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Permeability of Muschelkalk rocks (Middle Triassic) of the Krakow–Silesian Monocline in Tarnów Opolski area (South Poland)

Introduction

The rocks of Muschelkalk (Middle Triassic) constitute a rich and commonly used groundwater reservoir, which is mostly the result of their high permeability. According to the research of Motyka and Wilk (1976) and Staśko (1992), the values of hydraulic conductivity for these types of rocks exceed tens or even hundreds of m/d. Generally, these values were determined using various methods for fragments of the Muschelkalk lithological profile. However, in hydrogeological calculations they are commonly taken as mean values for the entire Muschelkalk profile. This kind of approach is usually caused by the lack of information about the permeability of every single layer separated from the limestone profile characterized by diverse permeability. Consequently, all of the layers of the Lower and Middle Muschelkalk are treated as a homogenous complex in the calculations, and the results of this approach often differ from the actually existing state.

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The Muschelkalk groundwaters are exploited on intakes and intensively drained by carbonate rocks quarries. Reliable hydrogeological calculations, i.e. an assessment of groundwater resources, prognosis of groundwater inflow to the mines, determination of influence range of mine draining and defining the boundaries of groundwater reservoirs' protection areas, all depend on the possibility of using detailed studies on the drained limestone permeability, including the permeability of its individual layers.

More detailed studies of the Lower and Middle Muschelkalk layers of the Krakow–Silesian Monocline were carried out in the Olkusz region (approximately 100 km SE of Tarnów Opolski). Pumping tests allowed the permeability of the Roethian Formation, Olkusz and Gogolin Beds, ore-bearing dolomites and Diplopora dolomites to be defined (Motyka and Wilk 1976). Wilk et al. (Wilk et al. 1985), using the results of laboratory studies of core samples from five boreholes. They confirmed the higher permeability of the dolomites compared to limestones from Olkusz and Gogolin Beds. The attempts of permeability determination for Gogolin Beds and the entire Lower and Middle Muschelkalk profile based on the calculation of inverse task in the numerical model of filtration are also worth mentioning (Szczygieł et al. 2006).

The aim of the article is to present the characteristics of the permeability of rocks constituting particular layers of Muschelkalk limestone (Middle Triassic). The basis for the solution of the equation was provided by research conducted in 16 piezometres in the area of Tarnów Opolski (approx. 15 km SE of Opole). Piezometers of an approximate depth of 40–60 m were primarily designed as research boreholes in order to recognize the geological structure of the limestone deposit. Therefore, they were not constructed only in the hydrogeologically-privileged areas. The location of boreholes in more or less water-bearing zones was usually random. The use of a filter in piezometers allowed for the pumping of every single layer of the Muschelkalk formation (Gogolin, Górażdże, Karchowice and Diplopora Beds). As a result, a map of Muschelkalk permeability in an outcrop zone near Tarnów Opolski was made.

I would like to express my gratitude to Lhoist SA in Tarnów Opolski for the opportunity to conduct studies in their piezometers.

1. Characteristics of the research area

The studied area is situated in southern Poland in the region of the so-called Strzelecki Division (Kondracki 2009). The landscape is characterized by hills of 200–300 m a.s.l., with the St. Anna Mountain (404 m a.s.l.) being the highest point. The area is devoid of surface waters, such as streams or natural lakes. The nearest streams are located several kilometers away. The Tarnów Opolski region can be considered the warmest place in Poland. The annual average temperature in the area is approximately 8.2°C and annual precipitation ranges from 600 to 800 mm (Woś 1999).

The study area is located within the so-called Middle Triassic escarpment which is a part of the Opole section of Krakow–Silesian Monocline. In this area, an unconformable Triassic formation lain above the Permian and Carboniferous deposits, and covered with locally occurring Neogenic and Quaternary deposits, is of primary importance.

Carboniferous and Permian deposits are represented mainly by sandstones, shales with interbeds of cinder, as well as greywackes and conglomerates.

The profile of Triassic formations starts with formations of lower variegated sandstone and finishes with diploporous layers of Middle Muschelkalk limestone. Higher layers of the middle and upper Muschelkalk were not found in the investigated area.

The terrestrial deposits of Lower and Middle Buntsandstein are composed of sandstones with silt inserts, greywackes and conglomerates of the total thickness of 60 m. The complex lies exceedingly on Lower Permian sediments. The Upper Buntsandstein (Roethian Formation), about 70–90 m thick, is built of marine deposits such as dolomites with gypsum intercalations and anhydrites in the lower profile, as well as marls, limestones and anhydrites in the upper profile. The Roethian Formation underlies the Lower Muschelkalk sediments being the main scope of the research. The Muschelkalk lithological profile begins with 45-meter-thick Gogolin Beds mainly composed of fine-grained limestones and limy-marly deposits, as well as silty marls with interbeds of limy sands (Stanienda 2014). 25-metre-thick Górażdże Beds built of fair, yellowish, grainy limestones are located above the Gogolin Beds. They are characterized by a high concentration of calcium carbonate and the minimal content of silt. They are also defined by high porosity resulting from the meteoric dissolution of aragonite grains (mostly bioclasts) (Stanienda 2016). Another element of the profile are the Terebratula Beds consisting of fine-grained limestones, coarse-grained limestones mostly made of trochistes, and wavy-bedded and nodular fine-grained limestones, with the intercalation of marls and Terebratula limestone. The thickness of the Terebratula Beds within the study area is 2.4–17 m. The upper part of the Lower Muschelkalk is formed by Karchowice Beds represented by medium-grained and coarse-bedded pelitic and organo-dendritic limestones, locally karstified and dolomitized. Their thickness reaches 18 m. Diplopora Beds, forming the lowest part of the Middle Muschelkalk, lay on them. They are represented by fine- and cryptocrystalline, partly marly 30-meter-thick dolomites (Senkowiczowa 1998).

