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Article

Using the Vertical Distribution of Magnetic Susceptibility in the Assessment of Soil Condition in the Krakow Area, Southern Poland

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Abstract: The paper concerns the distribution of apparent magnetic susceptibility in soil profiles located in the areas of topsoil magnetic susceptibility anomalies in Krakow. The type of land use, possible sources of magnetic carriers, and the type of soil were taken into account. Additionally, at each soil profile, a comparison between soil magnetic susceptibility and the results of geochemical analyzes of soil samples was made.

The study shows very characteristic changes in magnetic susceptibility with depth, reflecting the interdependencies between natural and anthropogenic factors. A visible magnetic susceptibility maximum at the depth of 10-30 cm is observed at each soil profile. The maximum is associated mainly with the deposition of atmospheric dust and its vertical range depends on the level of anthropopression and natural conditions of soils. At the depth above 40 cm in the eastern part of Krakow, a correlation between the magnetic susceptibility and the soil type (chernozems developed on loess) was found. All indicates that the thicknesses of contaminated upper horizons are not accidental and they depend on human interactions with the environment and the type of soil.

An attempt at template establishment with the sources of magnetic particle carriers for different places in the city was made. As the result, in high urbanized sites, the extreme values of magnetic susceptibility rapidly change in short vertical distances can identify the richness of anthropogenic layers with various types of anthropogenic ferrous material and/or additionally Fe-carrying objects buried in soils. In industrialized sites, anthropogenic input plays the most important role in the creation of soil magnetic characteristics. What is more, industrial pollution hides the natural magnetic properties of chernozems. In opposite, the studies at the sites under low anthropopression (mainly located in forests) allow for better insight into magnetic properties arising during pedogenic processes, indirectly giving information about soil conditions. In the forest areas, the lowest values of soil magnetic susceptibility were measured. Additionally, the influence of pedogenic and lithogenic factors on forest soils is manifested in the results.

Among the sites concerned, particular attention should be paid to the vicinity of the steel plant because of the agricultural land in the surroundings.

Keywords: magnetic susceptibility; soil magnetometry; vertical profiles; soil contamination; Krakow

1. Introduction

Magnetic susceptibility is a property of a material that can be of natural or anthropogenic origin. The value of magnetic susceptibility can be changed especially by temperature or/and pressure. From a petrological point of view magnetic susceptibility depends on:

- content of magnetic minerals (in particular ferrous and ferric oxides, hydroxides, iron sulfides, and carbonates),

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- mineral composition,
- magnetic properties of separate minerals,
- shape and size of magnetic grains,
- the texture and type of rock.

These components have a strong influence on the magnetic properties of rocks and loose sediments occurring in the weathering zone as well as soil cover. In a soil environment, natural reactions with an association of external processes formed magnetic properties.

In recent years, magnetic susceptibility plays a spectacular role in near-surface environmental studies. A wide range of applications was briefly referred to by Evans & Heller [1], Grabowska [2], and Tessaaire-Jeleńska with the team [3]. Magnetic studies are focused on different aspects of the environmental state for example:

- air pollution [4]–[6],
- contamination/pollution of soils [7]–[11] with the emphasis on the topsoil layer,
- state of river sediments [14].

Predominant materials in a laboratory are samples of: industrial dust and fly ashes [15],

urban dust [16]–[18], soils [19], lake sediments [20]. A wide range of materials, even sometimes very unusual like snow, leaves or spider webs, allow us to study all types of the environment. In studies on soil, magnetic susceptibility is one of the indicators of soil pollution [21] and can be successfully used as a tool/geophysical marker in different tasks of the localization of contaminated/polluted areas before performing sampling for geochemical studies.

The highest positive correlation between magnetic susceptibility and iron content has been established in studies on fly ashes emitted by industry [22], the correlation coefficient was 0.99. In industrial and urban areas, the most intensive magnetic susceptibility anomalies of soils accompany geochemical anomalies, especially in the case of iron, lead, zinc, and cadmium.

Magnetic susceptibility in environmental studies mainly concerns its spatial distribution obtained by taking surface measurements in situ. The spatial distribution of anomalies can be tested using geostatistical Gaussian simulation [23], [24]. Apart from surface techniques, studies into magnetic susceptibility can be performed also in vertical profiles i.e. boreholes, opencasts, or hand-drilled holes.

The magnetic susceptibility reflects the changes in soil's magnetic properties due to different anthropogenic and natural sources. The first involves fires, deposition of dust and ashes on the ground surface, and strong irrigation. The second, responsible for the natural magnetic enhancement, can be caused by physical and chemical processes, i.e. oxidation, reduction, hydration, dissolution, etc. as part of lithogenic and/or pedogenic processes.

The paper concerns the changes in soil magnetic susceptibility in vertically drilled holes in established sites in the area of the historical city of Poland. The measurements were done at sites for which the apparent magnetic susceptibility value of topsoil was above 50 ·10-5 SI (probably contaminated areas). In effect, over 70% of the area of Krakow was in interest.

In this study, the attention was focused on the application of soil magnetometry in:

- description of soil magnetic properties,
- assessment of soil contamination/pollution,
- recognition of the main factors that influenced soil magnetism in the vertical holes.

In general, the study area is very differentiated in terms of the magnetic particle sources and their different strength impact, negatively affecting the soils. The most important factors are: dust and fly ashes emitted by industrial plants, road traffic emissions, and also dust from coal combustion in local boiler houses and home furnaces. What is more, the topography of Krakow and city development has a crucial role in the creation of unfavorable conditions of air masses circulation. In effect particulates from the air are usually deposited on the ground at a close distance from the emitters. Additionally, many different objects of anthropogenic origin can be detected in soil which gives rise to soil magnetic enrichment.

The paper also involved characterization of the type of land use, type of soil, description of possible sources of Fe-bearing particles, and the results of geochemical analyzes (heavy metals content in soils and pH conditions).

