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VLF MAPPING AND RESISTIVITY IMAGING OF CONTAMINATED QUATERNARY FORMATIONS NEAR TO "PANEWNIKI" COAL WASTE DISPOSAL (SOUTHERN POLAND)

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ABSTRACT
The purpose of this work was to detect groundwater pollution and to identify the conditions of soil and groundwater near the coal waste disposal "Panewniki" Halemba-Wirek Coal Mine using geoelectrical measurements. The first applied method was the VLF (Very Low Frequency) technique. This method, using military signals, allowed to perform the in-phase and the quadrature maps. Data were collected from four study areas located near the coal waste dump. Observed anomalies on both maps for each area showed places with different conductivity allowed to detect the contaminated and uncontaminated zones. The VLF survey indicated that the contamination occurs in the eastern part of study area and is characterized by positive values of both measured electrical fields (the in-phase and the quadrature components). After preliminary contaminated zones were recognized using VLF method, an electrical imaging method was applied. Two electrical imaging profiles were carried out near the waste dump. The measurements allowed to create the geoelectrical model of surrounding area and to investigate the leachate plume. The electrical imaging showed that the greatest pollution occur in the area immediately adjacent to the coal waste what is confirmed by VLF survey. Based on the geological and geophysical knowledge from archives and on present researches, the contaminated aquifer with electrical resistivity of 5 to 15 Ωm deposited at depths of 3 to 7 m was found.

KEYWORDS: electrical resistivity imaging, electrical conductivity, VLF method, groundwater contamination, coal waste dump

INTRODUCTION

Landfills of post-mining waste are sources of groundwater and soil pollution due to the production of leachate and its migration through embankment (Adepelumi et al., 2005; Komnitsas et al., 2001; Rubin and Hubard, 2005). The influence of coal waste on quality of soil and groundwater depends on content and type of constituents washed out to the ground, their activity and time of the deposition. Physical and chemical processes occurring in the deposited waste can provide the contamination of groundwater for many years after its deposition therefore coal waste landfills are required to be studied and observed. Water balance of landfill, hydrogeology and geology of the ground below the landfill determine the conditions for leaching and transport of pollutants from landfill to water. They also determine the scale and scope of pollution (Twardowska et al., 1988). Coal waste disposal produces the pollutant due to the oxidation of the inherent pyrite and the generation of sulfuric acid. (Komnitsas et al., 2001). Coal mine drainage (CMD) is characterized by low pH what impacts on the ion exchange and sorption processes occurring in the embankment and the ground (Appelo and Postma, 2005). The CMD varies widely in composition, but mainly consists: sulphates, iron, manganese, aluminum and other ions. (Komnitsas et al., 2001). Produced contamination causes the increase of electrical conductivity due to increasing amounts of ions in aquifer (Komnitsas et al., 2001). Increases of the electrical conductivity can be detected by the geophysical methods, mainly geoelectrical.

The geophysical measurements, especially electrical and electromagnetic were widely used to investigate soils and water pollution caused by deposition of waste disposal (Adepelumi et al., 2005; Benson, 1997; Frid et al., 2008; Kaya et al., 2007; Kirsch, 2009).

The aim of this study was to investigate the groundwater pollution and to identify the conditions of soil and groundwater near the coal waste landfill 'Panewniki' Halemba-Wirek Coal Mine using geoelectrical measurements.

CHARACTERISTICS OF THE 'PANEWNIKI' WASTE DISPOSAL OF 'HALEMBA-WIREK' COAL MINE

The "Panewniki" waste disposal is located in the Silesian region on the border of towns: Ruda Slaska, Mikołów and Katowice. The "Panewniki" landfill covers area of 118.4 ha. There are deposited 15 700 000 m^3 of the waste corresponding to

Table 1 Particle size distribution in coal waste from "Panewniki" waste disposal (after Wolny and Walter, 2002).