In the terrain depressions of the basement below the Cenozoic, Neogene rocks only occur locally. They are represented by several-meter-thick clays with lignite inserts and sandy-gravely sediments. The thickness of the Quaternary deposits comes up to approximately a dozen meters but is typically equal to about 4 m. The deposits are of glacial or fluvio-glacial origin (sands and clays, less often gravels) and of fluvial origin – the youngest sediments in the Holocene river valleys.

The rocks of Middle Triassic are characterized by the presence of numerous tectonic faults which form two separate systems, the first of NNE-SSW direction and the second – orthogonal with the course close to parallel. The faults give the geological structure the nature of block tectonics. The throw of the fault in the first system is estimated to be about 40 m.

The Quaternary deposits in the study area, due to their minor thickness and discontinuity, are usually waterless. Only the waters of Muschelkalk and Buntsandstein aquifer of

Triassic systems are used for supplying. There are two water-bearing layers: the upper one related to the Karchowice and Diplopora Beds, and the lower one within the limestones of the Górażdże Beds, which belong to the Muschelkalk aquifer. Both horizons divide the barely permeable Terebratula Beds. The basement is built of less permeable Gogolin Beds. An active porosity of the aquifer rocks ranges from 13 to 32%, fissured porosity from about 1 to 4% and hydraulic conductivity from $1.7 \cdot 10^{-4}$ m/s to $4.8 \cdot 10^{-3}$ m/s (Staśko 1992). Within the study area, the Muschelkalk aquifer is characterized by an unconfined water table stabilized at the altitude of 160–180 m a.s.l. Within the Buntsandstein deposits, either the Roethian Formation (Upper Buntsandstein) or Middle and Lower Buntsandstein complex is of a water-bearing nature. Groundwater of the Upper Buntsandstein aquifer, Roethian carbonate sediments, occur in fractured limestones and dolomites. The water table is confined here and its pressures become stable at the altitude of 190–220 m a.s.l. Hydraulic conductivity of the Roethian Formation deposits ranges from $1.9 \cdot 10^{-6}$ m/s to $5.3 \cdot 10^{-4}$ m/s (Kryza and Staśko 2000; Staśko 1992). The Lower and Middle Buntsandstein aquifer occurs in moderately solid sandstones. It is characterized by a confined water table stabilizing at the altitude of 180 m a.s.l. The hydraulic conductivity of this aquifer, determined by a pumping test, is equal to $6.9 \cdot 10^{-6}$ m/s (Kryza 1994).

The groundwaters in Permian and Carboniferous sandstone formations are researched to a low degree. They are of a subartesian nature and are characterized by a higher temperature and mineralization.

2. Methodology

The aim of the field studies was to determine the hydraulic conductivity of Muschelkalk rocks. The research was conducted in November 2018 in the period of a low level of groundwaters and consisted of drilling 16 observation boreholes filtered in Muschelkalk layers, located near Tarnów Opolski. A short pumping test was planned in each borehole, together with their flooding and observing the groundwater table recovery after the stopping of the pumping. In practice, the construction of a borehole made it impossible to conduct all the planned tests in each borehole. The main obstacle was the borehole's insufficiently large diameter which prevented setting the pumps of a bigger diameter and discharge. This, in turn, would make creating a greater depression possible. Additionally, a small diameter of boreholes impeded its fast flooding which is a requirement for significant water table recovery for highly permeable rocks.

Every pumping test was conducted as a single pumping. The implementation of pumping in the hydrotechnical system was impossible because of overly large distances between the existing boreholes. Whenever possible, the pumping test in every borehole was carried out with various discharges, which allowed for an interpretation of the obtained results using methods dedicated to the conditions of steady and unsteady flow to the piezometer. Key data on the pumping tests are presented in Table 1.

Table 1. Key data on the pumping tests

Tabela 1. Zestawienie podstawowych danych wykonanych pompowań

Piezo-meter No.	Pumping discharge (m^3/h)	Water table depression (m)	Borehole radius (m)	Length of an active part of filter (m)	Aquifer thickness (m)	Depht of natural water table (m)
1	7.20	0.14	0.113	–	25.00	20.14
2	1.52	0.43	0.050	2	28.60	22.37
3	0.78	1.46	0.050	2	28.30	22.65
4	2.08	0.04	0.050	14	43.00	10.11
5	1.55	0.05	0.032	2	33.00	17.09
6	1.22	0.08	0.050	2	20.00	29.22
7	1.37	2.73	0.050	2	24.00	18.83
8	1.17	2.11	0.050	2	24.00	27.53
9	0.17	0.80	0.050	2	16.80	36.00
10	0.36	2.50	0.050	2	23.00	35.68
11	1.28	0.01	0.050	4	18.40	30.31
12	1.08	0.07	0.040	2.5	39.00	31.59
13	5.30	2.14	0.203	15	37.00	33.26
14	0.09	8.30	0.050	2	22.00	16.18
15	0.06	8.16	0.375	3	15.80	23.14
16	0.86	4.33	0.375	3	18.50	27.65

The calculation of the values of hydraulic conductivity k in the steady flow conditions was based on the Dupuit equation:

$$k = \frac{0,735 Q \log \frac{R}{r}}{H^2 - h^2} \tag{1}$$

- Q – pumping discharge,
- r – borehole radius,
- H – static hydraulic head,
- h – dynamic hydraulic head,
- R – cone of depression, calculated from the equation:

$$R = \sqrt{\frac{Q_e}{\pi M_d}} \tag{2}$$

Q_e – estimated value of exploitable resources [m^3/h], calculated using the results of pumping in piezometers (Q, s),

M_d – coefficient of renewable resources [$m^3/h \cdot km^2$] according to regional hydrogeological or hydrological studies (Kowalczyk et al. 1997) in a range of M_d = 3.9–15.2 $m^3/h \cdot km^2$.

