Review

Pollution of Mała Panew River Sediments by Heavy Metals: Part I. Effect of Changes in River Bed Morphology

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Abstract

Relations between changes in bed morphology and heavy metal concentrations were investigated in the Mała Panew River channel in southern Poland. Samples of bed sediments were collected at ten locations 12 times during two years. Concentrations of cadmium, zinc and lead in the river sediments are among the highest in Poland and in silt-clay fraction it reaches 600, 4000 and 500 ppm, respectively. At most channel locations, migration of one or two sand bars was observed. Usually a dead water zone, which was a particularly important sink for fine, strongly polluted organic sediments, appeared in front of the bar. Here, also the highest heavy metal concentrations occurred. The dead water existed usually for several months until it was destroyed by a flood or filled with sand sediments in the case of the bar front accretion. As a result, a marked drop of metal concentrations, accompanied by higher flow velocities, followed in a relatively short period.

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

Introduction

A river bed which is composed of noncohesive material is easily modified into various bed forms. The dimensions and number of bed forms in a particular river reach depends on channel gradient, sediment supply from bank and bed erosion or from tributaries and on water discharge. The topography of the perennial river bed can change within one year. It is considered that bankfull flow, with a recurrence interval of about 1-1,5 years, models channel and channel forms the most effectively [1]. Generally, in a sand bed channel, with increase of the flow, small, rather slowly migrating ripples may be overtaken by larger ones. This, when added to the increase in scour depth associated with the larger forms, eventually leads to the formation of dunes or sand waves of the order of meters high. Also, point bars which occur on the convex sides of the meanders with a series of scroll shaped ridges on the top can migrate downstream during each flood for several tens of metres [2].

The spatial variability of bed forms in polluted river channels results in variable heavy metal concentrations. Usually, in perennial rivers, the highest concentrations occur in zones with slow current velocity and the lowest ones are in a thalweg zone. However, a reversed sequence of metal concentrations can be observed in channels receiving effluents from polymetallic ore mines [3]. Also, during low water stages there are examples of higher metal concentrations in pools than in sand bars reworked in riffles [4]. The highest heavy metal concentrations in gravel bed channels can be found in eddy drop zones and in mid-channel bars, while riffles and glides typically have the lowest concentrations [5]. On the contrary, in channels of episodic rivers, the maximal concentrations occur in the zone of the most frequent flow and much smaller concentrations are in the nearbank deposits [6].

Floods and discharges higher than average cause erosion and redeposition of fine strongly polluted sedi-

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ments [7, 8]. It is generally considered that the length of the period between consecutive floods affects heavy metal concentrations in bed sediment [9]. However, it is not well known to what extent sample collection for the monitoring of river sediment pollution, repeated usually once a year, reflects changes in river pollution and to what extent it is influenced by changes in bed morphology.

The purpose of the presented investigations was to detect pollution of the Mała Panew River sediments. A particular focus is by frequently repeated bed sediments sampling to illustrate rehations between changes in morphology of sandy bed and heavy metal concentrations.

Study Area

The Mała Panew flows in southern Poland. From its sources in the western part of the Silesia Upland to its confluence with the Odra River its length is 132 km. The mean annual discharge in the middle reach, downstream from the confluence with the Stoła River, is ca. 10 m^3/s. The river channel is incised into fluvioglacial sands. Relatively rapid bank erosion, of the order of 0.5 m/year, supplies sandy material to the channel which, in the form of numerous sandbars, is transported downstream.

