

Hydrogeological characterisation of an integrated Managed Aquifer Recharge system in southern Poland using Electrical Resistivity Tomography

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Groundwater represents the primary source of drinking water in many European countries, making the sustainable use and protection of this resource a strategic priority. However, climate change, intensive abstraction, and contamination of aquifers are increasingly negatively affecting them. Managed Aquifer Recharge (MAR) can enhance groundwater quantity and quality, but its effective implementation requires a detailed understanding of the site's hydrogeological characterisation. This study assessed the geological framework and hydrogeological conditions of the Świerczków well field in Tarnów, Poland, using Electrical Resistivity Tomography (ERT). Eight ERT profiles (54–315 m in length) were acquired, allowing the determination of subsurface structures at depths of 10–24 m. The data, jointly interpreted with borehole logs and groundwater monitoring results, enabled the delineation of three principal zones: an unsaturated zone (40–200 m and 200–650 m), a high-resistivity aquifer (up to 1500 m), and a Miocene aquitard (4–200 m). Spatial electrical resistivity variations reflect differences in lithology and groundwater electrical conductivity, supporting identification of zones influenced by MAR recharge and areas receiving inflow of more mineralised native groundwater from the industrial zone. ERT results contributed to optimising the placement of new observation wells and improving the conceptual and groundwater flow model of the site. This research indicates that ERT is a reliable method supporting MAR system management.

Key words: Electrical Resistivity Tomography, near-surface geophysics, Managed Aquifer Recharge, aquifer characterisation, infiltration ditches, riverbank filtration.

INTRODUCTION

Groundwater in Europe is of strategic importance as the main source of drinking water for the population. Unfortunately, aquifers are increasingly exposed to pressures from climate change and human activities. A promising approach to mitigating these pressures involves the use of Managed Aquifer Recharge (MAR) techniques. MAR refers to the intentional recharge of aquifers under controlled conditions to achieve benefits for water management and/or the environment, such as increasing groundwater availability or improving and maintaining water quality (Dillon et al., 2019, 2020; Sitek et al., 2025). Moreover, MAR represents one of the promising tools that can contribute to achieving the overarching objective of the EU Water Framework Directive, namely the improvement and maintenance of the good status of surface and groundwater bodies (European Commission, 2025).

The success of MAR implementation and its proper functioning depend on a wide range of technical and non-technical factors, which may ultimately determine whether a project succeeds or fails (Imig et al., 2022; Sitek et al., 2023). Therefore, the design, operation, and management of MAR systems must be based on the principles of sustainable water resources management, taking into account ecosystem protection and societal needs. This process should also be preceded by a comprehensive cost–benefit analysis, an evaluation of hydrogeological conditions, appropriate technical planning, and continuous monitoring of groundwater quality and quantity at all stages of the MAR system's operation (Zhang et al., 2020; Halytsia et al., 2022; Ross, 2022; Zheng et al., 2023; Janik et al., 2025; Sitek et al., 2025).

In recent years, increasing attention has been paid to the application of various near-surface geophysical methods in studies assessing the suitability of locations for MAR projects and evaluating their effectiveness (Parker et al., 2022). One of the most commonly used and promising techniques is Electrical Resistivity Tomography (ERT), which enables detailed characterisation of subsurface hydrogeological structures such as the location and boundaries of permeable deposits, confining units, depth of bedrock, preferential recharge zones and the pres-

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ence of water zones with various total dissolved solids (TDS) (Sendróš et al., 2020a, b; Parker et al., 2022; Perzan et al., 2023; Arboleda-Zapata et al., 2025; Mamud et al., 2025).

Previous hydrogeophysical studies conducted in Poland have demonstrated the usefulness of modern, non-invasive, near-surface geophysics methods for identifying hydrogeological structures, recharge zones and groundwater quality contrasts in Quaternary deposits (Mościcki et al., 2014; Oryński et al., 2016; Olichwer et al., 2017). Recent studies demonstrate the usefulness of ERT in imaging Quaternary porous aquifers and fluvial deposits, including delineation of sand–gravel aquifers and identification of buried channel structures, as well as in diagnosing hydrogeological heterogeneity in human-impacted valley environments (Bania and Woźniak, 2022). ERT has also been successfully used to assess the impact of groundwater mineralisation and anthropogenic contamination, where increased porewater conductivity produces low-resistivity anomalies that can be distinguished from lithological contrasts (Bania, 2018). Moreover, ERT surveys performed in river valley peatlands in Poland further demonstrate that resistivity imaging supports the interpretation of groundwater–surface water interactions and shallow hydrostratigraphy in lowland settings (Kaczmarek et al., 2024; Kowalczyk et al., 2025; Sinicyn et al., 2025). This regional body of work highlights that resistivity ranges observed in groundwater systems are strongly site-dependent and controlled by both lithology and groundwater chemistry. Therefore, they should be interpreted against comparable hydrogeological analogues and supported by complementary datasets, at least based on borehole data, as demonstrated by Mendecki et al. (2025) in coastal aquifers affected by saltwater intrusion.

The subject of this study is the Świerczków well field, located in Tarnów, Poland. The facility consists of several production wells recharged primarily through a system of infiltration ditches and, to a lesser extent, by riverbank filtration from the River Dunajec. An additional, minor inflow of native groundwater originates from the eastern side, where an extensive industrial zone is situated (Fig. 1). Together with the Kępa Bogumiłowska well field (Janik et al., 2024, 2025), the Świerczków site constitutes the main groundwater abstraction system operated by Waterworks Tarnów, supplying water to the Tarnów agglomeration. The Świerczków well field exemplifies an integrated MAR system that combines the infiltration ditches technique with riverbank filtration, which poses specific challenges for operation and monitoring (Treichel et al., 2015; Sitek et al., 2023, 2025).

