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Numerical model schematization of a complex hydrostructural Cretaceous groundwater basin for the purpose of protection zone evaluation

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Abstract: One of the major projects in regional hydrogeological investigations in Poland is a multi-annual cycle of studies on the implementation of programs and documentation in relation to the establishment of protection areas for the Major Groundwater Basins (MGBs). Depending on the size of the area and complexity of the selected aquifer system, the work on the numerical model becomes adequately demanding. The model must in this case be designed as a three-dimensional, multi-layered, taking into account the role of a near the surface aquifer in the potential rate of migration of contaminants. It is particularly difficult to design models of the basins located in the older Mesozoic hydrogeological structures of dual-porosity characteristic, covered by Neogenic and Quaternary sediments. One of these basins is MGB No. 317 (ed. Kleczkowski 1990) identified within the northern Sudetic trough. The boundaries of the MGB are associated with the occurrence of structural aquifer limits, including the relatively large area of outcrops of the upper Cretaceous sediments with a narrow zone of Triassic outcrops. The paper presents the main assumptions of the model schematization, especially regarding the parameterization of hydrostructural conditions in integration with geoinformatic tools and MODFLOW modules. This study is focused on the problems associated with the proper schematization of the multilayer groundwater system on a regional scale, particularly with regard to the first aquifer and its hydraulic contact with the Mesozoic water-bearing horizons of the MGB. Model simulations, together with a semi-analytical analysis of the rate of flow in the vadose zone, finally allowed to determine the protection area of the MGB that is presented.

Keywords: numerical model, schematization, MGB, geoinformatic systems

INTRODUCTION

According to the regional division of fresh groundwaters taking into account groundwater bodies (GWB) (ed. Paczyński & Sadurski 2007) the MGB 317 is located in the central region of the Odra River, the sub-region of the Sudety Mts. (Fig. 1). The basin has an elongated shape with the axis of NW-SE and extends from the southern border of the Lubuskie voivodship to the Złotoryja area in the south-east reaching a total length of approx. 60 km. The boundaries of the MGB 317 are relatively regular and reflect the structural extent. The average annual precipitation in the area amounts to 700–750 mm/year. Several large groundwater intakes are located within the basin, which is structurally associated with sandstones and limestones of Cretaceous and Triassic age. The characteristics of the Cretaceous aquifer have been presented in the study of Tarka (2006). The multi-layered aquifer system covered by the model is influenced by natural drainage, thanks to the varied terrain, and in particular deeply incised valleys of rivers and streams.

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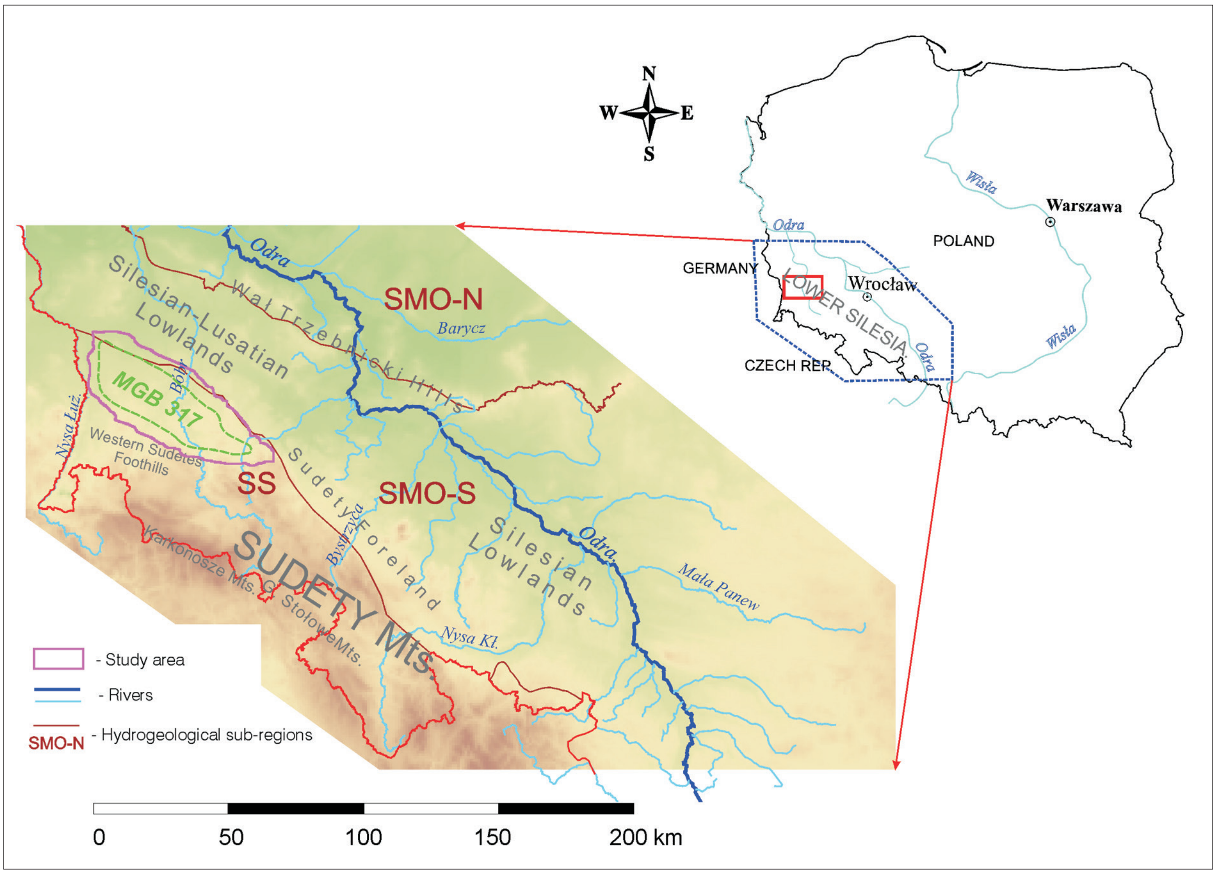

Fig. 1. *Location of the study area*

The catchments are drained by major rivers like: Bóbr, Kwisa, Czerna Wielka, Czerna Mała, Skora, Kaczawa and their tributaries. However, of greatest importance in the drainage of groundwater are the Bóbr River and the Kwisa River the basins of which occupy the entire central part of the area (Fig. 1). These valleys intersect the area of the model both at the inflow as well as the outflow from the area. Therefore, the direction of groundwater flow is to the north and lateral inflows mainly come from parts of the southern border.

