The reconstruction of river system pollution changes with metals in shallow floodplain water reservoirs during the onset of the post-industrialisation period

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Abstract: Towards the end of the 20th century, Poland's economy experienced a transformation in terms of its industry and increasingly stringent environmental requirements. Together, these resulted in the general improvement of the quality of the aquatic environment. The Chechło River catchment is an example of such changes, where the closure of many industrial plants (including a zinc-lead [Zn-Pb] mine), the reclamation of several hot spots and the extension of sewage treatment contributed to a general decline in sediment pollution with Zn, Pb and Cd. The aim of the investigations was to evaluate the rate of these changes in order to assess the river recovery rate to the pre-industrial pollution level. The research involved the comparison of sediment pollution in subsidence reservoirs from two different eras: the peak of pollution and the post-industrial era. We observed a decrease in sediment pollution, mostly influenced by the closure of the Zn-Pb mine in 2010, despite many sources being closed or mitigated at that time. The change in sediment pollution was very well observed in the younger reservoir of the post-industrialisation period which is an efficient trap for sediments transported since ca. 2007. Considering that the sampling took place less than 10 years after the closure of the mine, we could regard the 3–4-fold drop as a rapid change. In older reservoirs, which were active already during the period of peak river pollution but connected with the river only by narrow ditches, changes in sediment pollution were minor. Pollution changes expected in the future will be much slower because the supply of pollutants from diffuse sources has dispersed in the prevailing part of the catchment.

Keywords*:* sediment, pollution, river, heavy metals, recovery, reservoirs

INTRODUCTION

Extensive industrialisation induced the widespread pollution of river systems with heavy metals. Over the industrialisation period, the metals entered rivers with waste waters being discharged directly into rivers and via leakages from sewage purification systems, storage reservoirs and waste heaps. The largest sources involved metal mines and smelters, electroplating, paint chemistry and the metal machinery industry which, in industrialised regions, generated large amounts of mixed metal compounds being transported downstream for tens or even hundreds of kilometres

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(Foster & Charlesworth 1996). Whereas the peak in the pollution with metals of the largest rivers in most of the Northern Hemisphere occurred between 1950 and 1980 (Dendievel et al. 2020), smaller river basins may have been polluted by intermittent metal mining activity over a much longer operational period (Macklin et al. 2023). Individual peaks of metal mining separated by phases of mining declining could be usually not longer than several decades until ore exhaustion (Byrne et al. 2012). Generally, toward the end of the 20th century, developed countries transformed heavy industry into becoming more environmentally friendly, many metal ores had been exhausted, and associated smelters were closed. This, together with shifting the heavy and energy consuming industry to rapidly developing economies, resulted in a general decrease of river systems pollution with heavy metals (Meybeck 2013). The post-industrial era began with recovery of river systems, which often is meant as the period needed to evolve into equilibrium characteristic for stable or low pollution of the preindustrial period (Moore & Langner 2012).

The industrial era left a legacy of sediments resulting from human transformation of the environment, which is viewed as the industrial and agricultural testimonies of past anthropogenic activities reflected in the physical and chemical properties of sediments (Gardes et al. 2020). Human activity could be recorded in sediments which accumulate in different sub-environments of all river systems. The reconstruction of the pollution in the sediment strata, particularly after closure of most the important polluters in a catchment, help to estimate the rate of system recovery and the need for sediment or hot spots remediation (Bird 2016). The accuracy of the reconstructions depends on many features of the particular sub-environment sampled, sediment properties, and a pollution source. Overbank sediments are the most widespread sampling medium present in every river valley. Nonetheless, sediments of lowland rivers with regular flood inundation of the valley are the best for reconstructions where sampling sites are selected of moderate and relatively constant sediment deposition rate and in proximity of a pollution source with possibly the highest metal content (Ciszewski 2003). In mountain or upland river valleys sediments are deposited by higher flow velocity currents with dominating coarse sediments (Dieras et al. 2013). Rivers have higher energy and intensively erode both river banks and even previously stored deposits making difficult preservation of longer sediment sequences and pollution records can have gaps which are difficult to identify (Taylor 1996).

The best for reconstructions are lake sediments, where steady deposition with moderate sedimentation rate promises sufficient resolution and due to larger depths, of the order of several or more metres, the sediments are not disturbed by wave action or bioturbation (Schindler & Kamber 2013). Other important factors are grain-size distribution, mineralogical composition, adsorption and redox processes (Couillard et al. 2004). Unfortunately lakes are rare in river valleys and can be utilised for only sporadic deciphering of pollution records. In some river systems, sediments from artificial reservoirs can be successfully used as an effective archive of pollution changes. Nevertheless, records of reservoir sediments can be strongly affected by hydrological regime of reservoirs with erosion of long sediment sequences during emptying or rapid sediment inflow during flood episodes (Sedláček et al. 2013). Oxbow lakes are the other type of the fluvial sub-environment utilised for reconstruction of alluvial sedimentation (Shen et al. 2021). They are usually representative for pollution of large lowland river systems where regular connectivity with the river ensures regular inundation and effective fine sediment entrapment (Bábek et al. 2008). Permanent oxbow lakes in wide lowland valleys provide better archives for long-term chronologies, when supplemented by historical maps or isotope dating, than usually narrow and shallow abandoned channels of upland and mountain rivers (Nguyen et al. 2009).

This study aimed to reconstruct the rate of the pollution change in the Chechło River, a small upland catchment in Upper Silesia, southern Poland, in response to local industrial transformation. For this purpose we utilised sediments filling shallow floodplain water reservoirs that appeared in two different periods of time in the valley floor as a result of land subsidence caused by mining activities. We aimed the comparison of the sediment pollution in reservoirs of the two different ages in order to assess the river recovery rate to the preindustrial level. Because of clear difference between the industrial and post-industrial phases the reservoir sediments represent, we sampled them in a way making the comparison straightforward, i.e. surface and subsurface strata of the same thickness in both reservoirs, supplemented by profiles collected together with the ground surface of the former floodplain. The method applied for reconstruction of a river system pollution changes with metals is unique as it effectively utilises specific site with subsidence reservoirs of known age, which appeared in the period of local industry transformation. For the sampled reservoir sediments, we did not perform high resolution sampling because of their short deposition age (ca. 10 years after the younger reservoir emerged), strongly variable deposition rate, and erosional gaps made isotopic dating of little value. Instead, the detailed isotope chronology was applied for overbank sediments and only for the longest profiles from the older reservoir (Ciszewski & Łokas 2019).

