Bulletin of Geography. Physical Geography Series, No. 11 (2016): 55–69
http://dx.doi.org/10.1515/bgeo-2016-0015

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

ISSN 2080-7686

Łukasz Mendyk[1]*, Piotr Hulisz[1], Grzegorz Kusza[2], Marcin Świtoniak[1], Leszek Gersztyn[3], Barbara Kalisz[4]

[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 geomorphologists 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 (Giedrojć 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 (Szuszkiewicz 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 (Strzyszcz 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 paper 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.

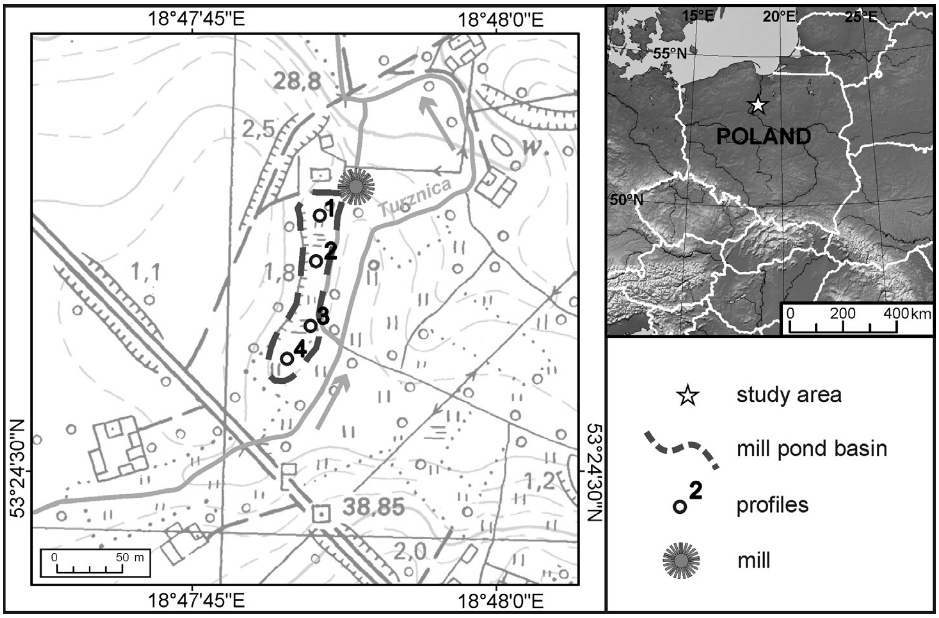

Fig. 1. Location of the study area and soil profiles

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 H_2O 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.

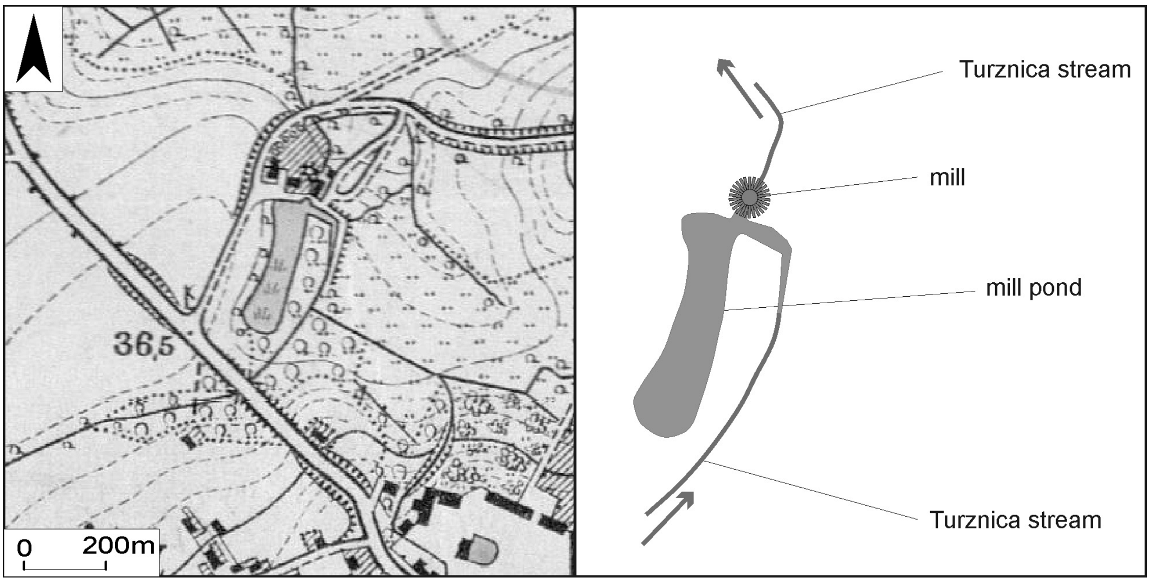

Fig. 2. A: Turznice mill pond on the Messtischblatt Map, sheet No. 2578, AD 1909, B: model of the water management system (Podgórski 2004, modified)

