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Floodplain morphodynamics and distribution of trace elements in overbank deposits, Vistula River Valley Gorge near Solec nad Wisłą, Poland

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ABSTRACT:

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Geological and geochemical investigations were carried out in the floodplain of the Vistula River Valley gorge near Solec nad Wisłą (Małopolska Gorge of the Vistula River). Geological mapping was supported by DEM and remote sensing analysis. Sediment samples were taken from depths of 0.5 m and 1.5 m from all geomorphological features identified. The geochemical analysis included determination of Cr, V, Sr, Ba, Ni, Cu, Co, As, Pb and Zn concentrations. Results indicate that the main factors affecting the pattern of features in the floodplain of this area are (1) the highly dynamic flood flow in the narrow section of the gorge and (2) the relief of the top surface of the sub-alluvial basement. The variable concentrations of trace elements are closely related to the floodplain features. Their concentrations can be considered as valuable geochemical proxies that enable a more thorough reconstruction of the sedimentary evolution of the Vistula River Valley and other similar river valleys, especially in gorge sections.

Key words: Vistula River; Gorge reach; Fluvial processes; Alluvial deposits; Trace elements; Poland.

INTRODUCTION

River valleys are extremely valuable natural landforms of enormous economic importance. The main objective of integrated studies of river valleys is to identify the environmental conditions and to determine their evolution. This would constitute the environmental background necessary for specific intended technical solutions in order to adopt a particular mode of the management of the area. The content of trace elements in surface sediments is one of the index parameters that identify environmental conditions (Miller and Orbock-Miller 2007) and the degree of their transformation under the influence of natural and anthropogenic factors (cf. Vanderberghe 2002).

Trace metals such as Cd, Pb, Cu, Zn and Ba are widely recognised as indicators of anthropogenic environmental change. An increase in their content in fluvial sediments may result from mining operations, concentration of heavy and chemical industries, and intensive agricultural activity in the river basin (Helios-Rybicka 1986; Taylor 1996; Bojakowska and Sokołowska 1996; Lecce and Pavlowsky 2001; Santos Bermejo *et al*. 2003).

River channels are in fact the basic zones (routes) of migration of these elements, and the surfaces of floodplains are the major areas of their concentration (accumulation) and redeposition (Ciszewski 2003). However, despite a direct relationship between the content of anthropogenically introduced elements in river water and alluvial sediments, their concentrations in the individual grain-size fractions often show significant differences (Martin 2004). Changes in the supply of trace elements in the history of the drainage basin in the particular section of the river valley can also show a completely different record in the individual morphodynamic zones of its floodplain (Falkowska and Falkowski 2015). This stems from the fact that the amount of transported elements depends on both the geochemical and mineralogical characteristics of the sediment, as well as on the chemical and dynamic properties of the water environment (Förstner and Wittman 1983; Miller 1997; Ciszewski *et al*. 2004).

Most of the trace elements in river waters are transported in suspension, with 90–99% in the grain-size fraction <63 μm (Horowitz 1991). Various mineral components of the suspension bind trace elements to a different extent. Therefore, their concentrations in sediments are affected by its mineral composition, the clay fraction content, and the contents of organic matter, $CaCO_3$, iron oxides and hydroxides (Velde 1995; Miller and Orbock-Miller 2007; Falkowska and Falkowski 2015). The sedimentary conditions of individual minerals in the river bedload, that bind various trace elements within the fluvial environment, vary and depend on both the geomorphological conditions of the flow and hydrological regime of the river (Miller 1997; Miller *et al*. 1998; Walling *et al*. 2003; Ciszewski *et al*. 2004; Galán *et al*. 2008; Conde Bueno *et al*. 2009).

To date it has been shown that the concentration levels of trace metals in sediments relate to the distance of their deposition measured from the river channel (Graf *et al*. 1991; Marron 1989; Macklin 1996; Ciszewski 2003; Bradley and Cox 1990; Wyżga and Ciszewski 2010) and to the ratio of floodplain width to river channel zone width. The second of these parameters characterises the dynamics of discharge across a vast floodplain (Wyżga and Ciszewski 2010). Various geomorphological features of the floodplain along the lowland river's mature valley contain characteristic trace elements (Falkowska and Falkowski 2015).

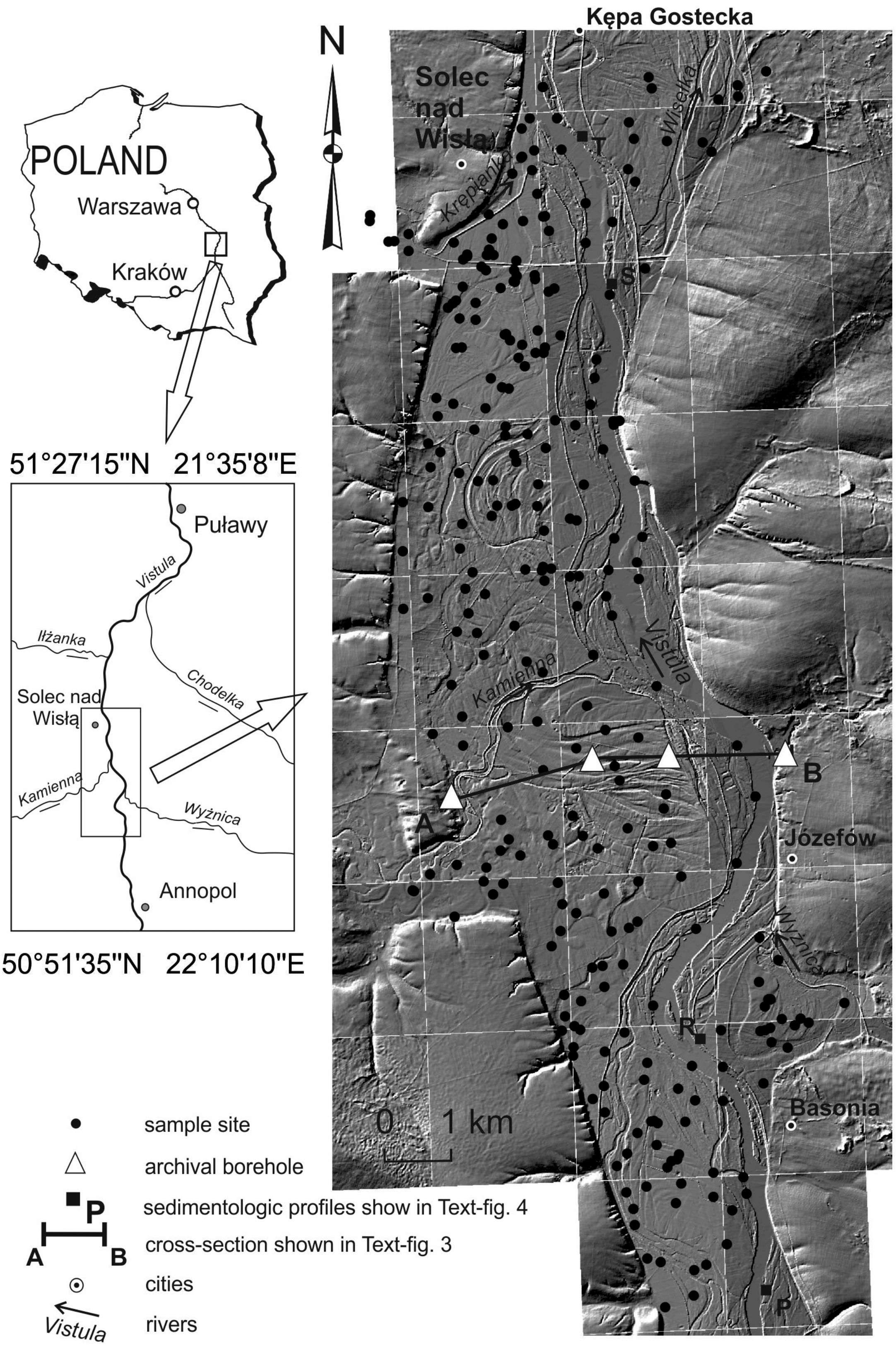
Morphodynamically the valley floor area is usually divided into the proximal floodplain adjacent to the river channel and the distal zone, also known as a flood basin (Bridge 2003). The nature of morphodynamic processes on the floodplain surface changes along the course of the valley, visible through the presence of the alternating zones of the valley floor narrowing and broadening (Fryirs and Brierley 2013). The origin of such diversity may result from the geological structure of the basement, the erosional susceptibility of rocks forming the erosional base of the valley (Pożaryski and Kalicki 1995), and the degree of tectonic deformation of the valley's basement rocks (Spitz and Schumm 1997; Brzezińska-Wójcik 1999; Gargani 2004; Zhang *et al*. 2004; Wang *et al*. 2005), or from a complex origin (polygenesis) of the valley (Falkowski 1997).

