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Review

Pollution of the Mała Panew River Sediments by Heavy Metals: Part II. Effect of Changes in River Valley Morphology

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Abstract

This paper examines the relations between the dispersal of sediment-borne heavy metals and changes in morphology of the Mała Panew River valley in southern Poland. Sediment samples were taken in 66 vertical profiles up to 60 cm deep, situated at different heights above a water table. Alluvial levels of similar width and height appear with different frequency along river banks within 7 selected 1km-long river valley reaches. Moreover, heavy metal concentrations at levels of similar height are similar throughout the Mała Panew valley. This suggests that both the width of the river valley over which sediment-associated heavy metals accumulated as well as the volume of these sediments stored within particular river reaches, change downstream. Generally, the wide, natural reaches of the river valley, which have been sinks for metal-associated sediments in the 20th century, are an important secondary pollution source, whereas narrow valley reaches in which flow regulation caused incision of the river channel are mainly transition zones for the polluted sediments conveyed in the river valley.

Keywords: river sediments, heavy metals, pollution, valley morphology, fluvial processes

Introduction

The morphology of the river valley changes downstream. The change includes: valley gradient and width, floodplain and terrace height, and channel width and depth. Also, floodplain topography is different in wide and narrow valley sections. Typically, the upper, mountainous valley section is steep and narrow. The river transports a large amount of coarse material and flows in a multithread channel which can occupy an entire valley bottom. In the middle, lowland river course, valley gradient is lower. Meandering river transports mainly sand or finer material and, by lateral migration or avulsion, floodplain topography is a mosaic with paleochannels, levees and crevasse splays. In the lower, coastal section with the lowest valley gradient, a stream produces smaller distributaries and transports relatively the finest material [1].

Moreover, the morphology of many river valley sections is affected by human activity, Aggradation of the channel bed and valley bottom take place upstream of dams and weirs while, downstream a rapid channel incision is observed [2, 3]. Entrenchment of the channel, which can also be a result of its regulation, decreases frequency of sediment accumulation on the floodplain [4]. Also, confining a river floodplain by embankment makes smaller the area of sediment deposition [5].

The relation between valley morphology and dispersal of the heavy metal polluted sediments was observed in mountain valleys. Usually, the sediments accumulate rather in wider sections of a mountain valley than in the narrow bedrock controlled sections with steeper gradients [6]. Greater valley width favours polluted sediment ac-

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cumulation not only during long, several ten-year periods but also during single floods. Mass balance calculations demonstrate that during large floods, along reaches with narrow valleys (<450 m), approximately 10-65% of Hg-polluted sediment was stored in overbank deposits, whereas more than 90% accumulated in reaches with wider valleys [7]. The passing of the dam-burst flood by narrow arroyo in New Mexico caused pollution of river sediments with ^{230}Th over several tens of kilometres. The variations in stream power and shear stress, which alternated between higher and lower values was also related to local valley cross-sectional geomorphology and controlled variable sediment accumulation [8]. Also, large crevasse splays, which consisted of polluted sediments, were formed during high power flood downstream of the narrow valley reaches [9].

In lowlands, the rate of the polluted sediment accumulation in the wide alluvial valley is very often affected by human activity [10, 11]. The presented paper shows the effect of weirs construction and then degradation and channel regulation on the dispersal of heavy metal polluted sediment in the Mała Panew River valley, situated in the Silesia Lowland, in southern Poland.

Research Area

The length of the Mała Panew River from its sources at the western border of the Silesia Upland to its confluence with the Odra River is 132 km. The mean annual discharge in the middle reach is ca. 10 m^3/s and the channel width varies between 10-20 m. The Holocene valley bottom in the investigated middle course of the Mała Panew between Krupski Młyn and Staniszcze Wielkie is several hundred meters wide. The river channel is incised into fluvioglacial sands and in the lower reach its bed reaches Lower Triassic shales.