MATERIALS AND METHODS

Study area

The Chechło River is a small, 2nd order river, about 23 km long and ca. 1.5 $m^3 \cdot s^{-1}$ of discharge, which drains one of the most industrialised parts of Poland (Fig. 1). The river flows across the zone of tectonically dislocated Tertiary horst hills where grabens are filled with fluvioglacial sands. The river channel is weakly modified in the forested area of the upper reach and changes dramatically in the densely inhabited middle reach affected by mining. The channel is straightened and lined on the prevailing part of this reach until it reaches the lower section, where the river dissecting sandy deposits becomes naturally meandering. In the lower reach, the channel gradient decreases and the average width of the channel varies between 5–8 m.

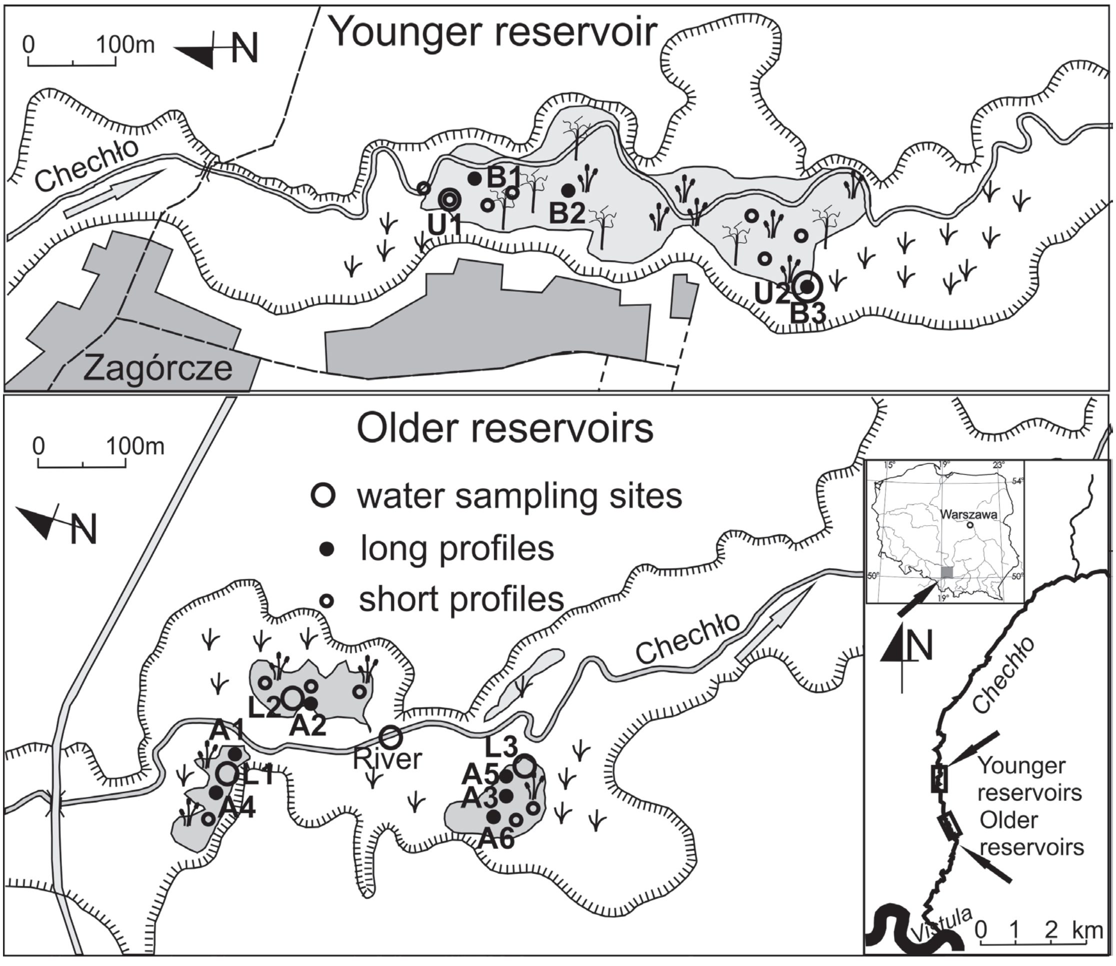

Fig. 1. *Location of research area and sampling sites. Long profiles: A1–A6, B1–B3; water sampling sites U1–U2, L1–L3, river; names of short profiles are not given*

The 110 km^2 of surface Chechło catchment covers an area of historical lead and zinc mining which, the most intensively, exploited metal ores between 1968 and 2009. The mine was situated in the middle reach of the river and it discharged mine waters amounting up to as much as one third of the river's discharge. The operation of the mine contributed the most in river sediment pollution with zinc, lead and cadmium which exceeded in some cases local geochemical background by 1,000 times (Ciszewski 1997). However, the mine was not the only single pollution source of the river. The mid-part of the catchment was inhabited by over 60,000 peoples living mainly in the cities of Chrzanów and Trzebinia. There were also many large industrial plants functioning in the two cities: an oil refinery, coal mine and power plant, railway engines factory, metal smelter, meat producing plant, rubber plant, fireclay and cement plant and many smaller enterprises. At the beginning of the 1990s, most of the industrial sewage was treated in own sewage treatment plants but part of the industrial and also domestic effluents were insufficiently treated and discharged directly or indirectly into the river (Ciszewski 1997).