The area covered by the model, the same as the field of investigation, occupies 1570 km^2, while the designated region of the water balance calculations of the MGB 317 has an area of 839.7 km^2, which is slightly more than 50% of the active part of the model.

The calculations on numerical model were conducted in order to find out the components of the water balance, assessment of recharge and renewability of the aquifer system, estimation of resources and the protection area of the MGB, which is a very important source of water supply in the region.

MATERIAL AND METHODS

The basic material constituted a database of hydrogeological boreholes, made thematic maps and cross-sections. These data were used to compile the database of hydrogeological parameters, in particular to determine the top and bottom of aquifers, the relationship with separating layers, and to delimitate hydraulic contact zones and outcrops affecting the topology of the entire system. The principles of preparing and compiling data for numerical models of large hydrogeological units are described in many studies (e.g. Anderson & Woessner 1992, Gurwin 2003, 2012, Gossel et al. 2004, Lubczynski & Gurwin 2005, Hunt et al. 2006, Mylopoulos et al. 2007, Gurwin & Serafin 2008, Michalak 2008). A proper identification of near the surface aquifers is crucial due to the role in formation of groundwater resources of multilayer systems (Macioszczyk 1997, Gurwin 2003). Spatial distribution of parameters was interpreted using geostatistical modeling tools with built-in GIS software.

Numerical groundwater flow model

A numerical modeling is considered as the primary method of determining groundwater resources in regional studies of multilayer aquifer systems and the same is true in relation to establishing protection areas of MGBs. The MODFLOW package (Mc Donald & Harbaugh 1988, Mc Donald et al. 1991, Harbaugh et al. 2000) in GMS environment, being used in enormous regional investigations, has been selected to develop a 3D numerical flow model. A calculation module is based on the finite difference method utilizing advanced iteration procedures for solving filtration equations.

The southern and south-western borders of the model were determined by morphological and hydrographic conditions. The northern border was appointed generally in accordance with outflow of the groundwater streams and mostly drawn along the surface watercourses. On the other parts, it was outlined as a boundary condition of the first type. The western boundary of the model led partly along the river and partly in accordance with the established hydrodynamic net. The whole system of groundwater circulation was separated into Quaternary, Neogene, Cretaceous, Triassic and also, to a small extent, older rocks. The surface outlining the system in a vertical position is poorly permeable bedrock or the range of saturated rocks, mainly Cretaceous sandstones.

Archival data from geological, hydrogeological and geophysical surveys indicate that six numerical layers are necessary to establish an appropriate scheme of the model, taking into account the diversity of the layers and parameters. The 1st layer – consisting mainly of Quaternary sands and gravels within river valleys and water-glacial deposits on uplands – is of particular importance, since it has a decisive influence on the distribution of recharge throughout the aquifer system and forming contact with surface water. On the uplands, the thickness of the unconfined aquifer is small, from 2 m to 5 m, and the average hydraulic conductivity is 15.3 m/d. In river valleys (the Kwisa River and the Bóbr River) the thickness reaches 10–25 m and more, and hydraulic conductivity is 10–15 m/d. The 3rd permeable layer covers in model schematization Neogene aquifers of subordinate importance and is found only in the western part of the MGB. The 5th permeable layer includes a major aquifer in the Upper Cretaceous rocks and partly outcrops of Triassic rocks, hence the main collector of groundwater is a fissured-porous series of sandstones. The 2nd and 4th layers have been mapped as poorly permeable separating layers. However, the second layer partially plays a role of Quaternary aquifer in the eastern part of the area. The 6th layer underlies the adopted aquifer system. All of the embedded aquifers interact with one another by separating layers through hydraulic contacts. A three-dimensional variability of numerical layers was exactly reproduced on the model using geospatial GIS analysis (Fig. 2). Together with parameter estimation based on detecting and quantifying patterns in data it provides a perspective in understanding relationships within the whole hydrogeological system. A prior execution of a digital terrain model DTM matched to the course of the river network exerted a strong influence on the quality of spatial geometry of the model (Fig. 3).

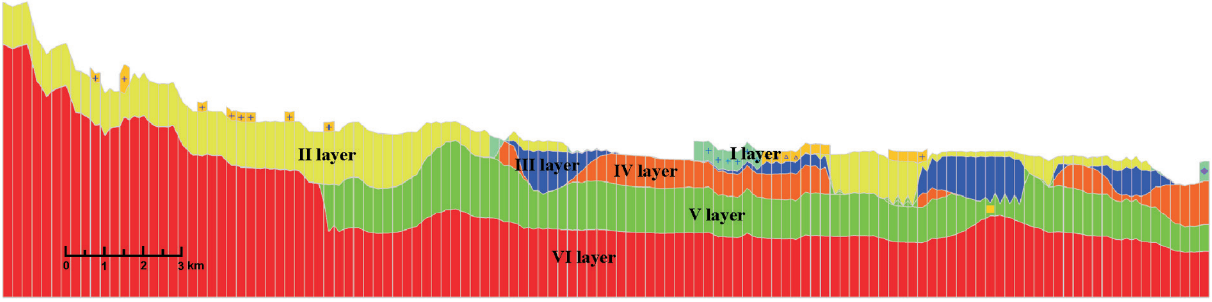

Fig. 2. *Spatial interpretation of the model layers, cross-section S-N (A-A' line in Fig. 3B)*

