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ROLE OF GEOPHYSICAL SURVEYS IN THE IDENTIFICATION OF WATER ESCAPE ZONES FROM RETENTION LAKES: A CASE STUDY ON A SELECTED OBJECT IN UPPER SILESIA

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Abstract

The main scientific goal of this work is the presentation of the role of selected geophysical methods (Ground-Penetrating Radar GPR and Electrical Resistivity Tomography ERT) to identify water escape zones from retention reservoirs. The paper proposes a methodology of geophysical investigations for the identification of water escape zones from a retention fresh water lake (low mineralised water). The study was performed in a lake reservoir in Upper Silesia. Since a number of years the administrators of the lake have observed a decreasing water level, a phenomenon that is not related to the exploitation of the object. The analysed retention lake has a maximal depth between 6 and 10 m, depending on the season. It is located on Triassic carbonate rocks of the Muschelkalk facies. Geophysical surveys included measurements on the water surface using ground penetration radar (GPR) and electrical resistivity tomography (ERT) methods. The measurements were performed from watercrafts made of non-metal materials. The prospection reached a depth of about 1 to 5 m below the reservoir bottom. Due to large difficulties of conducting investigations in the lake, a fragment with an area of about 5,300 m^2, where service activities and sealing works were already commenced, was selected for the geophysical survey. The scope of this work was: (1) field geophysical research (Ground-Penetrating Radar GPR and Electrical Resistivity Tomography ERT with geodesic service), (2) processing of the obtained geophysical research results, (3) modelling of GPR and ERT anomalies on a fractured water reservoir bottom, and (4) interpretation of the obtained results based on the modelled geophysical anomalies. The geophysical surveys allowed for distinguishing a zone with anomalous physical parameters in the area of the analysed part of the retention lake. ERT surveys have shown that the water escape zone from the reservoir was characterised by significantly decreased electrical resistivities. Diffraction hyperboles and a zone of wave attenuation were observed on the GPR images in the lake bottom within the water escape zone indicating cracks in the bottom of the water reservoir. The proposed methodology of geophysical surveys seems effective in solving untypical issues such as measurements on the water surface.

Key words: Ground penetrating radar (GPR) method, electrical resistivity tomography (ERT) method, retention lake, water reservoir

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INTRODUCTION

Geophysical surveys are rarely performed on water reservoirs. There are only a few reports on the issues related to hydrotechnics, sedimentology, geochemistry, and Quaternary geology of the bottoms of water reservoirs, which have applied geophysical methods.

An interesting report which describes the ground penetration radar method used in the study of shallow water reservoirs is by Karczewski and Ziętek (2009). Similar GPR surveys were used by Mieszkowski *et al.* (2017) to map the elevations in the top surface of Miocene–Pliocene clays under the Vistula River bed in the vicinity of Warsaw. Baumgart-Kotarba *et al.* (2003) and Charlet *et al.* (2005) have shown the application of the seismic method in the studies of lake bottom sediments. Chich-Hou Yang *et al.*

(2002) used the ERT method in the studies of lake bottom structures. Filina *et al.* (2006) applied aero-gravimetry to recognise the distribution of gravitation above selected lakes in Antarctica. The ERT method was used to identify privileged zones of water infiltration from the Mirror Lake (USA) by Toran *et al.* (2015). Amiri *et al.* (2016) presented the role of vertical electrical sounding (VES) in solving the problem of decreasing water level in the Urmia Lake in Iran.

A separate branch, with which geophysical surveys, particularly seismic methods, are linked is the monitoring of hydrotechnical objects: their stability of the reservoir slopes (Bestyński and Trojan, 1975) and technical conditions of concrete and earth dams (Bestyński *et al.*, 2015, Bugajski *et al.*, 1994, Ślusarczyk, 1992, 2001).

The role of geophysical surveys strictly for the identification of water escape zones from retention lakes was presented by Szymanko and Stenzel (1973). They performed measurements along profiles located on the water surface of water reservoirs using the self-potential method at variable potential electrode spacing. The effects included graphs with DV voltage distribution. According to Stenzel and Szymanko (1973), negative DV anomalies indicated the presence of water escape zones in the reservoir bottoms. A low resolution was the limitation of this method.

The authors of this report aim at developing the studies of Stenzel and Szymanko (1973) to expand the range of geophysical methods which may facilitate in locating water escape zones from retention lakes. A retention lake with noted water escape into the rock massif, located in southern Poland (Upper Silesia), was selected for the survey. The reservoir is characterised by variable depth reaching 10 m. The studies were performed on the water surface using two methods: ground penetration radar (GPR) and electrical resistivity tomography (ERT). A fragment with a surface area of about 5,300 m^2 was selected for the surveys. The complete surface area of the lake is about 7 ha (Fig. 1).

