

## Review of selected geophysical methods used in the assessment of water resources for agriculture

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**Abstract.** In the recent decade Poland was repeatedly affected with severe droughts that caused significant losses in the agricultural sector. To minimize the effects of hydrological drought and rationalize the management of water for agricultural purposes, a continuous monitoring of ground water should be implemented country-wide. Such a monitoring network already exists in Poland – State Groundwater Monitoring, based upon direct measurements, however its density and temporal resolution is too coarse to effectively inform about the levels of groundwater and its availability for agriculture. The existing monitoring network can be supplemented with various remote geophysical methods, allowing wide-area estimations on groundwater availability. This publication aims at screening available geophysical methods and their suitability for assessing groundwater levels and stocks.

**Keywords:** drought, water table, groundwater levels monitoring, geophysical methods.

### INTRODUCTION

This article constitutes an overview of selected geophysical methods of monitoring groundwater level, with considerations for their suitability in assessing water availability for agriculture.

Groundwater lies beneath the Earth surface at varying depths in free spaces within the rock bed. It is a very important element of the hydrological cycle in nature. Changes in groundwater level may occur as a result of natural processes (climatic changes, e.g. droughts, downpours) and the economic activity of man (e.g. urbanization, water abstraction for agriculture and industry) (Parusel, 2004).

In the last decade an increase in the frequency of droughts in Poland has been observed. The scenarios of cli-

mate change indicate a 10-fold increase of this frequency in the area of Poland in the coming decades (Parry et al., 2007). According to NOAA and NASA, the year 2017 was the second warmest year in meteorological measurement and analysis (since 1880) in the world (NOAA, 2018; NASA, 2004).

The 2015 drought in Poland had a very negative impact on agricultural crops. In addition to large losses in agriculture, the very hot and dry summer also caused hydrological drought (IUNG-PIB, 2015). Partial shortage of water also occurred in 2016 (IUNG-PIB, 2016). In 2017, however, throughout the majority of reporting periods (9 out of 14 reports) agricultural drought was not recorded in Poland (IUNG-PIB, 2017). The year 2018 had only one reporting period which did not state the occurrence of agricultural drought in Poland (IUNG-PIB, 2018).

There are three stages of drought development (ZODR, 2003): atmospheric drought caused by lack of rainfall, high temperature and low humidity; soil drought, which is characterized by shortage of water available for plants; hydrological drought (water table lowering), which has the greatest consequences for the economy. Hydrological drought causes a reduction in the level of groundwater, which adversely affects, among others, deeply rooted trees, in addition to causing the groundwater table to sink deeper. This may lead to some water intakes completely drying out. Atmospheric and soil droughts disappear rapidly, while in the case of hydrological drought, the renewal of surface water and groundwater resources requires considerable time (ZODR, 2003).

Undoubtedly, the accurate measurement of the level of groundwater and its quantity poses a considerable problem. In Poland, Groundwater Monitoring is applied, which is one of the basic tools for assessing water status and managing water resources (Kazimierski, 2008). It is based on around 1135 quantitative monitoring points (Cabalska et al., 2015) forming an observation and research network on the territory of Poland.

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High hopes are placed in the Water Framework Directive (WFD, 2000), which sets out the principles of operation in the field of water policy. It is the result of many years of work accomplished by European countries. It imposes an obligation upon the Member States to rationally use and protect water resources according to the principle of sustainable development. According to the WFD, monitoring the resources and quality of water is an essential measure to ensure the safety of the public. According to the general principle of charging fees for the use of the environment, it should be expected that sooner or later fees will be introduced for sourcing irrigation water. As a result of limited resources and increasing frequency of drought occurrence, it seems that this direction will enforce saving water not only in industry but also in agriculture.

For the purposes of rational water management, Underground Water Monitoring can be enriched with the studies of the groundwater level using various geophysical methods.

The purpose of this article is to review selected geophysical methods based on the possibility of their use in monitoring the level of groundwater.

Geophysical methods allow for conducting research, using the laws of physics, to determine the structure and physical properties of the studied geological medium, without the need for invasive interference (e.g. drilling, excavation). Geophysical methods are divided into: seismic, ground-penetrating radar, electrical resistivity, gravimetric and electromagnetic ones.

### SEISMIC METHODS

Seismic geophysical methods are used in the non-invasive investigation of a geological medium which determines, among others, water table elevation, location and form of geological strata and underground voids.

The depth of application for geophysical methods ranges from a few meters to over a dozen kilometres (Robinson et al., 2008). Seismic methods are sensitive to the rate of propagation of various types of seismic waves (Robinson et al., 2008), which are artificially excited by means of a hammer, pile driver, blast of explosives, vibrators, etc. (Milsom, 2003). The generated seismic waves are elastic waves, which are divided into the following wave types: spatial (longitudinal P and transverse S), and surface ones (Rayleigh and Love) (Novotny, 1999).