The fall of communism in Poland at the end of 20th century resulted in large structural changes in industry. In the Chechło catchment they were accompanied by exhaustion of the metal ores and decline of the ore excavation from the beginning of the 21st century. The zinc and lead mine was finally closed in 2010, and the metal smelter in 2013. The other plants were closed or – due to more strict environmental regulations –were forced to improve sewage treatments. Some of them in the same period were connected to a significantly extended sewer system in both cities, and also over 6,000 individual households were connected to a central biological treatment plant in Chrzanów (Bogusz 2020).

The region of eastern part of the Upper Silesia is known for extensive longwall coal mining, and land subsidence in the Chechło River valley first appeared at the beginning of the 1990s. It resulted in flow-through depression filled with water and alluvia and later on with autochthonous organic material. The reservoirs appeared at a time of peak river pollution from a lead-zinc mine and from several plants operating in the upstream part of the catchment (Fig. 1). Again, about 1 km upstream of the older reservoirs, the ground subsidence – which started at about 2007 – resulted in the appearance of the other flow-through reservoir. This phenomenon coincided with the closure of the metal mine and overall decline of the industry in the region.

The older subsidence basin extends over the distance of ca. 600 m with the river flowing through its central part. It is confined to the average width of 200 m by Pleistocene terrace, up to 8–10 m high (Ciszewski & Sobucki 2022). At present, due to sedimentation of alluvia, the water is ponded in three separate shallow reservoirs connected with the main channel by artificial ditches, whereas the channel itself is separated from the rest of the ponded depression by the natural levee 0.5–0.6 m high. The average depth of reservoirs is about 30–50 cm but maximum values reach about 1–1.2 m. Their area is ca. 0.5–1 ha but the prevailing part of their surface is overgrown with macrophytes. The area of the younger reservoir is about 5 ha and with a width equal to the Holocene valley bottom; its length is about 500 m (Fig. 1). In its proximal part with intensive sedimentation processes, the river forms a delta and muddy deposits periodically emerge over the water table on one third of the reservoir. This section of the ponded depression is overgrown with a forest of dead trees. The depth of the depression in its central part within the former channel exceeds 2 m, but on the side parts with the former floodplain, the depth of water is about 1 m. The littoral part of the reservoir is colonised with reeds and filled with organic deposits.

Sampling and measurements

Sediment sampling sites were tested several times until a location with at least a 20-cm-thick stratum of mud was found. Sediment cores of 4.5 cm in diameter were retrieved standing on the bottom in shallow parts of the ponds or from a dinghy with a multisampler piston corer (Eijkelkamp, Giesbeek, Netherlands). In total, 12 short (20–30 cm) and 9 long (30–60 cm) sediment cores were taken.

Short sediment cores were obtained from six sites in the younger reservoir and in six sites in the older reservoirs (Fig. 1) and then split into surface and subsurface strata, of equal thickness, each 10–15 cm thick. Moreover, sampling sites for longer sediment cores were selected considering different sediment deposition rates, potentially varying from the highest (the largest sediment thickness), through moderate (moderate thickness) to the slowest with smallest thickness of the muddy sediment. The coring aimed to reach sediments of the former floodplain surface where possible and considering the distance from the inflow of river water from the channel. The sediments filling ponded depressions are represented by fine grained muds, which in most of profiles were easily distinguishable in profiles from the sediments of the former valley bottom, so in most cases it was relatively easy to group them into the three classes of the sedimentation rate basing solely on the relative differences in their thickness. In total, nine sediment cores up to 60 cm thick were taken from young reservoir (B1, B2, B3) and from old reservoirs (A1, A2, A3, A4, A5, A6) and were divided into sediment strata 5–10 cm thick.

Waters were sampled from three reservoirs in the older depression and in two sites (inlet and outlet) of the younger reservoir (Fig. 1). Additionally, waters were sampled from the river in the older subsidence depression as well as from the unpolluted reservoir situated in the lower part of the Chechło River basin, about 1 km west from the river. All samples were taken four times a year (April, July, September and October).

Sediment samples were dried at 105°C and sieved through a 0.063 mm sieve. 0.5 g of each sample was digested with concentrated 10 mL of nitric acid and 2 mL of perchloric acid using microwave digestion technique. The concentrations of Zn, Cd and Pb were determined using inductively coupled plasma-mass spectrometry (Perkin Elmer ELAN 6100, PerkinElmer Polska Sp. z o.o., Krakow, Poland) in the certified laboratory at AGH University, Poland, according to quality control procedure (PKN 2007).

The water samples were measured for pH, conductivity, Cl^-, NO_3^-, PO_4^{3-}, NH_4^+, Mg^{2+}, Ca^{2+} and Zn, Cd and Pb. pH and conductivity were measured using a WTW (Multi 340i/SET 2) handheld multimeter. Water samples were filtered through 0.45 µm syringe filter and analysed for anions and cations within 48 hours using ion chromatography (DIONEX, Dionex Corporation, CA, USA). Concentrations of Zn, Cd and Pb were measured in total and in dissolved fraction (after filtration through a 0.45 µm filter) using atomic absorption spectrometry with graphite furnace (Varian 20, Varian Techtron, Melbourne, Australia). Standard reference material SPS-SW1 (NIST) was used for checking the accuracy of the analyses.

RESULTS

The long sediment profiles are presented in Figures 2–4. In each profile, different thickness of the organic sediments (black), silty-sands with organics and sands were identified. All long profiles were divided into three groups, operationally referred to here as: profiles of the highest (cores A1, A2, B1), medium (cores A3, A4, B2) and the lowest (cores A5, A6, B3) deposition rate.

Profiles of the highest deposition rate are represented by profiles A1 and A2 of the old reservoirs where the thickness of organic sediment is equal to 0.5 m (Fig. 2). These organic sediments are clearly distinguished from the sandy bottom, which was identified by caesium isotope dating as the former floodplain surface (Ciszewski & Łokas 2019). The floodplain sediments are relatively easy to identify macroscopically also in the profile A2 as a hard surface of uniform and relatively bright, medium grained sands. The overlying sediments consist of dark muds which, towards the top, become black with a presence of poorly degraded organic particles. Both profiles are situated close to the river channel (5–10 m) at the ditch inlet and at the levee. We also included in this group the profile B1 from the younger reservoir collected in its proximal part, in the lateral zone of the delta section. In this part, the rapid sedimentation forms a delta, which moves progressively toward the reservoir centre even by dozen or so metres per year. The delta sediments consist mainly of medium grained sands, but the presence of sand decreases toward the marginal zone of the delta where slow flow conditions promote the deposition of muds. The 0.6-m-long profile B1 did not reach the floodplain bottom, but it consists of several-year-old sediments from the initial phase of the young reservoir existence, so the pollution fully reflects the post-industrial period.

