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MULTILAYER NUMERICAL GROUNDWATER FLOW MODEL IN THE AREA OF NOWA DĘBA WATERWORKS

WIELOWARSTWOWY MODEL NUMERYCZNY PRZEPŁYWU WÓD PODZIEMNYCH W REJONIE EKSPLOATACJI UJĘCIA NOWA DĘBA

Wielowarstwowy model numeryczny przepływu wód podziemnych w rejonie eksploatacji ujęcia Nowa Dęba (południowo – wschodnia część Polski) został wykonany pod kątem późniejszego wykorzystania przy modelowaniu transportu mas zanieczyszczeń organicznych: trichloroetylenu (TCE) i tetrachloroetylenu (PCE), których stężenia przekraczające wartości dopuszczalne 25–125 krotnie stwierdzono w wodach podziemnych badanego obszaru. Lokalny 5-cio warstwowy (zmienność litologiczna czwartorzędowego poziomu wodonośnego oraz zmiany prędkości filtracji wód podziemnych zarówno w pionie jak i w poziomie) hydrodynamiczny model został wykonany dla obszaru spływu czwartorzędowych wód podziemnych do ujęcia, stanowiących główne źródło wód pitnych w tym obszarze. Badania modelowe objęły obszar 23.75 km^2 i zostały zrealizowane (wg stanu rozpoznania na 2010 rok) przy wykorzystaniu programu Visual Modflow na podkładzie mapy sytuacyjno-wysokościowej w skali 1:10 000. Wykorzystano dostępne materiały archiwalne, uzupełnione wynikami badań terenowych i laboratoryjnych. Przygotowanie modelu hydrogeologicznego oparto na archiwalnych materiałach dokumentacyjnych i kartograficznych, jak również na wynikach rozpoznania terenowego, zwłaszcza prowadzonego w otworach badawczych i studniach. Dla prawidłowego rozpoznania stosunków wodnych na obszarze objętym badaniami modelowymi wykorzystano dane meteorologiczne i hydrologiczne oraz stany wód i przepływy w ciekach powierzchniowych. Obszar badań został podzielony siatką dyskretyzacyjną na 165 kolumn i 200 wierszy o kroku obliczeniowym dx = dy = 30 m. Symulacje wykonano dla poboru zgodnego z rzeczywistym średnim poborem wód podziemnych przez ujęcie wg stanu na 2010, czyli na czas wykonania kartowania hydrogeologicznego, a także do tzw. warunków pseudonaturalnych badanego obszaru, tj. Sprzed uruchomienia eksploatacji ujęcia Nowa Dęba. Dla lepszego zobrazowania bilansu wód podziemnych w modelowanym obszarze, symulacje wykonano dla całego rejonu a także dla dwóch zlewni cząstkowych: Koniecpólka i Dęba. Opracowany, zweryfikowany i skalibrowany model hydrodynamiczny umożliwił: (1) określenie warunków krążenia wód podziemnych w czwartorzędowym piętrze wodonośnym, w powiązaniu z ciekami powierzchniowymi, (2) zestawienie bilansów wodnych i ocenę odnawialności piętra wodonośnego, (3) określenie wzajemnych relacji wód podziemnych i powierzchniowych, (4) określenie aktualnego wpływu eksploatacji ujęcia na warunki hydrodynamiczne w modelowanym obszarze, (5) określenie warunków użytkowania wód podziemnych w badanym obszarze oraz (6) budowę modelu bazowego dla modelu transportu mas zanieczyszczeń (TCE i PCE).

1. Introduction

Groundwater is the largest body of freshwater in the European Union and, in particular, also a main source of public drinking water supplies in many regions. In Poland groundwater supplies 70% of the population [1]. Inasmuch as groundwater supplies drinking water to many people, the quality of water is of paramount importance. Worldwide, aquifers are experiencing an increasing threat of pollution from urbanization, industrial development, agricultural activities and mining enterprises. The European Environmental Agency (EEA) estimates the existence of 250,000 contaminated sites requiring clean up in the EEA members countries, from which only 80,000 have been remediated. It is expected that the number of sites needing remediation will increase by 50% by 2025 [2]. In Poland there is an estimate of 611.61 km^2 of devastated and degraded land requiring reclamation and management measures [3].

The Water Framework Directive (WFD) [4] and Groundwater Directive (GWD) [5] are the major European drivers which provides a legal framework to protect and restore clean water in Europe and ensure its long-term and sustainable use, based on achievement of 'good status' for water bodies by 2015, using quality and quantity-based criteria. They include objectives to reduce contamination from 'priority substances', prevent deterioration of chemical status and gradually reduce groundwater pollution. They also require the reversal of increased trends of pollutant concentrations in groundwater. However, for example ca. 30-60% of the groundwater bodies in the EU are reported to be at risk of not achieving 'good status' by 2015 [6]. This is a significant driving force for remediation of contaminated sites, particularly with many contamination sources and diverse pollutants.

Many efforts have been made at local, national and European levels to regulate contaminated land and groundwater. After the introduction of GWD for the protection of groundwater against pollution and deterioration [5], some changes in water resources management, water protection and water status reporting in Poland were required. Therefore, groundwater quality and drinking water standards have been restricted [7, 8], and new substances were included in the list of priority (e.g. tetrachloroethylene –PCE and trichloroethylene –TCE), as a result of their particular risk to drinking water supplies and their exposure to the aquatic environment.

TCE and PCE are halogenated alkenes used commonly from the 20's of the last century to the present as industrial solvents. PCE and TCE are considered to be of health concern and are included in the list of probably carcinogenic to humans [9]. A detailed description of the impact of TCE and PCE on human health can be found in the IARC monography [9] and USEPA's website [10]. Both substances can be transformed by biotic and abiotic processes, leading to the production of daughter products that are also of health concern. Chlorinated solvents and many of their daughter products have densities higher than water and, thus they can migrate down to the bottom of aquifer in a separate phase via preferential pathways forming DNALP (dense than water non aqueous phase liquid) plumes [11]. Along the transport pathway a variety of physical, chemical or biological processes influence contaminants' migration, including: sorption, dispersion, dilution, volatilization and biodegradation [12]. These compounds also have low solubility in water, which means that the loss of contaminant by dissolving in water is rather a slow process. Additionally, they demonstrate relatively low affinity to sorption onto aquifer materials (particularly gravels and sands) [13].

Before 2008, problems associated with the presence of TCE and PCE in groundwater were very rare in Poland. These substances were identified only in few locations, including: waterworks in Białogon, Tarnowskie Góry and Nowa Dęba [14]. After more restricted water quality standards came into force in 2008, followed by the obligation to inspect these substances in groundwater, contamination of aquifers by TCE and PCE has been found in several locations: Gryfino, Gołdap, Srebrna Góra, Budzowie, Łomianki, Poniatowa [14]. It is expected that the problem will growth with time as it was observed in other EU countries and the USA during the 80's and 90's, after introducing drinking water standards for TCE and PCE. Consequently, there is an increased concern and need to investigate these sites and the effects of contaminants in groundwater, especially on those sites where the resource is used for supplying drinking water to the population.

