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Groundwater modelling in the upper Bobrza river catchment area

A six-layer hydrogeological numerical model was constructed in the area of the upper basin of the Bobrza river. The model calculations were conducted by means of a hydrogeological program - Woterloo Hydrogeologic Visual Modflow Pro ver. 4.3.0 WATERLOO HYDROGEOLOGIC, Inc. 180 Columbia St. W. - Unit 1104 Waterlo, Ontario, Canada. A multilayer (3D) model, calculated in the uniform filtration field with the determined flow conditions, was used for the solutions. The objective of the conducted model research was to determine the admissible volume of the extracted groundwater in the municipal capture in Zagnańsk and to present the groundwater circulation system in the area of the conducted model research. The original and the current hydrodynamic fields appearing in the aquifer were reconstructed on the model, and then the balance for the well influence area with determined safe yield was prepared.

Keywords: **groundwater capture, numerical modelling, groundwater balance, groundwater flow, Poland**

Introduction

The studied groundwater model is located in the south of Poland in the major groundwater basin MGB 414 Kielce. The municipal groundwater intake in Zagnańsk - the biggest intake in the region - is located in the eastern part of the upper basin of the Bobrza river. The Zagnańsk intake is the main source of water supply for the northern and eastern part of the city of Kielce. The exploited water originates mostly from the Lower Triassic aquifer, of the porous-karstic type, which is the main source of groundwater, with one well exploiting water from the Devon aquifer and two wells exploiting the combined Perm-Triassic aquifer [1]. In the area of the upper basin of the Bobrza river, a six-layer hydrogeological numerical model was constructed in order to estimate the admissible volume of the extracted groundwater in the municipal intake in Zagnańsk and to present the groundwater circulation system in the area of the conducted model research. The original and the current hydrodynamic fields appearing in the aquifer were reconstructed on the model, and then the balance for the well influence area with determined safe yield was prepared.

1. Hydrogeological model

1.1. Tools

The model calculations were conducted by means of a hydrogeological program - Woterloo Hydrogeologic Visual Modflow Pro ver. 4.3.0. A multilayer (3D) model, calculated in the uniform filtration field with the determined flow conditions, was used to obtain the solutions. The calculations were performed by the definite difference method on the rectangular calculation grid [2].

1.2. Construction of the groundwater circulation model

The mathematical model covered the eastern part of the major groundwater basin MGB 414. The borders of the modelled area have natural character and correspond to the hydrodynamic borders marked by the surface watercourses (Fig. 1). The outer borders of the model are: the Krasna and the Czarna Taraska rivers in the north, the tributaries of the Czarna Taraska and the Olszówka in the west, the Olszówka river and the tributaries of the Bobrza and the Sufraganiec rivers in the south and the Lubrzanka river with its tributaries in the east.

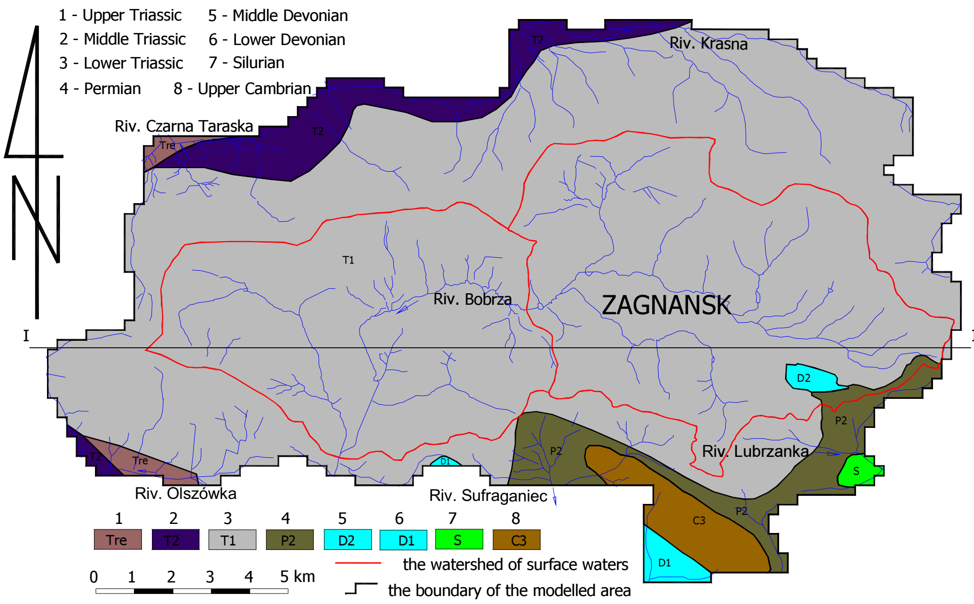


Fig. 1. The schematic map of the geological structure of the study area

Rys. 1. Mapa schematycznej budowy geologicznej w badanym obszarze

The modelling research area was divided into squares forming a net with the constant grid spacing x = y = 250 m. The model covers an area of 220.81 km^2 with 22062 active blocks in the whole model. The mathematical model is composed of the following layers: layer I of the model comprises Pleistocene formations:

medium-grained sands, fine-grained sands, dusts; clays, river alluvia form sub-surface layer. Layers II-VI of the model comprise water-bearing Lower and Middle Triassic formations (Fig. 2), in the southern part of the model occur low-permeable Older Paleozoic, Cambrian, Sylurian and Lower Devonian formations. The Lower Triassic is the level of the greatest, prevailing significance in the study area. It consists of sandstones and siltstones with claystone intrusions. This is a karstic-porous level. In the study area it serves as the main exploitation aquifer. Its waters are mostly unconfined. The depth at which the Lower Triassic level is located is varied. It ranges from 0÷5 m in fluvial valleys to 15÷50 m in the uplands [3-7].

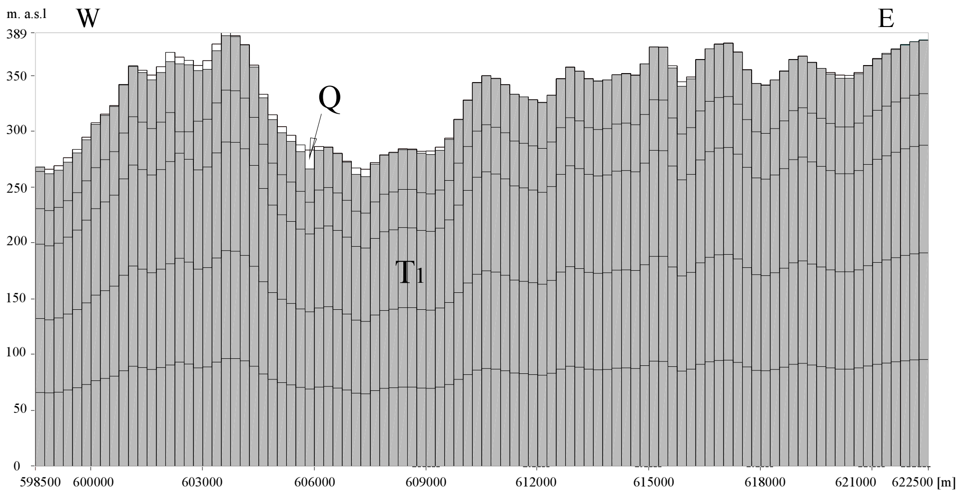


Fig. 2. Geological cross-section on the model I-I' - row 38 (Q - Pleistocene formations; T_1 - Lower Triassic formations)

Rys. 2. Przekrój geologiczny na modeu I-I' - wiersz 38 (Q - utwory plejstoceńskie, T_1 - utwory triasu dolnego)

Mathematical calculations were conducted in determined conditions, with the possibility to dehydrate and irrigate the blocks. The following boundary conditions were assumed for the model:

- recharging the aquifer through the rainfall infiltration - condition of type II (Q = const.) was introduced in the first active layer of the model,
- the exploitation of aquifer by means of exploitation wells - condition of type II (Q = const.) was introduced inside the model in the calculation blocks simulating the operation of the particular dewatering wells,
- the discharge and infiltration of the aquifer by the rivers-boundary conditions of type III were introduced inside and outside the model.

For the simulation on the model the multiannual rainfall (1955-2009) was adopted - it amounted to 679 mm per annum (precipitation station "Bartków"). The annual rainfall in 2009 in this post amounted to 685 mm [8]. Variable values of effective infiltration were adopted for the area covered by the research, depending on the lithological formation, spatial management of the aeration zone, and the