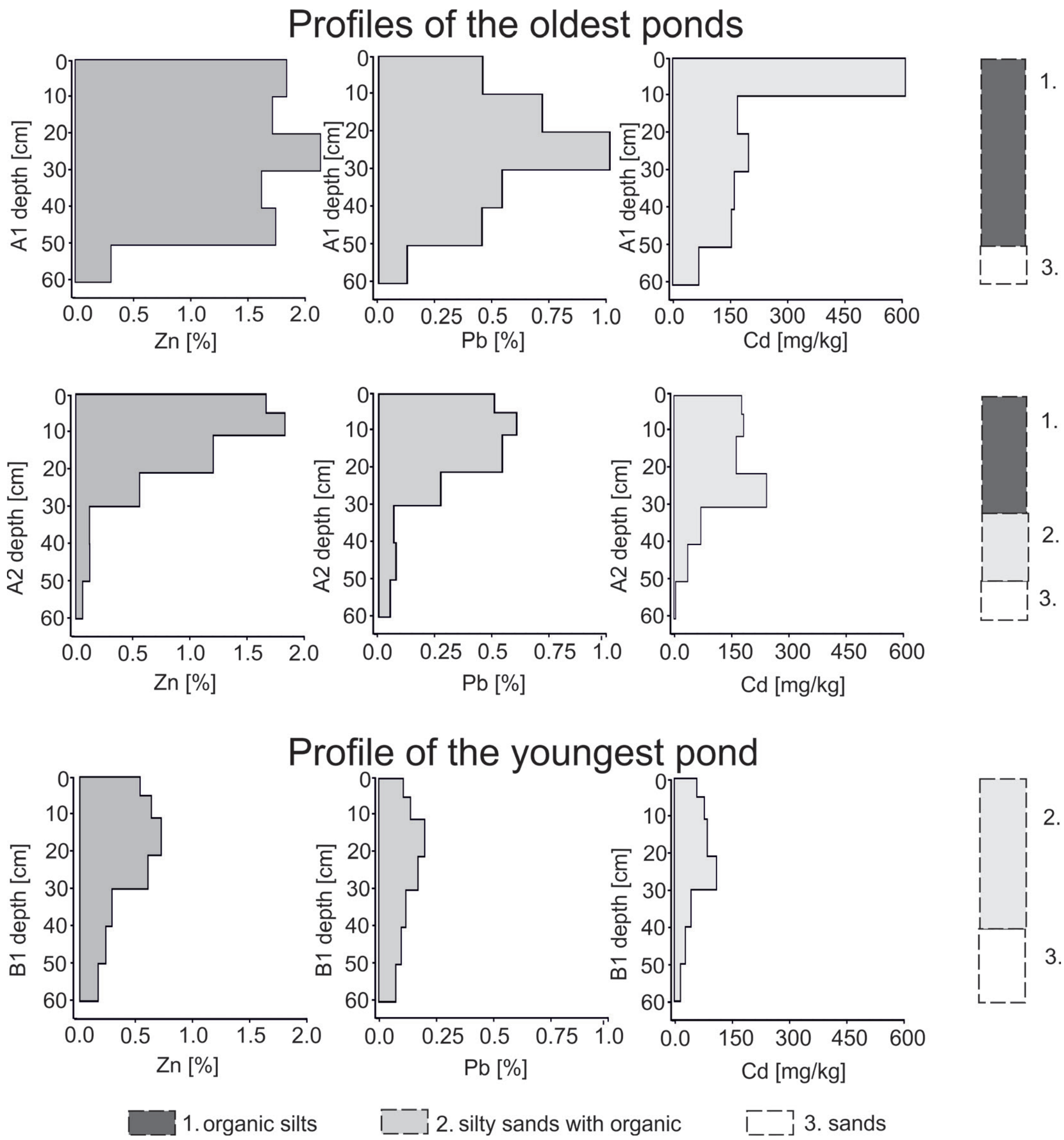

Fig. 2. *Sediment profiles of the highest deposition rate*

Sediments of medium deposition rate from the older reservoirs are represented by profiles A3 and A4 (Fig. 3). They differ from the sediments of higher accretion rate in regard to the smaller thickness of the muds resting on the medium grained sands, identified as the former floodplain bottom. Their thickness is equal to about 30 cm and the transition from bottom sands to organic muds is rapid, while dark mud stratum does not exist. Both profiles are situated in the central part of two reservoirs about 70–100 m from the outlet of ditches draining the reservoirs' waters. This part of both reservoirs is the space of open water and not overgrown with macrophytes (Fig. 1). This group include also profile B2 from the younger reservoir (Fig. 3). The profile is situated in the outer part of the delta section with sandy deposits intercalated with muds. However, as the distance from the river mouths to the profile is comparable to that between the respective profiles and the drainage ditches in the older reservoirs, the bottom sands could not be certainly identified as the former floodplain bottom. Probably medium and coarse grained sands of the profile bottom can be related to initial stage of the delta formation after the ground subsidence. Nevertheless, the young age of the sediments is clear, as well as their representativeness for the post-industrial period of pollution.