The effects of contaminants in groundwater and the definition of management actions are usually difficult to assess because of the complex nature and interrelated factors in groundwater systems. Flow models constitute a powerful tool in simulating rates and directions of groundwater flow through aquifers. Models are simplified representations or approximations of real hydrogeological systems, and they may incorporate a number of processes operating within groundwater. Results of modeling depend on the quality and quantity of the field data available to define input parameters and on boundary conditions [15].

This paper describes the construction of a groundwater numerical flow model for the area of Nowa Dęba waterworks. The area under study is contaminated with TCE and PCE (one of the largest concentrations in Poland of these substances – recognized by the Inspectorate of Environmental Protection as an "ecological bomb") [14]. Representation of this complex problem required the construction of a multi-layer numerical model to incorporate complexity of real system. The developed model will then be used for the construction of the contaminant transport model, which necessitates a more detailed hydrogeological conceptual model.

2. Groundwater Modeling

The use of groundwater models is an important tool in the field of environmental hydrogeology. Models can be defined as simplified representations of a real system and simulate system's response to different phenomena of interest (artificial recharge, pumping, the introduction of a contaminant and the change on boundary conditions) using mathematical equations [15, 16]. Simplification of the model is introduced as a set of assumptions, which express the nature of the system and features on its behavior that is relevant to the problem under investigation [17]. Because a model is a simplified representation of the real world, it does not provide exact descriptions of physical systems or processes. The usefulness of a model depends on how close the mathematical equations approximate the modeled system.

Models use a single or a set of governing equations that represent the occurring process. These equations may be solved using different types of models. *Analytical models* are exact solutions to equations that describe very simple flow or transport conditions. *Numerical models* alternatively, may be approximations of equations that describe very complex conditions. Each model may also simulate one or more of the processes that govern groundwater flow or contaminant migration rather than all of the flow and transport processes. Each model, whether it is a simple analytical model or a complex numerical model, may be applicable and useful in hydrogeological and investigations, as well as in selecting effective remedial measures [18-20].

Basically, groundwater flow models are used to simulate the rate and direction of water movement through the subsurface. The construction of a groundwater model includes: (a) the identification of the nature of the problem and modeling purpose; (b) development of a conceptual model; (c) development of a numerical model and code; (d) model calibration and parameter estimation, and (e) prediction [15,17].

In many cases of modeling an aquifer is simplified as a single layer, represented as either homogeneous or heterogeneous layer. When modeling an area composed of a multi-layer aquifer with a significant difference of aquifer parameters, assuming a single layer may produce a significant discrepancy on numerical approximation comparing to observed field data. For the present study, a multi-layer numerical model was created to represent the heterogeneity of the studied aquifer and incorporate the vertical migration of the contaminant into the aquifer to get more realistic simulation results. Both: single layer and multi-layer transport models are appropriate to simulate lateral movement of a contaminant in an aquifer, but a single layer model is less complex, easier to build than a multi-layer model; however, it may produce an oversimplification of the real system and generate inaccurate results.

3. Description of the Modeled Area

The study area of about 30 km^2 is located in an approximate distance of 1.5 km to the town of Nowa Dęba (South-East Poland), in the northern part of the Carpathian Foredeep (21°40'-20°50'E and 50°20'-50°30'N). A documentary map of the site under study is shown in figure 1.

The investigated aquifer belongs to the Groundwater Body (GWB) no. 135 and partially to the Major Groundwater Basin (MGWB) no. 425 according to the Polish hydrogeological classifications. The aquifer is unconfined and consists of Quaternary river deposits of sand, silt, clay and gravel. The thickness of the quaternary deposits is of approximately 30 m, lying on impermeable layer of Miocene clays. Miocene deposits, represented by non-permeable Krakowieckie clays, lie on Carboniferous rocks and reach the thickness of hundreds of meters. The most permeable deposits occur in the bottom part of the unconfined aquifer (Fig. 2). The aquifer is the main source of drinking water for the town of Nowa Dęba, supplying 20,000 inhabitants and some industries. Depths to the groundwater table vary from 0.5 to 16.5 m based on field data from 2010. Recharge to the alluvial and terrace deposits come mostly from infiltration of precipitation. Average annual rainfall is 847 mm (status on 2010) from which 20-25% is infiltrated into the soil. Transmissivity varies from 100 to 500 m^2/d [21]. The drainage occurs naturally into Dęba and Koniecpólka rivers and other tributary streams. Groundwater flows direction is predominately from south-north towards the waterworks. The groundwater table fluctuates seasonally, rising during periods of high rainfall in the winter months and falling in mid-late summer (low rainfall) with fluctuations no greater than 0.8 m. The groundwater flow regime is influenced by the water extraction at the municipal waterworks.

In the modeled area, there are surface water and groundwater divides, which do not have a relationship. The reason is that, at present the river is located in a different place that it was many years ago. Moreover, due to deposition and erosion processes in the subsurface the groundwater divide is formed by an erosion channel.