The main aim of the study was to apply the ERT method towards a detailed characterisation of the geological framework and hydrogeological conditions within the well field area. Identification of lower-resistivity zones in the Quaternary, high-resistivity freshwater aquifer at the Świerczków well field may also indicate inflow of contaminated water from the eastern industrial area. Based on these objectives, we demonstrate how the application of the ERT method can support decision-making processes related to the design, monitoring, and safe operation of MAR systems.

In the context of the increasing global importance of MAR in groundwater resources management, and the growing requirements for quality control and performance monitoring of such systems (Dillon et al., 2019; Zheng et al., 2023), the use of diagnostic tools such as ERT often complemented by other methods, including environmental tracers and numerical modelling (Sitek et al., 2025), may be crucial for their effective and safe management.

STUDY SITE

The Świerczków well field is located in the northwestern part of Tarnów (southern Poland), between the right bank of the River Dunajec to the west and a floodbank to the east, within a flat alluvial terrace that gently rises southwards (Fig. 1).

The subsurface structure of the research area consists of Quaternary fluvial and glaciofluvial deposits underlain by Miocene clays and mudstones. The unconfined Quaternary aquifer comprises mainly medium to coarse sands and gravels with pebble admixtures. This region's only aquifer forms a highly permeable layer up to 6–12 m in thickness. The aquifer is overlain by 1–4 m of semipermeable sandy loams, loams, silts and organic silts, which provide limited protection from surface contamination. Within the Świerczków well field itself, data from all borehole logs reveal a consistent lithostratigraphy comprising consistently low-permeability surface sandy loams, underlain by a sandy gravel aquifer with pebbles, and the Miocene beds, which act as a regional aquitard.

Under natural conditions, the groundwater flow direction is from the east and south-east towards the River Dunajec. Nowadays, these flow patterns are significantly modified by the operation of pumping wells and MAR facilities at the Świerczków well field. The groundwater table at the well field ranges from 183 m a.s.l. in the north-west to 185.5 m a.s.l. in the south-east. The Świerczków well field includes 17 abstraction wells, of which 15 are currently in operation, and four infiltration ditches (Fig. 1). The site has a long history of groundwater use. The first wells were constructed in 1910. The most recent modernisation included the drilling of seven replacement wells in 2012 and nine observation wells in 2021. Current groundwater extraction averages 6,500–7,000 m³/d, representing 76–82% of the permitted water volume. Water from the production wells is supplied through two siphon pipelines to a collector caisson located behind the floodbank (Treichel et al., 2015; Sitek et al., 2023, 2025).

Two complementary MAR techniques are employed at the Świerczków well field: infiltration ditches and induced riverbank filtration. These techniques were introduced to enhance groundwater resources and to mitigate the inflow of contaminated groundwater originating from the neighbouring industrial zone, situated directly east of the floodbank (Fig. 1). Historical contamination of the shallow aquifer is a legacy of decades of industrial and chemical activities, including fertiliser production and waste disposal. The neighbouring industrial zone (Fig. 1) began development about a decade after the Świerczków well field. The primary chemical works in the Tarnów–Mościce area was established in the late 1920s, with subsequent expansion over the following decades. Given the facility's strategic importance, detailed time series of historical emission intensity or production-cycle seasonality are not available within the scope of this study; therefore, we did not attempt to quantify seasonal contaminant loading. Nevertheless, the groundwater pollution caused by chemical plant operations can be primarily linked to historical industrial activity. The currently observed elevated levels of ions are associated with concentrations of dissolved inorganic constituents: major ions and nitrogen compounds (Wojtał, 2013; Sitek, 2022). The company places strong emphasis on environmental protection by minimising the impact of its activities, implementing waste management and recycling practices, ensuring legal compliance, and adopting integrated management systems in accordance with ISO standards.

