope	0.00018		0.000135		0.00030
Bankfull width (m)	82.8		64.2		64.8
Bankfull discharge ($m^3 s^{-1}$)	397		196		242

3. Study methods

Unlike laboratory channels, the hydraulics of flood flows on rivers are difficult to measure prior to linking them with the pattern of floodplain sedimentation. Velocity measurements on rivers flowing overbank are rare, and limited mostly to individual cross-sections under bridges, the geometry of which may deviate significantly from that of natural cross-sections. Recently, two-dimensional finite element and finite difference techniques have been proposed to model the spatial pattern of floodplain flows (Bates et al., 1992) and overbank sedimentation on floodplains (Nicholas and Walling, 1995). However, the techniques require a detailed knowledge of the surface morphology before a flood and their usefulness seems limited to small well documented floodplains. In this paper we use a method which enables the mean velocity of flow in the channel and floodplain zones to be estimated for a given total discharge taken from a stage–discharge curve (Wyżga, 1999). This method uses the information concerning discharges carried in the total cross-section which is contained in the rating curve. Importantly, it also accounts for lateral transfer of momentum between the channel and floodplain zones by which flow is accelerated over the floodplain and decelerated in the channel zone (cf. Knight and Shiono, 1996). Out-of-bank channel flows are estimated under the assumption that the interface planes between the channel zone and the floodplain are included in the wetted perimeter for the channel subarea, and thus the relationship between velocity and discharge, characteristic of the uppermost in-bank flows, is extrapolated for out-of-bank flows conveyed in the channel zone. The floodplain flows are then calculated as residual values, after subtracting the flow in the channel zone from the total discharge (Wyżga, 1999). The method has been successfully applied earlier to explain spatial (Wyżga, 1999) and temporal differences (Wyżga, 2001; Lach and Wyżga, 2002; Wyżga, 2008) in the hydraulic and depositional conditions in the rivers of southern Poland.

After the flood of July 2001 had receded, field observations were undertaken in the three cross-sections. Synthetic turf traps are frequently used to determine the amount of flood-related metal deposition at predetermined locations (e.g. Asselman and Middelkoop, 1995; Walling et al., 2003; Baborowski et al., 2007). In the present study, sediment samples were collected from a natural, grassy floodplain surface. Overbank deposits of the flood could be easily differentiated from the soil as they were typically deposited on a film of old leaves or living grass and herbaceous plants covering the ground. This enabled selection of sampling sites that optimised representation of the lateral variation in thickness and grain size of the flood deposits for particular cross-sections. Moreover, this technique avoided deploying traps, which could be destroyed by human or animal activities. Finally, it also precluded the necessity of monitoring the weather and water conditions to install sediment traps immediately before a flood. In each cross-section, the thickness of the flood deposits was determined, and sediment samples were collected at 12

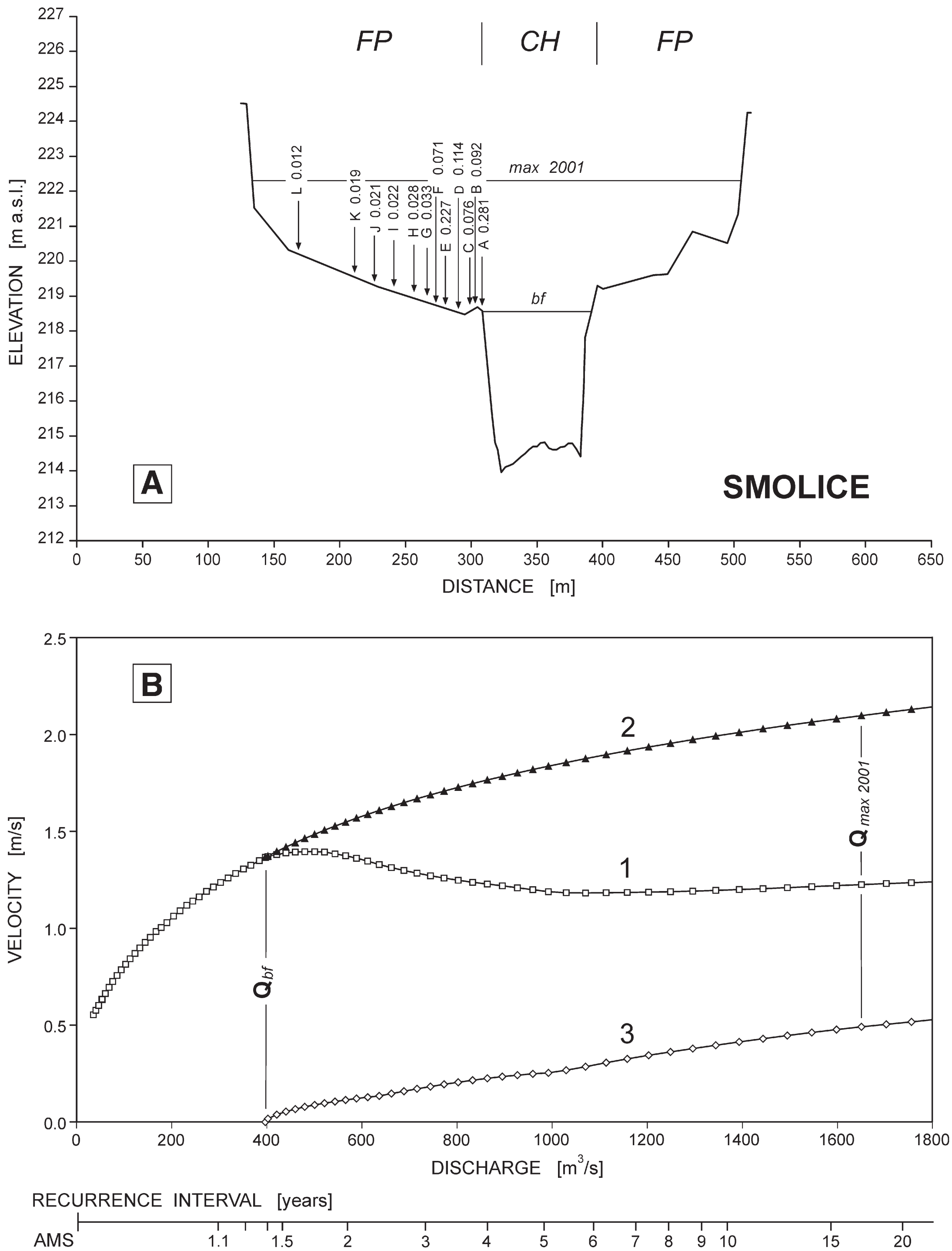

Fig. 2. (A) Pre-flood morphology of the Vistula River cross-section at the Smolice gauging station. Arrows indicate location of sediment samples, and numbers following sample symbols refer to mean grain size of the sediments in millimetres. Morphological zones of the cross-sections shown in Figs. 2A, 3A and 4A: *CH* — channel; *FP* — floodplain; *TR* — terrace. (B) 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 Smolice gauging station during the flood of July 2001. Q_{bf} denotes bankfull discharge. Points in Figs. 2B, 3B and 4B represent conditions for stage changing at 10 cm intervals, and discharges are referred to their recurrence interval determined by the annual maximum series method from the years 1951–2001. An interpretation of the rating curve was continued beyond the flood peak to recognise the pattern of flow velocities for the flows of at least 20-year recurrence.

sites across one side of the floodplain. All samples were taken throughout the whole thickness of the flood deposits. A part of each sample was used for grain size determination and another for chemical analyses. The grain size distributions were determined by sieving or hydrometer analyses.