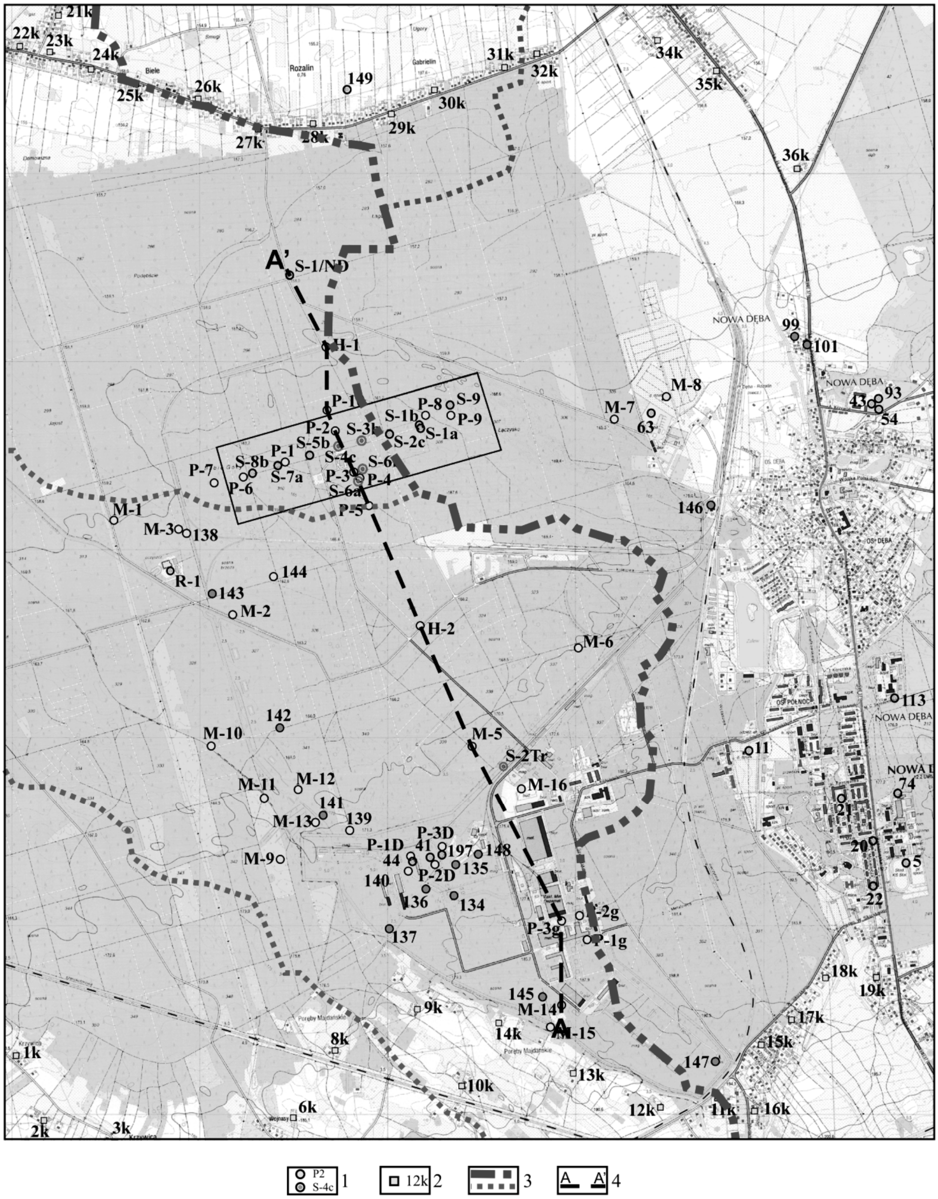

Fig. 1. Documentation map of the studied area
Notation: 1 – observation points (piezometeres and wells), 2 – dig wells, 3 – surface divides: 3^rd^ and 4^th^ kind, 4 – cross-section line

Rys. 1. Mapa dokumentacyjna obszaru badań
Oznaczenia: 1 – punkty obserwacyjne (piezometry i studnie), 2 – studnie kopane, 3 – działy wód powierzchniowych III i IV rzędu, 4 – linia przekroju hydrogeologicznego

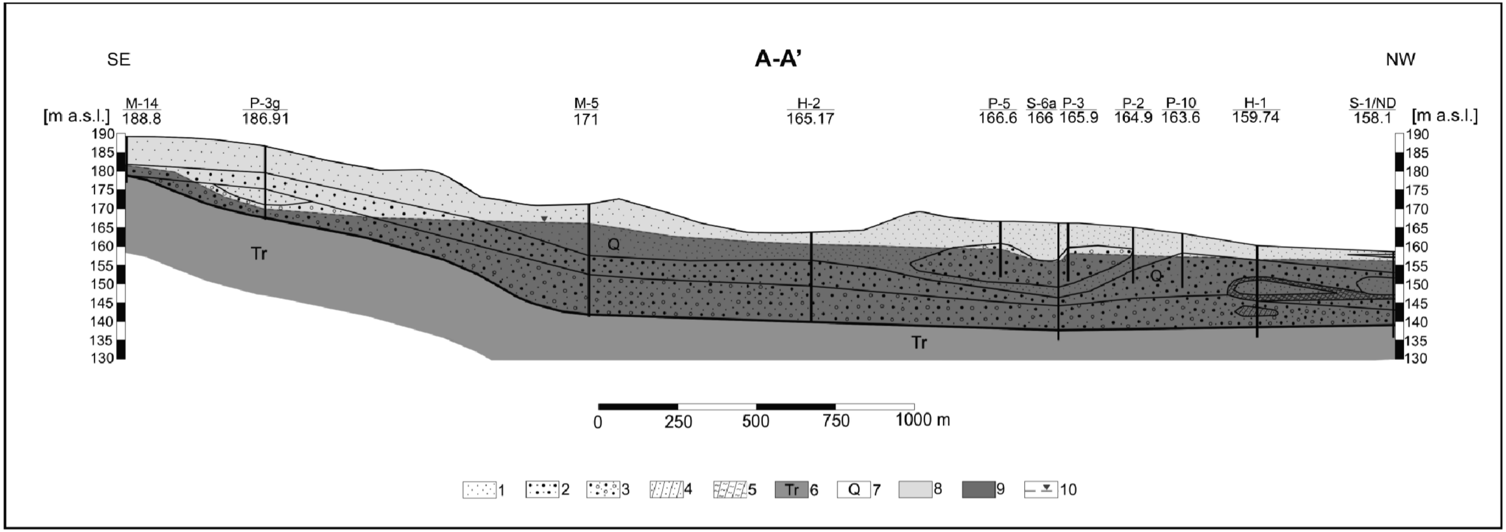

Fig. 2. *Hydrogeological cross-section of the studied area*
Notation: 1 – fine-medium sands, 2 – fine-medium sands with gravels, 3 – sandy gravel, 4 – sandy clay, 5 – clays and silts, 6 – Miocene – Krakowieckie clays, 7 – Quaternary, 8 – unsaturated zone, 9 – saturated zone, 10 – groundwater level (status on 2010)

Rys. 2. *Przekrój hydrogeologiczny przez obszar badań*
Oznaczenia: 1 – piaski średnie i drobne, 2 – piaski średnie i drobne ze żwirem, 3 – żwir piaszczysty, 4 – glina piaszczysta, 5 – gliny i pyły, 6 – Miocen – iły krakowieckie, 7 – czwartorzęd, 8 – strefa aeracji, 9 – strefa saturacji, 10 – zwierciadło wód podziemnych (stan na 2010 r.)

4. Model Development

The development of the numerical model was based on the conceptual groundwater flow model of the system. It involved (1) selecting the computer program to solve the mathematical model numerically; (2) translating the conceptual model to the numerical model including determining the system geometry, discretizing the spatial domains—designing a spatial grid, and formulating boundary conditions; and (3) selecting measurements of physical properties and hydrologic aquifer measurements state, such as water levels in wells—heads and flow to and from the aquifer. The conceptual model and available data were integrated into the numerical model, which was subsequently calibrated, whereby model parameters were adjusted to match the simulated and observed heads and flows.

4.1. Hydrogeological Conceptual Model

A groundwater conceptual model is a schematic description of the groundwater system, including a delineation of the hydrogeologic units, the system boundaries (recharge, rivers, lakes), groundwater flow directions, hydrogeological parameters (conductivity), extraction or injection from wells (location, depth, screens, rates), and observations of groundwater table levels. The construction of an appropriate conceptual model for a given problem is the most important step in the modeling process [22]. However, in translating the conceptual model into a qualitative mathematical model some simplification is required. Oversimplification can lead to unsatisfactory results without the required information. Underestimation on the other hand, can generate a lack of information required for model calibration. Inappropriate or wrong assumptions may lead to a poor representation of the features of interest within the system behavior [23]. It may be emphasized that conceptual model is the author's interpretation of available geological, hydrogeological data.

