Original Research

Investigation of Soil Contamination Using Resistivity and Induced Polarization Methods

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Abstract

The subject of this study was the postmining landfill located near the village of Buków in southern Poland. The pile is situated about 200 m from the Odra River in the vicinity of the "Buków" flood polder. The resistivity and induced polarization imaging methods were applied to recognize the influence of the deposited waste on the underground water. In the storage yard area, under a thin and non-continuous impermeable cover, there is a water-bearing layer of considerable thickness. This layer enables the transport of chlorides and sulphates from the landfill. Since the aquifer in the investigated area is not homogeneous containing numerous impermeable, clayey interbeddings, the unambiguous interpretation based only on the ERT results of would not be reliable. The results using induced polarization allowed some of the contaminated zones to be unambiguously identified. The results obtained show that the postmining waste and hydrotechnical objects built of them influence the underground water, and areas of contamination can be identified successfully by the combination of resistivity and induced polarization imaging, even in the complex lithological structure.

Keywords: Buków polder, postmining waste, inorganic contamination, resistivity imaging, time-domain induced polarization

Introduction

The long-term intensive exploitation of hard coal creates a huge quantity of postmining waste. Despite the recycling that has been in progress for several years, even today more than 500 million tons of postmining waste is deposited in storage yards in Upper Silesia. These areas become a serious threat to the quality of surface and underground water because of the lack of isolation from the ground and the significant impact of atmospheric factors on the waste. Through the action of the oxygen and water, sulphides, especially pyrite, contained in the coal can be transformed into SO_4^{2-}. Additionally, such storage yards are not only considerable sources of sulphates and chlorides, but under certain conditions heavy metals can be released. In an acidic environment without carbonates, metallic elements can be simply leached and transported into the surface and underground waters.

The combined resistivity and induced polarization methods have become more popular in environmental studies, but up till now they were not applied to investigate the influence of hard coal postmining waste and hydrotechnical objects built of it on underground water in the vicinity of a storage yard.

The efficiency of the resistivity imaging method (ERT) for investigations in environments where contamination leaching from landfills occurs is well-known and has been repeatedly reported in literature [1-5]. However, in certain geological conditions the obtained results do not permit the unambiguous identification of the polluted area. This happens when the polluted layer adjoins with clayey sediments. In such cases the best option is the extension of the recognition for the measurement of the induced polarization (IP) [6-10].

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The induced polarization phenomenon is an effect of the electrochemical interactions that occur when mineral grains and water come into contact with each other [11]. The presence of negatively charged clay particles causes the accumulation of cations on the border between the clay and electrolyte. The cloud of cations in a pore space performs the role of a membrane. When the DC potential is applied ions are transferred through the pore space; when the power is off, the ions return to equilibrium.

Chargeability (M), which is a typical measure of the IP effect in time domain, can be defined as the area under the potential decay curve, normalized relative to the initial potential V_0 [12].

$$M = \frac{1}{V_0}\int_{t_1}^{t_2} V_p(t)dt$$

This so-defined chargeability depends on grain size, clay and water contents and water mineralization. This chargeability represents the measure of polarization magnitude relative to conduction magnitude [13, 14] and thus it is approximately related to bulk resistivity.

Dividing the chargeability by resistivity gives the normalized chargeability (MN) or specific capacity [14]. This parameter is independent of bulk resistivity and thus it is more sensitive to surface geochemical phenomena. Slater and Lesmes [14] demonstrated that normalized chargeability helps the lithological IP effects to be distinguished from the effects due to water mineralization because it is more sensitive to lithology than to water conductivity. The characteristic pattern due to contaminated water is low resistivity associated with low normalized chargeability, whereas clayey areas are characterized by low resistivity and raised normalized chargeability value.

The Area of Investigation

Buków mine waste dump is situated about 10 km south of Racibórz town, about 170 m north of the Odra River. The waste delivered from the Rydułtowy-Anna coalmine has been stored there since 1976. The area of the storage yard is approximately 45 ha. Initially, sublevel storage held waste that filled a trough formed as a result of gravel excavation. Later, the waste material was piled up 20 m high (Fig. 1).