Each sample was dried, thoroughly mixed, and sieved through a 1 mm sieve. With the total amount of each sample passing through the sieve, proportions of heavy metals were unaffected by this normalising procedure. Subsequently, 0.5 g of the obtained material was digested with concentrated nitric acid in Teflon bombs. Cadmium, copper, lead, manganese and zinc concentrations were determined using atomic absorption spectrometry. Bulk density of the analysed sediments was obtained by squeezing each sample to a constant volume in polypropylene cylinders. Their density ranged from 1.2 g cm^{-3} in the case of silty–clayey sediment to 1.6 g cm^{-3} for sand, and was similar to the values obtained in a similar study performed on the Rhine River

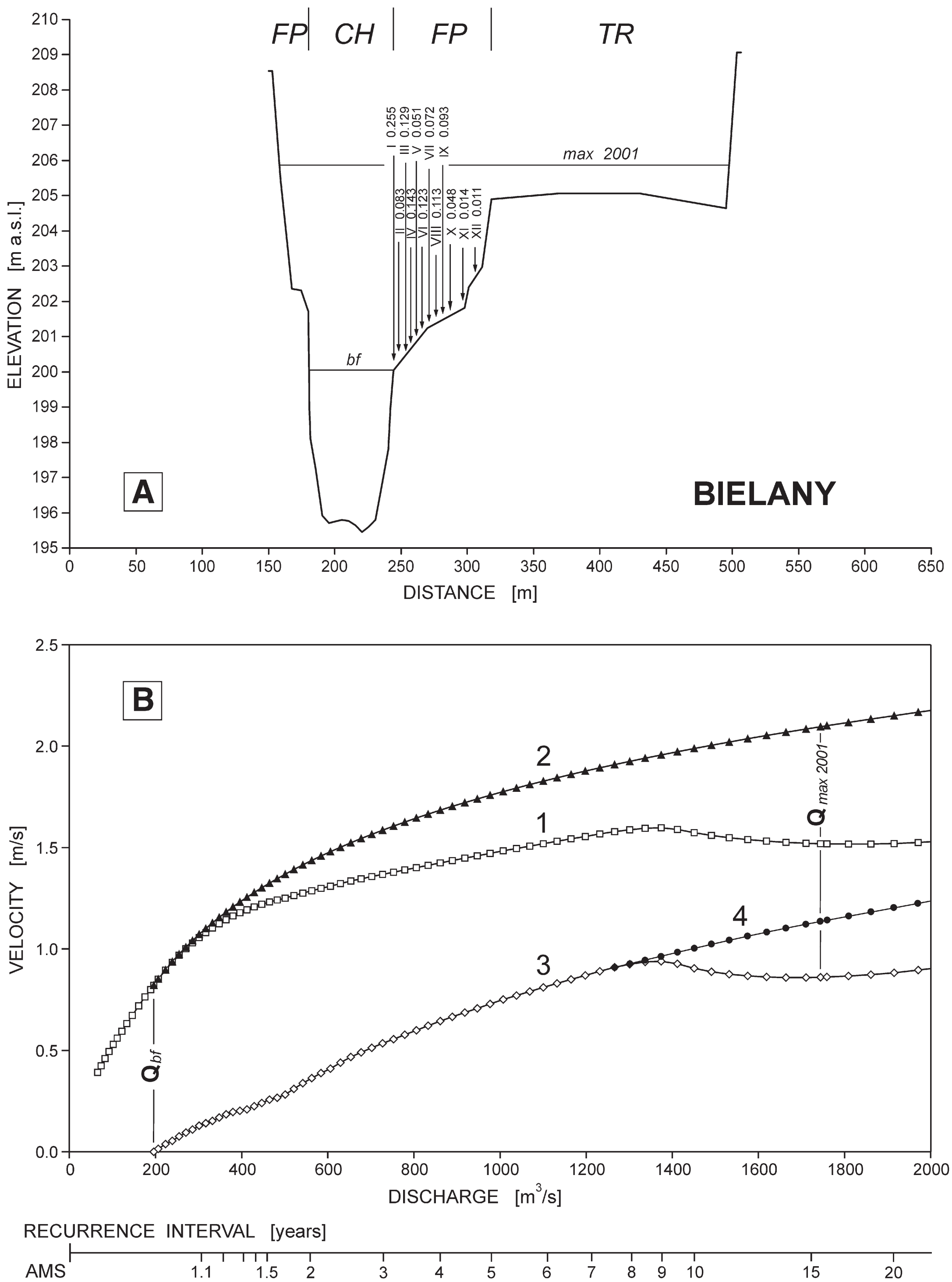

Fig. 3. (A) Pre-flood morphology of the Vistula River cross-section at the Bielany gauging station. (B) Relationship between the mean flow velocity in total cross-section (1), in channel zone (2) and in extra-channel zone (3) of the cross-section, and discharge for the Bielany gauging station during the flood of July 2001. Signature (4) depicts velocities over the floodplain itself after the start of inundation of the terrace.

floodplain (see Middelkoop, 2000). Finally, metal loads, i.e. the amounts of particular elements deposited on unit floodplain area, were calculated from known concentrations, sediment densities, and the thickness of deposition during the 2001 flood at particular sites.

4. Flow velocity in the investigated cross-sections

Reconstructed flow velocities are given for the stage–discharge curves valid for the rising phase of the July 2001 flood. At Smolice, the right bank is located about 0.7 m higher than the left one (Fig. 2A). Mean flow velocity in the cross-section (Fig. 2B) increased from about 0.55 m s^{-1} at the lowest flow to 1.37 m s^{-1} at bankfull discharge, and to 1.40 m s^{-1} when water started to inundate the right-hand floodplain at a discharge of 480 m^3 s^{-1}. Then, velocity decreased progressively to a minimum of 1.18 m s^{-1}, attained when water reached the toes of the dikes at a discharge of 1070 m^3 s^{-1}, subsequently increasing slowly to 1.23 m s^{-1} at the peak discharge of the July 2001 flood.