GEOLOGICAL SETTING

The analysed retention lake is located on Middle Triassic rocks, which in this area are developed as carbonates and include: the Gogolin Beds, Gorażdże Beds, Ore-bearing dolomites, Diplopora dolomites, Boruszów Beds, Wilkowiec Beds, and Tarnowiec Beds, which terminate the Muschelkalk succession. Triassic limestones are economically viable as an important material used e.g. in road construction. The Gogolin Beds are developed as wavy, plate, conglomeratic and cellular limestones (Kotlicki, 1967) and compose the direct basement of the retention lake. The presence of economically significant zinc and lead ore concentrations is linked with the ore-bearing dolomites (Gruszczyk and Paulo, 1976). Overlapping of various processes shaping the pore space in the geological history, such as compaction, recrystallization and cementation of the initial sediment, dolomitization of limestones, breakup of the massif, sulphide mineralization, and karst processes, led to the creation of voids of different size and with variable connections (Wilk *et al.*, 1985). Strong saturation of the Triassic carbonate rocks with water indicates the presence of karst phenomena. Karst occurrences are rare on the surface, but observations of mining excavations and borehole analysis indicate the occurrence of a system of caverns, karst channels and other karst forms. Due to the occurrence of carbonate rocks directly below the Quaternary deposits, they are prone to the leaching activities of meteoric water infiltrating into the rock massif.

METHODOLOGY OF STUDIES

The choice of appropriate geophysical methods depended on the depth of the retention lake, the required resolution of prospection measurements and depth of prospection. In the selected part of the reservoir, its depth was about 3 m. In this case the selected methods included GPR and ERT.

The theory of the GPR method

Nowadays, the ground penetrating radar (GPR) is a commonly accepted geophysical technique. The method uses radio waves to probe the “ground” which means any low loss dielectric material. GPR is an active method that transmits electromagnetic pulses from surface antennas into the ground, and then measures the time elapsed between when the pulses are sent and when they are received back at the surface (Conyers and Goodmen, 1997). GPR trace times are measured in nanoseconds. As the antennas are moved along the ground surface, individual reflections are recorded about every 2–10 cm along the transects, using a variety of collection techniques (Neal, 2004). The form of the individual reflected waves that are received from within the ground is then digitized into a reflection trace, which is a series of waves reflected back to one surface location. When many traces are stacked next to each other sequentially, a two-dimensional vertical profile is produced along a transect, over which the antenna was moved (Figs. 5, 6). Reflected radar waves that are processed into two-dimensional profiles are recorded in the time elapsed from their transmission to their reception back at the surface. This time may be converted to an approximate distance in the ground, giving each of the reflections precise depth information that is not available from other near-surface geophysical methods. The amplitudes of the reflected waves are particularly important because their variations are directly related to the changes in the physical and chemical properties of different materials in the ground (Conyers, 2013).

In its earliest inception, GPR was primarily applied to natural geologic materials. Now GPR is equally well applied to a host of other media such as wood, water, concrete, and asphalt. The most common form of GPR measurements deploys a transmitter and a receiver in a fixed geometry, which are moved over the surface to detect reflections from subsurface features. The ground penetration radar method was widely discussed by Jol (2009) and Karczewski *et al.* (2012, 2017).