The stored waste came from hard coal dressing processes. More than 90% of the waste is coarse-grained material. Lithologically it consists of compact mudstones (70%) and dants. The stored waste is characterized by very low absorbability, considerable permeability, and an inability to self-seal [15]. All of the above-mentioned features make possible the unrestrained infiltration of water into the pile, and afterward into the underground water.

Since 1997 the pile has been recycled and coal is recovered from the waste. The aeration and irrigation processes connected with the recycling enhance the decay of sulphides. The released chemicals migrate unobstructed into the underground water and thus they can cause appreciable changes in the water quality in the vicinity of the storage yard.

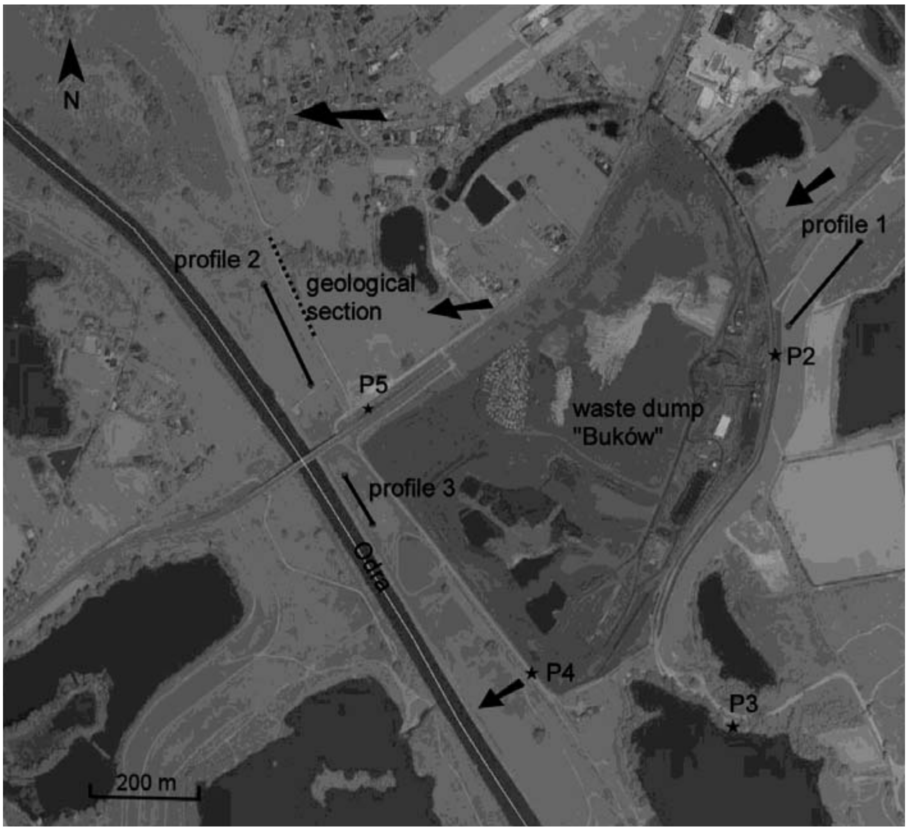

Fig. 1. Location of the survey area. Arrows indicate direction of underground water flow. (accor. Google Earth.com).

Geological and Hydrogeological Structure of the Investigated Area

Sediments situated on the right bank of the Odra are characterized by its relatively uncomplicated geological structure [16]. A network of piezometers surrounding the storage yard, documentation of open-pit gravel exploitation, and numerous drillings connected with a major repair of the Odra flood banks provide detailed lithological information. A lithological structure of the investigated area is presented in Fig. 2.

Cohesive and impermeable sediments of the Miocene age are found in the foundation of the investigated area. The thickness of these sediments is considerable and for the entire investigated area it exceeds 20 m. This layer is built mainly of dusty clays and loams, but numerous large lenses of gravels and coarse-grained sands can be noticed within the impermeable sediments. The roof of the Miocene is almost flat and generally it is situated at a depth of about 10-12 m.