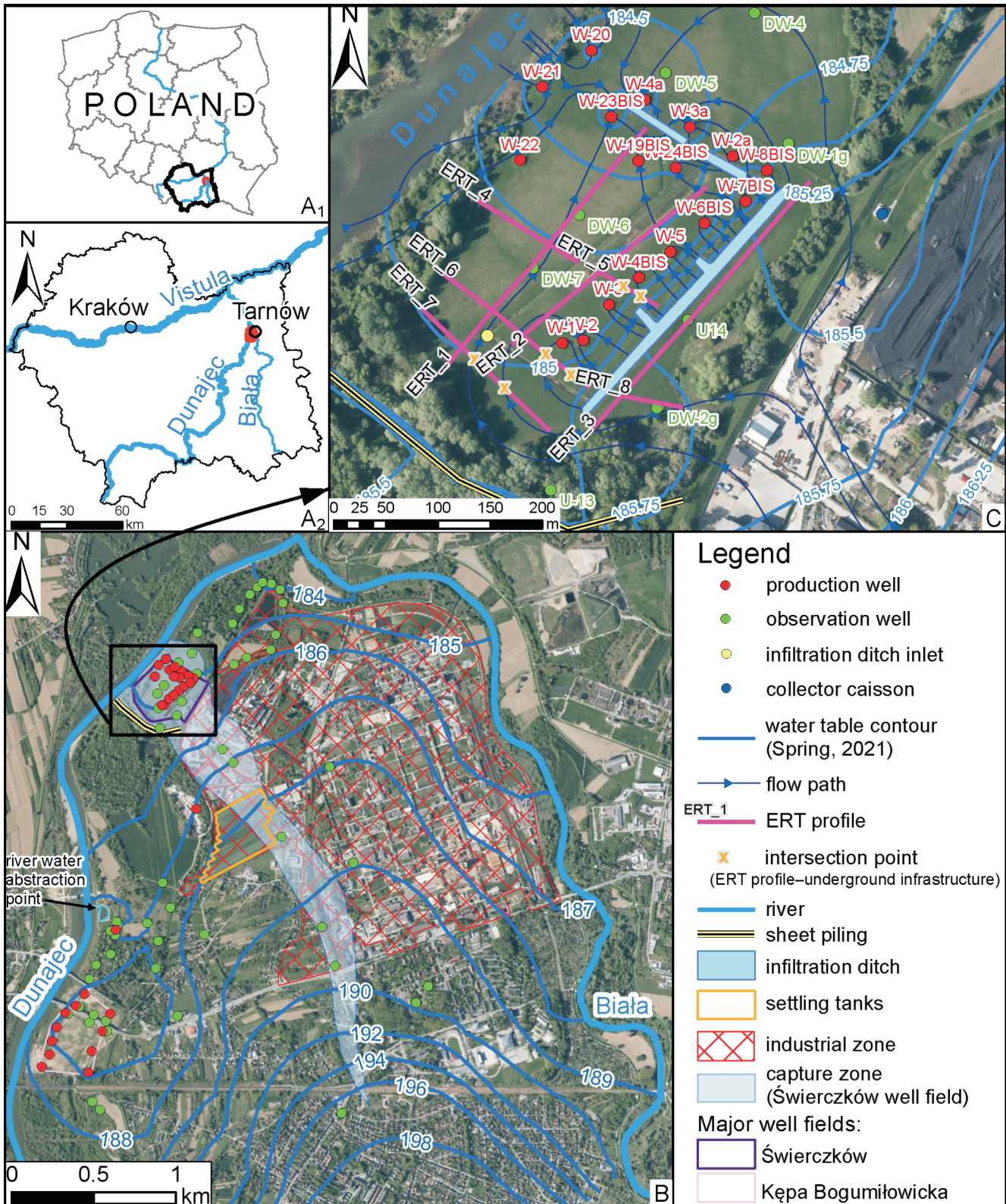


Fig. 1. Regional context (A₁–A₂), local hydrogeological settings (B), and detailed map of the Świerczków well field (C)



Fig. 2. LUND electrical imaging system with a Terrameter SAS 1000/4000 (ABEM Malå) used for the ERT measurements

The LUND electrical imaging system consists of an instrument, an electrode selector, two multielectrode cables, electrodes, cable-electrode joints and a battery

The infiltration ditches, located along the eastern and northern boundaries of the well field (Fig. 1), are supplied with surface water from the River Dunajec at an average rate of 4,300 m³/d. The maintained high water level in the ditches creates a hydraulic mound that serves as a hydraulic barrier, thereby limiting the inflow of polluted groundwater from the adjacent industrial area. Artificial recharge through the ditch beds improves both the quantity and quality of the groundwater, supporting the sustainability of the water supply. At the Świerczków wellfield, a complementary MAR method to the infiltration ditches is induced bank filtration. Riverbank filtration occurs in the western part of the well field near the riverbank. Pumping the wells situated near the River Dunajec lowers the local groundwater table and generates a hydraulic gradient that promotes river-to-aquifer infiltration. The intensity of riverbank filtration depends on both pumping rates and river stage fluctuations, which in the Dunajec are highly variable and responsive to rainfall and snowmelt events (Janik et al., 2025; Sitek et al., 2025). Chemical analyses confirm that groundwater recharged via MAR shows significantly improved quality compared with naturally inflowing groundwater from the industrial side. Monitoring conducted under the DEEPWATER-CE project (2019–2022) indicated significant reductions in nitrogen species (Sitek et al., 2023, 2025).

MATERIALS AND METHODS

ERT METHODOLOGY

The measurements were performed using the LUND electrical imaging system (Fig. 2) with a Terrameter SAS 1000/4000 produced by ABEM Malå (Guideline Geo). The instrument measures voltage responses (between two potential electrodes) created by the transmitter current (between two current electrodes) while rejecting both DC voltage and noise. The LUND electrical imaging system consists of 41 electrodes,

each of which is used as a current and potential electrode. The ratio V/I is automatically calculated, displayed and recorded by the Terrameter. The transmitter was operating at 500 mA with resolution of 0.02 mW for a single reading. The median value from four stackings was used for the single resistivity measurement. During the field acquisition a limited number of negative apparent resistivity values were observed. These data points were identified as non-physical anomalies occurring in the vicinity of underground infrastructure. Following standard data processing protocols, these outliers were removed from the dataset prior to the inversion process to ensure the reliability of the final models. The measurements were supplemented using the Wenner-Schlumberger electrode configuration with 3 m electrode separations. This particular array was chosen because it is moderately sensitive to both horizontal and vertical structures, and offers better horizontal coverage and signal strength compared to other arrays.

Eight ERT profiles, from 54 m up to 315 m in length, depending on the area conditions, were carried out during the fieldwork in December 2019 (Fig. 1 and Table 1). The data were interpreted with RES2DINV software (Geotomo Software) which uses an iterative smoothness-constrained least-squares method to create a model of resistivity of the subsurface. The resulting models were based on 112–330 points for the shorter profiles (ERT4, ERT5, ERT8) and 539–1035 points for the longer profiles (Table 1). The root-mean-squared error (RMS), which indicates the differences between the calculated and measured values of apparent resistivity in the model, varied from 2.4 to 6.1% for the 5th iteration (Table 1).