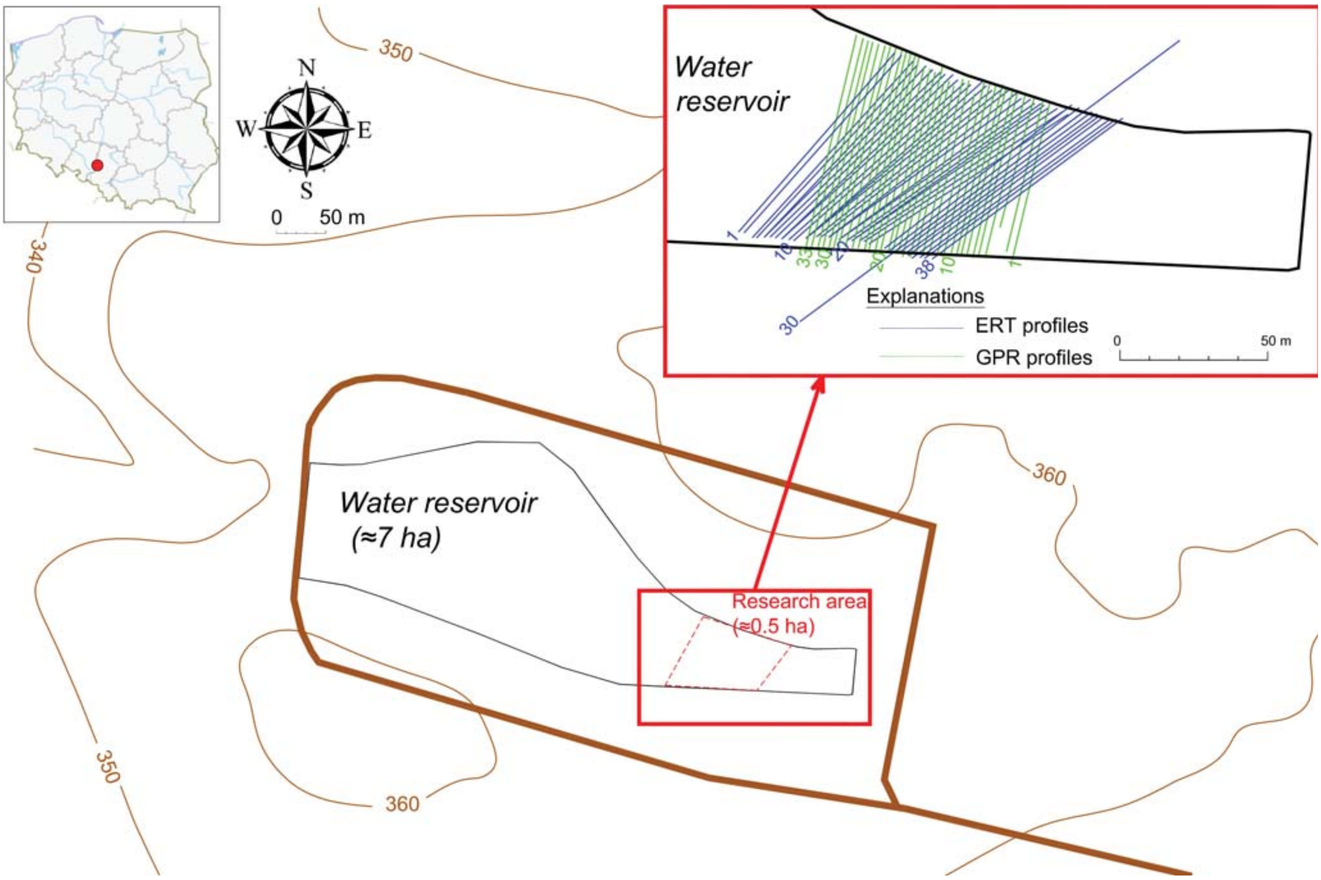

Fig. 1. Location of the study area.

Methodology of GPR research

The MALÅ GroundExplorer (GX) with a screened 160 MHz antenna was used in the surveys. The measurements were performed from a dinghy. The depth range of the surveys (in the existing electrical conditions of the basement rocks) reached to about 1 m below the lake bottom. The measurements were made in parallel profiles with a spacing of 2 m located between the reservoir margins (Fig. 1). A total of 34 profiles was made with lengths from 45 to 74 m. Each GPR profile in the field was positioned using a GNSS-RTK device, configured in coordinate system 2000 in reference to the ASG EUPOS reference correction network. Selected measurement settings are presented in Table 1.

Table 1. Parameters of GPR surveys with a 160 MHz antenna

Distance of GPR profile	60÷73 m
Trace number on GPR profile	3000÷4000
The time emission	Every 0.05 sec.
Distance between traces (m)	≈ 2 cm
Average antenna velocity	≈1.5 km/h
Time window (ns)	400 ns
Number of samples	924

The echogram reflecting the internal structure of the medium was elaborated using RadExplorer software with the application of the following filters:

- Move starttime – correction of the first start time;
- DC-shift – removal of the constant component of the georadar signal
- Background Removal – removal of random noise
- Deconvolution – removal of the influence of the attenuation of the electromagnetic wave and noise resulting from medium impurity
- Frequency filtration – removal of noise and gain of signal of the selected wave frequency
- AGC gain.

Theory of the ERT method

The vertical electrical sounding (VES) method for soil surveying was developed by the Schlumberger brothers in 1920 (Loke, 2000).

Measurement of electrical resistivity usually requires four electrodes: two electrodes called A and B that are used to inject the current ("current electrodes"), and two other electrodes called M and N that are used to record the resulting potential difference ("potential electrodes")

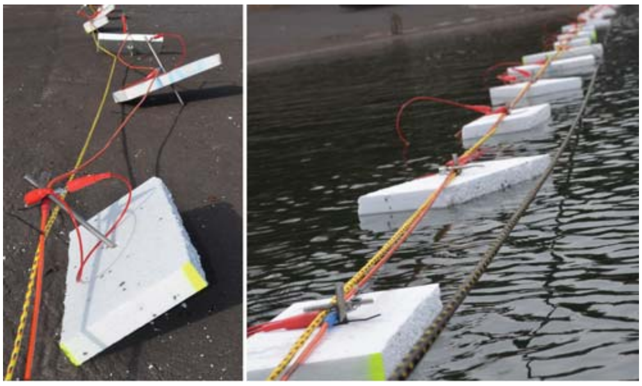

Fig. 2. Technics of ERT measurements on the water surface.

(Samouelian *et al.*, 2005). The current electrodes A and B, and the potential electrodes M and N can be placed in the field at the soil surface. The electrical resistivity (ρ) is calculated using the following equation:

$$\rho = K \cdot \frac{\Delta V}{I}$$

where:

K – geometrical coefficient that depends on the arrangement of the four electrodes A, B, M and N,

ΔV – potential difference [mV]

I – current [mA]

One-dimensional arrays using four-electrode cells A, B, M, N are commonly used in the field for vertical electrical sounding (VES). The latter consists of electrical measurements, during which the distances between the electrodes are successively increased. At each step, the depth and volume of the soil investigated increase and the measurement displays the variation of soil resistivity with depth without taking into account the horizontal variation (Loke, 2013). For VES data interpretation, it is usually assumed that the subsurface consists of several horizontal layers.