The largest sources of pollution of the Mała Panew River are situated in the upper part of its drainage basin (Fig. 1). The town of Tarnowskie Góry (about 60,000 inhabitants) discharges untreated effluents via the Stoła River. The sewage contains both domestic and industrial effluents from several electrochemical plants. Additionally, leaching of spoil heaps of the former chemical plants in Tarnowskie Góry to the ground waters causes pollution of the Stoła River with barium, boron and strontium, whereas zinc, cadmium, copper and lead are released in much lesser amounts. The conductivity of the Stoła River waters in 2002 was about 1200 μS, ChOD over 300; the content of phosphates was about 15 mg/l, ammonium 35 mg/l and sulphides 0.08 mg S/l [10]. Heavy metals are discharged into the Stoła River via the stream Graniczna Woda from a zinc smelter in Miasteczko Śląskie. About 0.1 mln m^3 effluents discharged in recent years contain 70-100 kg of zinc, 10-15 kg of cadmium and 30-50 kg of lead per year. However, in the 1970s and the 1980s the plants discharged much higher loads of zinc, lead and cadmium, which reached 60, 6 and 18 tons/year, respectively.

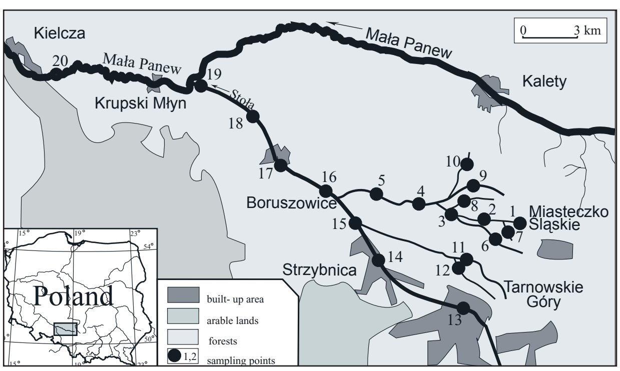

Fig. 1. Research area and sampling points.

The pollution of the river sediments by heavy metals was investigated already in the 1970s. The concentrations of barium, cadmium, copper, lead and zinc were elevated above background values in Stoła and in Mała Panew downstream of the confluence with Stoła and (in bulk samples) reached 2500, 116, 200, 490 and 5000 ppm, respectively [11]. Monitoring of river sediments in the lower course of the Mała Panew and investigations of the Stoła Rivers also confirmed high metal contamination, especially by cadmium in the 1990s [12, 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].

Method

Sandy bed sediments were collected 12 times in the period 4.12.2000 – 29.10.2002 every 1-3 months. Grab samples were taken from the active channel bed at exactly the same 0.5 m^2 surfaces at 6 locations in Krupski Młyn and at 4 locations in Kielcza. At every time stream velocity over the sampling surface and water depth were measured. Additionally, samples of bed sediments were taken at 19 points from the Stoła and Graniczna Woda channels as well as from several streams and ditches draining the area close to Miasteczko Śląskie and Tarnowskie Góry (Fig. 1). Samples were collected into polyethylene bags and then dried at 105°C. Samples from Mała Panew were sieved through a 1 mm sieve, whereas the remaining samples, including near bank Mała Panew sediments, were sieved through a 0.063 mm sieve. About 0.5 g samples were digested in Teflon bombs using a microwave technique with 10 ml of concentrated HNO_3 and 2 ml H_2O_2. The concentrations of barium, cadmium, copper, lead, zinc, manganese and iron were subsequently determined using atomic absorption spectrometry. Analytical precision and accuracy were determined by inserting blind duplicate and a reference sample and were generally better than 10%. The organic matter was estimated by loss on ignition at 450°C for 5h. Moreover, samples were wet sieved to determine the content of silt and clay fractions.