The interpretation of the results of pumping test in unsteady flow conditions was based on the Theis method (Dąbrowski and Przybyłek 2005; Przybyłek et al. 1971) using the equations:

$$T = \frac{Q}{s} E(z) \tag{3}$$

$$k = \frac{T}{m} \tag{4}$$

T – transmissivity,

m – aquifer thickness,

s – water table depression (from the experimental chart),

$E(z)$ – auxiliary function (from the calibration curve).

Table 2. Key data on the observation of water table recovery

Tabela 2. Zestawienie podstawowych danych dotyczących obserwacji wzniosu zwierciadła wody

Piezometer No.	s_{max} (m)	s_{min} (m)	$\Delta s = s_{max} - s_{min}$ (m)	$\Delta t = t_{max} - t_{min}$ (s)	n
1	0.14	0.06	0.08	56	3
2	0.43	0.03	0.40	15	3
3	1.46	0.05	1.41	40	4
7	2.71	0.07	2.64	83	8
8	2.11	0.17	1.94	40	4
9	0.80	0.10	0.70	44	6
10	1.72	1.39	0.33	646	8
13	2.14	0.34	1.80	100	12
14	3.10	2.52	0.58	660	8
15	8.16	5.94	2.22	1 175	10
16	4.33	0.23	4.10	866	13

s_{max} – the greatest depression during the test, s_{min} – the smallest depression, Δt – the time interval between s_{max} and s_{min} readouts, n – number of tests within $s_{max} - s_{min}$.

After the stopping of pumping, the rate of water table recovery to the steady-state level was observed. Key data on the research and the pace of water table recovery is presented in Table 2 and in Figure 1.

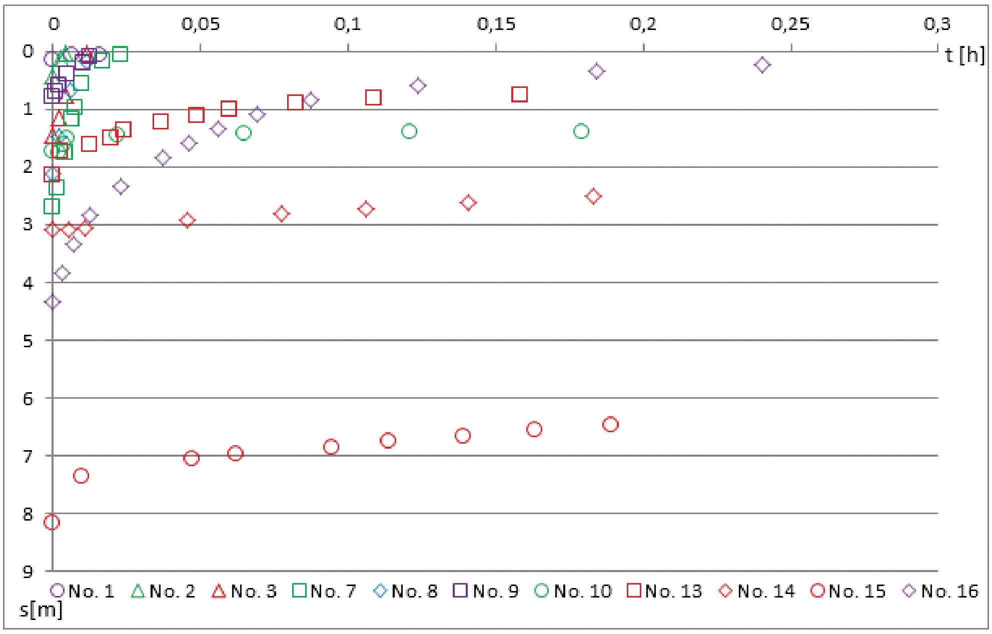

Fig. 1. Water table recovery in the holes after the stopping of pumping

Rys. 1. Wykresy wzniosu zwierciadła wody w otworach po zaprzestaniu pompowania

The values of hydraulic conductivity k were calculated based on two equations: Wieczysty and Theis. According to Wieczysty equation (Wieczysty 1970):

$$k = 2{,}303 \frac{\pi \sqrt[3]{r^5}}{AC60} \tag{5}$$

r – borehole radius,

C – constant value determined based on observations of groundwater table recovery:

$$C = \frac{\sum \left(t \log \frac{s_o}{s} \right)}{\sum \left(\log \frac{s_o}{s} \right)^2} \tag{6}$$

s_o – the greatest depression at the moment of pumping cutoff,
s – depression after time t from pumping cutoff,
A – coefficient related to the influence of borehole maintenance condition, its depth, inflow and construction:

$$A = ab$$

a – coefficient expressing the borehole maintenance condition (a = 1.8 for new boreholes and a = 1.6 for less-maintained boreholes),
b – coefficient expressing the sort of inflow to the borehole and its construction (value from charts).

According to Theis equation (Kruseman and De Ridder 1994; Pazdro and Kozerski 1990):

$$k = \frac{2.30Q}{4\pi\Delta s} \tag{7}$$

Q – pumping discharge,
Δs – residual depression difference, read out from a monologarythmic graph of interdependence,
$\Delta s = f(t/t")$, where t and $t"$ represent the time since the beginning and stop of pumping, respectively.

The last test carried out in the field consisted of flooding the borehole using from tens to hundreds of liters of water and observing the rate of the water table drop. The course of the tests is presented in Figure 2 and in Table 3. To calculate the value of hydraulic conductivity k, the Dobrzyński equation was used (Wieczysty 1970):

$$k = \frac{r^2}{2Hh_{ev}} \ln\frac{R}{r} \frac{\Delta h}{\Delta t} \tag{8}$$

r – borehole radius,
R – radius of influence,
H – aquifer thickness,
$h_{ev} = \frac{h_1 + h_2}{2}$,
$\Delta h = h_1 - h_2$ the height of water table recovery in the piezometer above the hydrostatic level,
$\Delta t = t_2 - t_1$ the time interval between h_1 and h_2 readouts.

