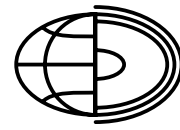


Sediment origin and pedogenesis in the former mill pond basin of Turznice (north-central Poland) based on magnetic susceptibility measurements



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Łukasz Mendyk^{1*}, Piotr Hulisz¹, Grzegorz Kusza², Marcin Świtoniak¹,
Leszek Gersztyn³, Barbara Kalisz⁴

¹ Nicolaus Copernicus University in Toruń, Poland

² University of Opole, Poland

³ Wrocław University of Environmental and Life Sciences, Poland

⁴ University of Warmia and Mazury in Olsztyn, Poland

* Correspondence: Department of Soil Science and Landscape Management, Nicolaus Copernicus University in Toruń, Poland. E-mail: mendyk@gmail.com

Abstract. This paper aims to assess the usefulness of magnetic susceptibility measurements in pedological studies of mill pond sediments. The study area includes the former Turznice mill pond basin located in the south-eastern part of the Grudziądz Basin. Four soil profiles were selected within the transect located along the longitudinal axis of the basin. The following soil properties were determined in the collected samples: bulk density, particle size distribution, pH, content of carbonates, approximate content of organic matter (LOI), total organic carbon (TOC), total nitrogen (Nt), and the pseudo-total contents of metals (Fe, Mn, Cu, Zn, Pb, Ni, Cd). The obtained results were correlated with the specific (mass) magnetic susceptibility (χ). This study revealed that the variability of the soil cover in the basin was driven by different sedimentation conditions. The different composition of natural terrace deposits versus mill pond sediments has been well reflected in the magnetic properties. However, the possibility cannot be excluded that a pedogenic (gleyic) process is the key factor causing the vertical variability of magnetic properties in studied soils.

Key words:
mill pond sediments,
magnetic susceptibility,
Gleysols,
heavy metals

Introduction

Water mills were one of the earliest hydro-technological constructions in Poland. They appeared at the turn of the 12th century and became common in the 13th century (Dembińska 1973). The energy of the water was not used for grinding grain only, but also in fulleries, granaries, oil mills, tanneries, sawmills and hammermills (Baranowski 1977; Podgórski 2004).

Researchers dealing with mills focus mainly on the area of location factors (e.g. Podgórski 2004) and activities connected with the restoration of post

mill pond areas, including so-called 'small retention' (e.g. Łoś 1978; Kreft 1999; Brykała 2005). The construction and operation of water mills influenced the transformation of the surrounding natural environment. The greatest changes are seen in relief and water conditions (Podgórski 2004). In addition, the soil cover is also an important element of the environment which is characterized by fast reaction to such anthropic pressure. Beside the fact of the transformation of the natural soils, completely new ones have also been developed, especially within the areas of former mill pond basins.

The other area is research of mill pond sediments, which are studied mainly by geomorpholo-

gists and sedimentologists. They use these deposits as an indicator of anthropogenic environmental changes (e.g. Kocel 1995; Michalska and Szpikowski 1999; Klimek et al. 2003; Szwarczewski 2003; Sypka et al. 2007; Niemitz et al. 2012; Kittel et al. 2015). Some of these investigations have practical application in the agricultural use of mill pond deposits after dredging (e.g. Madeyski and Tarnawski 2006). There are also studies concerning the influence of mill ponds on geomorphological and geochemical processes in catchments (Hupp et al. 2012).

Apart from several exceptions, there is a lack of pedological studies on mill pond sediments (Jonczak and Florek 2013; Mendyk et al. 2015). Related studies are connected mainly with the characteristics of soils developed in the area of former fish ponds (Giedroń et al. 1992; Hulisz et al. 2007; Łabaz and Bogacz 2011).

The magnetic properties of soils reflect different mineral compositions of soils. The minerals present in soils are of both natural (lithogenic, pedogenic) and technogenic (e.g. industrial dusts) origin (Szuskiewicz et al. 2016). The magnetic susceptibility can differ due to the source of those minerals. The occurrence of minerals of anthropogenic origin in soil can be easily detected by the measurement of magnetic susceptibility, which is a concentration-dependent parameter (Thompson and Oldfield 1986).

Detailed investigation of magnetic susceptibility changes in vertical patterns is a simple way to explain the origin of magnetic soil anomalies and has been applied by many authors. In pollution studies, magnetic susceptibility in vertical topsoil profiles has been used to characterize the distribution of technogenic magnetic particles and related heavy metals (Strzyszc et al. 1996; Petrovsky and Ellwood 1999; Magiera et al. 2013). This research approach requires the assessment of background values of magnetic susceptibility in natural environments, e.g. forest soils (Magiera et al. 2013, 2016) and its anomalies (Magiera et al. 2011). There is also investigation into magnetic soil properties at archeological sites (Tite 2007) or studies focusing on human impact, e.g. the application of wastewater in organic soils used for biomass production (Sokołowska et al. 2016). However, study of the magnetic susceptibility of soils developed from mill pond sediments has not been conducted yet. That is why this pa-

per aims to assess the usefulness of magnetic susceptibility measurements in the pedological study of these specific materials. Despite the fact that this research is broadening the knowledge about soils derived from mill pond sediments, it is still a preliminary study and should be expanded for detailed interpretation, especially in the field of mineralogy.

Material and method

Study area

The study area comprises the former Turznice mill pond basin located in the south-eastern part of the Grudziądz basin on the edge of the 5th terrace of the Vistula River. The mill was built on the Turznica stream, which drains the edge of the till plain to the south (Fig. 1).

According to Podgórski (2004) the history of the Turznice mill (Turznice-2 in the mentioned study) begins in the middle of the 17th century. It operated with some interruptions until the middle of the 20th century (Fig. 2). The mill pond was constructed by setting four dams surrounding the pond basin. In 1875, the pond covered an area of 0.43 ha and was 175 meters long (Podgórski 2004).

The Turznice mill pond was located laterally to the stream. The water inflow and outflow were located close to each other (Podgórski 2004, Fig. 2). This specific type of water management in the Turznice mill pond system led to a modification of the typical accumulation patterns of simple flow-through reservoirs.

According to Köppen–Geiger climate classification, the region is located in a warm temperate, humid zone with warm summer (Kottek et al. 2006). The average annual air temperature is about 8 °C. The average annual precipitation is 505 mm (Wójcik and Marciniak 1987a, b, 1993).

