Deposition of overbank sediments within a regulated reach of the upper Odra River, Poland

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Abstract Rivers and their flood plains are in a state of flux. Due to agricultural, urban and industrial development, and river training works, the natural erosion and sedimentation processes of the Odra River were modified in the 19th century. The geometry of the river channel has changed drastically, and the rates of overbank sedimentation are relatively high when compared to rates calculated for natural conditions. The rates of overbank sedimentation were assessed using the heavy metal content in overbank deposits. Only sediments deposited directly along the pre-regulation channels were considered. Fluvial processes in the studied, trained river channel seem to be more intensive than in the natural channel. Overbank deposition in the studied reach of the Upper Odra changed from 1.3 to 1.8 cm year^{-1} in the 19th century to 2–5 cm year^{-1} at present, which means that the rate of over-bank sedimentation has increased up to 3-fold.

Key words flood plain sedimentation rates; regulated river; heavy metals; Odra River

INTRODUCTION

The accumulation of sediment on a flood plain due to overbank flow causes the vertical accretion of its surface (Klimek, 1999). As a result of lateral river erosion, high river flows may set the previously deposited alluvia back in motion and cause their redeposition further downstream on the flood plain (Brown, 1996). The deposition processes in a river reach must therefore prevail over the erosion processes in order for flood plain sediments to accrete (Gradziński *et al*., 1986).

Human influences, both direct and indirect, have caused significant changes in river channel patterns and in the sedimentation rate within flood plains. The deforestation of basins and the development of intensive (e.g. mechanical) agriculture accelerates the rate of sediment accretion on alluvial plains. On the other hand, urbanisation, the commercial use of the flood plains, and the regulation of rivers (usually following periods of intensified sedimentation) effectively causes accretion rates to decrease (Falkowski, 1982; Walling & He, 1999). Regulation works, which are reflected by channel stabilisation, limit or impede the lateral accretion of the flood plain. Another impact of river regulation is the local increase in channel incision, or conversely, channel shallowing may take place leading to changes in the frequency of flood plain inundation (Czajka, 2005). As a result, the rate of overbank sediment accumulation also changes (Hughes *et al*., 2010). This is often stimulated by the construction of flood embankments, which limits the area inundated during high water episodes.

Vertical accretion is a result of the overbank deposition of sediments during floods. It has been shown to be the dominant process along many of the low gradient single-thread channels where there is insufficient stream power to induce channel migration. Similarly, vertical accretion is also favoured where channel migration is constrained by engineering structures. In general, vertical accretion deposits are fine-grained and characterised by horizontal and sub-horizontal layers deposited in single flood events, with each consisting of a fining-upwards sequence from sand to silts and clays (Klimek, 1999).

This study examines the difference in flood plain sedimentation rates between a straightened section of the Odra River and a section of pre-regulation channel composed of meander cut offs. Preliminary studies showed that the rate of overbank sedimentation along the trained Upper Odra channel was relatively high (Czajka, 2005; Ciszewski *et al*., 2008) but it is uncertain if these rates are typical or accelerated by river regulation.

STUDY SITE AND METHODS

The study reach of the Upper Odra is a sand-bed river with a catchment area of 7500 km^2. The river drains northward through the Raciborz Basin (Fig. 1) which is a submontane depression in southern Poland. The Upper Odra catchment is underlain by Upper and Middle Miocene clay covered by fluvioglacial sediments of Pleistocene age. The headwater tributaries of the Upper Odra River drain the eastern parts of the Sudety Mountains (in the Czech Republic) and the major tributary of the reach studied, the Olza River, drains from the western parts of Carpathian Mountains which results in a high sand concentration in the Upper Odra flood sediments.