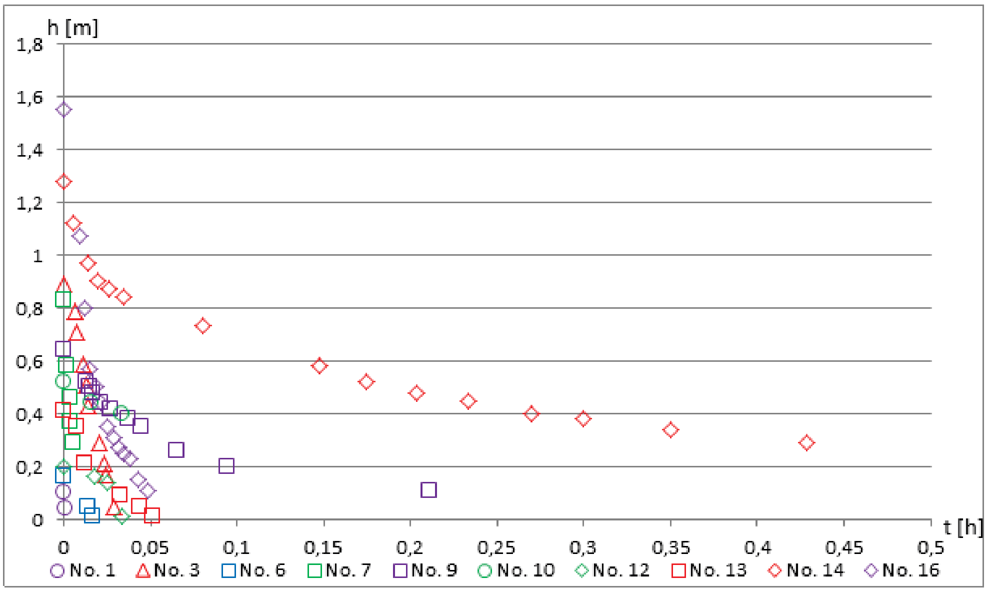

Fig. 2. Water table drop after the slug test

Rys. 2. Wykresy obniżania zwierciadła wody po zalaniu otworów

Table 3. Key data on the slug test

Tabela 3. Zestawienie podstawowych danych dotyczących badań metodą zalewania otworu

Piezometer No.	h_{max} (m)	h_{min} (m)	$\Delta s = h_{max} - h_{min}$ (m)	$\Delta t = t_{max} - t_{min}$ (s)	n
1	0.10	0.04	0.06	5	2
3	0.89	0.05	0.84	105	10
6	0.16	0.01	0.15	61	3
7	0.83	0.29	0.54	83	8
9	0.64	0.11	0.53	460	11
10	0.52	0.40	0.12	120	3
12	0.20	0.01	0.19	120	3
13	0.41	0.01	0.40	185	6
14	1.28	0.29	0.99	1 453	15
16	1.55	0.11	1.44	175	13

h_{max} – maximum level of water table recovery in the piezometer above the hydrostatic level, h_{min} – minimum level of water table recovery in the piezometer above the hydrostatic level, Δt – the time interval between h_{max} and h_{min} readouts, n – number of tests within $s_{max} - s_{min}$.

An interpretation of the results of field studies was preceded by gathering archival materials, especially borehole logs. The information on the geological profile (aquifer thickness), stratigraphy of aquifer, filter length and borehole diameter included in borehole logs was used for calculation. The height of the seepage face was neglected because of its marginal values being the effect of a small depression which occurred during the short pumping and a high aquifer thickness. In the case of pumping in a partially penetrating well, the discharge Q_n was corrected to discharge Q (fully penetrating well) using the Forchheimer correction b:

$$Q = \frac{Q_n}{b} \tag{9}$$

$$b = \sqrt{\frac{l}{h}} \sqrt[4]{\frac{2h - l}{h}} \tag{10}$$

↳ l – length of an active part of filter (m),
h – height of a dynamic water table in well (m).

The last stage of works included the calculation of the values of specific capacity q based on the equation:

$$q = \frac{Q}{s} \tag{11}$$

↳ Q – pumping discharge,
s – water table depression.

3. The results

The conducted studies allowed the values of specific capacity q (11) and hydraulic conductivity k of Muschelkalk carbonate layers to be calculated using maximum four methods (1), (3), (5, 7), (8). The determined values of hydraulic conductivity k range from $8.56 \cdot 10^{-8}$ to $3.63 \cdot 10^{-3}$ m/s and the values of specific capacity of well q from 0.0075 to 128 m^3/h/1mS (Table 4). In the analysis of the results obtained using various methods, the following conditions influencing their credibility should be taken into account:

- construction of a well and its maintenance state – all of the studied boreholes were fully functional and most of them were not older than a couple of years;
- determining hydraulic conductivity as a result of short pumping (3) is considered the most accurate but not error-free, especially in the case of works conducted in individual boreholes – each of the pumping tests was carried out individually;

- high water accumulation in the aquifer, and borehole construction preventing the usage of a highly efficient pump resulted in obtaining relatively low depressions in several piezometers (No. 1, 4, 6, 8, 12 and 13) during the pumping;
- the methods of hydraulic conductivity k determination based on slug test (8) are considered less reliable compared to the methods based on observation of water table recovery after the stop of pumping (5, 7) that were intended for steady flow conditions, although, in fact, the flow was unsteady (Wieczysty 1970).