The Mała Panew is a naturally meandering river in forested valley reaches: Krupski Młyn-Kielcza and Zawadzkie-Kolonowskie, which are 4 and 7 km long, respectively (Fig. 1). Channel intensively erodes its non-cohesive sandy banks. The rate of its lateral migration averaged 0.5 m/year during the last 100 years. However, the river channel was stable laterally at Krupski Młyn, Zawadzkie and Kolonowskie. At these localities meadow iron ores have been reworked since the second half of the 18th century. Small, usually 2 meters high weirs were constructed at every smelter and mill for energy supply. In the second half of the 19th century production collapsed and almost all constructions were abandoned and destroyed [12]. In consequence, at Kolonowskie and at Krupski Młyn channel incised 2-3 meters into the valley bottom, whereas sediments accumulated upstream from the weir, which is preserved to the present at Żędowice (close to Zawadzkie). Channel reach between Żędowice and Zawadzkie was regulated and for over 100 years was stable both laterally and vertically.

Lead and zinc ores have been mined in the upper part of the Mała Panew drainage basin since the 16th century. Production of lead and silver was continued until the 18th century and revived in the 19th century. Industrial production significantly expanded in the 20th century. After World War II chemical plants in Tarnowskie Góry and the zinc smelter in Miasteczko Śląskie became one of the largest pollution sources of heavy metals in Poland. Moreover, in Tarnowskie Góry several small electromechanical plants have been operating since the early 1970s. Production in chemical plants has been in decline since the end of the 1980s and the plants were closed in 1995, whereas the emission of lead, zinc and cadmium from zinc smelter has been decreasing since 1990.

The extensive industrial activity caused the pollution of the river sediments by heavy metals. Investigations carried out in the early 1970s showed that the concentrations of Ba, Cd, Cu, Pb and Zn were elevated above background values [13]. Extensive pollution of both sediments and soils in the upper part of the drainage basin by cadmium, zinc and lead was also reported in the Geochemical Atlas of Upper Silesia 1:200,000 [14]. Very high cadmium, zinc and lead concentrations in river bed sediments have also been observed recently [15].

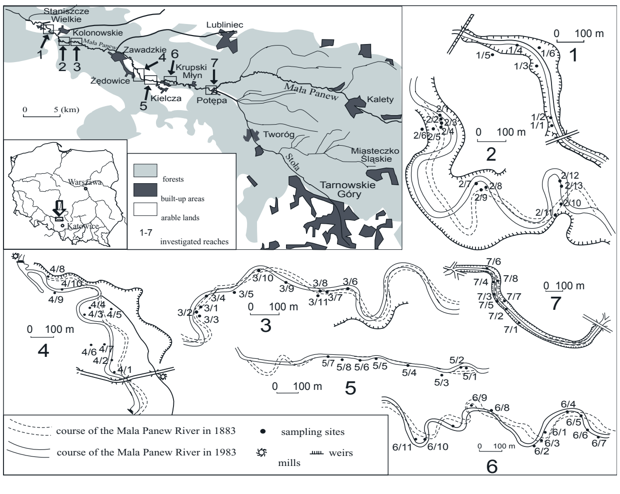

Fig. 1. Research area and sampling points.

Materials and Methods

The height, length and maximum width of a floodplain, terraces, terrace steps, benches as well as large turf slumps and side bars stabilized with grass have been determined along the 28.5 km long reach of the Mała Panew River, between Potępa and Staniszcze Wielkie. In further considerations these forms altogether will be called here the alluvial levels. The position of these levels in a 50 m wide zone on each bank has been marked on a map. Then the river reach was divided into 1413 20 m long sections, in which the frequency of alluvial levels <1 m, 1-1.9 m, 2-2.9 m, 3-4 m and >4 m high was calculated. Seven 1 km long reaches with different valley floor morphology were selected for studies of sediment contamination on a base of differences in the alluvial levels frequency and changes in lateral channel shifting between map editions in 1883 and 1983 (Fig. 1).

Table. 1. Frequency of alluvial levels (%) along the middle reach of the Mała Panew River.

Level height	Reach number						
	1	2	3	4	5	6	7
0-0.9 m	15	14	8	65	8	19	25
1-1.9 m	14	53	26	47	41	47	32
2-2.9 m	21	27	15	21	66	83	43
3-4 m	55	43	94	-	-	-	10
> 4 m	95	46	-	-	-	-	61

In 1 km long reaches, 200 samples of overbank sediments were collected in vertical 60 cm profiles. Profiles were localized to represent all height ranges in particular river reaches. At every profile samples were taken at 0-10, 10-30 and 30-60 cm. Concentrations of Ba, Cd, Cu, Pb, Zn Mn and Fe in fraction <1 mm were determined using atomic absorption spectrometry (details are given in: [15]).