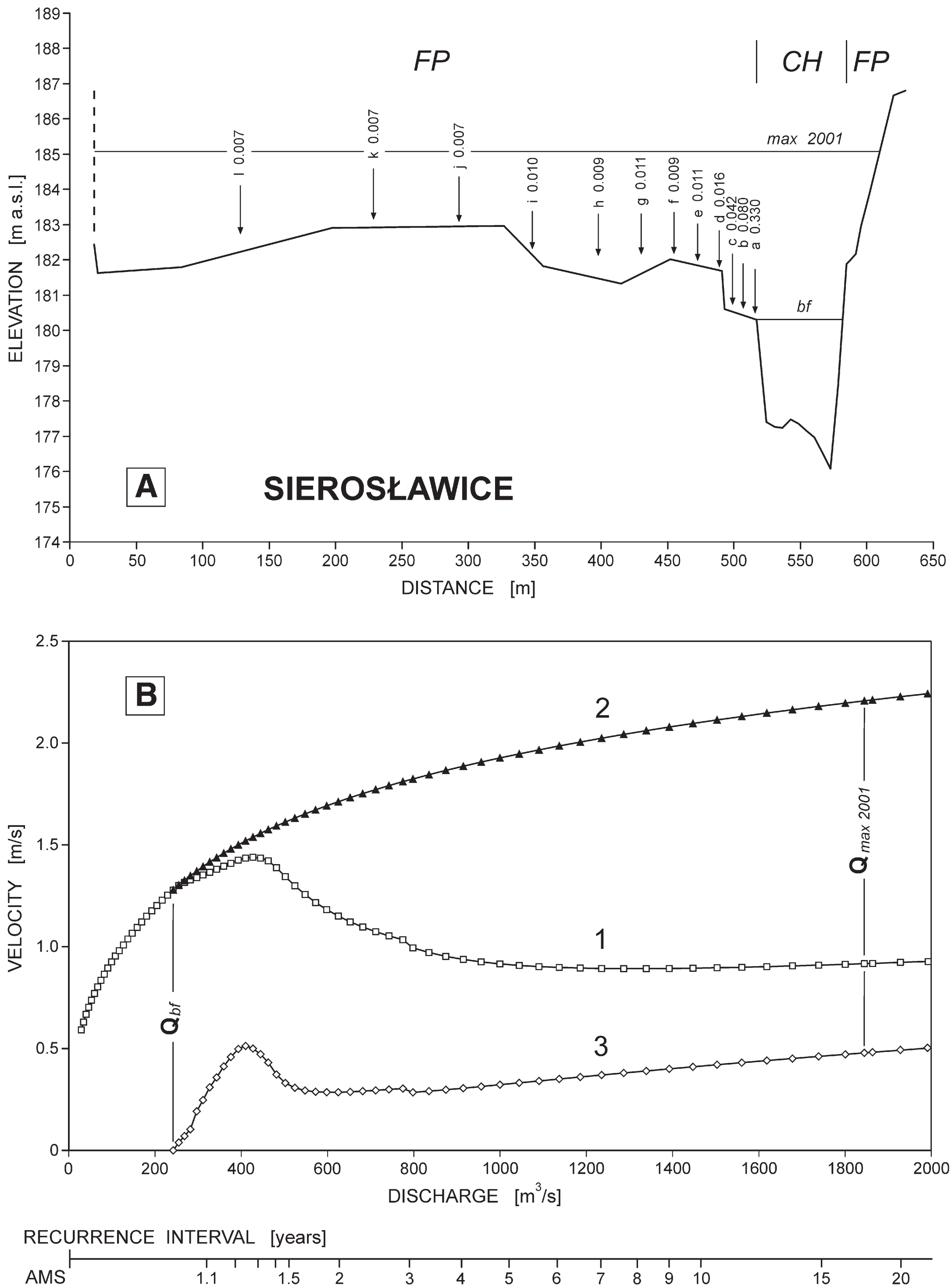

Fig. 4. (A) Pre-flood morphology of the Vistula River cross-section at the Sierosławice gauging station. (B) Relationship between the mean flow velocity in total cross-section (1), in channel zone (2) and in floodplain zone (3) of the cross-section, and discharge for the Sierosławice gauging station during the flood of July 2001.

Mean velocity in the channel zone (Fig. 2B) attained 1.46 m s^{-1} when water reached the right bank top, 1.88 m s^{-1} when the entire inter-dike zone became inundated, and 2.10 m s^{-1} at the maximum discharge of the flood. Mean velocity on the floodplain (Fig. 2B) increased slowly with increasing out-of-bank discharges, and attained 0.49 m s^{-1} at the flood peak. However, the rate of increase in velocity of the flow over the floodplain varied being slower when water spread onto the two levels of the right-hand floodplain and faster when linked with the constrained conditions of the floodplain inundation.

At Bielany, the extra-channel zone consists of the narrow floodplain and the wider terrace (Fig. 3A). Mean flow velocity (Fig. 3B) increased here from about 0.4 m s^{-1} at the lowest discharges to 0.82 m s^{-1} at bankfull stage. It further increased to 1.24 m s^{-1} reached when the flow on the floodplain reached the terrace slope at a discharge of 482 m^3 s^{-1}, and to a maximum value of 1.60 m s^{-1} attained shortly after water started to inundate the terrace. Subsequently, with water covering the terrace, velocity fell gradually to 1.52 m s^{-1} at the maximum discharge of the July 2001 flood.

Mean velocity in the channel zone (Fig. 3B) attained 1.35 m s^{-1} when water reached the slope of the terrace, 1.89 m s^{-1} at the onset of inundation of the terrace, and 2.10 m s^{-1} at the flood peak. At the same time, mean velocity on the floodplain (Fig. 3B) increased quite rapidly to 0.89 m s^{-1} attained at the beginning of the terrace inundation, and to 1.14 m s^{-1} at the peak discharge of the flood. This rate apparently increased after the whole width of the floodplain became inundated. Mean velocity in the whole extra-channel zone attained a maximum value of 0.94 m s^{-1} shortly after the onset of the terrace inundation, but subsequently, with an increasing proportion of the water transferred over the terrace, it decreased gradually to 0.86 m s^{-1} at the maximum discharge of the flood.

At Sierosławice, mean flow velocity (Fig. 4B) increased rapidly from 0.6 m s^{-1} at the lowest flow to 1.28 m s^{-1} at bankfull discharge, and then increased at a slower rate, attaining a maximum of 1.44 m s^{-1} shortly after water started to cover higher levels of the floodplain. Afterwards, it decreased progressively to a minimum of 0.89 m s^{-1} attained when the highest level of the floodplain became submerged to a depth of 1.2 m at a discharge of 1340 m^3 s^{-1}. It finally reached 0.92 m s^{-1} at the maximum discharge of the flood.

Mean velocity in the channel zone (Fig. 4B) reached 1.82 m s^{-1} at a discharge of 798 m^3 s^{-1} inundating the whole width of the floodplain, and 2.21 m s^{-1} at the flood peak. Initially, with overbank flow conveyed only over the lowest level of the floodplain, mean velocity in the floodplain zone (Fig. 4B) increased rapidly, attaining a maximum of 0.51 m s^{-1} when water started to inundate the higher floodplain levels. Subsequently, with water spreading across the floodplain, it dropped to 0.29 m s^{-1}, and remained nearly the same until the inundation of the highest level of the floodplain. Since then, it increased slowly to 0.48 m s^{-1} at the peak discharge of the flood.

As shown above, morphological differences between the investigated cross-sections were reflected in dissimilar patterns of flood flow velocities. In the wide Smolice and Sierosławice cross-sections (Figs. 2A, 4A), the mean velocity of the floodplain flow was relatively low, when considered in absolute values (Figs. 2B, 4B) and also when compared with the mean flow in the channel zone (Table 2). In contrast, in the Bielany cross-section with the narrow floodplain (Fig. 3A), the mean velocity of the floodplain flow was relatively high, both in absolute values (Fig. 3B) and compared to the mean flow in the channel zone (Table 2).

Flood flow velocity patterns were reconstructed taking into account lateral transfer of momentum from a faster flow in a channel zone to the slower flow on the floodplain (Wyżga, 1999). Using hydraulic formulae such as the Manning equation, flows (and their velocities) in channel and floodplain areas can also be calculated under the assumption that no interaction between them would occur. It is interesting to compare the results obtained by the two methods for the investigated river cross-sections in order to show the modification to the pattern of mean velocities in channel and floodplain zones resulting from the momentum exchange between the flows. Such a comparison is presented for the Bielany cross-section with the narrowest floodplain and for the Sierosławice cross-section with the widest floodplain (Fig. 5). The Bielany cross-section exhibited considerable retardation of the channel flow and acceleration of the extra-channel flow. Apparently, constricting the flow on the narrow floodplain enabled efficient transfer of momentum between the channel and floodplain flows. At Sierosławice, where a large proportion of the floodplain flow was conveyed far away from the channel, lateral transfer of momentum had relatively little effect on the mean velocities in both zones of the cross-section. Here, only the flow conveyed on the lowest floodplain level was significantly accelerated due to the lateral transfer of momentum from the adjacent channel flow.

Table 2
Mean velocity in the floodplain area as a percentage of mean velocity in the channel zone at the Smolice, Bielany and Sierosławice gauging stations.

	Smolice	Bielany	Sierosławice
Q_5	13.8	41.5	16.8
Q_{10}	20.1	45.5	19.6
Q_{15}	22.7	41.2	21.1
Q_{20}	24.1	41.0	22.0

Q_x denotes discharge of given recurrence interval.