Time of the coal waste deposition	Particle size distribution [%]			
	Stone fraction	Pebble fraction	Sandy fraction	Silty fraction
Fresh waste (1 year)	65.2	30.7	3.9	0.2
After 5 years	7.2	56.0	26.2	10.6

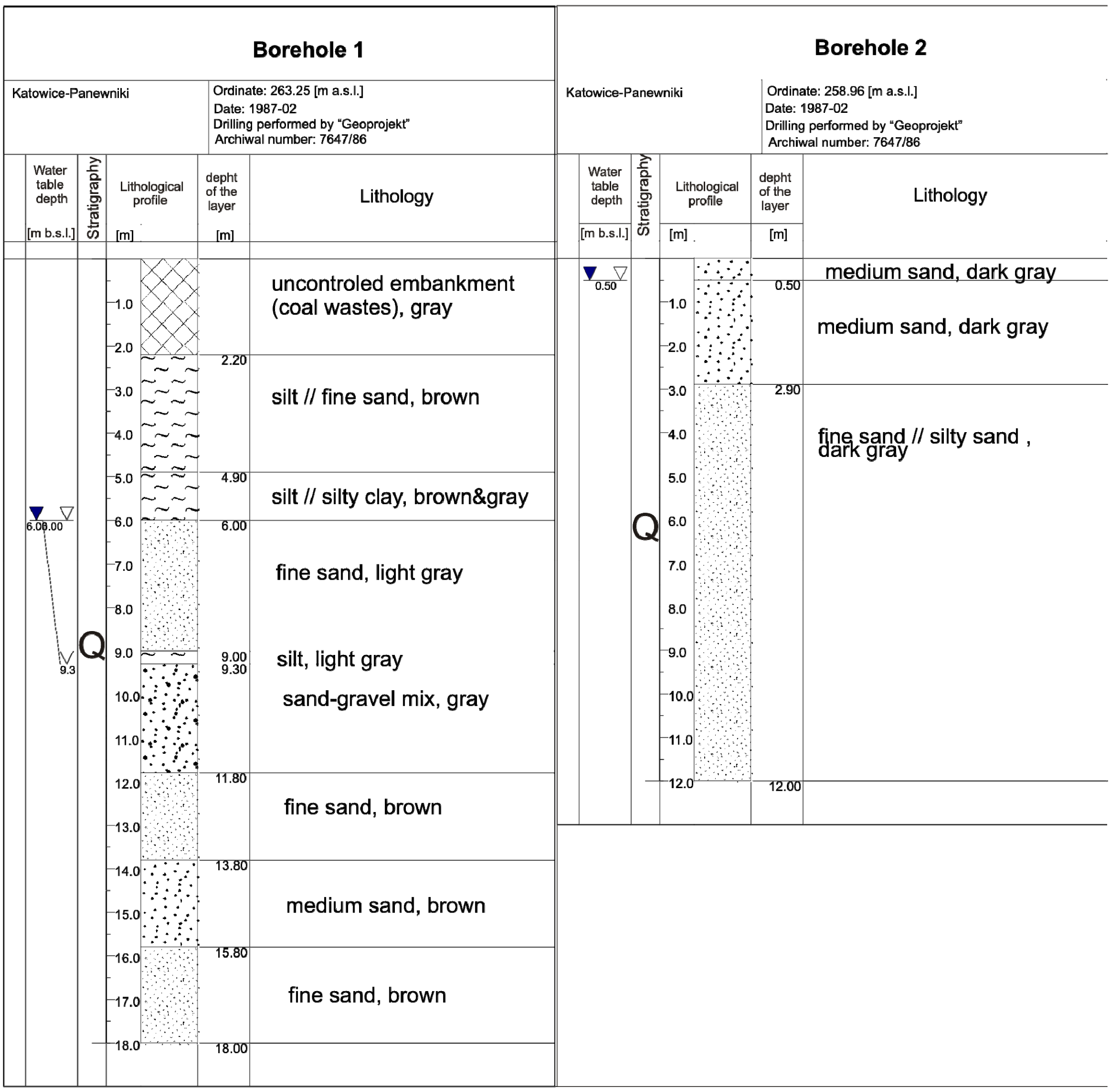

Fig. 1 Archival lithological profiles (borehole 1 - BH1 and borehole 2 - BH2) carried out by "Geoprojekt Katowice" company.