When a seismic wave reaches the interface between strata with different lithological parameters, part of the seismic wave energy will be reflected (reflection wave) according to the law of wave reflection (Fig. 1). Some of the energy will be propagated at the interface of strata, and in accordance with the Huygens principle, the above-mentioned energy will travel back towards the surface (refraction wave) (Fig. 1), and the remaining part will go further, but

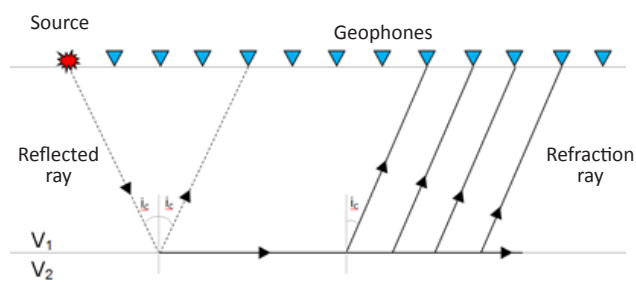


Figure 1. Seismic ray path of reflection and refraction ray (Saad et al., 2017).

at a different angle in accordance with Snellius law (Milsom, 2003).

By changing the attributes of seismic waves, among others the velocity (Table 1) caused by changes in the studied geological medium, e.g. porosity, discontinuities, density, mineral composition, filling of porous space with media (Pilecki, Kłosiński, 2005), the parameters and properties of this geological medium can be determined, and, possibly, the centre can be divided into geological strata.

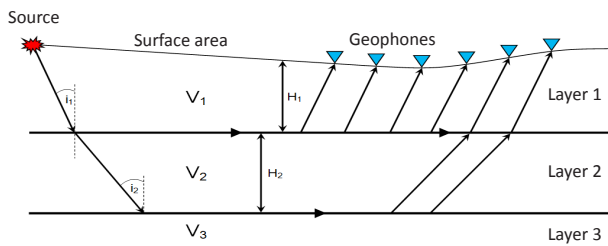
Table 1. The P-wave velocities of various earth materials (Saad et al., 2017).

Material	P-wave velocity (m/s)
Air	332
Water	1400–1500
Granite	5500–5900
Sandstone	1400–4300
Limestone	5900–6100
Sand (unsaturated)	200–1000
Sand (saturated)	800–2200
Clay	1000–2500

Receivers – geophones – are applied in order to register seismic waves excited by the source. Geophones can be spaced in various geometrical arrangements depending on the measurement method, research goal, terrain shape, depth and accuracy. The data from the measurement is processed in the seismic recorder and sent to a computer in which a hodograph is created (Milsom, 2003). Hodographs undergo relevant analysis and interpretation.

The seismic methods which are useful in studying groundwaters include the refractive and reflective methods.

The refractive method consists in creating an appropriate velocity-depth model based on the dependence of the first entry times and the different refractive velocity in the medium (Pilecki et al., 2003) (Fig. 2).



where:

- $V1$  – velocity of waves P in layer 1
- $V2$  – velocity of waves P in layer 2
- $V3$  – velocity of waves P in layer 3
- $H1$  – thickness of layer 1
- $H2$  – thickness of layer 2
- $i_1$  – critical angle for the refractive wave at the boundary of layers 1 and 2
- $i_2$  – critical angle for the refractive wave at the boundary of layers 2 and 3

Figure 2. Refractive method research (Pilecki et al., 2003).

The time of the arrival of the refractory wave generated by an artificially excited seismic source (hammer, pile driver, etc.), created at the boundary of two layers differing significantly in wave velocity, at the seismic receiver – the geophone is the time of the first ascent. Possessing data on the arrival times of refraction waves, the data on the location of the seismic receivers and the position of the artificial excitation point, the depth of the boundary between the layers can be precisely determined.

The reflective method consists in the artificial excitation of a seismic wave, which after reaching the boundary of the layers is reflected and returns to the surface, where it is registered by the receiving points (Fig. 3).

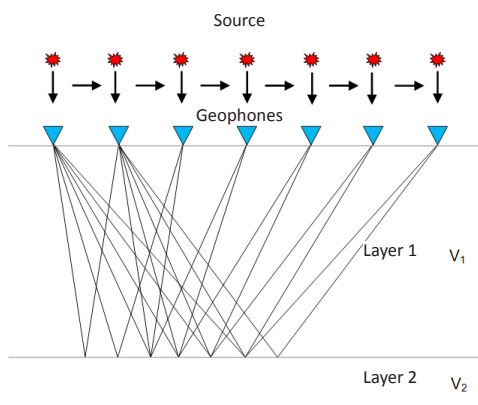


Figure 3. Reflection method research (Pilecki et al., 2003).

Excitation points and receiving points should be designed in such a way that tens of seismic wave beams pass through the point of reflection at the boundary of layers to amplify the signal that comes from a given point of reflection (Milsom, 2003).