5. Depositional patterns resulting from the flood of July 2001

The considerable differences identified between the gauging sections with regard to the velocity of floodplain flow (Figs. 2B, 3B, 4B) and to the varying relationship between mean flow velocity in the channel and on the floodplain (Table 2) suggest that these differences are reflected in distinct depositional patterns resulting from the flood of July 2001. Field observations were undertaken in these cross-sections a few days after the event in order to examine this suggestion.

The lateral distribution of grain size and thickness of the flood deposits is presented in diagrams in which the width of the sampled floodplain in each cross-section is normalised by stretching it across the whole width of the diagram (Fig. 6). The flood deposits at Smolice exhibited considerable differences in grain size and thickness across the floodplain (Figs. 2A and 6). Next to the river bank a zone of levee deposition, about 35 m wide, occurred. The levee deposits (samples A–F) were 7–17 cm thick, and mostly consisted of fine to very fine sands. Medium-grained sands occurred only immediately adjacent to the channel margin. The levee sediments showed cross-lamination indicative of the transport in traction before their final deposition. Laterally, the sediments terminated sharply at low avalanche slopes. Outside the levee, the flood deposits progressively thinned laterally from about 4 cm at the location of sample G to less than 0.5 cm near sample L. Muds occurred in the middle part of the floodplain (samples G to K), giving way to clayey muds 140 m from the channel margin (sample L).

At Bielany, lateral variation in the thickness and grain size of the flood deposits was much less pronounced (Figs. 3A, 6). The deposits thinned at a slow rate, from 15 cm on the bank top to 3 cm in the distal position. This general trend, however, was accompanied by the fluctuations of sediment thickness from site to site. The sediments deposited across most of the floodplain width were sands, medium-grained on the bank top (sample I), while fine to very fine farther away from the channel margin (samples II–IV and VI–IX). Muds, however, occurred at distances of 17 m and 42 m from the channel (samples V and X), whereas clayey muds were deposited close to the slope of the terrace (samples XI and XII). On the terrace surface, which was also inundated during passage of the flood crest (Fig. 3A), only a film of sediment on grass blades could be observed.

At Sierosławice, an exponential decrease in thickness and grain size of the flood deposits with increasing distance from the channel was most evident (Figs. 4A, 6). The sediment thickness first diminished rapidly from 20 cm on the bank top (sample a) to 4 cm at the location of sample c and then at a slower rate to merely 2 mm near sample l. Close to the channel margin the sediments fined rapidly from medium-grained sands on the bank top to silts at the distal end of the lowest floodplain level (sample c). Farther away from the channel muds and clayey muds occurred (samples d–i), giving way to silty clays in the distal half of the floodplain width (samples j–l).

The observed depositional patterns accord with the reconstructed patterns of flow velocity in the investigated gauging sections. In the wide Smolice and Sierosławice cross-sections, a marked contrast in mean velocity between the channel and floodplain flows must have led to a strong velocity gradient across the floodplain width. This resulted in rapid deposition of the majority of the sediment carried in suspension into the floodplain area near to the channel margin, and in the remarkable differences in thickness and grain size between the proximal and distal overbank deposits. In contrast, the difference in velocity of flow between the channel and the floodplain was much less pronounced at Bielany, and hence no suitable conditions occurred for

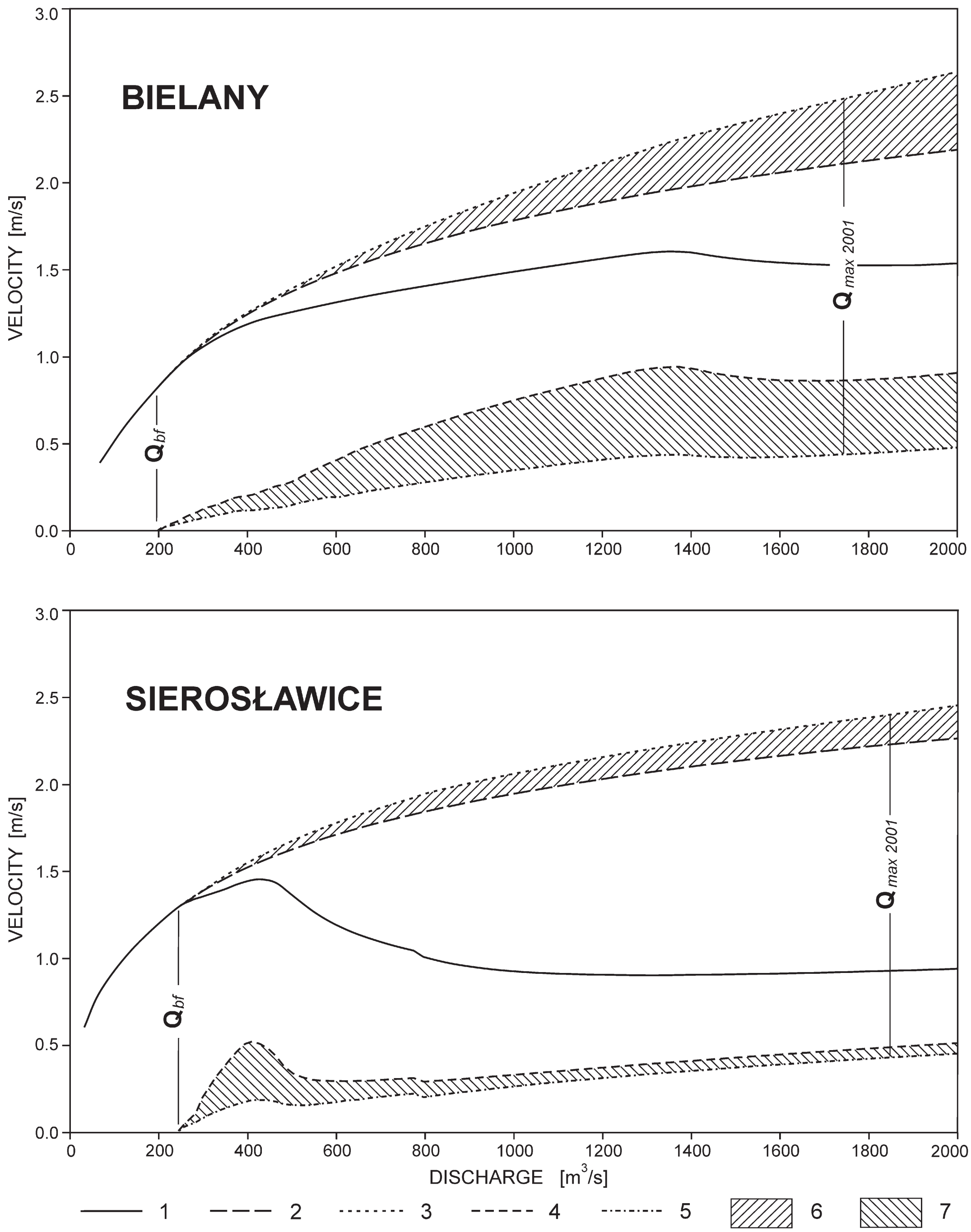

Fig. 5. Estimated changes in flow velocity of the channel and extra-channel flows during the flood of July 2001 in the Bielany and Sierosławice cross-sections resulting from lateral transfer of momentum. 1 — mean flow velocity in total cross-section; 2 — mean flow velocity in channel zone estimated with allowance for the lateral transfer of momentum; 3 — mean flow velocity in channel zone calculated from the Manning equation; 4 — mean flow velocity in extra-channel zone estimated with allowance for the lateral transfer of momentum; 5 — mean flow velocity in extra-channel zone calculated from the Manning equation; 6 — slowing-down of channel flow resulting from the interaction with extra-channel flow; 7 — acceleration of extra-channel flow resulting from the interaction with channel flow. Q_{bf} denotes bankfull discharge.

rapid deposition of suspended sediment close to the channel margin and for levee formation. With a weaker velocity gradient across the floodplain width, the depositional conditions on the floodplain were less variable laterally, resulting in the smaller contrasts in thickness and grain size between the proximal and distal overbank deposits.

