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## Extended Abstracts

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title: **Use of geophysical methods for the assessment of migration of contaminants from the coal-mining waste dumps**

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## INTRODUCTION

Faculty of Geology, Geophysics and Environment Protection at AGH University of Science and Technology in Cracow (Department of Hydrogeology and Engineering Geology and Department of Geophysics) together with Faculty of Earth Sciences at Silesian University in Sosnowiec for more than a dozen years have conducted research on the application of hydrogeological and geophysical methods for monitoring of migration of different liquid contaminations in the geological medium (Golebiowski et al., 2010; Marcak, Tomecka-Suchon, 2009; Marcak, Golebiowski, 2006; Wzientek et al., 2005).

In the paper there is shown an attempt of correlation of the results of geophysical and hydrogeological research, which were conducted in the region of the selected mine waste dump in Upper Silesia. A strong impact of stored mine waste on mineralization of groundwater was observed in the area under investigation (Twardowska et al., 1988).

Nowadays in Poland, mineralization of groundwater is estimated mainly on the basis of laboratory analysis of physicochemical properties of water samples collected from the selected places. Such analysis allows to construct, among others, the maps showing variation of mineralization of groundwater in the examined area. In order to increase the accuracy of these maps, more places for collection of water samples should be designed. However such a solution is costly and time and work consuming. An alternative may be geophysical research, which gives continuous information about the distribution of anomalies in the geological medium. Among the wide range of geophysical methods, the most appropriate for monitoring of mineralization of groundwater are electric and electromagnetic techniques.

On the basis of laboratory analysis carried out by many researchers, e.g. Plewa and Plewa (1992), a relationship (1) was established between the increase in water mineralization, and the decrease in electrical resistivity of electrolytes, which is tantamount to the increase in electrical conductivity of solutions.

$$\rho_{fluid} = \frac{1}{\sigma_{fluid}} = \frac{10}{\sum(C_{ai}V_i f_{ai} + C_{ci}U_i f_{ci})} \quad (1)$$

where:  $\rho_{fluid}$  [ $\Omega\text{m}$ ] – electrical resistivity of electrolytes,  $\sigma_{fluid}$  [ $\text{S/m}$ ] – electrical conductivity of solutions,  $C_{ai}$ ,  $C_{ci}$  [ $\text{mol}$ ] – concentration of i-th anion and i-th cation in solution,  $V_i$ ,  $U_i$  [ $\Omega\text{m}\cdot\text{cm}^2\cdot\text{mol}^{-1}$ ] – electrolytic mobility of anions and cations,  $f_{ai}$ ,  $f_{ci}$  [-] – conductivity coefficient for anions and cations.

In 1942, Archie connected electrical conductivity of porous medium with electrolytic conductivity of liquid filling the porous space, by the relationship (Plewa and Plewa 1992):

$$\sigma_{geological\_medium} = \frac{1}{\rho_{geological\_medium}} = a\phi^m s^n \sigma_{fluid} \quad (2)$$

where:  $\sigma_{geological\_medium}$  [ $\text{S/m}$ ] – electrical conductivity of medium,  $\rho_{geological\_medium}$  [ $\Omega\text{m}$ ] – electrical resistivity of medium,  $a$  [-] – tortuosity factor,  $\phi$  [%] – porosity of medium,  $m$  [-] – cementation factor,  $n$  [-] – wettability factor,  $s$  [%] – fluid saturation.

For shallow geophysical research, carried out in a small area, it is correct to assume that the examined volume of the geological medium will be characterised by a constant value of tortuosity ( $\alpha$ ) and porosity ( $\phi$ ) factors, constant values of  $m$  and  $n$  factors and the assumption that the  $s$  value for the saturation zone is constant is also correct. Given the above assumptions, the values of  $\sigma_{geological\_medium}$  and/or  $\rho_{geological\_medium}$ , measured with geophysical methods, will be, according to the formula (2), only functions of  $\sigma_{fluid}$ , thus functions of water mineralization.