The results of the geophysical survey were shown together with simplified logs of the three observation wells (DW-2g, DW-6, DW-7) and four production wells (W-1, W-3, W-4BIS, W-6BIS) present in the research area (Figs. 3 and 4). The borehole logs provided detailed data on the lithology and thickness of the unsaturated and saturated zones as well as information on the top of the aquitard (Miocene bed).

Table 1

Parameters for field data acquisition for ERT survey

Profile no	Data points	RMS [%]	Depth of penetration [m]	Profile length [m]	Profile coordinates (latitude, longitude)	
					Start point	End point
ERT_1	859	6.2	23.6	290	50.027853, 20.899257	50.029878, 20.902036
ERT_2	774	4.3	23.6	240	50.028004, 20.900109	50.029323, 20.902780
ERT_3	1035	2.8	23.6	315	50.027270, 20.901174	50.029364, 20.904205
ERT_4	330	3.0	23.6	110	50.029273, 20.899723	50.028662, 20.901107
ERT_5	158	3.0	12.9	66	50.028632, 20.901265	50.028260, 20.902181
ERT_6	546	2.6	23.6	171	50.028628, 20.899222	50.027565, 20.901223
ERT_7	539	2.7	23.6	171	50.028363, 20.898905	50.027219, 20.900662
ERT_8	112	2.4	9.56	54	50.027548, 20.901471	50.027427, 20.902379

ELECTRICAL CONDUCTIVITY MEASUREMENTS

EC was measured in situ over a 1-year monitoring period at a monthly sampling frequency. Prior to sampling, observation wells were pumped to remove stagnant water from the casing and to ensure that the measurements reflect formation groundwater. EC measurements were then conducted directly in the field using calibrated portable EC-meters (Elmetron CC-401). Groundwater mean EC values at the Świerczków well field ranged from $\sim 324 \mu\text{S}/\text{cm}$ in infiltration ditches to $1001 \mu\text{S}/\text{cm}$ in observation well U14. Additionally, in selected wells, automatic EC dataloggers were installed, providing continuous, high-temporal-resolution records of groundwater conductivity. All EC values reported in this study correspond to measurements taken at a single depth within the screened interval of each well. No vertical EC profiling was performed.

RESULTS

The ERT measurements allowed tracking of the subsurface structure to depths of 10–13 m for profiles ERT_8 and ERT_5, and to ~ 24 m for the remaining profiles (Figs. 3 and 4; Table 1). In addition, the following zones were distinguished in each profile: the unsaturated zone, the saturated zone, and the top of the aquitard (Miocene deposits).

The unsaturated (aeration) zone in the research area is represented by a soil layer 0.5 m thick, underlain mainly by sandy loam, loam, or silt. The unsaturated zone has an electrical resistivity of 44–200 $\Omega\cdot\text{m}$ and is ~ 4.5 m thick in the southern part of the research area. In the northern part, the unsaturated zone is thinner and more resistive ER: 200–650 $\Omega\cdot\text{m}$, and 2.5 m thick (Table 1). This contrast is clearly visible on the profiles ERT_1–ERT_2 (Fig. 3) and reflects the geology of the area: the lower values of electrical resistivity are connected with the thicker layer of sandy loam and loam compared to the thinner layer occurring in the northern part (Fig. 3). The layer of soil and loam or silt is underlain by the layer of gravels with pebbles and

sands, which has an electrical resistivity of 200–1500 $\Omega\cdot\text{m}$; it lies at a depth of 2.5–4 m and is 3 m (i.e. ERT_3) to 9 m (i.e. ERT_1) thick (Fig. 3).

The electrical resistivity of the saturated zone is closely associated with the high resistivity of pebbles, which are present throughout the aquifer. It is also related to the amount of substances dissolved in water, as indicated by chemical analyses, where the average values of electrical conductivity of the water in the wells range from $\sim 350 \mu\text{S}/\text{cm}$ in W-3a to $1780 \mu\text{S}/\text{cm}$ in DW-3. In areas where infiltration from surface waters originating from infiltration ditches and the river is substantial, the resistivity values of the aquifer tend to be higher (i.e. ERT_1, ERT_2, ERT_4). Generally, the saturated zone forms a continuous, high-resistivity layer between the low-resistivity unsaturated zone (200–650 $\Omega\cdot\text{m}$) and the low-resistivity aquitard, represented here by silty clay (4–200 $\Omega\cdot\text{m}$; Figs. 3 and 4). The wide range of electrical properties in the vertical profile is due to the considerable diversity of the deposits.

Because electrical resistivity is controlled by multiple factors, including porosity, lithology, water saturation, TDS, temperature, clay content and grain size distribution (Stasiński et al., 2025), an integrated interpretation approach was applied. To minimise uncertainty, the ERT results were analysed together with archival studies, lithological logs, groundwater EC data, chemical tracers and numerical modelling results (Wojtal, 2013; Treichel et al., 2015; Sitek, 2022; Sitek et al., 2023, 2025).