6. Patterns of heavy metal accumulation on the Vistula floodplain during the flood of July 2001

Patterns of the accumulation of heavy metals in the overbank deposits of the July 2001 flood varied considerably among the investigated cross-sections (Figs. 7–9). In the Smolice cross-section of intermediate width, concentrations of heavy metals in the levee deposits, within a distance of 30 m from the channel, were relatively low. Immediately outside the zone of levee deposition, metal concentrations rapidly increased laterally, but they remained at a constant, relatively high level beyond 50–60 m from the channel margin (Fig. 7). However, the variability of metal concentrations across the floodplain width exhibited some differences between individual elements. Manganese concentrations varied by about nine times, lead concentrations by six times, the copper ones by four times, while those of zinc and cadmium by only three. The lowest

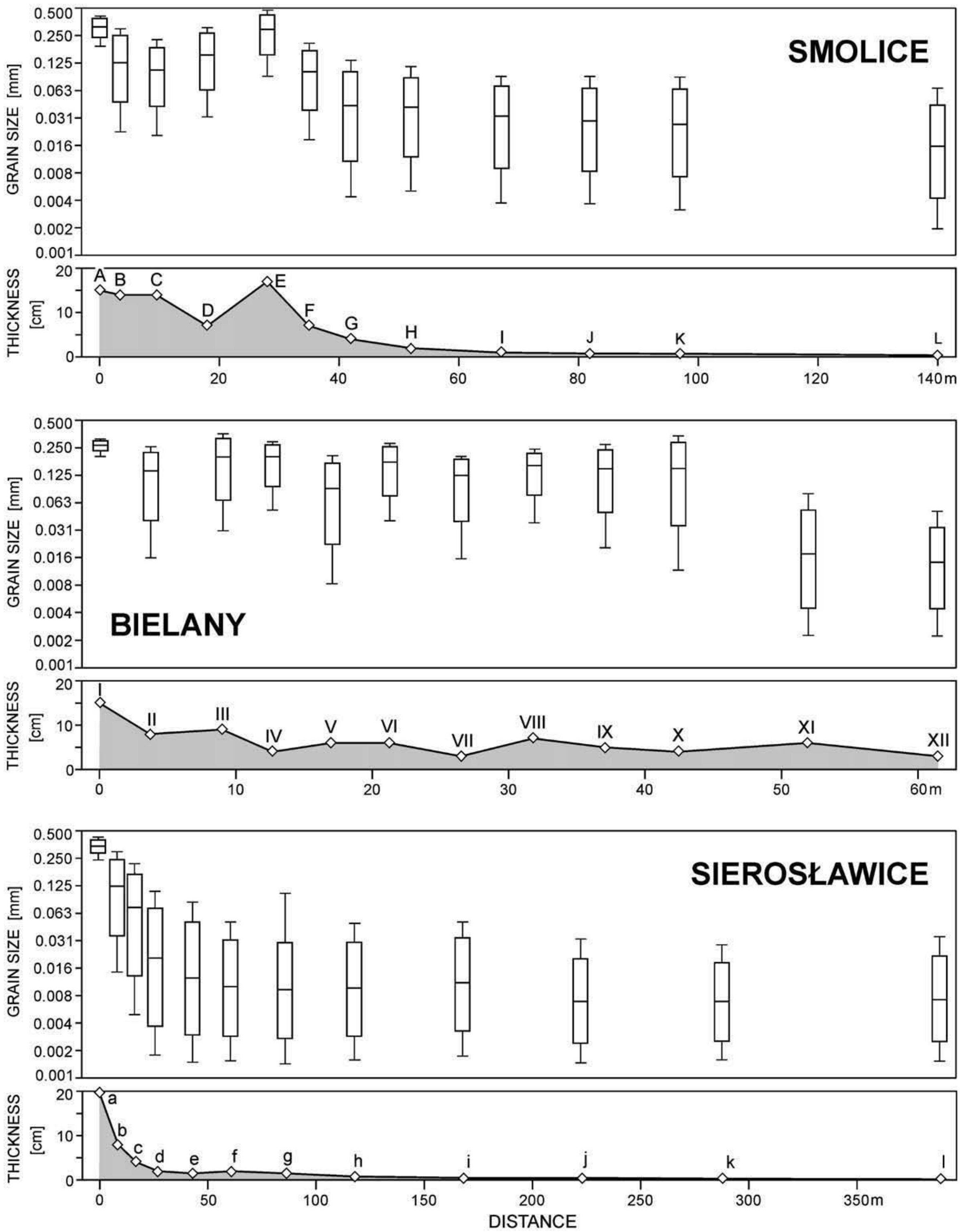

Fig. 6. Grain size distribution and thickness of overbank sediments deposited by the July 2001 flood on one-side floodplain of the Smolice, Bielany and Sierosławice cross-sections. Box and whisker plots show median (internal horizontal line), quartiles (ends of box) and 16th and 84th percentiles (whiskers) of the grain size distribution of each sample.

concentrations of Mn, Pb and Cu typified the coarsest overbank sediments deposited on the bank top, with a secondary minimum occurring at site E, where the sediments were also relatively coarse. The concentrations of Cd attained a minimum at site E, from which they increased considerably in both proximal and distal direction (Fig. 7).

Loads of the heavy metals accumulated in the flood deposits at Smolice mostly followed the lateral changes in sediment thickness, decreasing markedly with increased distance from the channel (Fig. 7). The highest loads of all the investigated elements were recorded within the levee deposits, either on the bank top or at a short distance from the channel margin. The high dependence of metal loads on the thickness of the flood deposits is emphasized by a fairly low deposition of the contaminants at site D, where the levee deposits were relatively thin. The loads of Mn, Zn, Cu and Pb varied by 24–32 times across the floodplain width. The variation in the loads of Cd was even greater, with their 50-fold decrease between the bank top and the most distal site L (Fig. 7).