Electrical permittivity of the geological media saturated with mineralized water with high value of electrical conductivity, is described by a complex number, in the following form (Plewa and Plewa 1992):

$$\varepsilon_{geological\_medium} = \varepsilon_{real} - i\varepsilon_{imag.} = \varepsilon_{real} - i \frac{\sigma_{geological\_medium}}{\omega\varepsilon_0} \quad (3)$$

where:  $\varepsilon_{geological\_medium}$  [F/m] – electrical permittivity of medium,  $\varepsilon_0 = 8.85 \cdot 10^{-12}$  [F/m] – electrical permittivity of vacuum,  $i$  – imaginary unit,  $\omega$  [rad/s] – angular frequency.

For the range of frequencies used in engineering geophysical methods, it is correct to assume that  $\varepsilon_{geological\_medium}$  is not a function of frequency  $\omega$ . As it results from the relationship (3) also the value of the complex electrical permittivity of the geological medium should depend on the variations in electrical conductivity, thus depend on the amount and the mineralization of groundwater.

This short theoretical description, presented above, shows that the amount of water and, above all, the change in mineralization of groundwater will influence the change of electrical properties of the geological medium. Therefore, methods which base on the variation of mentioned properties ( $\varepsilon_{geological\_medium}$ ,  $\sigma_{geological\_medium}$ ,  $\rho_{geological\_medium}$ ), where chosen for the geophysical research, i.e. electrical imaging technique and georadar method. Among various measurement techniques using in georadar method, constant-offset reflection profiling was chosen for the research. This technique uses reflected waves, and the reflection coefficient  $R$  [-] on surface dividing clear medium (aeration zone) and medium with changeable mineralization (saturation zone) is described as follow (Annan 2001):

$$R = \frac{Z_{aeration} - Z_{saturation}}{Z_{aeration} + Z_{saturation}} \quad \text{where} \quad Z = \sqrt{\frac{i\omega\mu_{geological\_medium}}{\sigma_{geological\_medium} + i\omega\varepsilon_{geological\_medium}}} \quad (4)$$

where:  $Z$  [ $\Omega$ ] – impedance of medium,  $\mu$  [H/m] - magnetic permittivity of medium.

For georadar measurements it is correct to make the following assumptions for the relationship (4): magnetic permittivity  $\mu$  has a constant value equal to the value for the vacuum, i.e.  $\mu_0 = 4\pi \cdot 10^{-7}$  [H/m] and impedance  $Z$  is not a function of frequency  $\omega$ . Given these assumptions, impedance  $Z$  will be a function of  $\varepsilon_{geological\_medium}$  and  $\sigma_{geological\_medium}$ , so as it results from the formulae (2 and 3),  $R$  will depend on the amount and mineralization of groundwater.

## HYDROGEOLOGICAL CONDITIONS

The above-ground mine waste dump, where the researches were conducted, has an area of 140 hectares and pollutions are stored on cone dumps (up to 350 m above sea level), settling ponds and spoil banks. The waste was supplied to the dump for a few dozens of years, till the year 2000.

The waste was stored without appropriate precautions. As a result water from precipitation infiltrated into the stored waste material and then to the ground. The penetration of water through the waste caused lixiviation of ions (mainly  $\text{Cl}^-$  i  $\text{SO}_4^{2-}$ ), which had a strong impact on the physicochemical composition of groundwater. The water which infiltrates into the ground in the area of the dump drain off into the nearby streams.

Moreover, since 2003, in the selected area of the dump, coal has been reexploited from the waste, which results in further contamination of the groundwater.

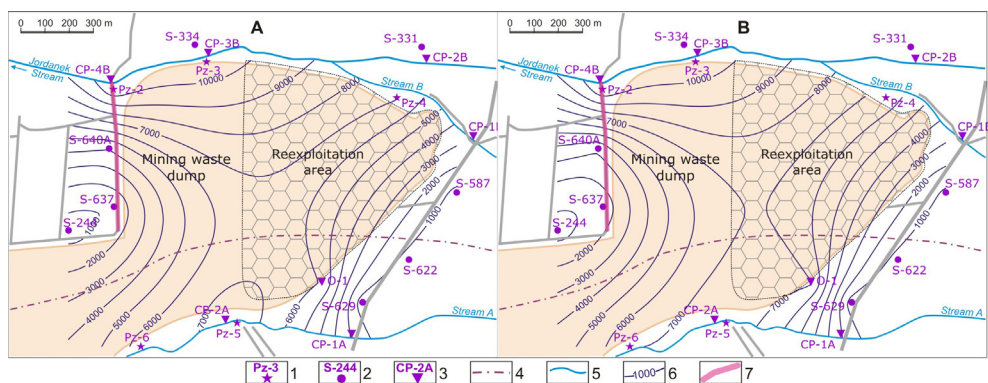
The geological medium in the surrounding of the dump is built of Quaternary and carboniferous formations. Carboniferous formations contain mudstone series and Upper Silesia sandstone series. Triassic formations (marls, sands and mudstones) occur locally, directly on carboniferous rocks. Neogen formations contain mainly loams and mudstones, locally with interbeddings of sands and sandstones. The Quaternary Period is represented by tills, dusts, peats, sands and gravels (Strzetelska-Smakowska, Hojka 2008).