2. The origin of soils

The overlapping of the Scandinavian ice sheet from the north in the Pleistocene was of significant importance in the formation of the parent soil in the area of Krakow. The rock material transported across the glacier was composed of igneous and metamorphic rocks of the Fennoscandia crystal shield. Pleistocene sediments were formed during glacial and aeolian accumulation and water accumulation.

In the vicinity of Krakow, the post-glacial formations were formed mainly in the form of sands and gravel, less often moraine clays with a thickness of up to 25 m [25], [26]. Pleistocene fluvioglacial sediments (generally sandy sediments), formed during the Krakow glaciation and the Central Polish glaciation, formed extensive river terraces of the Vistula River and inflow cones of its tributaries [27], [28]. River terraces were created during the transgression and regression of the ice sheet when river valleys were filled alternately with material applied from the south (due to the lack of water inflow to the sea) and erosive deepening of the valley bottoms. The inflow cone of the Białucha River (Figure 1), created over a vast area, covered the present center and northern districts of Krakow [25]. Pleistocene sands and clays are the parent formations of the soils in the southern part of Krakow.

In addition, the formation of loess in Krakow is attributed to Quaternary glaciations. Less, reaching a thickness of 8 m was made of blown material comes from the area of clay sediments in the foreland of the ice sheet [25]. In Krakow, the loess belt occurs in the northern part of the city, with an extension to the east (Figure 1). Loess also appears in the western part of the city, in the vicinity of the Wolski Forest and the neighboring Sikornik on the eastern side [29].

The parent formations for the soils of Krakow, apart from the Pleistocene formations, are:

- Upper Jurassic formations occurring on the west and south sides of the city, exposing in places in the form of rocky limestones,
- lobes of chalk marls and rocks in the southern part of Krakow,
- Miocene clays were found in some places in the south-western part of the city, deposited during a sea transgression [30], [25], [29], [26].

From the beginning of the Holocene, the soil bedrock little changed, mainly because of natural processes related to the deposition of silt, sand, and gravel in river valleys, streams, and depressions of the land surface.

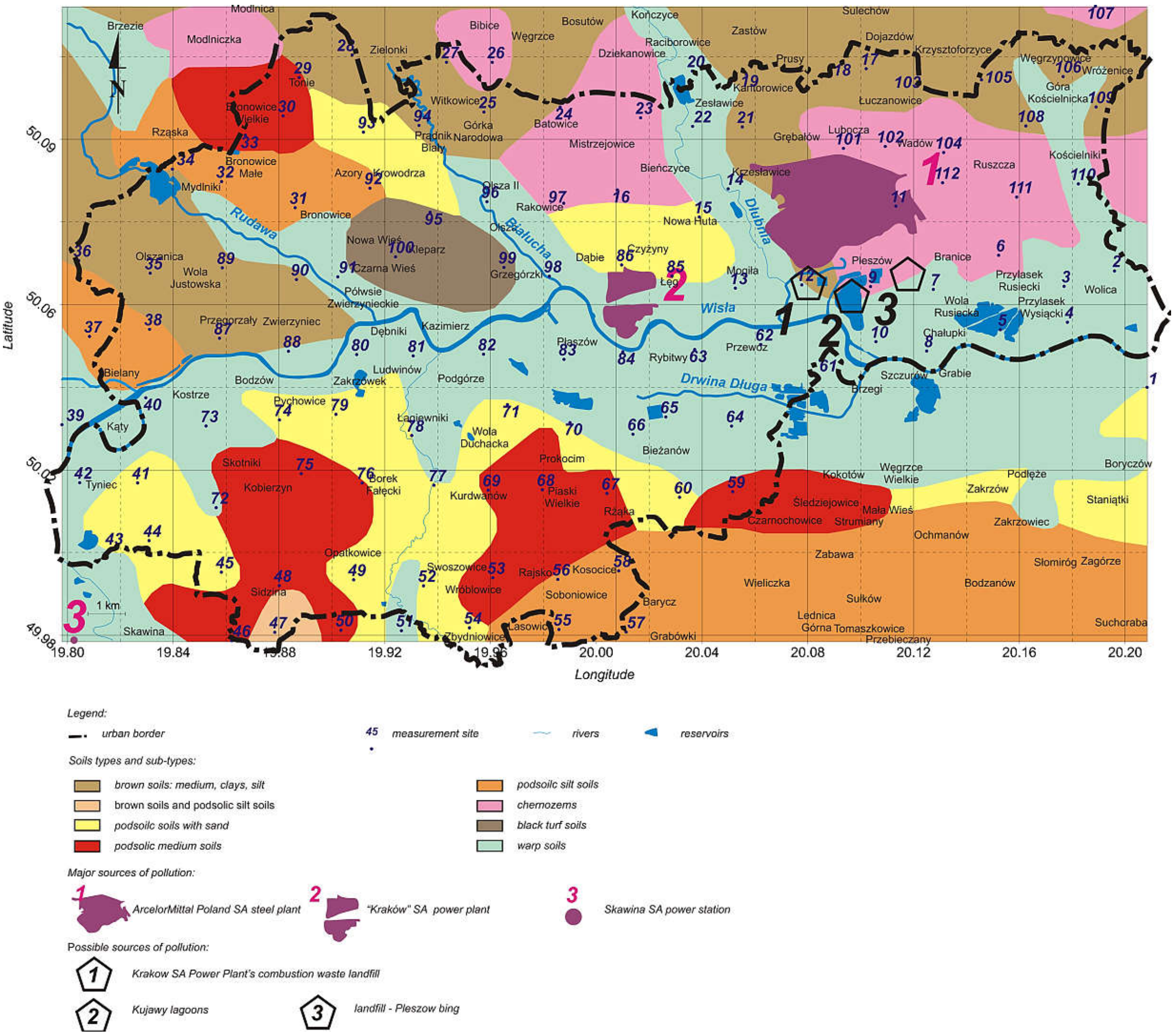

Figure 1. Distribution of various types of soils in the area of Krakow ([31], [32], modified).