DISCUSSION

ELECTRICAL RESISTIVITY SIGNATURES
IN MAR-AFFECTED AQUIFERS

Electrical resistivity in MAR settings shows highly diagnostic contrasts between the vadose zone, the freshwater-saturated zone, and the underlying low-permeability layers, allowing ERT to effectively track infiltration and recharge dynamics. The

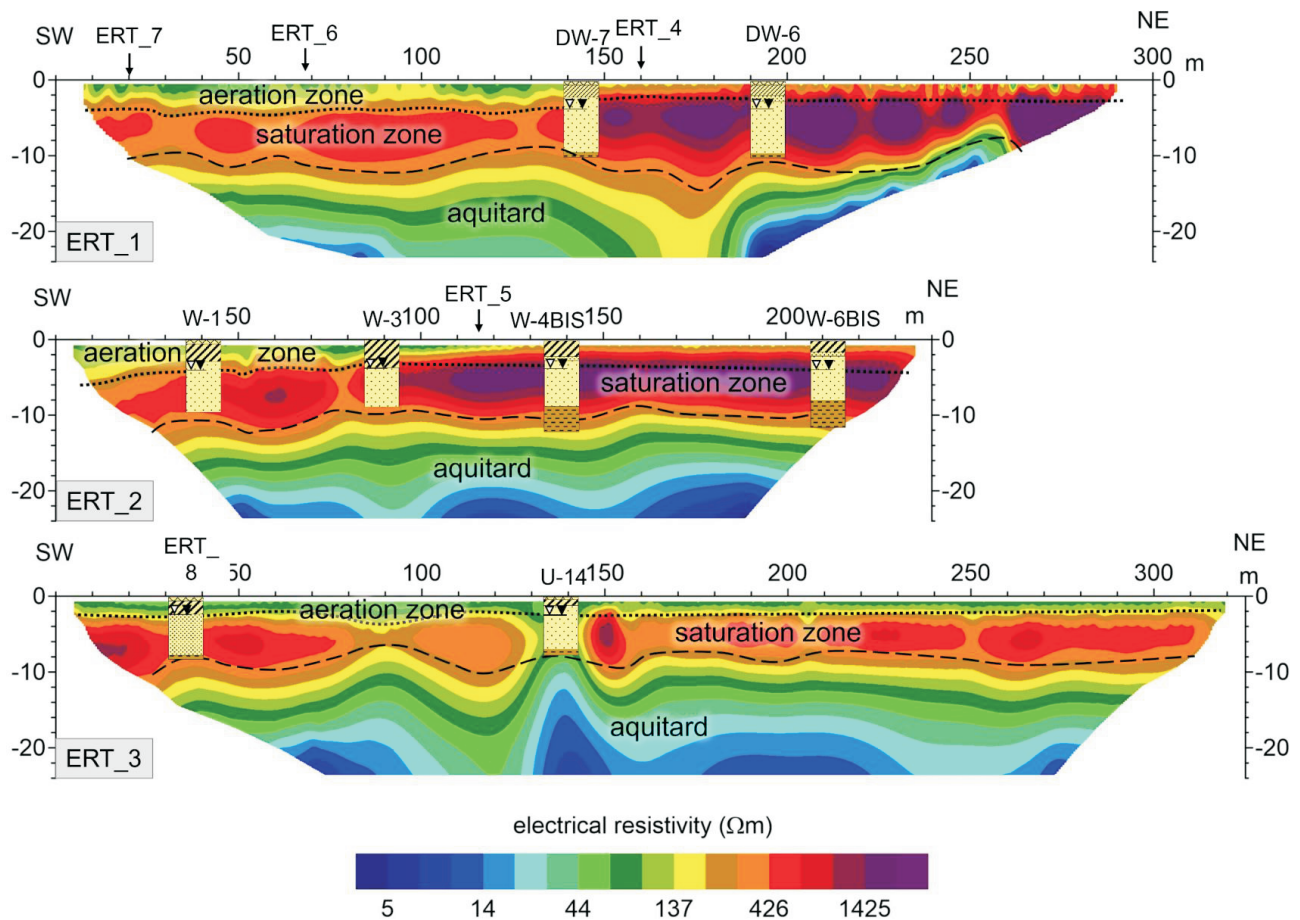


Fig. 3. Inversion results of ERT_1–ERT_3 measurements and borehole logs near the ERT profiles

For all ERT profiles, the dotted line indicates the boundary between the unsaturated and the saturated zone; the dashed line indicates the boundary between the saturated zone and the aquitard. A uniform electrical resistivity colour scale was applied to all profiles. The hatched areas on the boreholes from the top signify respectively for: DW-7 (soil; sandy loam; gravel, sand, and pebbles; silty clay); DW-6 (soil; sandy loam; gravel, sand and pebbles; silty clay); W-1 (soil; sandy loam; gravel with sand and pebbles); W-3 (soil; sandy loam; gravel with sand and pebbles); W-4BIS (soil, silt/sandy loam; sandy gravel and pebbles, silt), W-6BIS (soil, silt/sandy loam; sandy gravel and pebbles, silt); DW-2g (soil; sandy loam; sand, gravel and pebbles; silty clay); U-14 (soil, silty loam; sandy gravel and pebbles; silty clay)

vadose zone is typically characterised by high resistivity, commonly 100–1000 Ωm . However, higher electrical resistivity values are associated with lower volumetric water content and higher air saturation, which can be observed in coastal and alluvial MAR systems (Ulusoy et al., 2015; Tesfaldet and Puttiwongrak, 2019). In contrast, the saturation zone typically exhibits moderate resistivity (10–300 Ωm), with values dependent on porewater salinity and sedimentary texture, as demonstrated in coastal MAR experiments in Spain and Italy (García-Menéndez et al., 2018; Greggio et al., 2018). Where MAR systems interact with brackish or saline aquifers, resistivity may fall below 10–50 Ωm , providing a strong contrast that allows freshwater recharge bubbles to be easily distinguished from saline intrusion (Nenna et al., 2014). The impermeable or clay-rich layers consistently show very low electrical resistivity from 1 to 50 Ωm due to high cation exchange capacity and low hydraulic conductivity, forming resistive boundaries that constrain infiltration pathways (Haaken et al., 2016). Overall, these characteristic resistivity signatures make ERT one of the most powerful non-invasive geophysical methods for monitoring MAR performance, evaluating recharge efficiency, and quantifying the spatial distribution of infiltrating water in heterogeneous subsurface

environments. Against this general background, the resistivity patterns observed at the Świerczków well field show some site-specific features that merit more detailed discussion.