26 690 000 tones of the waste (Central Mining Institute, 2002). On the "Panewniki" waste disposal are deposited post-mining wastes, which were generated from washing and cleaning of minerals. Coal wastes are a mixture of crumbs of claystones, siltstones and sandstones (Table 1).

Runoff from the waste disposal is discharged into the ditches by two settling ponds. The waste disposal is sited without insulation of the base. As a result of the implementation of the EU program all the deposited waste will be transformed into an aggregate and broken stone, which will be used for roads and engineering purposes. Therefore, the "Panewniki" waste disposal will be completely eliminated by 2025. After this time, the waste disposal will be rehabilitated (www.ekoinfo.pl).

At the waste disposal site the Pleistocene is presented by discontinuous layers of silt, clay, sand and gravel. Quaternary sediments are characterized by high variability in the lithology (Fig. 1). Holocene sediments are characterized as fine, silty sands and mud. They occur only in the troughs of the river. Thickness of Quaternary is 39.2 m to 71 m.

By the site of the waste disposal flow the watershed stream of the third row and Jamna Kłodnica River. It is represented by sands, gravels and locally silty sands, which fill the valley fossilized upright. The permeable formations are stratified with impermeable discontinuous layers of clays and silts. Quaternary groundwater level occurs at a depth of 5 - 7.5 m (CITEC, 2003) and in the area of the river valley at a depth of 1 - 2 m (Absalon et al., 1997). The local network of piezometers observed significant differences in water quality that are related to the heterogeneity of deposited material.

METHODOLOGY

Area of investigation is presented in Figure 2. Electrical and electromagnetic measurements were carried out to investigate the possible area of contamination plume from the coal waste disposal "Panewniki". The measurements were performed on the northern part of the coal waste disposal. On the rest of the terrain the geophysical surveys (electrical imaging and electromagnetic very low frequencies) have been already carried out (Kowalska, 2010; Kowalska and Pierwoła, 2010; Kowalska and Mendecki, 2010).

ELECTROMAGNETIC MEASUREMENTS

Electromagnetic measurements were performed by the Very Low Frequency (VLF) technique using ABEM WADI equipment. VLF data were collected from four study areas situated near the coal waste dump (the Northern part; Fig. 2). As is shown in Figure 2 the first two areas are located on the left side of dump and the second two – on the right. Each area consists of a measuring grid with the distance between nodes 10 m.

The WADI utilizes the magnetic components of the electromagnetic (EM) field generated by long-distance military radio transmitters in the VLF band. Generated EM waves propagate through the earth penetrating various geological structures. Conductive structures, in this case an aquifer filled with contaminated water, affect locally the direction and strength of the EM field generated by the transmitted radio signal. Using WADI the radio signal distortion is measured. Induced currents and their associated secondary magnetic fields differ in phase from the primary field and can, in accordance with a fundamental property of sinusoidal waves, be resolved into components that are in-phase and out-of-phase with the primary. VLF magnetic field measurement makes use of E-polarization in which a transmitter is selected in the direction of strike and measuring profiles are taken perpendicular to the strike direction (Sharma and Baranwal, 2005). The measured horizontal and vertical components of magnetic fields are used to calculate real and imaginary anomalies as follows (Smith and Ward, 1974):

$$\tan 2\alpha = \pm \frac{2(H_z/H_x)\cos(\Delta\phi)}{1-(H_z/H_x)^2}, \quad (1)$$

$$e = \frac{H_z H_x \sin(\Delta\phi)}{H_1^2}, \quad (2)$$

where α is dip angle, e is ellipticity, H_z and H_x are the amplitudes, the phase difference $\Delta\phi = \phi_z - \phi_x$, in which ϕ_z is the phase of H_z and ϕ_x is the phase of H_x and H_1 is defined as:

$$H_1 = \left| H_z e^{i\Delta\phi} \sin\alpha + H_x \cos\alpha \right|, \quad (3)$$

The tangent of the tilt angle is a good approximation of the ratio of the real component of the vertical secondary magnetic field to the horizontal primary magnetic field. The ellipticity is a good approximation of the ratio of the quadrature component of the vertical secondary magnetic field to the horizontal primary field (Paterson and Ronka, 1971). These quantities are called the real (= tan a × 100 %) and imaginary (= e × 100 %) anomalies, respectively and they are normally expressed as percentage (Sharma and Baranwal, 2005).

