



# Geophysical characterization of groundwater aquifers in the Western Debrecen area, Hungary: insights from gravity, magnetotelluric, and electrical resistivity tomography

Musaab A. A. Mohammed<sup>1,2</sup> · Norbert P. Szabó<sup>1</sup> · Joseph O. Alao<sup>3</sup> · Péter Szűcs<sup>1</sup>

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## Abstract

The recent study followed a multi-methodological approach integrating gravity, magnetotelluric (MT), and electrical resistivity tomography (ERT) to investigate the geometry and hydrological characteristics of the main hydrostratigraphical units in the Western Debrecen area, Eastern Hungary. The integration of these methods aims to delineate potential zones for groundwater development and guide effective extraction strategies. In the gravity investigation, the Bouguer anomaly map undergoes spectral analysis for the separation of shallow and deep features, offering a preliminary indication of basement rock depth. Subsequently, gravity data inversion is employed to map variations in basement rock topography, revealing a basin structure, with sediment thicknesses extending up to 2 km. On the other hand, the MT data are modeled using the 1D Occam inversion algorithm to validate the results of the gravity data analysis. This inversion, constrained with lithological logs is further utilized to delineate the main hydrostratigraphical units in the study area. Accordingly, four units are identified, including the Nagyalföld Aquifer, Algyő and Endrődi Aquitards, the Badenian Aquifer, and the Pre-Neogene Aquitard. Consequently, Dar Zarrouk parameters based transmissivity and the hydraulic conductivity of the aquifer units are measured. The Nagyalföld aquifer showed a hydraulic conductivity that ranged between 7.9 and 11.9 m/day, while the Badenian aquifer showed an average hydraulic conductivity of 13.1 m/day. The ERT data are employed to map the spatial distribution of the depth to the water table. The shallow water table is observed in regions characterized by an elevated thickness of sedimentary rocks, attributed to their high specific capacity. Integrating these hydrogeophysical methods provided a comprehensive understanding of the subsurface hydrology and enabled better-informed decision-making for groundwater development.

**Keywords** Debrecen · Geophysical inversion · Hydrostratigraphy · Dar Zarrouk · Hydraulic conductivity

## Introduction

Hydrogeological investigations play a crucial role in understanding the characteristics of groundwater aquifers (Fejes et al. 2021; Mohammed et al. 2023d). Accurate knowledge about aquifer geometry and hydrogeological

properties is essential for effective groundwater resource management and sustainable development (Mohammed et al. 2023c). As one of the primary locations for groundwater extraction in Eastern Hungary, the Western Debrecen area presents unique hydrogeological challenges due to its complex geological setting (Szűcs and Madarász 2006). The subsurface aquifers in the Debrecen area exhibit significant heterogeneity in lithology, permeability, and connectivity (Tóth and Almási 2001; Mohammed et al. 2024). The shallow and deep aquifers are the primary source of water supply in Debrecen to fulfill the drinking and irrigation needs (Szanyi 2004). Excessive production from these aquifers resulted in various issues, including aquifer consolidation, subsidence, and groundwater deterioration (Bendefy 1968). For the delineation and characterization of groundwater aquifers, the geophysical methods have gained significant prominence in recent years (Szabó

✉ Musaab A. A. Mohammed  
musab20501@gmail.com

<sup>1</sup> Faculty of Earth and Environmental Sciences and Engineering, University of Miskolc, Miskolc 3515, Hungary

<sup>2</sup> College of Petroleum Geology and Minerals, University of Bahri, Khartoum 1660, Sudan

<sup>3</sup> Department of Physics, Air Force Institute of Technology, Kaduna, Nigeria

2015; Mohammed et al. 2023b). These methods help to construct accurate hydrogeological conceptual models that help identify potential zones and support developing effective groundwater management strategies (Gao et al. 2019; Agyemang 2021; Miner et al. 2022).

Applying potential field methods such as gravity, magnetotelluric (MT) and electrical resistivity tomography (ERT) contributes significantly to understanding the hydrogeological conditions (Dudash et al. 2009). These methods are commonly used in groundwater exploration as they provide detailed information about subsurface lithology variation and hydrogeological structures (Chandrasekhar et al. 2009). Gravity surveys are usually not primary data for hydrogeological investigation; however, they provide information about subsurface density variations (Rubin and Hubbard 2006) that can be used to detect the depth of the basement rock and delineate the geological structures (Layade et al. 2020). Since the sediments are substantially less dense than the underlying metamorphic rock, the depth to basement rocks is directly connected to the calculated gravitational field after proper corrections and modeling of the gravity data (Elawadi et al. 2012; Ibrahim and Elsidig 2019; Ghouili et al. 2022). MT is a passive geophysical method that measures natural variations of the Earth's electromagnetic fields to infer subsurface resistivity variations. MT data offers complementary information to gravity surveys as it provides information on groundwater occurrence, structural features, and hydraulic and petrophysical parameters (Agyemang 2020; Xu et al. 2020; Alkholy et al. 2023). Conversely, ERT is an active method that is used in imaging subsurface resistivity variations, allowing the delineation of hydrogeological features such as aquifers, faults, and aquitards (Mainoo et al. 2019). ERT provides valuable information about the subsurface distribution of electrical resistivity, which is directly related to the composition and moisture content of the subsurface materials.

In groundwater studies, potential field data analysis has been conducted to explore the groundwater aquifer's characteristics. However, integrated approaches that combine both shallow and deep analyses are rare, mostly due to budgetary constraints. This research explores the application of a multi-methodological framework using different geophysical methods, including gravity, MT, and ERT, to characterize the main hydrogeological units of the groundwater system in the Western Debrecen area, Eastern Hungary. This integrated approach aims to delineate the basement rock topography, characterize the main hydrostratigraphic units, and map the hydrodynamic conditions in the study area. By concurrently integrating shallow and deep investigations, this study will contribute to a more nuanced comprehension of the hydrogeological framework for successful groundwater resource development.