Above the described sediments, a continuous, alluvial layer that belongs to the Pleistocene can be ascertained. The permeable layer consists of gravels, sand-gravel, coarse-grained sands, and local interbeddings of fine-grained sands. Its average thickness is between 8-10 m, but locally it can increase up 20 m or decrease to below 4 m (toward the NW). This layer makes the horizontal expansion of contamination from the storage yard possible. According to different sources the value of the filtration coefficient for the permeable layer ranges from 6.1×10^{-5} to 3.6×10^{-4} m/s [17, 15].

The Holocene top layer is built of clays, sandy clays, and anthropogenic grounds. This layer is non-continuous with average thickness of 2 m. The impermeable overburden does not appear along the Odra River bed.

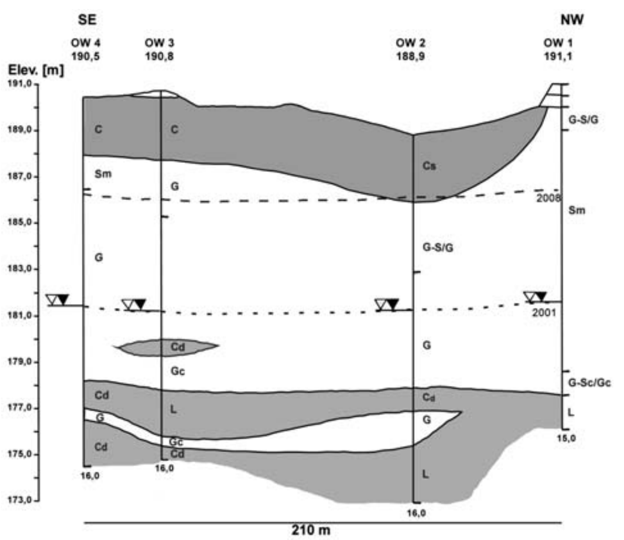

Fig. 2. The geological section of the investigated area.
G – gravel, G-S – sand-gravel, Gc – clayey gravel, Sc – coarse sand, Sm – medium sand, C – clay, Cs – sandy clay, Cd – dusty clay, L – loam

In the investigated area, the water-bearing level is connected with alluvial sediments. In general, it is characterized by an unconfined water table, but a slightly confined water level can be observed locally. The above-mentioned aquifer is hydraulically connected with the surface water and is thus supplied by rainfalls. The fluctuations of the water level amount to several meters. The area of investigation is drained by the Odra, thus the main drainage direction is SW, but depending on time in certain places, the flow direction can change, which is caused by pumping water within the existing gravel pits.

Geoelectrical Survey

The area surrounding the coal waste dump is not accessible for geoelectrical research due to the variable terrain morphology, road, and communal infrastructure elements, and agricultural crops carried out to the north and west of the dump. Some of these factors can significantly influence geoelectrical survey results, particularly those of induced polarization whose measured signal is very weak. Thus the measurement lines were located considering these undesirable factors mentioned above. We also avoided measuring in crop areas.

Geoelectrical recognition was carried out along 3 profiles (Fig. 1). The first was situated NE of the storage yard where the inflow of uncontaminated water was expected. The length of the measurement line was 200 m. The next two lines were placed in the sites of the strongest expected dump influence. Profile 2, with the same length as profile 1, was situated to the east of the storage yard and parallel to the Odra. The third line was traced to the south of the pile. Its length was 100 m. The area of investigation was free of any human noise sources.

The geoelectrical survey was performed using a LUND Imaging System (ABEM) and non-polarizing Cu-$CuSO_4$ electrodes. For measurements, the dipole-dipole electrode array with electrode spacing of 5 m (profile 1, 2) or 2.5 m (profile 3) was applied. The array was chosen in consideration of low electromagnetic coupling, which is essential in an induced polarization survey. The IP measurements were performed in a time domain where chargeability is a measure of the polarization effect.

The applied current intensity was 10-200 mA, but currents in the range of 100-200 mA were dominant. The on/off time was set at 2 s and initial delay amounted to 10 ms. The chargeability was measure in ten time windows with a length of 20 ms each.