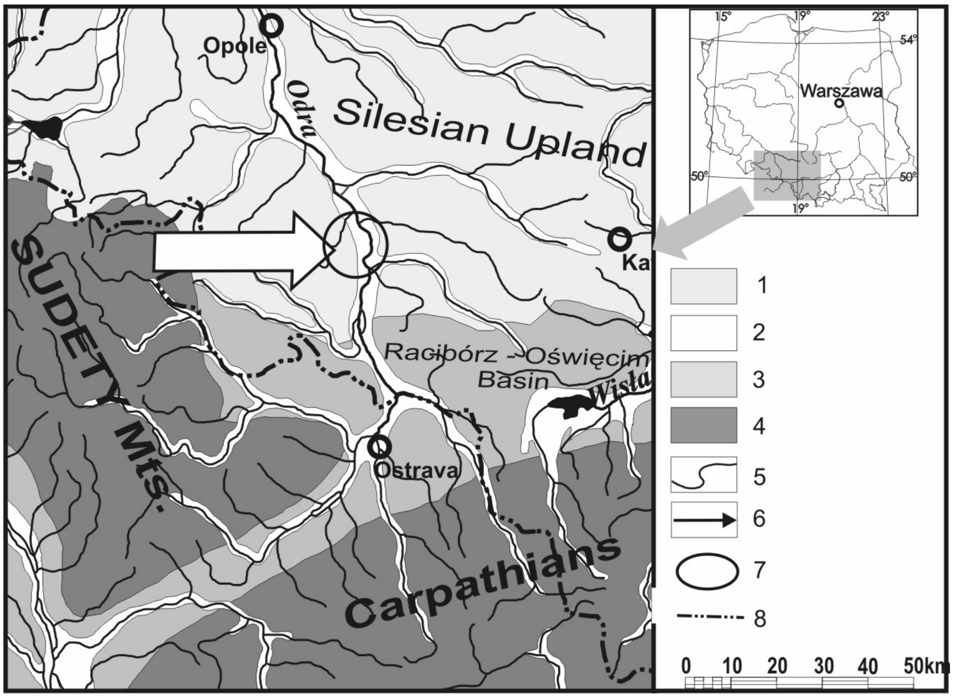

Fig. 1 Study site: (1) uplands, (2) river valleys, (3) submontane basins, (4) mountains, (5) rivers, (6) studied channel reach, (7) sampling area, (8) state border.

The mean discharge of the reach studied is approximately 65 m^3 s^{-1}. Draining the coal-mining area resulted in river regulation for navigation purposes. The training works started in 1786 and finished in 1821. The normalisation works included the decrease of channel sinuosity by cutting off the meander bends, the decrease of channel width by constructing groins, and the reduction of active flood plain width by embankment. As an effect of channel shortening, sinuosity of the Upper Odra channel decreased by 36% and the channel gradient increased by 37% to 0.4 m km^{-1}. The average bankfull width ranges from 30 to 50 m.

Analysis of historical maps has identified a heavily modified channel reach in the Raciborz Basin (for location see Fig. 1). Here, the new, straightened channel was constructed by cutting of six river meanders in a row (Fig. 2). As a result of the river regulation, the channel sinuosity decreased from 3.9 to 1.03. Channel width has been reduced by up to 150 m (Table 1), while the length of the channel within the studied section has been shortened by a factor of three. At present, meanders of the former channel are almost completely filled with sediments.

The geometry of the pre-regulation channel was determined using a GPS for the former channel width measurements and by coring for depth measurements. The parameters for the present channel were estimated using maps for depth and airborne images for width. The present channel width was also verified in the field.

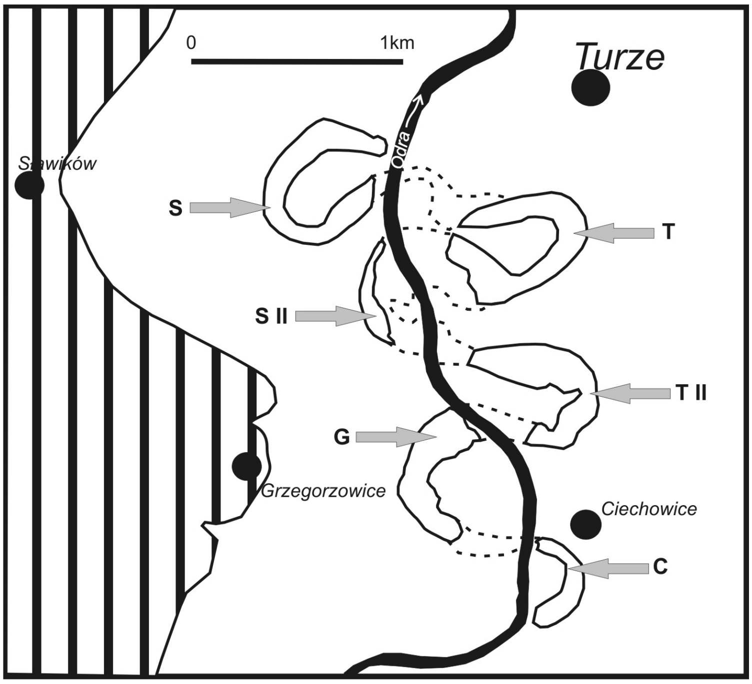

Fig. 2 Present course of the Odra channel in the studied reach shown in Fig. 1 and the cut-off meanders with the location of core sampling sites.