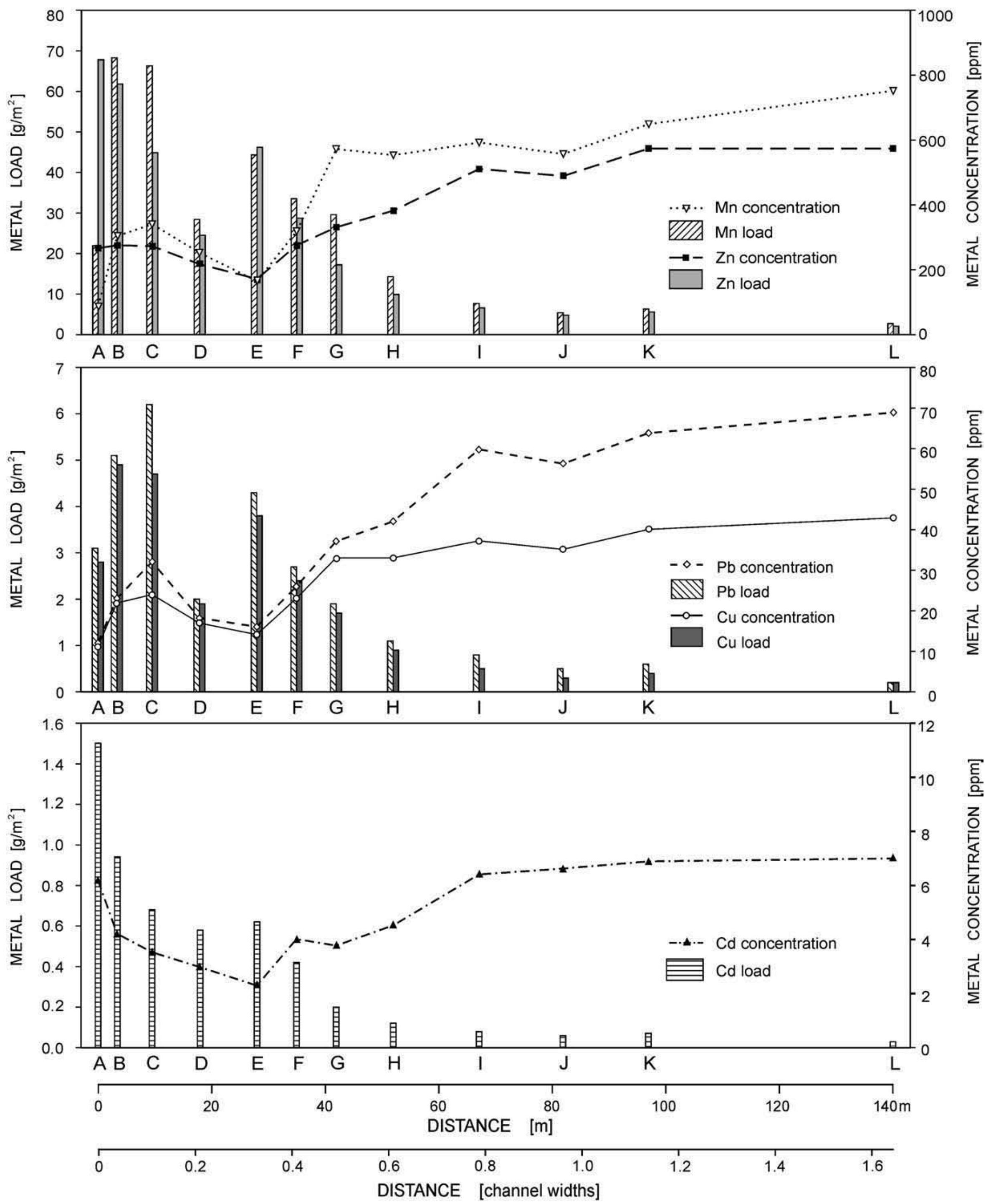

Fig. 7. Load and concentration of Cd, Cu, Pb, Zn and Mn in the overbank sediments deposited by the July 2001 flood on one-side floodplain of the Smolice cross-section. Distance from the Vistula channel is shown both in absolute and relative (scaled by channel width) values.

On the narrow floodplain at Bielany, metal concentrations in the flood deposits increased slowly with growing distance from the channel, and this general trend was associated with considerable fluctuations of the concentrations from site to site. In the distal part of the floodplain, the rising trend of manganese, lead and copper concentrations intensified (Fig. 8). The variation in metal concentrations on the floodplain was similar to that at Smolice, with manganese concentrations varying by eight times, lead concentrations by six, copper by four, and those of zinc and cadmium only twice. However, unlike the metal distribution pattern at Smolice, here the concentrations of all the investigated elements exhibited similar trends across the floodplain (Fig. 8).

Loads of the heavy metals deposited by the flood of July 2001 at Bielany fluctuated across the floodplain and no consistent pattern of their distribution was apparent (Fig. 8). The highest loads of zinc and cadmium occurred close to the channel margin, while those of the three other elements were recorded far from the channel. The lowest amounts of heavy metals were deposited at site IV (Zn and Pb) or VII (Mn, Cu and Cd), where the thickness of the flood deposits was relatively low. The variation of metal loads on the floodplain was

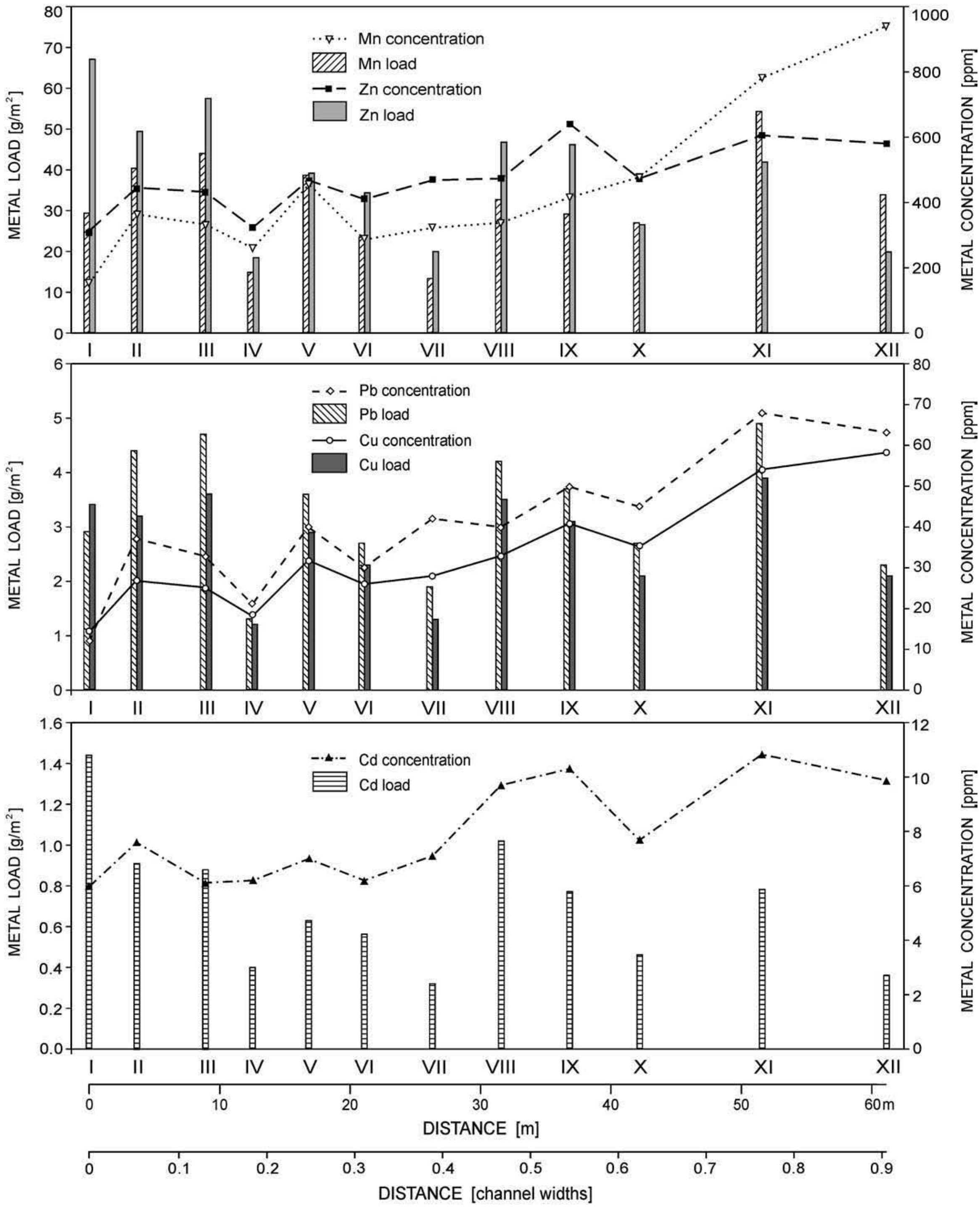

Fig. 8. Load and concentration of Cd, Cu, Pb, Zn and Mn in the overbank sediments deposited by the July 2001 flood on one-side floodplain of the Bielany cross-section. Distance from the Vistula channel is shown both in absolute and relative (scaled by channel width) values.

substantially lower than at Smolice, ranging from 3 times in the case of copper to 4.5 times for cadmium (Fig. 8).