During the processing measured data were filtered, using Fraser filter, processed in EMIXVLF software and were plotted in form of maps using Krigging method in Surfer software. Always two maps were obtained for one survey area: in-phase map and quadrature map. Generally an anomaly in the imaginary part (quadrature) is much more difficult to interpret than in the real part. Filtered real part (in-phase) show a positive peak above a conductor, while the imaginary part can show as well a positive as a negative peak, depending on the conditions of subsurface layer. Therefore, it has been assumed that positive anomalies observed for both maps indicate the contaminated area, but areas with stronger positive anomalies only on in-phase maps show zones with presence of ground water (ABEM 2000; Ariyo et al., 2009; Marcak et al., 2011).

ELECTRICAL IMAGING

Two profiles of electrical imaging were carried out in areas selected on the basis of archival information about geology and hydrogeology of that terrain. The selection of measurement was also determined by off-road capabilities: the profiles could

Fig. 2 Area of investigation in Southern Poland - "Panewniki" waste dump, A-A', B-B' – geoelectrical profiles, 1-4 area of electromagnetic measurements, BH1 and BH2 – lithological profiles.

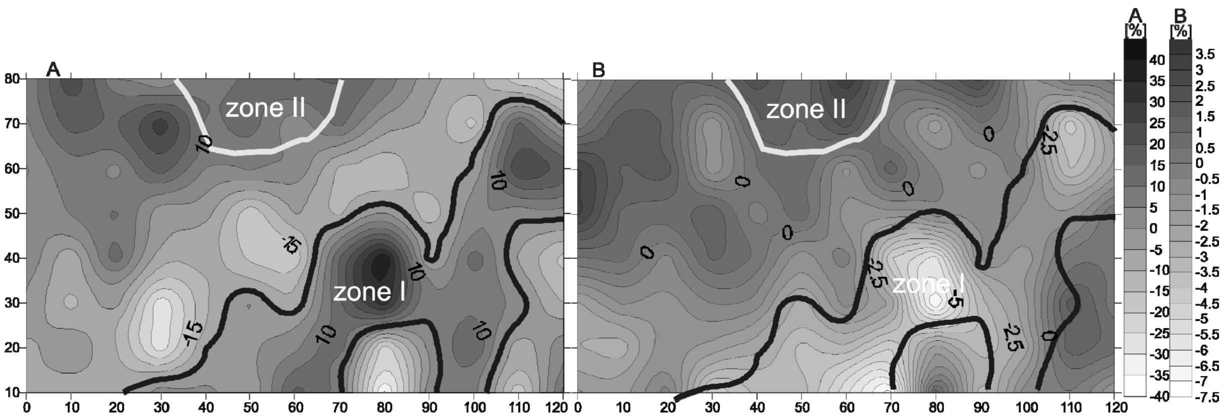

Fig. 3 Map of electromagnetic measurements – area 1, A - in-phase data, B - quadrature data, zone I – uncontaminated zone, zone II – contaminated water.

not be carried out in areas with dense vegetation and ditches which drain the wetland areas.

The geoelectrical profiles were performed using electrical imaging system 16G-N company P.A.S.I. Two pseudo-tomography surveys were carried out along A-A' and B-B' profiles (Fig. 2) using 32 electrodes connected to a multi-core cable. A laptop microcomputer with an electronic switching units (one Linkbox for 16 electrodes) were used to automatically select the relevant four electrodes for each measurement. For each profile 340 numbers of electrical resistivity were obtained. The spacing between adjacent electrodes was 5 m, and maximal electrode spacing was 155m. Wenner-Schlumberger array was used to obtain accurate horizontal coverage of the ground, significant depth penetration and good signal-to-noise ratio (Loke and Barker, 1996a).

