

# Use of the electrical conductivity of water and the electrical resistivity tomography of rocks in the recognition of groundwater circulation and discharge in strongly tectonized carbonate massifs

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## ABSTRACT:

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In protected mountainous areas, groundwater surveys are usually restricted to studies of their recharge by springs and streams. In the case of fissured rocks, which represent a highly heterogeneous medium, classical hydrogeological methods may be supplemented by electrical resistivity tomography (ERT) techniques. The studies presented here were focused on explaining issues related to groundwater circulation and recharge in such a complex structure, based on the study of Gorczyński Ravine situated within the Pieniny Klippen Belt. The groundwater of that area is recharged by the Macelowy Stream and its spring. Electrical conductivity of water (EC) measurements have indicated the existence of a privileged groundwater recharge zone of the stream and a different groundwater recharge zone of the spring. ERT surveys were used to explain the observed EC measurements. The analysed rock massif is clearly heterogenic, as documented by the wide range of electrical resistivity values, from c. 50  $\Omega\text{m}$  to above 19 000  $\Omega\text{m}$ . Interpretation of the results was limited by the lack of documentation from wells, which would have allowed precise correlation between geoelectrical layers and geological units. Despite these restrictions, ERT surveys facilitated the explanation of the observed hydrogeological phenomena and supplied new data on the complex structure of this part of the Pieniny Klippen Belt.

**Key words:** Electrical conductivity of water; Electrical resistivity tomography of rocks; Groundwater; Pieniny Klippen Belt; Poland.

## INTRODUCTION

Fissured rocks represent a highly heterogeneous hydrogeological medium, in which groundwater flow concentrates in large fractures or is dispersed in the rock massif within fine fissure networks and pores (Baena *et al.* 2009). In strongly tectonized massifs, the heterogeneous nature of the rock medium is enhanced by the lithological and stratigraphic variabil-

ity of the rocks which form a strongly faulted, folded, and often brecciated structure. An additional difficulty in recognizing groundwater circulation and its discharge routes is often the lack of wells supplying hydrogeological data (coefficient of hydraulic conductivity, aquifer thickness, depth to the groundwater table). Drilling new hydrogeological wells in mountain massifs is usually restricted by technical or legal issues related with environmental protection.



In such regions, groundwater studies are usually restricted to non-invasive remote sensing techniques and studies of groundwater discharge through observations in springs and streams. Despite such restricted access, valuable data may be acquired through monitoring of the electrical conductivity of water (EC). Using EC changes it can be concluded whether the rock massif is dominated by flow in large voids or in fine, dispersed fissures, and if the directions of groundwater flow depend on the water saturation of the massif (Baena *et al.* 2009; Stroj *et al.* 2020). Moreover, EC data allow for the identification of zones and intervals of intensified groundwater discharge by surface waters (Harvey *et al.* 1997; Rodríguez-Rodríguez *et al.* 2018) or surface water discharge on behalf of groundwater (Mieszkowski *et al.* 2018).

Geological and hydrogeological studies of fissured and karst media are effectively enhanced by electrical resistivity tomography (ERT) (Binley *et al.* 2015; Kozłowska *et al.* 2016). It is worth noting, however, that the interpretation of ERT results in mountainous areas is impeded by the lack of wells allowing for the correlation of geoelectrical layers with lithological units. The resolution of this method may also be lower compared to that achieved in a porous medium due to similar resistivity values of soil, weathering cover, and solid rock (Cheng *et al.* 2019), the resistivity of solid carbonate rocks usually being much higher (Chalikakis *et al.* 2011). The resistivity of a rock massif depends also on its saturation with water (Samouëlian *et al.* 2005; Huang *et al.* 2024). Difficulties in the interpretation of geophysical surveys are caused by the material infilling the rock voids. The fissures may be filled with air, unconsolidated material, groundwater or their mixture, resulting in each case in a different geophysical image (Chalikakis *et al.* 2011).

The studies reported herein were aimed at applying EC measurements of ground- and surface water, coupled with ERT surveys used to recognise the aquifer structure, to reconstruct the circulation network and identify the preferred sites of groundwater discharge in a strongly tectonized and fissured medium. The study area was the Gorczyński Ravine (Pieniny Mountains), situated in the Pieniny Klippen Belt, a strongly folded and faulted structure referred to as a 'tectonic megabreccia' (Birkenmajer 2003).