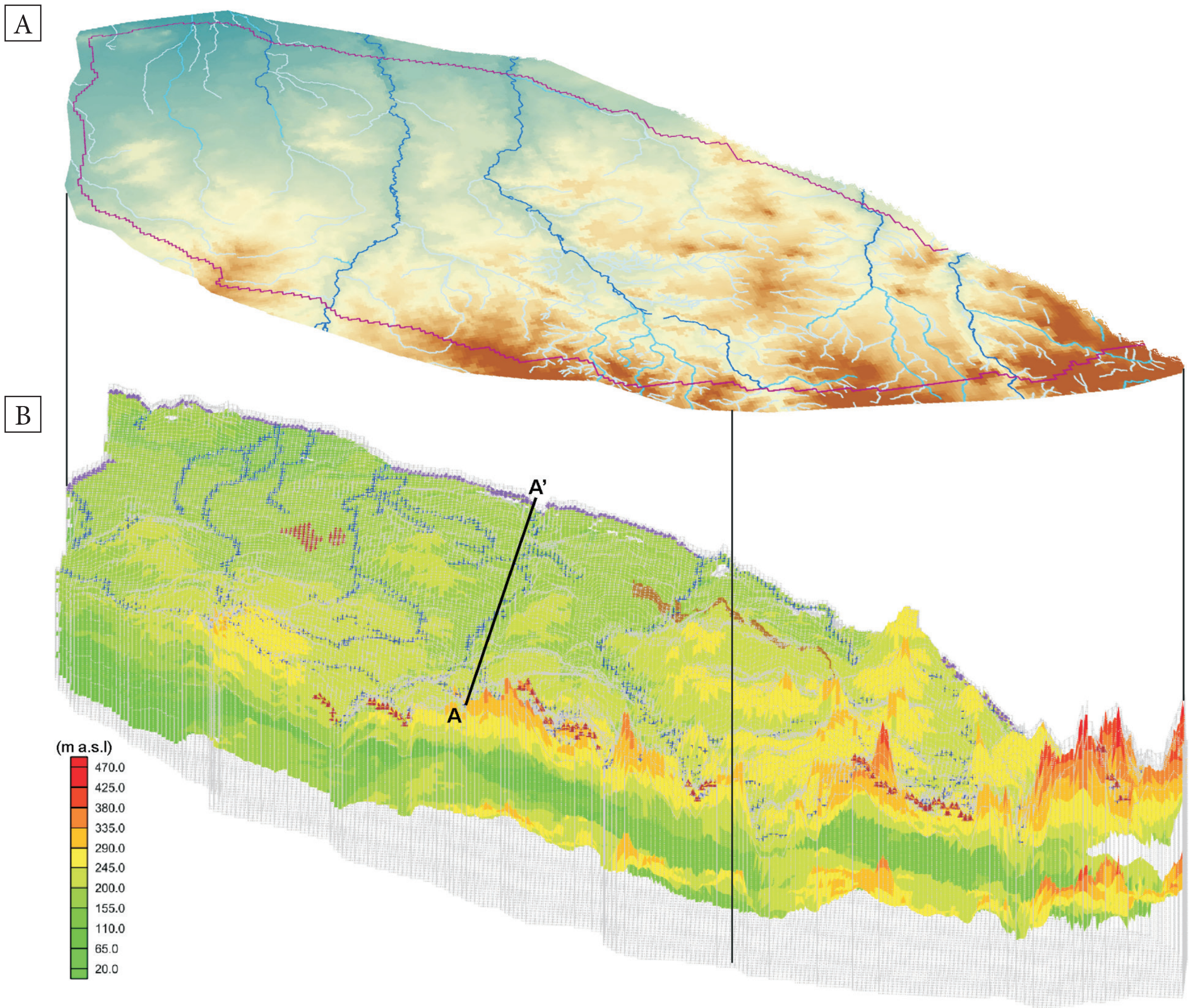

Fig. 3. *DTM (A) and 3-D view of the model (B). A – A' – line of cross section from Figure 2*

The schematization procedure and its influence on the model assumptions and constraints has already been discussed by Gurwin (2016). The measurements in monitoring points were performed in 2012 to gather appropriate values for model calibration.

Calculations of the protection zone

For the purpose of protection zone delimitation, a semi-analytical method for trace particles on the MODPATH model was used, wherein upon designation of a few hundred particles as well recharge as discharge zones throughout the multilayered system could be identified. The pathlines were calculated in successive time steps every 5 years, and the time of groundwater flow to the MGB border could be determined on this basis. Combining these results with the time of infiltration through unsaturated zone helped to reach a final verification of the proposed limits of the protection zone.

The measure of the protecting role of near surface sediments against pollution is the time of the vertical migration of conservative pollution. So, the average time of water infiltration through an unsaturated zone was estimated in accordance with the formula as follows (Witczak & Żurek 1997):

$$t_a = \sum_{i}^{n} \frac{m_i \cdot (w_{oi})}{I},$$

where:

t_a – time of water seepage through unsaturated zone [d],
m_i – thickness of unsaturated zone [m],
w_{oi} – soil moisture [–],
I – net recharge [m/a].

The methodology and scheme of the GIS modelling of water seepage time through an unsaturated zone was the same as presented in another study (Gurwin 2015).

RESULTS AND DISCUSSION

Model grid and boundary conditions

Recognition of the spatial structure of the hydrogeological system was considered sufficient to achieve a reasonable 3D model consisting of 6 layers. A discretization of the area was made using a rectangular grid with S-N orientation creating model compatible with the GIS system. The active part of the model, after the final reduction in space, has been designated by 196 rows and 268 columns, which gave a very large number of cells (more than 300,000) approx. 60% of which stand for active blocks. The grid was established as a regular $\Delta x = \Delta y = 250$ m. This resulted in an optimally high density of calculation cells (Figs. 3, 4) that directly affects the quality of the model.

Boundary conditions of the 1st type – H = const. (Dirichlet's) were adopted in accordance with known geological conditions and head contours only on the outflow of groundwater from the aquifer system at an appropriate distance from the borders of the MGB and thus had no impact on the results of water balance. It occurs in many parts of the outer northern and north-eastern border. The external boundary conditions of the third type (General Head Boundary Package – GHB) $Q = f(H)$ were introduced on parts of the southern border, mostly in places where the river valley crosses the boundary of the model and thus there is an intensive outflow in the layer. The boundary conditions $Q = 0$ were fixed to other parts of the external border in the first layer and in areas of the groundwatershed and additionally in the case of the boundary line parallel to the pathline. Recharge was implemented within the entire active area as a boundary condition of the second type Q = const. All the groundwater intakes in the area of research were simulated using inner boundary conditions of the second type Q = const., as an average annual pumping rate in cubic meters per day. Boundary conditions of the third type $Q = f(H)$ were used to depict the impact of water level in the river on groundwater, thus all major rivers were simulated with the *RIVER* package. Only a few small tributaries were created using the *DRAIN* package allowing them to become dry during calculations (Fig. 4).