Results and Discussion

Channel Sediments Pollution

Generally, concentrations of heavy metals in fine fraction of the investigated bed sediments are very high. Particularly, high cadmium, lead and zinc content in the Graniczna Woda suggests that in spite of improved sewage treatment efficiency, the zinc smelter in Miasteczko Śląskie still discharges strongly polluted effluents into this stream (Fig. 2). However, the high metal content could also reflect the accumulation of fine, strongly polluted particles in the river bed for a fairly long time. This could

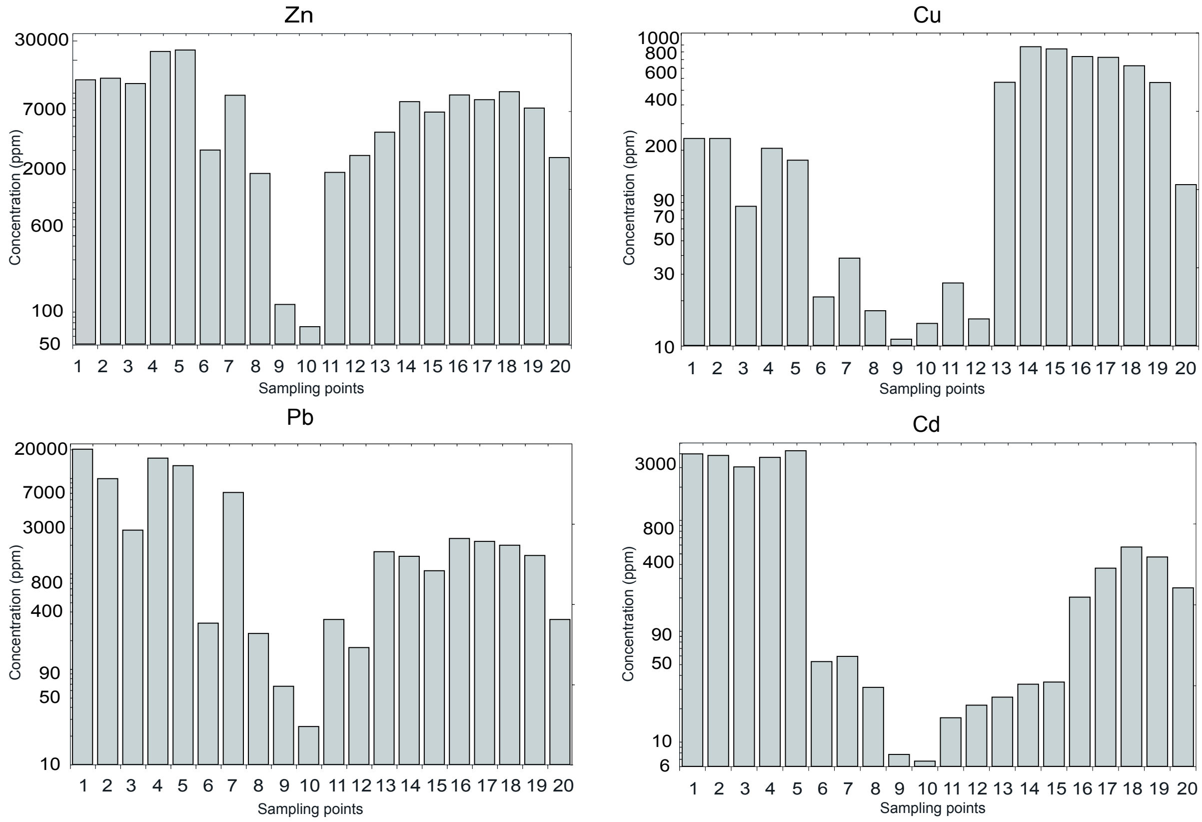

Fig. 2. Heavy metal concentrations in river bed sediments (see map for numbers of sampling points).

have taken place because rare, high water discharges in mainly artificially swelled streams, makes the erosion and winnowing of fine polluted sediments episodic. Certainly, in some sampling points, over 30% organic matter content also affected metal concentration.