Table 4. Calculation results

Tabela 4. Zestawienie wyników obliczeń

Studied layers*	Piezometer No.**	Hydraulic conductivity k [m/s]					Specific capacity q (11) (m^3/h · 1mS)
		short pumping		water table recovery		slug test	
		steady flow conditions Dupuit equation (1)	unsteady flow conditions Theis equation (3), (4)	Wieczysty equation (5)	Theis equation (7)	Dobrzański equation (8)	
T_a^{k+j}	1	**$2.53 \cdot 10^{-4}$**	–	$4.44 \cdot 10^{-5}$	$2.22 \cdot 10^{-4}$	$1.06 \cdot 10^{-5}$	51.4
T_a^{k+j}	2	$3.96 \cdot 10^{-5}$	**$4.79 \cdot 10^{-5}$**	$8.62 \cdot 10^{-5}$	$3.87 \cdot 10^{-6}$	–	3.53
T_a^{k+j}	3	$4.74 \cdot 10^{-6}$	**$5.67 \cdot 10^{-6}$**	$1.39 \cdot 10^{-6}$	$1.36 \cdot 10^{-6}$	$1.50 \cdot 10^{-7}$	0.54
T_a^{k+j}	4	**$3.77 \cdot 10^{-4}$**	–	–	–	–	52.0
T_a^{k+j}	5	**$5.08 \cdot 10^{-4}$**	–	–	–	–	31.0
T_a^{k+j}	6	**$2.45 \cdot 10^{-4}$**	–	–	–	$2.89 \cdot 10^{-4}$	15.2
T_a^{g}	7	$5.56 \cdot 10^{-6}$	**$5.91 \cdot 10^{-6}$**	$1.74 \cdot 10^{-6}$	$1.82 \cdot 10^{-6}$	$1.62 \cdot 10^{-6}$	0.50
T_a^{g}	8	$6.23 \cdot 10^{-6}$	**$7.18 \cdot 10^{-6}$**	$2.89 \cdot 10^{-6}$	$1.39 \cdot 10^{-6}$	–	0.55
T_a^{g}	9	$3.70 \cdot 10^{-6}$	**$5.09 \cdot 10^{-6}$**	$2.00 \cdot 10^{-5}$	$8.29 \cdot 10^{-7}$	$1.93 \cdot 10^{-5}$	0.21
T_a^{g}	10	$3.47 \cdot 10^{-6}$	**$4.17 \cdot 10^{-6}$**	$1.62 \cdot 10^{-6}$	$7.96 \cdot 10^{-6}$	$5.32 \cdot 10^{-6}$	0.14
T_a^{g}	11	**$3.64 \cdot 10^{-3}$**	–	–	–	–	128.0
T_a^{g}	12	**$3.49 \cdot 10^{-4}$**	–	–	–	$6.42 \cdot 10^{-4}$	15.4
T_a^{go}	13	$7.99 \cdot 10^{-6}$	**$8.11 \cdot 10^{-6}$**	$3.47 \cdot 10^{-6}$	$7.59 \cdot 10^{-6}$	$2.43 \cdot 10^{-6}$	2.48
T_a^{go}	14	$4.17 \cdot 10^{-8}$	**$8.56 \cdot 10^{-8}$**	$2.66 \cdot 10^{-7}$	$1.95 \cdot 10^{-7}$	$1.74 \cdot 10^{-8}$	0.011
T_a^{go}	15	$1.74 \cdot 10^{-8}$	**$3.18 \cdot 10^{-7}$**	$2.66 \cdot 10^{-7}$	$1.23 \cdot 10^{-7}$	–	0.0075
T_a^{go}	16	$1.10 \cdot 10^{-6}$	**$1.30 \cdot 10^{-6}$**	$2.55 \cdot 10^{-6}$	$1.41 \cdot 10^{-6}$	$3.36 \cdot 10^{-7}$	0.20

* Aquifer layers symbols: T_a^{k+j} – Karchowice and Diplopora Beds; T_a^{g} – Górażdże Beds; T_a^{go} – Gogolin Beds. The most probable and credible values accepted for further analysis are in bold.

** The number in accordance with Figure 3.

The range of the obtained values is wide because the studies focused either on highly permeable rocks (Karchowice and Diplopora Beds) or those characterized by low permeability (Gogolin Beds). Moreover, the highest values are related to more tectonically fractured zones or karsty areas (La Moreaoux 1991; Kryza and Staśko 2000). The values of *k* in the same boreholes, calculated based on various methods, are similar. The visible differences might result from the above mentioned factors. The arithmetic average values of *k*, calculated from the results of 7 boreholes for which the calculations using all the methods had been carried out, enter within the scope between $3.023 \cdot 10^{-6}$ m/s and $4.434 \cdot 10^{-6}$ m/s. It can generally be claimed that the calculations made using the Dobrzański equation resulted in slightly lower values. In the situation where similar results were obtained using 2–3 methods based on short-term water pumping and observations of water table recovery (equations 1, 3–4, 5, 7), only those obtained using the Theis method were further interpreted. It has been assumed that it will be more correct to make an interpretation based on a limited number of methods using trial pumping in this case, and the results obtained using other methods are to make it more credible. The results accepted for the rock permeability description are bolded in Table 4.

4. Characteristics of Muschelkalk layers permeability

The permeability of the studied layers of the Muschelkalk is clearly varied. The Karchowice and Diplopora Beds are characterized by the highest values of hydraulic conductivity *k*, several dozen meters per day on average. The rocks of the Gogolin Beds are noticeably less permeable, with the average *k* value equal to $2.43 \cdot 10^{-6}$ m/s (Table 5). In the analysis of the average values of a specific capacity, the highest one was also determined for the Karchowice and Diplopora Beds, alongside the Górażdże Beds. The *q* values for these rock formations come up to 25.62 and 24.14 m^3/h/1mS, respectively. A visibly lower average value of a specific capacity was determined for Gogolin Beds, namely 0.67 m^3/h/1mS (Table 6).

Table 5. Basic statistics of hydraulic conductivity of the Muschelkalk layers

Tabela 5. Podstawowa statystyka współczynnika filtracji warstw wapienia muszlowego

Taken aquifers*	Number of investigations	*k* (m/s)			
		max.	min.	average	standard deviation
T2(GOR)	6	$3.64 \cdot 10^{-3}$	$4.17 \cdot 10^{-6}$	$6.68 \cdot 10^{-4}$	$1.46 \cdot 10^{-3}$
T2(K&D)	6	$5.09 \cdot 10^{-4}$	$5.67 \cdot 10^{-6}$	$2.40 \cdot 10^{-4}$	$1.91 \cdot 10^{-4}$
GO	4	$8.11 \cdot 10^{-6}$	$8.56 \cdot 10^{-8}$	$2.43 \cdot 10^{-6}$	$3.82 \cdot 10^{-6}$

* The symbols of the aquifers are the same as in Table 4.