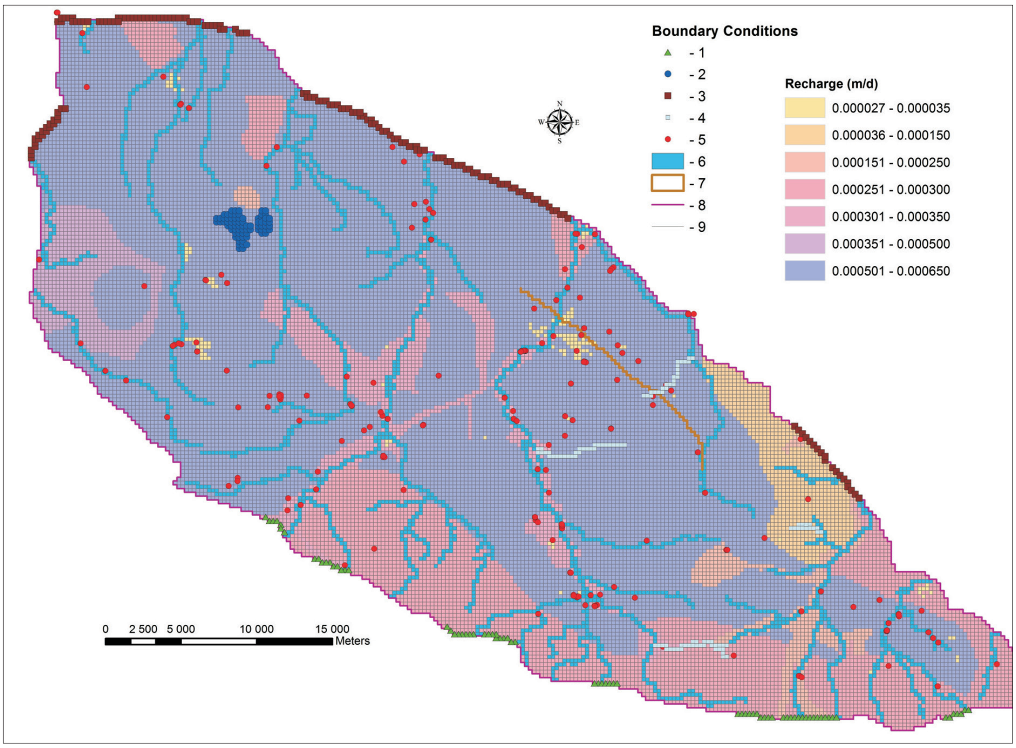

Fig. 4. *Boundary conditions of the model. Boundary conditions: 1 – 3rd type (GHB), 2 – 3rd type (Reservoirs), 3 – 1st type (H = const.), 4 – 3rd type (DRAIN), 5 – 2nd type (WELLS), 6 – 3rd type (RIVER), 7 – 3rd type (Barrier), 8 – active model boundary, 9 – model grid*

Model calibration and verification

Identification and verification of the numerical model of the MGB 317 was carried out in accordance with the hydrodynamical field, resulting from the elevation of the groundwater table in the boreholes and dug wells. Calibration was launched in the NW part, then in the middle of the area and further continued toward the east and south. Model calibration was carried out by successive approximations, the so-called trial-and-error method. The differences between measured and calibrated head values (Fig. 5) in reference points for all aquifers were usually between 1–2 m. However, sometimes the discrepancies were larger, mainly due to the fact that despite the sufficiently dense grid it was nevertheless possible because of the high diversity of terrain denivelation. In addition, the measurement and location errors could be imposed. Moreover, some points in the first layer refer to the suspended aquifer, which in most parts of the model becomes drained, so that some of them have been discarded. Therefore, in regard to the usable Quaternary aquifer (layer 2) in the western part, the calibration was simultaneously based on the hydroizohypses, which were designated in this area. Additionally, the calibration process was controlled in a separate dialog box, where the plots of the objective function were prepared. Finally, the quality of the results, considering the area of the model and calculating time, should be assessed as very good. The model showed a sufficient compliance between calculated and actual data that was confirmed by the resultant head contour maps, error values and the accompanying compatibility charts (Fig. 5).

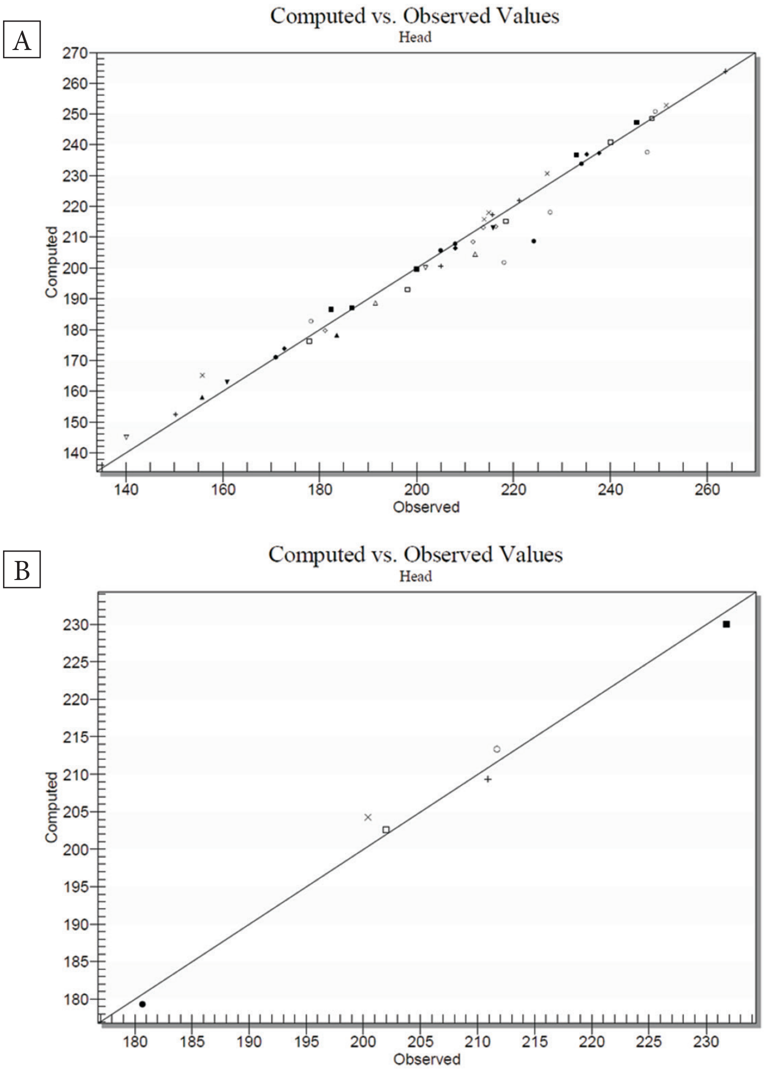

Fig. 5. *Simulated (H_{comp}) versus measured (H_{obs}) heads (m a.s.l.) in Quaternary (A) and Cretaceous aquifers (B)*

The error values are as follows:

- the mean error (ME):

$$1/n\sum_{i=1}^{n}\left(H_{pi}-H_{oi}\right)=0.8\ \text{m},$$

- the mean absolute error (MAE):

$$1/n\sum_{i=1}^{n}\left|H_{pi}-H_{oi}\right|=3.1\ \text{m},$$

where:

H_{pi} – measured values [L],
H_{oi} – calculated values [L].