## Study area

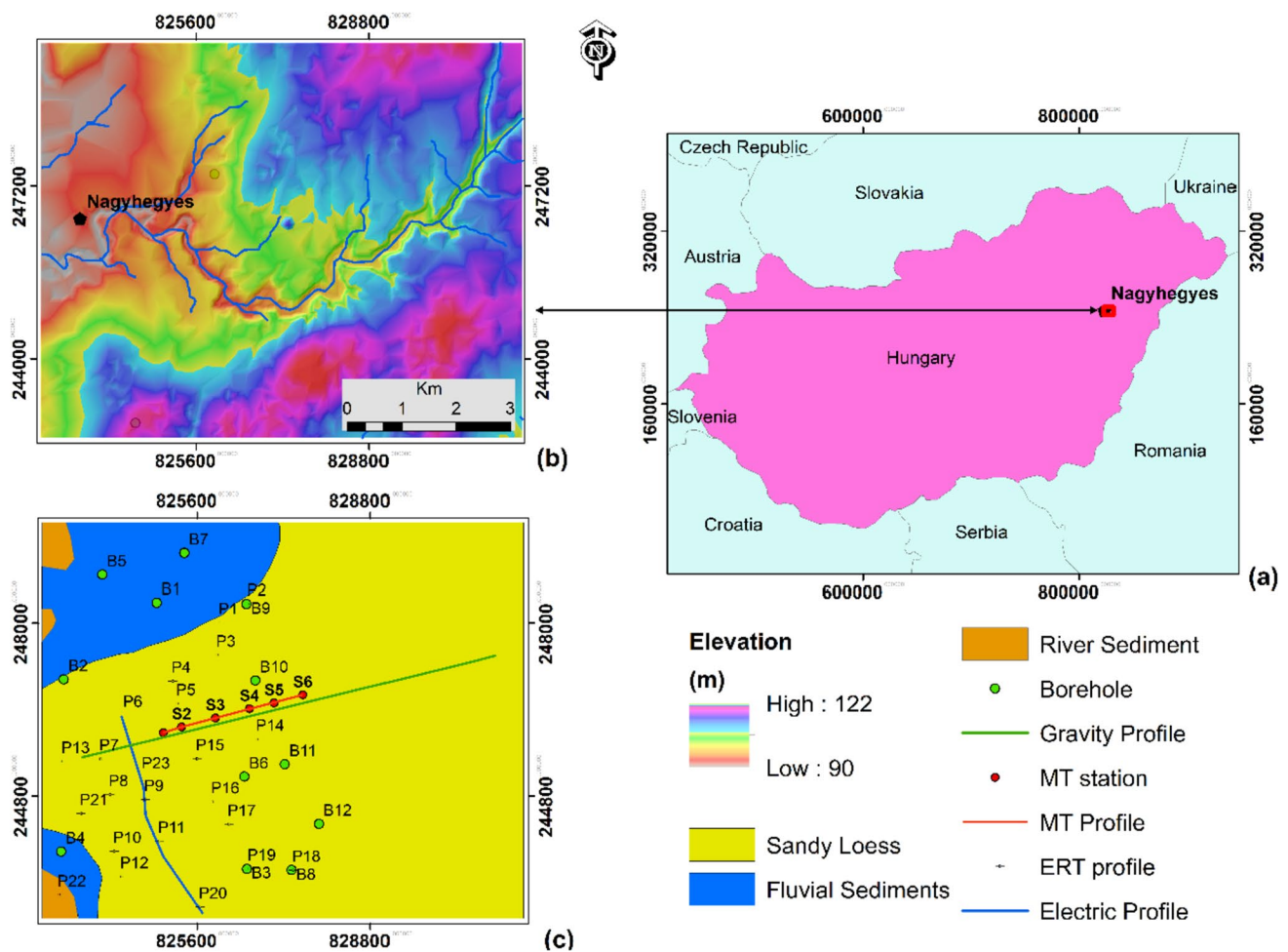
### Location and geology

The study area is located in the western part of the Debrecen area around Nagyhegyes City, Eastern Hungary (Fig. 1a). It is part of the Great Hungarian Plain (GHP) with an elevation range between 99 and 122 m above sea level (Fig. 1b). The climate is moderately continental, with average annual temperatures of 10–11 °C, maxima and minima of 36 and –17 °C, respectively, and precipitation of 550–600 mm.

Different geological formations are present in the study area, including Pre-Neogene basement rocks, Miocene, Pannonian, and Quaternary formations (Fig. 2). The basement rocks in this area are primarily composed of metamorphic and igneous rocks (Fülöp 1989; Buday et al. 2015). These rocks include schist granites, basalts, and gabbros that resulted from the metamorphism of older sediments (Mádl-Szőnyi et al. 2019). The rifting in the early Miocene resulted in the deposition of Submarine sediments, including sandstone, silt, and limestone, forming the Badenian Formation (Juhász 1991). The Pannonian Formation is composed of unconsolidated to semi-consolidated clastic sediments and is divided into Lower and Upper Pannonian (Tóth and Almási 2001; Buday et al. 2015). The lower Pannonian consists of coarse sandstone and sandy conglomerates laterally transformed into siltstone (Algyő formation), calcareous marl, and limestone (Endrőd formation) (Tóth and Almási 2001). The upper Pannonian consists of alluvial siltstone, sandstone, clay, marl, and quartz pebble beds. These deposits are represented in Újfalú and Zagyva formations (Kronome et al. 2014). The Újfalú Sandstone Formation consists of fine-grained and medium-grained sandstone with intercalated clay marl. At the same time, the Zagyva Formation is composed of fine sediments such as gray silt and clay marl. The surface geology of the study area is composed mainly of Quaternary deposits. These deposits consist of fluvial sediments, river sediments, and sandy loess (Fig. 1c). The thickness of the Quaternary deposits in the study area ranges from 150 to 250 m (Haas 2012). It is divided into three parts, including upper, middle, and lower Pleistocene beds (Buday et al. 2015).

### Hydrostratigraphy

The main hydrostratigraphical units in GHP include the Pre-Neogene Aquiclude, Pre-Pannonian Aquifer, Endrőd Aquitard, Algyő Aquitard, and the Nagyalföld Aquifer (Tóth and Almási 2001). The Pre-Neogene aquiclude with



**Fig. 1** a, b Geographical maps showing the location of the study area in Eastern Hungary. c The surface geology of the study area was modified after Gyalog and Síkhegyi (2005)

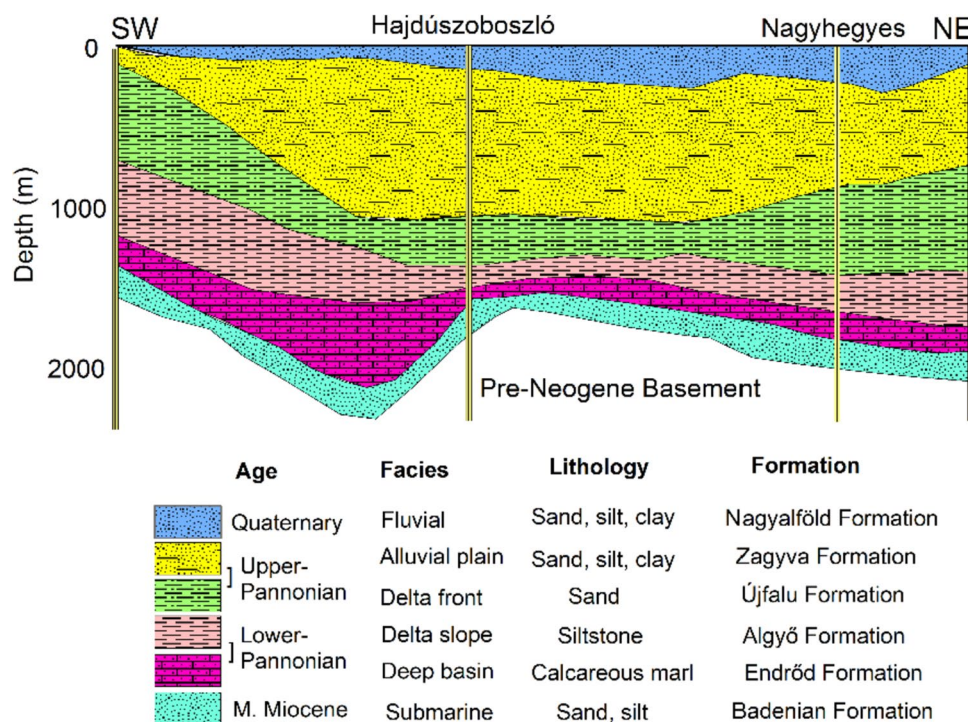
almost zero permeability is the bottom hydrostratigraphic unit in the study area. The Pre-Pannonian aquifer is the principal aquifer at the bottom of the groundwater flow basin hosted by the middle Miocene Badenian Formation (Simon et al. 2011). Its high permeability (around 100 mD) is caused by fracturing and faulting and the presence of coarse-grained sediments. The Endrőd aquitard is horizontally extensive throughout the study area and composed of a calcareous marl of permeability of 0.1 mD (Liebe 2006). The Algyő unit is identified as an aquitard with permeability ranging from 1 to 10 mD (Buday et al. 2015). The Nagyalföld aquifer is composed of the Újfalu and Zagyva Formations and Quaternary sediments and boasts a permeability greater than 1,000 mD (Tóth and Almási 2001; Buday and Püspöki 2011). Two hydraulic regimes are present in the GHP (Almasi and Tóth, 2001). Gravitational forces influence groundwater flow in the upper regime, whereas overpressure influences the lower regime (Szűcs et al. 2021). Hydraulic interaction between

the two regimes commonly happened, especially where low-permeability layers were pushed outward (Juhász 1991).