Locally, deluvia were made of material removed from the slopes. These include, for example, the loess deluvia in the north-eastern part of the city. In the southern part of Krakow, peats have formed on wetlands [25], [29]. On the other side, in the northern part brown soils, formed on fluvioglacial sediments and loess, dominate. The fertile chernozems developed in the north-eastern loess belt (Figure 1).

The local depressions in the north-eastern part of the city were often flooded, causing the gleization process and leading to the formation of glay-silt soils [29].

Black earth (phaeozems) has formed in the depressed, humid places in the city center (Figure 1).

Fluvic cambisols were formed on the sandy sediments and gravels along the river valleys. A wide strip of fluvic cambisols (fluvisols) stretches on both sides of the Vistula valley, except for the area on the left bank of the river, in the western part of Krakow (Figure 1). Along the valley of the Dłubnia river, on fluvioglacial sediments, a wide belt of clay fluvic cambisols was formed, which separates the northern and northeastern loess areas. The fluvic cambisols formed in the vicinity of the northern tributaries of the Vistula are clearly visible on the map (Figure 1). What is more, the fluvic cambisols cover large areas along the river valleys, which are the southern tributaries of the Vistula.

The predominant type of soil in the southern part of the city, except the fluvic cambisols, are poor luvisols soils, formed on Pleistocene sands and loam as well as Miocene clays [33]. Rendzina has formed on carbonate formations (limestones, marls, opoka) located in the near-surface zone.

Over the last half-century, the soils of the Krakow area, subjected to strong anthropogenic pressure, have been transformed in places into anthropogenic soils, which are represented among others by industrial soils, urbisoils, and cultivation soils (e.g. garden soils) [34].

3. Materials and Methods

3.1. Fieldworks

In the first stage, the measurements of upper soil horizons, to approx. 10 cm depth, were examined as a pre-screening method for the identification of soil magnetic properties in Krakow. The Bartington System consisting of the MS2 meter combined with the MS2D sensor (Bartington Instruments Ltd., Witney, UK) was used. The apparent magnetic susceptibility (κa) was measured:

$$k_a = \frac{(M_i + M_r) \cdot \mu_0}{\mathbf{TMI}} \tag{1}$$

where: M_i – induced magnetization [A/m], M_r – remanent magnetization [A/m], μ_0 – vacuum permeability [$4\pi \cdot 10^{-7}$ henr/m], TMI – total magnetic intensity [nT].

The surveys were carried out at 112 sites over a 2 x 2 km grid, covering an area of almost 327 km^2. The magnetic susceptibility anomalies observed on the map [9] are the subject of interest in this paper.

Depth measurements, concerning the next stage of the study, were made in 37 measurement sites with high topsoil magnetic susceptibility values (above $50 \cdot 10^{-5}$ [SI]). Measurements of the apparent magnetic susceptibility distribution with depth were executed in hand-drilled, shallow (up to 101 cm) holes, with a nominal diameter of 2.5 cm. Profiling the magnetic susceptibility of strata was possible using the MS2H downhole sensor, MS2 meter (Bartington Instruments Ltd., Witney, UK), and Multisus software (Bartington Company Ltd). This diameter of holes ensures proper contact between the sensor and the studied medium which is important due to the low horizontal resolution of the sensor.

The MS2H downhole sensor gives an excellent opportunity for the identification of Fe-bearing strata, especially in horizontally layered medium (soil formation). It is available to detect strata even such narrow as 1.25 cm in thickness so even identification of magnetic properties of soil horizons and sub-horizons is possible. What is more, in situ measurements provide high accuracy of the results because of the lack of influence of factors unrelated to investigated soil environment (another temperature or humidity, additional material supplied as a result of laboratory techniques, etc.).

At the beginning of the measurements, for temperature stabilization, the probe was placed into the hole for a few minutes before the measurements. Afterward, the readings with a resolution of 1 cm were obtained using depth control graduation marks placed on the probe consisting of the MS2H sensor and the extension tube. During measurements, the probe was hand-guided within a hole from the top to the bottom. At the same time, the data were presented by the PC software; the magnetic susceptibility values were listed in a form of a table and presented on the graph. A resolution of displayed values was 1 x 10^{-5} [SI]. After the measurements, the data correction for temperature changes was automatically applied by the software and the corrected data were saved.

The location of measurement sites was shown on the map (Figure 2) together with four areas distinguished for future discussion.

In this paper, apparent magnetic susceptibility distribution in soil vertical profiles was presented and described with attention only paid to anomalous areas with high surface magnetic susceptibility values.

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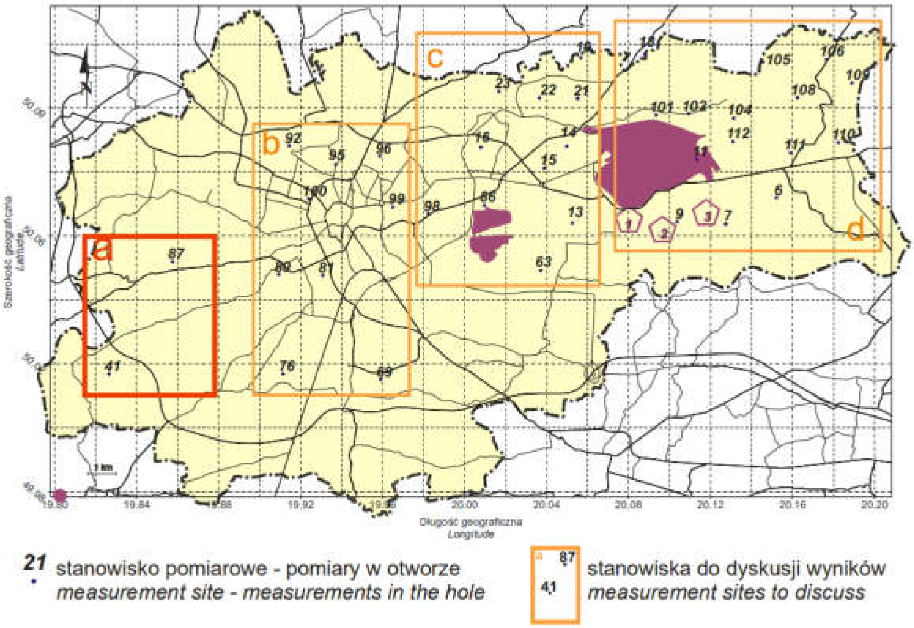

Figure 2. Location of 37 measurement sites for the apparent magnetic susceptibility investigations in shallow holes in the area of Krakow.