The potential natural vegetation of the study area are ash–elm riparian forests and hornbeam forests such as *Ficario-Ulmetum* and *Tilio-Carpinetum*, respectively (Matuszkiewicz 2008). Current vegetation around the former mill pond is of meadows, pastures and communities typical of arable lands.

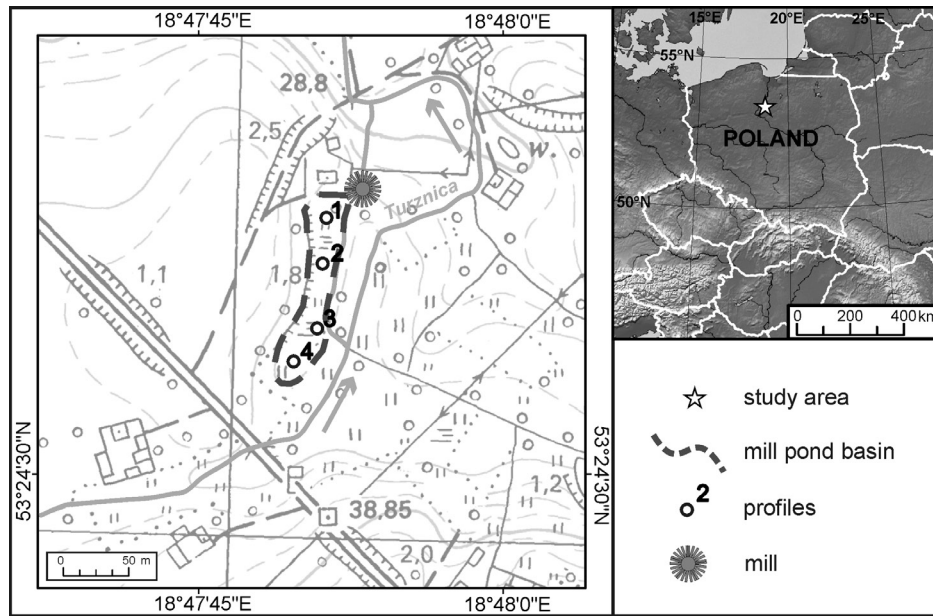


Fig. 1. Location of the study area and soil profiles

Field and analytical work

Four soil profiles (Figs 3–6) were selected along the transect located along the longitudinal axis of the basin (Fig. 1). The transect was drawn from the dam enclosing the former pond to the pond’s rear side.

Soil profiles were described in respect of Guidelines for Soil Description (Jahn et al. 2006) and samples (disturbed and undisturbed) were collected from all soil horizons. Disturbed samples were

air-dried, disaggregated, homogenized and sieved through a 2-mm sieve.

The following soil properties were determined in collected samples: bulk density by the oven-dry method, particle size distribution by the sieve method and the hydrometer (the Bouyoucos aerometric, modified by Cassagrande and Prószyński) method, pH in the soil-to-solution ratio of 1:2.5 using H₂O and 1 M KCl as the suspension medium, and content of carbonates by the Scheibler volumetric method. Approximate content of organic matter was determined using loss on ignition (LOI) analysis.

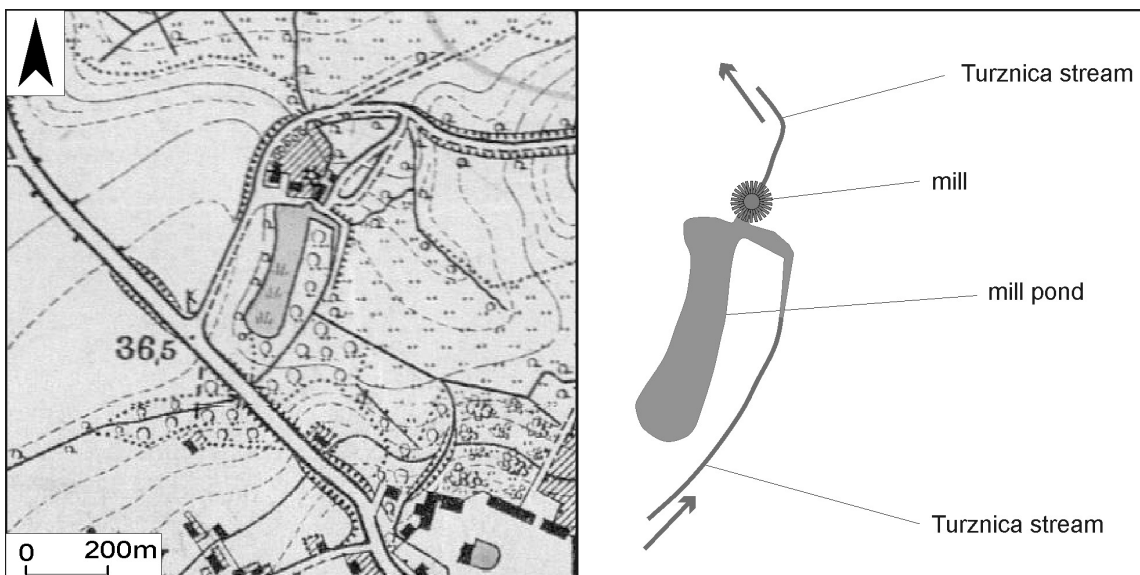


Fig. 2. A: Turznice mill pond on the Messtischblatt Map, sheet No. 2578, AD 1909, B: model of the water management system (Podgórski 2004, modified)

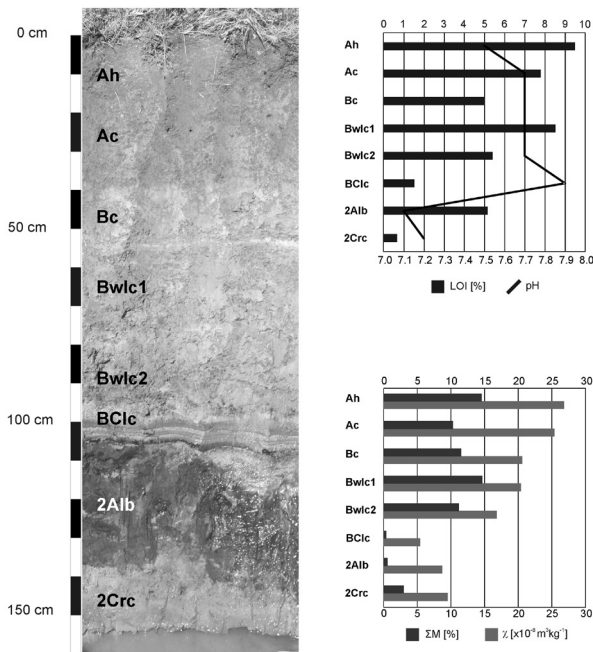


Fig. 3. Soil profile 1 – Morphology and vertical differentiation of LOI (loss on ignition), pH, ΣM (sum of heavy metals content), and χ (specific magnetic susceptibility)