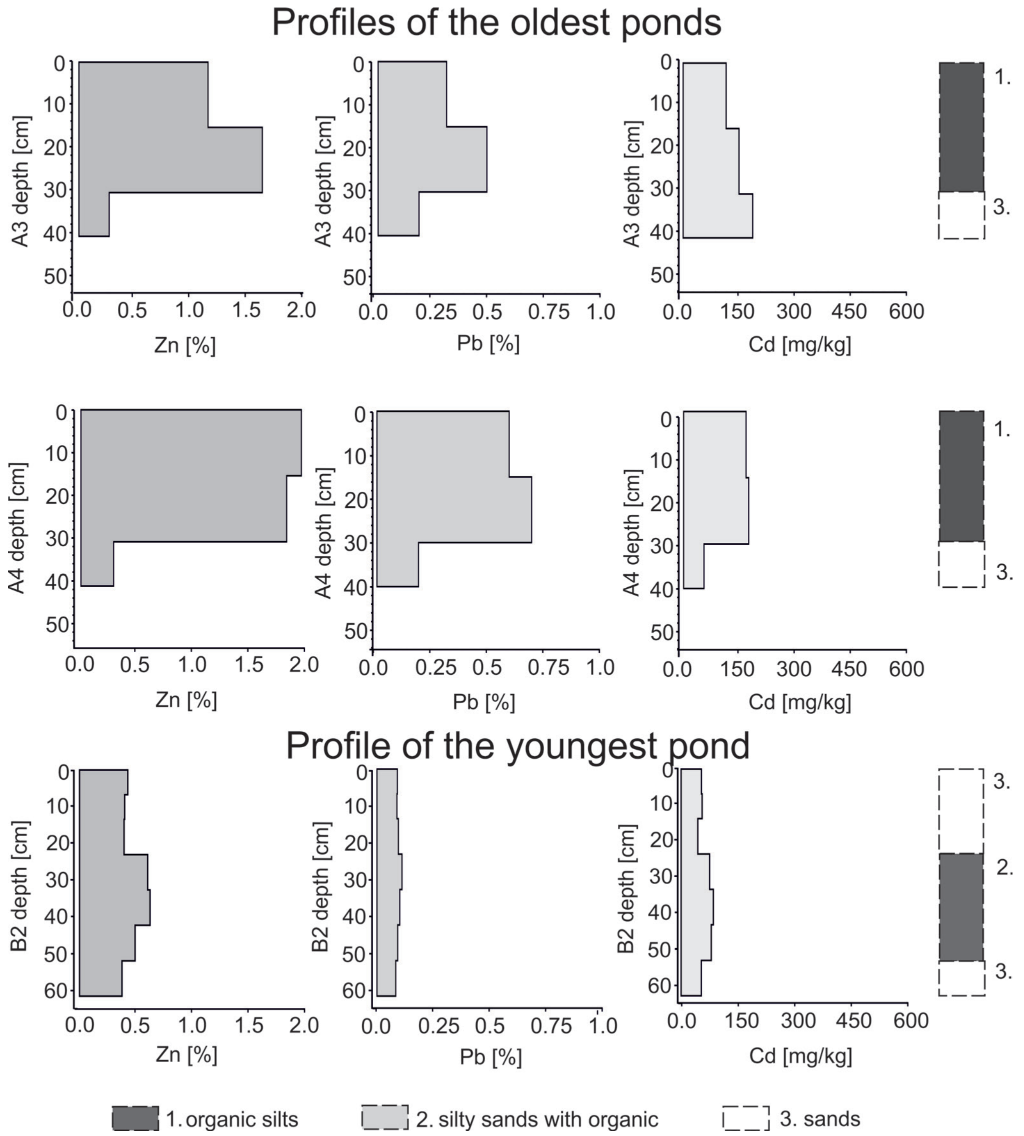

Fig. 3. *Sediment profiles of the moderate deposition rate*

Profiles A5 and A6 from the older reservoirs of the lowest deposition rate had the smallest thickness of the organic, black muds (Fig. 4). This is comparable in both profiles; however, they differ a little in respect of the stratigraphy. In the profile situated closer to the channel (Fig. 1), the 10-cm bottom part of the whole 15-cm organic stratum contains fine grained sands, probably due to sediment supply with floods. The former sandy floodplain surface is well distinguishable at the bottom of the profile. Surprisingly, the thickness of organic muds is smaller than in the profile A3 situated far from the channel, probably due to its isolation from the rest of the reservoir by the zone of dense macrophytes which diminish the possibility of inflow of sediments from the ditch. The relatively large distance from the inflow of water from the river makes the sedimentation rate comparably small also in the profile A6. In this part of the reservoir, organic muds are only 10 cm thick, with an additional 10 cm of intermediate strata of dark muds resting on brown sandy sediments. The transition from floodplain to reservoir sediments is not very distinct due to diagenetic processes. Belonging to this group, the profile B3 from the younger reservoir is situated most downstream from the inflow of river water to the reservoir (Fig. 1).