3.2. Laboratory analyzes

To analyze the heavy metals content and pH value, soil samples were collected. The soil material was taken from the uppermost soil horizons, mainly from the depth of 0-10 cm at each measurement site. All samples, in the amount of 37, were subjected to geochemical analyzes.

The soil reaction was determined by the potentiometric method using a pH meter under the Polish standard PN-ISO 10 390.

The content of six heavy metals (lead, zinc, copper, cadmium, nickel, and iron) in soils was performed using the atomic absorption spectrometry (ASA) technique. Measurements were carried out according to the procedure of acidic determination of heavy metals in soil. The extraction solution (reagent) was aqua regia consisting of a mixture of concentrated hydrochloric acid (HCl) and nitric acid (HNO_3) in a volume ratio of 3: 1.

4. Results

To relate surface and depth studies together, the results of depth measurements were described according to four topsoil magnetic susceptibility anomalies located in Krakow:

- the south-western part,
- the central part,
- the eastern part with its western part,
- the eastern part with its eastern part.

4.1. Magnetic susceptibility anomaly in the south-western part of the city

Within the magnetic susceptibility anomaly of the western part of Krakow, measurements of the magnetic susceptibility of soils in the hand-drilled vertical holes were carried out at measurement sites located in forest areas (site no. 41 - Tynieckie Forests and site no. 87 - Wolski Forest).

At measuring state no. 41, measurements were made to a depth of 48 cm. The average value of soil susceptibility is $61.3 \cdot 10^{-5}$ [SI]. On the magnetic susceptibility curve (Figure 3), in the upper horizons of the soil (organic level), there is a clear, slight elevation (up to 40×10^{-5} [SI]). This elevation is characteristic of contaminated forest soils, wherein the detritus horizon (O_f) there is the highest accumulation of heavy metals from atmospheric

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deposition of anthropogenic dust. At a depth higher than 10 cm, the magnetic susceptibility of soils is practically stable, reaching negative values in some places, corresponding to the susceptibility of diamagnetic minerals. The depth distribution of the magnetic susceptibility of soils corresponds to the anthropogenic soil profile.

At measuring station no. 87, the measurements were made to a depth of 67 cm (Figure 3). The average value of the magnetic susceptibility of soils is 72.8 · 10^{-5} [SI]. In this case, there is also an increase in susceptibility in the upper horizons of the soil (up to a depth of 10 cm). In the deeper part of the profile, there is a gradual but slight increase (up to 30-50 · 10^{-5} [SI]) of soil susceptibility with depth, which is probably caused by a pedogenic (geogenic) factor. A slight increase in compliance is observed at the depths of 20, 35, and 42 cm. The depth distribution of susceptibility corresponds to the anthropogenic soil profile with a pedogenic effect.

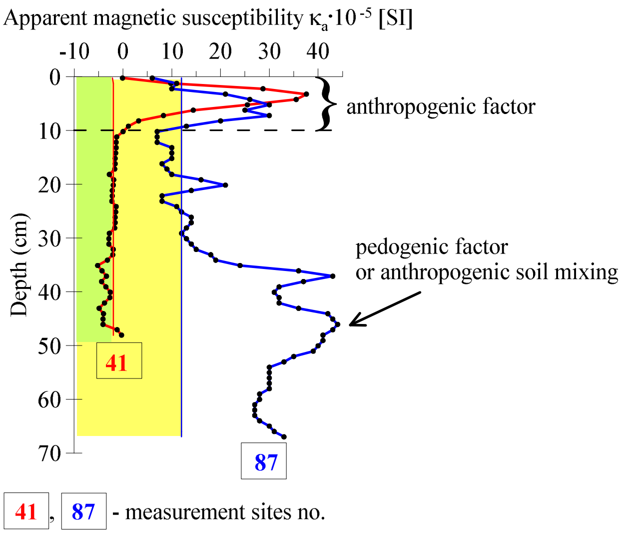

Figure 3. Vertical distribution of the apparent magnetic susceptibility of soils at measurement sites located in the area of magnetic susceptibility anomaly in the southwestern part of Krakow. Explanation: green and yellow areas mean background values established for the measurement site 41 and 87, respectively, calculated as a median value of lower magnetic susceptibility values (medians equal: -2 and 12·10^{-5} [SI], respectively).

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Table 1. Comparison of the results: depth of drilling (cm), statistical parameters of soil magnetic susceptibility (minimum, maximum, average, median) ($\cdot 10^{-5}$ [SI]), the type of land use: 1 – wastelands, 2 – lawns, city parks, 3 – meadows, 4 – cultivated fields, 5 - forests, type of soils (Tokarski; Komornicki): 1 - brown clay soils, clay, and dust (including loess), 2 - brown soils and podzolic dust soils, 3 - loess-sandy soils, 4 – loess-loamy soils, 5 – loess-dust soils (including loess), 6 - chernozem, 7 - black soils (peated), 8 - alluvial soils, values of pH, heavy metals content in soil: Pb, Zn ($mg \cdot kg^{-1}$).