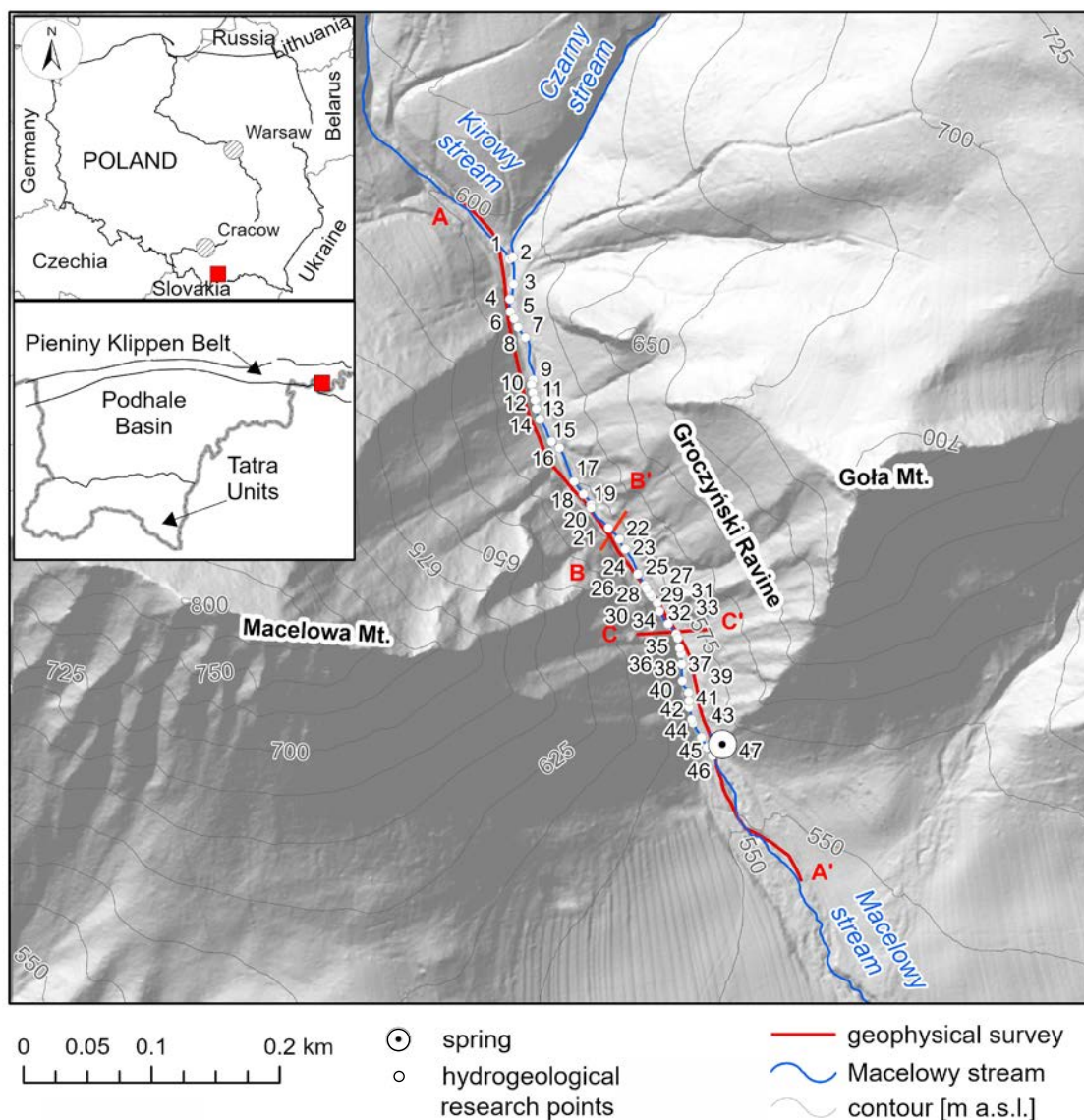
## GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The Pieniny Klippen Belt (PKB) separates two main structural units of the Carpathians, the Outer

Carpathians from the Inner Carpathians. It is typically considered to represent an area with the most complex geological structure in Europe. Mesozoic rocks deposited in a basin with an estimated width of 300 km were extremely strongly compressed; at present they are exposed in a narrow belt with a width of merely c. 3–5 km. It should be emphasized that the detailed geological structure of the area is not fully understood at present and is still widely discussed (Krobicki *et al.* 2003; Jurewicz 2005; Birkenmajer 2017; Golonka *et al.* 2018, 2019).

The complex geological structure of the PKB influences groundwater recharge, circulation and discharge. The results of previous hydrogeological analyses have made it clear that the groundwater within the PKB, despite the variable lithology of the hydrogeological medium, represents one aquifer horizon. Porous water in the Quaternary weathering covers and in the alluvia of valley bottoms are in hydraulic connection with fissure waters circulating in Mesozoic and Paleogene rocks. Groundwater recharge takes place through the infiltration of precipitation. Surface water infiltration may also occur locally. Groundwater discharge zones are represented by streams and springs, although the appearance of a spring in a certain locality does not mean that the surrounding rocks are drained by that spring (Małecka 1981; Humnicki 2007; Humnicki *et al.* 2019; Gruszczynski *et al.* 2024). The complex geological structure and conditions of groundwater occurrence mean that the application of solely hydrogeological methods in the PKB is often insufficient for a thorough understanding of groundwater circulation in this area.

Detailed surveys were performed in Gorczyński Ravine, which cuts through the southern slopes of the Pieniny Mountains between Macelowa Mt. (800 m a.s.l.) in the west and Goła Mt. (712 m a.s.l.) in the east. Macelowy Stream, the left tributary of the Dunajec (Vistula River catchment) flows in the ravine. The stream is formed through the connection of the Kirowy and Czarny streams (Text-fig. 1). The stream has a precipitation-meltwater hydrogeological regime. The lowest discharges in the hydro-metric cross-section located below the ravine (point 46 in Text-fig. 1) were observed during low winter flows (0.5 dm<sup>3</sup>/s), and the highest – after summer rainfall (84 dm<sup>3</sup>/s). The reaction of the stream to precipitation is very intense (within about 2 h after the event) and relatively short-term (Humnicki 2007; Szostakiewicz-Hołownia 2018). Groundwater in the ravine is drained by the Macelowy Stream and one