The Frequency of Alluvial Levels

Along the incised river reach 7 at Krupski Młyn, 3-5 m terrace occurs the most frequently on the left channel bank, whereas on the right bank 5 m terrace occur usually 50-100 m from the channel (Table 1). Terrace steps are 1.5-3 m high and up to 12 meters wide. The relatively high 3-5 m terrace along this reach is related to channel downcutting. This process probably followed abandonment of two mills and steel works in the second half of the 19th century. In this river reach a 1.5 m high floodplain was also formed on 200 m distance as a result of channel shifting in the years 1883-1983.

The channel incised also in reach 1 at Kolonowskie, downstream from the presently existing weir, which is associated with a 19th century steel work [16]. Along this reach, 4-6 m terraces dominate both river sides. Moreover, the river banks are steep and the channel is narrow as a result of erosion of relatively resistant Triassic shales. Sediment accumulation formed sparsely distributed, short and narrow terrace steps. The river channel has been laterally stable for over 100 years.

River reach 5 at Żędowice has been stable since its regulation in the first half of the 19th century. However, unmaintained river banks were eroded. The frequent sediment accumulation takes place on the turf slumps along the floodplain edge. The floodplain is 1.8-2.2 m high and over 300 m wide. Its flat surface has been extensively used as a meadow.

The weir at Żędowice, which has been operated at least since the beginning of the 18th century [16], caused accumulation of river sediments upstream. The height of the floodplain, along river reach 4 at Żędowice, varies between 0.4 m at the weir and raises slowly up to about 1.5 m at the other weir (Fig. 1). The floodplain surface gently decreases toward the valley margin. It can be estimated that the thickness of the sediments accumulated since the weir was constructed exceeds 1-2 m in some locations. Moreover, since 1883 the river channel has migrated laterally up to 60 meters.

The width of the Mała Panew River valley in its natural, meandering reaches 2, 3 and 6 (Fig. 1) varies between 200-600 meters. Floodplain with numerous paleochannels is usually 2-2.5 m high above average water level. The terrace 3-4 m high is also frequently observed along the channel (Table 1). The higher, 4 m Holocene terrace and 8-10 m high Pleistocene terrace occurs close to the river channel only sporadically. Moreover, the youngest sediments are stored in narrow terrace steps, which are lower than 2 m and are several to several tens of meters long.

Pollution of the Overbank Sediments

Medians of heavy metal concentrations in the investigated overbank sediments are clearly related to terrace height (Table 2). Heavy metal concentrations in alluvial levels higher than 4 meters, which are not inundated even at extremal floods, are close to background values. In alluvial levels lower than 2 m, cadmium content is several ten times higher than the background, whereas barium and zinc concentrations exceed background values by about a dozen times and lead and copper concentrations, usually several times. In every reach, the lowest metal content occurs in sediments accumulated at least 2 m above a water level. The metal content in fraction <1 mm is much lower than in fraction <0.063 mm [17]. Content of elements differs also between particular profiles and sediment layers. Below, typical examples of investigated profiles in different river reaches are presented.

Sediments Pollution in Reaches with Incised Channel

The lowest metal concentrations in reaches 1 and 7 with incised river channel occur in profiles localized on terraces higher than 4 m (7/5 Fig. 2). Metal concentrations in the deepest layer 30-60 cm represent geochemical background whereas cadmium, zinc and lead content is higher in the surface layer both in 4-5 m and 8-10 m terraces. It is probably related to metal emission from iron smelters situated in Ozimek and Zawadzkie, especially in the 1960s and 1970s [18].

Higher metal concentrations are observed in terrace steps 2-3 m high both at surface and at a depth of 30-60 cm (7/4 Fig. 2). However, barium and cadmium concentrations are much higher at the surface than in lower layers. High content of barium, which is a relatively less mobile element, only in thin sediment layer suggests rare accumulation of the polluted sediments in the 20th century on this surface. The content of more mobile cadmium and zinc in lower layers could be related to downward migration. Generally, weakly polluted sediments in the

Table 2. Medians and upper and lower quartiles of heavy metal concentrations in the Mała Panew overbank sediments in fraction <1 mm (ppm).