Site no.	Depth	Min	Max	Average	Median	Land use	Type of soil	$pH_{(H_2O)}$	Pb*	Zn*
Magnetic susceptibility anomaly in the SOUTH-WESTERN part of Krakow										
41	48	-5	38	1	-2	5	3	4,8	70	66
87	67	6	44	24	27	5	1	5,1	**139**	238
The north area of magnetic susceptibility anomaly in the CENTRAL part of Krakow										
92	60	4	365	81	72	2	5	6,4	33	97
95	97	18	1467	197	134	2	7	7,2	43	145
96	88	3	484	108	73	2	8	8,4	26	108
99	47	0	321	45	23	1	7	8,1	19	79
100	101	0	450	120	89	2	7	8,0	80	150
The south area of magnetic susceptibility anomaly in the CENTRAL part of Krakow										
69	64	-3	176	17	6	2	4	8,1	23	100
76	46	-2	39	7	1	5	4	5,3	21	39
80	39	-1	143	41	36	2	8	8,2	79	293
81	19	-3	98	45	41	2	8	7,9	35	154
The west area of magnetic susceptibility anomaly in the EAST part of Krakow										
13	50	2	818	128	32	2	8	6,3	63	256
14	87	13	275	83	45	1	8	8,9	22	128
15	63	16	517	88	43	2	3	6,6	37	274
16	74	4	195	46	30	1	6	6,6	33	207
19	79	29	144	63	48	4	1	6,0	30	108
21	62	5	256	97	64	2	1	8,7	23	119
22	87	6	129	59	59	1	8	8,5	22	111
23	78	7	79	36	35	1	6	8,2	17	78
63	72	3	1260	133	78	3	8	8,1	25	111
86	65	1	1961	118	34	2	3	6,9	60	263
98	65	2	2625	246	47	2	8	8,3	28	142
The east area of magnetic susceptibility anomaly in the EAST part of Krakow, in the vicinity of steelworks										
7	73	1	132	33	17	3	8	6,7	32	133
9	69	6	139	36	16	1	6	7,3	58	243
11	63	34	285	105	81	1	6	9,0	36	119
18	88	8	157	63	47	4	1	8,0	15	57
101	74	29	555	151	53	4	6	8,2	53	**1494**
102	87	16	370	112	53	4	6	6,8	37	**920**
104	87	12	355	97	56	4	6	7,8	29	**424**
112	89	14	424	175	112	4	6	8,5	45	**378**
The east area of magnetic susceptibility anomaly in the EAST part of Krakow, in the vicinity of north-eastern administrative border of the city										
6	64	3	79	24	18	2	6	6,9	33	127
105	98	4	106	53	48	4	1	8,1	17	91
106	87	5	149	68	45	4	1	8,1	24	97
108	89	6	476	151	72	4	1	5,3	21	126
109	85	5	241	71	39	4	1	7,7	22	114
110	85	5	200	90	57	4	8	8,6	31	137
111	84	8	409	99	27	4	6	8,5	27	131

* the limit value for lead is 100 $mg \cdot kg^{-1}$ and for zinc is 300 $mg \cdot kg^{-1}$ according to the Regulation of the Minister of the Environment of September 1, 2016.

4.2. Magnetic susceptibility anomaly in the central part of the city

In the area of the magnetic susceptibility anomaly in the central part of Krakow, the measurements in the vertical profiles were carried out on 9 measurement sites (Figure 2).

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The results are characterized by high variability at each site. A multi-peak distribution of soil magnetic susceptibility is observed (Figure 4). Much higher differentiation of magnetic susceptibility is observed in the profiles located in the northern part of the anomaly.

The shape of the susceptibility curves indicates a significant influence of the anthropogenic factor on the condition of the soils in the center of Krakow. Rapid changes in susceptibility within all holes (Figure 4) and its high values (κ_a> 100 10^{-5} [SI]) are probably related to the presence of anthropogenic deposits in the soil (e.g. brick crumbs, corroded metal elements).

Among the measurement stations located in the city center (Figure 2), only site no. 99, in the area of allotments in District II - Grzegórzki, the magnetic susceptibility of soils decreases with depth, reaching the value of zero at a depth of approx. 30 cm (Figure 4).

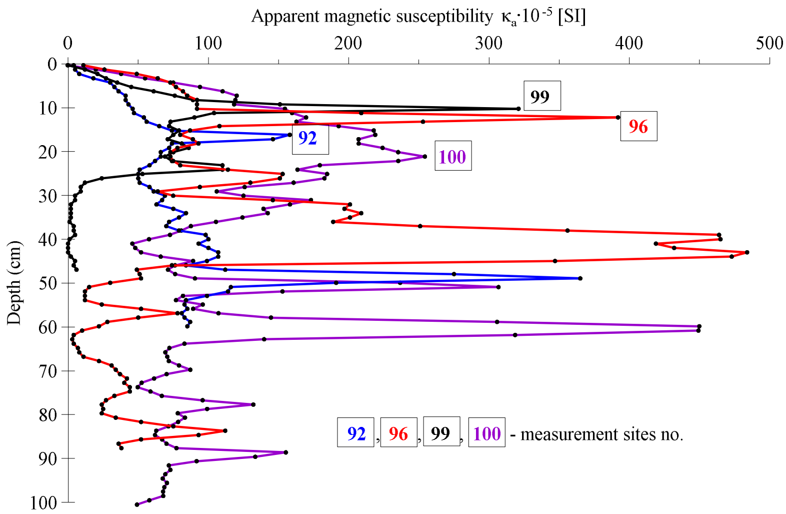

Figure 4. Vertical distribution of the apparent magnetic susceptibility of soils at the measurement sites located in the north area of magnetic susceptibility anomaly in the central part of Krakow.

The results of measurements of susceptibility in the profiles at the measurement sites located in the southern part of the discussed magnetic susceptibility anomaly are presented in Figure 5 and Table 1. All compliance curves measured down to a depth of 10 cm have elevated values.

The curves measured at site no. 69 and 76 (Figure 5), distant from the city center, in contrast to the other curves (sites no. 80 and 81), indicate low soil magnetic susceptibility from a depth of more than 10 cm. At site no. 69, located in Kurdwanów (District XI - Podgórze Duchackie), a significant increase in the magnetic susceptibility of the soil was observed, up to approx. 180 · 10^{-5} [SI], at a depth exceeding 60 cm, which may be caused by a lithogenic factor.