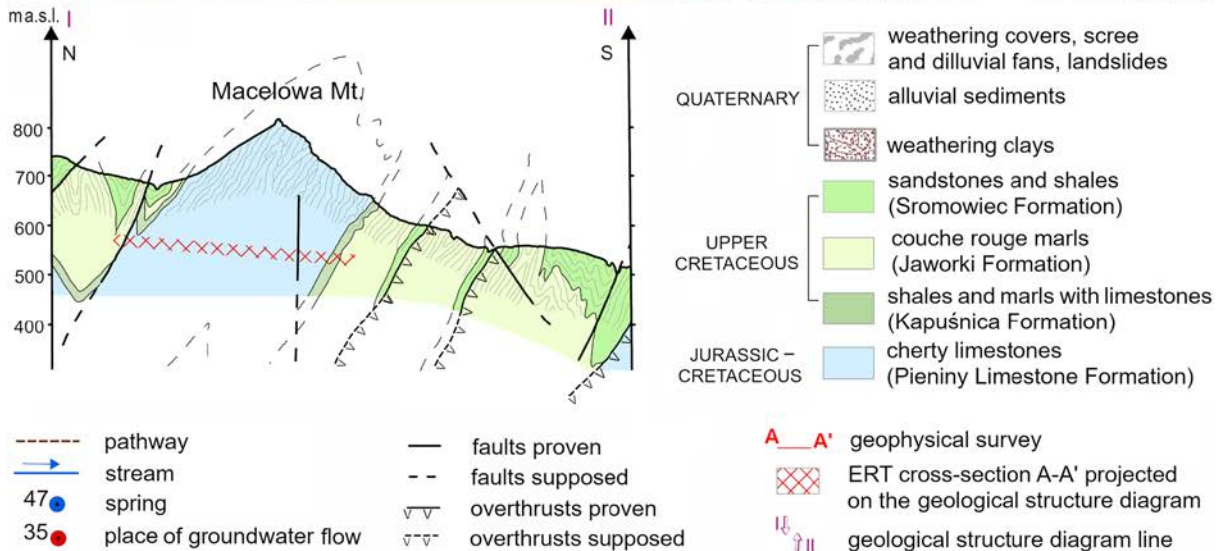
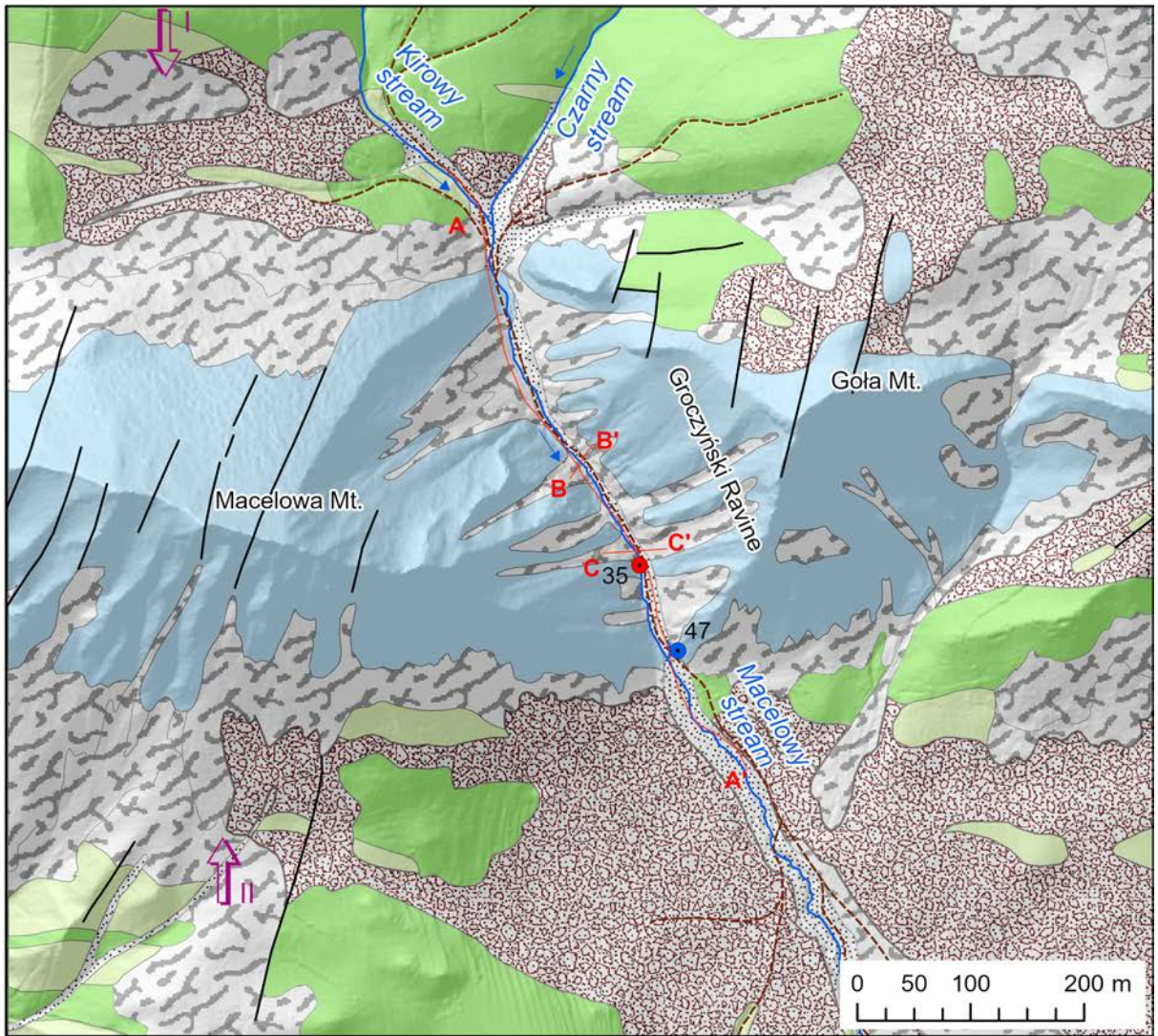


Text-fig. 1. Location of study sites in the Pieniny Mountains.