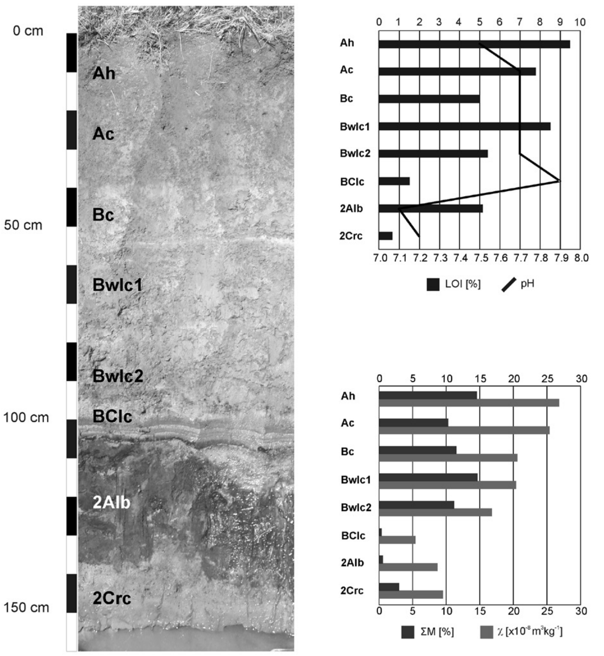

Fig. 3. Soil profile 1 – Morphology and vertical differentiation of LOI (loss on ignition), pH, ΣM (sum of heavy metals content), and χ (specific magnetic susceptibility)

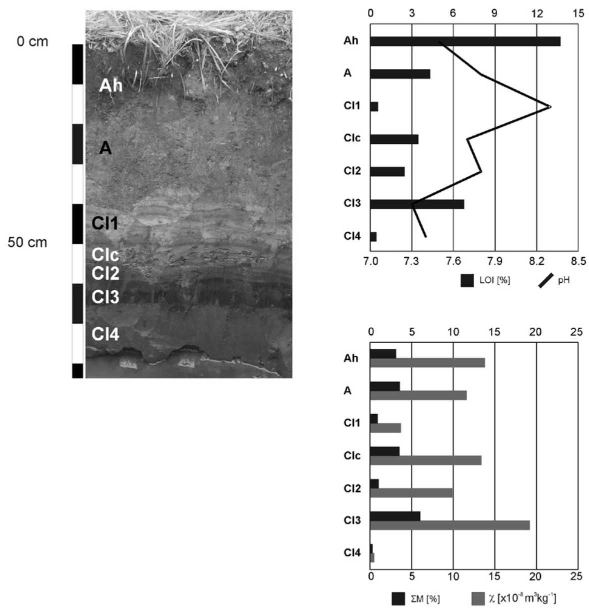

Fig. 5. Soil profile 3 – Morphology and vertical differentiation of LOI, pH, ΣM, and χ. Symbol explanations as on Figure 3

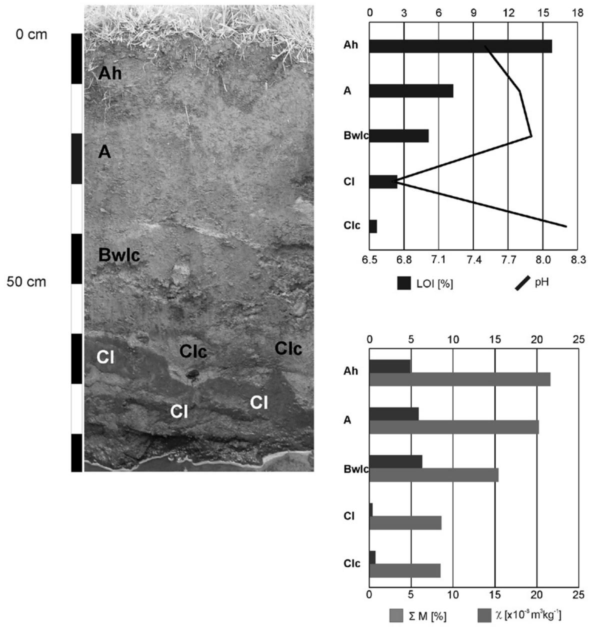

Fig. 4. Soil profile 2 – Morphology and vertical differentiation of LOI, pH, ΣM, and χ. Symbol explanations as on Figure 3