High content of cadmium, 30-50 ppm, and of zinc, 2000-3000 ppm, and much lower of lead, 200-300 ppm, in ditches draining the area very close to the zinc smelter suggests leaching of these elements from sandy forest soils, which have been severely polluted by dust emission since 1970. The cadmium and zinc leaching can also be confirmed by the high percentage of these elements in easily mobile exchangeable form. As much as 50-60% of cadmium and 20-45% of zinc contribute to this form in the most polluted hydromorphic soils, especially moderately and strongly acidified (<5.5 pH) [15]. Also in the polluted Mała Panew overbank sediments this contribution varies between 60-80% for cadmium and 30-60% for zinc [16]. It seems that, in spite of small discharge in ditches, the waters draining the polluted soils can significantly affect water and sediment quality in Graniczna Woda and in Mała Panew. Additionally, effluents from Tarnowskie Góry make pollution of the Stoła stream sediments significant.

All the sources cause contamination of the Mała Panew along its middle reach. Particularly high is the cadmium content which, in fine fraction, varies between 200 and 600 ppm. Heavy metal concentrations in the fine fraction of investigated sediments can be compared with sediments of the other rivers. Similar contamination occurs in rivers receiving effluents from zinc and lead mines [7, 17]. It is much higher than the pollution of larger European rivers [18, 19]. Both sediments and soils in the upper part of the Mała Panew drainage basin represent Poland's "hottest spot" with a possible long-term effect on the Mała Panew water quality.

Heavy Metal Concentrations in the Mała Panew River Bed Sediments

An analysis of the metal content in separated fine fraction gives an opportunity for the comparison of sediment pollution in different rivers. However, the metal content in bulk sample better reflects pollution of sediments. Mała Panew river bed sediments consist exclusively of fine and medium grained sands <1 mm and just this fraction was analyzed for metal content. Homogenous sands are reworked and mixed in the channel with fine, mainly organic sediments which originate both from pollution sources and from the decay of leaves and twigs, abundant in the channel along the entire forested river reach. The fine organic particles are transported in suspension during low, average and higher river discharges and accumulate in places with slow flow velocity. High losses on ignition of the order of 30-60% in fresh deposits on the grassy surface at the bank, a few hours after a small flood wave receded also proves the domination of organic matter in

Table 1. Medians and upper and lower quartiles of heavy metal concentrations in fraction <1 mm in the Mała Panew River bed sediments [ppm].

Sampling site			Zn	Cd	Cu	Pb	Ba	Mn	Fe
Krupski Młyn	I Bar	25%	151.7	17.6	7.7	12.8	27.5	22.1	1255
		Me	200.4	24.0	10.1	17.1	69	37.4	1713
		75%	287.4	29.8	14.4	25.2	189.5	49.3	2232
	II Bar	25%	158.9	15.8	8.1	11.5	21	28.1	1402
		Me	185.8	19.6	8.3	12.8	57.5	27.4	1542
		75%	201.2	18.9	12.1	20.6	117.5	52.6	1658
	III Bar	25%	145.8	15.1	7.6	10.6	10	19.5	1276
		Me	188.3	17.5	8.8	13.5	73.5	32.8	1507
		75%	177.1	18.4	9.6	17.7	105.5	36.7	1706
	IV Bar	25%	159	12.1	10.7	17.3	44	34.2	1497
		Me	223.1	18.1	12.8	25.8	101	58.6	2535
		75%	268	22.4	16.5	35.3	175	11.4	3379
	V Bar	25%	160.9	13.8	7.6	11.9	30.5	23.7	1303
		Me	171.9	16.8	8.1	13.2	86	28.6	1404
		75%	229.4	20.3	11.1	22.3	149	46.1	2062
	VI Point bar	25%	177.8	17.1	6.8	11.0	28.0	21.8	1355
		Me	163.4	19.6	8.2	12.2	17.5	22.6	1392
		75%	211.0	22.6	11.5	17.8	133.5	49.2	1780
Kielcza	VII River bank	25%	476.3	48.0	26.2	64.0	337	80.8	3987
		Me	626.4	62.2	33.8	79.9	437	119.1	6033
		75%	1093.0	120.0	57.3	134.8	983	150.7	10201
	VIII Current zone	25%	58.0	5.2	5.0	9.2	11	35	1450
		Me	75.5	10.1	5.9	11.5	28	81	1586
		75%	121.2	12.1	7.1	15.3	54	100	2374
	IX Bar at riffle	25%	181.4	30.1	8.1	17.3	21	13.5	1079
		Me	201.5	32.6	8.4	18.3	38	14.9	1167
		75%	229.0	39.5	8.7	21.2	44	16.2	1264
	X Dead zone	25%	288.6	32.9	13.8	27.3	68	37.6	1857
		Me	344.9	42.9	18.2	35.7	134	64.4	2305
		75%	454.6	64.5	31.7	71.1	275	89.2	4023