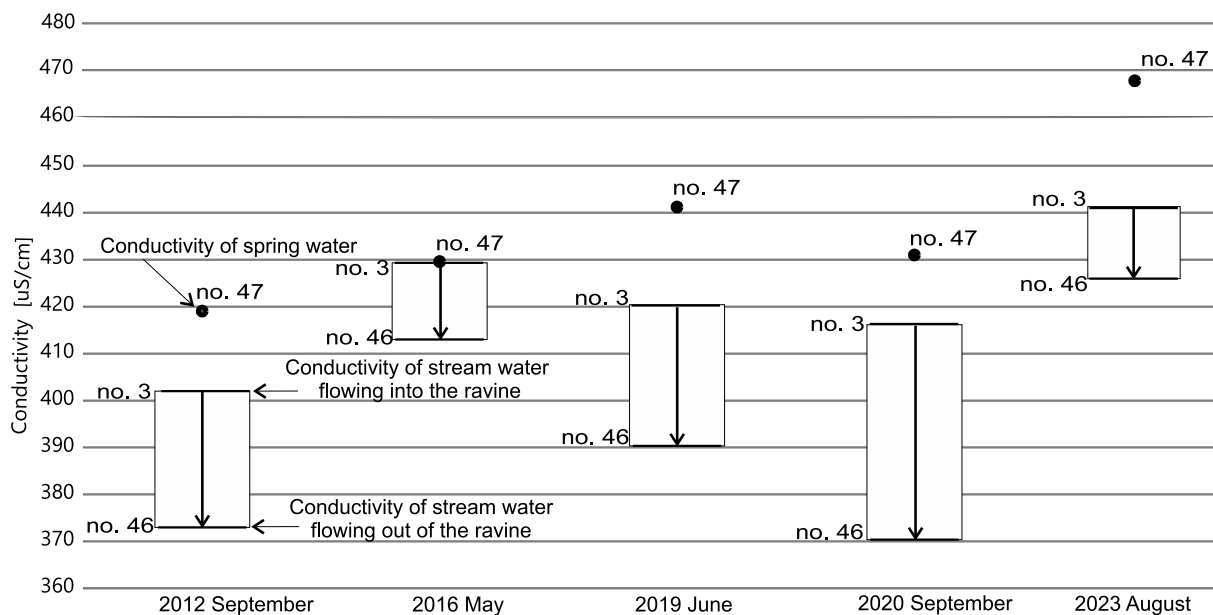
spring (no. 47, Text-figs 1 and 2). This is a fissure spring shielded by a weathering crust. Gorczyński Ravine is located within the Pieniny Klippen unit, composed here of cherty limestones and manganese radiolarites assigned by Birkenmajer (1977) to the Pieniny Limestone Formation. Locally solid rocks are exposed in the area, but usually they are covered by the products of their decomposition, diluvia and weathering clays. To the north and south of the ravine occur rocks of the klippen cover, i.e., sandstones and shales of the Sromowce Formation and couche rouge marls of the Jaworki Formation (Text-fig. 2).

## METHODOLOGY

In 2012–2023, EC surveys and temperature monitoring were conducted for waters of the Macelowy Stream above and below Gorczyński Ravine and of water drained by spring no. 47 located in the lower part of Gorczyński Ravine. In 2019–2023, Macelowy Stream was monitored in 46 points during different seasons and at various states of water saturation. During these surveys, EC and water temperatures were monitored using an Eijkelkamp 18.52.01 multi-meter. The atmospheric temperature was also monitored. EC values were compensated to a constant



Text-fig. 2. Geological setting of the study area (after Birkenmajer 2017, supplemented).



Text-fig. 3. Comparison of electrical conductivity (EC) of waters of Macelowy Stream above and below Gorczyński Ravine with waters drained by the spring (point no. 47).

reference temperature of 25°C and are expressed in mS/cm, approximately corresponding to the general mineralization of water expressed in g/dm<sup>3</sup> (Ford and Williams 2007).

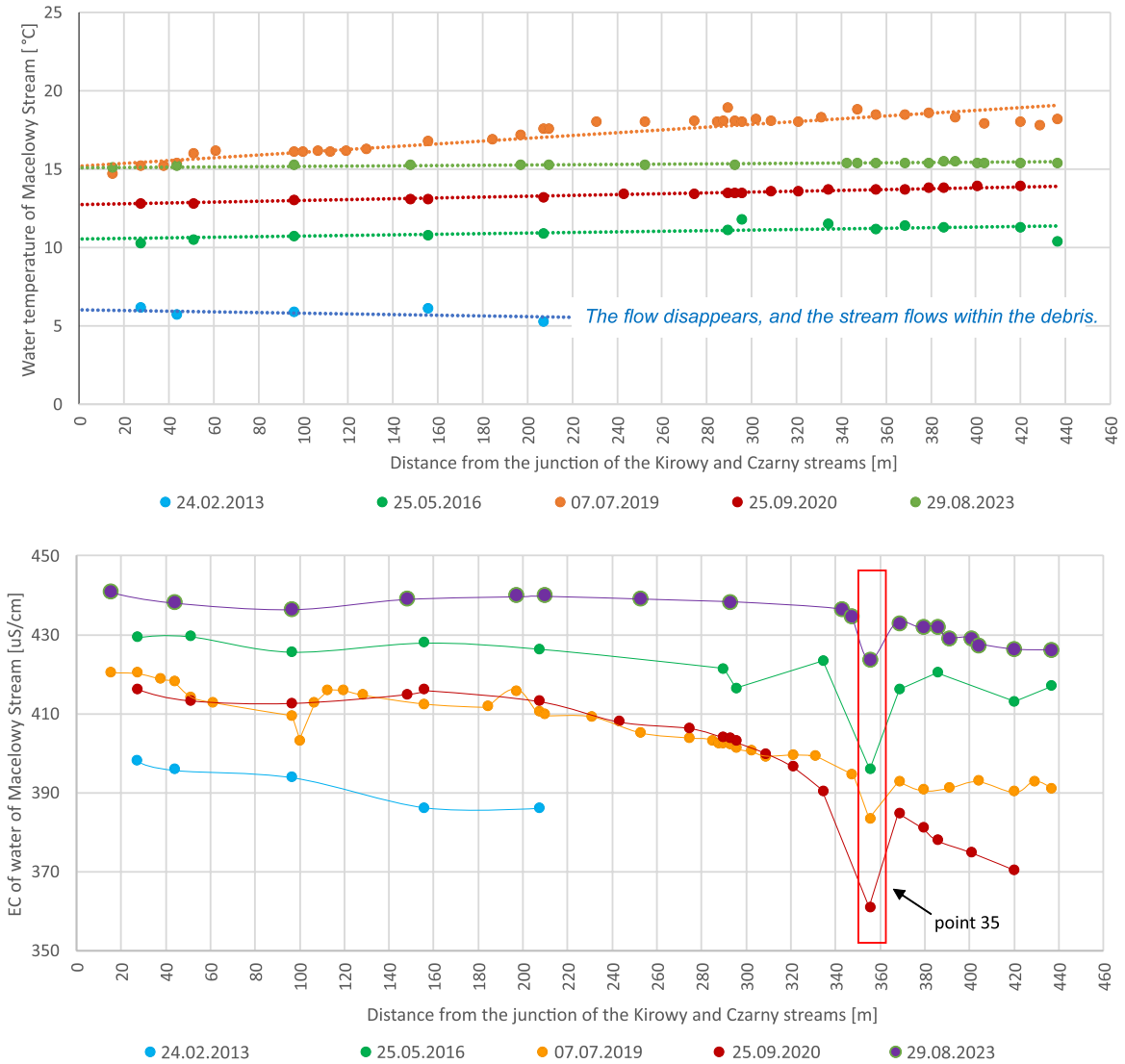
In 2020–2022, geophysical surveys included measuring the electrical resistivity tomography of the rocks (ERT). In the ERT method, the distribution of the electrical resistivity of a medium is modelled by blocks in 2D. Such modelling allows the determination of the variability of the resistivity of the medium both vertically and horizontally on the cross-section along the survey line. The general feature of ERT surveys is the placement of a large number of electrodes along the survey line. Knowing the characteristic ranges of resistivity for a given medium occurring in the study area and correlating the results of geophysical surveys with geological data, the obtained results (distribution of resistivity values) may be correlated with the lithology of geological units (Loke *et al.* 2015; Alcalá *et al.* 2022). In Gorczyński Ravine, ERT surveys were performed along three profiles, i.e., one located along the Macelowy Stream in the axis of the ravine (A–A') and two that were transverse to its axis (B–B' and C–C') (Text-figs 1 and 2). Interpretation of the results is limited by the lack of documentation from wells and, as a result, lack of correlation between the observed geo-