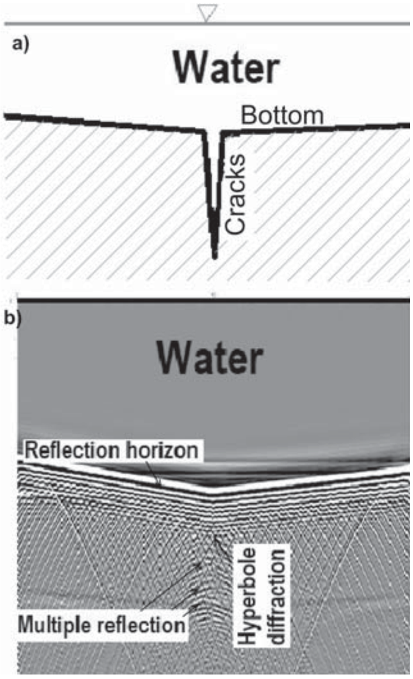

Fig. 3. GPR modeling (ReflexW software): a) diagram of soil and water conditions; b) modeled echogram.

The ERT method is an extension of the VES method. In the ERT method, two-dimensional multi-electrode arrays provide a two-dimensional vertical picture of the sounding medium (Samouelian *et al.*, 2005). The current and poten-

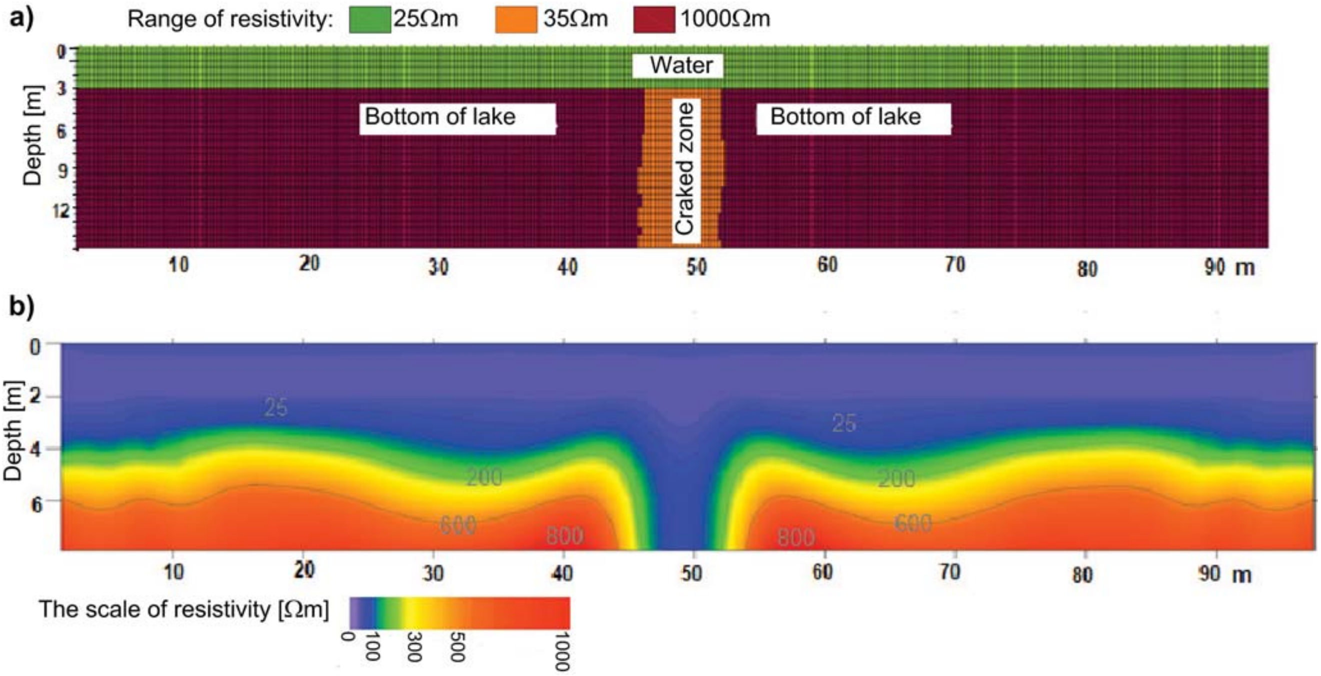

Fig. 4. Resistivity modelling: a) The resistivity model; b) The model of resistivity distribution in ERT research (Res2DMod software).