Table 6. Basic statistics of specific capacity of the Muschelkalk layers

Tabela 6. Podstawowa statystyka wydatku jednostkowego warstw wapienia muszlowego

Taken aquifers*	Number of investigations	q (m^3/h/1mS)			
		max.	min.	average	standard deviation
T2(GOR)	6	128	0.1440	24.14	51.24
T2(K&D)	6	52	0.5370	25.62	22.88
GO	4	2.477	0.0075	0.67	1.21

* The symbols of the aquifers are the same as in Table 4.

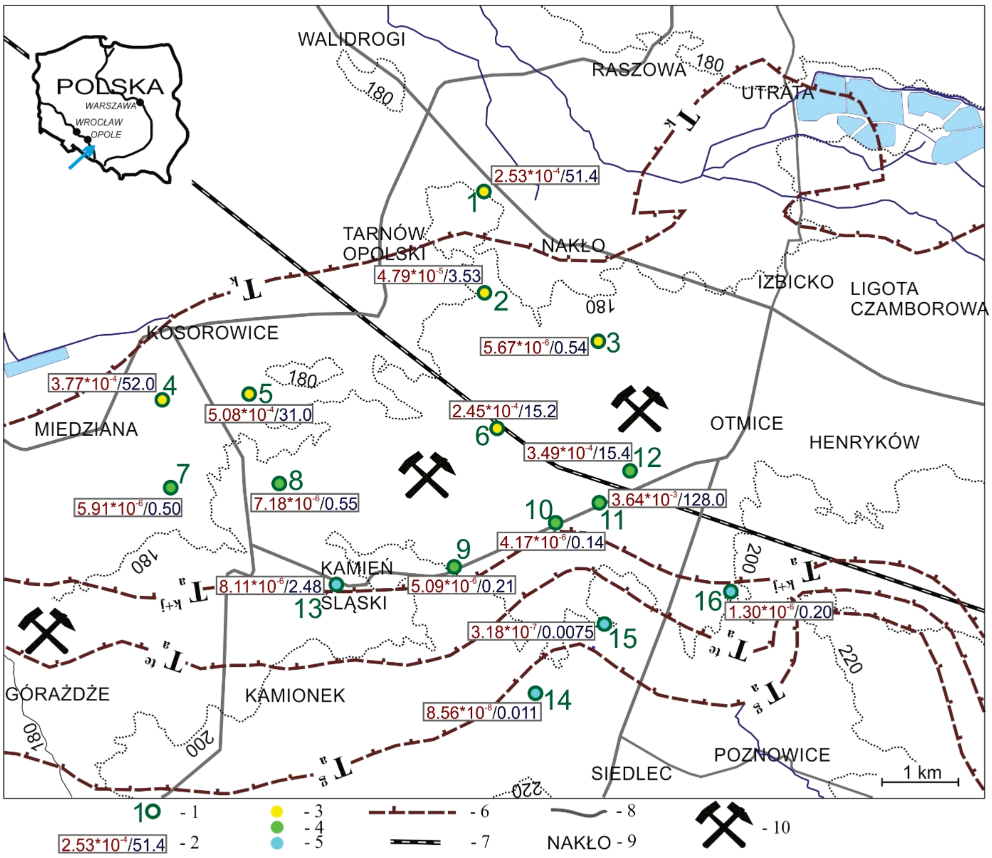

Fig. 3. The distribution of hydraulic conductivity and specific capacity of wells in the study area
1 – location and number of borehole, 2 – value of hydraulic conductivity (m/s) (red color) and specific capacity of well (m^3/h · 1mS) (blue color), 3 – borehole filtered in the Karchowice and Diplopora layers, 4 – borehole filtered in the Górażdże layers, 5 – borehole filtered in the Gogolin layers, 6 – range of the outcrops of the Muschelkalk and Keuper (T_a^g – Górażdże, T_a^{te} – Terebratula, T_a^{k+j} – Karchowice and Diplopora, T_k – Keuper), 7 – railway line, 8 – roads, 9 – towns, 10 – active quarries

Rys. 3. Rozkład wartości współczynnika filtracji oraz wydatków jednostkowych studni na badanym obszarze

The studied rock layers, based on the calculated hydraulic conductivity values, can be classified depending on their permeability and insulating properties. Generally, the highest permeability (high, occasionally medium and very low) was determined for the Karchowice Beds and Diplopora Beds, slightly lower for the Góraźdże Beds (low but locally high and even very high) and the lowest for the Gogolin Beds (low and very low) (Dowgiałło et al. eds. 2002). In terms of insulating properties, the Karchowice and Diplopora Beds, as well as the Górażdże Beds can be classified as non-insulating. Only the layers of the Gogolin Beds may be characterized as very poorly insulating.

The results of the conducted studies show that the most water-bearing zone of the area is related to the carbonate rocks of the Karchowice, Diplopora and Górażdże Beds, characterized by the highest values of hydraulic conductivity k (above $2 \cdot 10^{-4}$ m/s) and specific capacity q (above 15 m^3/h/1mS), in the belt stretching latitudinally through Kosorowice–Otmice (Fig. 3). The rocks of Górażdże Beds for which the lower values of k and q were determined to the south of this zone and to the north of Kamień Śląski, ranging from $3.70 \cdot 10^{-6}$ to $6.25 \cdot 10^{-6}$ m/s for k and from 0.14 to 0.545 m^3/h/1mS for q, respectively.