The conceptual model may be based on a thorough understanding of site hydrogeological conditions derived from field investigations and regional data obtained from academic or government studies. For the present study, the conceptual model is based on field data collected in 2010 (Fig. 3), with the following assumptions: (a) active groundwater circulation takes place only at a Quaternary aquifer, (b) the Quaternary aquifer is mixed: has unconfined-confined conditions, (c) recharge occurs mainly from precipitation and outside the modeled area, (d) the drainage occurs naturally through Dęba and Koniecpólka rivers and other tributary streams, (e) natural groundwater flow is influenced by the municipal Nowa Dęba waterworks.

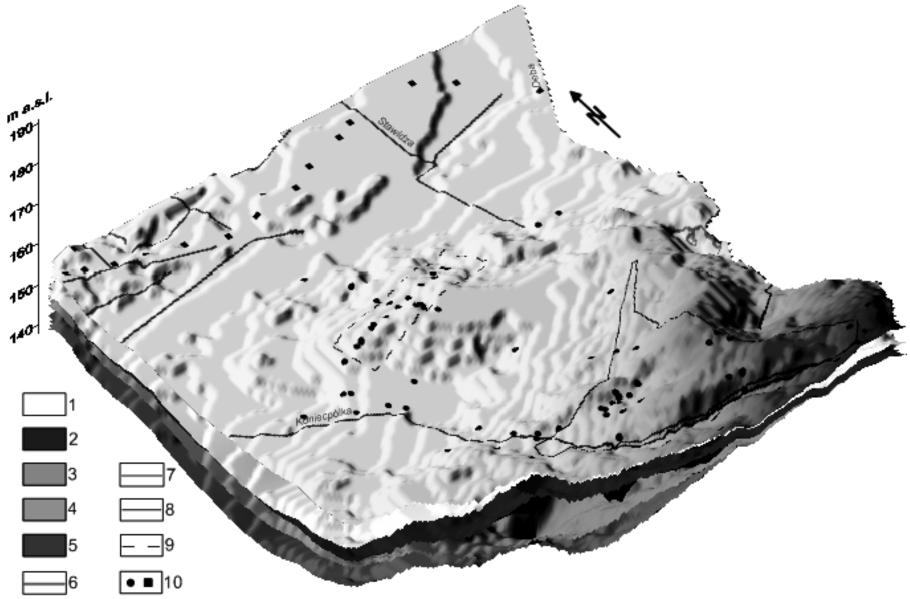

Fig 3. *Conceptual model of the Nowa Dęba waterworks area*
Notation: 1 – layer 1, 2 – layer 2, 3 – layer 3, 4 – layer 4, 5 – layer 5, 6 – rivers and streams, 7 –artificial lake, 8 – old metalwork area , 9 – Nowa Dęba waterworks area, 10 – observation points (piezometers, drilled and dug wells)

Rys. 3. *Model koncepcyjny rejonu ujęcia Nowa Dęba*
Oznaczenia: 1 – warstwa 1, 2 – warstwa 2, 3 – warstwa 3, 4 – warstwa 4, 5 – warstwa 5, 6 – rzeki i strumienie, 7 – zalew, 8 – obszar byłych zakładów metalowych, 9 – obszar ujęcia Nowa Dęba,10 – punkty obserwacyjne (piezometry, studnie wiercone i kopane)

4.2. Model Setup

Groundwater flow in the studied case was simulated with the 3-D finite-difference groundwater flow model Visual MODFLOW 4.2 for computing spatial and temporal variations in groundwater head distribution. In the MODFLOW software the 3-D groundwater flow is described by the partial differential equation [24]:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial}{\partial_z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where: *Kxx*, *Kyy*, and *Kzz* - values of hydraulic conductivity along the x, y, and z coordinates; *h* - potentiometric head; *W* - volumetric flux per unit volume representing sources and (or) sinks of water; *Ss* - specific storage of the porous medium, *t* = time.

The partial-differential flow equation can be approximated by replacing the derivatives with finite differences. The MODFLOW software represents the aquifer system with cells using a sequence of layers and a series of rows and columns. The software solves the finite-difference equations simultaneously using one of several numerical-solver algorithms and accounts for groundwater flow between cells and between cells and external sources or sinks of water, such as stream-aquifer hydraulic interaction, aquifer recharge, or groundwater withdrawal by wells. Aquifer properties are assumed to be uniform within each model cell, and hydraulic heads are assumed to be at the center of each cell.

Processing of raw data was done using the aid of Surfer 10, Grapher 9 and Corel X4. Hydrological settings of the modeled area were constructed from data collected during site investigations undertaken in August 2010.

The modeled area is of 29.7 km^2. The finite-difference grid for the flow calculations consisted of 33,000 blocks (200 rows and 165 columns). From the total spatial discretization of the model only 26 386 (23.75 km^2) were active cells. The vertical model grid spacing consisted of five layers of varying thickness (Table 1).

Tab. 1. Hydrological characteristics of model layers

Tab. 1. Charakterystyka hydrologiczna warstw modelu

Model Layer	Geological Unit	Aquifer type	Thickness [m]
1	Fine to medium grained sands	Unconfined	25
2	Gravel and varied-grained sands	Unconfined/Confined	19
3	Fine-grained sands	Confined	14
4	Clays and Silt	Confined	13.6
5	Gravels	Confined	19

As the software requires continuity of simulated layers for the whole modeled area, in areas without the presence of layer one, the parameters of layer two were subtracted. On the other hand, for layers two to five the parameters of a layer which was on the top of each layer were subtracted (Fig. 4 and 5).