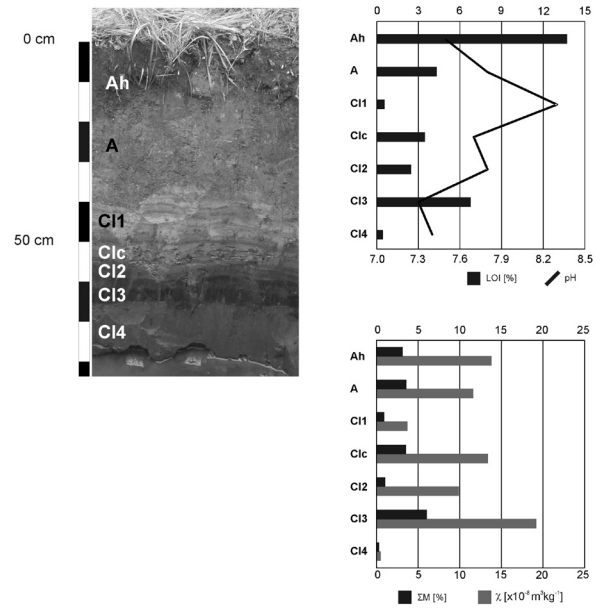


Fig. 5. Soil profile 3 – Morphology and vertical differentiation of LOI, pH, ΣM, and χ. Symbol explanations as on Figure 3

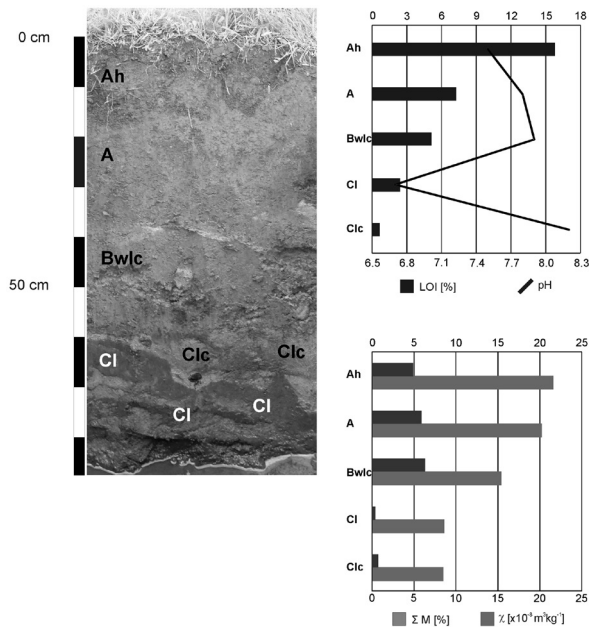


Fig. 4. Soil profile 2 – Morphology and vertical differentiation of LOI, pH, ΣM, and χ. Symbol explanations as on Figure 3

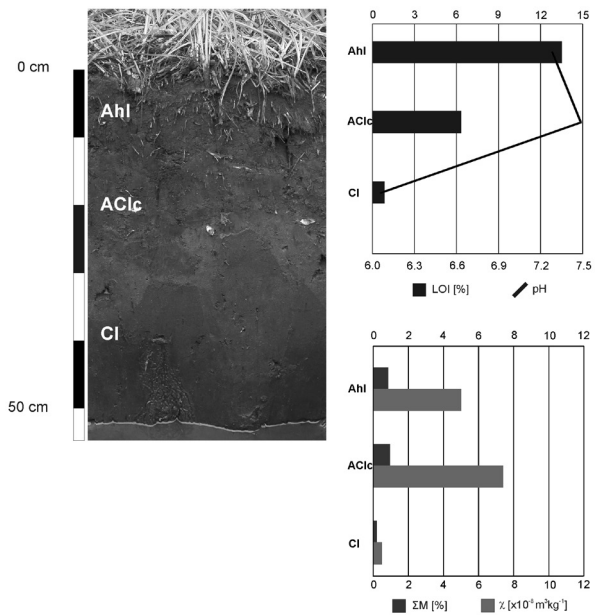


Fig. 6. Soil profile 4 – Morphology and vertical differentiation of LOI, pH, ΣM, and χ. Symbol explanations as on Figure 3

Each sample was ignited at temperatures of 550°C and 920°C in a muffle furnace. The total organic carbon (TOC) and total nitrogen (Nt) content were measured on a Vario MaxCube CN Elemental analyzer in steel cylinders. The soil colour was described for dry and wet samples according to Munsell Revised Standard Soil Color Charts (2002). The

pseudo-total content of metals (Fe, Mn, Cu, Zn, Pb, Ni, Cd) was determined by Varian Spectraa 400 Atomic Absorption Spectrometer, after soil sample digestion in aqua regia (m/v 1:10) in an open system with reflux (Ure 1995). This method is considered as the assessment of the maximum potentially soluble or mobile contents of metals that are not

a part of silicate matrix (Ure and Davidson 2002). Acid-leachable trace metals are treated as incorporated into the sediment from aqueous solution by processes such as adsorption and organic complexation (Ayyamperumal et al. 2006). The soils were classified according to the WRB classification system (IUSS Working Group WRB 2015). The USDA (Soil Survey Staff 1952) classification was used for description of soil texture.

Specific (mass) magnetic susceptibility (χ) was determined with the use of an MS2 “Bartington” laboratory magnetic susceptibility meter, equipped with a dual frequency MS2B sensor – low frequency (κ_{lf}) is 0.47 kHz and high frequency (κ_{hf}) is 4.7 kHz. Magnetic susceptibility (κ) was expressed in dimensionless SI units. Values of specific (mass) magnetic susceptibility (χ) were given in m^3kg^{-1} (Thompson and Oldfield 1986).