The occurrence of sections with different geological structures of the basement along the valley also results in considerable differentiation of depositional environments during floods. Sedimentary conditions change within the individual stages of the floods (Zwoliński 1992).

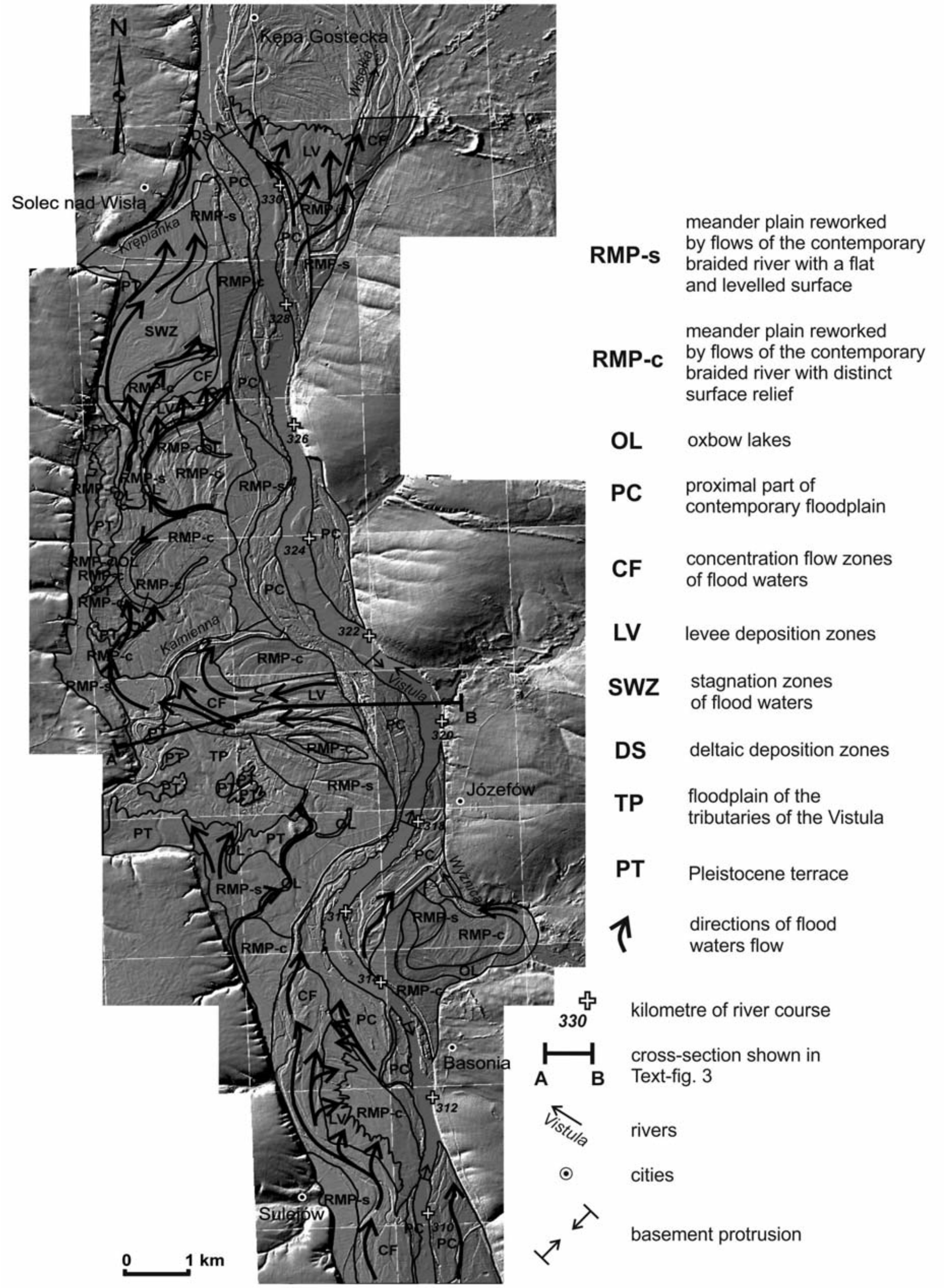
Concentrations of trace metals in overbank sediments should be closely linked to the dynamics of recent floods. These have been reworking the floodplain surface before man-made levees were constructed, and later as a result of failure in these structures (Wierzbicki *et al*. 2013). These events have left clear signs not only in the lithology and textures of surface deposits (Gębica and Sokołowski 2001), but also in the microrelief of the valley floor (Falkowska and Falkowski 2015). Morphodynamic analysis of the floodplain surface should therefore be a key to identify the diversity of sedimentary environments, affecting the specific contents of trace metals in contemporary overbank sediments, especially in zones of narrowing of the floodplain belt. The significance of flood discharge for the formation of surface relief and lithology in such narrow sections of valleys is higher than in areas of greater extent of floods.

The objective of the study was to determine the relationship between the content of trace elements and the individual morphodynamic floodplain features in the gorge (-restricted) section of the river valley.

A narrowing of the Vistula River Valley was selected as the study area, located in the Małopolska Gorge of the river (Text-fig. 1). The width of the valley along the entire gorge varies from 1.2 km to 10 km. It depends on the strata layout and weathering/erosion resistivity of rocks that compose the valley basement, as well as on the occurrence of fault zones within the basement (Pożaryski *et al.*



Text-fig. 1. Location of the study area and DMT showing the boreholes



Text-fig. 2. Morphodynamic features of the Vistula River valley stretch overlaying DMT

1994). The plateau that rises about 50 m above the valley floor is composed of Upper Cretaceous marls with cherts, siliceous marl (opokas) and gaizes, locally covered with Quaternary glacial or aeolian deposits (Pożaryski *et al*. 1994).

MORPHOGENESIS OF THE VISTULA RIVER VALLEY

The evolution of the Vistula River Valley in the Małopolska Gorge has been strongly affected by various fault zones in its basement (Text-fig. 2), parallel to the river course (Sawicki, 1933; Romanek and Złonkiewicz 1993; Pożaryski *et al.* 1994). Pre-Quaternary (Lewiński 1914; Samsonowcz 1922; Sawicki 1925; Pożaryski 1953, 1955; Pożaryski and Kalicki 1995) and/or early Quaternary erosion (Pożaryski *et al*. 1994, Pożaryski and Kalicki 1995) played the key role in the ultimate formation of the gorge. The Vistula River Valley existed in the area of the gorge already during the Małopolanian Interglacial (MIS 17-19), but its deepening took place only after the retreat of the Odranian Glaciation ice sheet (MIS 8) (Pożaryski *et al*. 1994; Ber 2006).

The existence of the river during the late Pleistocene under conditions of high bedload supply manifested itself in the valley by the formation of a system of overbank terraces, whose surface in undercut zones is composed of slope deposits (Pożaryski 1955) and aeolian deposits (Gębica 2004). In valley narrowing, only relics of these surfaces have been preserved.

Changes in the hydrological regime at the end of the Pleistocene and in the Holocene resulted in a gradual equalisation of the discharges and the development of a meandering river channel by the Vistula River. The meandering river incised into Pleistocene alluvial sediments composing the floodplain level that had been forming until the 17th century (Falkowski 1967).

Further evolution of the Vistula River system, which consisted in increasing differences between extreme discharges, occurred during the Subatlantic Holocene and mainly as a result of human activity (Falkowski 1967; Starkel 1983). This was recorded in the valley by the change of the river channel type of the Vistula from meandering to braided pattern. The overloaded river built up the river channel zone, simultaneously reworking the floodplain surface. This process was favoured by the specific nature of the geological structure of the valley, where there was the absence of a fully developed erosional base (Falkowski 2007).

This feature was particularly significant for the development of the valley at its narrowings. With the arrival of extremely high flows in the river channel, the depth of reworking by flood flow (vertical erosion of high waters) increased (cf. Leopold *et al*. 1964).

Deepening of the river channel during floods is hampered wherever rocks of the erosional base form morphological protrusions in the sub-alluvial bedrock. Surges of both rain and ice dam waters in such zones and invade onto the floodplain, modifying its surface. This phenomenon also occurred after the construction of flood banks as a result of failures in these embankments. Sediments deposited in the place of eroded older deposits are often characterised by a much greater variability in grain size and mineral composition than deposits from the period of the meandering river (Falkowski 2007; Falkowska and Falkowski 2015). Contemporary flood flows reworked also the oxbow lakes from the period of the meandering river, filling them, often completely, with mineral sediment.