The inversion of the obtained data was carried out using Res2Dinv software. A smooth inversion constraint was applied. At first, only the resistivity data were inverted in order to obtain sections with a maximum depth and maximum resolution. Later the resistivity/IP data were inverted simultaneously. The time interval 50-150 ms and normalized values were chosen to analyze chargeability.

All measurements were executed during a short time interval in similar weather conditions. Thus to facilitate the comparison, the obtained sections were shown in a uniform color scale.

Table 1. The chemical composition of underground water in the vicinity of the Buków storage yard.

Piezometer	Altitude [m a.s.l.]	Lithology		Water purity class	Qualifying factors
P-2	193	0÷0.6 m	soil	IV*, V**	γ_{25}, Na, K, Ca, Mg, Fe, Mn, Cl, SO_4, HCO_3, PO_4
		0.6÷4.2 m	dusty clay		
		4.2÷10 m	sand-gravel, clayey near the floor		
P-3	190	0÷1 m	anthropogenic ground	IV*, V**	Fe, Mn, SO_4, PO_4
		1.0÷6.6 m	sandy clay		
		6.6÷8.4 m	sand-gravel		
		8.4÷10 m	loam		
P-4	193.5	0÷2.0 m	clayey sand	IV*, V**	Na, SO_4, γ_{25}, Cl, PO_4
		2.0÷4.0 m	dust		
		4.0÷6.5 m	fine-grained sand		
		6.5 ÷7.0 m	coarse-grained sand		
		7.7÷13.5 m	sand-gravel		
		13.5÷14 m	loam		
P-5	194	0. ÷0.9 m	anthropogenic ground	IV*, V**	γ_{25}, Na, Mg, Fe, Mn, Cl, SO_4, K, Ca, PO_4
		0.9÷5.2 m	dusty clay		
		5.2÷7.5 m	gravel		
		7.5÷14.4 m	sand-gravel		
		14.4÷15.5 m	loam		

*According to [15], **According to [18].

Results of the Investigation and Discussion

Profile 1 was traced in the vicinity of the storage yard in the direction of where the inflow of uncontaminated water was expected. An embankment of the Buków polder separates the profile from the waste dump. The southern part of the search line (beginning at 125 m) is located on the slope of the embankment. Resistivity values for this line range from 5 to 210 Ωm. A 3-layer structure can be noticed (Fig. 3).

The bottom layer with the lowest resistivity, which correlates with increased normalized chargeability, may be considered as clayey Miocene sediment. Its roof occurs at a depth of 13-15 m. Piezometer P-2, situated between the embankment and the pile near the southern end of profile 1 at a depth of 10 m (altitude 183 m), did not reach the roof of the Miocene sediments (Table 1) [15].

Above the Miocene sediments, a layer of higher resistivity (> 50 Ωm) and low normalized chargeability was detected. It can be interpreted as a permeable layer built of sand-gravel. The lower part of the aquifer exhibits increased normalized chargeability values caused by increased clay content, which is in accordance with geological information from the nearby piezometer.

Near the surface the resistivity values decrease, which is most interesting when considering the expansion of contamination. A decrease in resistivity is clearly noticeable in the southern part of the section, where it falls to a level of over a dozen Ωm. On the ground of the resistivity obtained, it is not possible to ascertain whether the reason for this effect is the smaller grain size, the existence of the impermeable clayey layer, or the occurrence of the contamination.

An analysis of the normalized chargeability in this area exhibits very low values (< 2 mS/m) to a depth of 10 m. In the top layer, the chargeability increases slightly to the 3-4 mS/m only locally (20-25 m, 55-70 m). This correlates with moderate resistivity (20-30 Ωm) and thus can be interpreted as the discontinuous clayey cover. The northern part of profile 1 reflects the lithological characteristics of the uncontaminated sediments.