In the region of the dump, within the Quaternary groundwater level, two aquifers, divided by poorly permeable clays, may be distinguished. The upper aquifer, fed by infiltration of water from precipitation, is built of river sands and glacier sands ( $k = 2.31 \cdot 10^{-7} \div 1.83 \cdot 10^{-4}$  m/s). The groundwater table of this aquifer is located at the depths from 0.35 m to 8.2 m and its position undergoes significant seasonal changes (about 1 m on average). The flow of groundwater towards of streams valleys is observed. In the southern part of the dump a watershed occur. Alim-entation of carboniferous formations occurs in the areas of outcrops and through the water-bearing Quaternary deposits. The main alim-entation region comprises the area of the dump.

The quality of ground and surface water in the area of the dump is evaluated on the basis of local monitoring grid, which allows to observe the influence of the dump and reexploitation of the waste to the physicochemical composition of water. The monitoring system consists of 20 measurement points, i.e.: 5 piezometers and 8 household wells for examination of groundwater quality and 6 points in the streams and 1 in the drainage ditch for examination of surface water quality.

Unstable indicators, i.e. electrolytic conductivity and pH, are measured directly in the terrain. In the same time samples of water are collected and later submitted for detailed laboratory analysis (ICP-MS) to determine the macro-components (among others:  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ ,  $\text{Fe}^{+2}$ ,  $\text{Mn}^{+2}$ ,  $\text{Zn}^{+2}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^{2-}$ ).

Electrical conductivity of the geological medium is the most important physical value which can be examined by the proposed geophysical methods in the area of the dump. Therefore electrolytic conductivity of mineralized water, measured with hydrogeological methods was chosen for the correlation with the results of geophysical surveys. Spatial distributions of electrolytic conductivity of groundwater obtained in June 2009 (Fig. 1A) and in September 2009 (Fig. 1B) should be treated as a point of reference for the geophysical measurements carried out in July 2009.



**Figure 1.** Spatial distribution of electrolytic conductivity of groundwater in the area of the dump: in June 2009 (A) and in September 2009 (B). Explanations: 1, 2, 3 — hydrogeological monitoring points: 1 — piezometers, 2 — household wells, 3 — surface watercourse; 4 — approximate course of the watershed, 5 — watercourses, 6 — conductivity isolines, 7 — profile for georadar and electrical imaging measurements.