suspension.

Due to the small content of fine sediments in the bed, which usually does not exceed 1%, metal concentrations in the <1 mm fraction (Table 1) are much smaller than in fraction <0.063 mm (Fig. 2). The differences vary between 10-20 times and depend on the particular element. Nevertheless, cadmium concentrations are still exceptionally high in the coarse grained faction. Generally, medians of metal concentrations are similar in all sampling sites in which sand bars occur. Much higher concentrations occur in the dead channel zone and particularly at the river bank. Very low river bank (site VI) is inundated several times per year already at discharges higher than average. Frequent inundations enable accumulation of highly polluted organic matter and its thickness reaches a dozen or so centimeters. However, the lowest metal concentrations occur in the deepest site in channel cross-section – in the current zone. This confirms the earliest findings that high flow velocity precludes accumulation of fine, polluted particles or particles accumulated at low water stages are scoured during the higher ones [4]. However, higher manganium content than in sandbars could be related not to the particle accumulation but precipitation of manganium hydroxides on coarser grains of sand as a result of oxygen supply to the bottom by eddies [3].

Changes in River Bed Morphology and Heavy Metal Concentrations

Heavy metal concentrations differed several folds during the observation period in most sites of the active channel. The largest differences occurred in sites with pronounced changes in river bed morphology. On the contrary, the smallest ones were observed in sites, the morphology of which was less affected by changes in river current velocity and where water depth was related solely to river discharge. Almost all changes in metal concentrations are related to transport of bed material during higher water discharges in the form of sandbars. Bars in this relatively small, 10-20 m wide river are usually 40-60 cm high and several meters long. During the two relatively wet years, bankfull stages were observed 3 times and at sampling sites, bars could have been effectively migrated to at least a dozen meters downstream. Migration of bars at sites I and II are examples of relations between changes in bed morphology and metal concentrations (Fig. 3).

Initially, the bar was observed close to the river bank about 3-4 meters upstream from sampling site I. Bar top