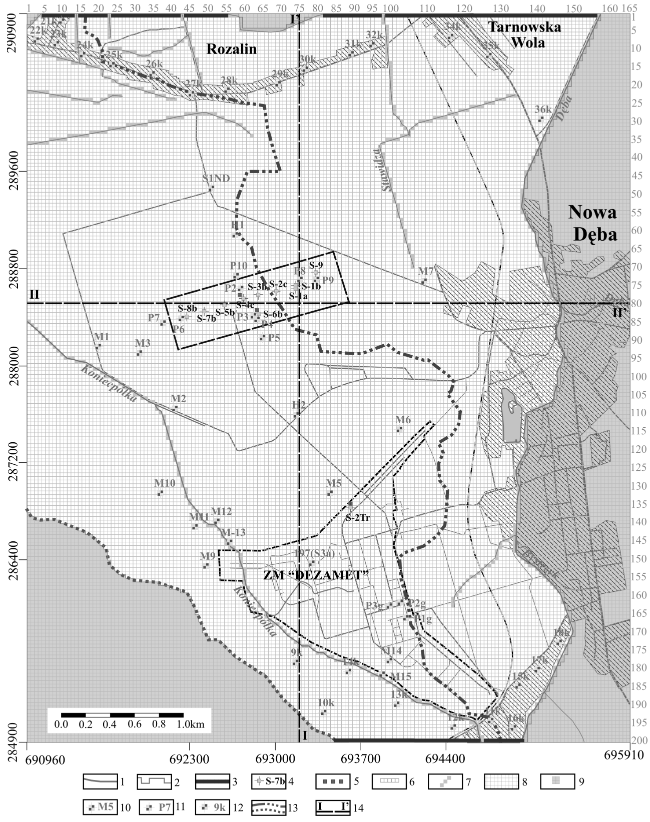

Fig. 4. *Documentation map of the Quaternary aquifer in the vicinity of Nowa Dęba waterworks*
1 – rivers; 2 – boundary of hydrogeological model; 3 – blocks with constant – head boundary conditions simulating lateral inflow and outflow of groundwater to or from the model; 4 – blocks with constant flux boundary conditions simulating groundwater extraction by wells; 5 – blocks with constant flux boundary conditions simulating extra effective infiltration of cleaned groundwater (nearby S-4c, S-6b and S-2Tr wells); 6 – blocks with constant flux boundary conditions simulating infiltration recharge; 7 – blocks with mixed boundary conditions simulating rivers and surface reservoirs; 8 – mathematical model grid; 9 – inactive blocks (out of the modeled area); Level marks with groundwater table measurements: 10 – piezometers – quality monitoring of groundwater at waterworks, 11 – piezometers – hydrodynamic monitoring of groundwater waterworks, 12 – dug wells, 13 – surface water divides 3rd and 4th order, 14 – cross-section line with discretization of geological structure

Rys. 4. *Mapa dokumentacyjna badań modelowych rejonu ujęcia wód piętra czwartorzędowego w Nowej Dębie*
1 – rzeki; 2 – granica modelu matematycznego; 3 – bloki z warunkami I rodzaju symulujące dopływ i odpływ lateralny wód podziemnych do lub z modelu; 4 – bloki z warunkami II rodzaju symulujące pobór wód podziemnych studniami; 5 – bloki z warunkami II rodzaju symulujące dodatkową infiltrację efektywną wód oczyszczonych (przy studni S-4c, S-6b i S-2Tr); 6 – bloki z warunkami II rodzaju symulujące efektywną infiltrację wód opadowych; 7 – bloki z warunkami III rodzaju symulujące cieki i zbiorniki powierzchniowe; 8 – siatka dyskretyzacyjna modelu matematycznego; 9 – bloki poza obszarem badań modelowych; Repery z pomiarami zwierciadła wód podziemnych: 10 – piezometry – monitoring jakościowy ujęcia; 11 – piezometry – monitoring hydrodynamiczny ujęcia; 12 – studnie kopane; 13 – działy wód powierzchniowych III i IV rzędu, 14 – linia przekroju dyskretyzacji budowy geologicznej

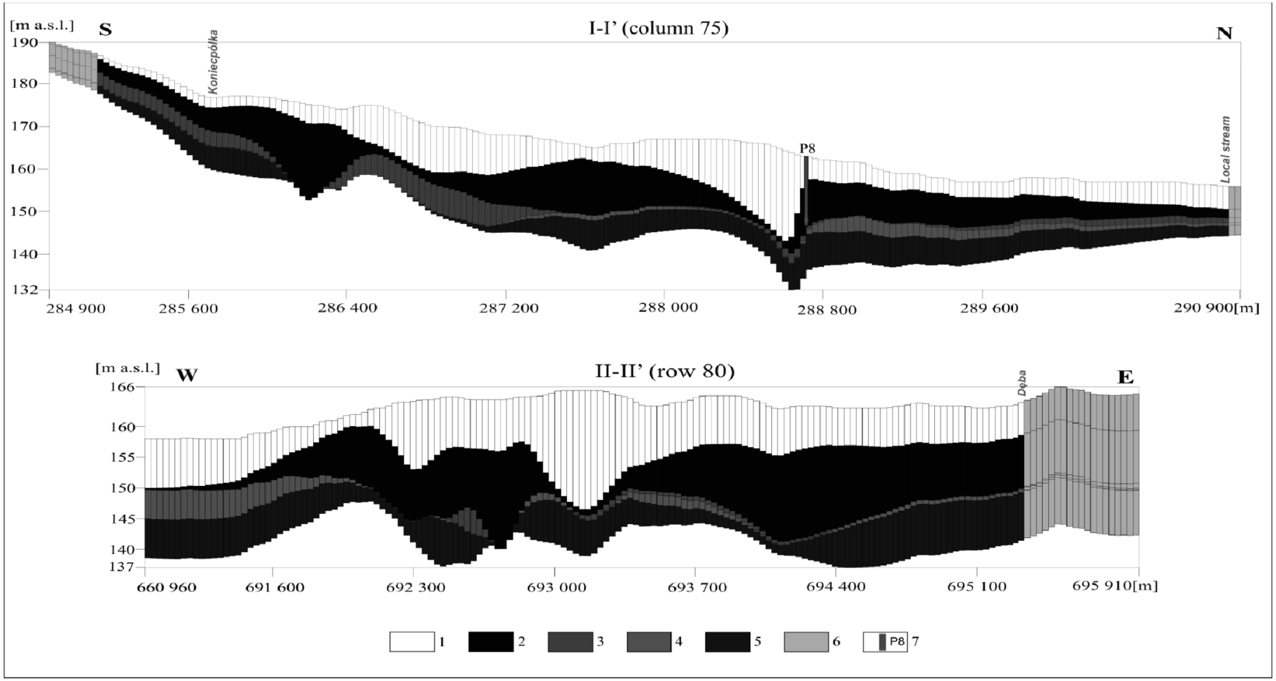

Fig. 5. Discretization of the geological structure on the model
Notation: 1 - Fine to medium grained sands, 2– gravel and varied-grained sands, 3– fine-grained sands, 4– clays and silt, 5– gravels, 6 – block outside modeled area, 7 – piezometers

Rys. 5. Schematyzacja budowy geologicznej na modelu
Oznaczenia: 1 – piaski średnie i drobne, 2 – żwiry i piaski różnoziarniste, 3 – piaski drobne, 4 – gliny i pyły, 5 – żwiry, 6 – bloki poza obszarem badań modelowych, 7 – piezometry

4.3. Boundary conditions

In the groundwater flow model, boundary conditions describe the flow into and out of the active areas of the model grid. They can be described by natural or hydrological boundaries. Every model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding systems and the outside boundaries of the model, and also in characteristic points inside the model. The outside boundary conditions describe boundaries of modeled area and simulate relationships with the surrounding system. The inside boundary conditions are given in simulated cells located inside model area, and they influence model filtration processes keeping constant flow condition or constant level of groundwater table [25].