Calibration essentially involved the following parameters: recharge and horizontal and vertical hydraulic conductivity of all layers, wherein the zones of hydraulic conductivity of the 5th layer (as a MGB) were generally maintained according to the previously designed distribution of the input data. Some minor changes have been made in the field of permeability of separating layers in order to determine the correct value of leakage. Calibration was also subjected to the boundary conditions of the 3rd type related to the impact of rivers. Some sections of these borders were changed, correcting parameters of the channel, particularly the position of the bottom within a cell. The shape and course of the boundaries of the MGB and the resulting lack of river basin closure caused great difficulty in determining the hydrological balance and verification of flows in streams.

The main objective of the verification process was to obtain a groundwater balance which takes into account the water exchange with the environment. The criterion of the water balance error, a difference between the total inlet and outlet of the system, expressed in percentage, was satisfied in a solved model achieving <0.05%

Proper schematization, selection of boundary conditions and parameters allowed to build a reasonable numerical model of filtration, which quickly obtained the convergence of calculation, and in the progress of calibration – fully acceptable level of adjustment for carrying the assumed simulations.

Calibrated parameters

The study area has good recharge conditions, influenced by the following factors: increased precipitation, in many areas a deeply surging water table, the presence of permeable sediments on the surface, including fractured Cretaceous outcrops. The output values have been slightly modified. Ultimately was obtained the range of recharge values from $3.0–4.0\cdot10^{-5}$ m/d to $5.0–6.5\cdot10^{-4}$ m/d, while maintaining the mean initial values. They vary in the range of $2.7–3.5\cdot10^{-5}$ m/d (<15 mm/year) in areas of dense urban development, in wetlands and the poorly permeable subsurface sediments. Recharge values at the level of $1.5–3.0\cdot10^{-4}$ m/d (~50–110 mm/year) occur mainly along river valleys and the values of $3.5–6.5\cdot10^{-4}$ m/d (130–240 mm /year) appear in the elevated areas - throughout the central and western parts of the area. In the southern part the values fall between $2.5\cdot10^{-4}$ and $3.0\cdot10^{-4}$ m/d. In the area furthest to the northeast, already beyond the reach of the MGB similar values occur and partly on the lower level of $1.5\cdot10^{-4}$ m/d (Fig. 6).

In terms of hydraulic conductivity, as few adjustments as possible were made for Quaternary aquifers, while maintaining the output value in accordance with subsurface lithology and in the area of occurrence of the usable aquifer in accordance with the preliminary spatial pattern. The values of hydraulic conductivity after corrections are in the range of less than 2.0 m/d to about 25 m/d. In the model layer 5, simulating a productive aquifer within the MGB, the values of hydraulic conductivity are between 2.0–5.0 m/d, while mostly 3.0 m/d. Adopted mean values are fully consistent with the findings of Tarka (2006). Making a detailed analysis of the permeability of the Cretaceous rocks in the Sudetes, he obtained the geometric mean values of 2.5–3.6 m/d. Hydraulic conductivity of semipervious layers, the most common type of sandy clay, was assumed equal to $5.7\cdot10^{-6}$ m/d in the areas of their occurrence, broadly throughout the central and eastern parts of the area.

Changes to the other set of inputs were small or negligible. Groundwater intakes were simulated by introducing well withdrawal defined for the consumption in 2012. In addition, simulations were subjected to lateral inflow and outflow of groundwater across the outer limits of the model. The quantity of these flows was established by modifying the external boundary conditions of the 1st or the 3rd type.