Element	Level height		Reach number						
			1	2	3	4	5	6	7
Ba	0.2-0.9	25%	168	11	59	69	152	34	61
		Me	556	30	90	136	196	92	94
		75%	920	39	163	317	204	107	188
	1-1.9	25%	145	4	100	49	135	69	187
		Me	228	34	183	110	267	89	336
		75%	1465	55	228	1229	344	221	465
	2-4	25%	36	1.5	30		75	27	4
		Me	61	2	65	-	96	123	11
		75%	97	3	162		122	321	29
	> 4	25%	30	1.3					3
		Me	64	1.4	-	-	-	-	3
		75%	163	2.5					40
Cu	0.2-0.9	25%	31	13	15	7	16	20	14
		Me	80	17	19	16	22	29	17
		75%	141	22	28	44	33	34	22
	1-1.9	25%	27	8	17	16	21	16	37
		Me	28	11	26	18	32	24	45
		75%	106	16	33	150	52	35	60
	2-4	25%	8	3	4		6	10	5
		Me	10	4	5	-	9	17	7
		75%	20	6	9		13	40	16
	>4	25%	3	2					3
		Me	5	3	-	-	-	-	5
		75%	11	8					6
Cd	0.2-0.9	25%	33	23.9	23.5	6.1	27.0	53.1	24.4
		Me	47.1	29.6	26.1	19.7	36.6	72.3	28.6
		75%	162	42.7	42.6	42.7	62.1	87.5	37.3
	1-1.9	25%	28.5	1.4	11.8	21.3	25.3	18.6	26.1
		Me	29.6	7.8	16.2	24.0	51.3	30.3	47.8
		75%	62.7	14.9	24.6	141.3	100.9	46.1	52.8
	2-4	25%	1.6	1.2	1.4		2.4	7.1	1.6
		Me	2.5	1.5	1.7	-	3.2	14.0	2.4
		75%	2.9	2.1	2.5		17.2	48.4	3.2
	>4	25%	1.1	1.3					0.6
		Me	1.2	1.4	-	-	-	-	0.7
		75%	5.6	2.1					0.8
Pb	0.2-0.9	25%	90	39	33	22	42	58	32
		Me	252	179	49	61	57	78	37
		75%	343	64	72	140	87	93	42
	1-1.9	25%	71	7	53	47	62	45	51
		Me	87	24	92	61	80	75	99
		75%	608	52	149	344	285	128	211
	2-4	25%	7	4	3		30	26	16
		Me	16	11	6	-	35	54	29
		75%	28	21	38		66	127	52
	>4	25%	0.7	4					1.8
		Me	9	14	-	-	-	-	13
		75%	33	58					26

Table 2. continues on next page...

Zn	0.2-0.9	25%	591	310	290	143	252	434	272
		Me	768	398	326	240	299	509	318
		75%	1532	630	548	706	538	728	348
	1-1.9	25%	293	45	152	189	286	227	455
		Me	427	137	179	264	523	370	534
		75%	872	220	294	1301	712	426	621
	2-4	25%	69	25	25		95	73	71
		Me	102	37	39	-	151	157	82
		75%	179	54	75		176	393	122
	>4	25%	28	17					9
		Me	38	22	-	-	-	-	14
		75%	103	59					21
Number of observations			18	39	34	30	24	32	24

2-3 m high levels had had to be accumulated before the maximum pollution of the Mała Panew River took place, probably in the 19th century. The age estimated agree with weirs abandonment in these reaches and incision of the channel in the second half of the 19th century.

Pollution of the 2-3 m terrace is higher in the lower incised reach 1. It could be related to the greater terrace width and more effective fine sediment entrapment by grassy surface because flood waters flow slower and are shallower on wider terraces than in narrow valleys [4].

Sediments that accumulated after the river channel had been incised are strongly polluted. This suggests that 1.3 m terrace step (7/8 Fig. 2) accumulated in the second half of the 20th century. The decrease of barium content toward the surface of this terrace is related to sewage treatment at chemical plants since the end of the 1960s. This decrease correlates well with the increase of cadmium content since about 1970, after a zinc smelter started to operate [15]. The lowest terrace steps, about 0.5 m high, consist of the young frequently accumulated sandy sediments interbedded with black organic layers (7/1 Fig. 2). The decrease of all metals content toward the terrace surface is related to the closure of chemical plants and improved sewage treatment in the zinc smelter. This suggests accumulation of the upper layers in this terrace after 1990.