In 2005, a publication was created describing the assessment of the condition of the substrate underlying fluvial-type system of flood banks by means of the seismic method (Pilecki, Kłosiński, 2005). The article describes the refractive method and its application to identify various types of changes in the geological structure of the geological medium and the location of the groundwater level, which may have a significant impact on the stability of the flood bank and its base (Pilecki, Kłosiński, 2005). The publication emphasizes that the result of the seismic interpretation is ambiguous, and anomalous changes in seismic parameters may result from various reasons. As an example, the reduced velocity of the refraction wave type P in a given zone was given, which may be the result of changes in lithology or the result of weakening the centre under the influence of water. For more precise interpretation, the results of a seismic survey can be compared with data obtained from test wells or with another appropriately selected seismic or geotechnical method (Pilecki, Kłosiński, 2005).

The publication from 2009 (Grelle, Guadagno, 2009) also treats about the ambiguous results of groundwater level tests using the refractive method. The article describes the results of research of geological media in three different locations, for which geological structure was known. Furthermore, during the field tests, the depth of the water table was possible to verify using piezometers installed on site. The tests measured the velocity of the longitudinal wave P (excited with a hammer) and the velocity of the transverse wave SH (excited by means of a special apparatus for generating an SH wave). Measurement of the above-mentioned velocity was used to calculate the special WSI index (Water Seismic Index):

$$WSI = \left( \frac{z\delta V_p}{V_p} \right) \cdot \left[ 1 - 3 \left( \frac{z\delta V_s}{V_s} \right) \right]$$

where:

- $V_p$  – longitudinal wave velocity P [m s<sup>-1</sup>]
- $V_s$  – transverse wave velocity S [m s<sup>-1</sup>],
- $Z$  – depth [m].

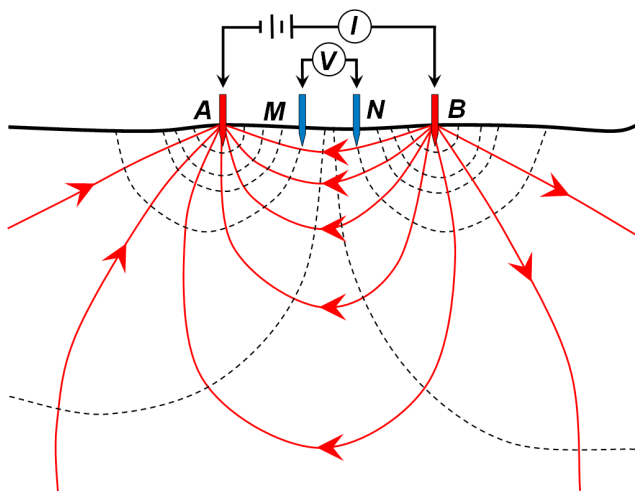
The WSI index is aimed at determining the exact depth of the water table (Grelle, Guadagno, 2009).

The test results for three different geological mediums confirmed that the WSI index gives direct information about the existence and depth of the water table. However, the above-mentioned index depends on the geological structure of the studied medium and the uneven decrease of the water level in various hydrological periods (Grelle, Guadagno, 2009). The article emphasizes that the WSI index is more sensitive to lithology and the transition between saturated and unsaturated formations than the ratio  $V_p/V_s$  (Bała, 2009) and Poisson’s ratio (Markowska-Lech et al., 2016).

## COMPARISON OF ELECTRICAL RESISTIVITY AND GROUND-PENETRATING RADAR METHODS

The electrical resistivity method belonging to the group of electrical methods investigates the variability of the electrical parameters in the medium.

The test consists in the flow of artificially created electric current of known amperage, generated in the control device through a system of electrodes A and B. The difference of potentials (voltage) which is generated in this way is measured with the potential electrodes M and N (Fig. 4). In the figure presenting a four-electrode measuring system (Fig. 4) the current flow lines are marked in red, while the equipotential lines are marked with a black dashed line (Lowrie, 2014). The system of electrodes is arranged in various configurations, depending on the nature of the measurements and the properties of the medium under study. The choice of the system depends on the type and shape of the structure under study, problem being solved, expected resistivity contrast, meter specification and the level of disturbance in the research area (Pasierb, 2012). Measuring systems differ in vertical and horizontal resolution as well as the depth range. The electrical resistivity method can be useful for locating the underground water table and aquifers.



A, B – current electrodes  
M, N – electrodes for measuring the potential difference

Figure 4. Schematic illustration of the resistivity method (Clark et al., 2011).

During the examination of the geological medium, the flowing current encounters varying resistivity, depending on the properties of the tested medium. Resistivity is a feature of a given geological formation, thanks to which it is possible to characterize it. This provides an opportunity for

determining the apparent resistivity of a given geological medium. Apparent resistivity is determined by measuring the current and voltage between the measuring electrodes:

$$\rho_a = k \frac{\Delta V_{MN}}{I_{AB}}$$

where:

$\rho_a$  – apparent resistivity [ $\Omega\text{m}$ ]

$\Delta V_{MN}$  – potential difference between measuring electrodes M and N [V]

$I_{AB}$  – the value of the current emitted into the substrate by electrodes A and B [A]

$k$  – geometric coefficient of the measurement system (distance between electrodes) [m] (Lech et al., 2016).