amount of rainfall. The value of effective infiltration adopted varied from 5.0 to 24% and it fell within the range of 36÷172 mm per annum. The mean low flow on the water mark Porzecze, closing the upper part of the Bobrza river catchment, was adopted in the model. The flow was calculated in the following way. In the years 1986-1988 IMGW (the Institute for Meteorology and Water Management) installed a local water stage-recorder in Porzecze, in that period the mean low flow was (SNQ) = 0.15 m^3/s (540 m^3/h) [9]. In the same period the mean water exploitation at the Zagnańsk intake was 921 m^3/h, the probable value of the underground outflow in the discussed period was adopted as 1461 m^3/h, which corresponds to the mean low flow of 0.41 m^3/s. The mean annual precipitation in the Bartków post in the years 1986-1988 was 604.3 mm [10], whereas in the year 2009 the precipitation was 685 mm [8], which gives the ratio of 1:1.13.
Considering the above, the underground outflow in the year 2009 was 1656.1 m^3/h, which gives the mean low flow in Porzecze equal to 0.46 m^3/s.
While tarring the model for the year 2009, the mean low flow at the Kołomań water stage-register was obtained, equal to 0.14 m^3/s (500 m^3/h), which corresponds to the mean low flows registered in the process of monitoring the Zagnańsk intake [9].
The total water withdrawal from the wells in the model area amounted to 9692.61 m^3/day out of which 9100.88 m^3/day withdrawn at the intake in Zagnańsk [10].

1.3. The groundwater circulation system

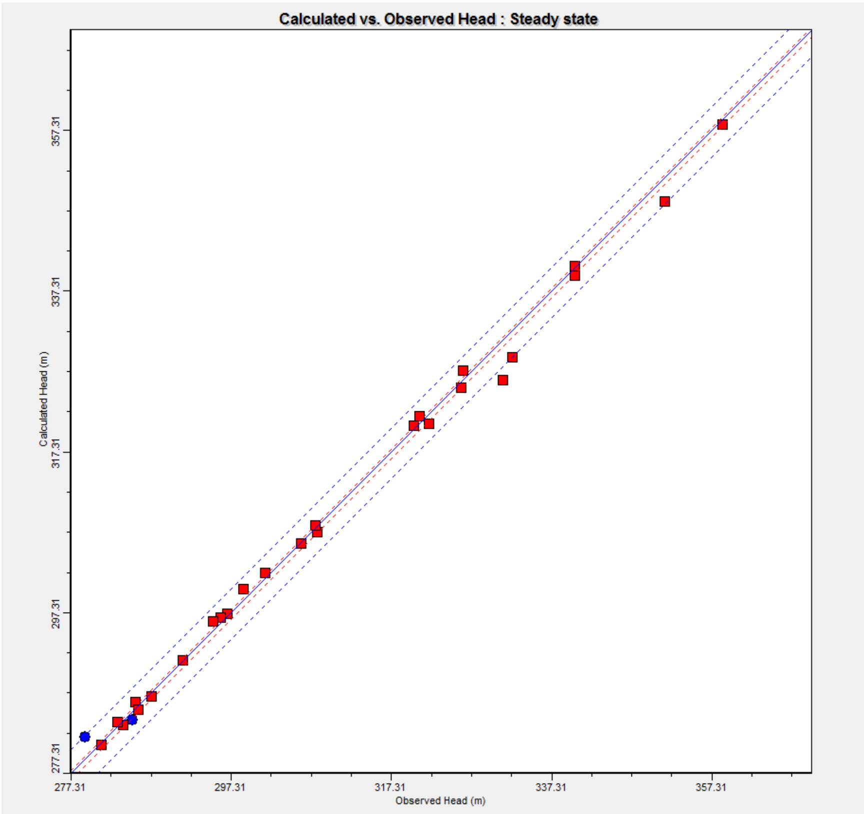
The main source of groundwater recharge on the modelling research area is the infiltration from rainfall.The southern part of the area is additionally recharged with overland flow from the surrounding hills composed of low permeable formations. The main discharge for the area is the Bobrza river. Most surface watercourses originate from the groundwater and have discharging character. In the study area, the underground water intake in Zagnańsk has been locally monitored since 1971 [10].
The water table is measured once a month in ten monitoring piezometers and seven dug wells, as a part of the monitoring. The monitoring points are located around the underground water intake in Zagnańsk. The water flow of the Bobrza river is also measured at the Kołomań weir as a part of the monitoring [8, 11].
The monitoring research results were used to analyse the underground water balance on the mathematical model. The monitoring research revealed that the water table in the Triassic aquifer is located at the depth ranging from 0.8 to 44 m [8].

The long exploitation of the groundwater intake in Zagnańsk caused the lowering of the groundwater table in the immediate area of the intake [10, 12]. Presently the western part of the intake has the lowest water table of the Lower Triassic aquifer at the ordinate of 280 m a.s.l. The highest water table occurs at the ordinance of 390 m a.s.l. in the north-eastern part of the Bobrza basin.The pressures difference between the zones of recharge and discharge of groundwater ranges from 10 to 60 m. The gradient of the water table of the discussed area is very variable. The smallest gradient occurs in the central part of the researched area and then the lowering gradually increases moving northwards, eastwards and westwards [10, 12-15].