MATERIAL AND METHODS

Geological mapping was performed in order to determine the lithological diversity of the Vistula Valley floor. The identification of the morphodynamic zones was based on a digital elevation model (DEM) and aerial images at a scale of 1:20 000. Survey points and boundaries of distinction were positioned in the field using DGPS (Differential Global Positioning System) code receivers. The results have been archived in the GIS database. During fieldwork, 110 sediment samples were collected for laboratory analysis.

The lithological characteristics of the deposits included grain-size (areometric and sieve) analysis, determination of calcium carbonate content (Scheibler method), and potentiometric pH_{H_2O} determinations (Myślińska 1984). The mineral composition of the clay fraction was determined by X-ray diffractometry (XRD).

Seventy-nine sediment samples, representative of the geomorphological features identified by their relief, were chosen to study the contents of selected chemical elements, including trace metals. Samples were collected using a probe from a depth of 45–50 cm, below the plant root zone and below the impact of agricultural management (ploughing, fertilizing), as well as from a depth of 150 cm. We avoided surfaces modified by soil-forming processes. Samples were taken during periods between flood events. They were stored in sterile plastic bags in a refrigerator at 6 degrees Celsius until further processing.

Samples were homogenised and averaged in the laboratory, then washed through a 1.0 mm sieve (Ciszewski 1998), dried and minced in a ball mill. The samples, each weighing 0.25 g, were digested with an acid solution of (2:2:1:1) H_2O-HF-$HClO_4$-HNO_3, then dried. 50% HCl was added to the residue and heated using a mixing hot block. The resulting solutions were analysed for the content of trace elements using the ICP-OES and ICP-MS methods. All concentrations were reported in mg × kg^{-1}. Analytical accuracy was determined using reference material standards STD OREAS25A-4A and multi-element soil standard STD OREAS45E (Ore Research & Exploration Pty Ltd). Both precision and accuracy were within 10%. Despite the fact that As is a metalloid it was considered together with the trace metals. All analytical determinations were carried out at the AcmeLabs Laboratory (Bureau Veritas Commodities Canada Ltd).

Loss on ignition (LOI) at 450 °C for 24 h was used to measure the organic matter content (Davis 1974).

Fe/Al ratio was calculated in the samples to estimate the content of authigenic Fe that precipitated from the river water (Lopez *et al*. 2006).

The results of analysis of the trace element content were grouped using the detrended analysis (DCA). One-way analysis of variance (ANOVA) was used to estimate the proportion of variation in the concentration of elements, explained by geomorphological diversity using the sum of squares between group means. The F-statistic and non-parametric Kruskal-Wallis statistics were used to measure significance level (p-level) (Appleton and Adlam 2012). Principal component analysis (PCA) and regression analysis were performed to identify the factors controlling the distribution of trace elements in the deposits. All of the statistical analyses were carried out using STATISTICA 10 software.

RESULTS

Geomorphology of the examined part of the Vistula River Valley floodplain

The following geomorphological features have been identified in the study area of the Vistula Valley floor (Text-figs 2, 3):

Meander plain reworked by flood flows of the contemporary braided river (RMP). It consists of a part with a flat and levelled surface (RMP-s), and a part with a more distinct surface relief (RMP-c)
Oxbow lakes (OL), genetically related to the RMP surface. The proximal part of the contemporary floodplain (PC) is associated with deposition in a contemporary braided river channel
Concentration flow zones of flood waters (flood channels) (CF)
Levée deposition zones (LV), which occur near the concentration flow zones (Vistula River channel and flood channels CF)
Stagnation zones of flood waters (SWZ)
Deltaic deposition zones (DS), small deltas that formed at the mouth of concentration flow zones of flood waters
Floodplain of the tributaries (TP) of the Vistula
Pleistocene terrace (PT).

The distribution of the identified features on the floodplain surface is strictly related to the dynamics of contemporary flood flows. Near Basonia (km 310–313), water damming was the reason for the formation of the zone of concentrated flow (CF) running across the floodplain surface west of the river channel. The waters that flowed there had cut off part of the floodplain (RMP) in the west (Text-fig. 2). The profile of this surface, exposed in the undercut slope at km 311, is composed of evenly horizontally laminated muds (Fh; (Text-fig. 4). The reworked surface of this feature was built up in the west by sands and silty sands representing the levée facies (LV) of concentrated flow (CF), and in the northern part by similar deposits but associated with the contemporary Vistula River channel (CP). This zone is composed of levees arranged diagonally to the flood channel.

The PC surface, situated to the east of the Vistula River channel, consists of channel sands (lithofacies Sp) overlain by flood deposits (proximal floodplain with lithofacies Sh, Fh SFh, FSh and SFm), about 1 m thick (Text-fig. 4).

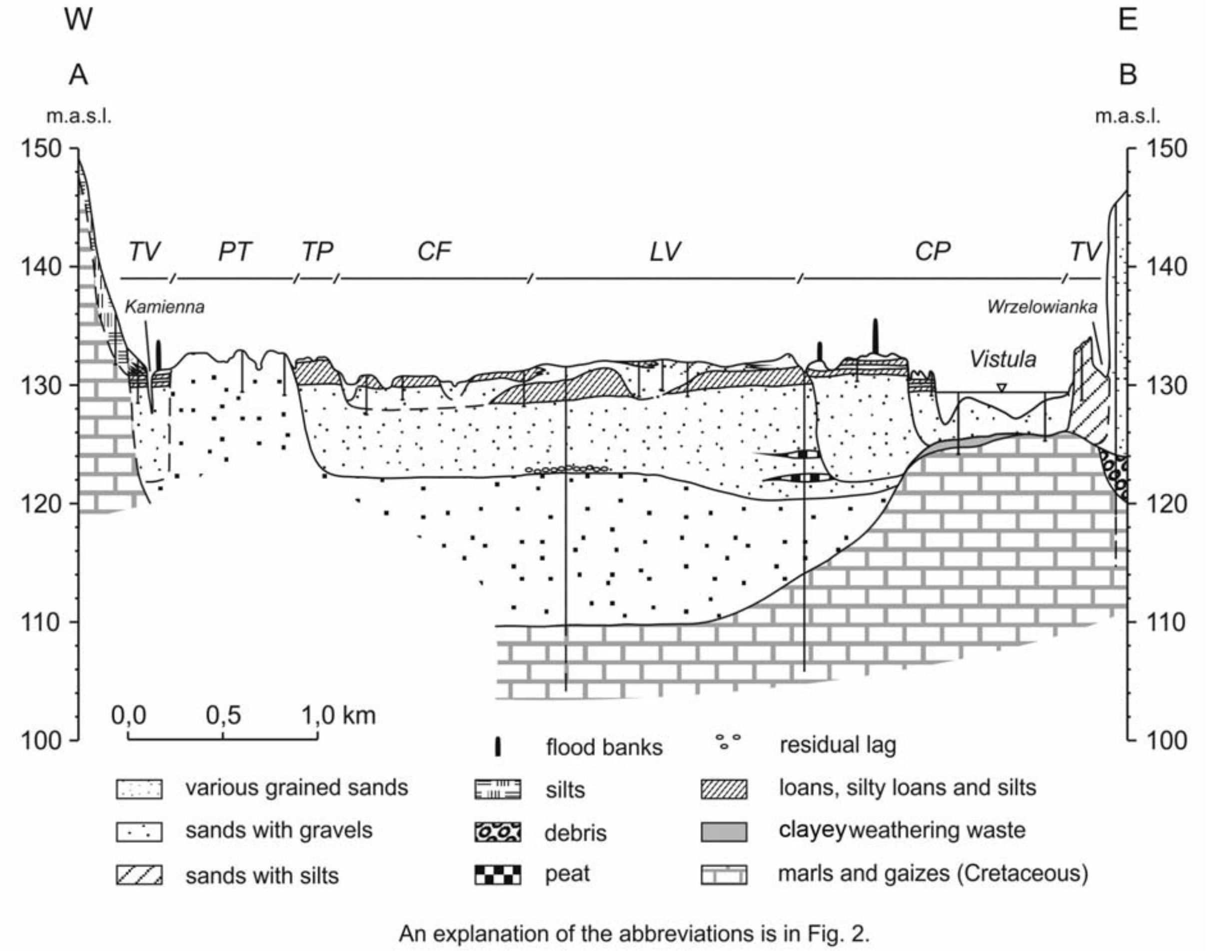
Downstream of the village of Basonia the floodplain surface widens to approximately 4.5 km. To the east of the river channel, near the mouth of the Wyżnica River, there is a niche cut approximately 1.5 km into the plateau escarpment. In this area, the valley floor is represented by the RMP surface, with an ancient oxbow lake (OL) clearly visible in the terrain morphology. This surface is represented by laminated silts (Fh) with a moderate thickness of 3 m, exposed in the river channel banks (Text-fig. 4). From the plateau side the RMP surface adjoins narrow benches of the Pleistocene terrace (PT). The surface of this part of the valley floor was reworked by recent flows, mainly of the Wyżnica, and by flood flows of the Vistula. The ancient oxbow lake (OL) is filled largely by the mineral deposits of such floods.