In the process of filtration there are three types of boundary conditions (on boundaries or inside the model), which can be used during the model development [26]:

1) constant head boundary: H = constant; it is used on main streams and surface aquifers of the modeled area,
2) constant flux boundary: constant rate of water budget - input and output of water- in the cell, Q = constant; used inside the modeled area; it can simulate:
   – recharge rate from direct infiltration to the first saturated layer on the model,
   – wells exploiting the aquifer with a given pumping rate,
3) mixed boundary conditions: for simulating the influence of a surface water body on the groundwater flow; it is a combination of 1st and 2nd kind of boundary condition; H = constant and conductance = constant.

Constant head boundary conditions were assigned at the north and south boundary to simulate the lateral inflow and outflow of groundwater to or from the model. Constant flux boundary conditions were assigned to simulate water extraction from wells. In wells (S-4, S-6, S-2tr) groundwater is being released to the air and afterwards infiltrated into the soil as a temporary measure to stop spreading of TCE and PCE towards adjacent wells. Next to these three wells other wells were simulated. These wells differ from others because they are adding water to the aquifer. The amount of added water is about 10% of the actual pumping rate. For these wells the constant flux boundary was assigned to simulate an extra effective infiltration of clean groundwater. In the same way, the constant flux boundary was assigned to the modeled area to simulate recharge from infiltration. Finally, mixed boundary conditions were assigned to the western boundary to Dęba and Bystrzyk Rivers, easter boundary to Koniecpólka river and other small streams. On the south – west border of the model, the boundary is the 4th kind surface divide (Fig. 4).

4.4. Model Input Parameters

Recharge. Groundwater recharge by infiltration of precipitation in the Nowa Dęba area is of 847 mm (2010) from which 20-25% is infiltrated into the soil. Based on this estimate, a uniform recharge rate of 200 mm per year was used in the groundwater flow model. This recharge rate is approximately 24% percent of the annual precipitation for 2010.

Groundwater withdrawal. Currently, Quaternary groundwater is the principal source of water for municipal, commercial and industrial uses in the town of Nowa Dęba. The average groundwater yield is of 4000 m^3/d, and the maximum yield is of 350 m^3/h. In 2010 water withdrawal ranged from 73 to 1240 m^3/d.

Hydraulic conductivity. Hydraulic conductivity changes on investigated area have been described based on data compiled in the Bank HYDRO database from Polish Geological Institute [27]. Hydraulic conductivity from this database was designated based on the results from pumping test performed to 31 points located on the site.

For the present work a specific value of hydraulic conductivity was assigned to each of the five layers of the model. For the case of layer four, the hydraulic conductivity value was taken from literature – as a typical value for non-permeable soils: clays and silts. Variability of hydraulic conductivity for all model layers of the Quaternary aquifer is shown in Table 2 and Fig. 6.

Tab. 2. Hydraulic conductivity values for each layer of the model

Tab. 2. Wartości współczynnika filtracji dla poszczególnych warstw modelu

Layer	Kx [m/s]	Ky [m/s]	Kz [m/s]
1	2.064×10^{-5}	2.064×10^{-5}	1.032×10^{-5}
2	2.975×10^{-4}	2.975×10^{-4}	1.4875×10^{-5}
3	1.064×10^{-5}	1.064×10^{-5}	5.32×10^{-6}
4	1×10^{-7}	1×10^{-7}	5×10^{-8}
5	3.925×10^{-4}	3.925×10^{-4}	1.9625×10^{-4}

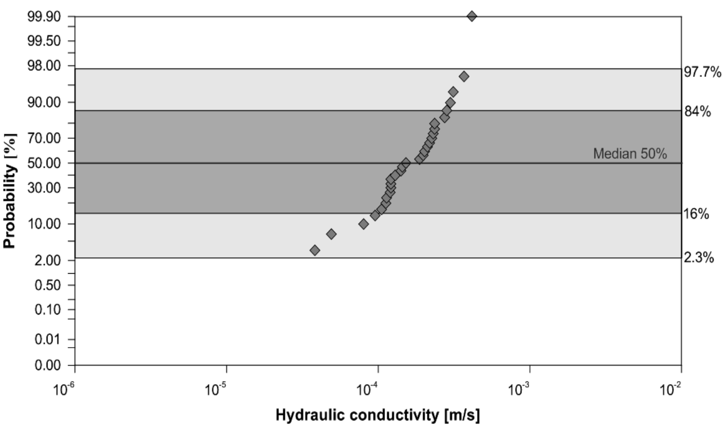

Fig. 6. Variability of hydraulic conductivity on the probability plot for the Quaternary aquifer of the modeled area

Rys. 6. Zmienność współczynnika filtracji utworów czwartorzędowych modelowanego obszaru na wykresie prawdopodobieństwa

4.5. Model Calibration

Model calibration is an iterative process of adjusting the 3-D distribution or structure of aquifer properties, aquifer property values, or properties of boundary conditions to improve the match between simulation results and observations [28]. Calibration process is very important, because the quality of the calibration inevitably determines the reliability of any conclusions and recommendations made using the simulation results [25]. Calibration process is usually performed based on known hydrogeological points, such as piezometers, wells, from which data about real groundwater table levels are taken [22].

For the present work, a total number of 75 points including drilled wells, dug wells, and piezometers (hydraulic heads) were used as observations for calibrating the model. The calibration process was done by comparing the model results with measured groundwater levels and adjusting aquifer properties manually by "trial-and-error". The 0.01 m difference between calculated and observed groundwater table elevations has been considered as a satisfactory level of adjustment. Such a precise level of adjustment was selected because this model will be used for the development of a contaminants transport model. The correlation coefficient for calculated and observed groundwater table levels is shown in Fig. 7. Distribution of measurement points near the diagonal layout proves that the calibration of the model has been done correctly [22]. The correlation coefficient for this model is 1.0 and the biggest difference between calculated and observed groundwater table levels is 0.5 m. The biggest difference observed in piezometer P-3. may be because the measurements of groundwater table level in the field were done in August 2010 (for the specific pumping rate at that moment), while the pumping rate used in the model is an average value for the considered year.