Changes in the magnetic susceptibility of soils at sites no. 80 and 81 are probably related to the presence of anthropogenic deposits.

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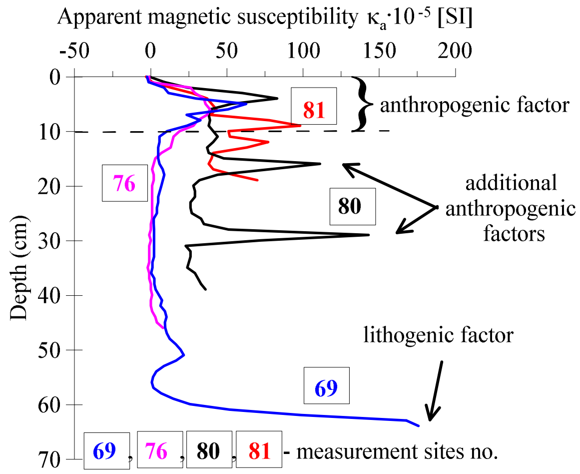

Figure 5. Vertical distribution of the apparent magnetic susceptibility of soils at measurement sites located in the south area of magnetic susceptibility anomaly in the central part of Krakow.

Another area where the magnetic susceptibility of soils was measured in shallow, vertical holes is located to the west of the industrial plant of ArcelorMittal Poland S.A. (Figure 2). The depth distributions of the magnetic susceptibility of soils are shown in Figure 6 and Figure 7.

At measuring stations located in the vicinity of the "Krakow" S.A. power plant the highest values of soil magnetic susceptibility were measured in the holes (Figure 6), which are related mainly to the presence of anthropogenic deposits within the soil profile. An increase in susceptibility to a depth of up to 20 cm was observed, probably due to magnetic particles from atmospheric deposition. The reduction of the magnetic susceptibility of the soil at greater depths (except for local maxima) to the value of approx. $10 \cdot 10^{-5}$ [SI] is visible.

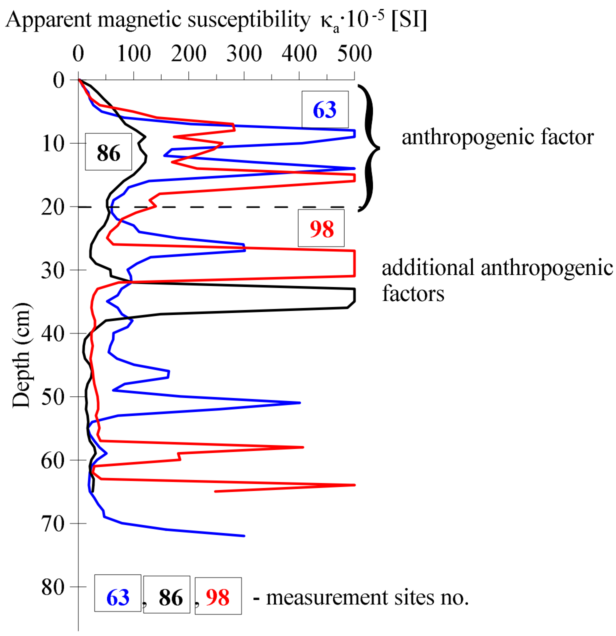

Figure 6. Vertical distribution of the apparent magnetic susceptibility of soils at measurement sites located in the west area of magnetic susceptibility anomaly in the east part of Krakow, in the vicinity of “Krakow” heat and power plant.

At the remaining measuring sites, an increase in the magnetic susceptibility of soils to a depth of 20 cm is also observed, related to the atmospheric deposition of anthropogenic dust (industrial activity, coal combustion, road traffic) (Figure 7) [35]–[37]. Below the depth of 20 cm, the magnetic susceptibility of soils is basically stable and ranges from 20 to 60 · 10^{-5} [SI]. However, in the case of site no. 14, located in the vicinity of an industrial plant, the magnetic susceptibility of soils decreases to the value of 20-60 · 10^{-5} [SI] only at a depth of 45 cm.

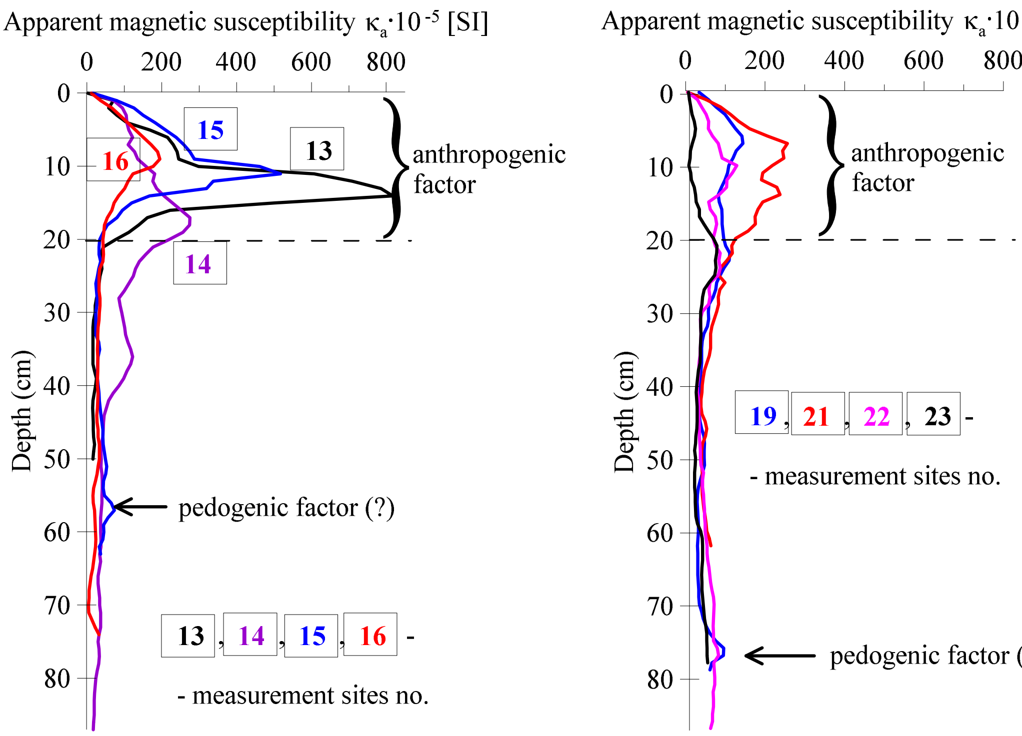

Figure 7. Vertical distribution of the apparent magnetic susceptibility of soils at measurement sites located in the west area of magnetic susceptibility anomaly in the east part of Krakow: (**a**) high urbanized "Nowa Huta" district; (**b**) north administrative border of the city.