## Materials and methods

This study employs integrated geophysical techniques, including gravity, MT, and ERT, to delineate and characterize groundwater aquifers in the Western Debrecen area, Eastern Hungary. Several challenges are encountered in the data collection. For gravity data, missing data points in certain portions of the study area affected the ideal coverage. However, this data gap did not significantly impact the overall analysis. The ERT data are primarily collected for infrastructure development purposes. Challenges included the non-optimized depth of investigation for hydrogeological purposes and limitations in the coverage of the study area.

**Fig. 2** Geological cross-section showing the main geological units in the Pannonian Basin modified after Tóth and Almási (2001)



Nonetheless, the collected data are repurposed to fulfill the specific needs of the recent investigation.

### Gravity data correction and modeling

In this study, the gravity data are used for the delineation of the basement rock relief and the thickness of the sedimentary sequences. More than 112 data points with a density of 4 points per km<sup>2</sup> data covering the study area is used in the recent investigation. The data are acquired relative to a local base network and later connected to Hungarian and European base stations. The data are corrected for terrain, free-air, and Bouguer in the MGH 50 system (IGSN30, Potsdam basic level) to obtain the complete Bouguer anomaly map. The corrections are adopted for a density of 2000 kg/m<sup>3</sup>. The resulting Bouguer anomaly map is subjected to a power spectrum analysis (Spector and Grant 1970) to separate the effects of various sources, encompassing both shallow and deep structures. These sources are commonly referred to as regional and residual anomalies (Pawlowski 1994). The power spectrum analysis is conducted with the aid of the Fast Fourier transform (FFT) that facilitates the extraction of essential frequency-related information.

The inversion of gravity data is a crucial step in determining the relief of basement rocks within the study area. To accomplish this, the GM-SYS program of Geosoft is employed, utilizing the methods proposed by Talwani et al. (1959) and the algorithms by Won and Bevis (1987). This program facilitates an interactive inversion process by formulating a mathematical model linking observed gravity

data to subsurface density. The inversion methodology involves forward modeling, where a hypothetical geological model is constructed, representing subsurface layers as polygonal bodies with associated density values. The gravitational potential produced by each polygon is calculated using the 3D Poisson's equation. The inversion process employs the least square method to iteratively minimize the misfit between observed and calculated data (Marquardt 1963; Ekwok et al. 2021). Notably, additional constraints are integrated into the inversion process to enhance stability and mitigate oscillatory solutions. These constraints are informed by prior knowledge derived from borehole data and previous geological reports.

### Magnetotelluric (MT) data

This study uses magnetotellurics (MT) data to delineate and characterize the main hydrostratigraphical units in the study area. MT method uses natural variations in the Earth's electromagnetic field to image subsurface geology and structures (Nádas et al. 2022). The Earth's electromagnetic field is generated by the motion of charged particles in the ionosphere, and the magnetosphere and MT method uses it to induce electrical currents in the subsurface. These induced currents generate a secondary electromagnetic field, which can be measured at the surface. The resistivity of the subsurface layers is inferred by analyzing the relationship between the primary and secondary fields.

In practice, the MT method involves measuring the electric and magnetic fields at the surface over a range of

frequencies. By analyzing the frequency-dependent impedance, it is possible to infer the resistivity of the subsurface. To measure the apparent resistivity using the MT method, a receiver coil is placed on the ground surface that measures the resulting magnetic field, which is used to calculate the impedance. In this study, the Phoenix MTU-5A receiver system is employed. Among the impedances, the more common one for practical use is the apparent resistivity (Arisbaya et al. 2023). Since the impedance is a complex number, each of its components can be represented in the context of apparent resistivity ( $\rho_a$ ) (Eq. 1) as

$$\rho_{a(i,j)} = \frac{|Z_{(i,j)}|^2}{\mu_0 \omega} \quad (1)$$

where  $Z$  is the impedance of the subsurface at frequency  $\omega$ , and  $\mu_0$  is the magnetic permeability of the medium. The apparent resistivity relates the impedance to the resistivity of the subsurface, which can be inverted to obtain an image of the subsurface resistivity.

The 1D Occam algorithm is used for inverting magnetotelluric (MT) data to obtain the true resistivity and thickness of the hydrostratigraphical units (Krieger and Peacock 2014). It is a linearized inversion method that assumes the subsurface is composed of a series of horizontal layers with uniform resistivity and thickness (Weaver and Agarwal 1993). The 1D Occam algorithm works by minimizing the difference between the observed MT data and the predicted data from a 1D layered earth model. The algorithm uses a regularization parameter to balance the trade-off between fitting the data and minimizing the model complexity. The regularization parameter controls the smoothness of the model, which helps to prevent overfitting and reduce noise in the inversion results.

## Electrical resistivity tomography (ERT)

The ERT survey is conducted along 24 profiles using the Syscal Pro multi-channel resistivity meter to map the variations in the depth of the groundwater table. Wenner–Schlumberger array (WSA) with 36 electrodes and 2 m electrode spacing is employed. WSA is a hybrid configuration combining Wenner and Schlumberger electrode arrays to optimize the trade-off between depth penetration and lateral resolution (Szűcs et al. 2021). The measured apparent resistivity is inverted using RES2DINV software (ver. 4.08) (Loke and Barker 1996). Before the inversion, the data are preprocessed to remove noise and correct systematic errors. For forward modeling, the finite-difference method (FDM) is used, which involves creating a numerical grid that represents the subsurface domain (Spitzer and Chouteau 1999). The grid consists of nodes that define the measured resistivity values

at different locations, and RES2DINV estimates the subsurface resistivity distribution from the measured data. In this study, the Gauss–Newton optimization method is employed to iteratively update the resistivity values to minimize the misfit between the observed and the calculated data (Ebong et al. 2021). During the inversion, the smoothness constraint regularization technique is used, which helps stabilize the inversion process by imposing constraints on the resistivity values to achieve a smoother subsurface resistivity distribution (Constable et al. 1987).

## Hydrogeological characteristics

In his study, the hydraulic characteristics of the hydrostratigraphical units are estimated based on the result of MT data inversion with the aid of Dar Zarrouk parameters (DZP). DZPs, including longitudinal conductance ( $S$ ,  $\Omega^{-1}$ ) and transverse resistance ( $R$ ,  $\Omega m^2$ ), are based on the comparison between the movement of electrical current and groundwater (Niwas and Singhal 1981). Layer thicknesses and real resistivity obtained from MT data inversion are incorporated in the calculation of DZPs using Eqs. 2 and 3 as

$$S = \frac{h}{\rho} = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (2)$$

$$R = h * \rho = \sum_{i=1}^n h_i * \rho_i \quad (3)$$

where  $h$ ,  $\rho$ , and  $n$  are layer thickness, true resistivity of the layer, and the number of layers, respectively.

A theoretical connection connecting the aquifer transmissivity ( $T$ ) and DZPs was proposed by Niwas and Singhal (1981) (Eqs. 4 and 5) based on the similarity between the Darcy law of groundwater flow and the Ohm law of electrical flow as

$$T = K \sigma R \quad (4)$$

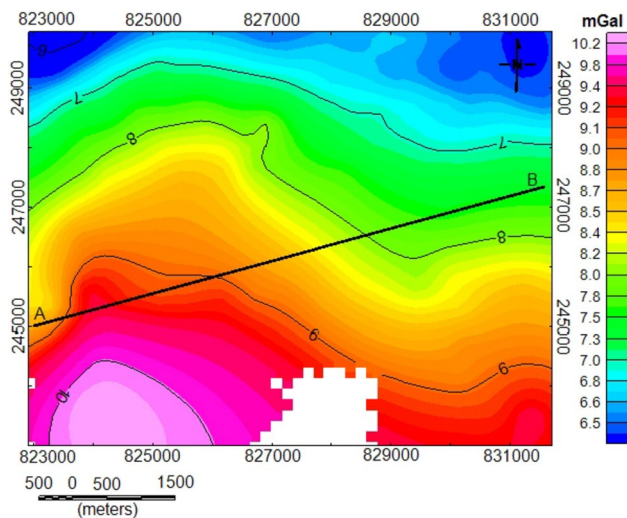
$$T = \frac{KS}{\sigma} \quad (5)$$

where  $K$  is the hydraulic conductivity and  $\sigma$  is the electrical conductivity (reciprocal of electrical resistivity).