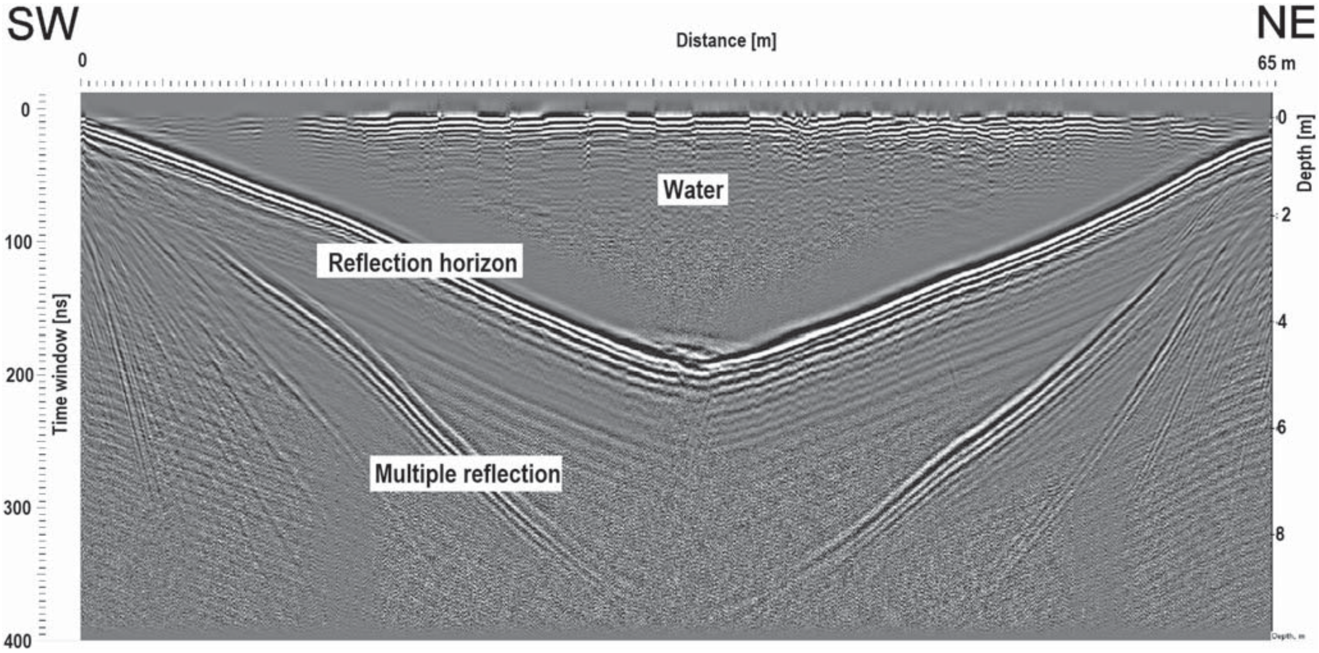

Fig. 5. Echogram without diffraction hyperboles in the lake bottom.

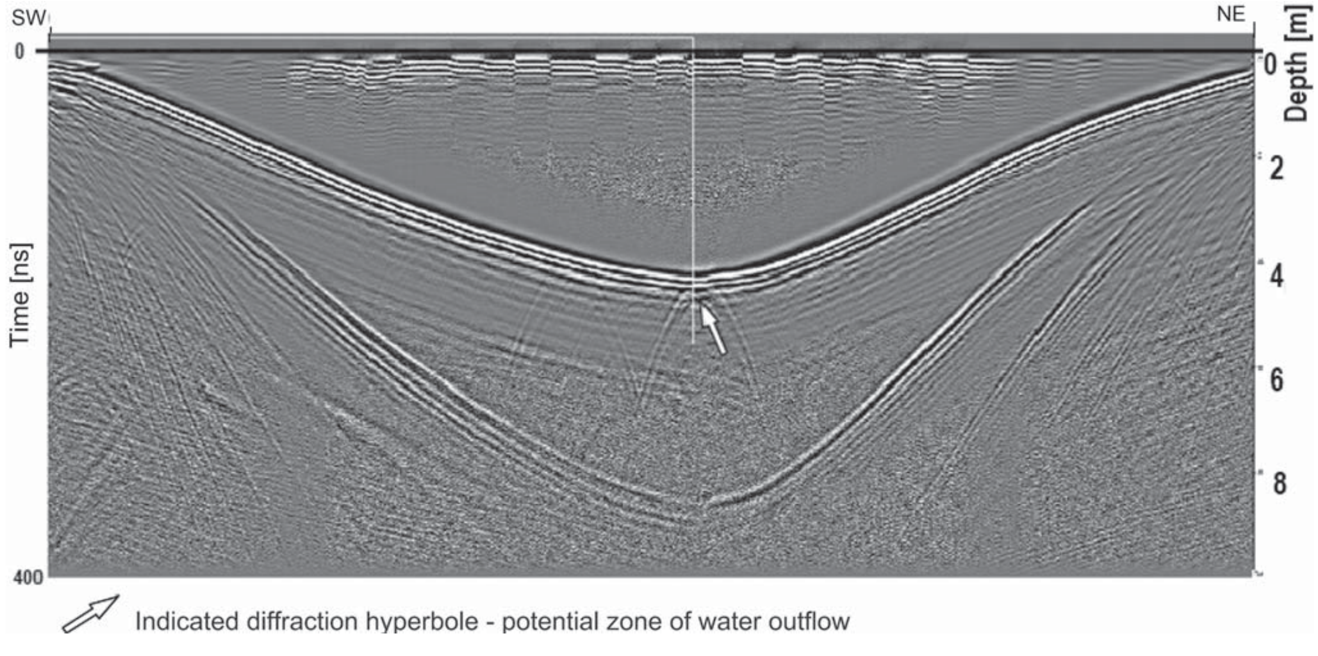

Fig. 6. Echogram with diffraction hyperboles in the lake bottom.