In the Józefów region, to the west of the wide (about 1.5 km) river channel zone with the proximal floodplain (PC), there is a wide floodplain zone of the meandering river reworked by recent flows (RMP) (Text-fig. 2). Strings of ancient oxbow lakes on this surface, with small curvature radii, form a drainage zone for the waters flowing down from the plateau. A part of the floodplain at the mouth of the Kamienna River valley bears traces of its channels from the period when the river was of the meandering type (TP). The Vistula flood flow that reworked the floodplain surface has not blurred the traces of its primary origin. Outliers of the upper, Pleistocene accumulation level (PT), are also encased in the surface. A well-marked bench of the Pleistocene terrace (PT) occurs within the Kamienna River valley (Text-fig. 2).

Upstream of the Kamienna River mouth (from km 319 to km 321) there is a zone of concentrated flow (CF) with a deposition zone (LV) extending about 1.5 km into the floodplain (Text-fig. 3). Zone CF runs near the reworked parts of the surface originally formed by the meandering Vistula River (RMP-c).

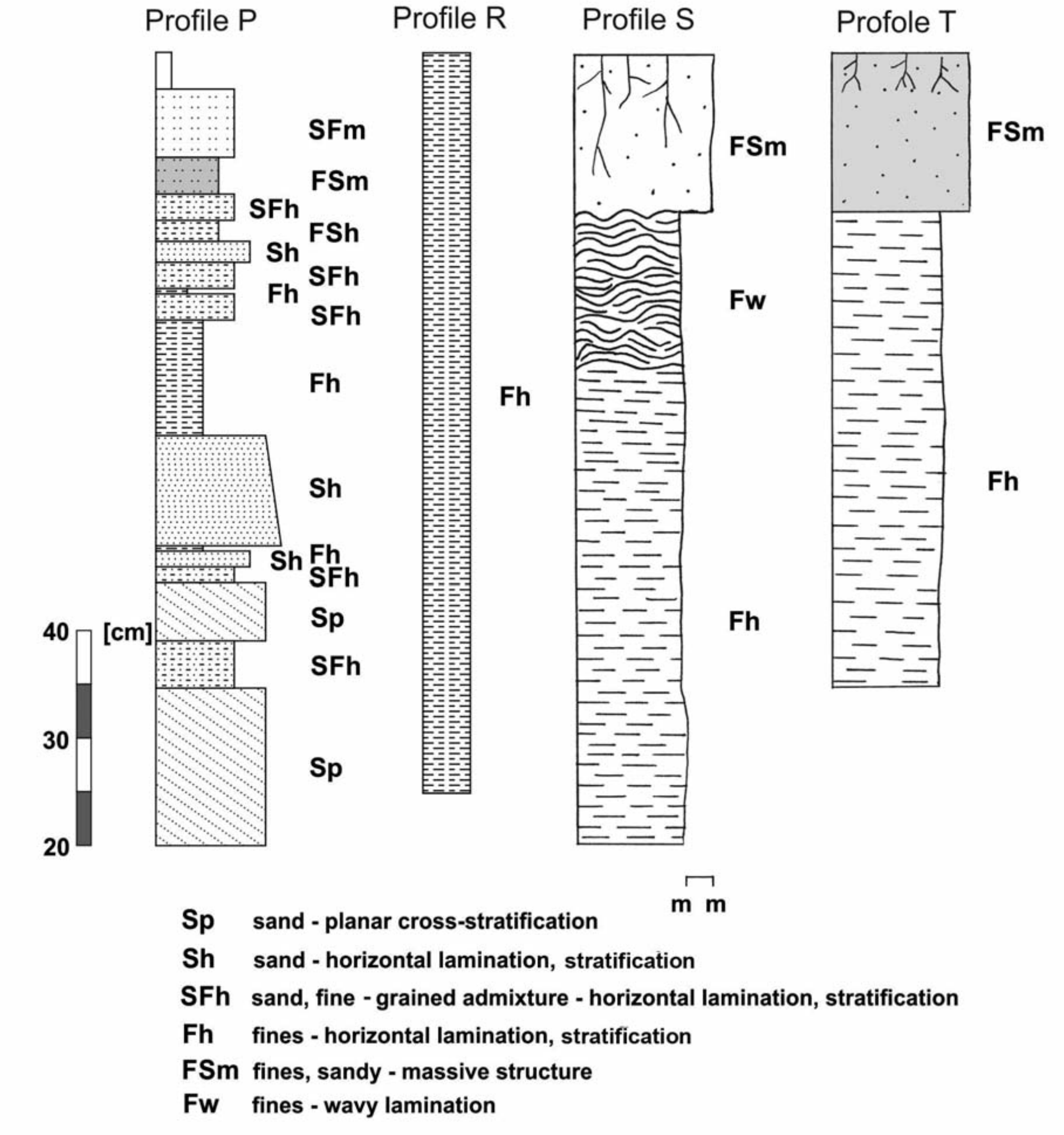
Part of the meandering river floodplain with the surface (RMP-s), reworked and levelled by smooth floods, stretches in a narrow belt along the channel zone of the contemporary Vistula (PC) from km 323 to km 326 and further on from km 326+500 to km 331. Laminated silts (Fh) that are exposed in the erosional undercut of this level cover the channel sands (Sp) (Text-fig. 4). Traces of flood flows are found in this zone at the foot of the plateau escarpment, visible as elongated erosional troughs filled with water and reworked into forms resembling oxbow lakes (OL). Close to the zones of concentrated flow there are narrow levée zones (LV) (Text-fig. 2). Floodwaters also reworked parts of the floodplain (RMP-c) from the meandering river period, depositing silty sediments on its surface.

To the east of the Vistula channel, from km 321 to km 325, there is only a narrow terrace bench of the reworked floodplain level (RMP-c) from the meandering Vistula period, which has been preserved attached to the plateau. The surface of the feature is composed of laminated silts (Fh) attaining a thickness of 4 m. The largest part of this surface has been preserved at km



An explanation of the abbreviations is in Fig. 2.

Text-fig. 3. Cross-section through the Vistula River valley in the Solec nad Wisłą area



Text-fig. 4. Sedimentological profiles of selected features from the Vistula River valley near Solec nad Wisłą (lithofacies after Zieliński 1998)

328. Horizontal and wavy-laminated silts with a thickness exceeding 3.5 m, exposed here in the channel's left bank (Fh, Fw), are overlain by a layer of massive fine sands and silts (FSm) deposited by recent flows.

The proximal floodplain surface (PC), shaped by the contemporary Vistula River, is composed in this zone by channel sands (Sp, Sl, Sr) interlayered by silts and sandy silts (Fh, FSh), overlain by massive sands and silts (FSm) (Text-fig. 4).

From km 326 to km 331 (mouth of the Krępianka), we find a zone of prolonged water stagnation (SWZ) with deposition of organic sediments (Text-fig. 2). Its development is associated with the occurrence of a culmination of sub-alluvial basement rocks in the Vistula River channel near the Krępianka mouth. This causes the water to rise high and contributes to the formation of ice-jams in this place. Near the Krępianka mouth (at about km 331) there is an elongated and narrow sandy delta (DS).

Blocking of the outflow downstream of the Krępianka River mouth was also the reason for the formation of a long trough to the east of the channel – a zone marking the path of concentrated flow of flood water (CF; near the village of Kępa Gostecka). A watercourse named Wisełka currently drains into the trough. That flood flow had cut off an elongated zone, about 2.5 km in width, from the RMP surface that widens to the east in this area. The southern part of the valley section has been built up by sands and silts in the form of levees (LV).