Furthermore, based on the correlation between hydraulic conductivity and the resistivity of the aquifer, Heigold et al. (1979) suggested an empirical formula (Eq. 6) to estimate the hydraulic conductivity ( $K$ ) as follows:

$$K = 386.4 \rho_{aq}^{-0.93283} \quad (6)$$

where  $\rho_{aq}$  is the resistivity of the aquifer layer obtained from MT data inversion.



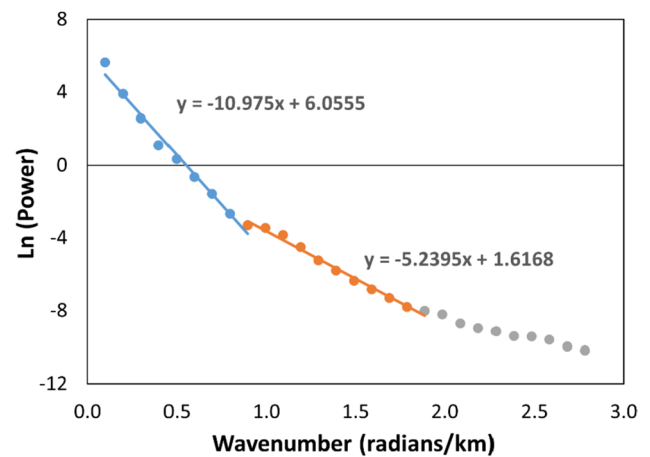
**Fig. 3** The complete Bouguer anomaly map of the study area

## Results and discussion

### Interpretation of the gravity data

The complete Bouguer anomaly showed a slight gradual variation that ranged between 6.4 and 10.2 mGal, with the highest anomaly indicated in the southern part and the lowest in the northern part of the study area (Fig. 3). The gradual variation in Bouguer anomaly is an indication of variation of the density of subsurface layers suggesting that the southern part of the study area is associated with higher density rocks. The complete Bouguer anomaly map is subjected to radial averaged spectral analysis to guide the residualization and regionalization of the anomaly (Spector and Grant 1970). The logarithmic decay of the energy curve distinguished the deep sources from shallow sources, and noise exhibited a sharp decline for deep sources and a softer decline at shallow sources (Basantaray and Mandal 2022). The Bouguer spectral analysis results are shown in Fig. 4. The spectra of gravity anomaly show a two-layer subsurface configuration. The shallow zone is described as sedimentary rocks, and the deeper represents a basement rock zone of relatively greater density.

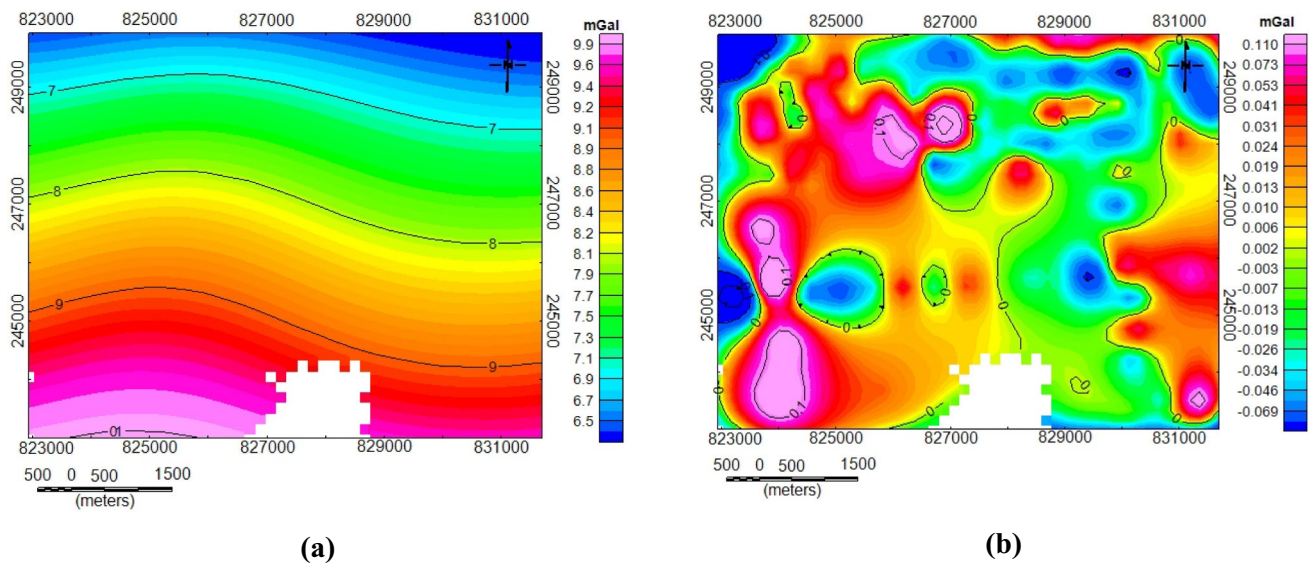
The spectral analysis also resulted in regional and residual maps of the Bouguer anomaly (Fig. 5) showing deep and shallow features. Regional anomaly maps identified the broad gravity patterns and large-scale anomalous bodies. The Bouguer regional map (Fig. 5a) exhibited a gradual change in the gravity anomaly from north to south. In the northern part of the area, the map depicts high positive anomalies, which gradually decrease southward. This progressive change in gravity values is indicative of underlying geological structures, with the high values in the north likely associated with denser geological formations and increased



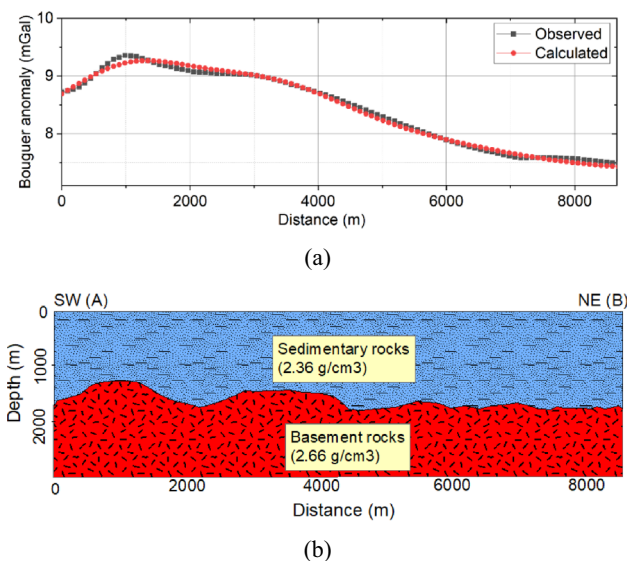
**Fig. 4** Radially averaged spectrum of the gravity data

thickness of sedimentary rocks (Ombati et al. 2022). The residual gravity anomaly map (Fig. 5b) unveils more localized and specific features within the study area. In this map, a pronounced positive anomaly is observed in the central and western regions of the area. This suggests that beneath these areas, there are anomalous subsurface structures that exhibit a positive higher density contrast compared to the surrounding rocks (Abdelrady et al. 2023).