1.4. The model calibration

The simulation computations on the model were conducted in such a way as to obtain the values of the water table that would differ as little as possible from the values measured in the field. The graph of matching the calculated and observed values is presented in Figure 3.

The model calibration was conducted using the values of the actual water table from the year 2009. The model identification involved establishing the variability of the hydrogeological parameters in particular layers of the model (hydraulic conductivity, infiltration recharge and the river bed transmissivity).



Legend:
● - points located in model layer number II,
■ - points in model layer number III,
X axis - observed head [m] in 2009,
Y axis - calculated head [m]

Fig. 3. Calculated and observed groundwater head in the Triassic aquifer

Rys. 3. Obliczone i obserwowane rzędne zwierciadła wody w utworach triasowych

2. Results and discussion

The obtained results of the simulation calculations make it possible to prepare the groundwater balance for the area covered by the modelling research. The groundwater balance was determined on the basis of the analysis of a 30-year-long operation of the intake well in Zagnańsk and the mean low flows in the upper Bobrza basin (section 1.2). The balance enables a detailed analysis and evaluation of the factors that influence groundwater resources in the modelled area.

Table 1 presents the groundwater balance for the area covered by the mathematical model and the balance for the upper Bobrza basin for the three calculation states.

- The original state was adopted without the well.
- The hydrogeological condition for the year 2009 took into account the values of water withdrawal from particular wells and the measuring results from piezometres and monitoring wells (section 1.3).
- The state of the admissible volume of the extracted groundwater (630 m^3/h) related to the optimum operation arrangement of particular wells.

Calculating the admissible volume of the extracted groundwater was made on the mathematical model assuming that the inviolable minimum flow will be preserved in the river. The calculations reconstructing the groundwater circulation in the conditions of groundwater intake exploitation were evaluated. As a result, the groundwater table in all the simulated aquifers was obtained together with the balance of the groundwater resources for the mean multiannual states. The total effective infiltration for the modelling research area of 220.46 km^2 amounted to 78 908.58 m^3/d (Tab. 1), which equals the mean effective infiltration of 130.0 mm per annum (19.0% of the mean annual rainfall). The total well water withdrawal in the modelled area amounts to 15 942.18 m^3/d, out of which 15 120 m^3/d is withdrawn in Zagnańsk intake. The Bobrza river in the Upper Bobrza basin infiltrates to the aquifer recharging 6006.56 m^3/d and discharges 31 571.42 m^3/d. Comparing the state of the admissible volume of extracted groundwater with the state in 2009 one can notice that the Bobrza river infiltration increases by 2363.75 m^3/d, i.e. by 65%. In comparison with the original state the river discharge decreases by 10 998.91 m^3/d, in comparison with the state in 2009 the river discharge will decrease by 5767.86 m^3/d. Within the boundaries of the resource area the Bobrza river recharges 4114.89 m^3/d and discharges 4420 m^3/d. The total effective infiltration for the resource area amounted to 15 604.49 m^3/d. On the basis of the modelling calculations it was estimated that the admissible volume of the extracted groundwater for the municipal intake in Zagnańsk amounts to 15 120 m^3/d (630 m^3/h). The well influence area with determined safe yield was within the boundaries of the capture zone [16]. The boundary of the adopted well influence area with determined safe yield in its north-western, western and southern part corresponds to the groundwater intake area, whereas in its north-eastern and eastern parts its boundary is based on the boundaries of the capture zone which are also the boundary of surface water basin (Fig. 4). The well influence area with determined safe yield covers 38.35 km^2.