Sediment Pollution in Aggrading River Valley Reach

The lowest metal concentrations in reach 4 at Żędowice occur in sediments accumulated on floodplain 0.5 m high, close to the weir. Moreover metal concentrations are low in river deposits sampled at a depth of 10-60 cm over the large floodplain area. Probably aggradation of the valley bottom with unpolluted sediment had been taking place for several hundred years before the pollution era. The 20th century river channel adjusted to the long-existing weir

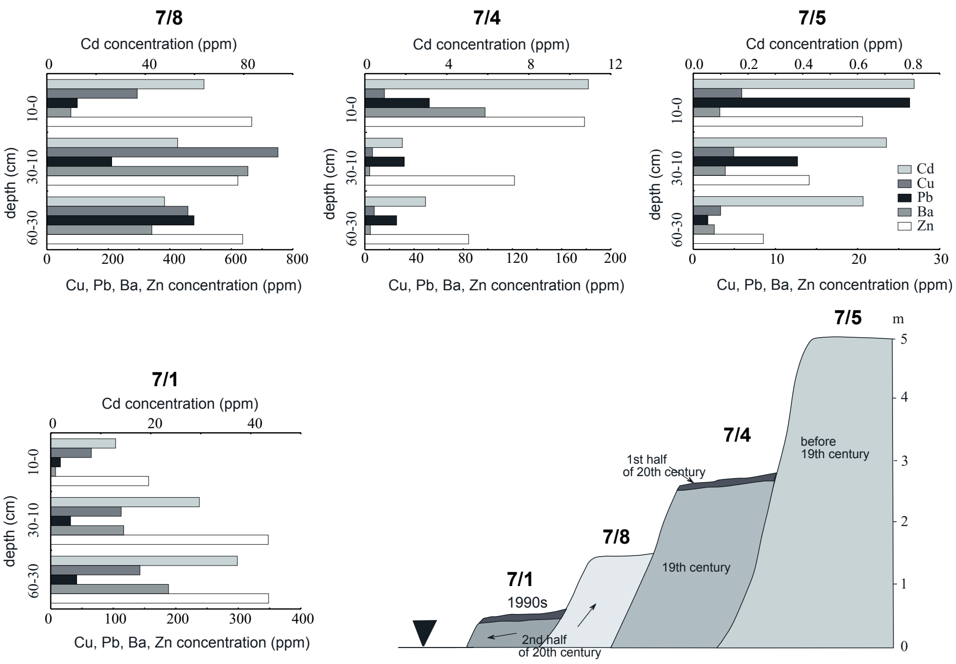

Fig. 2. Sediment pollution by heavy metals in valley with incised channel.

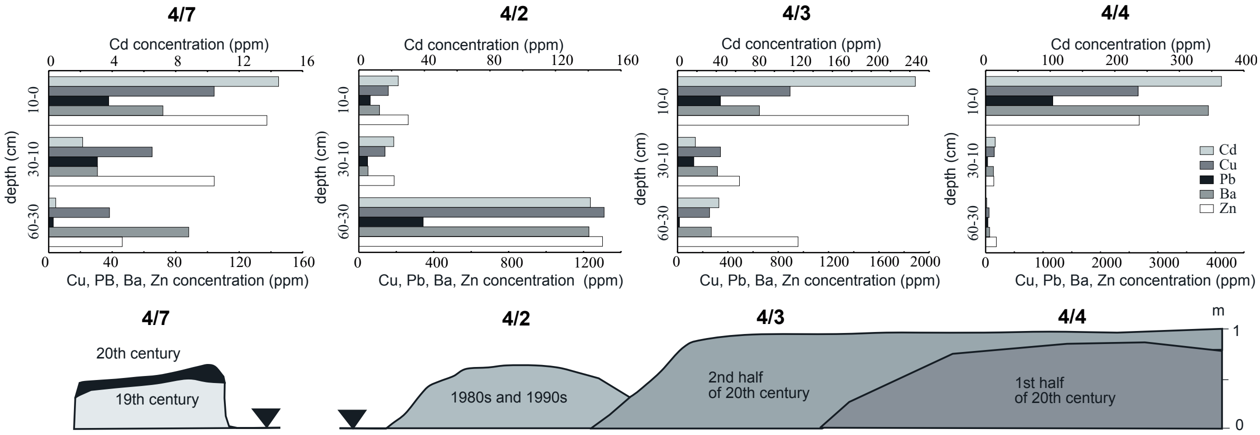

Fig. 3. Sediment pollution by heavy metals in aggrading river valley.