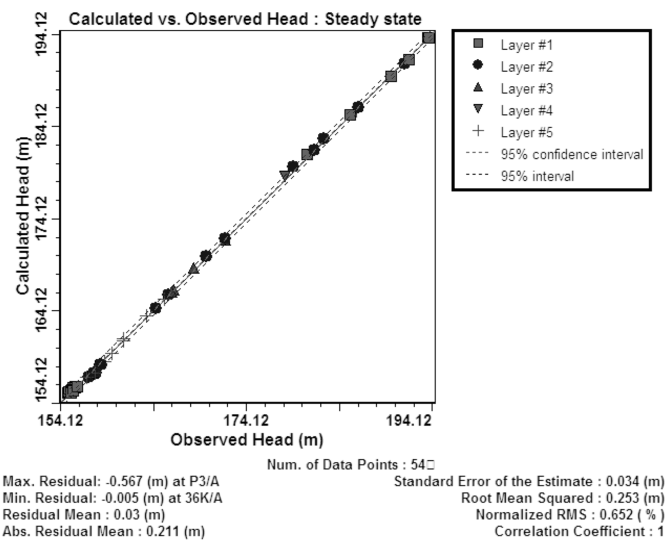

Fig. 7. Correlation coefficient for calculated and observed groundwater levels

Rys. 7. Współczynnik korelacji pomiędzy zwierciadłem wody obliczonym i obserwowanym

5. Results

The computed groundwater level contours follow the trend of observed groundwater levels in2010. The groundwater direction is from south to north towards the waterworks. Groundwater depression is higher at the waterworks area representing the influence of groundwater withdrawal (Fig. 8). In general, groundwater infiltrates in the vertical direction to the bottom of the aquifer and then it moves within the groundwater flow towards north area (Fig. 9). This situation reflects the geological structure of the aquifer, where the biggest sediments (gravels) are present at the bottom of aquifer (Fig. 2, Table 1).

In the modeled area groundwater balance has been simulated for two different scenarios: conditions for 2010, and pseudo-natural conditions before the existence of Nowa Dęba waterworks. The water budget of the entire area is presented in Tables 3 and 4. The total water budget shows a balance between inflows and outflows of water, which is consistent with the steady-state modeling assumption. Groundwater inflow from infiltration recharges the aquifer with most of its water. It is the primary model input and amounts to 13,090.1 m^3/d for both simulated conditions. The constant-head boundary is the secondary model input with1,113.0 m^3/d for 2010 conditions and 907.4 m^3/d for pseudo-natural conditions. The relatively low input is generated by recharge via rivers and clean groundwater infiltration with 215.4.0 m^3/d and 704.0 m^3/d, respectively for 2010 conditions. In the case of pseudo-natural conditions only recharge via rives is giving a minor input with 61.1 m^3/d. Model outputs are dominated by the constant-head boundary with 6,646.6 m^3/d and 9,192.0 m^3/d. Another important model output is represented by wells with 5,186 m^3/d for 2010 conditions. For pseudo-natural conditions, there is no influence of the wells. Lower losses occur via drainage through rivers with 3,287.8 m^3/d and 4,866.8 m^3/d, respectively for both conditions. The influence of water withdrawal is represented by 4.42% increase in water output for pseudo-natural conditions.

For better budget calculations (according to surface divides on the site) two basin were created: Koniecpólka basin on north – east part of the model with the area of 13.2 km^2 and Dęba basin (South – West) with the area of 10.55 km^2 (Table 4). Results show that the input and output from Dęba river is greater than from Koniecpólka river. Effective infiltration recharge is the main input for both basins, while groundwater exchange between basins is the main output.

Tab. 3. Groundwater balance for the modeled area

Tab. 3. Bilans wód podziemnych dla obszaru badań modelowych

Symbol and name of separated partial basin and balance elements	Conditions in 2010 [m^3/d]		Pseudo – natural conditions - variant 1 [m^3/d]	
	input (+)	output (-)	input (+)	output (-)
Model – F = 23.75 km^2				
1. Effective infiltration recharge	13,090.1	0	13,090.1	0
2. Recharge and drainage via rivers	215.4	3,287.8	61.1	4,866.8
3. Input/Output (constant - head boundary)	1,113.0	6,646.6	907.4	9,192.0
4. Wells	0	5,186.0	0	0
5. Infiltration of clean groundwater	704.0	0	0	0
Total	15,122.5	15,120.4	14,058.6	14,058.8

Tab. 4. Groundwater balance for separated partial basins based on modeling

Tab. 4. Bilans wód podziemnych dla wydzielonych powierzchniowych zlewni cząstkowych na podstawie badań modelowych

Symbol and name of separated partial basin and balance elements	Conditions in 2010 [m^3/d]		Pseudo – natural conditions - variant 1 [m^3/d]	
	input (+)	output (-)	input (+)	output (-)
Koniecpólka basin– F = 13.2 km^2				
1. Effective infiltration recharge	7,282.4	0	7,279.8	0
2. Recharge and drainage via rivers	97.7	1,106.4	6.6	1,608.6
3. Input/Output (constant – head boundary)	967.8	509.2	825.6	682.5
4. Wells	0	3,337.0	0	0
5. Infiltration of clean groundwater	704.0	0	0	0
6. Groundwater exchange between basins	1,634.8	5 732.4	2,343.3	7,869.7
Total	10,686.7	10,685.0	10,455.3	10,455.5
Dęba basin – F = 10.55 km^2				
1. Effective infiltration recharge	5,807.7	0	5,807.7	0
2. Recharge and drainage via rivers	117.7	2,181.4	57.1	3,020.2
3. Input/Output (constant – head boudary)	145.2	6,137.5	81.8	8,452.9
4. Wells	0	1,849.0	0	0
5. Groundwater exchange between basins	5,732.4	1,634.8	7,869.7	2,343.3
Total	11,803.0	11,802.7	13,816.3	13,816.4