Electrical resistivity studies are aimed at measuring resistivity and obtaining a spatial distribution of resistivity along with the depth that will be needed for further interpretation and analysis (Zawadzki, 2015).

Electrical resistivity research is divided into one-dimensional (1D) and two-dimensional (2D) methods.

One-dimensional methods (1D) are divided into vertical electrical sounding (VES) and electrical profiling (EP). With the use of vertical electrical resistivity sounding (VES), for the point located in the centre of the measurement system, changes in apparent resistivity can be measured at different depths increasing the distance between the current electrodes.

For electrical resistivity profiling (EP) measurements of apparent resistances are taken at a predetermined depth along the profile line with a defined sampling step, in series while maintaining constant distances between the electrodes (Pasierb, 2012).

Two-dimensional (2D) methods include primarily electrical resistivity tomography (ERT). It is a combination of electrical resistivity profiling (EP), due to measurements conducted along the profile and vertical electrical resistivity sounding (VES), due to the increasing depth range during the tests. Electrical resistivity tomography is based on performing over a dozen classical profiling with systems having different depth ranges and several dozens of soundings with different lengths of the power line (Rudzki, 2002).

The electrical resistivity tomography (ERT) method is characterised by a wide range of applicability in comparison to classical electrical resistivity methods. It can be used, among others to explore the geological structure, determine the depth and thickness of the layers. In hydrogeological studies the above-mentioned method can be used, among others to determine the direction of groundwater runoff and deposition and characterize sub-surface hydrogeological conditions (Pasierb, 2012).

The ground-penetrating radar method uses the phenomenon of an electromagnetic wave, which is generated by the ground-penetrating radar transmission antenna and sent

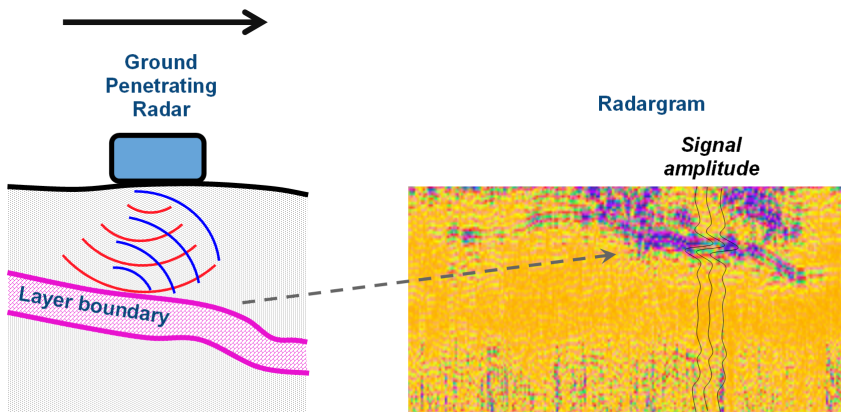


Figure 5. The georadar operation scheme (Badora D.).

into the studied rock or ground medium. A wave of specific frequency propagates in the medium and undergoes refraction, reflection at the boundaries between layers or damping. The receiving antennas register the reflected waves. The transmitting and receiving antennas are connected to the central unit (Fig. 5). The measurement consists in moving the ground-penetrating radar along a selected profile line. The result of such measurement is a radargram. A radargram is a registered wave image which depicts the internal structure of the medium (Karczewski et al., 2011).

The range of the GPR method and resolution are dependent on the frequency range of the antennas. Currently, antennas with frequencies ranging from 10 MHz to 2 GHz, of various designs (shielded and unshielded antennas) are used for ground-penetrating radars. The depth range of the ground-penetrating radar method, depending on the antenna used, is from a few centimetres to several tens of meters, which stems from high attenuation of the electromagnetic wave, as well as from the low power of the transmitting antenna. An antenna with a frequency of 400 MHz registers useful information from a depth of up to approximately 8 m, depending on the measurement conditions. By contrast, a 1 GHz antenna reaches to a depth of about 1 m, but with a very good centimetre resolution. The ground-penetrating radar achieves the deepest depth ranges on glaciers and salt beds (up to several hundred meters). However, in clayey formations and soils, the range may be negligible (Karczewski et al., 2011).

Vertical accuracy, or resolution, varies from a few millimetres to several metres. The relation of resolution and depth range is inversely proportional. This means that when the frequency of the generated wave increases, the resolution increases, while the depth range decreases (Karczewski et al., 2011).

In 2013, a publication was developed which compared the application of the GPR method and electrical resistivity tomography (ERT) to the observation of the position of the free water table in the first aquifer (Gańko et al., 2013).

On the research site an observation piezometer was built, enabling remote monitoring of water fluctuations in the first aquifer for the above-mentioned research periods. The article describes two models of the underground water table status: 1.9 m b.t.s. (meters below terrain surface) (research was carried out in August 2011) and 3.9 m b.t.s. (research was carried out in October 2012). Observations from an observational piezometer with a well-known lithology and hydrogeological conditions were used to verify the effectiveness of the studies using the

methods of ground-penetrating radar and electrical resistivity (Gańko et al., 2013).