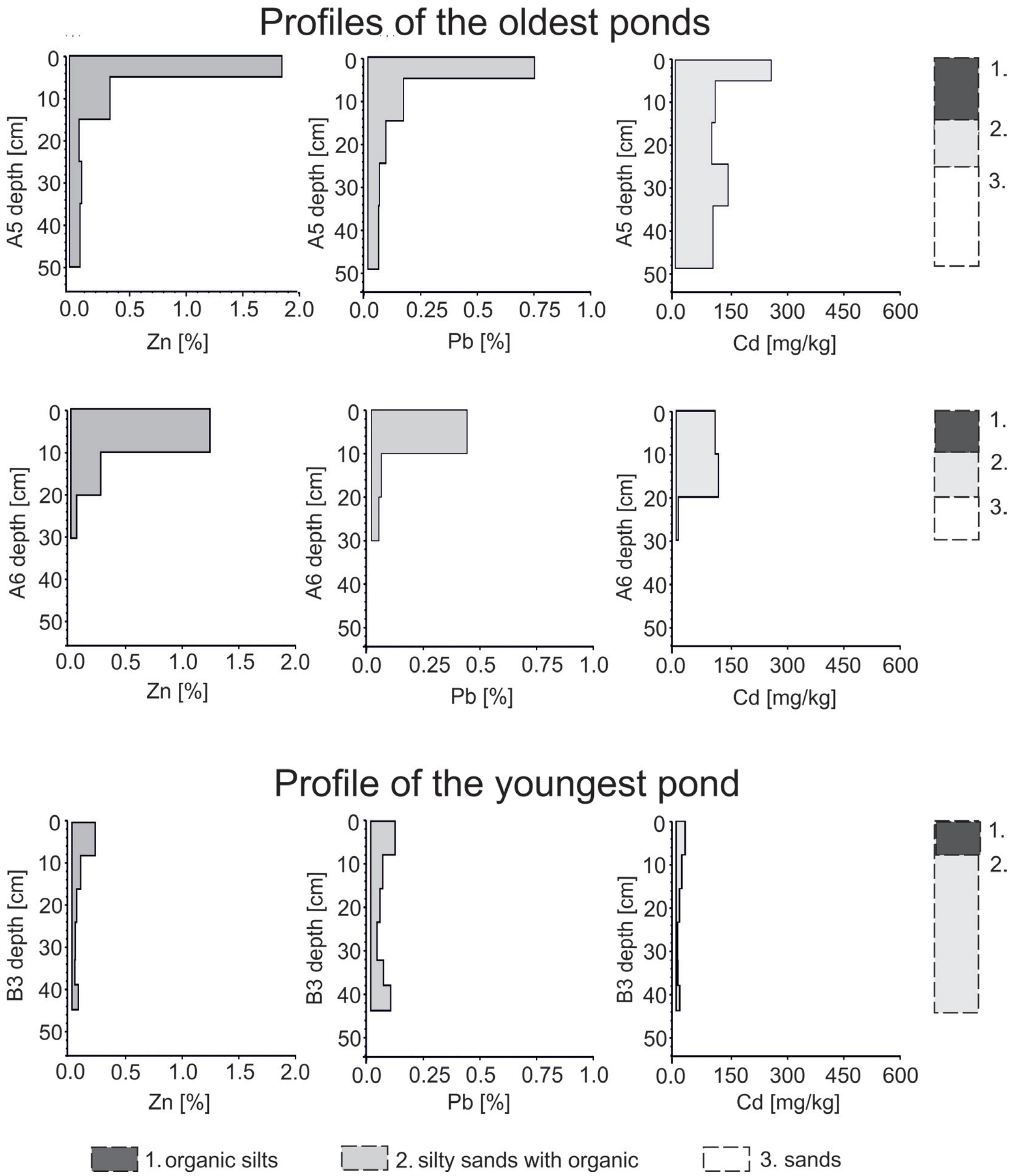

__Fig. 4.__ Sediment profiles of the lowest deposition rate

This distant part of the reservoir is virtually a dead zone, partly isolated from the main stream flowing in the central part of the basin. The organic sediments there are only at the 8 cm top of the profile, whereas the rest of the profile consists of weakly differentiated muds with a domination of clay deposits.

Surface and subsurface sediments sampled in twelve locations of all the reservoirs represent a uniform stratigraphy – mostly 20 cm of top strata of organic muds. The three locations from the delta section of the younger reservoir are the exception because autochthonous organics strata are not present there. The locations of these short profiles supplement the locations of the longer sediment profiles (Fig. 1). Their pollution with heavy metals is given in Table 1, separately for the older and younger reservoirs.

Water sampled in different locations of all the reservoirs allows for the identification of differences in the current status of the river and waters of particular reservoir (Table 2). Despite some differences in content of macroions, the presented values indicate a general similarity of river water quality and waters of the younger reservoir due to flow-through nature of the flow. In turn, much better quality of the waters in all three older reservoirs results from limited exchange capacity through the artificial ditch system between the river and the reservoirs. The water of the older reservoirs is of much better quality in terms of dissolved substances than in the younger one, however they are still much more polluted than waters of the reservoir supplied only with natural groundwater situated in the lower part of the Chechło River catchment.

Table 1
Metal concentrations in bottom sediments of younger and older reservoirs [mg/kg]. Number of samples N = 24

Sediment	Zn			Cd			Pb		
	Min	Me	Max	Min	Me	Max	Min	Me	Max
Older reservoirs of industrial era									
Surface sediments	9,553	12,066	19,901	89.4	160.6	612.3	2,021	4,419	5,817
Sub-surface sediments	2,176	15,810	19,816	95.4	160.4	236.3	404	5,016	7,235
Younger reservoir of post-industrial era									
Surface sediments	2,134	4,189	7,862	42.2	58.1	74.8	776	987	2,275
Sub-surface sediments	4,013	5,153	20,575	46.9	58.5	190.7	890	1,000	7,130

Table 2
Chemistry of waters in the investigated sampling sites of the Chechło River valley

Parameter	River Chechło	Younger ponds		Older ponds			Reference pond
		U1	U2	L1	L2	L3	
Conductivity [μS/cm]	820	841	840	501	450	513	318
pH	7.3	7.3	7.5	6.8	7.1	7.0	7.4
Na [mg/L]	40.4	42.0	40.0	18.8	13.0	24.7	12.3
Ammonium [mg/L]	3.600	3.800	1.900	0.980	0.068	1.500	0.120
K [mg/L]	7.8	7.8	7.7	5.1	2.8	5.8	2.4
Mg [mg/L]	20.0	20.3	21.1	7.9	13.5	13.9	10.0
Ca [mg/L]	70.5	71.8	72.8	54.9	56.4	43.8	28.9
Chlorides [mg/L]	61.9	63.7	63.2	38.0	29.5	39.2	25.0
Nitrites [mg/L]	8.70	0.15	0.17	0.16	0.04	0.02	0
Carbonates [mg/L]	193.9	188.0	202.0	183.4	184.2	184.2	114.5
Sulphates [mg/L]	129.0	134.5	135.0	64.5	40.2	65.7	26.4
Nitrates [mg/L]	10.30	6.70	12.40	9.80	2.15	0.85	0.20
Phosphates [mg/L]	0.85	0.64	0.68	0.14	0.34	0.50	0.08
Cd (total) [μg/L]	1.00	0.48	1.60	0.56	0.16	0.50	0.02
Cd (dissolved) [μg/L]	0.18	0.14	0.25	0.19	0.10	0.10	<0.01
Pb (total) [μg/L]	3.8	2.7	5.2	2.3	6.3	7.8	5.0
Pb (dissolved) [μg/L]	1.8	1.1	1.6	1.6	3.1	1.6	2.3
Zn (total) [μg/L]	57.6	50.4	71.0	34.8	40.0	31.6	9.4
Zn (dissolved) [μg/L]	32.5	22.3	49.3	23.7	15.9	15.5	4.0