Box-and-whisker plots as well as the scatterplots were drawn using STATISTICA 9.0 software (Statsoft Inc.) to determine the relationships between certain soil parameters in individual samples and along the studied transect.

Results and discussion

Basic physical and chemical properties of the studied soils

The analyzed soils were classified as Pantofluvic Phaeozem – Profile 1, Gleyic Fluvisol – Profile 2, Fluvisol Gleysol – Profile 3 and Reductigleyic Gleysol – Profile 4 (Tables 1–4). They are developed from deposits of different genesis which fill the former mill pond basin. Profiles 1–3 are built mainly of sediments accumulated in the reservoir during the operation of the mill. In general, the studied soil materials meet the criteria for *fluvisol* diagnostic material (IUSS Working Group WRB 2015). The exceptions are the two bottom horizons in Profile 1, 2Alb and 2Crc, which probably belong to the buried soil of the natural depression on the edge of the river terrace. Also, Profile 4 is most likely developed from the natural river terrace deposits. This could be explained by the results of previous research. Profile Tur-2D analyzed by Podgórski (2004), lo-

cated close to Profile 4 was considered to have the presence of the natural terrace deposits at a depth of about 1 metre. According to the aforementioned author, Profile 4 is located in the least transformed part of the basin. Moreover, it seems likely that the Cl4 horizon in Profile 3 may be built from natural sediments, but this has not been confirmed at this stage of research.

The analyzed soil profiles are developed from mineral and organo-mineral deposits characterized by diverse texture varying from silty clay loam to fine sand, with domination of silty loam and loamy fine sand (Table 1).

The content of total organic carbon (TOC) in the studied soils showed high variability. The surface horizons, whose origin is clearly connected with sedimentation in the mill pond, contained the largest amounts of organic carbon (3.68%–8.26%). In subsurface horizons it dropped with depth from about 3% to zero (Table 2). There were no significant differences when comparing the LOI distribution along the transect (for all analyzed samples in each profile) (Fig. 8). This is the opposite trend to that of classic results obtained for small flow-through reservoirs such as mill ponds. Generally, both TOC and LOI values rise along the transect from the proximal (the water inflow) to the distal (the water outflow) parts of the basins (or the reservoirs bottom) in response to the decrease in water energy (e.g. Michalska and Szpikowski 1999; Jonczak and Florek 2013; Mendyk et al. 2015). This is due to the specific water management system mentioned before. The mill pond sediments were accumulated under similar conditions for Profiles 1–3, as the water inflow and outflow were located close to each other in the northern, most transformed (natural deposits were removed out of the pond area) part of the basin (Fig. 2).

Carbonate content changed in a very irregular way, varying from 0.1% to 29.6%. The highest concentrations were observed in the sediments accumulated during the operation of the mill, as with total organic carbon content.

All analyzed samples are characterized by pH values (in H_2O) ranging from 6.1 to 8.3. Basically, these results were similar to those of other studies conducted in soils developed from mill pond sediments (Jonczak and Florek 2013; Mendyk et al. 2015).

Table 1. Basic physical properties of the studied soils

GENETIC HORIZON	DEPTH [cm]	COLOUR by Munsell		BULK DENSITY [g · cm ⁻³]	Percentage share of fraction [mm]			TEXTURAL CLASS	ART.*
		dry sample	wet sample		2-0.05	0.05-0.002	<0.002		
Profile No. 1 - Calcaric Cambic Pantofluvic Phaeozem (Geoabruptic, Amphisiltic, Humic) over Eutric Reductigleyic Gleysol (Arenic, Humic)									
Ah	0-15	10 YR 5/4	10 YR 2/3	0.95	19	75	6	SiL	O
Ac	15-39	10 YR 6/4	10 YR 3/3	1.00	17	70	13	SiL	O
Bc	39-54	10 YR 6/4	10 YR 4/3	1.21	12	63	25	SiL	O
Bwlc1	54-75	10 YR 7/4	10 YR 4/4	1.11	17	53	30	SiCL	-
Bwlc2	75-92	10 YR 6/4	10 YR 4/4	1.15	13	62	25	SiL	-
BClc	92-104	2.5 Y 6/2	2.5 Y 3/2	1.37	79	16	5	LFS	B
2Alb	105-140	2.5 Y 5/1	2.5 Y 2/1	1.31	79	19	2	LFS	O, CH
2Crc	>140	5 Y 6/3	5 Y 4/2	n.d.	86	6	8	LFS	-
Profile No. 2 - Epicalcaric Gleyic Fluvisol (Geoabruptic, Episiltic, Humic)									
Ah	0-15	10 YR 5/2	10 YR 2/2	0.74	26	65	9	SiL	O
A	15-35	10 YR 7/3	10 YR 3/3	1.03	19	69	12	SiL	-
Bwlc	35-57	10 YR 6/4	10 YR 4/3	1.01	13	59	28	SiCL	-
Cl	> 57-1/2	2.5 Y 5/1	2.5 Y 3/1	1.63	90	8	2	FS	-
Clc	> 57-2/2	2.5 Y 7/2	2.5 Y 4/2	1.38	96	4	0	FS	-
Profile No. 3 - Epicalcaric Reductigleyic Fluvisol (Geoabruptic, Humic)									
Ah	0-15	10 YR 5/2	10 YR 2/2	0.91	53	43	4	FSL	-
A	15-35/40	10 YR 7/2	10 YR 4/3	1.23	42	49	9	L	O
Cl1	35/40-50	10 YR 7/4	10 YR 4/4	1.54	90	8	2	FS	-
Clc	50-55	10 YR 7/2	10 YR 4/2	n.d.	12	69	19	SiL	-
Cl2	55-58	2.5 Y 6/2	2.5 Y 3/2	n.d.	86	11	3	LFS	-
Cl3	58-65	2.5 Y 7/3	2.5 Y 4/2	0.79	9	62	29	SiCL	-
Cl4	>65	2.5 Y 7/1	2.5 Y 3/2	n.d.	96	4	0	FS	-
Profile No. 4 - Eutric Reductigleyic Gleysol (Arenic, Humic)									
Ahl	0-10	2.5 Y 7/1	2.5 Y 3/2	0.63	74	23	3	LFS	-
AClc	10-27	2.5 Y 6/2	2.5 Y 3/2	1.16	61	34	5	FSL	O, F
Cl	27-60	2.5 Y 6/1	2.5 Y 2/1	1.70	94	4	2	FS	CH

*ARTIFACTS: O - other (e.g. glass, brick pieces), B - bones, CH - charcoals, F - fishbones

Selected metal contents and magnetic properties of investigated soils

Among all of the determined metals, Fe was marked by the highest content (0.46–47.6 g·kg⁻¹). The contents of the others in descending order are as follows: Mn (0.05–1.28 g·kg⁻¹), Zn (8.5–92.3 mg·kg⁻¹), Pb (0.5–41.1 mg·kg⁻¹), Ni (0.5–33.7 mg·kg⁻¹), Cu (1.9–21.3 mg·kg⁻¹) and Cd (0.4–2.2 mg·kg⁻¹) (Table 3).