The values of the discussed parameters decrease to a significantly lower level to the south of Kamień Śląski, which indicates a lower water accumulation in the rocks of the area. The values of hydraulic conductivity k vary from $4.17 \cdot 10^{-8}$ to $7.99 \cdot 10^{-6}$ m/s and specific capacity from 0.0075 to 2.48 m^3/h/1mS (usually below 0.25 m^3/h/1mS). The lowest values of both parameters were determined for the rocks investigated in the boreholes located furthest to the south from the studied area, where the poorly permeable Gogolin Beds are located.

Summary

The paper presents the results of determining permeability of the Muschelkalk rocks which form the Karchowice and Diplopora, Górażdże, and Gogolin Beds. The conducted studies complement the knowledge about the water-bearing capacities of the Muschelkalk aquifers on a regional scale. Such detailed research, allowing the parameters of separated Muschelkalk layers to be determined, had not been carried out in the area before. The obtained results allowed to classify the rock permeability as high (Karchowice and Diplopora Beds, and Górażdże Beds) and low (Gogolin Beds). The dense network of the research points enabled to demonstrate the surface variability of rock permeability and water-bearing capacity, determined mostly by the direction of the outcrops of individual layers.

The study area can be considered as a Polish limestone-concrete-field where several mines exploiting carbonate rocks from Muschelkalk operate. In the coming years, further exploitation of the existing quarries and launching new mines is planned. The results of the conducted studies may be useful for the correct prognosis of groundwater inflow either to the already existing quarries or to the newly designed mines. This is especially important in this area, where the Major Groundwater Basin is separated within the Muschelkalk layers.

REFERENCES

Dąbrowski, S. and Przybyłek, J. 2005. Pumping test in documentation of groundwater resources. Methodological guide (*Metodyka próbnych pompowań w dokumentowaniu zasobów wód podziemnych. Poradnik metodyczny).* Warszawa: Ministerstwo Środowiska, 292 pp. (*in Polish*).

Dowgiałło et al. eds. 2002 – Dowgiałło, J., Kleczkowski, A.S., Macioszczyk, T. and Różkowski, A. eds. 2002. Hydrogeological Dictionary (*Słownik hydrogeologiczny)*. Ed. 2. Warszawa: Ministerstwo Środowiska and PIG, 461 pp. (*in Polish*).

Kondracki, J. 2009. Regional geography of Poland (*Geografia regionalna Polsk*i). Ed. 3. Warszawa: Wyd. Nauk. PWN, 441 pp. (*in Polish*).

Kowalczyk et al. 1997 – Kowalczyk, A., Kropka, J. and Rubin, K., 1997. Groundwater resources of the Gliwice Triassic aquifer as the result of mathematical modelling (*Zasoby wód podziemnych zbiornika triasowego (GZWP) Gliwice na podstawie badań modelowych*). [In:] Górski, J. and Liszkowska, E. eds. *Współczesne problemy hydrogeologii, Tom 8*. Wrocław: WIND, pp. 85–90 (*in Polish*).

Kruseman, G.P. and De Ridder, N.A. 1994. Analysis and Evaluation of Pumping Test Data. Ed. 2. Wageningen: International Institute for Land Reclamation and Improvement (ILRI), 377 pp.

Kryza, J. 1994. Hydrogeological assessment of groundwater resources in the lower Triassic aquifer of Foresudetic Monocline. *Zeszyty Naukowe Akademii Rolniczej* 248, pp. 181–191.

Kryza, J. and Staśko, S. 2000. Groundwater flow rate and contaminant migration in fissure-karstic aquifer of Opole Triassic system southwest Poland. *Environmental Geology* 39(3), pp. 384–389.

La Moreaoux, PE. 1991. Environmental effect to overexploitation in karst terrain. Proc XXIII Int Congress Aquifer Overexploition. T. G. Arte, Juberias & CIA, Granada, pp. 103–115.

Motyka, J. and Wilk, Z. 1976. Vertical differentiation in the water permeability of carbonate Triassic rocks in the light of a statistical analysis of the results of pumping tests (Silesia-Krakow Monocline) (*Pionowe zróżnicowanie wodoprzepuszczalności węglanowych skał triasowych w świetle statystycznej analizy wyników próbnych pompowań (monoklina śląsko-krakowska)*). *Kwartalnik Geologiczny* 20(2), pp. 381–399 (*in Polish*).

Pazdro, Z. and Kozerski, B. 1990. General hydrogeology (*Hydrogeologia ogólna*). Ed. 4. Warszawa: Wyd. Geol., 624 pp. (*in Polish*).

Przybyłek, J., Brylska, E. and Dąbrowski, S. 1971. Calculation rules of indetermined filtration according to Theis and Hantush equations (*Zasady obliczeń filtracji nieustalonej według wzorów Theisa i Hantusha*). Warszawa: Wyd. Geol., 54 pp. (*in Polish*)

Senkowiczowa, H. 1998. Triassic of the north-eastern margin of the Upper Silesian Basin (*Trias północno-wschodniego obrzeżenia Górnośląskiego Zagłębia Węglowego*). *Biul. PIG* 378, pp. 5–66 (*in Polish*).

Stanienda, K. 2014. Mineral phases in carbonate rocks of the Gogolin Beds from the area of Opole Silesia (*Fazy mineralne w skałach węglanowych warstw gogolińskich obszaru Śląska Opolskiego*). *Gospodarka Surowcami Mineralnymi – Mineral Resources Management* 30(3), pp. 17–42 (*in Polish*).

Stanienda, K. 2016. Mineral phases in carbonate rocks of the Górażdże Beds from the area of Opole Silesia (*Fazy mineralne w skałach węglanowych warstw górażdżańskich obszaru Śląska Opolskiego*). *Gospodarka Surowcami Mineralnymi – Mineral Resources Management* 32(3), pp. 67–92 (*in Polish*).