DISCUSSION

The zinc, lead and cadmium concentrations in the investigated sediments are of similar magnitude as in the other sites and rivers affected by Pb-Zn mining worldwide (Byrne et al. 2012, Gutiérrez et al. 2016). Generally, these values are by one order of magnitude higher than the average pollution level of Asian and Europe riverine systems polluted from many industrial, agrochemical and domestic wastewater discharges (Zeb et al. 2024). Moreover, African river sediments polluted by industrial and domestic effluents have much lower metal concentrations than in the Chechło River, however recent growth of mining and mine waste generation heralds an increase of zinc and lead concentrations in many riverine systems there (Yabe et al. 2010).

The presented comparison reveals contrasting sediment pollution in reservoirs of different ages. The median concentrations of Zn and Cd in surface and subsurface strata are on average three times lower, and of Pb – even four times lower in the younger reservoir than in the older reservoirs (Table 1). The general decrease of Zn and Pb concentrations is also seen between subsurface and surface strata in both reservoirs; however, Cd concentrations remain at the same level (Table 1). This regularity is confirmed by the distribution of metals in the profiles of the high and medium sediment deposition rates (Figs. 2, 3). The position of Pb and Zn peaks indicates that the stratum of decreased pollution in these profiles is about 10–20 cm thick. In the profiles of low sediment deposition rate (Fig. 4), metal peaks situated in the top strata of not more than 10 cm suggest that sediments of post industrialisation period cannot be distinguished from the peak of pollution because of slow sediment deposition rate and obtained sampling resolution. Peaks of Cd in most of the profiles are at a different position to Zn and Pb, usually at lower levels. This fact, together with more even Cd distribution in sediments, as seen in Table 1, is related to the post-depositional mobility of this element. High mobility of this element, which can be either dissolved and removed with waters or reabsorbed and retained within sediments, is well known in the environment (Han et al. 2003). For the aforementioned reasons, Cd distribution does not reflect well the historical pollution changes (Ciszewski et al. 2012) but can be used here rather as the general marker of the sediment age.

The reconstruction of the river pollution change utilises the unusual coincidence of the appearance of subsidence reservoirs with the age of local industry transformation. The sediments of different reservoirs represent different pollution levels related to change from an industrial to a post-industrial age. The high pollution of the older reservoirs results most of all from operation of the Zn-Pb mine in Trzebinia which discharged large amounts of mine waters to the Chechło River via the small Luszówka stream but also to some – but not well known – extent from other industrial and municipal sources (Ciszewski 1997). Much lower sediment pollution of the younger reservoir is related to the collapse of industrialisation at the beginning of the 20th century in the drainage basin, together with the closure of the Zn-Pb mine as well as with the general extension of the sewer system. Whereas the observed sediment pollution pattern fits well with the industrial history of the drainage basin, there are important differences in the pollution degree of the youngest sediments in both reservoirs. In the younger reservoir, the pollution of the sediments is much lower than the pollution of the top strata in the older reservoirs, representing the same period of several years. This is evidently related to different fluvial sedimentary processes in the younger than in the older reservoirs.

Due to the capacity of the younger reservoir being relatively large compared to the low discharge of the river, about 1.5 $m^3 \cdot s^{-1}$, and the river's flow is central along the entire length of the subsidence basin, it can capture most of the sediment load transported by the river. The rapid sedimentation of coarse grained sediments transported as a bed load is induced by the suddenly slowed river flow in the mouth section of a river, whereas the wash load can be dispersed over the rest of a reservoir leading to its slower siltation (Rzętała et al. 2013). Shallow water reservoirs supplied with rivers draining the Upper Silesia are known as an efficient sink for a large load of pollutants (Rzętała et al. 2015). In comparison to these reservoirs, pollution of the Chechło River reservoirs with heavy metals is some of the largest in this region. Because the Chechło River cuts sandy fluvioglacial deposits which are prone to erosion, the river transports large amount of sands and rapid growth of the delta fan is observed. The deltaic sandy sediments originate predominantly from the zone situated immediately upstream of the reservoir, because the several kilometres long farther section of the river crossing the Chrzanów and Trzebinia cities is channelised with concrete reinforcements. The increase of the channel erosion rate is related to ground subsidence and disturbance of the longitudinal river profile, as evidenced by channel narrowing and several metres high outcrops in the river banks.

The entrapment of sediments in the younger reservoir has undoubtedly diminished the amount of sediments transported down the river. This phenomenon overlapped with a decrease in transported polluted sediments after the closure of the Zn-Pb mine. Reduced sediment transport corresponds to slower overbank sedimentation in the middle Chechło River reach (Ciszewski & Łokas 2019) and contributes to lower accretion of recently deposited sediments in older reservoirs situated ca. 1 km downstream. The older reservoirs are less sensitive to present day river pollution primarily due to their connection with the river solely by narrow ditches. The authors found that the rate of the sediment deposition in these reservoirs strongly depends on the distance from the outlet of a ditch to the river. The highest sediment deposition rate occurs in locations close to the ditches and in areas where the occasional inflow of water is not reduced by the growth of macrophytes. In more distant locations, sediment deposition is sporadic even during passage of the longest flood waves, as the profiles of the lowest sedimentation rate indicate (Fig. 4). The older ponded depression probably developed in a different way from the younger one because its lower depth prevented the development of a large alluvial fan, as thick sandy deposits were not found in the bottom of the overbank profiles (Ciszewski & Sobucki 2022). Instead, sandy sediments commonly intercalated with silts favoured the rapid formation of a levee along the river and currently they split the depression into three reservoirs. The analysed profiles, particularly of the highest deposition rate, suggest that the deposition close to the river was initially higher and it diminished with the accretion of a levee. Studies of fluvial sedimentation in subsidence reservoirs are sporadic; however, studies conducted in oxbow lakes confirm the large decrease of the sediment deposition rate with time and with distance from the river (Citterio & Piegay 2009, Sedláček et al. 2019).