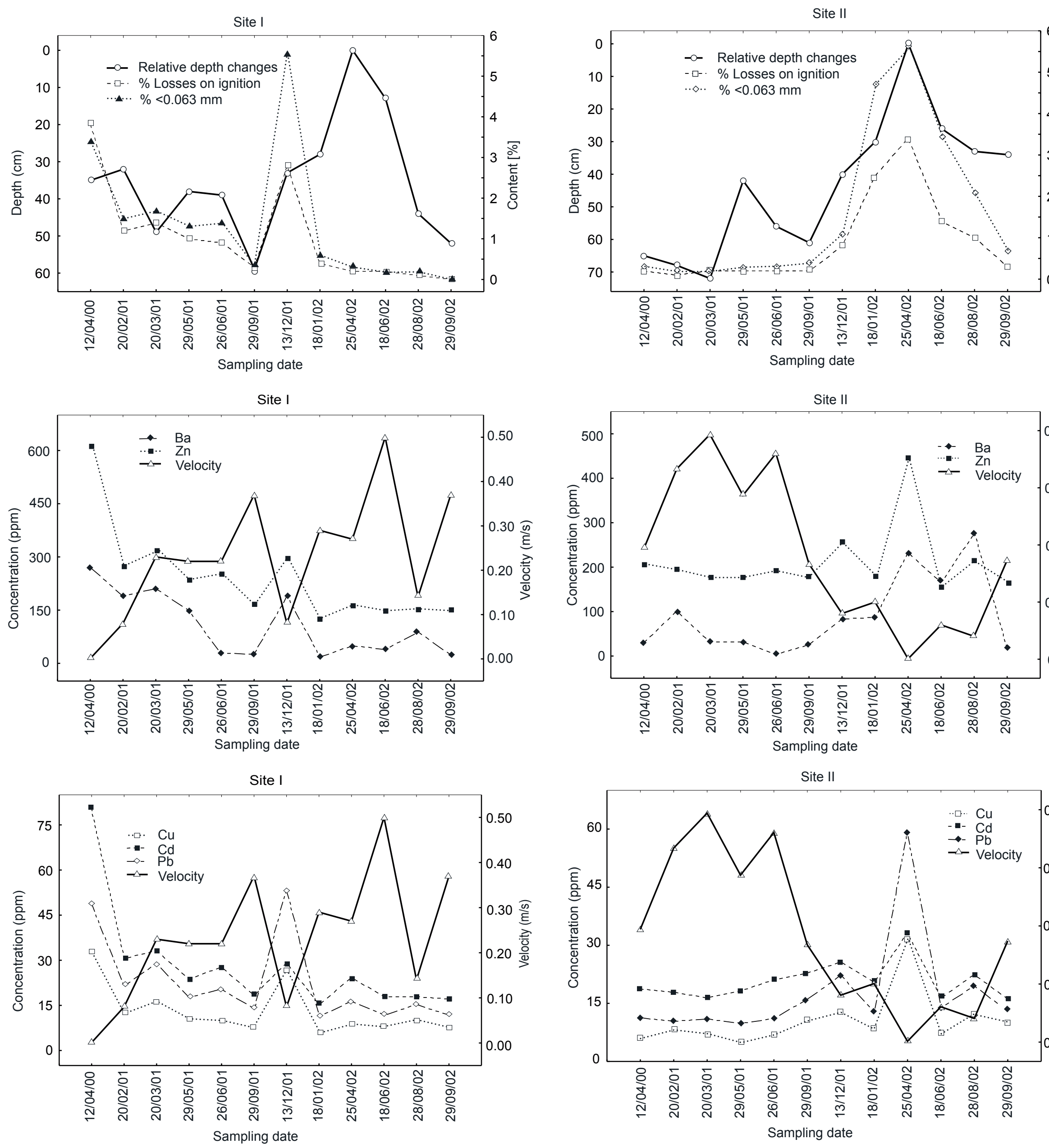

Fig. 3. Changes of the investigated parameters of bed sediments in sites I and II (details in the text).

reached almost the water surface and caused flow diversion towards the mid-channel. In consequence, the sampled surface was situated in a small accumulation basin of about 2m^2, separated by a sand ridge from the current zone, with almost no flow – the so-called dead zone. Here, about 2 cm thick, a black organic layer accumulated. Relatively high and similar content of both fine fraction and losses on ignition, indicate an accumulation of solely organic particles. The relatively high organic matter content resulted in high concentrations of the heavy metals investigated. The water depth in this place increased in the following few months as a result of dead zone and bar erosion during higher discharges. A slow increase in flow velocity to 0.2 m/s, observed on 20.03.2001, caused a marked drop both in organic matter and heavy metals content. A flood in April 2001 shifted the bar top slightly downstream from the sampling site. The bed surface accreted and the flow velocity increased also as a consequence of the other mid-channel bar accumulation in the proximity of the sampling site. Bankfull water stages in summer 2001 formed the next bar upstream, whereas sands of the first bar were scoured away. In consequence, water depth and stream velocity increased markedly. Again in autumn 2002, the next bar started to accrete and on 13.12.2001 the second dead channel zone became a sink for polluted fine sediments. During low and average flows in winter and early spring 2002 sand accumulation continued: the dead zone was filled with sands and the bar