The comparison of geophysical methods presented in the publication leads to the conclusion that the free underground water table level at the depth of 1.9 m b.t.s. was clearly marked on geophysical profiles for the ground-penetrating radar and electrical resistivity method. The water table at the depth of 3.9 m b.t.s. was marked with less clarity on the geophysical profiles. In the second measurement, there was an increased attenuation of electromagnetic waves for the GPR method and there was no clear contrast between the zone of aeration and saturation. This was due to the partial saturation of soil pores in the zone of the dynamic fluctuations in water level. Below the water table, electromagnetic waves are suppressed. This prevents the identification of deeper geological layers. The electrical resistivity tomography enables deeper recognition of geological layers below the water table (Gańko et al., 2013).

#### AEM METHOD AND EM METHOD

The electromagnetic method (EM) is another geophysical method for groundwater exploration. It consists in exciting a primary electromagnetic field by a transmitter. This field generates a secondary electromagnetic field in the medium. The receiver coil registers the size of the secondary field and the ratio between the primary and secondary fields. The secondary electromagnetic field is proportional to the conductivity of the medium and varies depending on the lithological properties, the density of the medium, the presence of impurities or groundwater (Milsom, 2003)

The electromagnetic method can also be used in the search for groundwater, which usually contains large

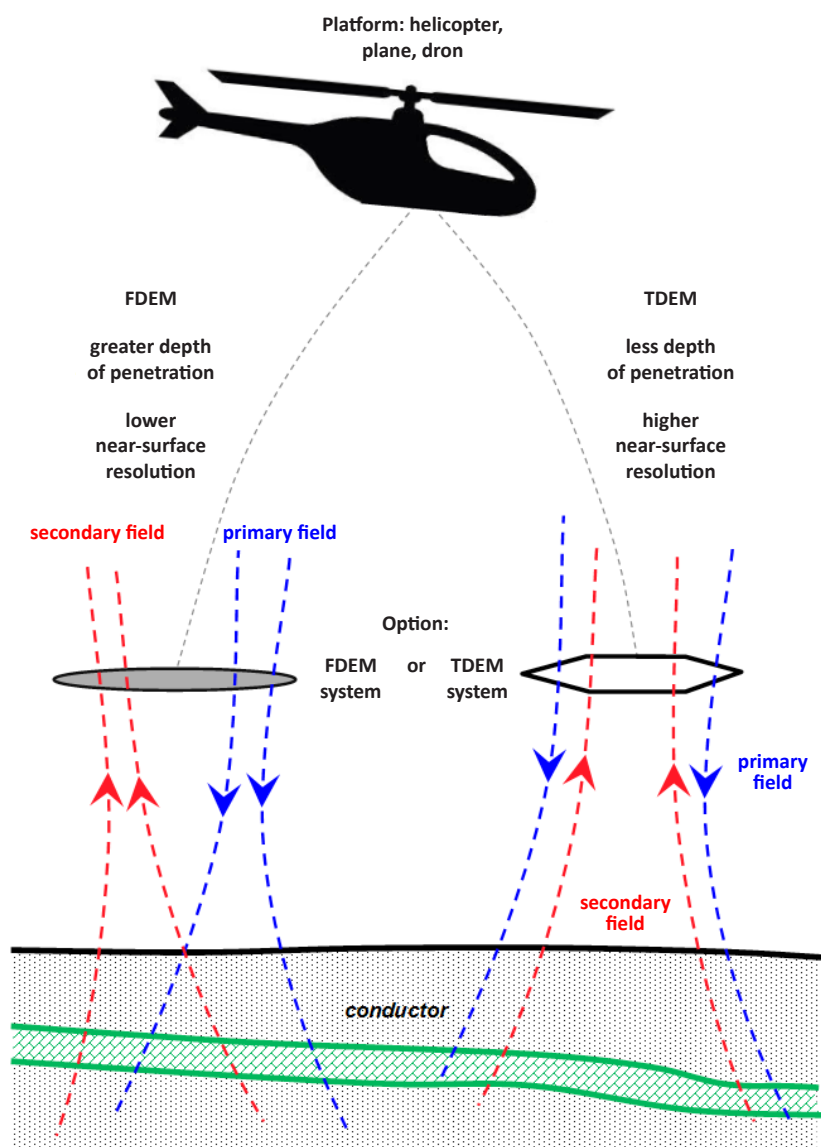


Figure 6. The AEM geophysical method – comparison of FDEM and TDEM systems (Badora D.)

quantities of mineral compounds. The content of mineral compounds reduces the resistivity of irrigated soil, which allows for identifying the water table.

The airborne electromagnetic method (AEM) works in a similar way to the EM method (AEM, 2006). The measurement is performed by a specially equipped aircraft or helicopter. Helicopters are used for smaller areas of research. Airplanes, on the other hand, are applied over larger areas. The AEM method is used in various configurations. The measuring systems have different shapes and sizes. However, the principle of operation of the measurement system using the electromagnetic energy source and the receiver is the same for all systems (Lane, 2014).