tial electrodes are maintained at a regular fixed distance from each other and are progressively moved along a line on the soil surface. One measurement is recorded at each step. The set of all measurements performed at this first inter-electrode spacing gives a profile of resistivity values. The inter-electrode spacing is increased then by factor n = 2, and a second measurement line is made. This process (increasing of the n factor) is repeated until the maximum spacing between the electrodes is reached. Larger n values result in greater survey depths (Fig. 4). Because the distribution of the current also depends on the resistivity contrasts of the medium, the depth of the investigation deduced from the spacing is referred to as the "pseudo-depth". The data are then arranged in a 2D "pseudo-section" plot that gives a simultaneous display of both horizontal and vertical resistivity variations (Edwards, 1977). During the survey made along the entire length of the electrical resistivity section in a single process controlled by the measurement equipment, all the electrodes are arranged at an even distance from each other prior to the analyses.

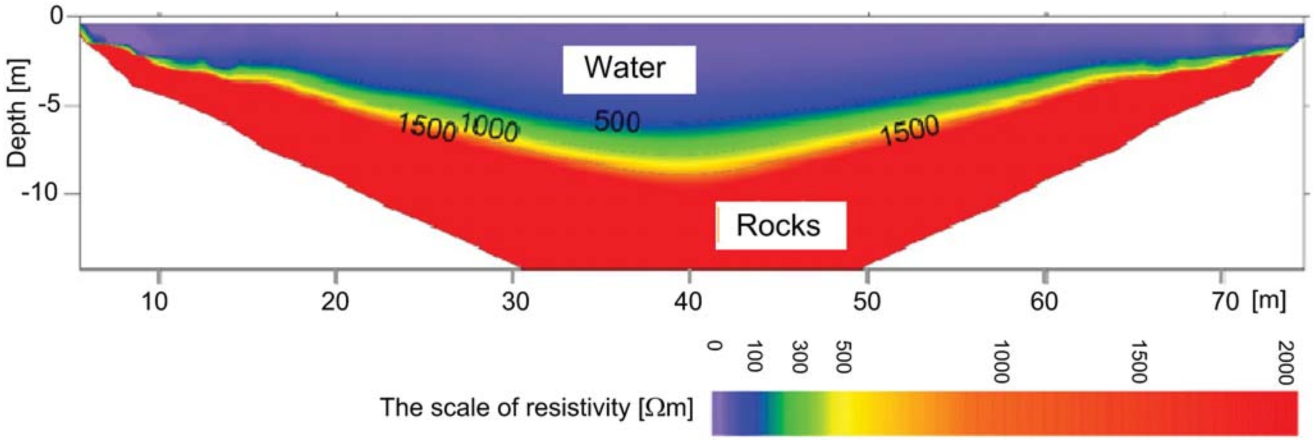

Fig. 7. ERT profile without anomalies in the lake bottom.

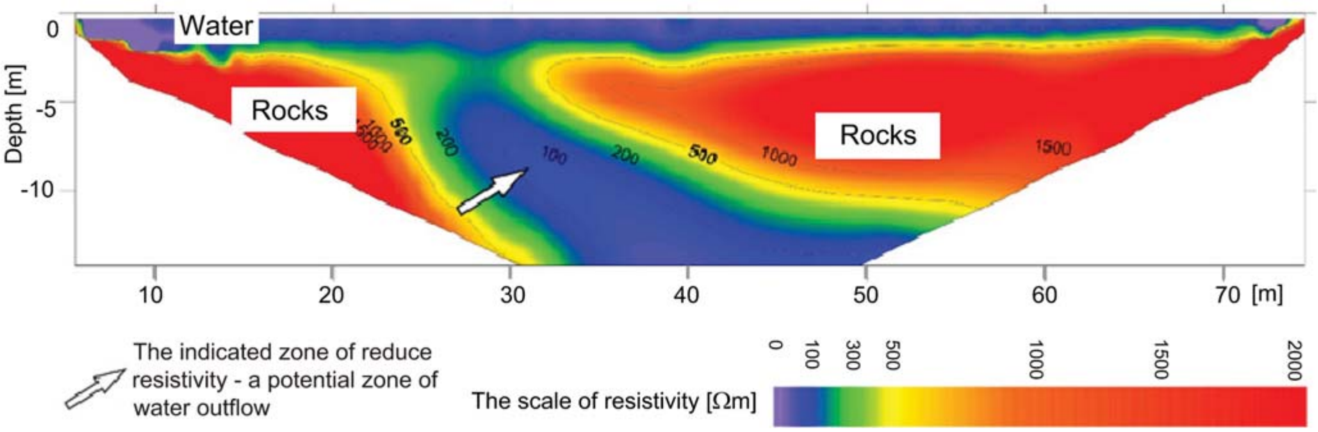

Fig. 8. ERT profile with anomalies in the lake bottom.