electrical layers and geological units. Due to this fact, literature data, a geological map at the scale 1:10 000, a geological cross-section of the Gorczyński Stream area (Birkenmajer 2017), and our own observations were used to interpret the ERT results.

## RESULTS

EC monitoring of waters of Macelowy Stream above and below Gorczyński Ravine have indicated a consequent decrease of EC values and thus also the mineralization of waters in Macelowy Stream along the Gorczyński Ravine. This decrease was observed both at low and high water levels, during both wet and dry, winter intervals (when surface flow decreased). This fact points to stream recharge by groundwater discharged from the cherty limestones of the Pieniny Formation, through which the ravine is eroded. These waters would be characterised by a lower EC than the stream waters and would have caused gradual dissolution of the components in the waters of Macelowy Stream (Text-fig. 3).

With regard to this, the EC values in spring no. 47 were rather surprising. Based only on the morphological location of this spring and the lithology of rocks occurring in the site where waters flow out



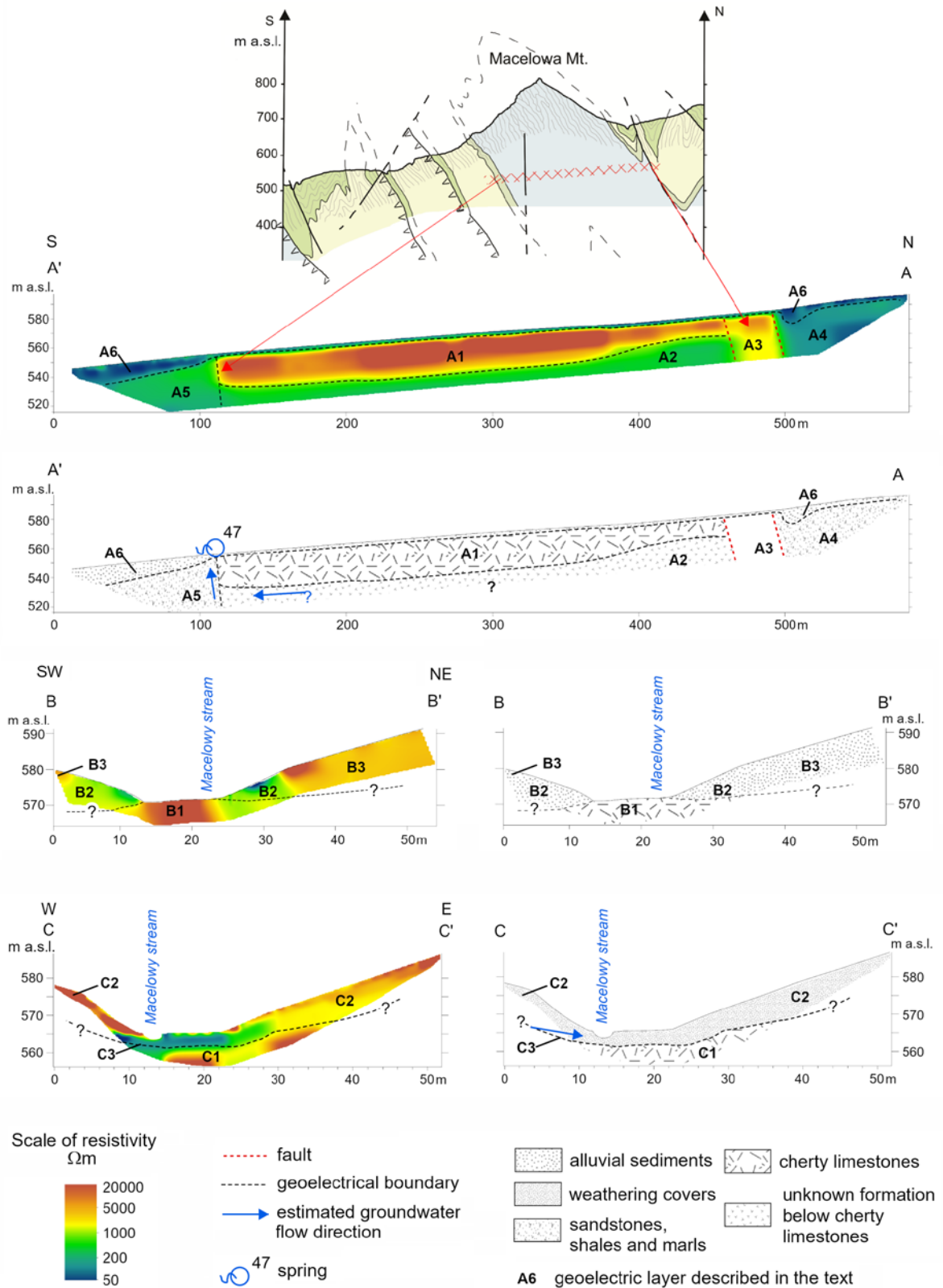
Text-fig. 4. Variations in temperature and electrical conductivity of water (EC) of the Macelowy Stream (red rectangle indicates lower EC values).