Characteristics of the geomorphological features identified

RMP: A meander plain reworked by flows of the contemporary braided Vistula River (mostly before the construction of the flood banks). This feature is characterised by considerable lithological variability. It is represented by alternating clayey sands, silts, silty loams, clayey silty loams, silty clays and clays with sand interbeds. At a depth of 0.5 m in the RMP-s and RMP-c profiles there is a higher clay content and greater variability in grain size. The organic matter content in these alluvial muds is low; the average value is below 2.5%. At a depth of 1.5 m, the RMP-s and RMP-c features were analysed jointly due to their similarity in sedimentary characteristics and the inability of distinguishing between them in terms of morphological features. Compared to the deposits in the upper section, these are more diverse because the clay content varies from 5 to 35%. They also contain larger amounts of organic matter. $CaCO_3$ is observed only locally in the deposits of this feature, and its content is up to 2.3%. The Fe/Al ratio values are moderate as compared to the deposits of the remaining features due to the amount of authigenic iron.

CF: Concentrated flow. This feature is composed of clayey sands, silts, loams and clayey silty loams, interbedded with sands of various thicknesses. The content of clay is highly variable in these deposits and they show its lowest average and median values. The top part of this feature has a higher clay content relative to the deposits found at a depth of 1.5 m (Text-fig. 5), while the organic matter content is similar and does not exceed 1.3%. These deposits frequently contain calcium carbonate of up to 1.6%. The Fe/Al ratio is lower only than the ratio determined for the SWZ and PC deposits, and comparable to that for the TP (PC) at a depth of 0.5 m. Moreover, deeper-seated deposits in the profile have a lower Fe/Al ratio than the PT deposits (Text-fig. 5).

The alluvial sediments that compose this feature are characterised by their relatively high clay content. At a depth of 0.5 m, the average and median clay contents are greater than in alluvial sediments of most of the remaining features. Granulometrically these alluvial sediments are referred to as silty loams, loams and silty clays, interbedded with fine and medium sands of different thicknesses from 0.1 m to 1.0 m. They sporadically contain $CaCO_3$.

LV: Levée. Among the floodplain deposits, those occurring here at a depth of 0.5 m are characterised by the lowest values of average and median content of clay, but also by the highest content variability of this component (Text-fig. 5). LV is composed of clayey sands, silts, sandy silts and loams. Clays are also locally observed. At a depth of 1.5 m the deposits are much more abundant in clay, like the alluvial sediments of the reworked floodplain. Thus, these deposits probably represent the latter feature. The organic matter content in these deposits is locally up to 4.5%, and the $CaCO_3$ content does not exceed 1%.

OL: Oxbow lakes. This feature is filled with loams, silty loams and silty clays containing up to 6% of organic matter (Text-fig. 5). The clay content variability is higher at the top of the feature than at a depth of 1.5 m (where the sediment is more clayey). These deposits locally contain also small amounts of $CaCO_3$ (up to 1.5%). OL contain the smallest amount of authigenic oxides from all landforms and features from a depth of 1.5 m.

SWZ: Stagnant water zone. This feature clearly shows lithological variability along its profile. The top part consists of more clayey silty loams and silty clays with the organic matter content up to 5%, whereas the bottom part is represented by less cohesive deposits (Text-fig. 5). The maximum clay content is 23%. The deposits also show considerable amounts of organic matter, attaining 24%. Locally, they contain up to 10% of $CaCO_3$. At a depth of 0.5 m there are high contents of authigenic iron oxides, which are however lower than at a depth of 1.5 m and vary within a narrow range.

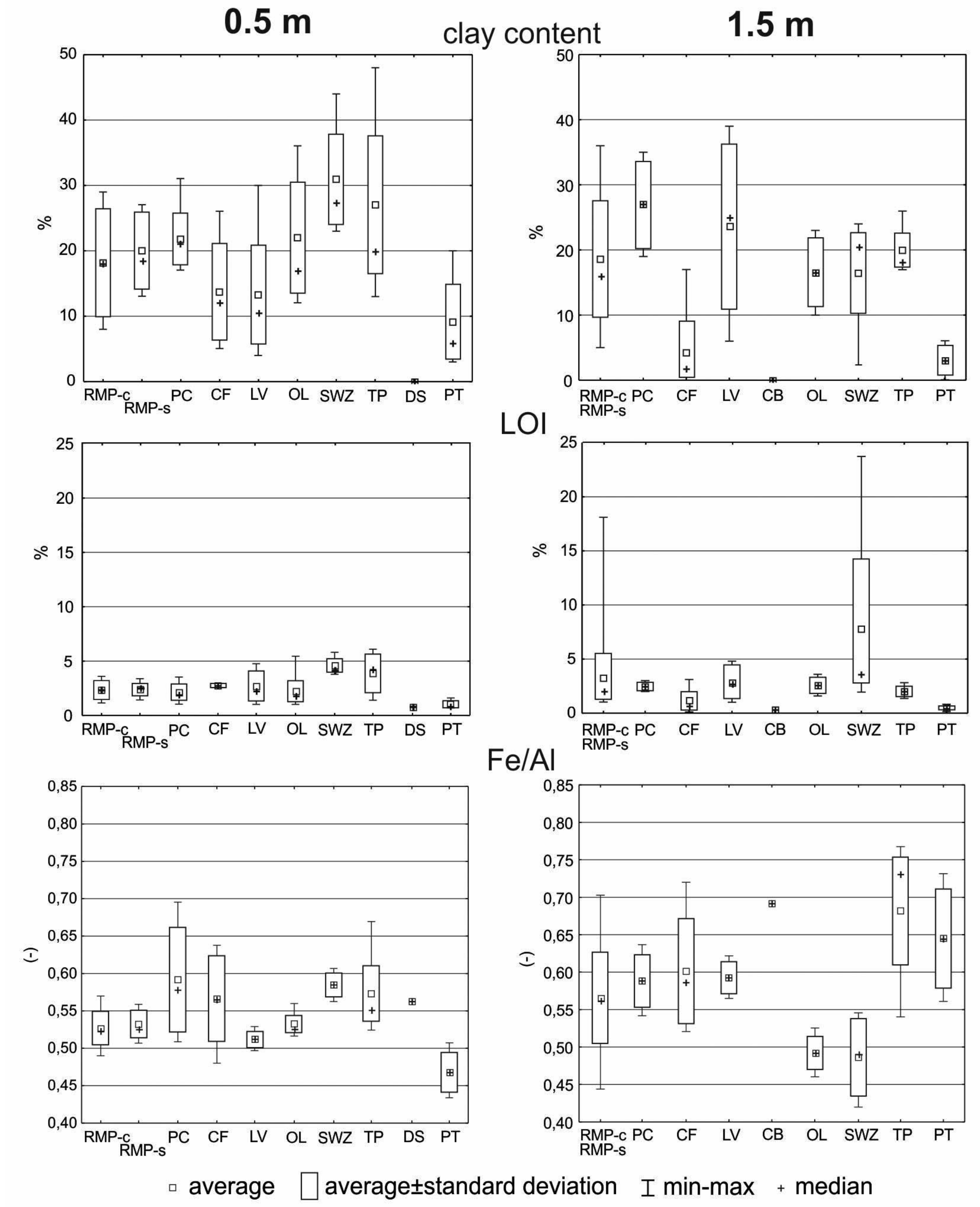
TP: Tributary floodplain. Tributary floodplains are composed of cohesive deposits with a high variability of clay content from 13 to 48% at a depth of 0.5 m, and from 8 to 26% at a depth of 1.5 m. The average organic matter content does not exceed 2.2%. These deposits are rich in authigenic Fe oxides and hydroxides (Text-fig. 5).

PT: Pleistocene terrace. Deposits of this landform are characterised by the lowest contents of clay and organic matter (Text-fig. 5). They are also carbonate-free and contain small amounts of authigenic Fe oxides at a depth of 0.5 m.

The clay fraction in flood deposits in the study area is represented predominantly by smectite, accompanied by small amounts of kaolinite, illite and mix-layered minerals.