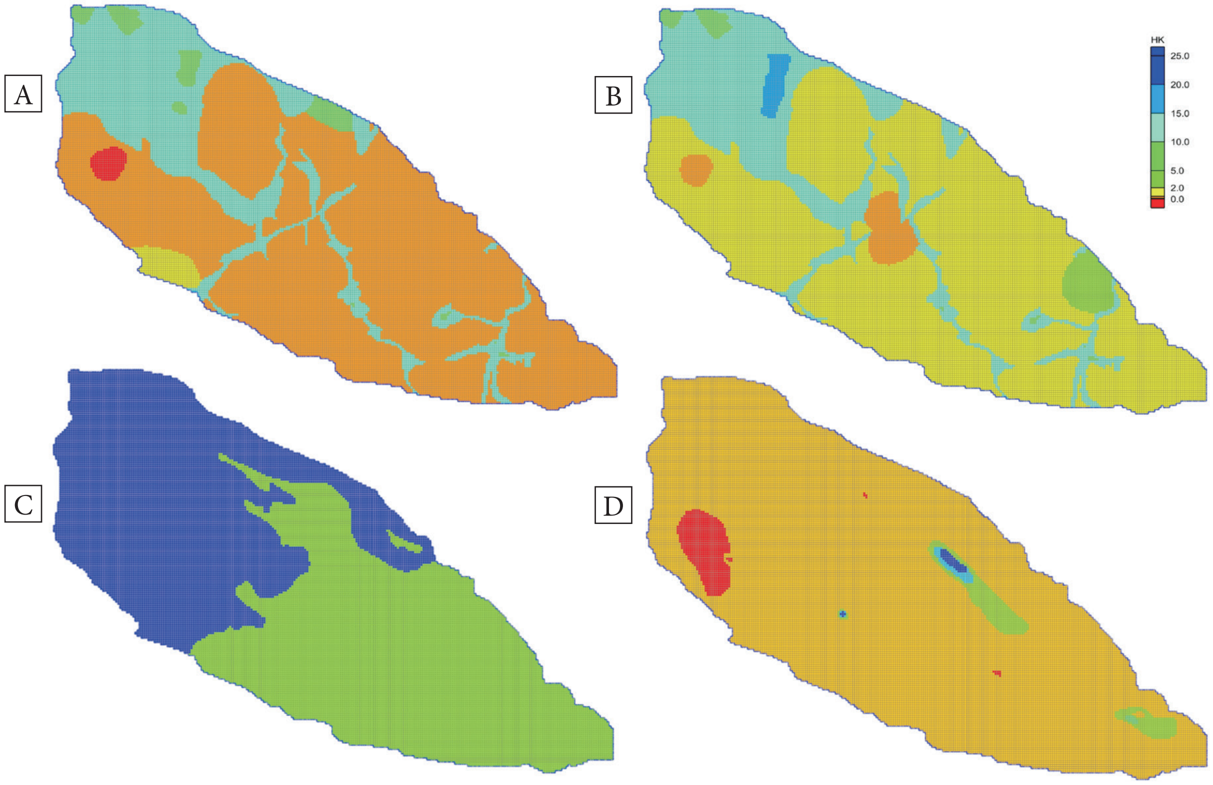

Fig. 6. *Spatial distribution of hydraulic conductivity (HK in m/d) in layer 1 (A), layer 2 (B), layer 3 (C), layer 5 (D)*

Water balance and groundwater resources

The module of a total renewability of the system according to simulations in steady-state conditions (Fig. 7) is **7.5 L/(s·km^2)** (27.0 m^3/(h·km^2)), meaning that the total quantity of groundwater renewable resources as the sum of recharge and other external inflows equals to **544,807.3 m^3/d**. The capacity of these resources depends on the vast majority of the effective infiltration, which represents 85% of the total renewability of groundwater, and the rest is formed by the lateral inflows from the recharge upland areas – mainly from the south. Taking into account also river infiltration, the share of surface water is of the order of 16% of the total sum of the positive components of the water balance (Tab. 1). Hence most of the intakes are located just in the river valleys. The total output of all active wells was set at 20,356.3 m^3/d and 40% of this falls on the MGB and amounted to 8,122.4 m^3/d. Recharge rate was fixed at **6.36 L/(s·km^2)** (22.89 m^3/(h·km^2)). Given the presence of large areas of the lack of the first subsurface layer, the value of recharge applied to the second layer is less giving a module of 4.44 L/(s·km^2) (16.0 m^3/(h·km^2)). The more that the first layer within the MGB occurs in the river valleys only, and its recharge is essentially the same as the discharge into rivers. Thus, supply of the MGB (5 layer) by infiltration from the top equals to 319,472 m^3/d (Tab. 1), which gives 4.4 L/(s·km^2) (15.8 m^3/(h·km^2)).

Renewable resources of the main aquifer, evolved in the Cretaceous and Triassic sediments (MGB 317), consists primarily of the effective infiltration and seepage from the layers lying above and lateral influx, formed mostly from the south, for a total value equal to **327,096.2 m^3/d**. Additional simulations were carried out on a calibrated model with regard to groundwater intakes in all usable aquifers with yields at the level of the admissible volume of extracted groundwater with a total value of 105,901.9 m^3/d, which is 5 times higher than in natural conditions at the current consumption.

Further prognostic simulations were carried out to determine the optimum exploiting conditions and to test the reaction of the system and its ability to compensate for fluxes. It was decided to increase total pumping in wells testing variant distributions of potential new big groundwater intakes while limiting consumption in over-exploited areas. Finally, a global withdrawal within the system was changed to a maximum of 210,000 m^3/d, which was twice the admissible volume of extracted groundwater and thus approx. fivefold increase in consumption in the MGB (layer 5) which amounted to 111,000.6 m^3/d. Taking into account that groundwater intakes did not work so far in the western part of the basin, this was a feasible extraction scenario. The simulation resulted in a change in the circulation of groundwater, and the distribution of cones of depression were adapted to the new conditions. The drawdowns descend on average in vicinity of the big intakes to s = 20–25 m in the westernmost area and 15–20 m in the area between the Bóbr River and the Czerna Wielka River. In the eastern part, in the lane between the Bóbr River and the Skora River, where some new wells were also introduced, depressions did not exceed several m. Thus, the reserve of groundwater resources was found throughout the basin and the locations of new intakes with pumping rate of 100–200 m^3/d at depression from a several to more than 20 m can be developed. The simulations clearly indicated that the extraction of groundwater at a specific level would be possible with evenly scattered distribution of wellfields within the MGB 317. The best suggestions for prospective areas for new intakes may be considered in the western part of the basin, especially downstream within the outflow zone or in the drainage zone of the regional groundwater flow system.