on the surface, it may be presumed that the spring is recharged by groundwater occurring in the cherty limestones. However, it has turned out that the waters drained by the spring, on the contrary, are always characterised by a much higher EC than the waters of Macelowy Stream (Text-fig. 3).

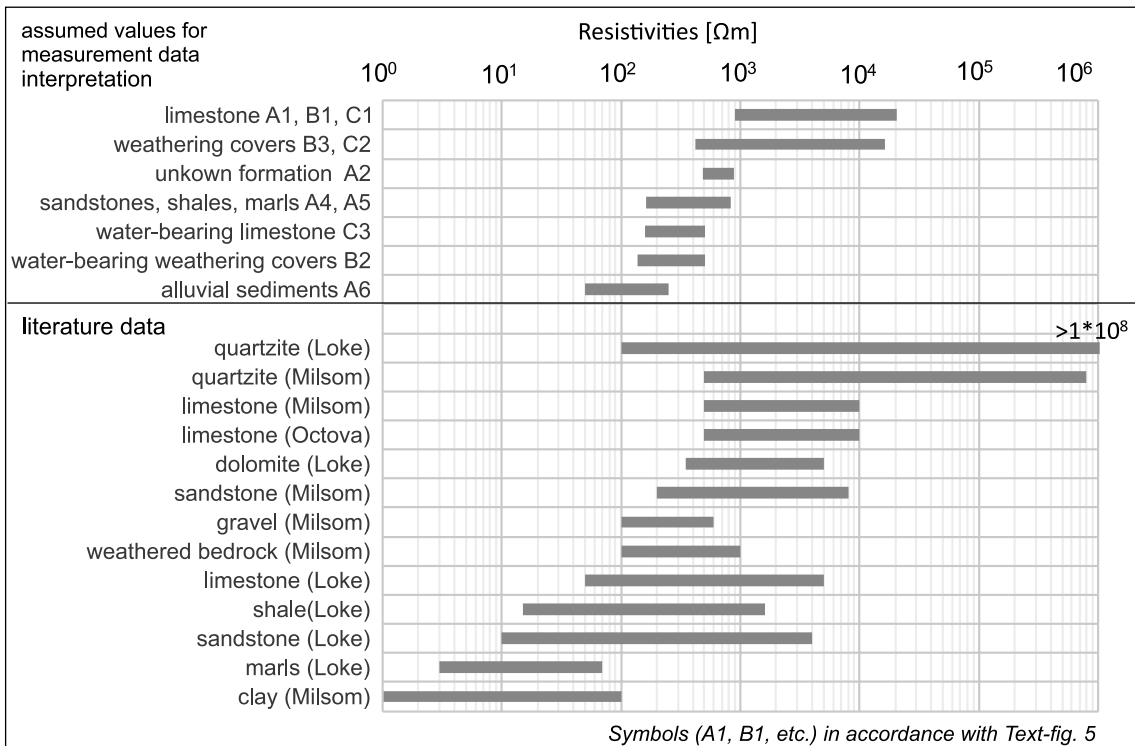
Beside the surprising EC values in spring no. 47, also interesting were EC values observed along the Macelowy Stream. In general, as mentioned above, there is a systematic decrease of EC values along with the water flow. However, in the vicinity of point no. 35 there is an anomalously intense decrease of EC values, which would point to a privileged groundwater discharge zone. It should be mentioned that there were no such changes in the case of surface

water temperature at this point (Text-fig. 4). Based on geological observations and analysis of available maps: at the scale of 1 : 50 000 (Kulka *et al.* 1985), at the scale of 1 : 10 000 (Horwitz 1963; Birkenmajer 2017), and at the scale of 1 : 5 000 (Birkenmajer 2005), no dislocation or contact zone between layers characterised by a differing lithology were observed in the vicinity of point no. 35 where groundwater flows to the stream that would represent a privileged groundwater recharge zone.

In order to explain the observed EC values and recognize the geological conditions, the ERT method was applied. The first geoelectrical profile was located along Macelowy Stream in the ravine axis (A–A'). The two other profiles are transverse:



Text-fig. 5. Results and interpretation of electrical resistivity tomography surveys.



Text-fig. 6. Resistivity ranges for particular lithological media after (Milsom 2003; Octova and Yulhendra 2017; Loke 2021).

profile C–C' was made in the region of groundwater EC decrease (point no. 35), and profile B–B' was made for comparison in a zone where no EC variability was observed (Text-fig. 5).