ORIGIN OF HIGH RESISTIVITY IN THE SATURATED QUATERNARY GRAVEL AQUIFER

The relatively high electrical resistivity values (up to 1000–1500 Ωm) observed within the saturated Quaternary aquifer at the Świerczków well field require interpretation in the context of local lithological and hydrogeochemical conditions. In this setting, the aquifer is composed predominantly of coarse-grained sands and gravels, including pebbles that increase in size and abundance with depth. The deposits are characterised by a very low clay fraction and high hydraulic conductivity ($K \approx 10^{-3}$ m/s), as confirmed by borehole logs and pumping tests (Wojtal, 2013; Sitek et al., 2025). Such lithological conditions limit surface conduction and result in high bulk resistivity even under fully saturated conditions.

Similar observations have been reported in other coarse-grained alluvial aquifers. Karlović et al. (2025) linked resistivity values of 500–1600 Ωm to coarse gravel deposits

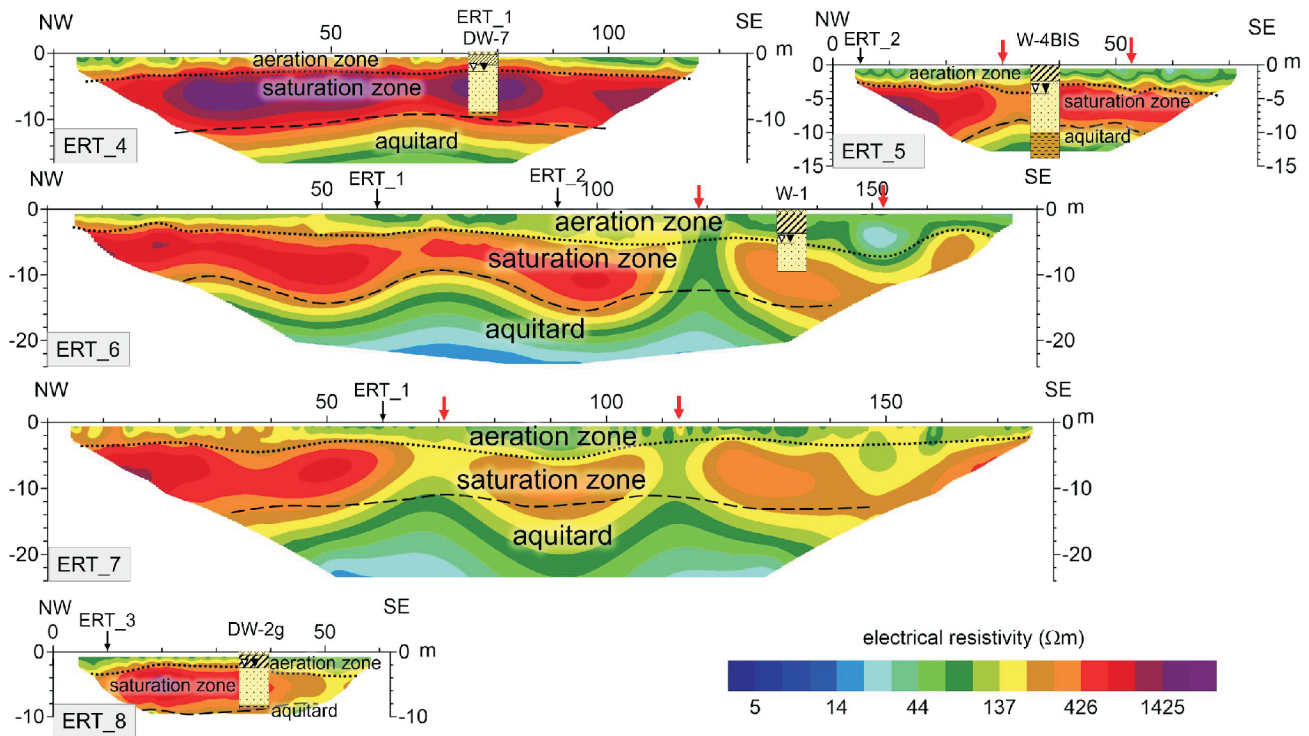


Fig. 4. Inversion results of ERT_4 – ERT_8 measurements and borehole logs near the ERT profiles

Red arrow: location of the contact with underground infrastructure. Other explanations are provided in the [Figure 3](#) caption

within the Varaždin alluvial aquifer in the western part of the Drava River valley (northern Croatia). Likewise, [Mościcki et al. \(2014\)](#), based on geophysical investigations including ERT conducted on the Vistula floodplain near Czernichów village, identified a layer of alluvial sands and gravels characterised by even higher resistivities exceeding 2000 Ω m.

In contrast, the overlying unsaturated deposits at the Świerczków site consist mainly of sandy loams and silts in the upper part (thickness: 1.5–2.0 m) and sand and gravel in the lower part (thickness: 0.5–2.5 m). These deposits exhibit lower resistivity values due to their higher clay content and enhanced surface conductivity.

Groundwater electrical conductivity data provide additional support for this high electrical resistivity interpretation. A consistent inverse relationship between groundwater EC and bulk resistivity is observed across the monitoring wells, with the highest resistivity values (>1000 Ω m) corresponding to zones dominated by low-mineralised MAR-derived water (EC 350–400 μ S/cm), and lower resistivity values (<600 Ω m) associated with inflow of more mineralised native groundwater from the eastern industrial area.