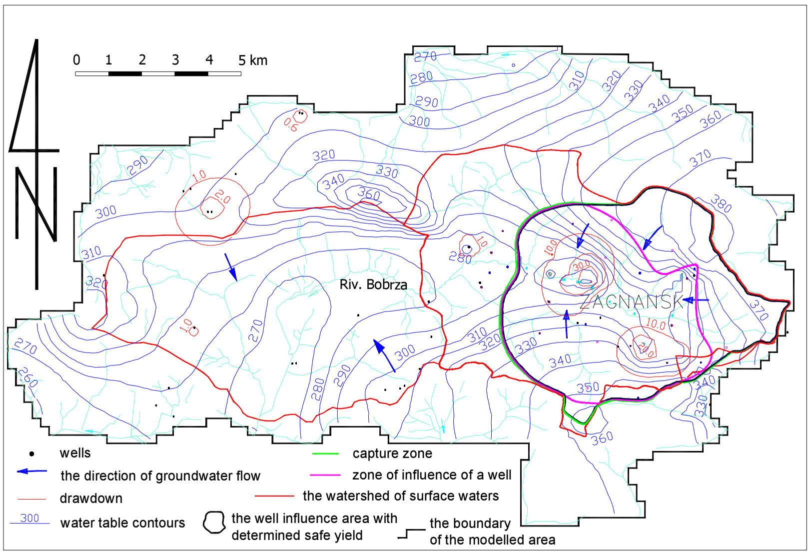


Fig. 4. Water table map of the Triassic aquifer simulated on the model, simulation for the admissible volume of extracted groundwater

Rys. 4. Mapa zwierciadła wód triasowego poziomu wodonośnego, symulacja dla zasobów eksploatacyjnych

Table 1. **Groundwater balance for the modelled area**

Tabela 1. **Bilans wód podziemnych dla obszaru badań modelowych**

Balance components	Calculation variants					
	Pseudonatural state m^3/d		State in 2009 m^3/d		The admissible volume of the extracted groundwater, m^3/d	
	inflow	outflow	inflow	outflow	inflow	outflow
The model balance						
Infiltration	78908.60	0.00	83273.00	0.00	78908.00	0.00
Rivers recharge and discharge	2094.57	81003.00	3827.70	77406.00	62063.00	69173.00
Zagnańsk intake exploitation	0.00	0.00	0.00	9100.80	0.00	15120.00
The remaining intakes exploitation	0.00	0.00	0.00	591.73	0.00	822.10
Balance	**81003.10**	**81003.00**	**87101.00**	**87101.00**	**85115.00**	**85115.00**
Balance error [%]	**0.00**		**0.00**		**0.00**	
The balance for the well influence area with determined safe yield						
Infiltration	15604.40	0.00	15604.00	0.00	15604.00	0.00
The Bobrza River recharge and discharge	582.60	14038.00	2353.00	7388.60	4114.00	4420.00
Zagnańsk intake exploitation	0.00	0.00	0.00	9100.80	0.00	15120.00
Lateral recharge to/from the basin area	1325.00	3474.00	1473.00	2941.70	1685.00	1865.30
Balance	**17512.00**	**17512.00**	**19431.00**	**19431.00**	**21405.00**	**21405.00**
Balance error [%]	**0.00**		**0.00**		**0.00**	

Conclusions

In order to evaluate the admissible volume of the extracted groundwater in the municipal intake in Zagnańsk in relation to the present groundwater circulation system in the area of the conducted model research, a hydrogeological model of groundwater flow was constructed. The original and the current hydrodynamic fields appearing in the aquifer were reconstructed on the numerical model, and then the balance for the well influence area with determined safe yield was prepared.

On the basis of the modelling calculations it was estimated that the admissible volume of the extracted groundwater in the municipal capture in Zagnańsk amounts to 15 120 m^3/d (630 m^3/h). The modelling calculations enabled determining the capture zone, the zone of influence of a well and the well influence area with determined safe yield (Fig. 4).

The well influence area with determined safe yield is within the boundaries of the capture zone (Fig. 4) and covers 38.35 km^2.

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Modelowanie zasobów wód podziemnych w obszarze górnej zlewni rzeki Bobrzy

W obszarze górnej zlewni Bobrzy wykonany został sześciowarstwowy numeryczny model hydrogeologiczny. Obliczenia modelowe przeprowadzono za pomocą modułu MODFLOW z bloku programowego VISUAL MODFLOW ver. 4.3.0, opracowanego przez WATERLOO HYDROGEOLOGIC, Inc. 180 Columbia St. W. - Unit 1104 Waterlo, Ontario, Canada. Do rozwiązań zastosowano model wielowarstwowy (3D), liczony w jednorodnym polu filtracji, w ustalonych warunkach przepływu. Celem wykonanych badań modelowych było określenie zasobów eksploatacyjnych ujęcia komunalnego w Zagnańsku oraz przedstawienie systemu krążenia wód podziemnych w obszarze prowadzonych prac modelowych. Na modelu numerycznym odtworzone zostało pierwotne i aktualne pole hydrodynamiczne występujące w warstwie wodonośnej, a następnie wykonany został bilans wodny obszaru zasobowego.

Słowa kluczowe: **modelowanie filtracji, ujęcie wód podziemnych, zasoby eksploatacyjne ujęcia wód podziemnych, bilans wód podziemnych**