The more complete theoretical description of the ERT is presented by Loke (2013). In detail the method of electrical resistivity tomography (ERT) was described extensively by Loke and Barker (1996), Mościcki and Antoniuk (1998), Zhdanov and Keller (1994) and Samouelian *et al.* (2005).

Table 2. Characteristics of the ERT surveys

No. of profile	Distance between electrodes [m]	Profile length [m]	Measurement arrays	Numerical points	Number of rejected points	Prospection depth [m below surface level]	RMS[%] at 5 iterations	Remarks
1–29	2	80	GRADIENT	518	0	≈14	4–9	Profile between lake margins
30	2	120		500	18	≈25	7.3	Profile on land and water. Topographic correction included
31–38	2	80		518	0	≈14	4–9	Profile between lake margins

Methodology of ERT measurements

To assure the high resolution of the electrical resistivity distribution in the lake bottom, the electrodes were spaced at 2 m on swimming Styrofoam buoys (Fig. 2). A prospection of about 14 m was achieved. The measurements were made using the gradient array (Dahlin and Zhou, 2006). The horizontal resistivity was about 2 m, and the vertical resistivity close to the lake bottom – about 1.5 m. An 8-channel Terrameter LS, of the Swedish company ABEM, was used in the surveys. The ERT profiles were positioned with GNSS-RTK.

The obtained data were processed in Res2DInv with application of inversion in the Marquardt and Occam variant because the electrical resistivity distribution correlated with the depth values of the lake bottom (Table 2).

MODELLING OF PHYSICAL IMAGES

Models, that is theoretical images of the echogram (Fig. 3) and electrical resistivity distribution (Fig. 4), were constructed in order to process and interpret the obtained

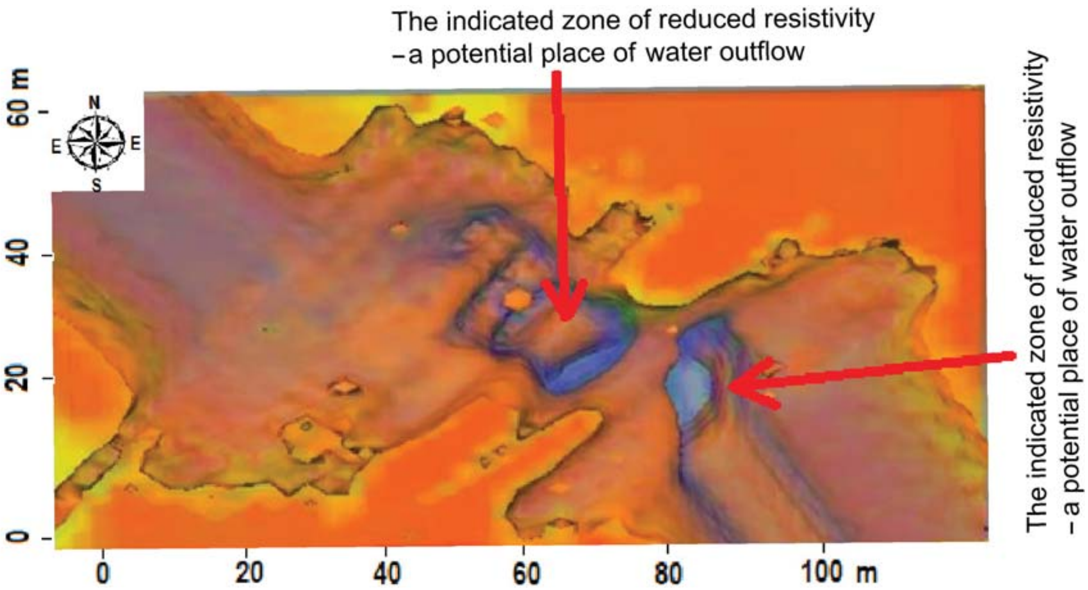

Fig. 9. Mapping of the reservoir bottom surface for the 300 Ωm contour lines.