In the part of profile 1 that belongs to the embankment, the top layer is characterized by the lowest resistivity values. According to the resistivity measurements the volume of the investigated embankment can be considered as electrically uniform. In the normalized chargeability section an increase in value is observed in the lowest part of the embankment, between 120 and 145 m. To the south the core of the bankt is characterized by low chargeability. From the technical documentation [18], it is known that the rock material coming from the pile was applied to construct the embankment of the Buków flood polder. Only the lower fragment of the inner slope was covered by the impermeable, clayey layer that reflects in the low resistivity and raised normalized chargeability values observed in sections.

Table 2. Mineralization of the underground water according to readings of the P-2 piezometer in 2006 (peak values) [18].

Piezometer P-2	
γ_{25}	5,740-7,310 μS/cm
SO_4	2,208-2,939 mg/dm³
Cl	594-637 mg/dm³
Na	554-901 mg/dm³
Mn	1.57-1.9 mg/dm³
Fe	19-22 mg/dm³
Cr_{org}	> 0.2 mg/dm³
Ni	> 0.25 mg/dm³

The low resistivity and low normalized chargeability values indicate the existence of contamination within the core and at the base of the embankment. It seems to be possible that the embankment became the local source of contamination. This conclusion is confirmed by hydrogeological information. Since the embankment was formed in 2002 piezometer P-2 has indicated a noticeable decrease of water quality (Table 2). The 10-fold increase of the sulphatic and chloridic mineralization observed from the direction of the pure water inflow was expected [18]. The unrestrained infiltration of rainfall water through the embankment material can cause leaching of the soluble compounds from waste. In 2007 and 2010 contact between the flood water with the polder embankment took place. The proof of the permeability of the bank is its soakage during the flood in summer 2010.

Profiles 2 and 3 were located inside the flood plain. Profile 2 was located near the area that is presented in the geological cross-section (Fig. 2), but closer to the Odra River. The floor of the permeable layer is detected at a depth of about 12 m. For the highly-resistive layer the resistivity values ranged from 50 to 300 Ωm (Fig. 4). It can be seen that these values are considerably higher than those obtained for the previous profile. This indicates thicker granularity of the investigated sediments. The inverted normalized chargeability for almost the entire layer is very low (< 2 mS/m). In the two locations just below the surface (25-80 m and 100-125 m), the slightly lower resistivity correlates with higher chargeability. The probable cause is a change to a smaller grain fraction. In the lithological section presented in Fig. 2, the roof of the permeable layer is built mostly of medium-grained sand. Even though profile 2 is situated in the vicinity of piezometer P-5 and bore-holes which exhibited the presence of the top layer built of clays, for this line the impermeable cover was not ascertained. According to geological data this cover disappears near the Odra river bed. The vertical disturbance, which is observed at 25-75 m for both resistivity (decrease) and normalized chargeability (increase) sections, seems to be an effect of flood damage, followed by sealing works that resulted in filling gaps with fine-grained, low-permeable material.

In the ERT and normalized chargeability sections nothing indicates the presence of pollution. The resistivity values obtained above the roof of the Miocene for the whole section remain at the same high level. This seems somewhat surprising because of chemical analyses of water samples from piezometer P-5 (Table 1, Fig. 1) indicate increased mineralization, raised value of specific conductance coefficient, and a presence of substances leached from the storage yard. The results of the resistivity imaging