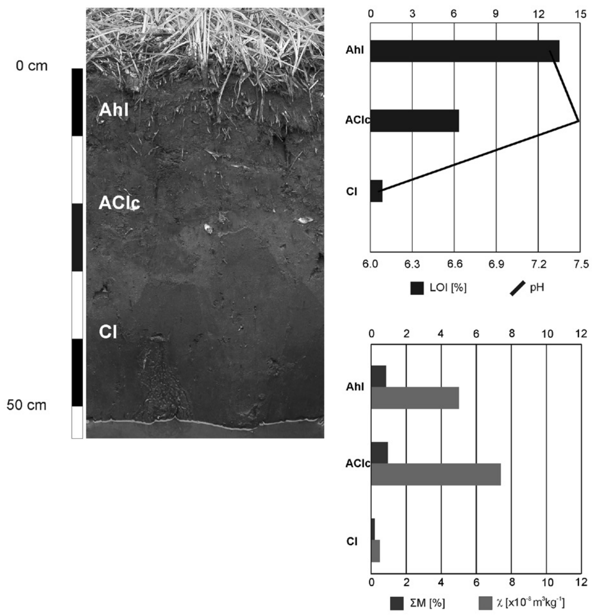

Fig. 6. Soil profile 4 – Morphology and vertical differentiation of LOI, pH, ΣM, and χ. Symbol explanations as on Figure 3

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 Elementar 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 (κlf) is 0.47 kHz and high frequency (κhf) 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, Fluvic 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 *fluvic* 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), located 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 Fluvic Gleysol (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_2O	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 Fluvic Gleysol (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, $CaCO_3$, clay content (maximum particle size < 0.002 mm) and pH values – were tested for their correlation with the content of determined heavy metals (ΣM). $CaCO_3$ 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 alkaline 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 [cm]	Fe [g · kg-1]	Mn	Cu [mg · kg-1]	Zn	Pb	Ni	Cd
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 Fluvic Gleysol (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	κlf	κhf	χ
	[cm]	[x10^{-5} SI]		[x10^{-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 Fluvic Gleysol (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-Naskręt 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

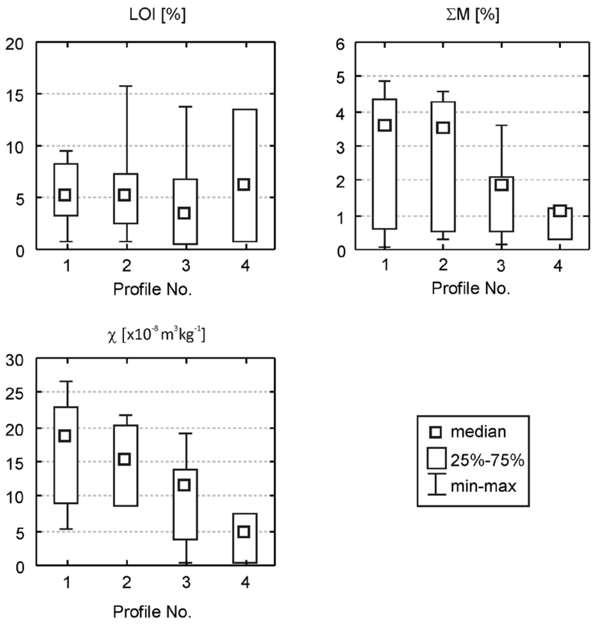

Fig. 7. Box plot showing the diversity of the selected soil parameters: sum of heavy metals content (ΣM), loss on ignition (LOI) and specific magnetic susceptibility (χ) along the studied transect

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.