Table 1 Pre- and post-regulation channel depth and width in the study section. See Fig. 2 for locations.

Site	Width before cut offs (m)	Present channel width (m)	Difference in width (m)	Bed elevation before cut offs (m a.s.l.)	Present bed elevation (m a.s.l.)	Difference in elevation (m)
S	123	44	–79	177.3	174.1	–3.3
S II	165	43	–122	176.7	173.5	–3.1
T	142	32	–110	177.2	174	–3.2
T II	70	47	–23	176.6	173.1	–3.5
C	100	50	–50	175.9	173.2	–2.7
G	193	42	–151	173.3	173.2	–0.1

Heavy metals transported by polluted rivers are largely associated with fine-grained sediment which, during floods, accumulates on adjacent flood plain surfaces. Metal mobility depends on the chemical properties of each particular element; however, heavy metals are generally considered to be immobile for a time scale exceeding 100 years (Ciszewski, 2003). For this reason, flood plain sediment sequences can preserve information on the history of contamination in the river system, as well as on the spatial and temporal patterns of sediment accumulation. The record is more accurate in polluted systems with rapid and well documented changes in river pollution history. This is usually the case in former mining and industrial regions with moderate or high rates of sediment accumulation (Lecce & Pavlowsky, 2001). Marked peaks of heavy metal concentrations within vertical sediment profiles can be correlated with particular events in the industrial history of the catchment, thereby providing an indirect method to estimate accretion rates. Furthermore, in vertical profiles where detailed correlation is impossible, the observed high metal content of sediment can be ascribed to the industrial era by comparison with geochemical background values characteristic of pre-industrial sediments (De Vos *et al*., 1996).

Cores for heavy metal depth profile analysis were obtained using a hand corer. Samples were taken at the six cut-offs of the Odra River, both from the former river banks and the deepest parts of each cut-off. Samples were also taken from two pits at Grzegorzowice (site G, Fig. 2). Sediment samples were dried at 105°C for 24 h and disaggregated. The samples were then divided and one portion of each sample was passed through a 0.063 mm sieve. The unsieved part of each sample was subjected to grain size analysis by sieve and hydrometer methods. Subsamples of the fine fraction (i.e. <0.063 mm) were then digested in 10 ml HNO_3 and 2 ml H_2O_2 using a microwave technique and filtering. Concentrations of zinc (Zn), cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb) and manganese (Mn) were determined using atomic absorption spectrometry. Here, we focus on sites S, S II, T, T II and C.

RESULTS AND DISCUSSION

Overbank deposits of the Odra River mainly consist of fine and silty sand. The 18th century channel bed deposits are composed of gravelly sand with a mixture of sandy gravel. In all sites the top layer consists of silty-sand, except site T (for location see Fig. 2) which consists of sandy-silts because the cut-off meander is located at some distance from the present channel. The middle parts of each profile are composed of sand and silty-sand. The average grain size varies between –0.04 and 4.68 phi (1.025–0.04 mm).

The pre-regulation channel bed was found at the depth of about 4 m beneath the surface of the present flood plain. The flood plain surface is elevated about 5 m above the average water table.

Concentrations of heavy metals within the deposits in the cut-off meanders are generally not high, and with limited down core variation, except for the top layer of the youngest alluvium. As an example, the concentrations of Zn, Cu and Pb in overbank deposits are presented in Fig. 3.

(i) **The 18th century river bed deposits** occur at a variety of sites: such as site C below 270 cm, site TII below 2 m, and site T at 70 cm below the present flood plain surface (Table 2). Concentrations of heavy metals were generally low and were similar for the cores collected from these sites with ranges of 50–80 ppm for Zn, 12–25 ppm for Cu, 16–28 ppm for Ni, 3–17 ppm Pb and ~1–1.8 ppm for Cd.

(ii) **19th century overbank deposits** are characterised by elevated heavy metal concentrations when compared to the 18th century channel bed deposits, but are lower than values for the youngest alluvia deposited in the 20th century. This suggests that the time of deposition may be before the maximum period of industrialisation and river pollution. The thickest deposit for this period, ~2 m, was measured at site C. At site S this layer was 1.84 m, while at sites T and T II it was 0.36 m and 1.65 m, respectively. Noticeable metal concentrations for this layer are Zn (50–90 ppm), Cu (15–30 ppm), Ni (15–25 ppm) and Cd (up to 2 ppm).