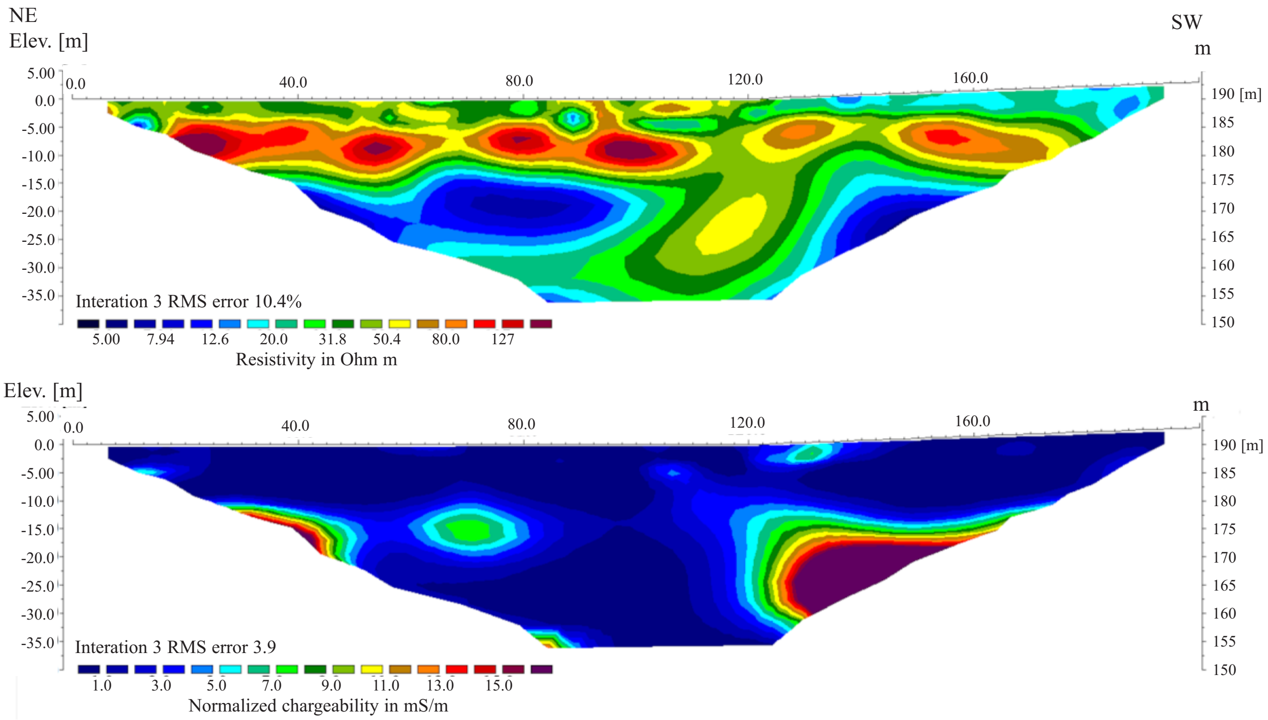

Fig. 3. Inverted resistivity and normalized chargeability values obtained for profile 1.

performed opposite the flood bank near piezometer P-5 exhibited the existence of a low-resistive zone (5-20 Ωm) just below the surface, with a length of 105 m and thickness of 5 m. The above-mentioned layer by the authors was interpreted as contaminated aquifer, whereas the issues of the laboratory electrical tests of water samples collected at a depth of 3 m pointed to resistivity value of 305 Ωm [15]. Thus the interpretation of the low resistive area is considerably unreliable. The extension of ERT measurements with the induced polarization measurements for this problematical interval would help to explain the reason for this anomaly, because it would confirm or exclude the existence of the clayey, impermeable sediments.

The absence of the layer characterized by low resistivity in profile 2 can be considered an effect of too large distance between electrodes relative to the thickness of the above-quoted layer what resulted in insufficient resolution of the resistivity/chargeability measurement. Another probable cause for such a situation is one of the anti-filter-diaphragms that were constructed within the permeable layer on the foreground of flood bank to the west and south of Buków in 2002. The planned line of the diaphragm [17], coincidental with the geological section presented in Fig. 1, proved to be almost parallel to profile 2. In spite of the fact that the exact dimension of the diaphragm is not well known, only its approximate range was available, it seems to be logical that it reaches the bridge over the Odra River protecting its foundation, and thus it can hinder the migration of contamination from the dump.