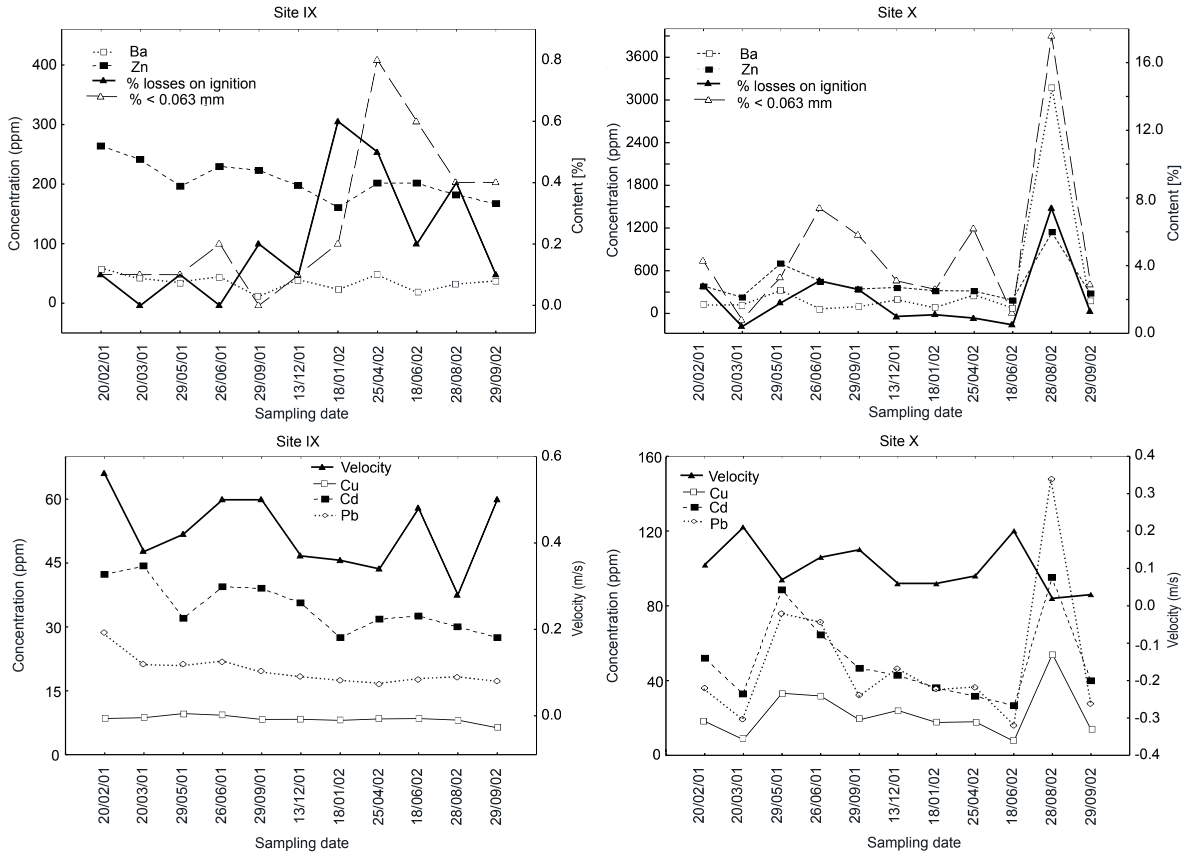

Fig. 4. Changes of the investigated parameters of bed sediments in sites IX and X (details in the text).

top emerged over the water level. The shallow, 10-20 cm, waters flowed with higher velocity, over 0.2 m/s as the bar became a part of the bigger transversal bar. Content of fine fraction as well as heavy metal concentrations were very low in the strongly reworked surface sediments of this bar. Further, the flood of June 2002 eroded this bar. Bed level lowering was continued also in autumn 2002 during average discharges.