and it migrated laterally with a rate similar to that in natural valley reaches. However, the much lower floodplain height in aggrading than in natural reaches enables more frequent inundation here. Higher metal concentrations, which are observed in surface deposits, reach in organic matter, reveal efficient sediment entrapment by grass, which overgrows the floodplain. The rate of the polluted sediments accumulation changes across the floodplain (Fig. 3). Heavy metal concentrations which, to some extent, reflects this rate, are highest in the zone of the flood waters flow toward the valley margin. Depressions in the floodplain in which flood waters stagnate for several days are sinks for polluted sediments and metal concentrations are the highest there. Besides, relatively high metal concentrations are observed at greater depths in sediments accumulated in the 20th century. Also, lateral channel shifting between the two map editions indicates the same age of the more polluted sediments. Larger floods, of the order of 20 years recurrence interval, inundate the entire valley bottom. Metal concentrations in channel bars accumulated during the 1997 flood are much lower than in older sediments at 30-60 cm depth (4/2 Fig. 3). This regularity is similar to that observed in incised river reaches.

Sediment Pollution in Reach with Stable Channel

Near-bank deposits of terrace steps are markedly polluted by heavy metals within the reach 5 with stable river channel. However, metal concentrations can change with the depth of profiles localized in levels of similar height (Fig. 4). It results from the slumping of relatively less polluted sediments from the edge of the 2 m floodplain. Then, on the slump tops more polluted sediments, which originate from upstream bank erosion or industrial sources in Tarnowskie Góry, accumulate. Also some turf slumps rotate and older sediments mix with the younger ones. Generally, levels lower than the floodplain consist of 20th century sediments and are polluted most of all by cad-

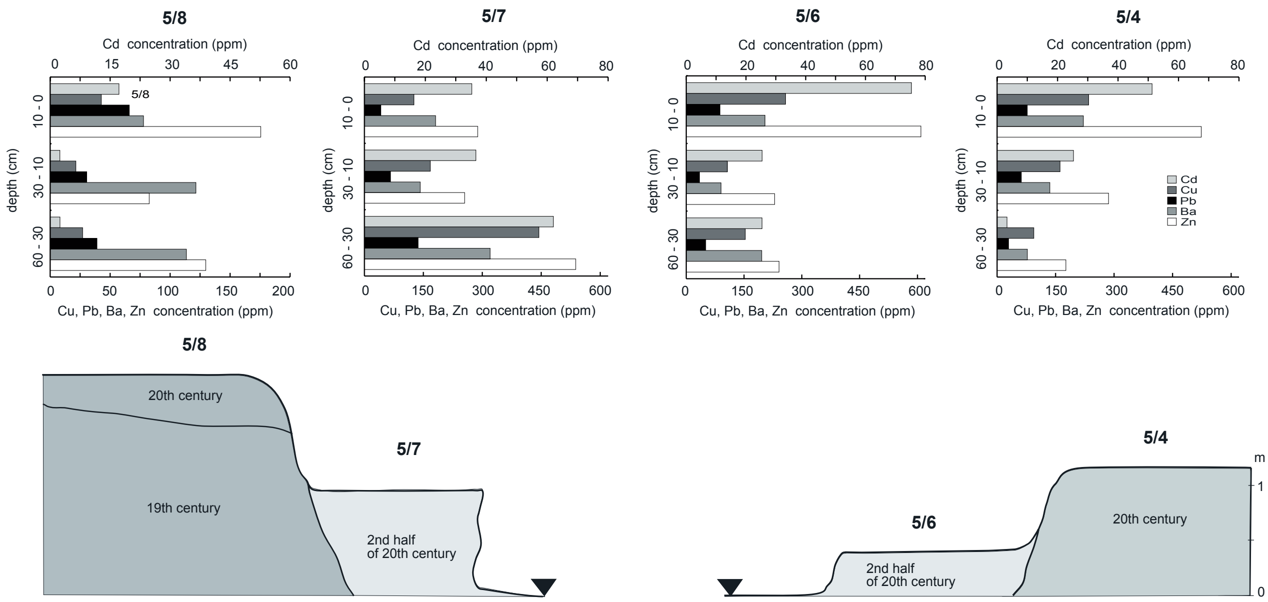

Fig. 4. Sediment pollution by heavy metals in valley with stable river channel.

mium. Floodplain sediments are much less polluted (5/8 Fig. 4). Metal concentrations in surface layer decrease as distance from the channel increases.