Profile 3, similar to profile 2, is traced near the Odra between the river bed and the flood bank. The impermeable base can be found at a depth of 8-9 m (Fig. 5). The top layer of this profile has decidedly different characteristics in comparison to those being previously analyzed. It is char-

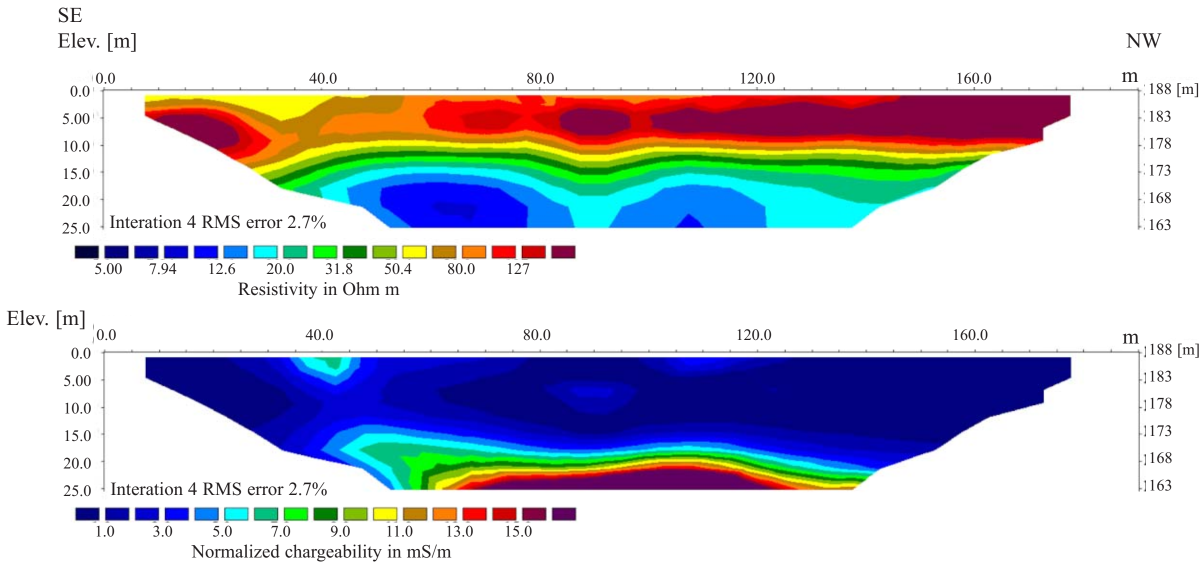

Fig. 4. Inverted resistivity and normalized chargeability values obtained for profile 2.