Clear horizontal and vertical differentiation in determined metals content was observed (Figs 4–9). It decreased along the transect (from Profile 1 to Profile 4) except for the cadmium, with an absolute

minimum in Profile 2. On the other hand, this trend was not as clear for the copper, lead, zinc and nickel as for the iron and manganese or the sum of determined metallic elements (Figs 7 and 8). Vertical differentiation is much more pronounced. Content of metals decreased from the surface horizons down to the bottom of the studied soil profiles, with a sudden change at a depth of about 1 metre in Profile 1, 0.5 metres in Profile 2 and 0.3 metres for Profile 4. Results obtained in samples collected from Profile 3 deviate from others. The sum of metals changes with depth in a very irregular way. This could be explained as the influence of recent modification of the mill pond basin. Profile 3 is located close to a

Table 2. Basic physico-chemical and chemical properties of the studied soils

GENETIC HORIZON	DEPTH [cm]	LOI [%]	Corg [%]	Nt [%]	C:N	pH		CaCO ₃ [%]
						H ₂ O	KCl	
Profile No. 1 - Calcaric Cambic Pantofluvic Phaeozem (Geoabruptic, Amphisiltic, Humic) over Eutric Reductigleyic Gleysol (Arenic, Humic)								
Ah	0-15	9.49	3.67	0.357	10	7.5	7.2	17.5
Ac	15-39	7.78	2.73	0.255	11	7.7	7.2	17.5
Bc	39-54	4.97	1.09	0.129	8	7.7	7.2	7.7
Bwlc1	54-75	8.51	1.35	0.145	9	7.7	7.2	10.5
Bwlc2	75-92	5.39	1.56	0.159	10	7.7	7.1	11.8
BClc	92-104	1.50	0.93	0.065	14	7.9	7.7	3.2
2Alb	105-140	5.14	2.59	0.163	16	7.1	7.1	4.0
2Crc	>140	0.65	0.07	0.013	5	7.2	6.5	0.1
Profile No. 2 - Epicalcaric Gleyic Fluvisol (Geoabruptic, Episiltic, Humic)								
Ah	0-15	15.8	7.17	0.670	11	7.2	7.2	17.9
A	15-35	7.27	2.81	0.250	11	7.8	7.3	27.1
Bwlc	35-57	5.14	1.49	0.138	11	7.9	7.3	13.9
Cl	> 57-1/2	2.42	1.28	0.093	14	6.7	6.5	0.2
Clc	> 57-2/2	0.65	0.24	0.009	26	8.2	8.0	0.5
Profile No. 3 - Epicalcaric Reductigleyic Fluvisol (Geoabruptic, Humic)								
Ah	0-15	13.7	6.43	0.637	10	7.5	7.3	18.0
A	15-35/40	4.34	1.51	0.160	9	7.8	7.4	29.6
Cl1	35/40-50	0.57	0.08	0.008	9	8.3	8.1	1.7
Clc	50-55	3.48	0.74	0.089	8	7.7	7.4	8.7
Cl2	55-58	2.48	0.80	0.070	11	7.8	7.7	2.8
Cl3	58-65	6.78	1.80	0.214	8	7.3	7.1	29.3
Cl4	>65	0.46	n.d.	n.d.	n.d.	7.4	7.2	0.3
Profile No. 4 - Eutric Reductigleyic Gleysol (Arenic, Humic)								
Ahl	0-10	13.5	8.26	0.663	12	7.3	7.3	9.5
AClc	10-27	6.33	1.99	0.208	10	7.5	7.2	27.1
Cl	27-60	0.86	0.26	0.015	17	6.1	5.9	0.3

country road and the sediments may have been disrupted during its preparation. Four variables which represent soil properties – TOC, CaCO₃, clay content (maximum particle size < 0.002 mm) and pH values – were tested for their correlation with the content of determined heavy metals (ΣM). CaCO₃ and clay content showed the strongest positive correlations with ΣM , with the latter having the higher correlation coefficient ($r=0.593$ for carbonates versus $r=0.778$ for clay – Fig. 9). This is due to the fact of the strong sorption properties of the clay fraction which dominates in this case over the sorption connected with organic matter and carbonates and with the limited mobility of trace elements in alkali-

line environments (Brümmer and Herms 1983; Hulisz et al. 2007; Kabata-Pendias 2010).

Magnetic properties such as specific (mass) magnetic susceptibility values were featured with large variability within the horizontal and vertical gradients, similarly to heavy metals content. Magnetic susceptibility decreased significantly along the analyzed transect from Profile 1 to Profile 4, as did the sum of determined metals (Tables 3 and 4, Fig. 7).

Box plot showing the diversity of the selected soil parameters: sum of heavy metals content (ΣM), loss on ignition (LOI) and specific magnetic susceptibility (χ) along the studied transect.