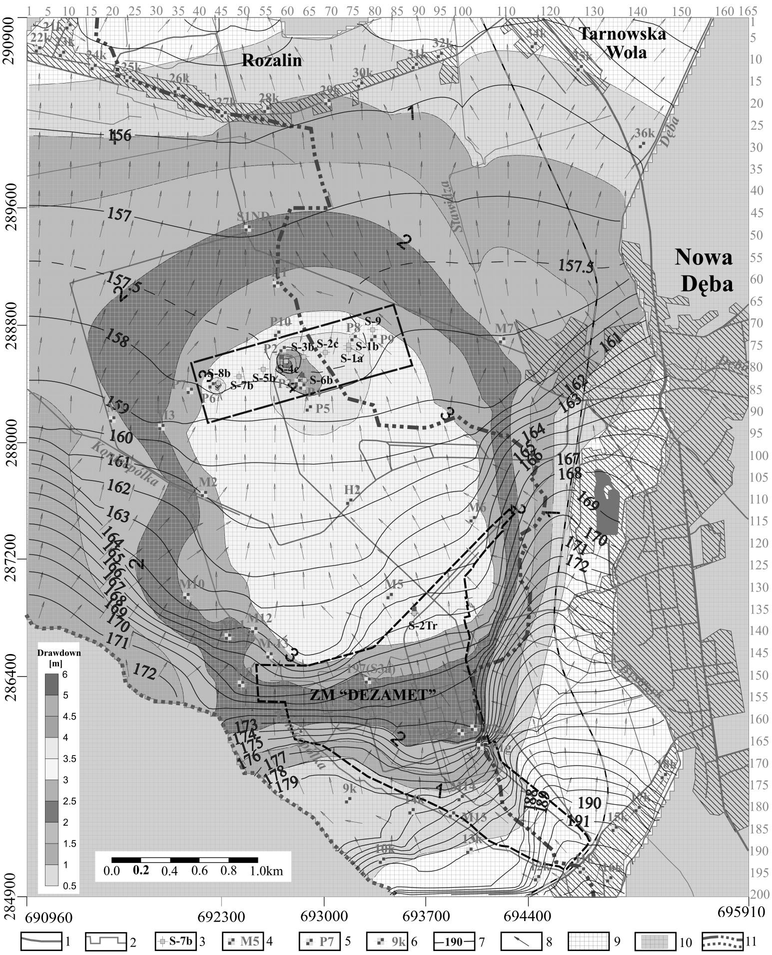

Fig. 8. *Hydrodynamic map of Quaternary aquifer in the area of Nowa Dęba waterworks; situation in 2010 reconstructed by the mathematical model*
Notation: 1 – rivers; 2 – boundary of mathematical model; 3 – groundwater extraction wells; Level marks with groundwater table measurements: 4– piezometers – quality monitoring of groundwater at waterworks, 5 – piezometers – hydrodynamic monitoring of groundwater at waterworks, 6 – dug wells; 7 – hydroizohips [m a.s.l.]; 8 – direction of groundwater flow; 9 – mathematical model grid; 10 – inactive blocks (out of the modeled area); 11 – surface water divides 3rd and 4th order.

Rys. 8. *Mapa hydrodynamiczna rejonu ujęcia wód piętra czwartorzędowego w Nowej Dębie; stan na 2010 odtworzony na modelu matematycznym*
Oznaczenia: 1 – rzeki; 2 – granica modelu matematycznego; 3 – studnie eksploatacyjne wód podziemnych; Repery z pomiarami zwierciadła wód podziemnych: 4 – piezometry – monitoring jakościowy ujęcia; 5 – piezometry – monitoring hydrodynamiczny ujęcia; 6 – studnie kopane; 7 – hydroizohipsy [m n.p.m.]; 8 – kierunki przepływu wód podziemnych; 9 – siatka dyskretyzacyjna modelu matematycznego; 10 – bloki poza obszarem badań modelowych; 11 – działy wód powierzchniowych III i IV rzędu

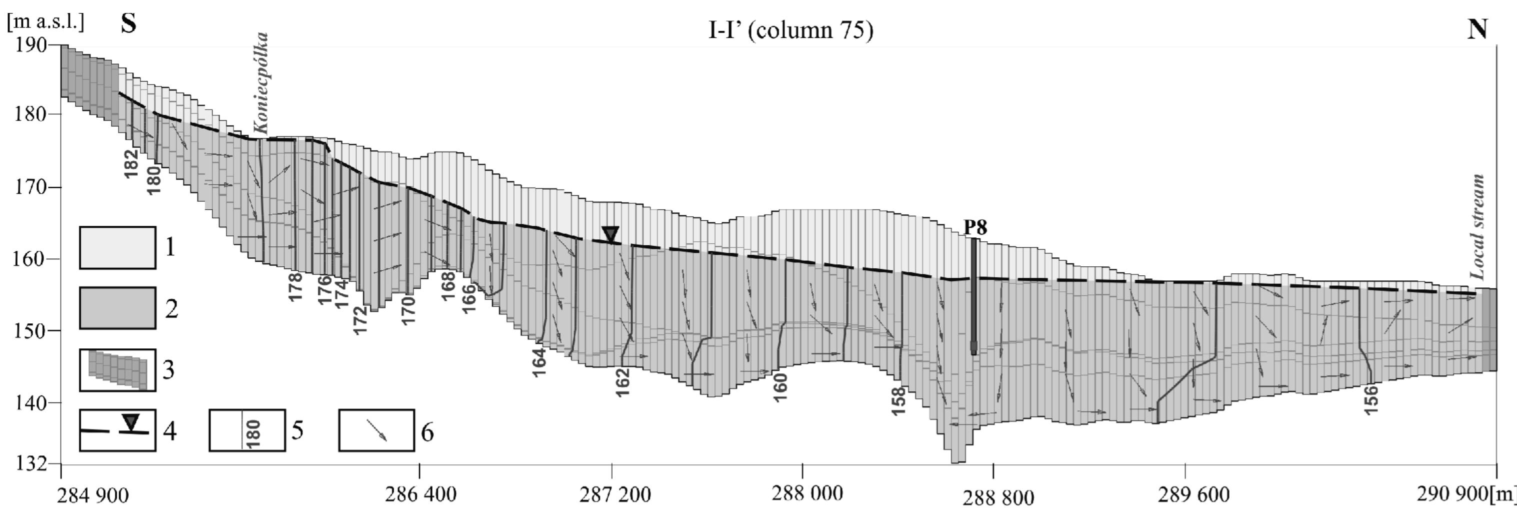

Fig. 9. *Hydrodynamic cross-section of Quaternary aquifer in the area of Nowa Dęba waterworks; situation in 2010 reconstructed by the mathematical model*
Notation: 1 – saturated zone, 2 – unsaturated zone, 3 – blocks outside modeled area, 4 – Quaternary groundwater level, 5 - equipotential lines of the water table, 6 – groundwater flow directions

Rys. 9. *Przekrój hydrodynamiczny przez rejon ujęcia wód piętra czwartorzędowego w Nowej Dębie; stan na 2010 odtworzony na modelu matematycznym*
Oznaczenia: 1 – strefa aeracji; 2 – strefa saturacji; 3 – bloki poza obszarem badań modelowych; 4 – zwierciadło wód poziomu czwartorzędowego; 5 – linie ekwipotencjalne zwierciadła wód; 6 – kierunki przepływu wód podziemnych

6. Conclusion

Groundwater models are an important tool for translating qualitative into a quantitative understanding of a hydrogeologic system that is consistent with the current available data. Producing a calibrated and validated groundwater model provides a level of confidence in the conceptual model of the main physical processes and forces that are controlling hydraulic heads and fluxes.

Our study highlighted groundwater under two different conditions: 2010 and pseudo-natural (before the existence of the waterworks). The computed groundwater level contours have shown to replicate the trend of observed groundwater during 2010.

Preparation of the model required very detailed field investigation taken in 2010 and creating a detailed structure based on the field investigation - knowledge about geology and hydrogeology of this area.

The calibration results for the developed numerical groundwater flow model were satisfactory with the correlation coefficient of 1.0. Groundwater modeling proved to be a very effective tool in simulating groundwater flow and thus identifying the groundwater flow patterns, well as groundwater budget components.

The groundwater budget indicated that in the Nowa Dęba area the major input comes from recharge mainly via infiltration of precipitation. Main groundwater outputs are through constant head boundaries and wells. Simulations for the two basins show that the total input and output from Dęba river is greater than from Koniecpólka river.

A very detailed structure of this model and high level of calibration, adequately describing field measurements in2010 indicate that this model can be used for the development of contaminants transport model.

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