Overall, the older subsidence basin, due to its smaller dimensions, was not as effective a trap for river borne pollutants as the younger one, despite the fact that it contains mainly much more polluted sediments of the industrial era. Isolation of the reservoir from the river and its low depth favoured a succession of macrophytes and a predominance of in situ organic rich sediments. The large difference between the present-day quality of the river and reservoir water quality (Table 2) confirm the isolation of all three reservoirs from the river and contribute to the explanation of its surprisingly low sensitivity to a decrease in river pollution at the onset of the post-industrial era. The much better quality of water in the older ponds than in the river could be related to the supply of these ponds in a greater amount (compared to the younger pond) with groundwater drained from the Pleistocene terrace. This groundwater, based on water analyses from the reference pond, is expected to be much less polluted than water in the river. The recently low rate of sedimentation with the persistently high pollution of the top strata of the older reservoirs suggests their possible preservation for many tens of years until infilling with organic sediments. Considering the present-day rate of the sediment deposition in the younger reservoir, it can be filled in excess of 50% even more rapidly and with cleaner sediments than the older reservoirs.

The observed decrease in sediment pollution in the Chechło River at the beginning of the 20th century reflects the transition from the industrial to the post-industrial era. The time frame and observed scale of pollution changes in this small but highly urbanised and industrialised catchment were parallel to the changes observed in Poland due to transformation of the whole Polish economy since the fall of communism. The changes in Poland, which started from 1989, induced the economisation of water consumption and the fall of sewage effluents production before 2010 by 30% (GUS 2005). The other changes which took place in the years 1999–2008 encompassed also the construction of over 900 sewage treatment plants, a 2–3 fold increase of tertiary treatment plants, the modernisation or closure of obsolete factories and more effective utilisation of manure and fertilizers, reducing the emission of nitrogen and phosphorus to the principal Polish rivers by ca. 25 and 35%, respectively (Pastuszak et al. 2012). Zn and Pb, which are widespread in industrial and urban effluents, together with Cd associated mainly with zinc mining and reworking, were discharged to rivers mainly in southern Poland due to the location of metal mining and smelting (Jaskuła & Sojka 2022). A drop in these metals load transported to the Baltic Sea in the principal Polish rivers, even by 80–90%, was observed already in years 1988–1997 (Niemirycz 1999). It also continued in the following years, contributing to maintaining pollution of the coastal marine environment at relatively low levels (Zaborska et al. 2019).

Despite a noticeable decrease in metal contamination of sediments in profiles with high and moderate sedimentation rate, their concentrations are still on average two orders of magnitude higher than regional background values. The future changes in pollution levels are expected to be much slower because they no longer can be related to closure or minimisation effects of point sources and simply winnowing of polluted sediments from the channel. Instead, the Chechło River catchment can be considered as a large diffuse source related to the historical metal mining and smelting with numerous spoil heaps, adits and tailings dispersed over half of the basin. The ore mining and smelting conducted since medieval times induced metal emissions and soil pollution with Zn and Cd, which was identified on the geochemical map (1: 25,000) on the prevailing part of the area (Pasieczna et al. 2008). High sediment pollution with metals has been observed even in the dam reservoir in the upper reach of the river far from the mining activity and external to the influence of domestic effluents (Koniarz et al. 2023). Considering the large extent of the catchment pollution, the remediation of the former mine tailing pond, which was only partially successful (Klojzy-Kaczmarczyk & Mazurek 2011), the large remediation project on the bauxite heaps or insulation of waste of the former zinc smelter in Trzebinia could be of minor importance. The soils, remnants of former mining and overbank sediments have to be considered the long-term source of pollution (Ciszewski & Sobucki 2019), which in many formerly mined catchments are expected to became the principal source of metals which will be remobilised for many years to come (Gore et al. 2007, Bird 2016). With time, the remobilisation of metals will contribute to maintaining elevated metal levels in sediments which accumulate in the investigated reservoirs. The reservoir sediment itself will also be a secondary pollution source of the river as these reservoirs constitute typical polluted wetlands drained by a river (Szkokan-Emilson et al. 2014).

CONCLUSIONS

The presented data exhibit a drop of the investigated sediment pollution in response to changes in the local economy. The transformation of industry at the beginning of the 20th century in the Chechło River catchment involved closure of the metal ore mine and smelter, closure of the coal mine, rubber plant, metal machinery plant, and restructuring of the other smaller plants including meat producing plants. In addition, the significant extension of sewage treatment, along with reclamation of mine tailing, smelter and bauxite waste heaps, contributed to a general decline in pollution of the Chechło River. There is not any rigorous data of the rapid improvement of the aquatic environment in the catchment because the final closure of each plant was preceded by a longer period of decline of the production. Nevertheless, considering the large share of mine waters in the river discharge, strong sediment pollution at the mine effluent outlet observed in the 1990s, and the present day reconstructions of sediment pollution with metals, we may point to the ending of the Zn-Pb mining as the principal agent influencing the drop in metal pollution. Considering that the sampling took place less than 10 years after the mine's closure, we can regard the 3–4-fold drop as a rapid change. The change of sediments pollution was different in reservoirs of different age. It was very well observed in the subsidence reservoirs of the post-industrialisation period which act as an efficient trap for sediments transported since ca. 2007, whereas in older reservoirs, active already during the period of peak river pollution, the changes in pollution were minor except for locations situated close to the river. In locations more distant from the river, sedimentation was dominated by organic sediments being products of in situ organic matter degradation. Pollution changes expected in the future will be much slower due to the supply of pollutants from diffuse sources in the prevailing part of the catchment.

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