Most of the tests are carried out at low altitudes along parallel measuring lines. The electromagnetic test consists in activation (induction) by a transmitter (coil), which is placed in a rigid, oval beam, towed approx. 40 meters below

the helicopter (in the FDEM system) of the primary electromagnetic field that permeates deep into the medium under study. It generates a secondary electromagnetic field in the studied geological medium, which is detected by the receiver, also placed in an oval beam (Fig. 6) (Spies, Woodgate, 2005).

Sub-surface materials show a very wide range of electrical conductivity values. Solid rock is generally a poor conductor of electricity, but graphite layers, metal objects, contaminants, mineralized groundwater and some metallic minerals containing iron, copper or nickel are very good electricity conductors (Lane, 2014).

The electrical properties of the tested medium depend on, among others, the degree of saturation, clay content, porosity, texture of sediments, chemical compounds in water and the content of metallic minerals (Korus, 2018).

From the obtained measurement data, the electrical conductivity maps of the medium are generated, which should be appropriately processed, specifying the flight parameters, with application of appropriate filters to separate the measurements from various depths.

The systems for the AEM method are classified in different ways by different authors. It is influenced by, among others, the type of platform (helicopter, plane, drone), the instruments used, the geometry of the transmitter – medium – receiver elements, and the nature of the transmitted and recorded signal (Lane, 2014).

There are two basic systems in the AEM method: in the frequency domain (FDEM) and time domain (TDEM). In the TDEM system, the measurement takes place with a lower surface resolution and a greater depth of penetration compared to the FDEM system (Fig. 6) (Lane, 2014). The FDEM system is suitable for high resolution research, especially when the terrain is too uneven for airplanes moving at higher velocities (Fountain, 2008).

Groundwater research is most often carried out with a helicopter-borne FDEM system. The TDEM system, which consists of a transmitter, most often similar in shape to a hexagon, and a receiver located within or above the transmitter (Fig. 6), is usually used to search for minerals. Modifications of this system allow for its application also in groundwater research (Siemon et al., 2009).

At the end of the 20th century, groundwater research was carried out for the San Pedro catchment in the United States using the TDEM system. The resulting publications (Gettings et al., 1999; Wynn et al., 2000) describe the existence of a good correlation between conductivity and the underground water table. The publication states that the increase in conductivity below the underground water table level probably reflects an increase in saturation with groundwater, which is a good conductor (Lane, 2014).

In the AEM methods there are many options for choosing the right platform and measurement system depending on the size of the area, depth of penetration, terrain shape, lithology and the resolution we want to achieve. This is useful in studies of underground water tables. In comparison to other methods of AEM research, they allow for obtaining data for large areas in a short time at relatively low costs (Siemon et al., 2009). The AEM method is most often applied to large-scale groundwater research.

#### THE GRAVIMETRIC METHOD AND THE GRACE MISSION

Gravimetry can also be used to look for groundwater. The gravimetric method is based on the measurements of the Earth's gravitational acceleration. The measurement results are mainly used to study the Earth's gravitational field, to determine the geoid and the construction of the geological structure. An anomaly, which is located in a geological medium, causes a change in the Earth's gravitational acceleration, depending on the density and volume of rocks it is built of and the environment, as well as its size, shape and depth at which it is located. Such anomaly can be a reservoir of groundwater. Gravimetric measurements consist in creating an appropriate grid of isohypses with the distribution of changes in gravity forces (Milsom, 2003).

Considerable opportunities in groundwater monitoring are associated with the Gravity Recovery And Climate Experiment (GRACE, 2002), a program implemented by the American National Aeronautics and Space Administration (NASA, 2004) and Deutschen Zentrums für Luft und Raumfahrt (DLR, 2006).

The GRACE program was launched in 2002. GRACE is a team of two satellites that move along the same orbit one after another at a distance of 220 kilometres. When the first satellite is above a land area of particularly strong gravity, it accelerates drifting away from the other satellite. The mutual distance between the satellites is precisely measured

by means of microwaves. After having passed over an anomaly, i.e. a terrestrial region of greater gravity, the satellite slows down. The other satellite behaves similarly when it is over an anomaly. However, when the satellites are outside the anomaly, their distance returns to their original value. The satellites, making many flights over the same site, can record changes in the local density of the Earth's crust. This may point to the movement of huge masses of water above and below the surface of the Earth. Data from satellites can be combined with GPS data while developing accurate maps of the Earth's gravitational field (Fig. 7).

The main assumption of the GRACE program is to determine the geoid and gravity anomalies over the entire globe and monitor climate change through changes in water resources (Birylo et al., 2015).