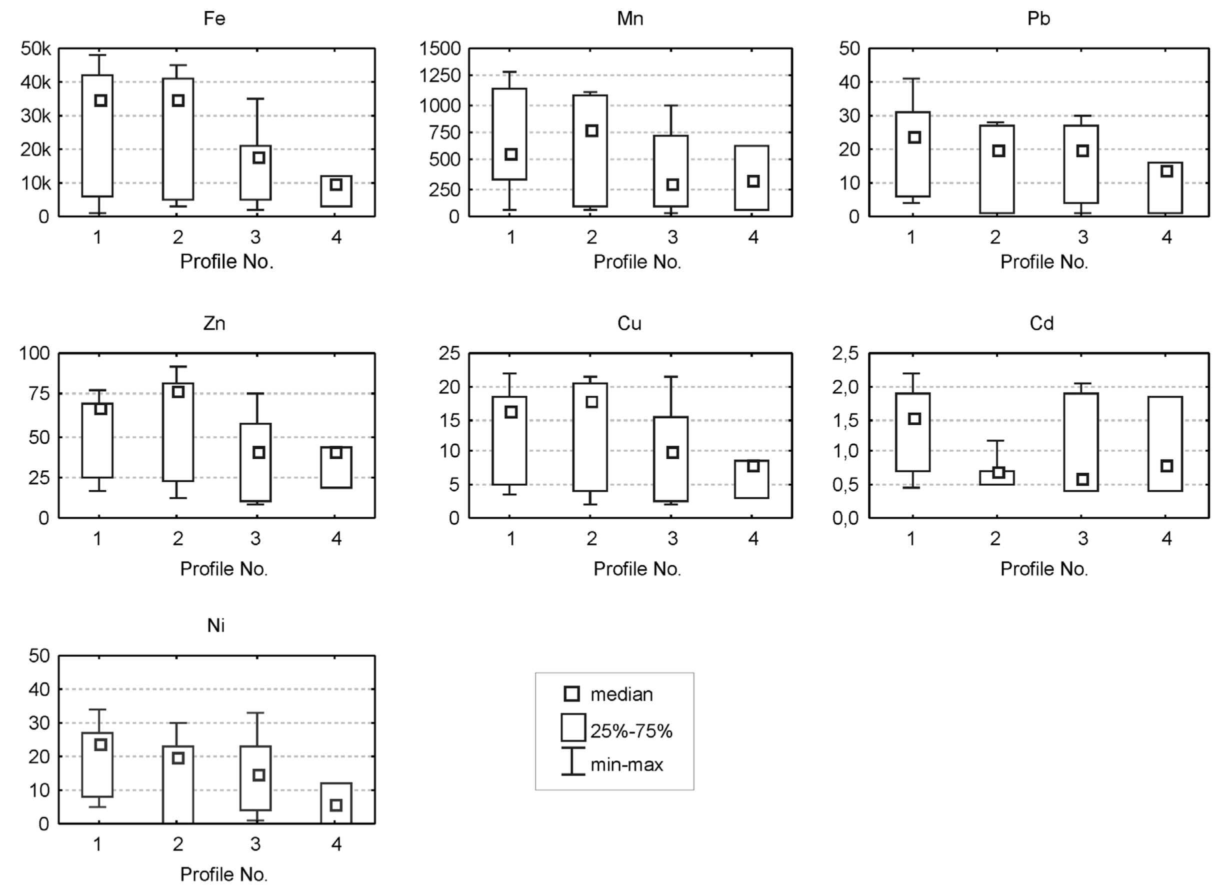

Fig. 8. Box plot showing diversity of the selected heavy metals content along the studied transect

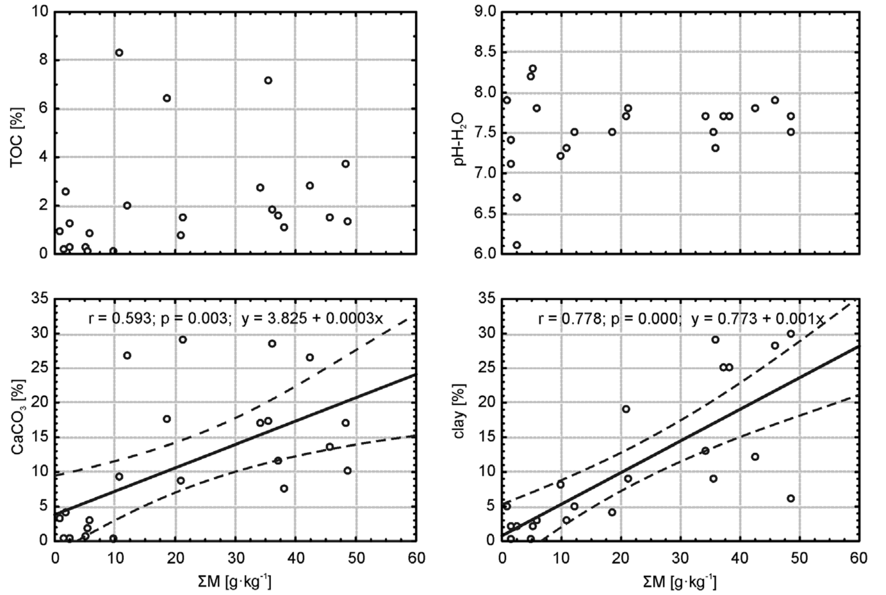

Fig. 9. Scatter plots of selected soil parameters: ΣM (heavy metals content), TOC (total organic carbon), pH in H_2O, $CaCO_3$ (carbonates content) and clay content