Where resistivity ranges of the unsaturated zone and the saturated aquifer locally overlap, the separation between these units remains robust when ERT results are interpreted jointly with borehole lithology and independently observed groundwater table depths. Taken together, the resistivity values observed at the Świerczków well field indicate that the freshwater gravel aquifer is not anomalous, but rather reflects site-specific lithological and hydrochemical controls.

IMPLICATIONS FOR MAR SYSTEM DESIGN, OPTIMISATION AND MONITORING

One of the main objectives of the geophysical survey conducted in the study area was to characterise the geometry and thickness of the high-resistivity freshwater gravel aquifer. The

research area is characterised by the occurrence of an aquifer with very high hydraulic conductivity parameters, but its thickness is relatively small. Therefore, information on locations where the top of the aquifer is closer to the ground surface, as well as on local depressions of its bed, is of particular importance.

ERT profiles provided a valuable basis for identifying the most suitable locations for new wells at the Świerczków well field. In locations where aquifer thickness is the highest, while maintaining the technical and environmental constraints required during well design, wells can be drilled deeper, allowing groundwater to be extracted under greater operational draw-down and thus increasing water production. The ERT technique therefore, appears to be a highly suitable method for optimising well-siting, contributing to cost minimisation ([Alao and Abubakar, 2025](#)). Moreover, ERT measurements are sometimes complemented by other geophysical techniques, which further enhance the identification of promising aquifer zones for MAR site selection ([Behroozmand et al., 2019](#); [Parker et al., 2022](#); [Szócs et al., 2024](#)).

Information on the variability in the depth to the top of the aquifer, and consequently on the thickness of the low-permeability near-surface sediments, is also of importance for the potential expansion of the infiltration ditch system at the Świerczków well field. Furthermore, data on the permeability of sediments beneath the bottoms of infiltration ditches or ponds allow for the estimation of potential infiltration capacities. At the Świerczków well field, the proper functioning of the infiltration ditches is of strategic importance not only because it significantly increases the groundwater resources exploited by the 15 extraction wells, but also because, in the case of the longest ditch in the east ([Fig. 1](#)), the intensive recharge through the ditches forms a groundwater mound beneath it, which impedes the inflow of contaminated groundwater from the industrial area ([Sitek et al., 2025](#)). [Uhlemann et al. \(2022\)](#) successfully investigated the hydraulic conductivity of sediments underlying infiltra-

tion ponds using the ERT method, while Mawer et al. (2016) highlighted the role of ERT in optimising MAR systems based on spreading techniques by constraining parameters controlling infiltration rates.

Data from eight ERT profiles enabled detailed mapping of the aquifer in the vicinity of the Świerczków well field, which was subsequently used in the development of a detailed numerical groundwater flow model for this area (Sitek et al., 2025). In addition to providing a detailed subsurface geological image, the ERT results also delivered data on the depth to the groundwater table and, indirectly, on the vertical variability of sediment permeability. As emphasised by Parker et al. (2022), unlike conventional groundwater monitoring data from wells and observation wells, which provide point measurements such as groundwater table elevations, ERT profiles allow for the visualisation of these parameters along an entire cross-section. In this way, ERT data complement borehole observations by providing additional hydrogeological information that supports the construction of numerical groundwater flow models, enables a more accurate representation of the aquifer system and reduces model uncertainty (Teatini et al., 2020; Lévesque et al., 2023). At the Świerczków site, the groundwater level is influenced by the location of the infiltration ditches. Therefore, west of the longest infiltration ditch and south of the other three infiltration ditches, the images on the ERT profiles indicate a noticeably shallower occurrence of the groundwater table below the surface than in the other parts of the profiles (Fig. 3).

RESISTIVITY CONTRASTS AS INDICATORS OF MAR-DERIVED AND NATIVE GROUNDWATER

Results from numerical modelling and tracer studies for the Świerczków well field (Sitek et al., 2025) demonstrated that intensive recharge through infiltration ditches leads to the persistence of a distinct groundwater lens characterised by low electrical conductivity values similar to those of the Dunajec. This phenomenon is clearly reflected in the ERT results, particularly in profiles ERT_1 and ERT_2, where the measured electrical resistivity in the central and northern parts of the sections is highest and distinctly different from that observed in the southern parts of the aquifer (Fig. 3). The decrease in electrical resistivity values in the southern sections is attributed to the inflow of contaminated native groundwater from the industrial zone, which increases groundwater conductivity, thereby lowering the measured electrical resistivity.

Based on archival hydrochemical data from the Świerczków well field (Wojtal, 2013; Sitek, 2022), groundwater contamination in the eastern part of the study area is primarily associated with elevated concentrations of dissolved inorganic constituents related to historical industrial activity. These include increased total dissolved solids, major ions, and nitrogen compounds, resulting in higher groundwater electrical conductivity. From a hydrogeophysical perspective, such contamination is therefore expected to reduce bulk electrical resistivity rather than produce distinct resistivity anomalies linked to specific contaminant species.

Semi-quantitatively, the electrical resistivity of the contaminated saturated zone ranged from 200–630 Wm, whereas values in the uncontaminated zone were notably higher, falling between 630 and 1500 Wm. These ranges are consistent with the observed ERT results and measured groundwater EC values from the monitoring network. It is emphasised that ERT does not allow direct identification of contaminant types; therefore, the interpretation relies on the integrated analysis of geophysical data, groundwater electrical conductivity measurements, hydrochemical indicators, and prior site investigations.