The data were interpreted in RES2DINV – a 2D and 3D interpretation software used commonly in geophysics (Loke and Barker, 1996a). The interpretation program calculates the true resistivity and true depth of the ground from the inputted raw data file. After the dissolution of the inverse problem, using Jacobian matrix calculation and forward modeling procedures, results of the interpretation are displayed as the 2D electrical resistivity image of the subsurface along the line of profile (Loke and Barker, 1996b).

RESULTS

Results of electromagnetic data are presented in Figures 3 - 6.

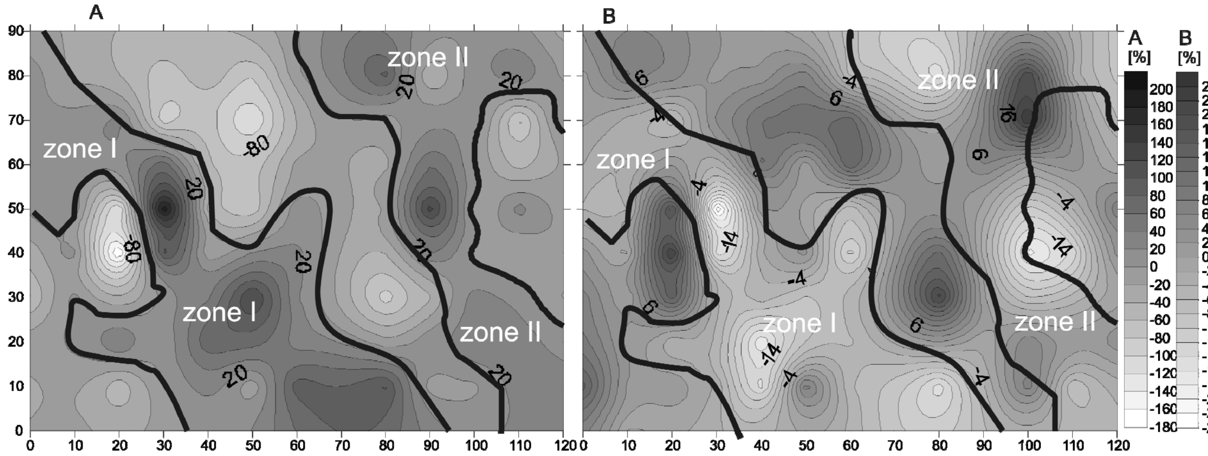

Fig. 4 Map of electromagnetic measurements – area 2, A - in-phase data, B - quadrature data zone I-II – uncontaminated zone.