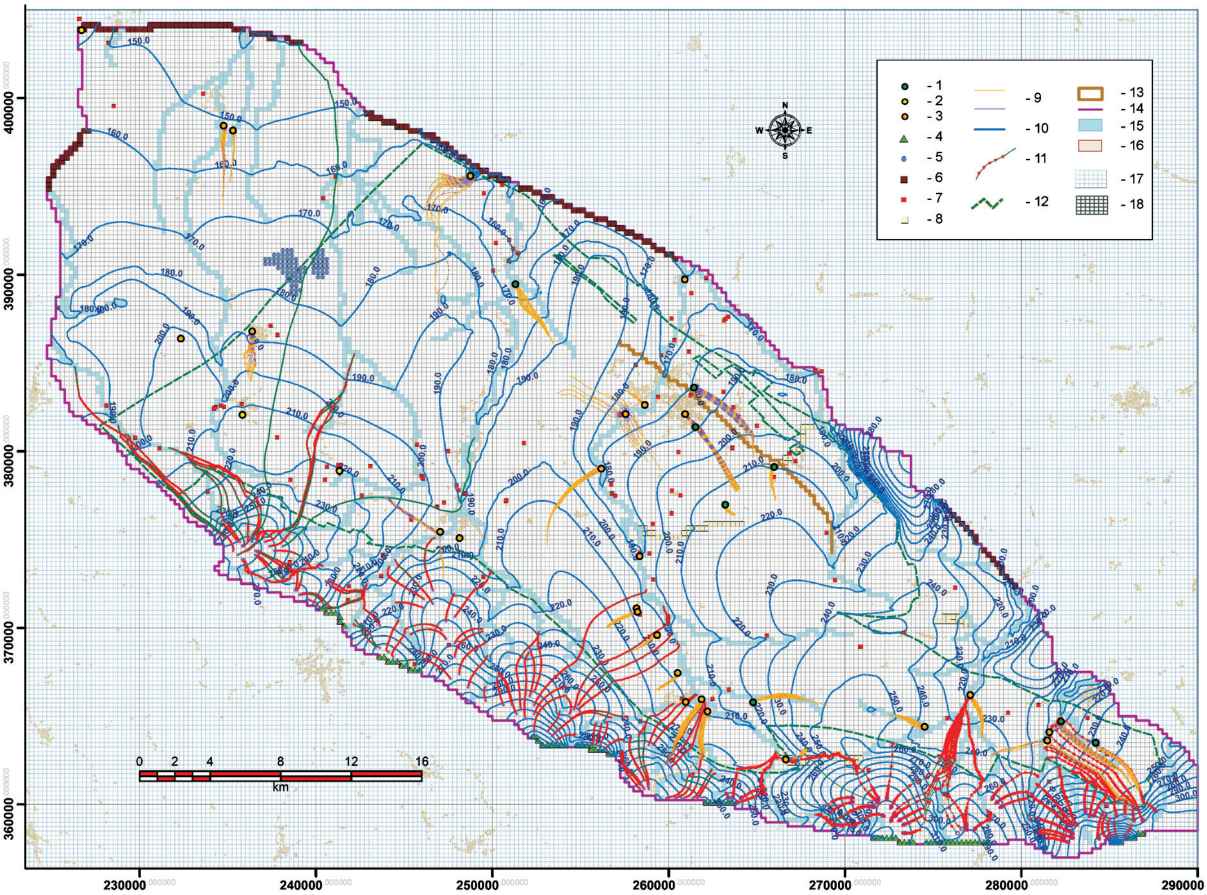

Fig. 7. *Head contours and pathlines from model simulations. Groundwater intakes in: 1 – Cretaceous aquifer, 2 – Neogene aquifer, 3 – Quaternary aquifer; boundary conditions: 4 – 3rd type (GHB), 5 – 3rd type (Reservoirs), 6 – 1st type (H = const.), 7 – 2nd type (WELLS), 8 – 3rd type (DRAIN), 9 – backward calculated pathlines to wells, 10 – hydroizohypses, 11 – forward calculated pathlines, 12 – MGB boundary, 13 – BC barrier, 14 – active model boundary, 15 – rivers simulated in the model (RIVER) 16 – built-up areas, 17 – inactive cells, 18 – model grid*

Table 1
Water balance within a hydrodynamic system of the MGB 317 according to the numerical model simulation for pumping conditions in 2012

No.	Water balance components MGB area = 839.7 km^2	Result [m^3/d]
1.	Effective infiltration	+461 324.9
2.	Inflow/outflow from external borders	+89 951.3/−62 163.5
	– usable aquifer – MGB, Cr + T – layer 5:	
	• inflow mainly from S	+7 624.0
	• outflow mainly to NE, E, S	−8 553.3
	– other layers, Q – Ng:	
	• inflow mainly from S, SW	+82 327.3
	• outflow mainly to N, NE	−53 610.2
3.	Recharge/drainage by rivers	+106 521.1/−566 539.7
4.	Recharge/drainage by reservoirs	+36 457.8/−45 113.9
5.	Exploitation-intakes (status for 2012)	−20 356.3
	– usable aquifer – MGB, Cr – layer 5:	−8 122.4
	• usable aquifer, Q – layer 2	−11 697.7
	• usable aquifer, Ng – layer 3	−536.2
6.	SUM +/−	+694 255.1/−694 173.4
7.	Leakage between aquifers:	
	– down/ to/from layer 2	+185 243.2/−495 252.1
	– up	+485 603.6/−498 312.4
	– down/ to/from layer 5	+ 319 472.2/−292.8
	– up	+583.0/−298 566.6
8.	Difference (inflow-outflow)	−81.8
9.	error	0.01%

An increase in the overall inflow of groundwater was observed into the water-bearing system to 732,000.7 m^3/d representing an increase of nearly 6%. An increment of seepage from the upper layer to the layer 5 by approx. 50,000 m^3/d was established as well, which is 17% compared to that of 2012. The total lateral outflow was concurrently reduced by 14% in relation to the actual conditions. Considering the usable Cretaceous-Triassic aquifer (MGB) the inflow was changed at the level of 3% as a result of increasing groundwater pumping and the simultaneous decrease in outflow less than 1,000–7,641 m^3/d was calculated, which was within 11% as compared with the simulation of actual conditions. In other aquifers, lowering of the external flux was approx. 15%. A recorded intensity of surface water infiltration amounted to 142,000 m^3/d, which represents approx. 30% rise, while a river drainage was lowered by approx. 20%.

Considering the karst fissured aquifer of the MGB 317 (high filtration velocity), and its partly non-insulated character, it was denoted by a high and medium level of hazard, which should be considered as an additional criterion limiting the disposable resources of this basin.

The model showed in terms of the water balance and hydrodynamic field that the level of exploitation that reached about 50% of calculated renewable resources did not negatively affect the aquifer system of the basin or the neighboring areas. On the basis of calculations and evidence relating to the protection of the MGB 317, it was finally decided to determine the value of disposable resources as equal to Q_d = 120,000 m^3/d.

Delimitation of protection zone

An analysis of groundwater advective flow in the aquifer system with the findings concerning the delimitation of protection zone of the MGB was the next crucial step of numerical simulations. The time of flow to the MGB boundaries in the natural hydrodynamic conditions was approx. 30–50 years. The most important were backward calculations to identify the isochrones for a period of 25 years. Additionally, the calculations were made to determine the capture zones of the main groundwater intakes (Fig. 7). The pumping wells within the MGB affected the hydrodynamic system of course, but calculations proved that it did not have a direct influence on the assignment of the external extent of the protection zone. A part of the zone exceeding the area of the MGB should be adopted only in places where the pathlines indicating the time of 25-year inflow to the intakes pass through the border. Finally, calculations revealed that the hydrodynamic system did not require the establishment of a protection zone beyond the accepted limits of the MGB.

unconfined or locally semi-confined aquifer, and river valleys occurring throughout the MGB. Estimations indicated that the lowest value of <5 years were obtained just along the river valleys (sand and gravel deposits, and shallow groundwater table), in drainage zones. Near the watershed divide areas, where the depth to the water table was greater and insulation cover better the values gradually increased from a dozen to more than 25 years. Therefore, the usable aquifer was not in danger of contaminants in this large territory under the influence of the current low-level exploitation.

