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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

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ABSTRACT

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.
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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).

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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

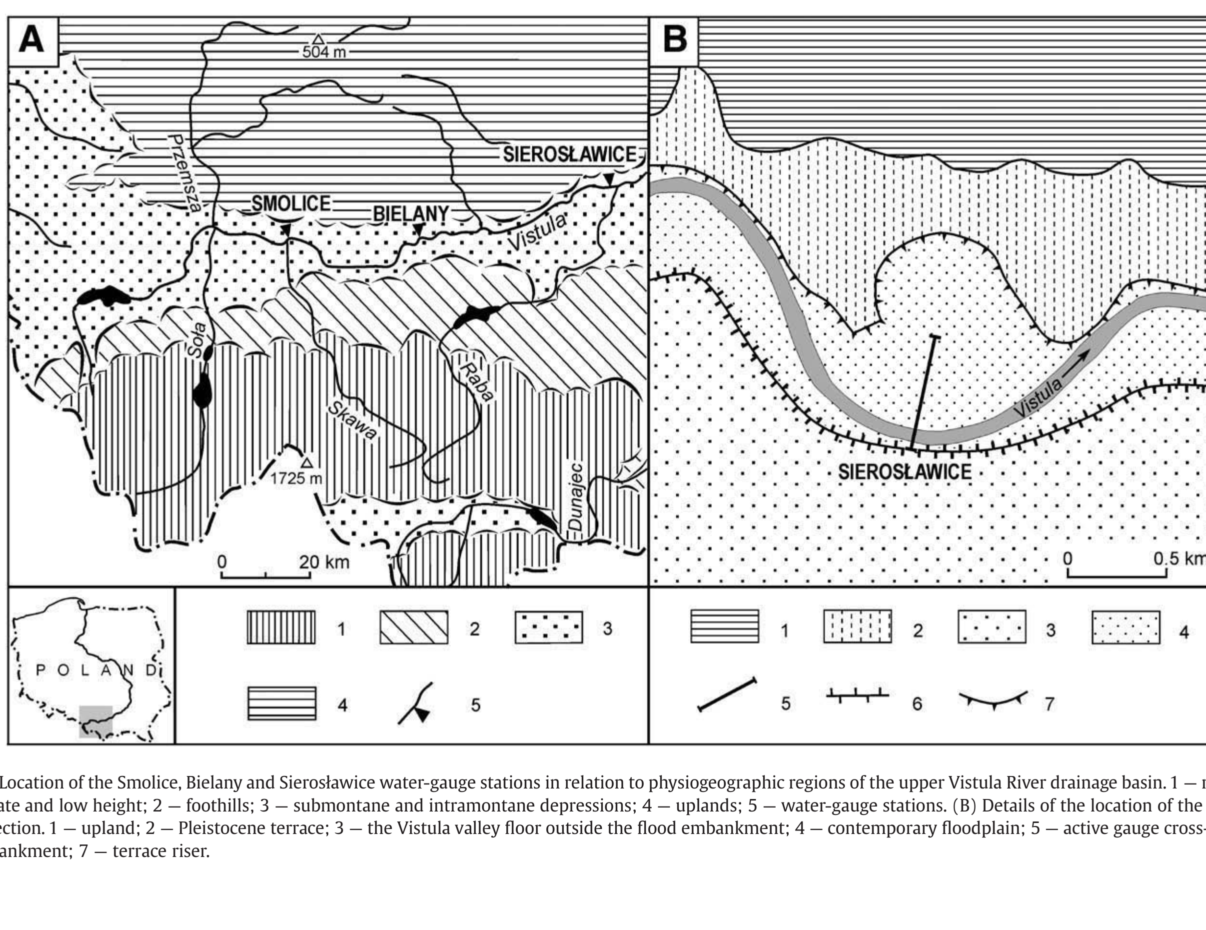

Fig. 1. (A) Location of the Smolice, Bielany and Sierosławice water-gauge stations in relation to physiogeographic regions of the upper Vistula River drainage basin. 1 — mountains of intermediate and low height; 2 — foothills; 3 — submontane and intramontane depressions; 4 — uplands; 5 — water-gauge 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.

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