(iii) **Alluvia deposited in the 20th century** are polluted by heavy metals, with concentrations ranging from 300 to 800 ppm for Zn, 45–55 ppm for Cu, 20–25 ppm for Ni, 60–120 ppm for Pb, and 2–3.5 ppm for Cd. Concentrations of Mn reach 400–450 ppm, and this metal is redistributed to the lower parts of the profiles. This top layer was 77 cm at site C, 35 cm at site T II, 36 cm at site S and 20 cm at site T. The thickness of this layer differs, in part, due to variations in the distance that the cores were collected from the present channel.

Table 2 Rates of sediment accretion in cut-off benches, derived from the heavy metal concentrations.

Site	18th century deposits [a] (cm)	Rate of accretion (cm year^{-1})	19th century deposits [b] (cm)	Rate of accretion (cm year^{-1})	20th century deposits (cm)	Rate of accretion [c] (cm year^{-1})
S	85	0.85	184	1.84	36	0.36
S II	–	–	60	0.6	20	0.2
T	19	0.19	36	0.36	33	0.33
T II	18	0.18	165	1.65	35	0.35
C	120	1.2	196	1.96	77	0.77

[a] Channel bed deposits, [b] pre-regulation overbank deposits, [c] present flood plain deposits.

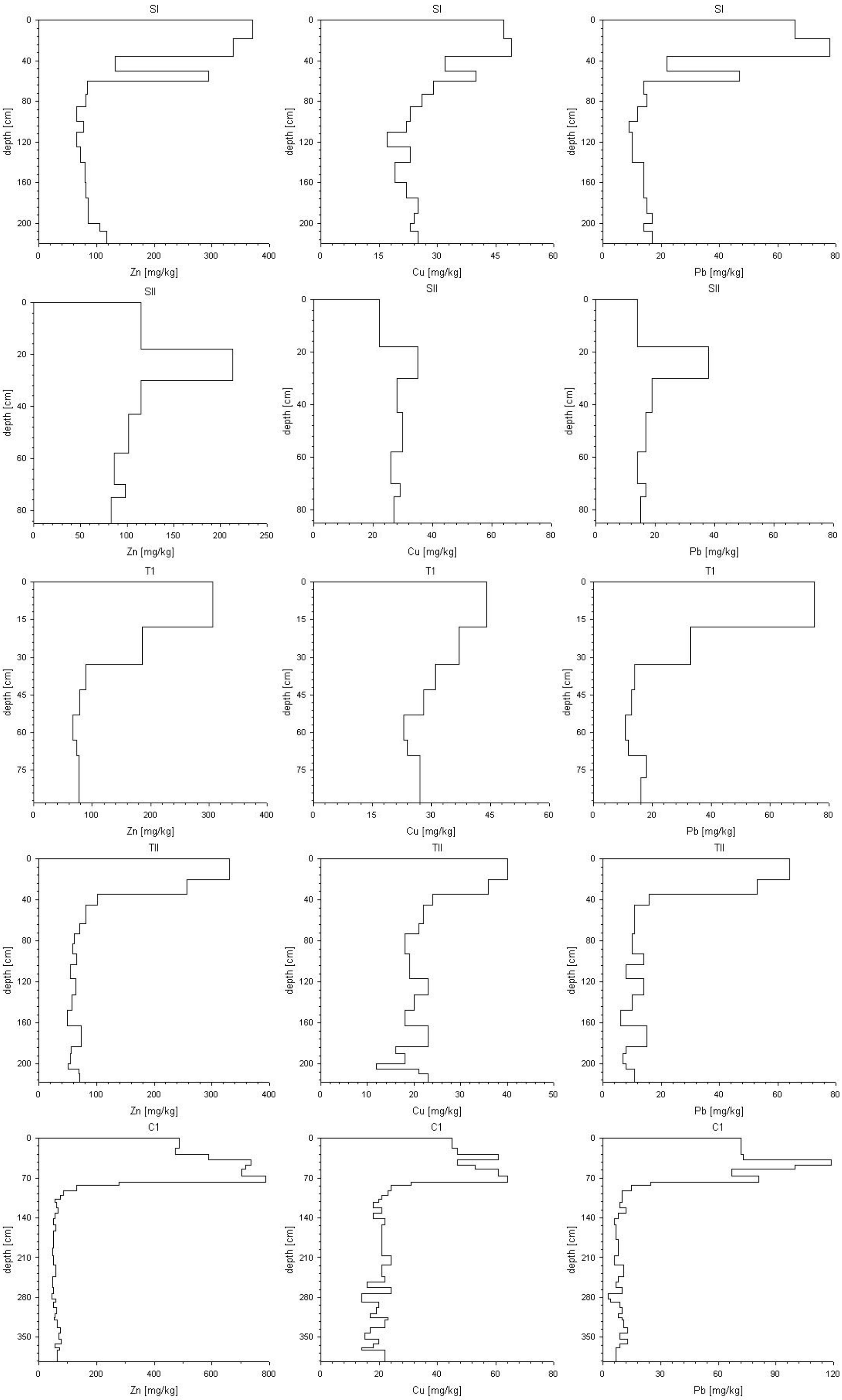

Fig. 3 Heavy metals concentrations in cores of overbank sediment from the study sites (see Fig. 2 for location).