## GEOPHYSICAL MEASUREMENTS

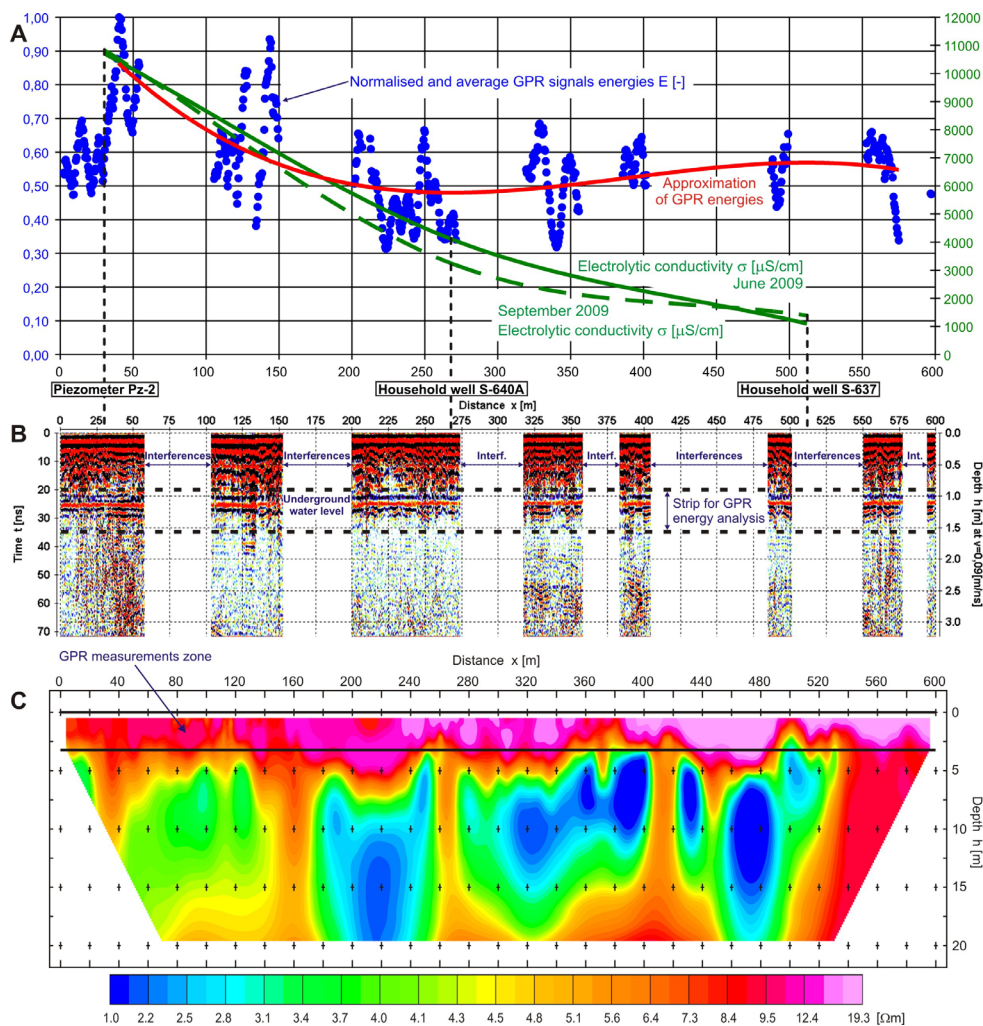
The area of the dump, where a strong changeability of mineralization of groundwater was observed, was chosen for the geophysical research (Fig. 1). The measurements were carried out in July 2009 along one profile (Fig. 1) designed by the boreholes: Pz-2, S-640A and S-637. The geophysical research was conducted in two stages.

In the first stage, an examination of the near-surface zone in the area of the first water table was carried out (Fig. 2B). The measurements were conducted with georadar (GPR) method with the use of 500 MHz antenna, with the mean resolution of about 0.05 m and maximum depth penetration in grounds of about 5 m. The measurements, with the use of ProEx georadar, were carried out in the standard of reflection profiling and traces were recorded along the profile every 0.025 m. Digital processing of the radargrams and their visualisation were made with ReflexW computer program.

As it was discussed in the introduction, mineralization of groundwater influences the value of the reflection coefficient of the electromagnetic (georadar) wave. Therefore the level of water mineralization was examined by the analysis of reflection coefficients distribution. From the radargrams a time window around the first water table was cut out, i.e. from 20 ns to 35 ns (Fig. 2B). The envelopes (energies) for such a window were calculated on the basis of Hilbert transformation (Annan 2001). Then the values of envelopes were averaged vertically and horizontally to calculate the trend of the energy change (Fig. 2A – blue dots). In the last stage, the curve (3<sup>rd</sup> degree polynomial) was calculated to approximate the distribution of mean energies along the whole profile (Fig. 2A – red line). In order to correlate the results of geophysical and hydrogeological research, in Fig. 2A the results of measurements of electrolytic conductivity were shown (Fig. 2A – green lines).

In the surrounding of the piezometer Pz-2, where mineralization of groundwater is high, the high energies of the reflected GPR signals are observed. When we move away from the piezometer Pz-2, the energies of the GPR signals decrease rapidly. The character of the energy change (Fig. 2A – red curve) is similar to the curves representing the change in the values of electrolytic

conductivity (Fig. 2A – green curves). Beyond the borehole S-640 low-amplitude fluctuation of the GPR energies is observed.