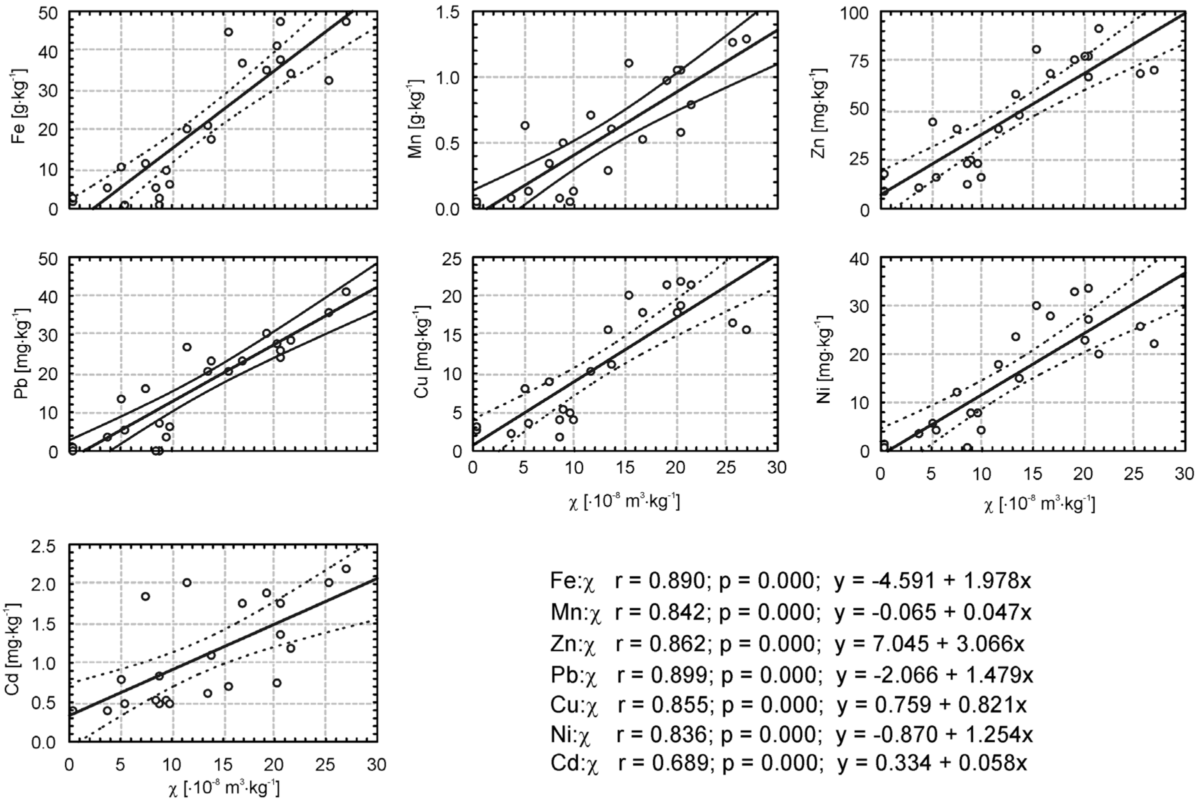

Fig 10. Scatter plots of heavy metals content and specific magnetic susceptibility

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.

Acknowledgments

The research was financed from the resources of UMK Grant No. 1697-G/2013 and within the framework of the "Krok w przyszłość – stypendia dla doktorantów V edycja" program, implemented by the Department of Education and Sport of the Kujawsko-Pomorskie Voivodeship Marshalls and co-funded by the European Union from the European Social Fund under the Sub-measure 8.2.2 of the Human Capital Operational Programme 2007–2013. We would like to thank the reviewers for their comments and suggestions, which improved the manuscript.

References

AIDONA E., GRISON H., PETROVSKY E., KAZAKIS N., PAPADOPOULOU L., VOUDOURIS K., 2016, Magnetic characteristics and trace elements concentration in soils from Anthemountas River basin (North Greece): discrimination of different sources of magnetic enhancement. Environmental Earth Sciences, 75(20), 1375.

AYYAMPERUMAL T., JONATHAN M.P., SRINIVASALU S., ARMSTRONG-ALTRIN J.S., RAM-MOHAN V., 2006, Assessment of acid leachable trace metals in sediments cores from River Uppanar, Cuddalore, Southeast coast of India. Environmental Pollution, 143: 34–45.

BARANOWSKI B., 1977, Polskie Młynarstwo. Zakład Narodowy im. Ossolińskich, Wrocław-Warszawa-Kraków-Gdańsk.

BRÜMMER G., HERMS U., 1983, Influence of soil reaction and organic matter on the solubility of heavy metals in soils. [in:] Ulrich B. (ed.), Effects of accumulation of air pollutants in forest ecosystems, Pankrath J.D. Reidel Publishing Company, Dordrecht: 233–243.

BRYKAŁA D., 2005, Rekonstrukcja retencji zbiornikowej zlewni Skrwy Lewej w ciągu ostatnich 200 lat. Przegląd Geograficzny, 77(1): 69–89.

CHILDS C.W., 1992, Ferrihydrite: A review of structure, properties and occurrence in relation to soils. Zeitschrift für Pflanzenernährung und Bodenkunde, 155: 441–448. DOI: http://dx.doi.org/10.1002/jpln.19921550515

DĄBKOWSKA-NASKRĘT B., 2013, Wiek i właściwości gleb wykształconych z osadów stawu młyńskiego w dolinie Jarosławianki (Równina Sławieńska). [in:] Jonczak J., Florek W. (eds.), Środowisko glebotwórcze i gleby dolin rzecznych, Bogucki Wydawnictwo Naukowe, Poznań-Słupsk: 33–40.