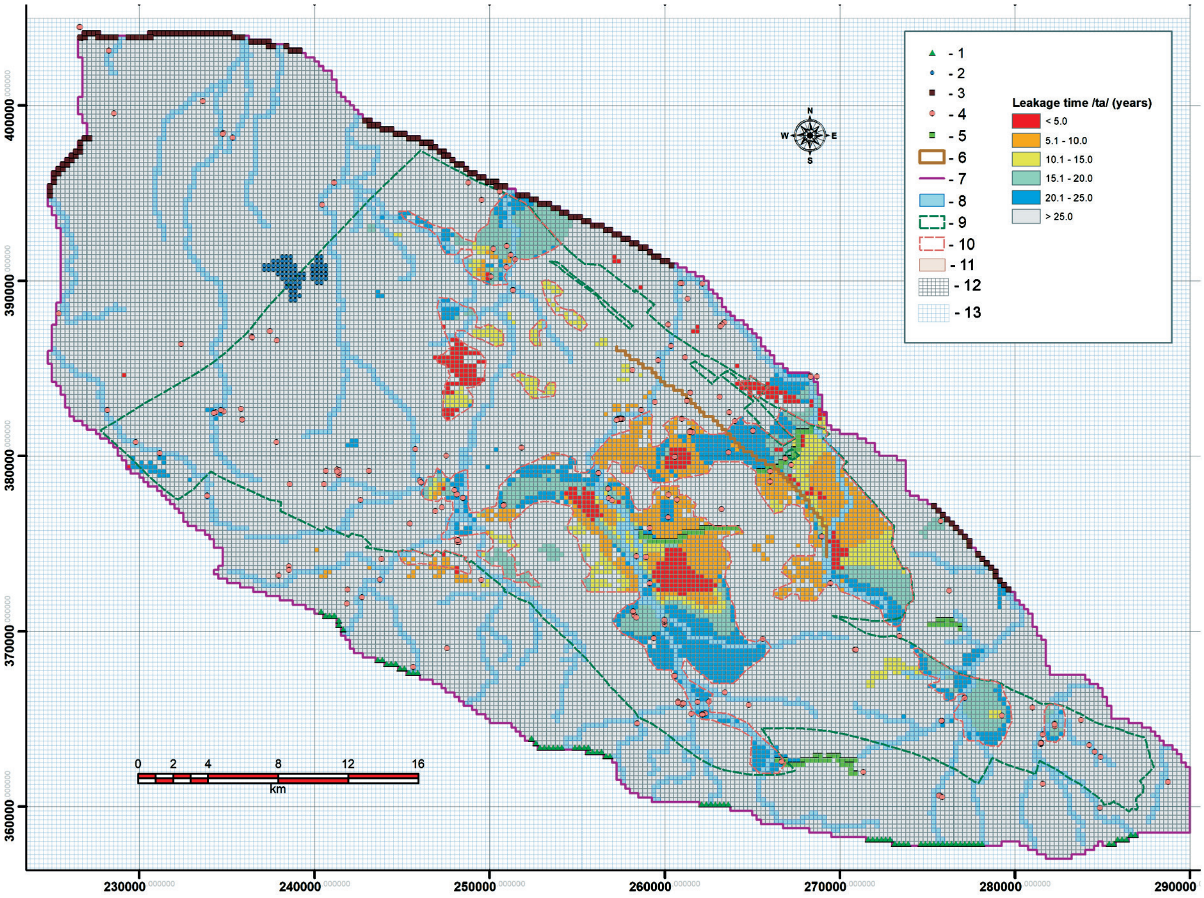

Fig. 8. *Protection areas of the MGB 317 established according to model calculations. Boundary conditions: 1 – 3rd type (GHB), 2 – 3rd type (Reservoirs), 3 – 1st type (H=const.), 4 – 2nd type (WELLS), 5 – 3rd type (DRAIN), 6 – 3rd type (Barrier); 7 – active model boundary, 8 – rivers simulated in the model (RIVER); 9 – MGB boundary, 10 – boundary of the protection area, 11 – built-up areas, 12 – model grid, 13 – inactive cells*

The resulting model matrix was the basis for calculating the percolation time (t_a) within the active part of the model and for each block of the grid (Fig. 8). The area of the MGB comprises largely devoid of areas of good insulation,

CONCLUSIONS

A numerical flow model of a multilayer system where Cenozoic discontinuous water-bearing horizons lie inconsistently on the Mesozoic aquifer, was developed in the finite difference method and solved for steady-state conditions that may cause inaccuracies. However, for the model of a regional scale such a solution is considered to be the most relevant in the identification of hydrodynamic conditions and groundwater balance. In the region of the MGB 317 a recognition of the hydrogeological conditions should be considered as inadequate both structurally as well as in relation to the hydrogeological parameters. According to a proper schematization, a prototype of a 3D model composed of 6 layers, 4 aquifers and 2 aquitards, was developed and then calibrated. The main water-bearing reservoir in the Mesozoic rock series was recreated as the 5th model layer. Due to the significant diversity of terrain denivelation, a small thickness or very often absence of the shallow aquifer, some wide dried areas for the 1st layer appeared as it was shown correctly on the model.

A regional outflow of groundwater is to the north and north-west, but locally in the areas of plateaus, runoff is diverging in different directions depending on the river network.

An average rate of recharge in the area of the MGB was set at 6.36 L/(s·km^2) (200 mm/a), or approx. 27% of the precipitation, but for the entire model site it was a lower value of about 175 mm/a. It should be emphasized that the resulting higher recharge rates for a fissured-porous water-bearing systems have been also confirmed by models made for other similar basins in Mesozoic series (e.g. Kowalczyk et al. 2004, Kowalczyk 2005, Bielecka et al. 2008).

Renewable groundwater resources of the MGB 317, as the sum of external inflows have been evaluated at 327,000 m^3/day. The quantity of these resources depends on the effective infiltration and seepage from the layers above and slightly from the lateral inflow. Hence, recharge from the top represents 98% of the total influx. Disposable resources for the MGB 317 can be taken at the level of 120,000 m^3/d, which represents approx. 35% of renewable resources and is 50% higher than the originally estimated value (Kleczkowski 1990).

Analyzing pathlines and isochrones of groundwater flow in combination with the spatial distribution of percolation time through the unsaturated zone gave an opportunity of a preliminary interpretation of the protection zone. Model simulations revealed that it was not required to establish a protection zone beyond the accepted limits of the MGB.

Consideration of other environmental or economic aspects in this area will allow for the final determination of the extent of the protection zone, which is likely to be close to this which has been established in the model.

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