The soils in more urbanized areas (District XVIII - Nowa Huta) have a higher magnetic susceptibility compared to the susceptibility of soils located at the northern administrative border of Krakow (less urbanized areas) (Figure 7a, Figure 7b, Table 1).

The depth distributions of the magnetic susceptibility of soils correspond to the anthropogenic type of soil profiles, with a possible pedogenic (geogenic) effect at sites 15 and 19.

4.3. Magnetic susceptibility anomaly in the eastern part (with its western and eastern part) of the city

The last areas where measurements of the magnetic susceptibility of soils in boreholes were measured were industrial areas and arable fields located in the eastern part of Krakow (Figure 8, Figure 9).

Analyzing the measurement results, the magnetic susceptibility curves show an uplift at a depth of up to 30 cm (Figure 8, Figure 9). In areas located to the east of the industrial plant (sites no. 11, 101, 102, 104, 112) and at the eastern border of the city (sites no. 108, 109, 110, 111), the magnetic susceptibility of soils is higher (up to 400 · 10^{-5} [SI]) probably due to the prevailing winds from the west, which blow the area with industrial emissions (Figure 8a, Figure 9a). In the sites located to the north and south of the industrial plant, the magnetic susceptibility of soils is much lower (Figure 8b).

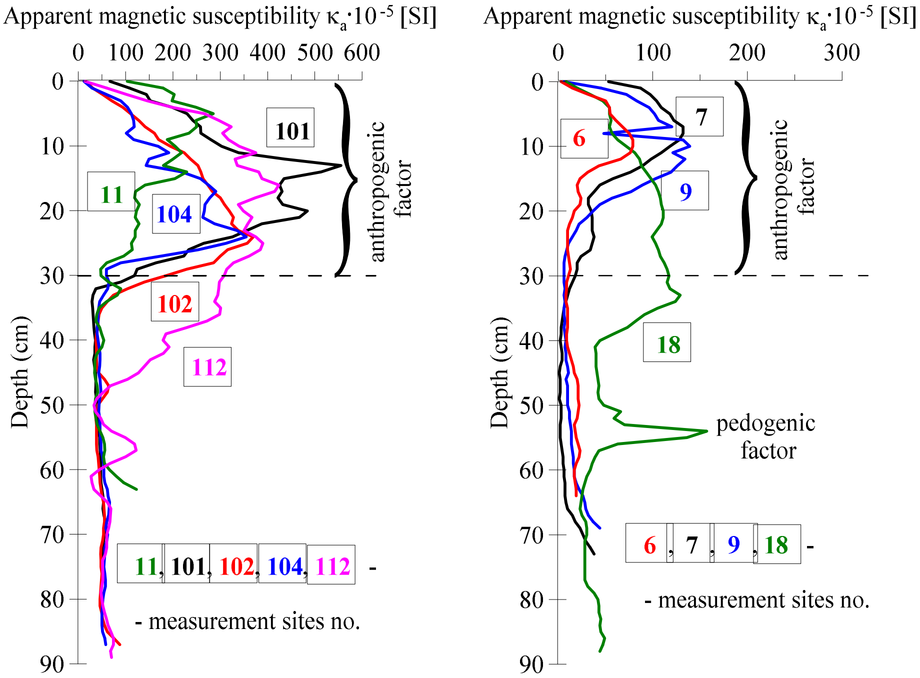

Figure 8. Vertical distribution of the apparent magnetic susceptibility of soils at measurement sites located in the east area of magnetic susceptibility anomaly in the east part of Krakow: (**a**) in the vicinity of steelworks; (**b**) from the north and south sides of the steelworks.

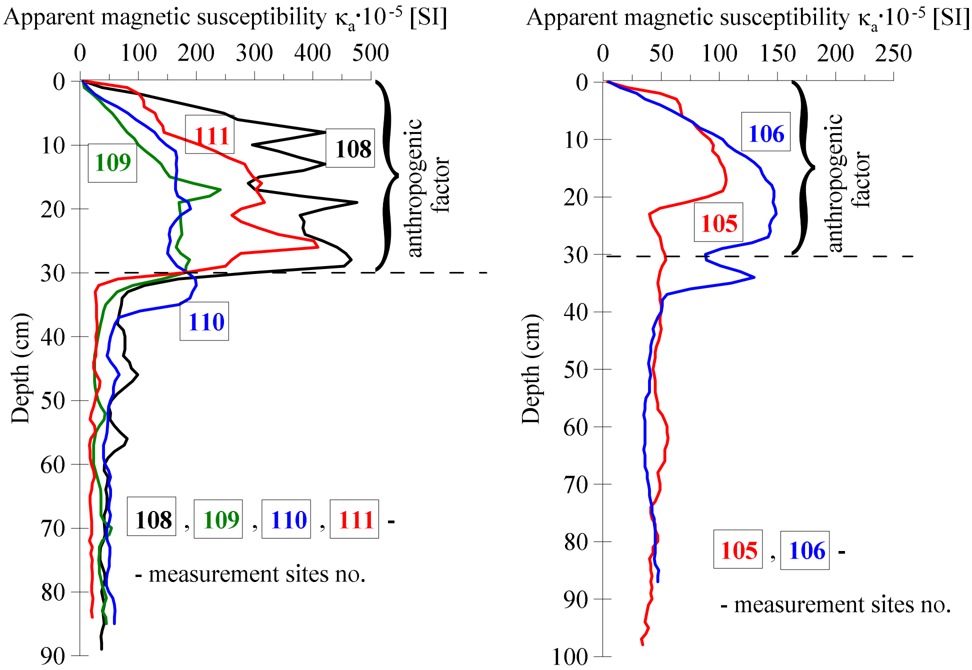

Figure 9. Vertical distribution of the apparent magnetic susceptibility of soils at measurement sites located in the east area of magnetic susceptibility anomaly in the east part of Krakow: (**a**) in the vicinity of the eastern administrative border of the city; (**b**) in the vicinity of the northern administrative border of the city.