Staśko, S. 1992. Grounwater in carbonate Triassic rocks in Opole region, SW Poland (*Wody podziemne w węglanowych utworach triasu opolskiego*). *Prace Geologiczno-Mineralogiczne* XXXII, 74 pp. (*in Polish*).

Szczygieł et al. 2006 – Szczygieł, I., Kryza, J. and Fic, A. 2006. Aquitard conductivity calibration of the Triassic aquifer numerical model of the Strzelce Opolskie area (*Kalibrowanie parametrów filtracyjnych warstw słabo przepuszczalnych na modelu numerycznym zbiornika triasowego w rejonie Strzelec Opolskich*). *Geologos* 10, pp. 271–283 (*in Polish*).

Wieczysty, A. 1970. Engineering hydrogeology (*Hydrogeologia inżynierska*). Warszawa–Kraków: PWN, 815 pp. (*in Polish*).

Wilk et al. 1985 – Wilk, Z., Motyka, J., Borczak, S. and Makowski, Z. 1985. Microhydraulic properties of the Muschelkalk and Rhoethian rocks of the southern section of the Krakow–Silesian Monocline (Poland) (*Własności mikrohydrauliczne utworów wapienia muszlowego i retu południowej części monokliny śląsko-krakowskiej*). *Rocznik Pol. Tow. Geol.* 55(3–4), pp. 485–508 (*in Polish*).

Woś, A. 1999. Climate of Poland (*Klimat Polski*). Warszawa: Wyd. Nauk. PWN, 302 pp. (*in Polish*).

PERMEABILITY OF MUSCHELKALK ROCKS (MIDDLE TRIASSIC) OF THE KRAKOW–SILESIAN MONOCLINE IN TARNÓW OPOLSKI AREA (SOUTH POLAND)

Keywords

hydrogeological parameters, pumping test, Krakow–Silesian Monocline

Abstract

The paper presents the results of hydrogeological parameters determination carried out in the area of the Muschelkalk outcrop (Middle Triassic) near Tarnów Opolski. The studies consisted of a short pumping test in 16 piezometers and then their flooding and observation of water table recovery after the stopping of the pumping. The test allowed the values of hydraulic conductivity and specific capacity of Muschelkalk layers ranging from $8.56 \cdot 10^{-8}$ m/s to $3.63 \cdot 10^{-3}$ m/s and from 0.0075 to 128 m^3/h/1mS, respectively, to be calculated. The wide range of values is related to the fact of studying the layers characterized by high permeability and water-bearing capacity (Karchowice Beds, Diplopora Beds and Górażdże Beds) as well as layers with low permeability (Gogolin Beds). The dense network of the research points made it possible to demonstrate the surface variability of rocks permeability and water-bearing capacity, determined mostly by the direction of outcrops of individual layers. The results of the conducted studies show that the most water-bearing zone of the area is related to the carbonate rocks of the Karchowice, Diplopora and Górażdże Beds, characterized by the highest values of hydraulic conductivity *k* (above $2 \cdot 10^{-4}$ m/s) and specific capacity *q* (above 15 m^3/h/1mS), in the belt stretching latitudinally through Kosorowice–Otmice. The studied area can be considered a Polish limestone-concrete field where several mines exploiting Muschelkalk carbonate rocks operate. The results of the conducted studies may be useful for the correct prognosis of the groundwater inflow either to already existing quarries or newly designed mines within the Major Groundwater Basins.

PRZEPUSZCZALNOŚĆ SKAŁ WAPIENIA MUSZLOWEGO (TRIAS ŚRODKOWY) MONOKLINY ŚLĄSKO-KRAKOWSKIEJ W REJONIE TARNOWA OPOLSKIEGO (POŁUDNIOWA POLSKA)

Słowa kluczowe

parametry hydrogeologiczne, próbne pompowanie, monoklina śląsko-krakowska

Streszczenie

Artykuł prezentuje wyniki badań parametrów hydrogeologicznych przeprowadzonych na obszarze wychodni warstw wapienia muszlowego (trias środkowy) w okolicach Tarnowa Opolskiego. Badania polegały na przeprowadzeniu w 16 piezometrach krótkotrwałych pompowań, zalewań badawczych otworu oraz obserwacji wzniosu zwierciadła wody po zaprzestaniu pompowania. Na podstawie przeprowadzonych badań obliczono wartości współczynnika filtracji *k* oraz wydatku jednostkowego *q* skał węglanowych warstw wapienia muszlowego w zakresie odpowiednio od $8{,}56 \cdot 10^{-8}$ m/s do $3{,}63 \cdot 10^{-3}$ m/s i od 0,0075 do 128 m^3/h/1mS. Duża rozpiętość uzyskanych wartości wynika z faktu

objęcia badaniami skał warstw karchowickich, diploporowych i górażdżańskich charakteryzujących się dobrą przepuszczalnością oraz zawodnieniem jak i słabo przepuszczalnych warstw gogolińskich. Liczna sieć punktów badawczych umożliwiła przedstawienie powierzchniowej zmienności przepuszczalności skał oraz ich zawodnienia, w dużej mierze zdeterminowanej biegiem wychodni poszczególnych warstw. Wyniki wykonanych badań wskazują, że na badanym obszarze strefa o największym zawodnieniu związana jest z występowaniem skał węglanowych warstw karchowickich i diploporowych oraz górażdżańskich, charakteryzujących się najwyższymi wartościami *k* (powyżej $2 \cdot 10^{-4}$ m/s) i *q* (powyżej 15 m^3/h/1mS), w pasie biegnącym równoleżnikowo przez miejscowości Kosorowice–Otmice. Omawiany obszar stanowi zagłębie wapienniczo-cementowe Polski, na którym funkcjonuje kilka kopalń eksploatujących skały węglanowe warstw wapienia muszlowego. Wyniki prezentowanych badań mogą być pomocne w prawidłowej ocenie prognoz dopływów wód podziemnych do odkrywek kopalni już istniejących, czy też projektowanych, leżących w większości w granicach głównych zbiorników wód podziemnych.