Trace elements concentrations

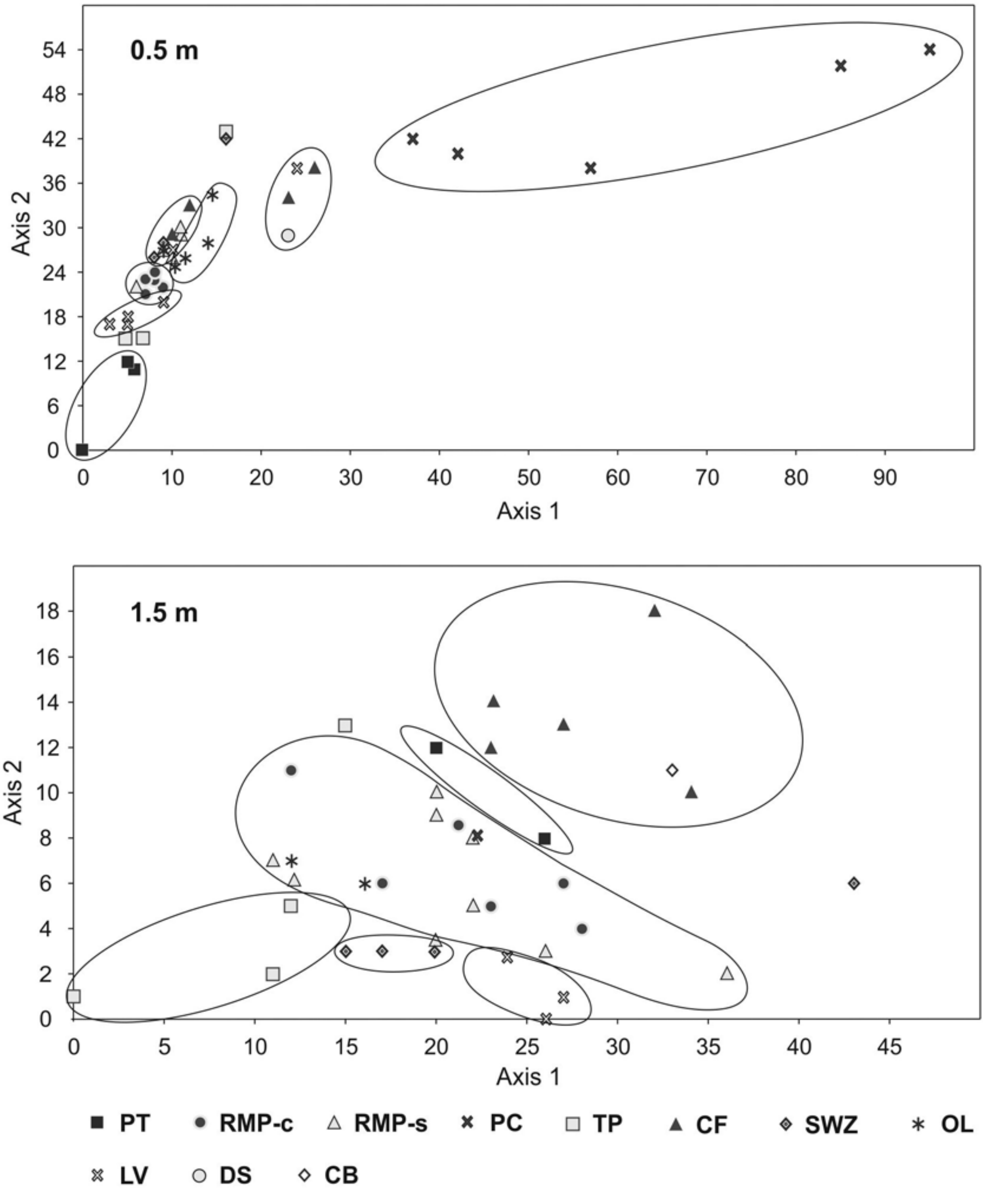
The concentrations of trace elements in the samples are higher than the geochemical background for the entire region, as determined for soils and presented in the geochemical maps of Poland (Lis *et al.* 1997).



Text-fig. 5. Content of clay, authogenic Fe (based on Fe/Al) and loss of ignition in deposits of the Vistula River valley analysed

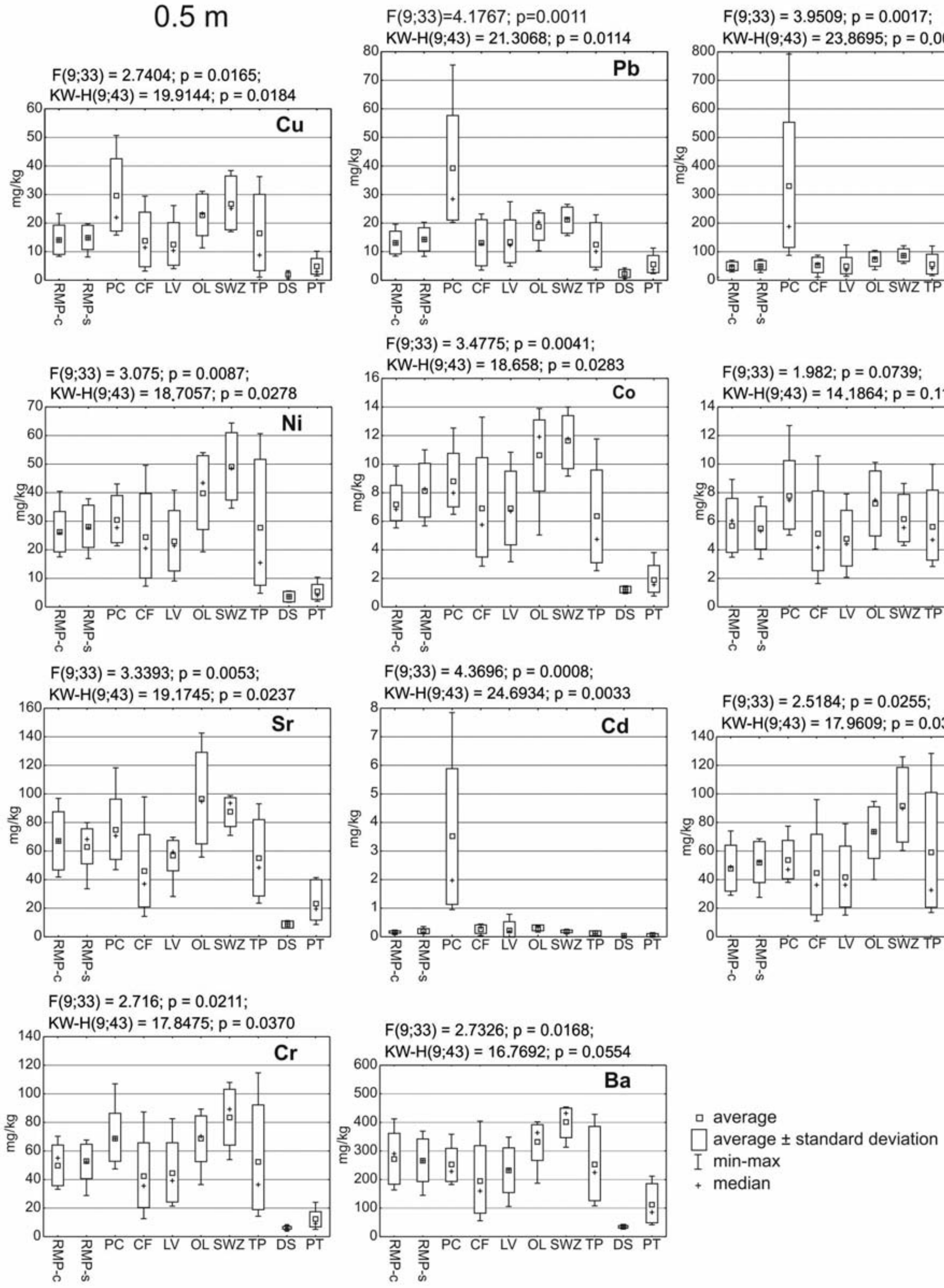
The distribution of these elements is uneven in the area of the Vistula River Valley. The detrended analysis (DCA) groups the trace elements according to the relief features, distinguished as a result of the geomorphological analysis (Text-fig. 6). At a depth of 1.5 m the division into two geochemically different sample groups in the floodplain, visible at a depth of 0.5 m, is no longer observed. At a depth of 0.5 m there are different modes of grouping trace elements in the zones of concentrated flow and levees. Different rules of concentrating trace elements are exhibited by sediments building the concentrated flow zone and its neighbourhood in the south of the study area.