The old channel deposits contain Cd which is probably redistributed from younger layers as the channel bed deposits could not be polluted with Cd at the time of deposition, given the known record of Cd pollution activity in the river basin.

CONCLUSIONS

The present-day overbank sedimentation rates within the studied section of the regulated Odra River typically varies between 2 and 5 cm $year^{-1}$ (Czajka, 2005), while in the 19th century values were lower and ranged between 1.3 and 1.8 cm $year^{-1}$. Flood plain sedimentation rates have increased by up to 3-fold in the studied valley section since the Odra meanders were cut off in 19th century.

The present channel of the Odra River is significantly narrowed and lies approx. 3 m deeper than the pre-regulation channel. The sinuosity of the regulated channel is 1.03, while the natural channel's sinuosity was 3.9. Changes in the geometry of the channel affects the fluvial processes as the river adjusts to the new conditions. The slope of the shortened channel has increased and, with the additional energy now available in the much narrower channels, has caused incision. The process of channel incision is being kept reasonably stable by the arrays of groins constructed along the river banks, which limits lateral migration. Also, overbank deposition is modified and accelerated in many places under these new conditions.

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REFERENCES

Brown A. G. (1996) Flood plain paleoenvironments. In: *Flood Plain Processes* (ed. by M. G. Anderson, D. E. Walling & P. D. Bates), 95–138. John Wiley & Sons Ltd., Chichester, UK.

Ciszewski, D. (2003) Heavy metals in vertical profiles of the middle Odra River overbank sediments: Evidence for pollution changes. *Water, Air Soil Pollut.* **143**, 81–98.

Ciszewski D, Czajka A. & Błażej S. (2008) Rapid migration of heavy metals and ^{137}Cs in alluvial sediments, Upper Odra River valley, Poland. *Environ. Geol.* **55,** 1577–1586.

Czajka A. (2005) Accumulation of sediments within the channelized reach of the Upper Odra River, Poland. In: *Geomorphological Processes and Human Impacts in River Basins* (ed. by R. J. Batalla & C. Garcia), 191–196. IAHS Publ. 299. IAHS Press, Wallingford, UK.

De Vos, W., Ebbing, J., Hindel, R., Schalich, J., Swennen, R. & VanKeer, I. (1996) Geochemical mapping based on overbank sediments in the heavily industrialised border area of Belgium, Germany and The Netherlands. *J. Geochem. Explor.* **56**, 91–104.

Falkowski, E. (1982) The pattern of changes in the Middle Vistula valley floor. In: *Evolution of Vistula River Valley during the Last 15000 Years*, Part I, (ed. by L. Starkel), 79–92. Geographical Studies, Special Issue no. 1.

Gradziński, R., Kostecka, A., Radomski, A. & Unrug, R. (1986) *Zarys sedymentologii*. Wyd. Geol., Warszawa, Poland.

Hughes, A. O., Croke, J. C., Pietsch, T. J. & Olley, J. M. (2010) Changes in the rates of flood plain and in-channel bench accretion in response to catchment disturbance, central Queensland, Australia. *Geomorph.* **114**, 338–347.

Klimek K. (1999) A 1000 year alluvial sequence as an indicator of catchment/flood plain interaction: the Ruda valley, sub-Carpathians, Poland. In: *Fluvial Processes and Environmental Change* (ed. by A. G. Brown & T. A. Quine), 329–343. Wiley & Sons Ltd, Chichester, UK.

Lecce, S. A. & Pavlowsky, R. T. (2001) Use of mining contaminated sediment tracers to investigate the timing and rates of historical flood plain sedimentation. *Geomorph.* **38**, 85–108.

Walling, D. E. & He, Q. (1999) Changing rates of overbank sedimentation on the flood plains of British rivers during the past 100 years. In: *Fluvial Processes and Environmental Change* (ed. by A. G. Brown & T. A. Quine), 207–222. John Wiley & Sons Ltd, Chichester, UK.