Table 3. Content of heavy metals in the studied soils

GENETIC HORIZON	DEPTH	Fe	Mn	Cu	Zn	Pb	Ni	Cd
	[cm]	[g · kg ⁻¹]		[mg · kg ⁻¹]				
Profile No. 1 - Calcaric Cambic Pantofluvic Phaeozem (Geoabruptic, Amphisiltic, Humic) over Eutric Reductigleyic Gleysol (Arenic, Humic)								
Ah	0-15	47.1	1.28	15.8	70.4	41.1	22.5	2.2
Ac	15-39	32.9	1.26	16.5	68.6	35.6	25.5	2.0
Bc	39-54	37.6	0.59	18.6	66.1	24.3	27.0	1.4
Bwlc1	54-75	47.6	1.05	22.0	77.2	26.3	33.7	1.8
Bwlc2	75-92	36.5	0.53	18.1	67.8	23.7	27.7	1.7
BClc	92-104	0.96	0.15	3.5	16.7	5.7	4.7	0.5
2Alb	105-140	1.28	0.49	5.6	25.1	6.8	7.7	0.8
2Crc	>140	9.77	0.05	5.0	23.4	3.5	8.0	0.6
Profile No. 2 - Epicalcaric Gleyic Fluvisol (Geoabruptic, Episiltic, Humic)								
Ah	0-15	34.6	0.78	21.6	92.3	28.4	20.2	1.2
A	15-35	41.5	1.07	17.8	76.7	27.4	22.6	0.7
Bwlc	35-57	44.6	1.12	20.2	81.1	20.4	29.7	0.7
Cl	> 57-1/2	2.62	0.07	4.0	23.5	0.5	0.5	0.5
Clc	> 57-2/2	5.01	0.09	1.9	12.9	0.5	0.5	0.5
Profile No. 3 - Epicalcaric Reductigleyic Fluvisol (Geoabruptic, Humic)								
Ah	0-15	17.9	0.62	11.3	47.2	23.0	15.1	1.1
A	15-35/40	20.5	0.71	10.3	40.7	26.6	17.6	2.0
Cl1	35/40-50	5.36	0.08	2.2	10.2	3.8	3.7	0.4
Clc	50-55	20.7	0.30	15.6	58.1	20.3	23.5	0.6
Cl2	55-58	5.85	0.13	4.0	15.4	6.7	4.7	0.5
Cl3	58-65	0.04	0.98	21.3	75.0	30.2	32.8	1.9
Cl4	>65	1.70	0.03	2.5	8.5	0.8	1.3	0.4
Profile No. 4 - Eutric Reductigleyic Gleysol (Arenic, Humic)								
Ahl	0-10	10.3	0.63	8.2	43.7	13.7	6.0	0.8
AClc	10-27	11.8	0.34	8.8	41.0	16.0	11.9	1.9
Cl	27-60	2.71	0.05	3.2	18.5	0.5	0.5	0.4

The correlation with each individual analyzed metal was also tested for, and a strong correlation was found with all of them, the strongest being for lead ($r=0.899$), iron ($r=0.890$) and zinc ($r=0.862$), while the weakest being for cadmium ($r=0.689$) – Figure 10. Similar results were reported from the area of eastern Czech Republic where in situ measurement conducted for forest soils showed strong and very strong correlations between concentration of Cu ($r=0.95$), Fe ($r=0.93$), Zn ($r=0.90$), As ($r=0.76$), and Pb ($r=0.68$) and magnetic susceptibility (Matysek et al. 2008). A strong correlation between magnetic susceptibility and concentration of Pb in soils was also recorded in the area of Anthemountas River Basin in Greece (Aidona et al. 2016).

The factor responsible for this pattern is higher amounts of iron and manganese in profiles with lower ground water table (due to location closer to the edge of the terrace). This is connected with a post-sedimentary, pedogenic (gleyic) process while iron oxide precipitation occurred in the dehydrated mill pond sediments, which is confirmed by the reddish colour of these horizons showing the accumulation of iron (Figs 3 and 4). These results correspond with research conducted by Kumaravel et al. (2010) for the paleocatenas of the Indian Himalaya. The authors described a strong relationship with magnetic susceptibility, soil colour and geochemistry resulting from the pedogenesis.

Table 4. Magnetic properties of the studied soils

GENETIC HORIZON	DEPTH	κ_{lf}	κ_{hf}	χ
	[cm]	[$\times 10^{-5}$ SI]		[$\times 10^{-8}$ m ³ kg ⁻¹]
Profile No. 1 - Calcaric Cambic Pantofluvic Phaeozem (Geoabruptic, Amphisiltic, Humic) over Eutric Reductigleyic Gleysol (Arenic, Humic)				
Ah	0-15	25.4	24.0	26.8
Ac	15-39	27.0	25.3	25.4
Bc	39-54	24.7	23.0	20.6
Bwlc1	54-75	23.0	20.7	20.4
Bwlc2	75-92	20.0	18.0	16.8
BClc	92-104	8.0	7.7	5.4
2Alb	105-140	10.3	9.7	8.7
2Crc	>140	14.7	13.0	9.5
Profile No. 2 - Epicalcaric Gleyic Fluvisol (Geoabruptic, Episiltic, Humic)				
Ah	0-15	20.0	19.0	21.6
A	15-35	22.7	21.7	20.2
Bwlc	35-57	18.0	17.3	15.4
Cl	> 57-1/2	13.7	13.0	8.6
Clc	> 57-2/2	11.8	11.0	8.5
Profile No. 3 - Epicalcaric Reductigleyic Fluvisol (Geoabruptic, Humic)				
Ah	0-15	13.7	12.3	13.8
A	15-35/40	13.0	13.0	11.6
Cl1	35/40-50	5.7	5.3	3.7
Clc	50-55	17.3	16.7	13.4
Cl2	55-58	13.0	12.0	9.9
Cl3	58-65	19.3	18.0	19.2
Cl4	>65	0.7	0.7	0.5
Profile No. 4 - Eutric Reductigleyic Gleysol (Arenic, Humic)				
Ahl	0-10	4.3	4.3	5.0
AClc	10-27	8.3	8.0	7.4
Cl	27-60	0.8	0.7	0.5

The opposite situation takes place in horizons under a gleyic process, while such environmental conditions lead to depletion of magnetic enhancement of soil due to the removal of reduced forms of metals (Maher 1998).