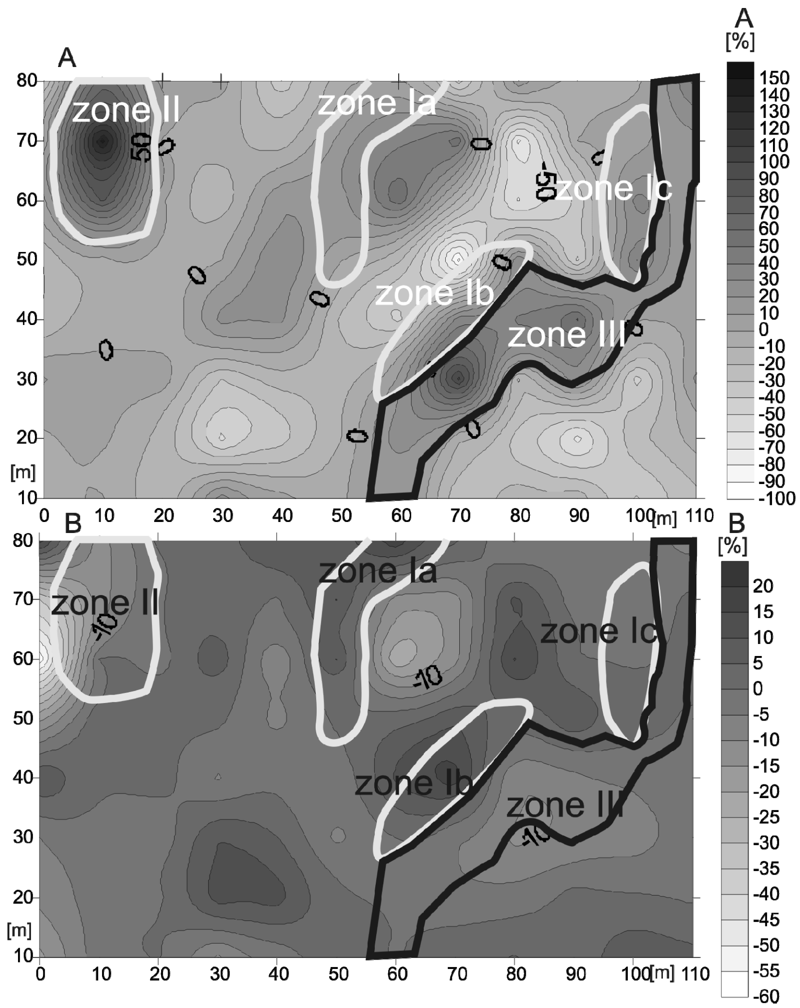

Fig. 5 Map of electromagnetic measurements – area 3, A - in-phase data, B - quadrature data, zone Ia, Ib, Ic, II - contaminated water, zone III – uncontaminated zone.

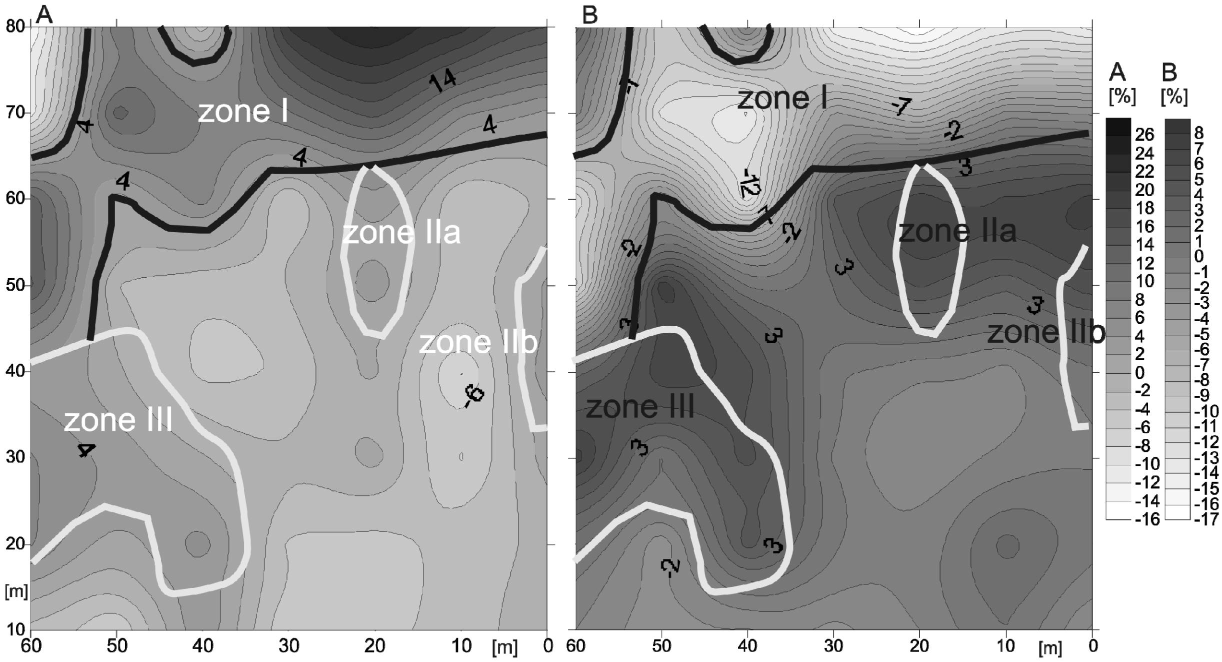

Fig. 6 Map of electromagnetic measurements – area 4, A - in-phase data, B - quadrature data, zone I – water uncontaminated, zone IIa, IIb, III – contaminated water.