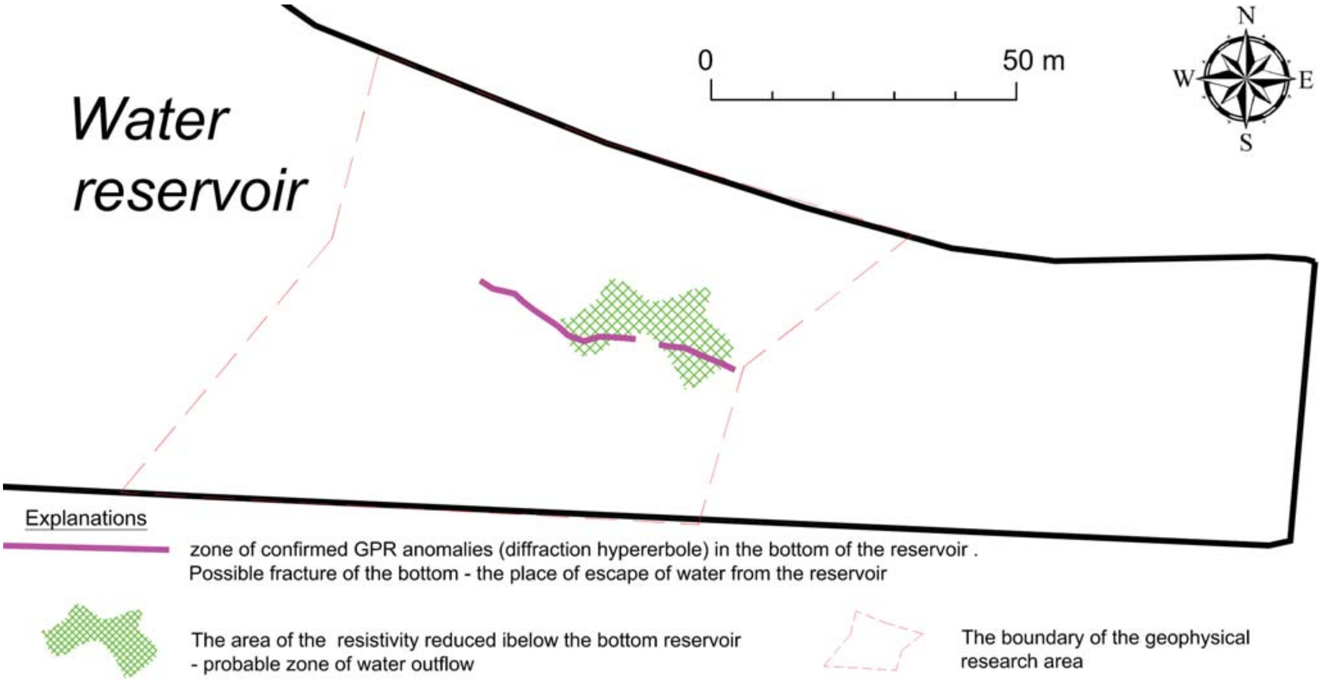

Fig. 10. Map of geophysical anomalies.

geophysical data for a situation when a crack, through which water escapes, is present in the lake bottom.

A reflection horizon from the lake bottom and its multiple reflection slightly deeper can be seen on the model echogram; a diffraction hyperbole is present in the crack bottom zone. Examples of resistivity distribution modelling are included in the articles by Kowalczyk *et al.* (2015, 2017).

A zone corresponding to water (electrical resistivity at ρ = 20÷40 Ωm) and a zone corresponding to the rock basement (limestones, dolomites with electrical resistivity at ρ = 500÷1000 Ωm) can be distinguished on the model of electrical resistivities. In turn, in the assumed water escape zone from the lake, the electrical resistivities distinctly decrease to values of several tens of Ωm.

RESULTS

The results were elaborated in order to identify anomalous places in the registered physical image, that is diffraction hyperboles on echograms and zones with lowered resistivities in ERT profiles in accordance with the model results. Comparison of *in situ* georadar echograms without and with diffraction hyperboles are presented in Figs. 5 and 6, respectively.

A similar comparison of ERT surveys is presented in Figs. 7 and 8.

The modelled resistivity ranges shown in Fig. 4a and 4b differ from the resistivity results shown in Fig. 8. The reason for these discrepancies is in the incompatibility between the ideal model of a homogeneous water-ground system and the real inhomogeneous and anisotropic water-bedrock system.

Another way of visualising electrical resistivity anomalies in the selected fragment of the lake bottom is the presentation of the variable localization of the contour lines for electrical resistivity e.g. for the value of 300 Ωm (Fig. 10). A zone of reduced resistivity values can be clearly seen in the central part of the map in Fig. 9.

Modelling of GPR anomalies in the cracked bottom of the water reservoir is characterised by the presence of a diffraction hyperbole (Fig. 3). Such anomalies have been identified on several GPR echograms (e.g. Fig. 6).

Modelling of ERT anomalies in the cracked bottom of the water reservoir is characterised as a zone of reduced electrical resistivity (Fig. 4a and b). Such anomalies have been identified on several ERT profiles (e.g. Fig. 8).

A compilation of the registered geophysical anomalies (GPR and ERT) is presented in Fig. 10. The modelling results suggest that the distinguished geophysical anomalies may initially refer to parts of the lake, in which water escape occurs. The reliability of the obtained results is confirmed by a similar localization of anomalies obtained from two independent geophysical surveys.

SUMMARY

The paper presents a study of the water reservoir bottom for the purpose of searching for a water escape zone with the application of two geophysical methods: ground penetration radar and electrical resistivity tomography. Both methods gave interesting and analogous results. The ERT method allowed to distinguish zones with reduced resistivity in the water escape zone, whereas the GPR images showed diffraction hyperboles that could be the result of cracks existing in the bottom of the retention lake. The results were also in accordance with the performed modelling. Shortly before submitting this paper, the authors were informed that a drilling was made in the proposed localization (Figs. 9 and 10). The lithological succession drilled below the reservoir bottom included an over 10 m thick interval of strongly fractured rocks with numerous caverns. It should be emphasised that the investigations were made only on a small fragment of the reservoir with a depth of about 3 to 4 m. In the case of larger depths (e.g. several tens of metres) or higher salinity of the water, the GPR method is not appropriate. In this case the application of the sub-bottom profiler (SBP) should give better results.

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