Sediment Pollution in Reaches with Meandering Channel

Metal concentrations in alluvial levels higher than 2.5 m in meandering reaches 2, 3 and 6 are low except for surface layer of floodplain in which they exceed several times background level. Very high metal content was observed also in 0-10 cm layer of the floodplain in fine fraction of sediments accumulated on the pre-20th century sediments [19]. This suggests inundation of the entire several hundred meters wide valley bottom during the largest floods in the 20th century. Former river channels (paleochannels), situated close to the present river channel are almost completely infilled. Very high metal concentrations in these infills outcropped in the river bank (6/3 Fig. 5) testify to the importance of floodplain depressions as polluted sediments sink.

Free river meandering, which is characteristic for low gradient alluvial valleys, makes the rate of sediment deposition across meander bend variable. Usually, vertical sediment accumulation is relatively slow on the outer bend, which is undercut by a river. This process is reflected by a small thickness, up to 10 cm, of the polluted surface layer in profile 6/2 (Fig. 5), which covers much less polluted 19th century sediments. Relatively higher zinc content in lower lying layers could be related to metal mobilization from the surface layer or to infiltration of the polluted flood waters.

Thickness of sediments accumulated during the period of high river pollution is much higher in the inner meander bends. Polluted sediments are up to 2.5 m thick on a distance from several to a dozen metres from the apex of the bend [17]. The thickness of these sediments decreases with distance from the present river bank. However, it can reach several decimetres in the floodplain on a distance up to 50-60 metres from the bank.

Metal concentrations both at the floodplain surface and in terrace steps 1-2 m high ranges between 200-400 ppm for barium, 20-200 ppm for lead and 5-20 ppm for cadmium. Decrease of metal content toward floodplain surface is observed in sediments accumulated in the 1980s and 1990s close to the channel bank (6/11 Fig. 5). Moreover, at levels lower than 1 m, cadmium and zinc concentrations are usually higher than in the floodplain. Surprisingly, contrary to reaches with more stable river channel, metal concentrations, especially of barium, are higher at the surface than at 10-30 cm in most profiles situated at these levels (6/4 Fig. 5).

Valley Morphology and Sediment Pollution

The investigations show that dispersal of the sediment-associated heavy metals within the alluvial valley of the Mała Panew are affected by valley morphology. The area of the floodplain that receives the sediments during floods, changes markedly between investigated reaches. The changes result from flow regulation works undertaken in the 19th century. Long lasting, several hundred-year weir operations, caused progressive increase of the sediment volume stored upstream and valley floor aggradation. Eventually, the older deposits were blanketed with a rather thin layer of the polluted sediments in the second half of the 20th century. Channel entrenchment most efficiently confined the area on which polluted 20th century sediments accumulated. High metal concentrations in the two incized reaches occur only in narrow terrace stages and it seems to be obvious that the total volume of metal polluted sediments along entrenched river reaches is smaller than in the