The inversion of the gravity data is carried out to determine the depth of crystalline rocks and the thickness of the sedimentary layers in the study area. The data along the profile are interpreted in a two-layered two-dimensional model with depth to the basement initially assigned as 1.7 km based on the prior information obtained from previous geological reports. Further, a primary density of 2.2 g/cm<sup>3</sup> is assigned to the upper sedimentary layers, while 2.75 g/cm<sup>3</sup> is assigned to the basement rocks. The gravity data are inverted along one profile (see Fig. 3) that is trending from NE to S. This profile reveals fluctuations in Bouguer anomalies ranging from 7.5 to 9.44 mGal (Fig. 6a), indicating variations in the petrophysical properties of the subsurface rocks. In the inversion process, the thickness and the density of the subsurface layers are iteratively adjusted to minimize the misfit between the observed and calculated anomalies. The inversion resulted in an average density of 2.36 g/cm<sup>3</sup> for sedimentary sequences, while the basement rocks have an average of 2.66 g/cm<sup>3</sup> (Fig. 6b). The obtained values fall within the density range of the sedimentary and metamorphic basement rocks. Accordingly, the depth of the basement rocks varies between 1200 m in the southwestern part and 2850 m in the northeastern part of the study area. The fluctuations in basement relief are influenced by tectonic events, erosion, and sedimentation (Tóth and Almási 2001). For instance, uplifting brings the basement rocks closer to the surface, while depositing sedimentary layers on top of the basement rocks can bury them deeper beneath the surface.



**Fig. 5** **a** Regional and **b** residual anomaly maps of Bouguer anomaly in the study area



**Fig. 6** **a** Variation of Bouguer anomaly and **b** the result of 2D inversion along the profile

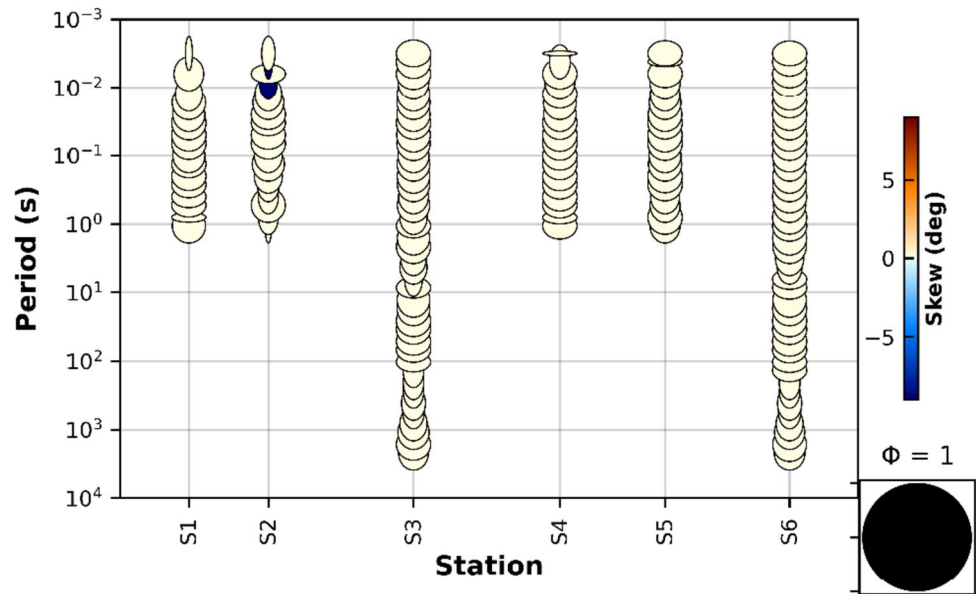
### Characterization of hydrostratigraphical units

The primary analysis of the MT data along the profile indicated a consistent probability distribution of the phase tensor ellipse and maximum skewness of nearly zero (Fig. 7), suggesting a geoelectric structure characterized by a lack of strong anisotropy (Maswah et al. 2021). This symmetry indicates a prevailing uniformity in geological conditions, where the dominant structures influencing electrical resistivity exhibit a horizontal orientation (Caldwell et al. 2004). Following this geological simplicity, the MT

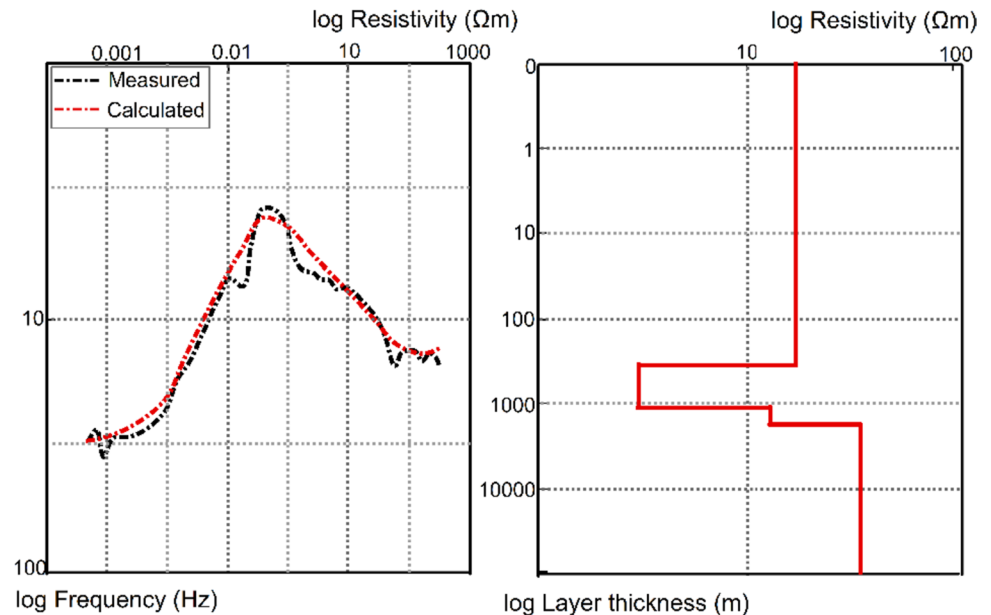
data is inverted based on the 1D Occam algorithm and the results are then interpolated and interpreted in a 2D cross-section. An example of the 1D inversion is illustrated in Fig. 8, where the fitted calculated to the measured resistivity along with its resulting depth four-layered model is indicated.

The 2D resistivity cross-section and the interpreted hydrostratigraphic units are shown in Fig. 9a and b, respectively. Based on the resistivity values, four hydrostratigraphical units are delineated, including the Nagyalföld Aquifer, Algyő and Endródi Aquitards, the Badenian Aquifer, and the Pre-Neogene Aquitard units. The Dar Zarrouk parameters and hydrogeological characteristics are shown in Table 1. The Nagyalföld unit represents the uppermost hydrostratigraphical unit and comprises the Újfalu and Zagyva Formations and the Quaternary sediments. It has an average resistivity and thickness of  $40 \Omega\text{m}$  and 600 m, respectively. The Nagyalföld unit is composed of sand, gravel, silt, and clay deposited by rivers and streams (Gyalog and Síkhegyi 2005). The longitudinal conductance of this aquifer ranged between 10 and  $15.6 \Omega^{-1}$ , while the transverse resistance varied between 25,075 and  $43,475.8 \Omega\text{m}^2$ . The lowest value of transverse resistance is more likely due to the abundance of fine particles (Mohammed et al. 2023c). The highest longitudinal conductance value denotes good aquifer potentiality (Kelly and Reiter 1984; Ebong et al. 2023). The hydraulic conductivity of this unit varied between 7.9 and 11.9 m/day. Consequently, the transmissivity varied between 5098 and  $7738 \text{ m}^2/\text{day}$ . Due to the low vertical resolution of the MT data, the obtained hydrogeological parameters are average value to the sandy layers within the Nagyalföld aquifer unit, as the silty and clayey layers are associated with

**Fig. 7** Analysis of the phase tensor ellipses for all frequencies (periods) across the MT stations



**Fig. 8** Example of 1D inversion of the MT data along station 3 showing the fitness between the measured and calculated resistivity along with the resulting depth model