At Sierosławice, in the widest investigated cross-section, concentrations of heavy metals in the flood deposits first rapidly increased with increasing distance from the channel. The concentrations then remained high over most of the floodplain width (Fig. 9). The rapid increase in metal concentrations took place within a distance of 60 m from the channel margin, corresponding with the zone of rapid lateral fining of the flood deposits. The metal concentrations varied to a greater extent than in the two other cross-sections, with the extreme concentrations of lead differing by nine times, those of manganese, copper and cadmium by seven and of zinc by five (Fig. 9).

Loads of heavy metals were highest close to the channel margin, and decreased exponentially with increased distance from it due to the rapid lateral thinning of the flood deposits (Fig. 9). Similar to the metal distribution at Smolice, the Sierosławice cross-section was typified by high variation of the metal loads across the floodplain. The extreme metal loads differed by 20–38 times, with cadmium exhibiting the lowest variation and copper the highest one (Fig. 9).

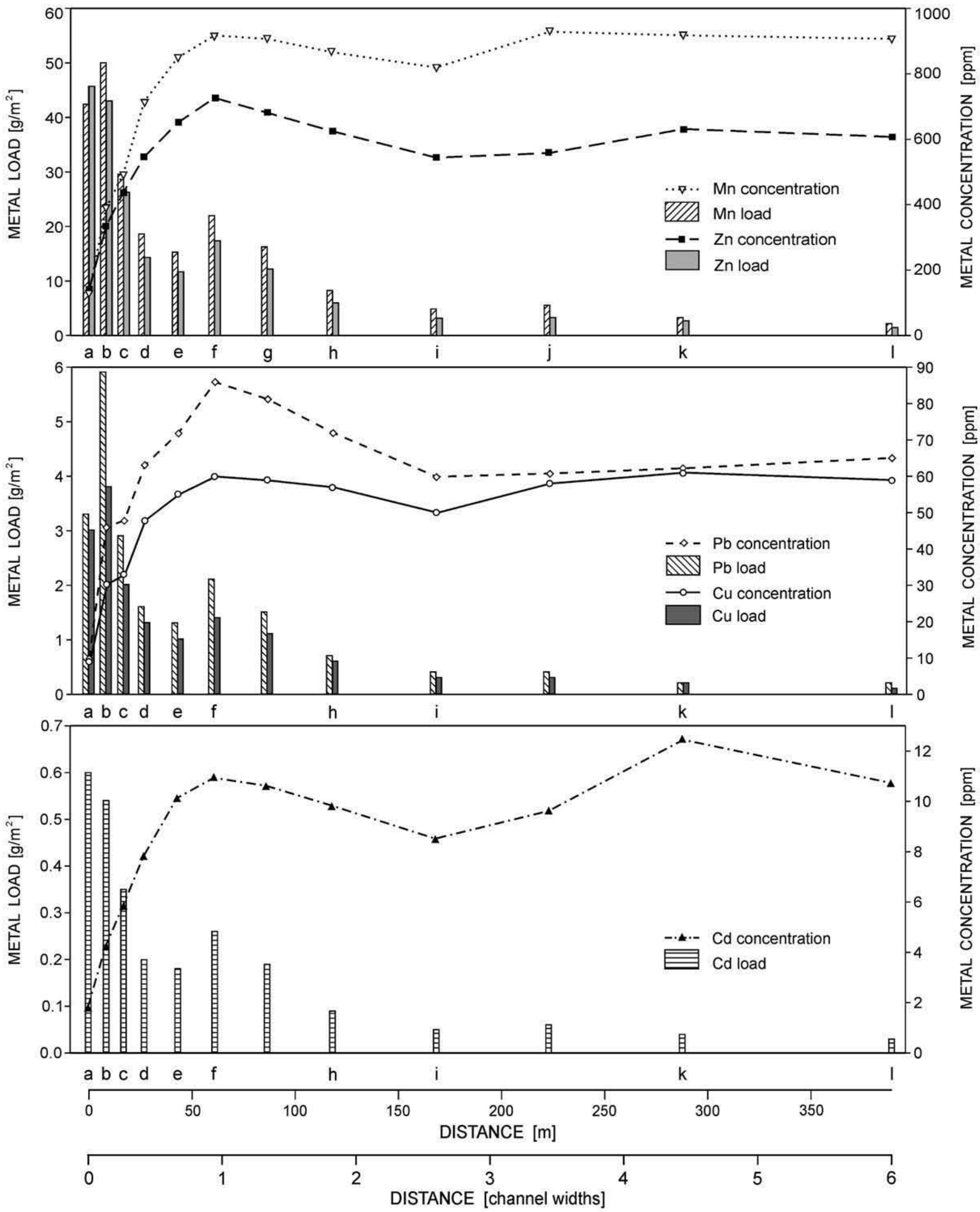

Fig. 9. Load and concentration of Cd, Cu, Pb, Zn and Mn in the overbank sediments deposited by the July 2001 flood on one-side floodplain of the Sierosławice cross-section. Distance from the Vistula channel is shown both in absolute and relative (scaled by channel width) values.

Metal concentrations in the investigated cross-sections were evidently related inversely to the particle size of the flood deposits. Lower concentrations occurred with coarse, proximal sediment and the higher ones were recorded in more distant locations with finer sediment. This relationship is emphasized especially by the large variability of the concentration of individual elements at Sierosławice, where the lateral variation in mean grain size of the flood deposits was double that in the two other cross-sections. (Figs. 2A–4A). Differences in the pattern of lateral changes in sediment grain size between the three cross-sections were reflected in distinct changes of heavy metal concentrations across the floodplain width at particular gauging stations.

With a small range of variation in sediment density (between 1.2 and 1.6 g cm^{-3}), variability of heavy metal loads mostly reflected differences in metal concentrations and in the thickness of flood deposition between particular sites. In the relatively wide Smolice and Sierosławice cross-sections, the metal concentrations increased laterally several times, whereas the thickness of the flood deposits diminished across the floodplain several dozen times at Smolice, and by a hundred times at Sierosławice. As a result, the variation in sediment thickness exerted a predominant influence on the lateral changes in metal deposition, with the loads of heavy metals being the highest close to the channel margin and decreasing exponentially with increased distance from the channel. In contrast, on the narrow floodplain at Bielany, the lateral increase in metal concentrations was counterbalanced by a similar reduction in sediment thickness in the distal direction, with the resultant lack of consistent changes in metal loads across the floodplain width.

7. Discussion

It is well known that valley (floodplain) width influences general hydraulic characteristics of flood flows, with narrow sections being typified by steeper stage/discharge curves, greater depths of inundation and higher average shear stress and unit stream power than the wide sections (e.g. Magilligan, 1992b). This study has demonstrated that floodplain sections of different width are also characterised by distinct patterns of mean velocities of channel and floodplain flows. The reconstructed velocity patterns indicate that the narrow cross-section at Bielany was characterised by the substantially higher velocity of flow over the floodplain and by the lower contrast between mean velocity of the channel and floodplain flows than the wider Smolice and Sierosławice cross-sections (Figs. 2B–4B; Table 2). The higher velocity of the floodplain flow at Bielany did not reflect a steeper longitudinal floodplain slope (which was the lowest among the three stations considered, Table 1) but indicated the higher intensity of momentum transfer between the channel and floodplain flows than in the wider cross-sections (Fig. 5).