The proposed interpretation is consistent with both the groundwater flow paths obtained from the groundwater flow model (Fig. 1) and the results of environmental tracer analyses used to determine the mixing ratios between native groundwater and infiltration water in the production wells (Sitek et al., 2025). Wells W-1 and W-2 receive relatively the highest proportion of native groundwater, whereas moving northwards toward well W-7BIS, the contribution of MAR water from the infiltration ditches becomes dominant. As a result, the resistivity values there are the highest among all the ERT profiles. Hence, the application of the ERT method can also serve as a tool for evaluating the long-term effectiveness of MAR operations, as well as for determining the infiltration dynamics and the spatial extent of artificial recharge influence on the aquifer.

Pronounced spatial variability in electrical resistivity values within the aquifer was utilised during the establishment of the groundwater monitoring network for the well field in 2021 and informed decisions regarding the location of observation wells. For this purpose, observation wells such as DW-1 and DW-2g (located in the eastern part of the well field to measure inflow of native, contaminated groundwater) and DW-6 and DW-7 (located in the central part of the well field to assess the effectiveness of artificial recharge) were installed (Fig. 1). The EC of groundwater measured in these observation wells shows an inverse relationship with the electrical resistivity values obtained. Where the piezometer DW-2g captures native groundwater contaminated by industrial activity in the adjacent area, electrical resistivity values range between 426–622 $\Omega\cdot\text{m}$. In contrast, where the proportion of MAR-derived water increases, such as near DW-7 (up to 850 $\Omega\cdot\text{m}$) and particularly at DW-6 (>1000 $\Omega\cdot\text{m}$), the mean EC values decrease to 575 $\mu\text{S}/\text{cm}$ for DW-7 and 372 $\mu\text{S}/\text{cm}$ for DW-6, compared to 818 $\mu\text{S}/\text{cm}$ for DW-2g.

LIMITATIONS, UNCERTAINTY AND PERSPECTIVES FOR TIME-LAPSE ERT

The analysis conducted for the Świerczków well field demonstrated that ERT measurements provide valuable information for the design of new MAR facilities and the optimisation of existing ones, thereby supporting sustainable groundwater resources management. However, despite its wide applicability, the ERT method has inherent limitations that contribute to uncertainty in the results (Parker et al., 2022; Alao and Abubakar, 2025). To reduce these uncertainties, it is essential to integrate ERT data with additional geological and hydrogeological information, which in the case of the site investigated was obtained from monitoring and field studies carried out between 2019 and 2022 within the DEEPWATER-CE project (Sitek, 2022), as well as from an analysis of archival materials. For the Świerczków site, identifying the layout of underground infrastructure was also crucial, as indicated by profiles ERT_6 and ERT_7, which show that such structures can locally disturb the actual electrical resistivity of the subsurface.

To capture the temporal changes associated with periods of intensive recharge, modifications of the ERT technique, referred to in the literature as time-lapse electrical resistivity tomography (TL-ERT), are employed. TL-ERT enables the study of time-dependent changes in the subsurface resistivity pattern. This approach has been applied, for instance, to assess the effects of MAR tests in pre-Alpine aquifers and to validate models under transient conditions (Teatini et al., 2020). Arboleda-Zapata et al. (2025) used TL-ERT to image the propagation of the wetting front from a drywell MAR experiment in California's Central Valley. These examples highlight the promising potential of future applications of TL-ERT at the Świerczków well field,

for instance, to assess the effects of possible optimisation of MAR methods, to monitor decreases in infiltration efficiency due to clogging development, or to detect the inflow of contaminated groundwater. Studies related to the use of electrical resistivity tomography imaging for these purposes are well-documented (Gasperikova et al., 2012; Sendrós et al., 2020b; Alao and Abubakar, 2025).

CONCLUSIONS

The ERT survey conducted at the Świerczków well field provided valuable insights into subsurface conditions that may directly support the optimisation of the two MAR techniques applied in this area. Variations in electrical resistivity within the Quaternary aquifer analysed enabled the identification of zones where inflow of contaminated native groundwater from the industrial area reaches the well field, as well as the delineation of the current extent of surface water infiltrating from the ditches. Higher electrical resistivity values in the central and northern parts of the well field corresponded to zones dominated by infiltrated water from surface water sources, whereas lower values in the southern sections reflected the presence of native groundwater with significantly higher TDS values. Based on this information, it was easier to choose the location for the new observation wells, which revealed the spatial variability of the qualitative conditions at the well field, demonstrating an approach transferable to other recharge schemes seeking to optimise monitoring networks.

The geophysical results enabled detailed mapping of high-resistivity freshwater gravel aquifer thickness and the depth of low-permeability surface sediments, allowing for the identification of locations most favourable for future well-sitting and improved adjustment of infiltration ditch layouts. These findings are especially relevant for enhancing infiltration efficiency, maximising drinking water production, and ensuring the long-term stability of the MAR system.

Despite its clear advantages, ERT has some methodological limitations that warrant careful integration with complementary datasets on land use, geology, and hydrogeology. This study confirmed that ERT data may be locally affected by underground infrastructure, which must be considered during interpretation. Our results were consistent with numerical flow modelling and environmental tracer mixing analyses, demonstrating that ERT may be a powerful tool for assessing the spatial impacts of MAR techniques worldwide.

The study provides both methodological and practical contributions relevant to researchers and practitioners working on aquifer characterisation and MAR optimisation and confirms that ERT is a highly effective tool for supporting the design, optimisation, and long-term evaluation of MAR. The demonstrated sensitivity of electrical resistivity to spatial variations in MAR processes allows us to recommend time-lapse ERT for future extended monitoring of infiltration efficiency, clogging development, and shifts in the balance between riverbank filtrate, recharge from ditches and native groundwater, both at this site and in comparable environments globally.

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