At 0.5 m depth, the highest concentrations of Cu, Pb, Zn, Cd and As are found in the contemporary floodplain sediments, evidenced by both average and

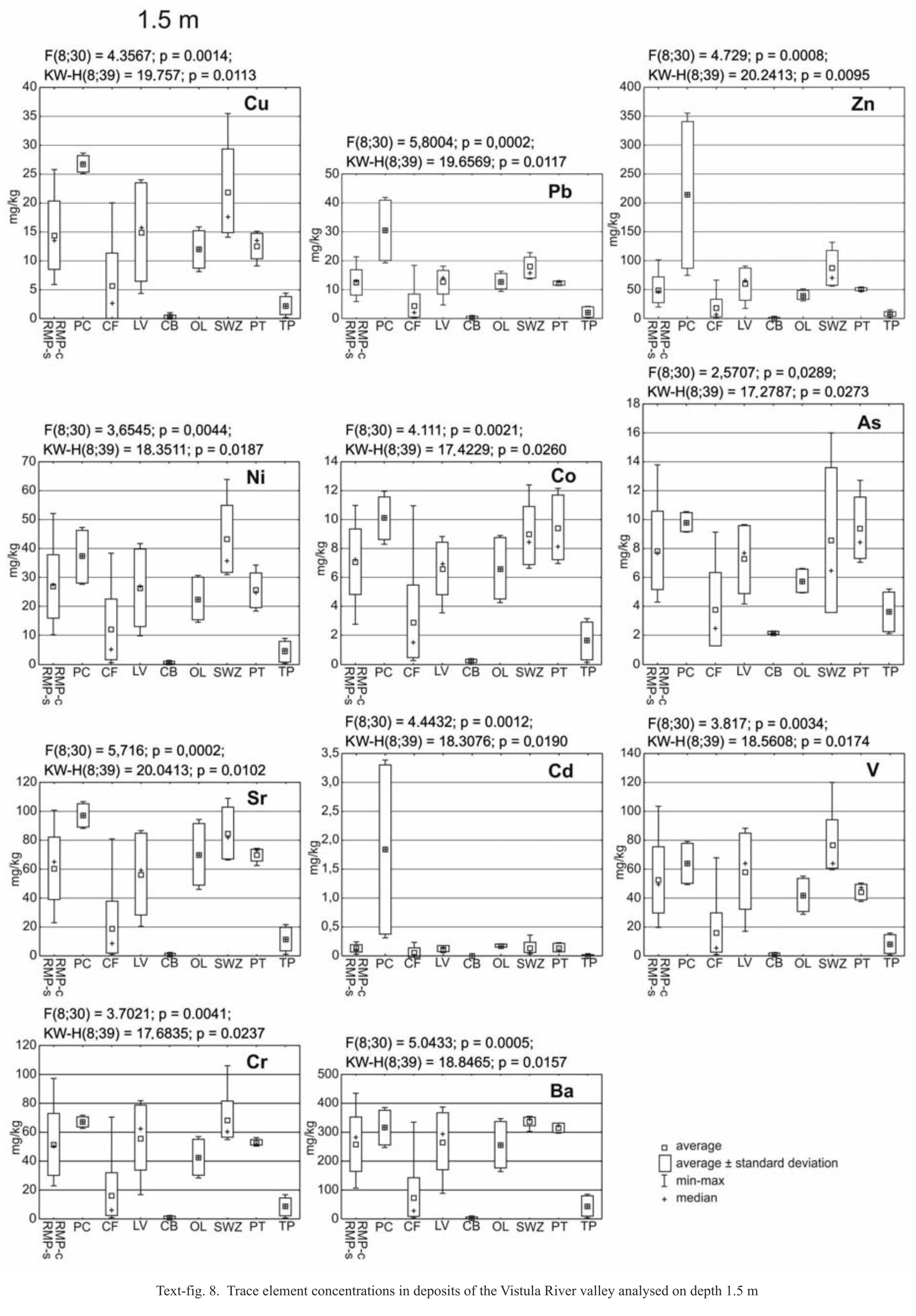


An explanation of the abbreviations is in Fig. 2.

Text-fig. 6. Detrended analysis (DCA) of investigated trace elements



Text-fig. 7. Trace element concentrations in deposits of the Vistula River valley analysed on depth 0.5 m



Text-fig. 8. Trace element concentrations in deposits of the Vistula River valley analysed on depth 1.5 m median values, although the dispersion of results is relatively high within this group (Text-fig. 7). Considerable concentrations of the same elements (Cu, Pb, Zn, Cd and As) were also determined in the sediments composing the water stagnation zones, which additionally contain the greatest concentrations of Ni, Co, V, Cr and Ba. Similarly, the highest Sr concentrations were found in sediments filling oxbow lakes and stagnant water zones. The lowest concentrations of all trace elements are present in the Pleistocene terrace sediments and deltaic deposition zones.

At 1.5 m depth, the levels of trace elements in the RMP-s, RMP-c and LV sediments are similar (Text-fig. 8). Higher Ni, Co, As, Sr, Cd, Cr and Ba concentrations than in the surface zone were found at this depth in the PC and TP sediments. Similar to 0.5 m depth, the highest concentrations of trace metals at 1.5 m were encountered in contemporary floodplain sediments, while the lowest ones were observed in the Pleistocene terrace sediments (PT). The exception was Sr and Co, the highest concentrations of which were found in the PC. Slightly lower Cu, Pb, Zn, Sr and Cd concentrations than at 0.5 m were measured in the SWZ sediments from 1.5 m depth. A similar distribution between the relief features to that in the sediments from a depth of 0.5 m was found for Cu, Pb, Zn and As.

The very high diversity of Zn, Cd and Pb concentrations in the contemporary floodplain sediments (PC) is worth noting.

DISCUSSION

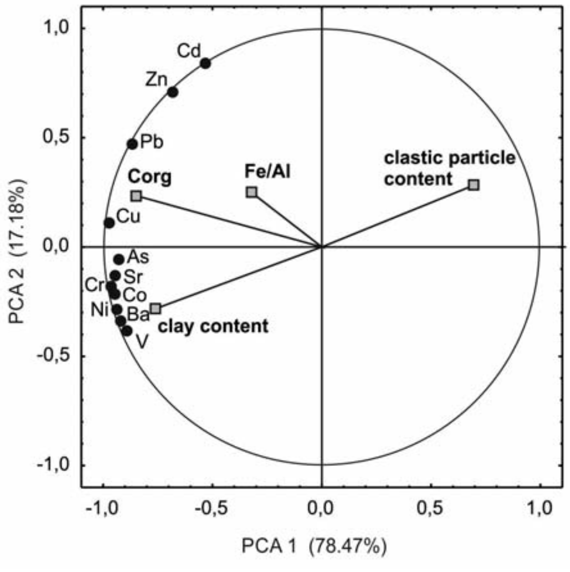
Trace metal concentrations in the Vistula River Valley sediments of the study area are lower than in floodplain sediments of contaminated European rivers, such as: Rhine (Martin 2004), Dill (Martin 2015), Seine River (Grosbois *et al*. 2006) or Odiel River (Santos Bermejo *et al*. 2003).

PCA analysis was carried out to identify factors controlling the distribution of trace elements in the alluvial sediments, (Text-fig. 9). The following components were considered as principal: clay content, organic matter, calcium carbonate, and free iron oxides and hydroxides estimated on the basis of the Fe/Al ratio. The analysis confirms the well-known geochemical affinity of elements between each other and between the selected principal components, characteristic for the individual geomorphological features (Förstner and Wittman 1983). PCA analysis was supported by multiple regression analysis, which also proves the strength of this effect for the individual principal components (Table 1). The results of these analyses indicate that the variability of V, Ni, Cr and Ba concentrations is controlled largely by the clay content. An important factor determining the variability in the concentrations of Cu, Pb, Co, Sr and As is also organic matter content. In contrast, the distribution of Zn and Cd is primarily controlled by $CaCO_3$ and, to a lesser extent, by organic matter.

An important factor in shaping the diversity of depositional environments within flood deposits in the study section of the Vistula River Valley was its geological structure, especially the position of the top of sub-alluvial basement.

Near the village of Basonia and near the Krępianka River mouth the top of Upper Cretaceous hard limestones and marls, overlain by a residual pavement, forms narrow, approximately 5–6 m deep troughs in the sub-alluvial basement. In the Józefów region, Upper Cretaceous rocks form an elongated ridge stretching over a distance of a few kilometres (Falkowski 2006, 2007). In contrast, the basement relief in the Basonia region and near the Krępianka River mouth can be related to the presence of fault zones running parallel to the Vistula River Valley (Sawicki 1933; Romanek and Złonkiewicz 1993; Pożaryski *et al*. 1994). The top of the basement of contemporary alluvial deposits in the study area is periodically exposed in the channel during high water flows and affects the structure of main river current, as demonstrated by echo-sounding surveys, carried out during different water levels (Falkowski 2006). The lack of ability for channel deepening by the river during rain-induced floods (cf. Leopold *et al*. 1964) leads to water damming in front of these natural barriers. In winters, the waters can dam up at these places due to ice blockage. The potential of ice to be piled up on a rocky surface of sub-alluvial deposits (the so-called grounded ice jam; Grześ 1985; Wiliams and MacKay 1973) is the parameter that contributes to the formation of an ice-jam. Analysis of flood events recorded throughout the Małopolska Gorge section (Falkowski and Popek 2000; Falkowski 2006) has shown the relationship of the sites where these occur with culminations of the basement of the contemporary alluvial deposits. Blocking of the flows influenced the nature of flood deposition to various extents.