Moreover, it was also stated that the relationship between soil colour and magnetic properties breaks down in the case of mixed mineralogy. Taking into account the above-mentioned fact, it can be assumed that soils and sediments of the Turznice mill pond basin are characterized with homogenous mineralogy in general. The predominant Fe-mineral which forms in changing redox conditions in a temperate climate is ferrihydrite (Schwertmann 1988; Dąbkowska-Naskręć 2013; Vodyanitskii and

Shoba 2016) while goethite is the most widespread iron hydroxide – in particular, in the soils of humid and semi-humid areas (Vodyanitskii 2010). In environments rich in humic substances (such as mill pond sediments) the amorphous Fe-minerals are dominative, as the presence of humic acids may cause complete inhibition of crystal formation (Childs 1992; Porsh et al. 2010). In soils with organic carbon content higher than 5%, ferrihydrite could prevail over lepidocrocite and goethite, as is reported for the area of Britain, Belgium and Germany (Schwertmann 1988). Mill pond sediments, as materials deposited by mud-forming processes (Okruszko 1969), are characterized by relatively high amounts of well humified organic matter. This

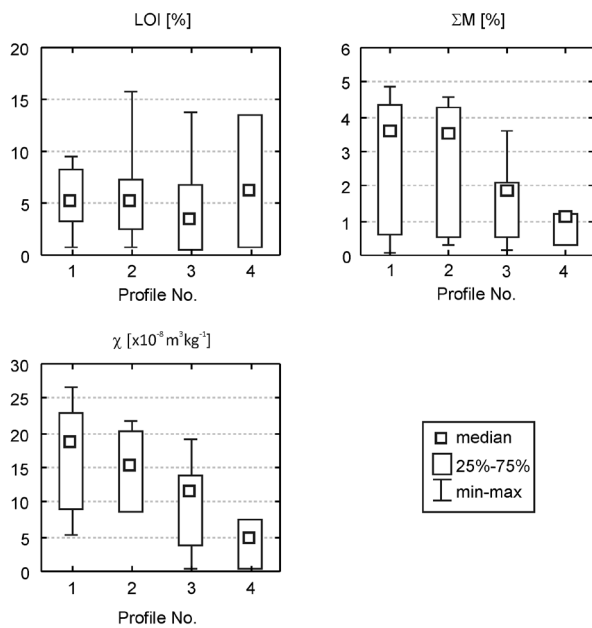


Fig. 7. Box plot showing the diversity of the selected soil parameters: sum of heavy metals content (ΣM), loss on ignition (LOI) and specific magnetic susceptibility (χ) along the studied transect

is also confirmed by results obtained for the Oleszek mill pond, where both high values of humification index and low values of A4:A6 ratio (according to Springer's method – Schlichting et al. 1986) were reported (Mendyk and Markiewicz 2015). On the other hand, lepidocrocite is also a common mineral forming in water-logged conditions during a gleyic process (Vodyanitskii 2010). Despite this fact, formation of lepidocrocite as a crystalline mineral could also be inhibited by the presence of organic matter (Vodyanitskii 1998, 2010). Ferrihydrite is also reported as a paramagnetic mineral with low positive magnetic susceptibility, as well as goethite, which is characterized as an antiferromagnetic mineral (Porsh et al. 2014). These facts stand together with the assumption that ferrihydrite and goethite are the prevailing Fe-minerals in the investigated samples. This explains the relatively high amounts of Fe and small values of specific magnetic susceptibility in samples taken from dehydrated soil horizons. However, this hypothesis cannot be confirmed without the support of detailed mineralogical studies.

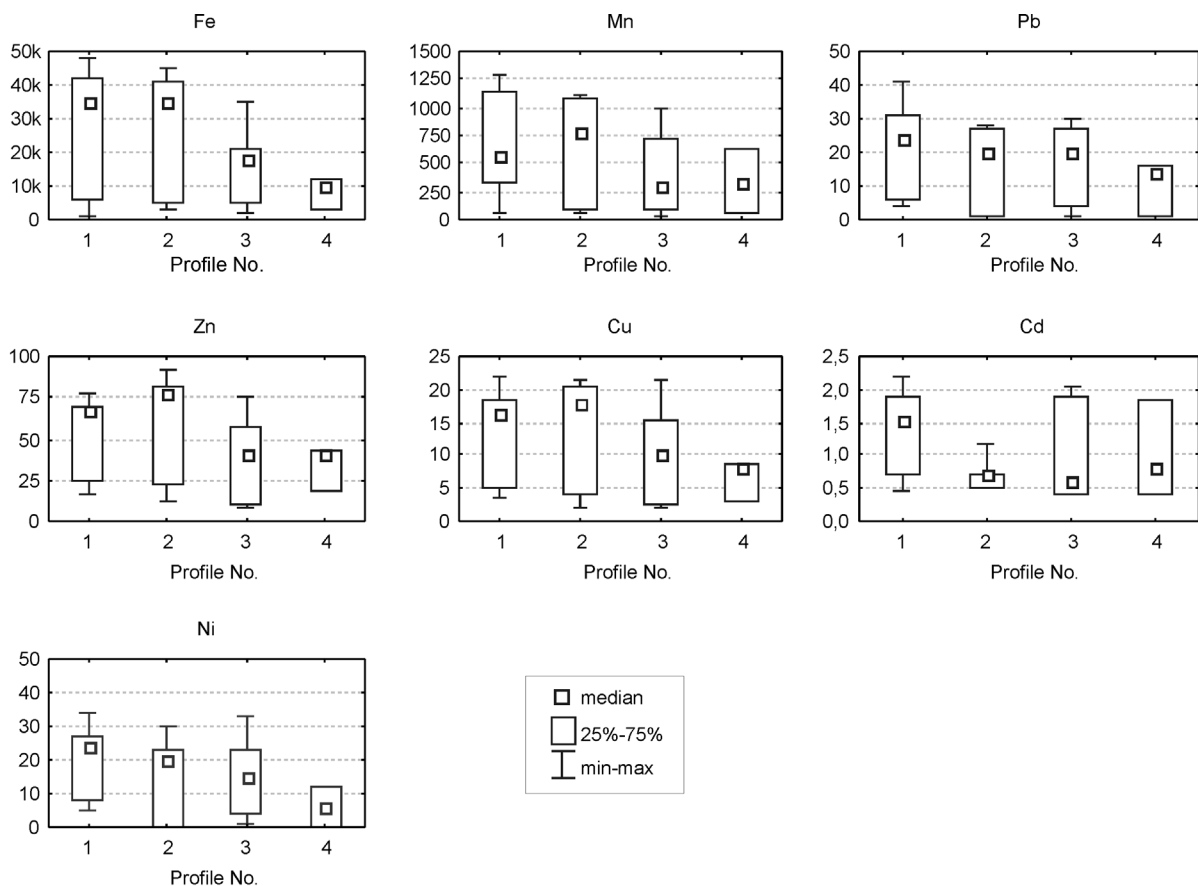


Fig. 8. Box plot showing diversity of the selected heavy metals content along the studied transect