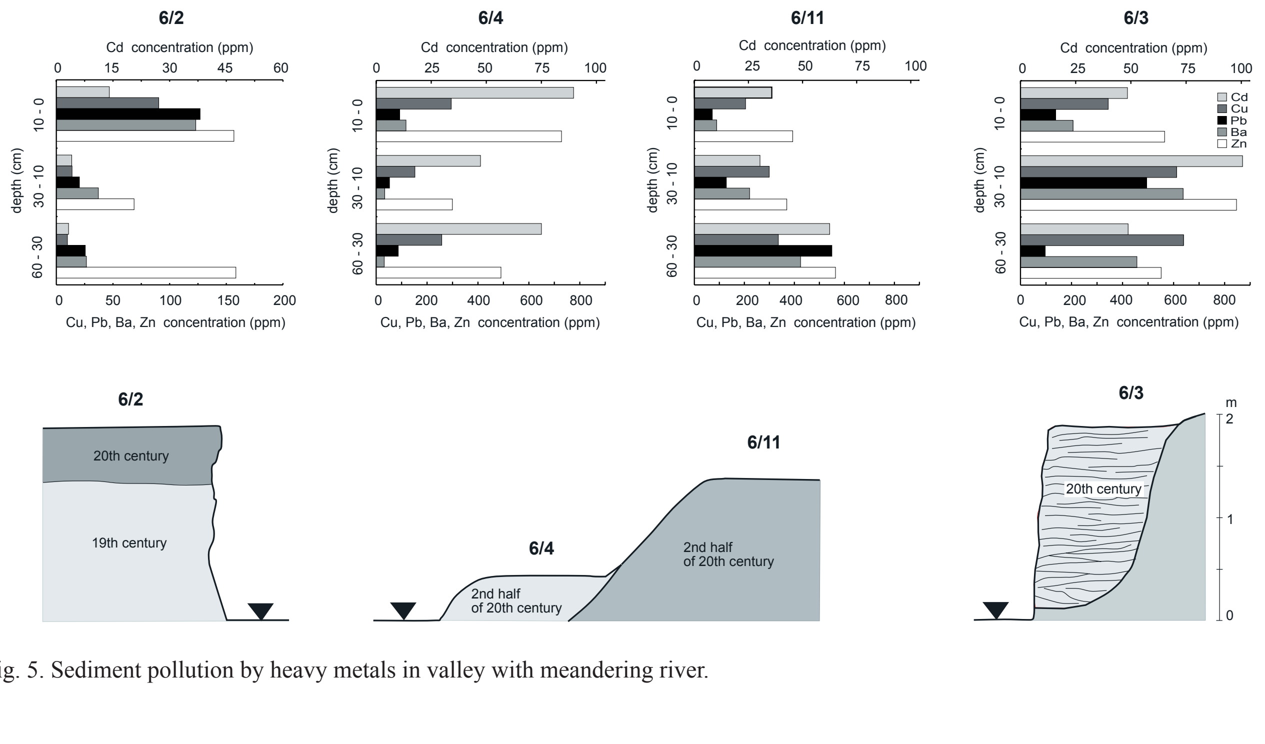

Fig. 5. Sediment pollution by heavy metals in valley with meandering river.

others. Also, reduction of the lateral and vertical channel erosion in regulated river reach made the rate of the polluted sediment accumulation relatively small. Low metal concentration in the floodplain could suggest that conveyance losses of the fine polluted suspended matter are negligible in this reach.

Polluted, fine-grained sediments are more intensively mixed with sandy sediments in valley reaches with meandering river channel. The rate of this mixing is proportional to the rate of lateral channel migration. The largest erosion takes place during floods at concave banks. As the bank retreats, sediments are entrained and accumulate on a point bar usually immediately downstream [1]. Fine sediments, which bore a marked portion of heavy metals, accumulate on the bar top as the flood wave recedes. Highly polluted investigated sediments often consist of a series of sands interbedded with black organic layers.

It seems that the relatively high rate of sediment erosion and deposition in meandering reaches in the 20th century caused pollution of the largest volume of sediments. The rate of lateral channel migration suggests that polluted 2.5 m-thick sediments, which accumulated during 50 years in the second half of the 20th century can be encountered in the 25 m wide zone along the present river channel. Moreover, the polluted sediments up to several decimetres thick cover older 20th and 19th century deposits with lower metal content at a distance up to 50 metres from the channel.

Presently, the relatively rapid lateral erosion supplies heavy metals, stored within the overbank sediments, to the channel. This process could be reflected in higher metal concentrations in surface layers of the lowest alluvial levels. However, decrease of heavy metal concentrations in most of the low localized profiles in reaches with longer channel stability is consistent with decrease of river pollution by heavy metals since about 1990.

Conclusions

1. Natural, actively meandering river reaches alternate in the Mała Panew river valley with more stable reaches affected by flow regulation.
2. The meandering reaches in which sediments have been mixed with intensively eroded fluvioglacial deposits are significant sinks for sediment-associated heavy metals. Sediments stored there are a long-lasting secondary pollution source.
3. The volume of the sediments accumulated in the second half of the 20 century is the smallest in incized river reaches in which the area inundated during flood was markedly confined. These reaches are exclusively transition zones for sediment-associated heavy metals conveyed downstream.
4. The thickness of the polluted sediments, accumulated on the wide floodplain both upstream from the weir and in the regulated reach, usually does not exceed a few centimetres except for a section in which lateral channel migration takes place. In the regulated reach metal polluted sediments are transferred mainly from the channel onto the floodplain. These reaches play a much less important role as a secondary pollution source than the meandering reaches.

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