Long-lasting low-dynamic floods can be associated with a more terminal stage of ice-jam floods. In such conditions, silt covers developed on the floodplain surface, and deltaic deposits accumulated at the mouths of tributaries (like the Krępianka mouth). The flood was sustained by changes in the hypsometry of the valley floor. Changes resulted from the



Text-fig. 9. Principal component analysis (PCA) for the trace element concentrations in the investigated deposits

evolution of the Vistula River system during the Subatlantic Holocene period („wild river“ as described here by Falkowski (1967, 1971) and Starkel (1983). These changes consisted (and still do) in the building up of the channel zone by the braided river overloaded as a result of changes in its hydrological regime. The initial phase of ice-jam floods as well as rain-induced flood flows during this process were characterised by greater dynamics than during the meandering period (cf. Zwoliński 1992), which is recorded in the floodplain surface by the reworking of the top part of the older flood deposits. In the study area, the reworking affected the entire valley due to its small width. This distinguishes the analysed section from the remaining areas of the Małopolska Gorge of the Vistula River.

The flood flow zone in the Kępa Gostecka area coincides with the course of a deep erosional trough that developed during the Masovian Interglacial, as delineated in this area by Maruszczak (1982) and Pożaryski *et al*. (1994). This confirms the significance of a rocky basement of alluvial deposits for the floodplain morphodynamics, not only contemporarily but also in the past.

The results of the analysis provide an insight into the relationship of trace metal content with the origin of the geomorphological features, although the differences between the contents are not large. This phenomenon can be attributed to the high dynamics of flood flows in this area of the Vistula River Valley. The floodplain depositional environment is, however, not entirely homogeneous, reflected in the considerable diversity of its surface relief, and in the corresponding sedimentological diversity of surface deposits. The complexity of floodplain surface structure corresponds to the diversity of trace metal content in the sediments composing the individual features. The Anova and Kruskal-Wallis non-parametric statistics for sediments grouped according to the floodplain relief features show a diversity and statistical significance of this division for all elements, excluding As (Text-figs 7, 8).

The highest contents of trace elements found in the contemporary proximal floodplain (PC) are caused by the nature of flood-wave movement through the levée-bounded channel zone. Floods are more frequent and longer-lasting in this area, and the water level during the floods is higher.

Trace elements	R^2 calculated for individual factors (step)				Parameters calculated for all factors			
	$CaCO_3$	clay	LOI	Fe/Al	R	R^2	F (4,49)	p
Cu	*0.02 (3)*	*0.07 (2)*	*0.85 (1)*		0.97	0.94	167.59	< 0.0000
Pb	*0.11 (2)*	0.01 (3)	*0.77 (1)*	0.01 (4)	0.94	0.89	91.107	< 0.0000
Zn	*0.59 (1)*		*0.21 (2)*	*0.02 (3)*	0.91	0.82	51.173	< 0.0000
Ni		*0.66 (1)*	*0.14 (2)*	0.01 (3)	0.90	0.82	49.266	< 0.0000
Co		*0.10 (2)*	*0.62 (1)*		0.85	0.72	28.426	< 0.0000
As	*0.05 (3)*	*0.10 (2)*	*0.47 (1)*		0.80	0.63	19.028	< 0.0000
Sr	*0.04 (3)*	*0.13 (2)*	*0.51 (1)*	0.01 (4)	0.83	0.68	23.812	< 0.0000
Cd	*0.56 (1)*	*0.02 (3)*	*0.15 (2)*	0.02 (4)	0.87	0.75	33.826	< 0.0000
V		*0.75(1)*	*0.07 (2)*	0.01 (3)	0.91	0.83	52.743	< 0.0000
Cr	0.01 (3)	*0.71 (1)*	*0.15 (2)*		0.93	0.87	72.119	< 0.0000
Ba		*0.65 (1)*	*0.07(2)*		0.84	0.72	28.310	< 0.0000

Italic typeface shows statistically significant values (p-value<0.05)

Table 1. Selected parameters of stepwise multiple regression

Thus, the intensity of modern deposition from suspension is higher in this zone than it was before the construction of man-made levees. This fact contributed to the higher contents of clay, organic matter and $CaCO_3$ (temporary stagnation and development of a quasi-lake environment with high primary production inducing increased OM and $CaCO_3$ sedimentation, and associated trace elements). The high levels of cadmium and copper could indicate the presence of agricultural contaminants supplied to the river channel with surface runoff, while the high levels of Zn and Pb presumably show the impact of mine waste discharges from the Silesian mining area (Bojakowska *et al.* 1992). These are probably mainly redeposited discharges from the years of greater production, when environmental protection was in its infancy.

Similar high concentrations of trace metals, especially Cr, V, Sr, Ba, Ni, Cu, Pb and Zn, found in the water stagnation zones, result from the nature of tranquil deposition of clays in these zones, containing considerable amounts of organic matter. Periods of organic-clay deposition were interrupted by episodes of more dynamic accumulation from flood flows. Such a framework results from the presence of the above-mentioned rapids, affecting the direction and nature of water flow during floods. Increased organic matter contents were also found in sediments filling oxbow lakes – mainly in peats containing much mineral matter. Such oxbow lakes, forming a sequence of depressions on the floodplain surface, were pathways for water transporting mineral sediments during flood events.

The lowest variability in the concentration of trace elements was found in the sediments building the top of the floodplain from the Holocene Climatic Optimum period, partially remodelled by modern flood flows (RMP). Slightly higher concentrations are present in this part of the feature, which has a smooth surface. This phenomenon can be associated with a higher content of clay deposited in these places during long-lasting and steady floods. Areas with an uneven floodplain surface and identifiable traces of meandering channel migration, as well as with short and dynamic flows over the surface, causing erosion of loamy muds, are characterised by a lower concentration of trace elements. At a greater depth the differences between these zones disappear.

Within the zones of concentrated flow, the contents of trace elements are lower at greater depths than in the top part of the profile. This may be the result of changes in the nature of deposition, which have taken place on the floodplain surface since the construction of man-made levees. Prior to their construction the zones of concentrated flow were shaped by flows of higher dynamics. For this reason, the sediments from a depth of 1.5 m show lower contents of clay and organic matter and, consequently, a lower content of trace metals. Contemporary floods are associated only with high water levels in the tributaries of the Vistula, or with failures in the man-made levees. Waters of these floods flow out of the floodplain surface slowly, which favours deposition of the finest fraction.

There is a genetic relationship between the concentrated flow zones and levée zones. Near Solec nad Wisłą they occur close to the contemporary Vistula River channel as well. This relationship is also manifested by the trace element content, but only at a depth of 0.5 m. At a depth of 1.5 m there are older alluvial muds covered by levée deposits of the RMP.

The differences in the content of trace metals between the levée deposits in the Basonia and Sulejów region (southern part of the study area) and the Solec nad Wisłą region (northern part) result from the different dynamics of flow processes in the compared environments. The former environment is associated with incidental flows, during major floods. The latter developed during the passage of a flood wave trough, the active channel of the modern Vistula River.

The lowest levels of trace elements were found in the sediments of the Pleistocene terrace that occurs in the valley floor in the form of outliers. This is due to the fact that the floodwaters were encroaching upon their surface only during extremely high water levels, without forming a layer of Holocene alluvial muds of significant thicknesses. These sediments have thus preserved low concentrations characteristic of deposition in severe conditions of abiotic environment with poorly developed weathering processes. Equally low values, found within sand bars, result from the small contents of clay and organic matter in these sediments. Trace elements in them are bound to iron oxides and hydroxides.

Our results indicate the significance of the identification of floodplain morphodynamics in analysing the principles of distribution of trace elements in flood sediments. The importance of this type of geomorphological analysis is particularly high in the case of river valley environments whose erosional base is not completely developed.

CONCLUSIONS

The framework of geomorphological features within the floodplain of the study area is associated with very dynamic flows in a narrow valley gorge, and with the presence of rapids related to water-damming sub-alluvial thresholds during floods.

The diversity of the contents of trace elements is closely linked to the identified floodplain features, and it well explains the dynamics of morphodynamic processes that have shaped them.

The content of trace elements in the sediments can be considered as valuable geochemical proxies that enable a more thorough reconstruction of the sedimentological history of the Vistula River Valley, especially along the naturally complex sections of the Małopolska Gorge.

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