Changes in bed morphology were observed also at site II (Fig. 3). However, only one channel bar migrated during two years over this site. Initially, for almost one year no changes of bed level were observed. During this period, relatively high velocities and low fine particles and organics content were accompanied by low heavy metals content, except for cadmium, which still occurred in high concentrations. In autumn 2001 a tree branch transported by the river stopped at the bank and initialized bar accumulation. The bar grew quickly upstream of the sampling site and within three to four months it shifted the stream current towards the opposite bank. At the sampling site the anticlockwise circulating current caused the separation of a dead water zone from the quickly flowing stream with a sand ridge. Again, in the dead zone formed on the distal side of a bar, fine, polluted sediments accumulated. The accumulation continued until the summer flood of 2002, which eroded the top part of a bar and winnowed fine material. As a result, bed level lowered and flow velocity increased markedly, although low water stages in the autumn of 2002 predominated.

Changes of river bed morphology were observed also in the other sampling points. However, not all the changes resulted in parallel changes of heavy metal concentrations. The examples given above show that these concentrations increase as soon as flow velocity is slower than 0.2 m/s. It is especially marked if flow velocity is below 0.1 m/s. Always, slow velocities enable polluted organic matter accumulation, which for small mass density is easily eroded even at a small increase in flow velocity. All the changes in morphology and pollution at particular channel locations were related to higher river discharges. Moreover, bars, when passing by sampling points, affected stream flow velocity, which in turn affected the pollution of surface sediments in these points.

Changes in bed morphology in several channel locations did not affect heavy metal concentrations and below, two examples are presented (Fig.4). The mid-channel bar localized at the end of riffle (site IX) was strongly reworked by stream current flowing at predominantly high velocities 0.4-0.5 m/s. Here, almost at all discharges, content of both fine and organic particles was very small, usually <0.2%. Small changes in the proportion of fine particles were unrelated both to flow velocity and metal content. In sediments of this bar, content of zinc, cadmium as well as lead decreased markedly during two years of observations.

This could reflect the decrease in pollution load discharged into the river system mainly from Tarnowskie Góry or the exhausting sources of the most mobile metals in soils and sediments around zinc smelters.

However, the persistant dead channel zone (site X) was an important sink for fine, heavy metal polluted sediments. No marked bed level changes were observed here. However, because of the large, 7 km distance from the gauge station, the conclusion is not supported by water stage observations. Variations in the proportion of fine sediment in samples taken on particular sampling occasions seem to be related mainly to water discharge. The layer of fine, organic sediment was the thickest in autumn 2002 at the lowest discharge observed during the two years. At this time water flowed slowly to the dead zone only through a narrow depression in the sand ridge and no sediment erosion was possible there.

Conclusions

1. Marked changes of river water discharge during 2 years affected the morphology of the Mała Panew River bed. Migration of small sandbars, which were several meters long and several tens of cm high, was observed at all locations of the active channel bed. Usually, a dead zone which trapped fine sediments polluted with heavy metals appeared in front of a bar. It occurred usually for several months until it was eroded by flood or filled with sand in the case of bar front accretion. During sampling one or two bars passed by most of the channel locations. As a result, significant, several fold changes of heavy metal concentrations were observed over a relatively short period.
2. The critical flow velocity for settling fine, polluted organic matter is about 0.2 m/s. However, maximum heavy metal concentrations occur in locations with velocities slower than 0.1 m/s. The bed area over which these velocities occur is confined to the near bank zone and expands markedly during low water stages. This suggests that length of channel banks, the largest in naturally meandering rivers, affects fine sediments entrapment.
3. The smallest variations in heavy metal concentrations occur both at channel banks and deep on the channel bottom, on which the relatively small variations in flow velocity and bed morphology occur. These places seem to be suitable for the observation of trends in river pollution without any sample normalization procedures.

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