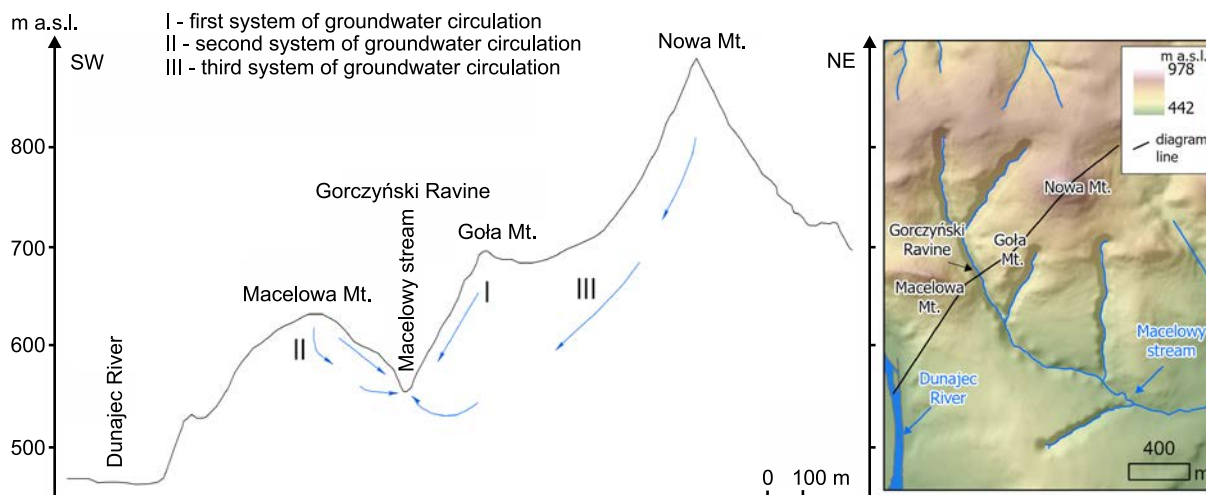
The ERT survey indicates a clear heterogeneity of the rock massif, with a wide range of electrical resistivity values from about  $50 \Omega\text{m}$  to over  $19\,000 \Omega\text{m}$ . The obtained values fall within the ranges reported in the literature for similar lithological media (Text-fig. 6).

In profile A–A', worth emphasizing is the zone of high resistivity (A1) stretching along the entire ravine, which may be correlated with the occurrence of cherty limestones. The high resistivity of these rocks comes from the fact that they are strongly silicified. Below the limestones occur rocks characterised by a much lower resistivity (A2), but at present their lithology and age cannot be determined. The resistivity values indicate rocks with a higher content of clay minerals. The ERT profile supplied new data on the structure of the analysed part of the PKB. So far, the existing cross-sections constructed on the basis of surface data have suggested that the cherty limestones continue inwards into the massif, to the level of at least  $450 \text{ m a.s.l.}$  (Text-fig. 5). According to new geophys-

ical data, cherty limestones lie at shallower depths in Gorczyński Ravine, at the level of c.  $530\text{--}550 \text{ m a.s.l.}$

In the northern part of profile A–A', ERT surveys have documented the presence of a dislocation zone (A3), which is concordant with the cross-section of (Birkenmajer 2017) (Text-fig. 5). To the north of the dislocation, lower resistivity values (A4) point to the occurrence of rocks forming the klippen cover, i.e., sandstones, shales and marls (Sromowiec and Jaworki formations). In the southern part of the profile, close to spring no. 47, there is a distinct change of electrical resistivity values, which should be related to a lithological change, i.e., contact between the cherty limestones and the klippen cover formations (shales, marls and sandstones; A5). Alluvia of Macelowy Stream (A6) overlie the older basement in the entire ravine and its vicinity.

In profile C–C', located near point no. 35, zones with high resistivity values (C1) were correlated with the presence of cherty limestones and dry rock debris of weathering covers (C2), accumulated on the ravine slopes. In turn, a zone of low resistivity values continuing to the west (C3) may be observed in the central part of the cross-section. Lower resistivity values point to the possible occurrence of a fractured,



Text-fig. 7. Scheme of three systems of groundwater circulation near Gorczyński Ravine.

loose zone with hollows filled with water. The zone of lower resistivity values continues in the valley bottom, covering also the lower parts of the eastern slope. This suggests water saturation of the alluvia and weathering covers accumulated in the valley.

A different geoelectric image was noted in profile B-B', located in a zone where there was no sudden change in the EC values of Macelowy Stream waters. This profile does not have a zone with decreased resistivity values. This indicates the lack of a privileged zone of groundwater flow. Discharge of these waters takes place through a system of fine fissures in the cherty limestones and a system of pores in the weathering covers. It also indicates variable resistivity values in the ravine slopes (B2 and B3). In zone B2, at the slope foot, pores in the weathering cover may be saturated with water, whereas in zone B3, higher resistivity values suggest infilling of the pores with air. High resistivity values noted in the valley bottom unequivocally suggest the presence of cherty limestones (B1), which is confirmed by field observations (the stream flows on solid rock).

## DISCUSSION

Hydrochemical monitoring of Macelowy Stream has indicated that the discharge of low-mineralization groundwater is concentrated in a narrow, dozen or so metres wide area, located in the lower part of Gorczyński Ravine (in the vicinity of point no. 35). ERT surveys have identified an area with low resis-

tivity values on the western side of the stream. These low resistivity values point to the possible presence of a fractured, loose zone acting as a privileged route of groundwater flow. ERT analyses confirm the opinion (at first suggested only on the basis of ER monitoring of the stream waters) of the existence of a privileged zone of groundwater recharge. The presence of such zone only on the western part of the stream would be responsible for the local decrease of EC in the surface waters. EC measurements were made exactly in the place where low-mineralized groundwater enters the system. EC measurements of surface waters beneath this zone do not show such low values due to the mixing of groundwater with stream waters. The mixing takes place very fast due to turbulent flow in a mountain stream.

The instantaneous mixing of surface and groundwater and the zonal, non-concentrated, flow of groundwater to the stream hamper a reliable determination of the chemistry of the water flowing through the privileged zone. It can only be assumed that the inflowing water is characterised by a lower EC than the surface water. This water is probably recharged in the Macelowa Mt. massif, a local culminating point. The low EC of the discharged waters points to their contact with the relatively low-solubility cherty limestones of the Pieniny Formation when flowing through the rock massif. This fact excludes the possibility of their recharge in the highest parts of the Pieniny Mountains, which in the study area are composed of sandstones, shales and marls of the klippen cover (Text-fig. 7).