DEARING J., DANN R., HAY K., LEES J., LOVELAND P., MAHER B., O'GRADY K., 1996, Frequency-dependent susceptibility measurements of environmental materials. Geophysical Journal International, 124: 228–240. DOI: http://dx.doi.org/10.1111/j.1365-246X.1996.tb06366.x

DEMBIŃSKA M., 1973, Przetwórstwo zbożowe w Polsce Średniowiecznej (X–XIV wiek). PAN, IHKM, Wyd. PAN, Wrocław-Warszawa-Kraków-Gdańsk.

GIEDROJĆ B., KASZUBKIEWICZ J., BOGDA A., 1992, Określenie właściwości fizycznych i chemicznych gleby dna stawowego w różnych kategoriach stawów. Zeszyty Naukowe Akademii Rolniczej we Wrocławiu, Melioracja XL, 211: 117–132.

HULISZ P., PLUTA I., POKOJSKA U., 2007, Wpływ antropopresji na skład chemiczny gleb w otoczeniu zbiorowiska wód kopalnianych "Bojszowy". Zeszyty Problemowe Postępów Nauk Rolniczych, 520(1): 65–73.

HUPP C.R., NOE G.B., SCHENK E.R., BENTHEM A.J., 2013, Recent and historic sediment dynamics along Difficult Run, a suburban Virginia Piedmont stream. Geomorphology 180–181: 156–169. DOI: http://dx.doi.org/10.1016/j.geomorph.2012.10.007

IUSS Working Group WRB, 2015, World Reference Base for Soil Resources 2014, update 2015, International soil classification system for naming soils and creating legends for soil maps, World Soil Resources Reports 106. FAO, Rome.

JAHN R., BLUME H.P., ASIO V.B., SPAARGAREN O., SCHAD P., 2006, Guidelines for Soil Description. FAO, Rome.

JONCZAK J., FLOREK W., 2013, Wiek i właściwości gleb wykształconych z osadów stawu młyńskiego w dolinie Jarosławianki (Równina Sławieńska). [in:] Jonczak J., Florek W. (eds.), Środowisko glebotwórcze i gleby dolin rzecznych, Bogucki Wydawnictwo Naukowe, Poznań-Słupsk: 33–40.

KABATA-PENDIAS A., 2011, Trace Elements in Soils and Plants. Fourth Edition. CRC Press, Boca Raton-London-New York.

KITTEL P., MUZOLF B., PŁÓCIENNIK M., ELIAS S., BROOKS S.J., LUTYŃSKA M., PAWŁOWSKI D., STACHOWICZ-RYBKA R., WACNIK A., OKUPNY D., GŁĄB Z., MUELLER-BIENIEK A., 2014, A multi-proxy reconstruction from Lutomiersk-Koziówki, Central Poland, in the context of early modern hemp and flax processing. Journal of Archaeological Science, 50 (2014): 318–337. DOI: http://dx.doi.org/10.1016/j.jas.2014.07.008

KLIMEK K., KOCEL K., ŁOKAS E., WACHNIEW W., 2003, Osady denne stawu w dolinie Rudy. Dorzecze górnej Odry. Zastosowanie metod kartograficznych i radioizotopowych w określaniu tempa sedymentacji. [in:] Waga J.M., Kocel K. (eds.), Człowiek w środowisku przyrodniczym – zapis działalności, PTG Oddział Katowicki, Sosnowiec: 74–78.

KOCEL K., 1995, Stawy w dolinie Rudy (Górny Śląsk) jako wskaźnik antropogenicznych zmian krajobrazu. [in:] Przeobrażenia środowiska geograficznego w przygranicznej strefie górnośląsko-ostrawskiego regionu przemysłowego, Materiały Sympozjum Polsko-Czeskiego, WNoZ UŚ, PK CKKRW, Sosnowiec, 57–62.

KOTTEK M., GRIESER J., BECK C., RUDOLF B., RUBEL F., 2006, World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 15(3): 259–263. DOI: http://dx.doi.org/10.1127/0941-2948/2006/0130

KREFT A., 1999, Mała retencja – problemy i możliwości. [in:] Kostrzewski A. (ed.), Funkcjonowanie geosystemów zlewni rzecznych, Cz. 2, UAM, Zakład Geoekologii i Monitoringu Środowiska Przyrodniczego, Stacja Geoekologiczna w Storkowie, Poznań: 41–48.

KUMARAVEL V., SANGODE S.J., SIVA SIDDAIAH N., KUMAR R., 2010, Interrelation of magnetic susceptibility, soil color and elemental mobility in the Pliocene–Pleistocene Siwalik paleosol sequences of the NW Himalaya, India. Geoderma, 154: 267–280. DOI: http://dx.doi.org/10.1016/j.geoderma.2009.10.013

ŁABAZ B., BOGACZ A., 2011, Zawartość wybranych metali ciężkich oraz zasobność gleb podstawowych występujących na terenie obniżenia milicko-głogowskiego. Ochrona Środowiska i Zasobów Naturalnych, 49: 256–267.