Given the patterns of flood flow velocities, different distributions of the overbank deposits were found in individual cross-sections, the differences being especially pronounced between both wider cross-sections and the narrow cross-section at Bielany (Fig. 6). In the wider cross-sections, the marked contrast between velocity of the channel and floodplain flows led to a rapid decrease in flow competence outward away from the channel. This resulted in rapid deposition of sand particles close to the channel margin and decrease in thickness and grain size of the flood deposits in the distal direction (see Marriott, 1996; Wyżga, 1999). At Smolice, a perpendicular component of the floodplain flow seems to have occurred, resulting in tractive movement of the sand particles falling from suspension and in an extension of the width of levee deposition in comparison to that observed at Sierosławice (Fig. 6). In the narrow cross-section at Bielany, the lower contrast in velocity between the channel and floodplain flows resulted in the more uniform thickness of sediment across the floodplain, whereas the high velocity of flow on the floodplain enabled deposition of sand over most of its width. However, it should be stated that such a depositional pattern cannot reflect sediment transfer to the floodplain zone by convection (which would be difficult to operate in the quasi-straight compound channel occurring in that location) but rather a weak velocity gradient across the floodplain. The competence of the floodplain flow as well as the concentration and size of suspended sediment particles decreased relatively slowly with increased distance from the channel.

Patterns of heavy metal concentrations in the flood deposits reflected the distribution of sediment grain size. Generally, metal concentrations were relatively low in proximal sandy deposits, whereas higher concentrations typified silty–clayey sediments deposited at more distant locations of the floodplain. At Sierosławice, the rapid increase in metal concentrations occurred within a distance of 60 m from the channel (Fig. 9), where the rapid, lateral change from well-sorted, medium-grained sands to muds with a small percentage of sand particles was recorded (Fig. 6). At Smolice, metal concentrations were relatively low within the sandy sediments of the levee but a rapid lateral increase took place immediately beyond the levee (Fig. 7), with rapid fining of the flood deposits (Fig. 6). In the Bielany cross-section, the gradual change from medium-grained sands on the bank top to muds at site X was accompanied by the tendency of metal concentrations to increase slowly across the floodplain width. In the distal part of the floodplain, the more rapid fining of the flood deposits was accompanied by the more rapid increase in the manganese, lead and zinc concentrations (Figs. 6, 8). Heavy metals in the flood deposits were associated with the silt and clay fractions, whereas sand particles dispersed contaminated finer particles (cf. Zhao et al., 1999). The increase in metal concentrations with growing distance from the Vistula channel, which accompanied the lateral decrease in grain size of the flood deposits, is consistent with that observed in sandy–clayey overbank sediments of some large and small rivers (Zhao et al., 1999; Middelkoop, 2000) but opposite to the pattern of concentrations found along rivers transporting metals associated mostly with coarse sediments (Macklin and Dowsett, 1989; Marron, 1992).

While the concentrations of four investigated metals in the Vistula floodplain sediments are similar to those recorded along the lower courses of other large European rivers (Middelkoop, 2000; Grosbois et al., 2006; Baborowski et al., 2007), the cadmium content is higher owing to the proximity of lead and zinc mines. Generally, in a given cross-section concentrations of all the investigated metals exhibited similar trends of lateral changes because of the association of the elements with fine sediment particles and the dispersal mechanism of the sediment. The high concentrations of cadmium close to the channel margin at Smolice were an exception, suggesting that this metal was here less strongly associated with fine sediment particles. Such behaviour of cadmium could be related to higher mobility of this element under aerobic conditions and adsorption on sand particles. It is possible at Smolice, which is located a few kilometres downstream of the mouth of the Chechło River that drains a lead–zinc mine at Trzebinia and is highly polluted with cadmium (Ciszewski, 1997). Cadmium distribution distinct from that typifying other heavy metals was also observed on the River Severn floodplain receiving contaminants from former ore mining (Zhao et al., 1999).

The distinct patterns of overbank sediment deposition in the cross-sections of different width (Fig. 6) were also reflected in different lateral distribution of heavy metal loads in the flood deposits (Figs. 7–9). In the relatively wide Smolice and Sierosławice cross-sections, the reduction in thickness of the flood deposits across the floodplain was substantially greater than the associated increase in metal concentrations. As a consequence, the largest amounts of heavy metals were deposited close to the channel margin and heavy metal loads exhibited an exponential decrease with growing distance from the channel. On the narrow floodplain at Bielany, the lateral decrease in thickness of the flood deposits was much less pronounced and was accompanied by the opposite tendency of metal concentrations. Here, metal loads only fluctuated from site to site, without a consistent trend across the floodplain width. Despite the mentioned differences in the lateral distribution, maximum deposition of heavy metals in the three cross-sections exceeded up to ten times that recorded on the floodplains of Rhine and Meuse Rivers during a flood of 40-year recurrence interval (Middelkoop, 2000). The disparity reflects a substantially higher rate of accretion of the proximal overbank sediments on the upper Vistula floodplain coupled with similar concentrations of heavy metals in the floodplain sediments deposited along the three rivers.

8. Concluding remarks

This study demonstrates the influence of floodplain width on the dispersal of sediment-associated heavy metals. Patterns of flow velocity during the major flood of July 2001 on the upper Vistula River, southern Poland, were reconstructed for three cross-sections of different width and related to the observed overbank deposition and heavy metal distribution.

In the Smolice and Sierosławice cross-sections, 4.5 and 9 times wider than the respective channel widths, mean velocity of the floodplain flow was low and showed a marked contrast with mean velocity in the channel zone. In the Bielany cross-section, only 2.6 times wider than the channel width, mean velocity of the floodplain flow was high, both in absolute values and in comparison to that in the channel. These diverse velocities of the floodplain flows reflected different intensity of the interaction between the channel and floodplain flows in the wide and narrow river cross-sections.

High rates of lateral thinning and fining of the overbank sediments deposited by the flood of 2001 were observed in the Smolice and Sierosławice cross-sections. The changes were especially rapid near the channel margin at Sierosławice but slower at Smolice, where a sandy zone of natural levee deposits originated. In contrast, relatively little variation in thickness and grain size typified the sediments deposited on the narrow floodplain at Bielany.

At Sierosławice, heavy metal concentrations in the flood deposits first rapidly increased with distance from the channel and then remained high over most of the floodplain, whereas at Smolice they were relatively low within the levee deposits but high over the rest of the floodplain. However, due to the rapid lateral thinning of the flood deposits, the loads of accumulated heavy metals were the highest close to the channel, decreasing exponentially with increased distance from it in both cross-sections. At Bielany, the concentrations of heavy metals slowly increased with distance from the channel but their loads fluctuated across the floodplain width, with the highest load of some metals occurring near the channel margin and that of others being recorded far from the channel.

Floodplain width and the resultant flow hydraulics exert a significant influence on the lateral distribution of floodplain sediments and the associated heavy metals. In wider floodplain sections, the largest amounts of heavy metals accumulate close to the channel margins. These findings have important implications for both the management and environmental monitoring of highly polluted rivers. Overbank deposition is likely to become a dominant component of development of floodplains of channelised rivers due to limited channel migration and reworking of floodplain sediments (Walling et al., 1996). As many of these rivers have been polluted for a long time, it is reasonable to expect that a fairly large load of heavy metals is stored close to their banks. For instance, in the investigated reach of the Vistula River, overbank sediments with heavy metal concentrations significantly exceeding the geochemical background were more than 2 m thick (Macklin and Klimek, 1992). This implies a high pollution risk for river waters at times of erosion of overbank sediments. Thus, bank reinforcement structures need to be maintained in such rivers in order to prevent bank erosion and remobilisation of heavy metals stored in near-channel floodplain sediments.

This study of heavy metal deposition on the Vistula River floodplain shows that analysis of only the concentrations of contaminants accumulated in overbank deposits is not sufficient and may lead to inappropriate evaluation of the potential threat to the environment. The threat will depend on the total amounts of accumulated contaminants. Data from the environmental monitoring, focused only on concentrations, would mislead when heavy sedimentation takes place on the floodplain with simultaneous storage of large volumes of contaminated sediment.

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