Groundwater temperature monitoring made exactly in the same points as the EC data was used to indicate sites of intense interaction between surface water and groundwater (Constantz 2008; Baena *et al.* 2009). In lowland rivers, in which the channel bottom is filled with sediments, temperature measurements are taken in the hyporheic zone (0.2 m below the river bottom; Conant 2004). In the case of small mountain streams this approach is not possible because the bottom sediments are usually represented by coarse gravels or the stream flows on solid rock. Due to this fact, temperature measurements were taken directly in Macelowy Stream.

In the temperate climate conditions typical of Poland, zones of intense groundwater discharge are usually characterised by lower temperatures in the summer and higher ones in the winter (Conant 2004; Bubliewska *et al.* 2017). In the case of Macelowy Stream, a slight but consequent temperature increase of the stream waters was observed during summer, whereas a gradual temperature decrease was noted in winter. Temperature changes were not observed in the site with privileged groundwater flow. Therefore, the stream temperature did not serve as an indicator of privileged groundwater discharge. This means that low discharge coupled with turbulent water flow result in the dominant role of atmospheric temperature on the temperature of surface waters.

ERT surveys also have explained why waters recharging Macelowy Stream are characterised by a lower mineralization, whereas the waters drained by the spring have a higher mineralization than the stream waters. Spring no. 47 is located in the contact zone of the cherty limestones and the rocks of the klippen cover (sandstones, shales and marls). This contact zone, whose precise location could be determined through geophysical surveys, is probably the privileged zone of groundwater flow of deeper circulation, whereas the recharge zone of waters drained by the spring is probably the Nowa Mt. massif (Text-fig. 7). Waters infiltrating this massif flow in accordance with the hydraulic gradient, at first through a system of fissures in the limestones, and in the lower part – through a contact zone between the limestones and the rocks occurring below and characterised by a different resistivity (Text-fig. 5). The higher EC of groundwater drained by the spring can be explained by their contact with rocks other than limestones, as opposed to waters occurring solely in the cherty limestones of the Pieniny Formation.

Presently, the lithology and age of rocks occurring below the limestones cannot be stated unambiguously. They could be Jurassic limestones and spotty

marls with shales of the Supra-Posidonia Beds observed in stratigraphic succession below the Pieniny Limestone Formation and exposed on the surface in Nowa Mt. massif, situated to the north of Gorczyński Ravine (Horwitz 1963; Kulka *et al.* 1985).

Studies conducted in Gorczyński Ravine have allowed the recognition and documentation of three systems of groundwater circulation within a small area (Text-fig. 7). The shallowest system (I) comprises groundwater flowing in the basal parts of the scree and in the topmost part of the cherty limestones where sets of weathering fissures occur. Water discharge from this aquifer causes a gradual but low decrease in the mineralization and conductivity of surface waters along the entire ravine. The deeper system (II) includes waters that flow through the fissures and loosened zones in the cherty limestones. These waters recharge the stream only locally, through fissure zones that contact directly with the stream or its alluvia. Discharge of these waters is documented by a sharp EC decrease near point no. 35. Waters of the shallowest (I) and the deeper (II) circulation system are characterised by a lower mineralization than the surface waters flowing to the ravine. Lower groundwater mineralization results from the dissolution of the cherty limestones being obstructed by their silicification and presence of radiolarians. Previous studies have documented that the dominant process (over 90%) shaping groundwater chemistry in the Macelowy Stream catchment is limestone dissolution (Szostakiewicz-Hołownia 2018). A manifestation of the deepest circulation system (III) is a high-mineralization groundwater discharge in spring no. 47.

Summing-up, it should be stated that ERT surveys in highly tectonized carbonate massifs may supply much valuable information on groundwater circulation and discharge, but it should also be emphasized that in terms of methodology, they cause several difficulties, both related to technical issues and interpretation. In the case of very variable morphology in mountainous areas, there is often a problem with scheduling and conducting a sufficiently long ERT profile, maintaining the correct placement of electrodes in relation to the surface, or cases when it is not possible to insert the electrode at a required depth. This particularly applies to sections, where solid rocks are exposed on the surface. In the presented study, such technical issues occurred in the case of the transverse profiles B–B' and C–C'.

The main difficulties in the interpretation included the lack of well cores that would enable correlation of the identified geoelectric layers with lithology. In the case of a complex geological structure, there is often

a problem with distinguishing lithological boundaries from faults and dislocations. Additionally, lithological boundaries are often poorly identified due to the unknown depth to the groundwater table, because water causes a significant decrease in the electrical resistivity of rocks.

## CONCLUSIONS

The presented results mainly have a local significance but they have also allowed us to draw a number of conclusions on the application of indicative water analyses (measurements of electrical conductivity and temperature) and geophysical surveys for the recognition of hydrogeological conditions even in areas with a very complex geology.

According to previous surface surveys, the cherty limestones of the Pieniny Formation near Gorczyński Ravine were considered to continue into the rock massif. In this work we have documented that the lithological boundary, probably corresponding to the base of the limestones, occurs at the depth of about 25 m below the ravine bottom. The contact zone between the limestones and the underlying rocks acted as a zone of privileged groundwater discharge in the deeper circulation system. The limestones are characterised by the presence of numerous fissures and loose zones acting as preferred routes of groundwater flow.

The performed surveys have shown the applicability of EC measurements for the identification of zones of intensified groundwater discharge by surface waters. The usage of temperature monitoring of stream waters for the identification of zones of privileged groundwater flow has not proved feasible due to the dominant impact of atmospheric temperature on the temperature of surface water.

A number of obstacles were encountered when interpreting the geophysical data. The difficulties were both technical and interpretational, characteristic for mountain areas with a very diverse morphology, complex geological structure and intensely tectonized. Despite that, such surveys should be continued as they are a valuable supplementation of classical hydrogeological methods.

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