ŁOŚ M.J., 1978, Likwidacja młynów wodnych i jej skutki. Gospodarka wodna, 38(12), PWN, Warszawa, 99–108.

ŁUKASIK A., MAGIERA T., LASOTA J., BŁOŃSKA E., 2016, Background value of magnetic susceptibility in forest topsoil: Assessment on the basis of studies conducted in forest preserves of Poland. Geoderma, 264: 140–149. DOI: http://dx.doi.org/10.1016/j.geoderma.2015.10.009

MADEYSKI M., TARNAWSKI M., 2006, Ocena stanu ekologicznego osadów dennych wybranych małych zbiorników wodnych. Infrastruktura i ekologia terenów wiejskich. PAN, Oddział w Krakowie, Komisja Technicznej Infrastruktury Wsi, 4/3: 107¬–116.

MAGIERA T., JANKOWSKI M., ŚWITONIAK M., RACHWAŁ M., 2011, Study of forest soils on an area of magnetic and geochemical anomaly in north-eastern Poland. Geoderma, 160: 559–568. DOI: http://dx.doi.org/10.1016/j.geoderma.2010.11.004

MAGIERA T., GOŁUCHOWSKA B., JABŁOŃSKA M., 2013, Technogenic magnetic particles in alkaline dusts from power and cement plants. Water, Air & Soil Pollution, 224(1389): 1–17. DOI: http://dx.doi.org/10.1007/s11270-012-1389-9

MAHER B.A., 1998, Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications. Palaeogeography, Palaeoclimatology, Palaeoecology, 137(1): 25–54. DOI: http://dx.doi.org/10.1016/S0031-0182(97)00103-X

MATUSZKIEWICZ J.M., 2008, Potential natural vegetation of Poland. IGiPZ PAN, Warszawa.

MATYSEK D., RACLAVSKA H., RACLAVSKY K., 2008, Correlation between magnetic susceptibility and heavy metal concentrations in forest soils of the eastern Czech Republic. Journal of Environmental & Engineering Geophysics, 13(1): 13–26.

MENDYK Ł., MARKIEWICZ M., 2015, Organic matter of soils derived from Oleszek millpond sediments. [in:] Markiewicz M., Mendyk Ł. (eds.), Meeting of the Polish Humic Substances Society, Chapter of IHSS, Toruń, 17–20 June 2015, Program – Abstracts, Toruń, 5.

MENDYK Ł., ŚWITONIAK M., BEDNAREK R., FALKOWSKI A., 2015, Genesis and classification of the soils developed from the sediments of the former Oleszek mill pond basin (the Chełmińskie Lakeland, N Poland). Soil Science Annual, 60(1): 29–35. DOI: http://dx.doi.org/10.1515/ssa-2015-0016

MICHALSKA G., SZPIKOWSKI J., 1999, Akumulacja osadów w Stawie Młyńskim na Parsęcie (Storkowo, Górna Parsęta). [in:] Kostrzewski A. (ed.), Funkcjonowanie geosystemów zlewni rzecznych. Cz. 2, UAM, Zakład Geoekologii i Monitoringu Środowiska Przyrodniczego, Stacja Geoekologiczna w Storkowie, Poznań: 131–136.

Munsell Revised Standard Soil Color Charts. 2002.

NIEMITZ J., HAYNES C., LASHER G., 2013, Legacy sediments and historic land use: Chemostratigraphic evidence for excess nutrient and heavy metal sources and remobilization. Geology, 41(1): 47–50. DOI: http://dx.doi.org/10.1130/G33547.1

OKRUSZKO H., 1969, Powstawanie mułów i gleb mułowych. Roczniki Gleboznawcze – Soil Science Annual, 20(1): 25–49.

PETROVSKY E., ELLWOOD B.B., 1999, Magnetic monitoring of air-, land-, and water pollution. [in:] Maher B.A., Thompson R. (eds.), Quaternary climates, environments and magnetism, Cambridge University Press, Cambridge: 279–322.

PODGÓRSKI Z., 2004, Wpływ budowy i funkcjonowania młynów wodnych na rzeźbę terenu i wody powierzchniowe Pojezierza Chełmińskiego i przyległych części Dolin Wisły i Drwęcy. Wyd. UMK, Toruń.

PORSH K., DIPPON U., RIJAL M.L., APPEL E., KAPPLER A., 2010, In-Situ Magnetic Susceptibility Measurements As a Tool to Follow Geomicrobiological Transformation of Fe Minerals. Environmental Science & Technology, 44: 3846–3852. DOI: http://dx.doi.org/10.1021/es903954u

PORSH K., RIJAL M.L., BORCH T., TROYER L.D., BEHRENS S., WEHLAND F., APPEL E., KAPPLER A., 2014, Impact of organic carbon and iron bioavailability on the magnetic susceptibility of soils. Geochimica et Cosmochimica Acta, 128: 44–57. DOI: http://dx.doi.org/10.1016/j.gca.2013.12.001

SCHLICHTING E., BLUME H.P., STAHR K., 1986, Bodenkundliches Praktikum, 2 Auflage. Blackwell Wissenschafts Verlag, Berlin, Wien.