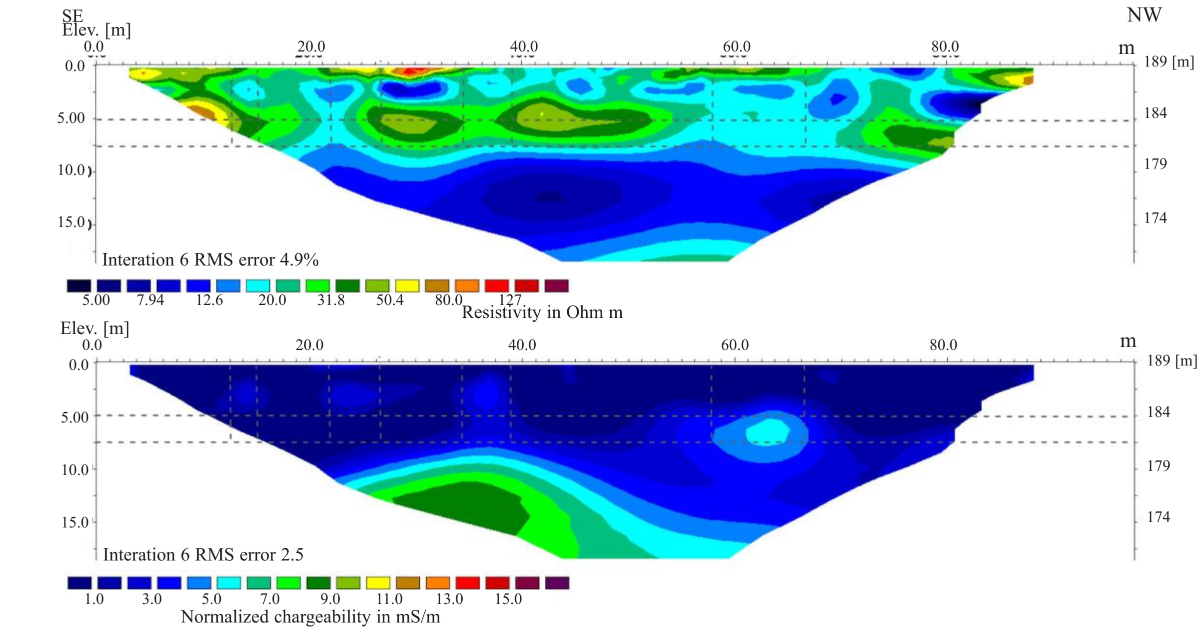

Fig. 5. Inverted resistivity and normalized chargeability values obtained for profile 3.

acterized by significantly lower resistivity values than those observed in the earlier-described profile, and its features are similar to those noticed for the southern part of profile 1. The resistivity for the layer situated above the roof of the Miocene does not exceed 100 Ωm, and values between 13 and 40 Ωm dominate in the profile. The most interesting feature of this profile is a sequence of low-resistive (< 15 Ωm) anomalies that can be noticed at a depth of 2-4 m. This feature might indicate the occurrence of the contamination or the presence of impermeable interbedding. Both of these cases are equiprobable in the examined area and without induced polarization measurement it cannot be resolved. For most of these above-mentioned anomalies located in the SE part of the search line the lowest resistivity correlates with an increase of chargeability and thus they appear to be caused by clayey or dusty interbeddings and lenses within the gravels and sands. The low-resistive lenses in the NW interval of the profile (beginning at 40 m) do not correlate with chargeability increase. Therefore, they are interpreted as areas of intensive infiltration of contamination from the deposited waste material. The nearest of the piezometers (P-5), which is situated at a small distance to the north of the analyzed line, shows increased values of Na^{+}, SO_4^{2-}, Cl^{-}, Mg^{2+}, Fe^{2+}, Fe^{3+}, and Mn^{2+} (Table 1), which confirms the results of the geoelectrical survey. Piezometer P-4 situated near the SE corner of the dump also indicates the presence of undesirable leakage toward the river.

Conclusions

The geoelectrical investigations performed northwards and southwards of the "Buków" storage yard with the studied search lines allowed us to indicate some of the permeable zones where the infiltration of contaminations occurs.

On the northern side of the pile the area characterized by low resistivity and low normalized chargeability can be indicated, which is located above the roof of the coarse-grained layer, within the embankment. The embankment of the polder, built of postmining waste material from the storage yard, was identified as the source of the contamination.

On the southern side of the waste-dump where intensive infiltration of contamination toward the Odra occurs, the numerous zones were ascertained at a depth of about 2-4 m.

The leaching that occurs to the southwest from the storage yard seems to be partially hindered by the anti-filter barrier situated between the flood embankment and the river. Conclusions of the conducted geoelectrical study are in good accordance with the hydrogeological information.

The obtained results show that the area where the waste from hard coal mining is stored and hydrotechnical objects built of postmining waste impact surface and underground water quality, and it is possible to identify this spatial threat by resistivity and induced polarization methods. A detailed determination of the flow paths from the coal waste dump would require a larger number of precisely arranged high-resolution search lines free from electrical noise sources.

The combination of resistivity and IP survey can be considered a valuable instrument in environmental studies, especially connected with the infiltration of contaminative solutions from postmining waste-dumps and hydrotechnical objects built of postmining waste. This combination might be especially useful in areas with complicated lithological structure, where the impermeable, clayey sediments and the inorganic leakage co-occur. In situations described an unambiguous interpretation of the obtained results, only on the basis of ERT recognition is it very difficult due to similarity of resistivity for these two geological media. Because of the slowness of induced polarization measurements, it seems to be the optimal solution to perform the relatively fast ERT method for long search lines at first. Afterward, induced polarization measurements should be executed for select, difficult-to-interpret segments.

In spite of the fact that time-domain-induced polarization measurements are time-consuming and logistically more complicated than resistivity measurements, their results can significantly facilitate the interpretation of the presumed zones of infiltration.

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