**Figure 2.** Results of the geophysical measurements: A) distribution of the georadar signals energies along the profile (July 2009) and the change of electrolytic conductivity of groundwater obtained from the hydro-geological measurements (June and September 2009); B) Radargram after processing – white vertical strips are removed zones with high interferences; C) Distribution of electrical resistivity along the profile (July 2009).

In the second stage, the measurements to the depth of about 20 m were carried out, in order to determine the distribution of deeper located, contaminated zones of the ground. On this stage, the surveys with electrical imaging were conducted with the use of multi-electrodes Lund Imaging device.

Electrical measurements were carried out with the following assumptions: constant distance between electrodes equal to 2.5 m, Schlumberger S measurement scheme, standard deviation 1 %, currents min. 50 mA and max. 200 mA. For the interpretation of the results, Res2Dinv software was used and Oasis Montaj program was used for graphical presentation of the resistivity cross-section (Fig. 2C). The cross-section in Fig. 2C is characterised by very low values of resistivity, varying from 1  $\Omega$ m to 20  $\Omega$ m.

The results of electrical imaging surveys show that in the examined area the geological stratification is strongly disrupted. Very low resistivity may indicate the presence of loam and sand-loam deposits highly saturated with water. One of the crucial factor which determines such low resistivity is undoubtedly, in the region under investigation, high mineralization of groundwater.

Resistivity in the shallow zone of the ground (to the depth of about 5 m), tends to increase in the direction towards the end of the profile, which confirms the changes which were observed for hydrogeological analysis and for the results of georadar measurements.

## CONCLUSIONS

Laboratory examination of water samples, collected from the monitoring points, allow to determine, in a detailed way, physicochemical properties of water in selected places. Spatial distribution of physicochemical properties obtained on the basis of laboratory analysis has, however, certain limitations. First of all such analysis provide only information from the sampling points. These points are usually several dozens or even several hundreds of meters away one from another. Therefore spatial distribution of physicochemical properties of water is uncertain, because is the consequence of localisation of monitoring points, the density of points distribution and the depth from which the samples are collected. A solution is to complement the hydrogeological measurements with geophysical surveys, which allow the continuous examination of the geological medium, e.g. allow the continuous visualisation of changes of groundwater mineralization, between the monitoring points.

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## REFERENCES

- Annan A.P., 2001: *Ground Penetrating Radar, Workshop Notes*. Sensors & Software Inc., Canada.
- Golebiowski T., Tomecka-Suchon S., Marcak H., Zogala B., 2010: *Aiding of the GPR Method by Other Measurement Techniques for Liquid Contamination Detection*. Proceeding of XIII International Conference: GPR'2010, Lecce, Italy.
- Marcak H., Tomecka-Suchon S., 2009: *The GPR Measurements for Assessment a Mineralization of Soil Water*. AGH Geology, vol. 21, iss. 2/1, AGH Edition, Cracow, Poland, (in Polish).
- Marcak H., Golebiowski T. (Ed.), 2006: *Detection of Hydrocarbon Contamination in the Groud Using Geophysical and Atmogeochemical Methods*. AGH Edition, Cracow, Poland, (in Polish).



Strzetelska-Smakowska B., Hojka M., 2008: *New Coal Deposits in Upper Silesian Coal Basin and Concept of its Using*. Mineral Resources Management, vol. 24, iss. 2/2, IGSMiE PAN Edition, Cracow, Poland, (in Polish).

Plewa M., Plewa S., 1992: *Petrophysics*. Geological Editions, Warsaw, Poland, (in Polish).

Twardowska I., Szczepanska J., Witczak S., 1988: *Influence of Coal Mine Waste on Water Environment. Evaluation of Risk, Forecasting and Prevention*. PAN Edition, Wroclaw, Poland, (in Polish).

Wzientek K., Zogala B., Zuberek W.M., Dubiel R., Rusin-Zogala M., 2005: *The Resistivity Imaging Survey of the Chemical Waste Dumping Site*. Proceedings of the 11<sup>th</sup> Meeting of Environmental and Engineering Geophysics, Palermo, Italy.



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