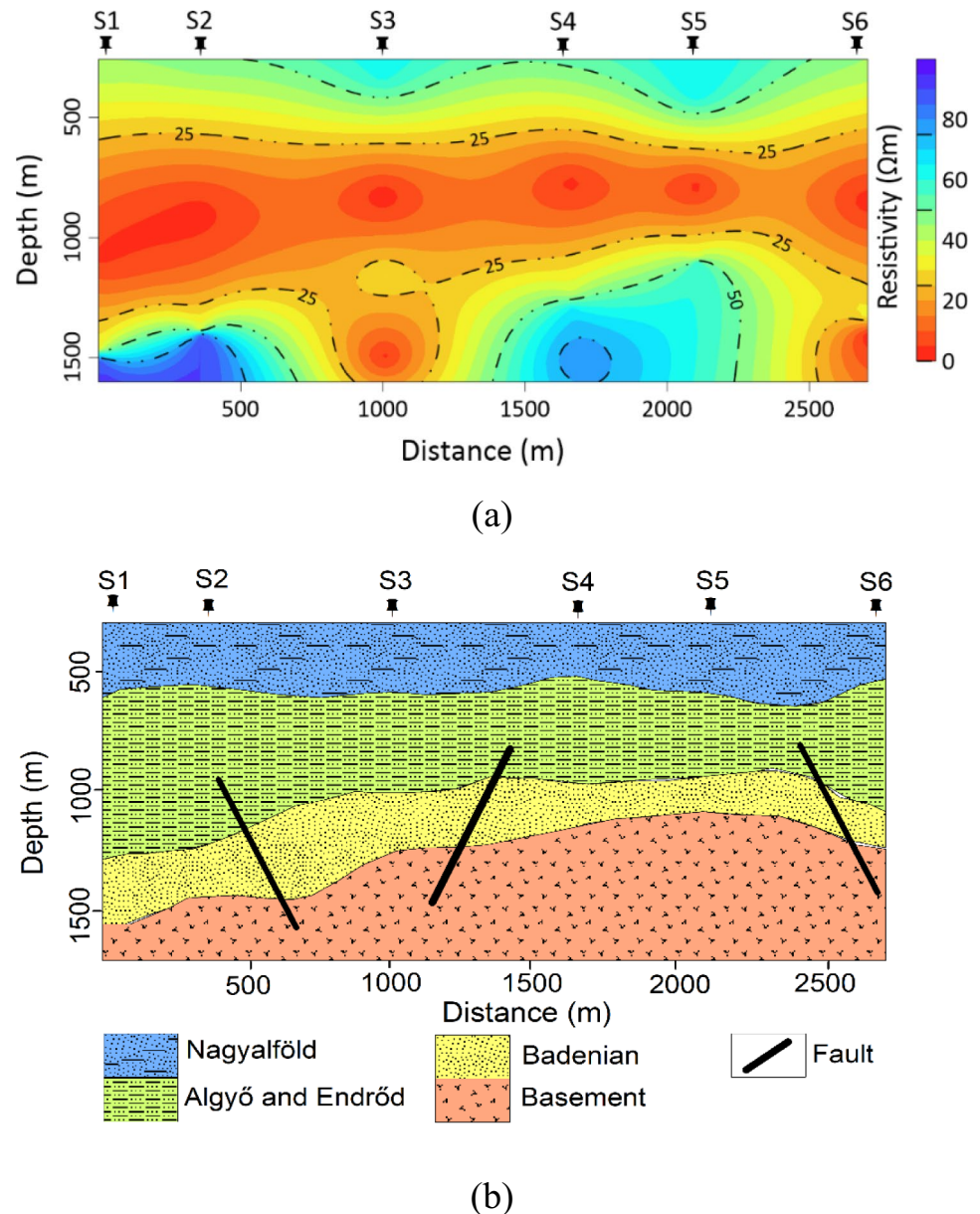
lower hydraulic conductivity and transmissivity (Flores et al. 2023).

The Algyő and Endrődi unit represents the second hydrostratigraphical unit in the section. It has a thickness of 750 m and an average resistivity value of 3  $\Omega\text{m}$ . The lower resistivities indicate the presence of impermeable materials, representing a significant aquitard in the study area (Buday et al. 2015). These impermeable materials consist mainly of clay, silt, and marl with 0.1 mD average permeability (Tóth and Almási 2001). The transverse resistance of the Lower Pannonian unit varies from 550 to 2856  $\Omega\text{m}^2$ , and the longitudinal conductance is between 161.9 and 454.5  $\Omega^{-1}$ . The lower transverse resistance is due to the low resistivity

of the layer, while the higher longitudinal conductance is due to the higher thickness. The higher longitudinal conductance increases the ability of the layer to hold back the surface and subsurface pollutant movement and thus reduce the vulnerability of the aquifer to contamination (Oladapo and Akintorinwa 2007).

The Miocene Badenian Formation is the third hydrostratigraphical unit, with an average thickness of 170 m and a resistivity value of 35  $\Omega\text{m}$ . This unit forms an essential hydrostratigraphic unit, which is made up primarily of sandstones, silt, and clays (Tóth and Almási 2001). Within this Formation of 100 mD permeability, the permeable sandstone layers act as valuable thermal water aquifer (Buday

**Fig. 9** **a** Geoelectrical and **b** geological cross-section obtained from 2D inversion of MT data



et al. 2015). The average transverse resistance and longitudinal conductance of this unit are  $5712.5 \Omega\text{m}^2$  and  $4.8 \Omega^{-1}$ , respectively. The hydraulic conductivity of this aquifer ranged between 12.3 and 13.9 m/day, while the transmissivity was between 1201.6 and 3476.7  $\text{m}^2/\text{day}$ . The groundwater quality of this unit is likely to be good as this layer is overlaid by the Algyő and Endrőd aquitard and has higher protective strength (Mohammed et al. 2023a). The Pre-Neogene basement rock is the bottommost unit in the hydrogeological section. It serves as the geological foundation and has the highest resistivity values with an average of  $60 \Omega\text{m}$ . The basement rock from the bottom hydrostratigraphical unit in the study area consists of impermeable metamorphic rock, potentially acting as a barrier to vertical groundwater

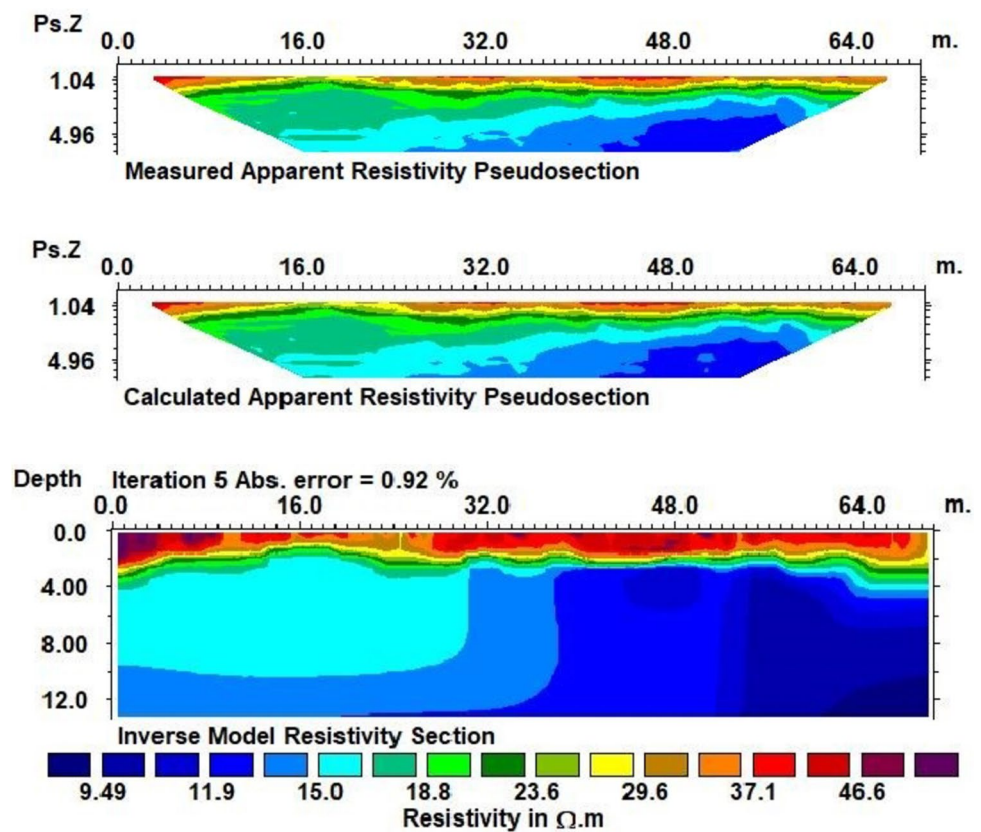
movement. Fracture and faulting, however, increase the permeability of this unit (Tóth and Almási 2001).