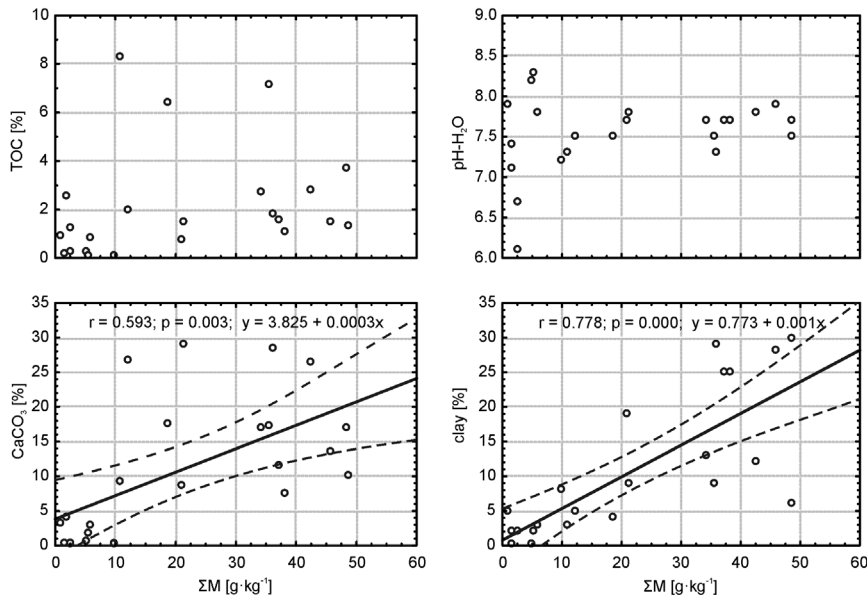


Fig. 9. Scatter plots of selected soil parameters: ΣM (heavy metals content), TOC (total organic carbon), pH in H₂O, CaCO₃ (carbonates content) and clay content

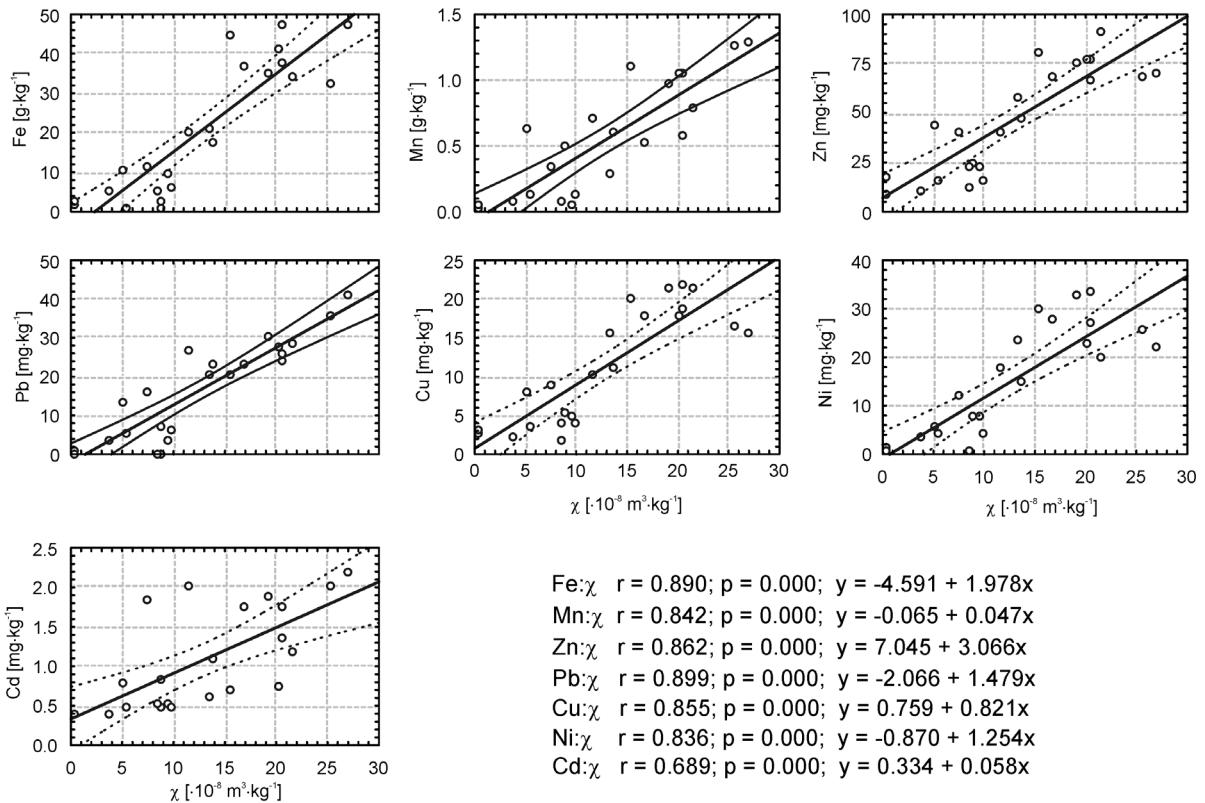


Fig 10. Scatter plots of heavy metals content and specific magnetic susceptibility

Conclusions

The analyzed sediments were characterized by varied magnetic properties in both the spatial

(along the transect) and the vertical (in profiles) gradients. The specific type of water management system conditioned a specific pattern of sediment accumulation in the mill pond. Profile 1 and 2 located in the deepest, most transformed part of the basin near the inflow and outflow of the river water

were characterized by the highest contents of heavy metals and highest magnetic susceptibility. It is likely that the type of water management influenced the sedimentation process in the mill pond. There was also a difference between the magnetic properties of sediments deposited in the mill pond and the natural bedrock.

The variability of the soil cover in the basin, driven by different sedimentation conditions, and the various composition of natural terrace deposits versus mill pond sediments has been well reflected in the magnetic properties. However, interpretation of both horizontal and vertical diversity can be difficult due to the complexity of the pedogenic processes occurring after exposure and dehydration of mill pond sediments. Thus it cannot be excluded that the pedogenic (gleyic) process is the key factor causing the vertical variability of magnetic properties in studied soils.

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