The elevation of the water level which we receive from the GRACE mission data is TWS (Terrestrial Water Storage) (Rodell et al., 2006). The measurement and recording of the water level by the GRACE mission is performed in vertical resolution. As a result, groundwater, snow cover and soil moisture are recorded in the form of a common water level, without the possibility of separating them into individual layers (Rodell et al., 2006). In order to calculate the groundwater level ( $\Delta$ Groundwater) one should use the data from GLDAS: Soil Moisture and Snow Water Equivalent (GLDAS, 2004):

$$\Delta\text{Groundwater} = \Delta\text{TWS}_{\text{GRACE}} - (\Delta\text{SoilMoisture}_{\text{GLDAS}} + \Delta\text{SnowWaterEquivalent}_{\text{GLDAS}})$$

where:

$\Delta$ Groundwater – groundwater level

$\Delta\text{TWS}_{\text{GRACE}}$  – the water level elevation obtained from the GRACE mission data

$\Delta\text{SoilMoisture}_{\text{GLDAS}}$  – soil moisture

$\Delta\text{SnowWaterEquivalent}_{\text{GLDAS}}$  – snow cover level

The Global Land Data Assimilation System (GLDAS, 2004) is a system whose task is to integrate terrestrial and satellite observations using modern data modelling techniques to create results, showing changes in, among others, the groundwater level. GLDAS provides information useful in large-scale soil research – variables stored in the database describe, among others, soil temperature, precipitation index, atmospheric pressure, surface runoff and soil moisture at several depth levels (Kędzior et al., 2012).

The juxtaposition of GRACE mission data with GLDAS data provides great opportunities for monitoring the level of groundwater over large surfaces with a monthly frequency of data compilation, which allows on-going tracking of changes and forecasting adverse phenomena in the form of drought or flood (Badora, 2016).

In 2015, a publication was developed comparing the  $\text{TWS}_{\text{GRACE}}$  and TWS measurements obtained as a result of  $\text{SoilMoisture}_{\text{GLDAS}}$ ,  $\text{SnowWaterEquivalent}_{\text{GLDAS}}$  and

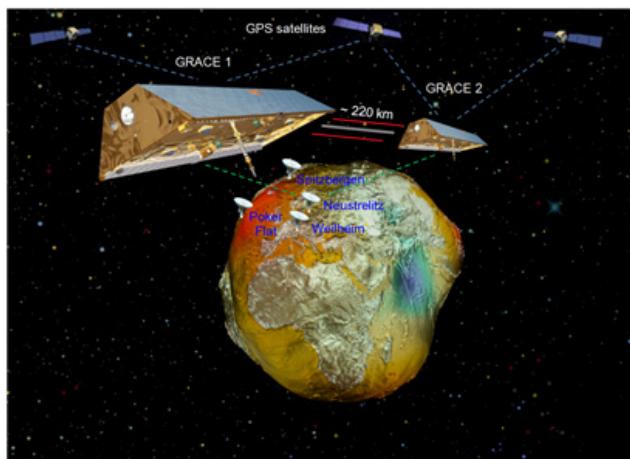


Figure 7. GRACE mission concept (DLR, 2006).

Groundwater additions (observations of the groundwater table in wells) (Xiao et al., 2015). The research was carried out on the area of the west coast of the United States. Measurements spanning the years 2005–2011 indicate a high similarity between  $TWS_{GRACE}$  and the TWS obtained from the summation of individual parameters. The publication clearly shows periods in a given year with a reduced TWS value, as well as periods with a high TWS value. Dry and humid years are also well-reflected in comparison with  $TWS_{GRACE}$ .

GRACE mission data is useful for assessing changes in water resources for large areas. This is due to the low resolution of the measurement data, which is  $1^\circ \times 1^\circ$  (approx. 110 km by 110 km). For monitoring groundwater level in smaller catchments, the above data is insufficient, but it can be a good complement from a global perspective.

#### SUMMARY AND CONCLUSIONS

The presented methods of geophysical research are used, among others for finding the underground water table and measuring groundwater resources. Geophysical methods are also applicable in geology, searching for groundwater pollution and engineering works.

When planning surveys of the water table and groundwater resources, attention should be paid to the selection of appropriate measurement date and the lithology of the substrate. One should also choose the appropriate method for the size of the studied area, terrain shape, depth of measurement and resolution. It is also important to choose appropriate programs for processing the acquired geophysical data.

For small areas up to several hundred square meters, seismic (refractory, reflective) methods, as well as electrical resistivity (vertical electrical sounding VES, electro-resistivity profiling EP, electrical resistivity tomography

ERT), ground-penetrating radar, electromagnetic EM and gravimetric methods can be used.

In seismic methods, the velocity of the seismic wave propagation varies depending on the lithology. Seismic wave velocity also changes during the transition between saturated and unsaturated formations. Because of this, it is possible to detect the underground water table.

A publication issued in 2009 described ambiguous results of groundwater level tests using the refractive method (Grelle, Guadagno, 2009). The article describes the results of research in geological media in three different locations, for which the geological structure was known and the verification of the underground water table was possible. The tests measured the longitudinal wave P and the transverse wave SH, which were used to calculate the special WSI index (Water Seismic Index). The WSI coefficient is aimed at determining the exact depth of the underground water table (Grelle, Guadagno, 2009).