It has been found that conductor with resistivity much smaller than surrounding material (a resistivity ratio $\rho_{surr}/\rho_{conduct}$ is greater than 1,000) is characterized by negative correlation of in-phase and quadrature part (Kaikkonen, 1980; Karous 1989). In these case, during the study we came across sediments with uncontaminated and contaminated ground water, thus the resistivity differences are not large. The occurance of contamination generates lower resistivity response than surrounding material filled clean water. As Karous (1989) showed there is positive correlation for resistivity ratio between 10-100. Maximum observed resistivty is 640 Ohmm, minimum 5-10 Ohmm, what gives ratio equal 64-128. Therefore, it was established that a very good conductor (contaminated zone, saline water) the anomaly in the filtered imaginary part can has the same size as the anomaly in the real part. Lack of anomaly in imaginary part but its presence in real part indicates relative high resistivity area (ABEM, 2000). Thus, an interpretation of VLF data was based on the comparing of in-phase (real part) and quadrature (imaginary part) maps (Figs. 3–6). Positive anomalies of in-phase data, which were not correlated with quadrature data were interpreted as an uncontaminated zone. Occurring the positive correlation between in-phase data and quadrature data was interpreted as a zone of contamination, the occurring of high mineralization in saturation zone. Presented results for the waste dump indicate the area of contamination especially in northeast zone.

Geoelectrical profiles (Fig. 7 and Fig. 8) were interpreted on the basis of the electromagnetic data and archival data. The water tables occur at depths of between 0.5 m to 9.5 m (Fig. 1). This information is confirmed on electrical imaging profiles, because at these depths can be seen a significant decrease in the value of electrical resistivity comparing to the formations in the vadose zone.

In the profiles A-A' and B-B' (Fig. 7 and Fig. 8) can be seen saturation zone with electrical resistivity values varying from 5-15 Ωm. These low values of electrical resistivity can indicate high mineralization in the saturation zone. Water-bearing sands which bring water with a mineralization from 0.8 to 0.5 g/dm^3 should be characterized by electrical resistivity of 35 - 300 Ωm (Antoniuk, 2005). Electrical resistivity can be also reduced by the clays occurring in the sands, but it still should not fall below 10 Ωm so the layer of electrical resistivity from 5-15 Ωm indicates the place of groundwater pollution and the mineralization of water above 0.8 g/dm^3.

Electrical resistivity of 15 - 150 Ωm in the vadose zone can be interpreted as clay, silty clay, dust, sand and clay stratification, whereas higher electrical resistivity than 150 Ωm in the same area can be interpreted as the dry sand. High electrical resistivity layer can be seen on the depth of 16 m x-coordinate in the profile BB' (Fig. 8). It was identified as a layer of clay, sand with medium-sized boulders correlating it with borehole profiles (Fig. 1).

CONCLUSIONS

Based on the VLF measurements the contamination was detected in the northeastern part of the waste dump. The correlation between in-phase and quadrate maps indicate the high conductivity connected to contamination occurring in the northeastern part. The significant contamination in the northwest part has not been detected by VLF surveys. We suppose that the contamination in this part can be too low to give a significance secondary response. What is more, assumptions of positive or negative correlation betweene real and imaginary part had been carried out for vertical condutor, but int this case there are not vertical plates of conductor what complicates interpretation and this issus need more research.

The electrical imaging allowed to investigate the geological structure occurring near coal wastes disposal 'Panewniki'. The geological strata were distinguished based on knowledge of geological and geophysical archival data and presented researches. First of them was represented by clay, dust, sand with clay (15 - 150 Ωm) which isolate layer of water-bearing medium and fine sands (5-15 Ωm). Correlations of the borehole data with electrical imaging profiles allow to find the contaminated aquifer with electrical resistivity of 5 to 15 Ωm at depths of 3 to 7 m. On the AA' profile it can be found at distinguish depth from beginning (0 m) to 110 m of the profile. However, BB' profile shows that contaminated aquifer extends over the entire length of the profile.

The well-correlated VLF and electrical resistivity data and developed methodology will help to map the contaminant plume during to future works.

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