In the area of loess and chernozems, in the deeper parts of the measurement profiles (sites no. 105, 106), the magnetic susceptibility increases to approx. 50 · 10^{-5} [SI] (Figure 8, Figure 9) due to stronger magnetic properties of these formations [38], [39]. Contrary to loess and chernozems, the muds found at sites no. 7 and 9 (Figure 2, Figure 8b) have a magnetic susceptibility close to zero.

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The results of the geochemical analysis reveal mostly alkaline soil and exceedance of the permissible values of heavy metals in the soil for lead and zinc (Table 1). Very high pH values (pH_{max} = 8.99) are caused by enrichment of the soil with compounds of anthropogenic origin with alkalizing properties, e.g. metal oxides. The alkaline reaction is shown mainly in the soils in the northeastern and central parts of the city.

5. Discussion

The depth recognition of magnetic susceptibility presented in this article is the first attempt to recognize the magnetic properties of lower horizons for the whole area of Krakow. In 2017 the map of topsoil magnetic susceptibility was published [9]. The measurements and sampling were carried out in a mesh of 2 x 2km providing the most accurate data for magnetic susceptibility mapping in this high urbanized area. But the deeper insight has been made only selectively, on the local scale, for example in the Main Market Square [40]. In this place, the natural primary sands with the lowest values of mass magnetic susceptibility ($0.3 \cdot 10^{-8} m^3 kg^{-1}$) were described at the depth of 535 cm. Therefore, there is not possible to make a correlation with the results because of much shallower measurement profiles (in the center up to 100 cm, Figure 4).

The magnetic susceptibility method gives us a rapid characterization of soil magnetic properties arising during natural or/and anthropogenic processes. The maximum magnetic susceptibility values can point out the location of causative bodies which pose generally ferrous objects. High peaks of magnetic susceptibility in historical-cultural layers, in the city center, can identify anthropogenic remains with archaeological features (artifacts). Non-magnetic parent material makes detection easier and more accurate. The input of anthropogenic and pedogenic factors can be distinguished and vertical ranges of enrichment soil can be defined (Figures 3, 5-9).

The higher magnetic susceptibility of loess and chernozem soils (lithogenic factor) in the northeastern part of Krakow are connected with their natural higher magnetic which are the result of pedogenetic processes and climate. The natural magnetic enrichment of the chernozems soils in comparison with other types of soils in the Poland area was also established by Polechońska [38, annex 7].

Finally, it was confirmed (Pasieczna, 2003) that alkaline soils predominate in the study area (Table 1).

6. Conclusions

Studies into magnetic susceptibility of soil in Krakow, in the vertical holes, have shown that the magnetic properties of soils changes in very wide ranges. A significant differentiation of magnetic susceptibility is well visible in statistical parameters, namely for all measured values, the average value is 86 10^{-5} [SI], while the median is 48 10^{-5} [SI].

The depth distribution of soil magnetic susceptibility is closely related to the location of measurements and depends among others on soil contamination. The high values of soil magnetic susceptibility and their strong variability were recognized in the center of Krakow. It can be associated with: soil contamination, the presence of iron-containing artifacts in soil, and also the possibility of the mixing of soil. Attention should be paid here to the surroundings of the heat and power plant because of the highest values of soil magnetic susceptibility in this region and their very high variability with depth.

The obtained depth distributions of soil's magnetic susceptibility correspond to the anthropogenic type with a characteristic maximum for the upper layer. The maximum magnetic susceptibility in the near-surface layer (including the organic horizon) was visible for all measurement sites. Usually, its intensity and the vertical range were primarily connected with soil contamination (dust deposition):

- in forest soils (measurement sites no.: 41, 87) the maximum occurred to the depth of 10 cm,
- in urbanized areas (the vicinity of heat and power plant, Nowa Huta district) the maximum was observed to the depth of 20 cm,

- in areas subjected to high anthropopressure associated with long-term industrial activity (surroundings of the industrial plant) the maximum was visible up to 30 cm in depth.

Despite the high influence of anthropogenic factors in the studied area at some locations, a possible influence of pedogenic (sites no. 15, 19, 87) and lithogenic factors (sites no. 11, 18, 69, 112) was found.

As it was mentioned the depth distribution of soil magnetic susceptibility is closely related to the location of measurements, depends on soil contamination, and what is more, it depends also on the geology of this area (parent rocks for soils, type of soils). In the case of parent rocks which are very weak magnetically as limestones, fluvioglacial sediments, and the clay sediments of Miocene, very low values of magnetic susceptibility (close to zero) in the deeper part of the profiles were observed:

- in the south-western part of the city (measurement sites no.: 41, 76),
- in the center of the city (measurement site no. 99),
- to the west of the industrial plant (measurement sites no.: 86, 13, 14, 15, 16),
- to the south of the industrial plant (measurement sites no.: 7, 9).

Whereas in the case of loess and chernozem soils occurring in the north-eastern part of Krakow, the magnetic susceptibility of soils was not decreased to zero, but it was stabilized at constant level c.a. $50 \cdot 10^{-5}$ [SI].

In summary, the studies into magnetic susceptibility of soils in vertical profiles in Krakow gave a better insight into the magnetic properties of contaminated soils and showed the layers which are the most affected by anthropopression.

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