SCHWERTMANN U., 1988, Occurrence and formation of iron oxides in various pedoenvironments. [in:] Stucki, J. W., Goodman, B. A., & Schwertmann, U. (eds.), Iron in soils and clay minerals, Springer Netherlands: 267–308.

SOIL SURVEY STAFF, 1952, Soil Survey Manual. US Department of Agriculture. Hanbook No. 210. Washington.

SOKOŁOWSKA Z., ALEKSEEV A., SKIC K., BRZEZIŃSKA M., 2016, Impact of wastewater application on magnetic susceptibility in Terric Histosol soil. International Agrophysics, 30: 89–94. DOI: http://dx.doi.org/10.1515/intag-2015-0064

STRZYSZCZ Z., MAGIERA T., HELLER F., 1996, The influence of industrial immissions on the magnetic susceptibility of soils in Upper Silesia. Studia Geophysica et Geodaetica, 40: 276–286. DOI: http://dx.doi.org/10.1007/BF02300743

SYPKA M., SZWARCZEWSKI P., CISZEWSKI D., ŁOKAS E., WACHNIEW P., 2007, Osady wypełniające dna niecek dawnych stawów młyńskich – wybrane cechy teksturalne oraz tempo sedymentacji określane różnymi metodami (na przykładzie doliny rzeki Okrzeszy). [in:] Szwarczewski P., Smolska E. (eds.), Zapis działalności człowieka w środowisku przyrodniczym, Wydział Geografii i Studiów Regionalnych UW, Wydawnictwo Szkoły Wyższej Przymierza Rodzin, Warszawa, 3: 137–146.

SZUSZKIEWICZ M., ŁUKASIK A., MAGIERA, T., MENDAKIEWICZ M., 2016, Combination of geo-pedo-and technogenic magnetic and geochemical signals in soil profiles – Diversification and its interpretation: A new approach. Environmental Pollution, 214: 464–477. DOI: http://dx.doi.org/10.1016/j.envpol.2016.04.044

SZWARCZEWSKI P., 2003, Zapis naturalnych i antropogenicznych zmian środowiska przyrodniczego w okolicach Żyrardowa na przykładzie osadów wypełniających nieckę stawu młyńskiego. [in:] Waga J.M., Kocel K. (eds.), Człowiek w środowisku przyrodniczym – zapis działalności, PTG Oddział Katowicki, Sosnowiec: 213–219.

TITE M.S., 1972, The influence of geology on the magnetic susceptibility of soils on archeological sites. Archeometry, 14(2): 229–236. DOI: http://dx.doi.org/10.1111/j.1475-4754.1972.tb00065.x

THOMPSON R., OLDFIELD F., 1986, Environmental Magnetism. Allen and Unwin, London.

URE A., 1995, Methods for analysis of heavy metals in soils. [in:] Alloway B.J. (ed.), Heavy metals in soils, Blackie Academic and Professional, London: 58–102.

URE A. M., DAVIDSON C. M., 2002, Chemical speciation in soils and related materials by selective chemical extraction. [in:] Ure A. M., Davidson C. M., (eds.), Chemical Speciation in the Environment, Second Edition, Blackwell, London: 265–300.

VODYANITSKII Y.N., 1998, Solubility of iron oxides of forest soils in the Tamm reagent. Eurasian Soil Science – POCHVOVEDENIE, 31: 1083–1092.

VODYANITSKII Y.N., 2010, Iron hydroxides in soils: a review of publications. Eurasian Soil Science, 43(11): 1244–1254. DOI: http://dx.doi.org/10.1134/S1064229310110074

VODYANITSKII Y.N., SHOBA S.A., 2016, Ferrihydrite in soils. Eurasian Soil Science, 49(7): 796–806. DOI: http://dx.doi.org/10.1134/S1064229316070127

WÓJCIK G., MARCINIAK K., 1987a, Thermal conditions in central part of the North Poland in the years 1951–1970. AUNC Geografia, 20: 29–50.

WÓJCIK G., MARCINIAK K., 1987b, Precipitations in central part of the North Poland in the years 1951–1970. AUNC Geografia, 20: 51–69.

WÓJCIK G., MARCINIAK K., 1993, Precipitations in Lower Vistula Valley in the years 1951–1980. [in:] CHURSKI Z. (ed.), Environmental and Socio-economic Development of the Lower Vistula Valley, IG UMK, Toruń: 107–121.

Received 4 November 2016
Accepted 30 November 2016