### Mapping of groundwater table

ERT survey is conducted to delineate the contact between the saturated and unsaturated zones and thus map the variations in the depth to the water table. The ERT profiles of 70 m length are inverted, and an example of the 2D inversion is illustrated in Fig. 10, in which the measured and calculated electrical resistivity and the model results area are shown. The apparent resistivity values range between 11.8 and  $45.5 \Omega\text{m}$  with an average value of 20.02. However, the modeled resistivity ranged between 8.23 and  $51.3 \Omega\text{m}$ . The

**Table 1** The result of 1D inversion of MT points and their associated hydrogeological characteristics

| Station | Layer | Thickness (m) | $\rho$ ( $\Omega$ m) | Hydrostratigraphy | $S$ ( $\Omega^{-1}$ ) | $R$ ( $\Omega$ m <sup>2</sup> ) | $K$ (m/d) | $T$ (m <sup>2</sup> /d) |
|---------|-------|---------------|----------------------|-------------------|-----------------------|---------------------------------|-----------|-------------------------|
| S1      | 1     | 650           | 41.7                 | Nagyalföld        | 15.6                  | 27,105                          | 11.9      | 7738.2                  |
|         | 2     | 680           | 4.2                  | Algyő and Endrődi | 161.9                 | 2856                            | –         | –                       |
|         | 3     | 250           | 35.3                 | Badenian          | 7.08                  | 8825                            | 13.9      | 3476.7                  |
|         | 4     | –             | 87                   | Pre-Neogene       | –                     | –                               | –         | –                       |
| S2      | 1     | 600           | 49.7                 | Nagyalföld        | 12.07                 | 29,820                          | 10.1      | 6064.2                  |
|         | 2     | 670           | 2.8                  | Algyő and Endrődi | 239.3                 | 1876                            | –         | –                       |
|         | 3     | 150           | 40                   | Badenian          | 3.75                  | 6000                            | 12.4      | 1856.4                  |
|         | 4     | –             | 92                   | Pre-Neogene       | –                     | –                               | –         | –                       |
| S3      | 1     | 620           | 42                   | Nagyalföld        | 10                    | 38,440                          | 8.2       | 5098.4                  |
|         | 2     | 500           | 1.1                  | Algyő and Endrődi | 454.5                 | 550                             | –         | –                       |
|         | 3     | 165           | 29.2                 | Badenian          | 5.6                   | 4818                            | 13.7      | 2260                    |
|         | 4     | –             | 65                   | Pre-Neogene       | –                     | –                               | –         | –                       |
| S4      | 1     | 615           | 52                   | Nagyalföld        | 11.8                  | 31,980                          | 9.7       | 5958.9                  |
|         | 2     | 500           | 3.2                  | Algyő and Endrődi | 156.3                 | 1920                            | –         | –                       |
|         | 3     | 180           | 40                   | Badenian          | 4.5                   | 7200                            | 12.4      | 2227.7                  |
|         | 4     | –             | 67                   | Pre-Neogene       | –                     | –                               | –         | –                       |
| S5      | 1     | 673           | 64.6                 | Nagyalföld        | 10.4                  | 43,475.8                        | 7.9       | 5326.1                  |
|         | 2     | 430           | 2.9                  | Algyő and Endrődi | 148.3                 | 1247                            | –         | –                       |
|         | 3     | 100           | 40                   | Badenian          | 2.5                   | 4000                            | 12.4      | 1237.6                  |
|         | 4     | –             | 60                   | Pre-Neogene       | –                     | –                               | –         | –                       |
| S6      | 1     | 590           | 42.5                 | Nagyalföld        | 13.9                  | 25,075                          | 11.7      | 6903                    |
|         | 2     | 620           | 1.8                  | Algyő and Endrődi | 344                   | 1116                            | –         | –                       |
|         | 3     | 80            | 32.5                 | Badenian          | 2.5                   | 2600                            | 15.02     | 1201.6                  |
|         | 4     | –             | 20.2                 | Pre-Neogene       | –                     | –                               | –         | –                       |

**Fig. 10** Example ERT data inversion showing the measured and calculated apparent resistivity along with the modeled resistivity section in profile 6

upper zone (0–3 m) showed high resistivity values, gradually decreasing with depth. The high resistivity values observed in the upper zone of the profile may indicate a relatively dry and less conductive layer. This layer consists of materials with low moisture content of clay, silt, or consolidated rocks (Tóth and Almási 2001). However, deeper into the profile, the resistivity values decrease. This transition zone may indicate a zone where the moisture content gradually increases, forming the saturated zone. Accordingly, the contact between the saturated and the unsaturated zone is delineated (Fig. 11).

The upper boundary of the saturated zone is the groundwater table; consequently, the variations in the groundwater table mapped across the study area and presented in Fig. 12. The southern part of the study area shows a deep groundwater table (about 4 m from the ground surface), while the northern and central parts show a shallow groundwater table (about 2 m). The contrasting water table depths in different parts of the study area can be linked to variations in groundwater recharge. The deep water table indicates that the aquifer has limited recharge sources and is poorly connected to surface water sources. The annual precipitation in the study area is sufficient to maintain the water table within 6–8 m below the surface of the interfluvium, even beneath the highest sand hills, and within 0–2 m in the river valleys. The former studies indicated that the hydraulic head values are highest in the northern part of the region, reaching up to 120 m, while they are lower in the southwest, which is in line with the topography (Flores et al. 2023).

### Hydrogeophysical compilation

The modeling of the gravity data delineated the depth relief of basement rocks, particularly the Pre-Neogene Aquitard that constitutes the basal hydrostratigraphical unit in the study area (Mádl-Szőnyi et al. 2019). This low-permeability aquitard unit significantly shapes the hydrogeological framework at the base of the GHP. The delineation of the top of this unit contributes to the understanding of the hydrodynamics of the study area as this unit restricts the vertical downward movement of groundwater (Tóth and Almási 2001). Moreover, the gravity data indicated the thickness of sedimentary sequences that have a higher potential for groundwater. The MT data validated the depth of the Pre-Neogene Aquitard obtained from gravity data analysis and provided the thickness and characteristics of the hydrostratigraphical units above the Pre-Neogene Aquitard. In general, a positive correlation is observed between the depth of the basement rock and the transmissivity of Nagyföld and Badenian aquifers. Based on the obtained hydraulic conductivity and transmissivity of these aquifers in the central parts of the study area, these aquifers are considered highly productive and ideal for groundwater development (Krásný