The test results for three different geological media, conducted by Grelle and Guadagno (2009), confirmed that the WSI index gives direct information about the existence and depth of an underground water table. However, the index depends on the geological structure of the studied medium and the uneven sinking of the water table in various hydrological periods (Grelle, Guadagno, 2009).

In 2013, a publication comparing the application of the ground-penetrating radar method and electrical resistivity tomography (ERT) to observing the position of the free water table of the first aquifer (Gańko et al., 2013). On the site of the research an observation piezometer was built, which enabled remote monitoring of water fluctuations in the first aquifer for the above-mentioned research periods. The article describes two models of the underground water table status: 1.9 m b.t.s. (research was carried out in August 2011) and 3.9 m b.t.s. (the research was carried out in October 2012). Observations from an observation piezometer with a well-known lithology and hydrogeological conditions were used to verify the effectiveness of ground-penetrating and electrical resistivity tests (Gańko et al., 2013). The methods of ground-penetrating radar and electrical resistivity tomography (ERT) yielded comparable results during the first measurement, where the water table at the depth of 1.9 m b.t.s. was clearly marked on geophysical profiles. The water table at the depth of 3.9 m b.t.s. was marked with less clarity on the geophysical profiles. In the second measurement, there was an increased attenuation of electromagnetic waves for the ground-penetrating radar method and there was no clear contrast between the zone of aeration and saturation. This was due to the partial saturation of soil pores in in the zone of the dynamic fluctuations in water level. Below the water table, electromagnetic waves are suppressed. This prevents the identification of the geological layers occurring deeper. The electrical resistivity tomography enables deeper recognition of geological layers below the water table (Gańko et al., 2013).



In order to achieve more detailed comparison and analysis of seismic, electrical resistivity, ground-penetrating radar, electromagnetic and gravimetric methods, it would be necessary to conduct their verification for several common areas of different lithology and hydrogeological conditions.

The AEM method offers great capability for measuring groundwater resources and their water table. In the AEM methods there are many options for choosing the right platform and measurement system depending on the size of the area, depth of penetration, terrain, lithology and the resolution we want to achieve.

At the end of the 20th century, groundwater research was carried out for the San Pedro catchment in the United States using the TDEM system. The resulting publications (Gettings et al., 1999; Wynn et al., 2000) describe the existence of a good correlation between conductivity and the underground water table. The publication states that the increase in conductivity below the underground water table probably reflects an increase in the saturation with groundwater, which is a good conductor (Lane, 2014).

Compared to other methods, AEM research allows for obtaining data for large areas in a short time at relatively low costs (Siemon et al., 2009). The AEM method is increasingly often applied in large-scale groundwater research.

By using the AEM method it is possible to measure river catchments which extend over large areas in a relatively short time at appropriate time intervals. Thanks to this, a well-reflected model of water resources and their changes over time can be obtained.

The satellite mission GRACE has been in operation since 2002, the main assumption of which is to determine the geoid and gravity anomalies over the entire globe and to monitor climate change through changes in water resources (Biryło et al., 2015). The data on water level that we receive from the GRACE mission data is TWS (Terrestrial Water Storage) (Rodell et al., 2006). The measurement and recording of the water level by the GRACE mission is performed in vertical resolution. As a result, groundwater, snow cover and soil moisture are recorded in the form of a common water level, without the possibility of separating them into individual layers (Rodell et al., 2006). In order to calculate the underground water table level, the soil humidity and snow cover height from the GLDAS database (GLDAS, 2004) should be from  $TWS_{GRACE}$  values. The juxtaposition of the GRACE mission data with GLDAS data provides great opportunities for monitoring the level of groundwater on large surfaces with a monthly frequency of data compilation, which allows on-going tracking of changes and forecasting adverse phenomena in the form of drought or flood (Badora, 2016).

In 2015, a publication was developed, comparing the  $TWS_{GRACE}$  and TWS measurements obtained as a result of the summation of soil moisture, snow cover height (obtained from GLDAS databases) and observation of the un-

derground water table in wells (Xiao, 2015). The research was carried out in the area of the west coast of the United States. The measurements spanning the years 2005–2011 indicate a high similarity between  $TWS_{GRACE}$  and TWS obtained from the summation of individual parameters. The publication clearly shows periods in a given year with a reduced TWS value, as well as periods with a high TWS value. Dry and humid years are also well reflected in comparison with  $TWS_{GRACE}$ .

GRACE mission data is useful for assessing changes in water resources for large areas. This is due to the low resolution of the measurement data, which is  $1^\circ \times 1^\circ$  (approx. 110 km by 110 km). For monitoring groundwater level in smaller catchments, the above data is insufficient, but it can be a good complement from a global or regional perspective.

Groundwater monitoring enriched with measurement data obtained through the use of one of the geophysical methods discussed in this article assist in determining the actual level of groundwater in Poland, as well as in the reliable monitoring of this level, which is of strategic importance both in current water management for agriculture and population, as well as in the design of adaptation and mitigation measures related to the adaptation of agriculture to climate change (Olesen et al., 2010).

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