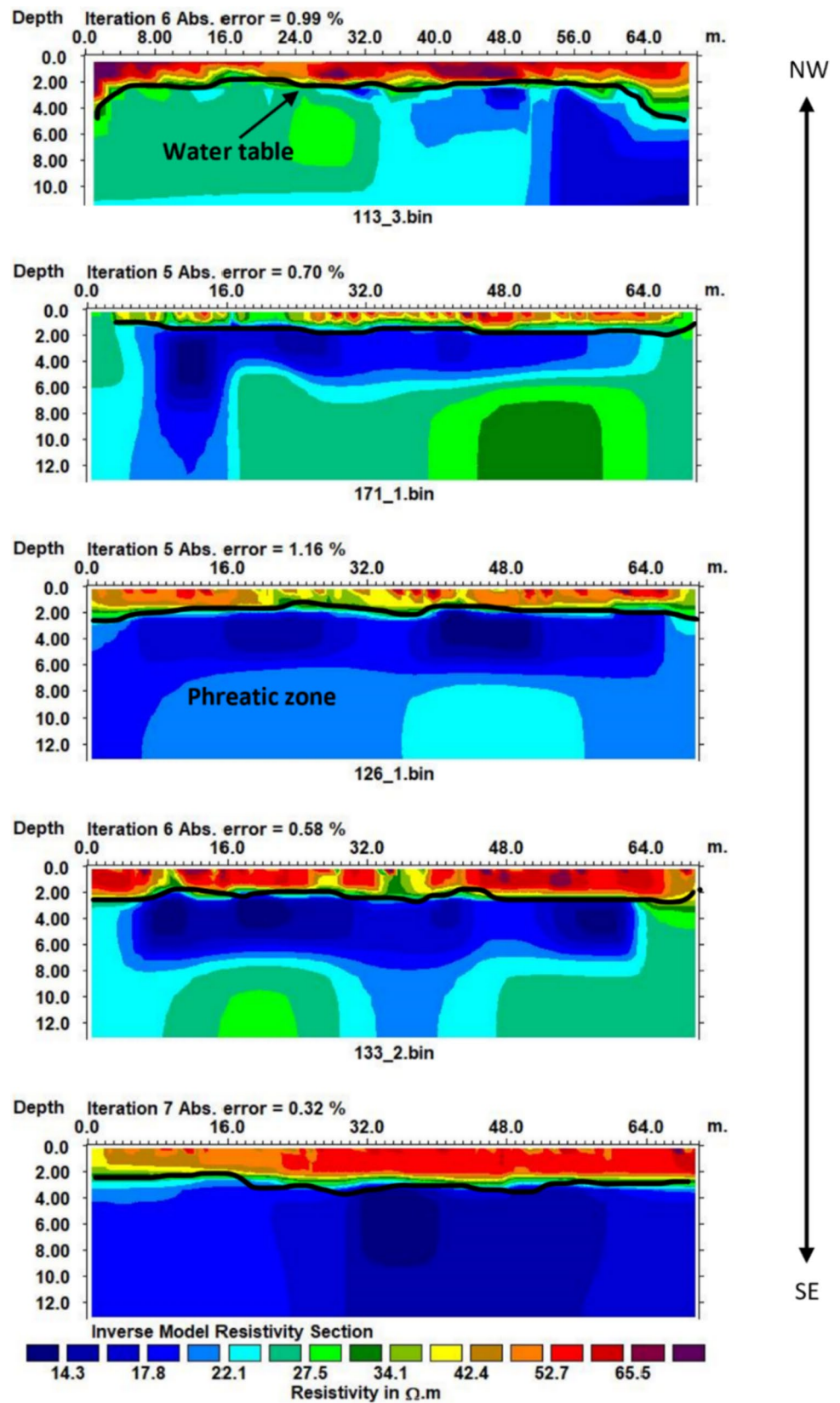
1993). The analysis of the ERT data further contributed to this conclusion and indicated a shallower water table in the central and northern parts of the study area that is characterized by higher sedimentary rock thickness and deeper basement depth. The thick sediments provide increased water storage capacity and hydraulic conductivity compared to thin sedimentary layers that allow for greater retention of infiltrated water (Woessner and Poeter 2020). The integrated approach established an effective framework for delineating the thickness, estimating the hydrological properties of aquifer units, and comprehending shallow aquifer dynamics. This information provides an understanding of the aquifer system behavior and promotes informed decisions for efficient groundwater development in the Western Debrecen area.

### Conclusions

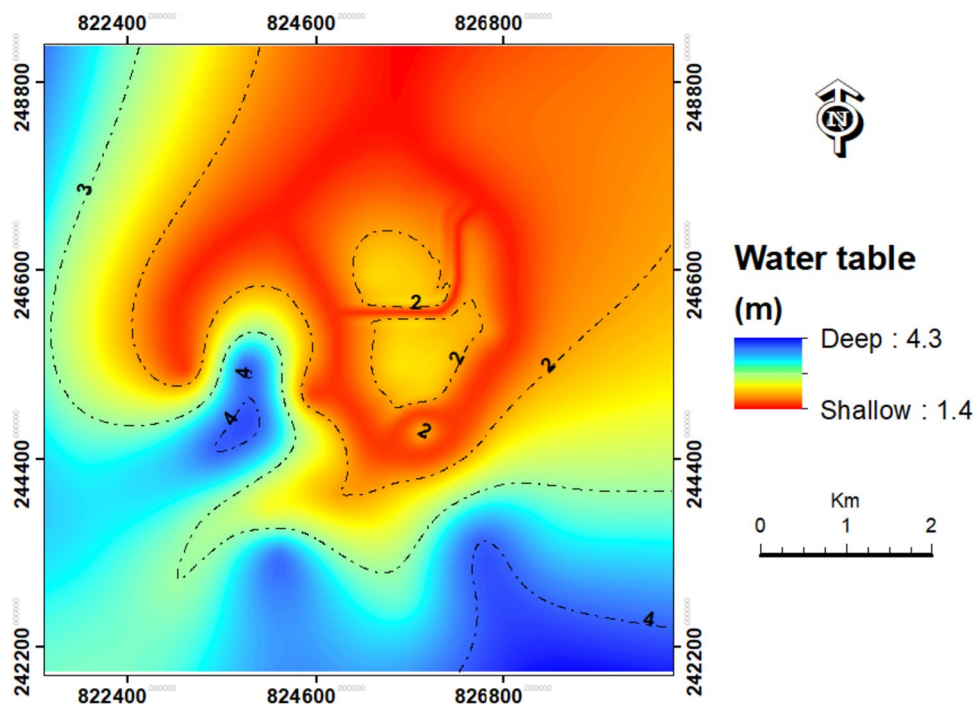
The Western Debrecen area is a significant hydrogeological region in Eastern Hungary that supplies both thermal water and groundwater. The groundwater aquifers in the study area are overly exploited resulting in groundwater deterioration. This research used geophysical data to enhance the understanding of the aquifer properties that can assist in informed decisions for groundwater development plans. The hydrogeophysical methods of gravity, MT, and ERT demonstrated their effectiveness in characterizing the main aquifer units, and the conclusions can be summarized as follows:

- Gravity proved a reliable method for mapping variations to depth to basement rock as a bottom hydrostratigraphical unit in the study area. The 2D modeling of the gravity data showed that the depth to the Pre-Neogene basement rock varied between 1200 and 1900, indicating a deep basin with a high potential for groundwater development. This result is confirmed by the modeled MT data. Furthermore, the MT data showed great potential in differentiating hydrostratigraphic units above the Pre-Neogene rocks. These units included Nagyföld Aquifer, Algyő and Endrődi Aquitard, and Badenian Aquifer. The hydraulic conductivity and transmissivity of the aquifer units indicated that Nagyföld and Badenian aquifers are highly productive and ideal for groundwater production.
- ERT data have successfully mapped the water table by measuring subsurface electrical variations between the saturated and unsaturated zones. Generally, a shallow groundwater table is observed; however, the central and northern parts of the study area are associated with a shallower water table compared to the south. The shallow water table has resulted from slower groundwater percolation and extended water storage within the sediments, contributing to a higher and more sustained water table.

**Fig. 11** 2.5 D inversion of ERT data along the electrical profile to map the contact between the saturated and unsaturated zones



**Fig. 12** Variations in the depth to water table obtained from the analysis of ERT data



- The findings of this research hold significant implications for the development of the study area as identifying highly productive aquifers signifies their contribution to fulfilling groundwater supply for agricultural and domestic uses.

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**Availability of data and materials** The dataset analyzed during the current study is confidential.

## Declarations

**Conflict of interest** The authors declare no financial or non-financial interests that are directly or indirectly related to this work.

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