Acta Geologica Polonica, Vol. 64 (2014), No. 3, pp. 353–360
DOI: 10.2478/agp-2014-0019

Anisotropy modelling of the fissure-karstic aquifer of the Opole–Zawadzkie Major Groundwater Basin (south-west Poland)

MAREK WCISŁO[1], TOMASZ OLICHWER[2] AND STANISŁAW STAŚKO[3]

University of Wrocław, Institute of Geological Sciences, Department of General Hydrogeology, pl. M. Borna 9, 50-205 Wrocław, Poland.
E-mails: [1]marek.wcislo@ing.uni.wroc.pl, [2]tomasz.olichwer@ing.uni.wroc.pl, [3]stanislaw.stasko@ing.uni.wroc.pl

ABSTRACT:
Wcisło, M., Olichwer, T. and Staśko, S. 2014. Anisotropy modelling of the fissure-karstic aquifer of the Opole–Zawadzkie Major Groundwater Basin (south-west Poland). *Acta Geologica Polonica*, **64** (3), 353–360. Warszawa.

The problem of the anisotropy and heterogeneity of karstic aquifers has been previously described. The Opole–Zawadzkie Major Groundwater Body (south-west Poland) was chosen for this investigation. The parameters for anisotropy were analysed on the basis of well yield and observation of macro-fractures (field scale) compared with micro-fractures. Statistical tools were used to assess the directions and values of anisotropy. The estimated parameters were tested on two different models realized in Visual Modflow code. The anisotropy of hydraulic conductivity was recognized as an essential factor for groundwater flow direction and water table depletion prognosis as well as for water budget modification. The second model (M2), representing anisotropy flow conditions, gave an 11% lower value of safe yield in comparison with the first model (M1-isotropic). Additionally, anisotropy conditions caused water table lowering and limitation of aquifer recharge. The results of these studies indicate the need for more attention to be paid to the anisotropy problem in the area, where fracture-karstic aquifers are the main source of groundwater supply.

Key words: Numerical modelling; Anisotropy; Groundwater resources; Fissure-karstic aquifer; Fracture directions.

INTRODUCTION

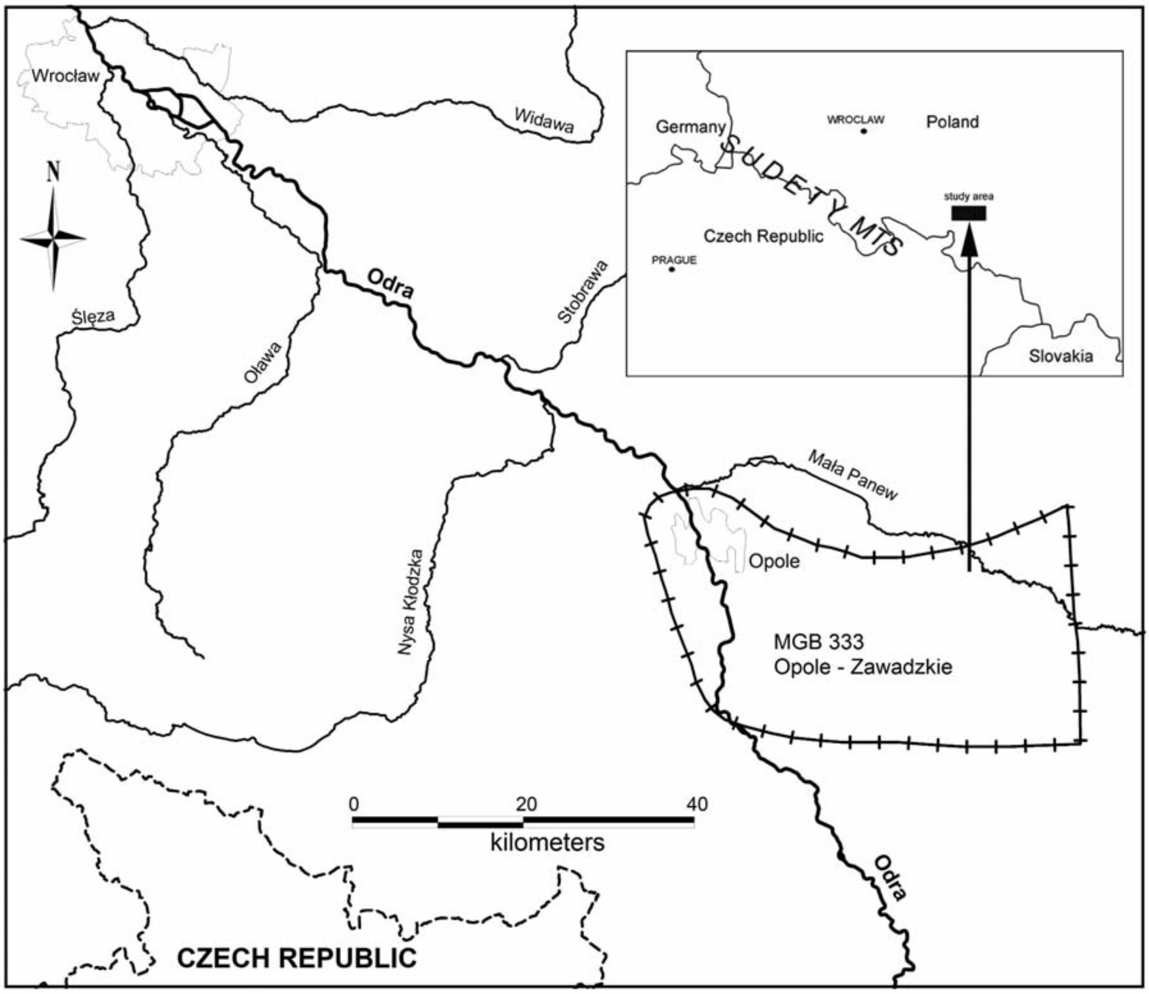
The parameters for assessing groundwater flow in karstic and fissure-karstic aquifers represent one of the greatest challenges of modern research and modelling. Many results of current investigations suggest that one of the main problems is the heterogeneity of the hydrogeological medium (Zimmerman *et al*. 1998; White 2002).

The main progress has been in the implementation of stochastic methods and uncertainty assessment in dealing with heterogeneity. Studies by Zimmerman *et al*. (1998) and White (2002) do not take into consideration another characteristic that is very typical of karst: the anisotropy (A) of hydraulic conductivity (C). Investigation of this phenomenon allows us to obtain more accurate hydraulic parameters for determining the distribution of flow direction in proximity to wells and the location of the groundwater table. The development of the hydrodynamic field under anisotropy conditions suggests that both safe yield and water table lowering are significantly modified in comparison with the isotropic medium. The above-mentioned modification can be expressed by means of numerical investigation on the basis of a groundwater model calibrated with the same accuracy for two different cases: anisotropy and isotropy of hydraulic conductivity. However, due to the lack of representative data, anisotropy is not easy to determine. Usually, we do not obtain sufficient observations from pumping tests from well fields and there are not enough piezometers. In this case, the best solution is to rely on the indirect measurement of physical characters that manifest themselves at many scales: micro-fractures (micro-scale), meso-fractures (outcrop scale) and distribution of aquifer parameters (macro-scale). All of these data are usually available or easy to obtain, as in the case of the site selected for our studies, the Opole–Zawadzkie fractured-karstic aquifer. The analyses presented that are oriented towards an explanation of the anisotropy problem are based on a confirmed relationship (Motyka 1998) that channel system networks develop under the strong influence of fracture orientation. The interpretation of fracture measurements can be directly implemented in the environment of karstic channels and entire aquifers.

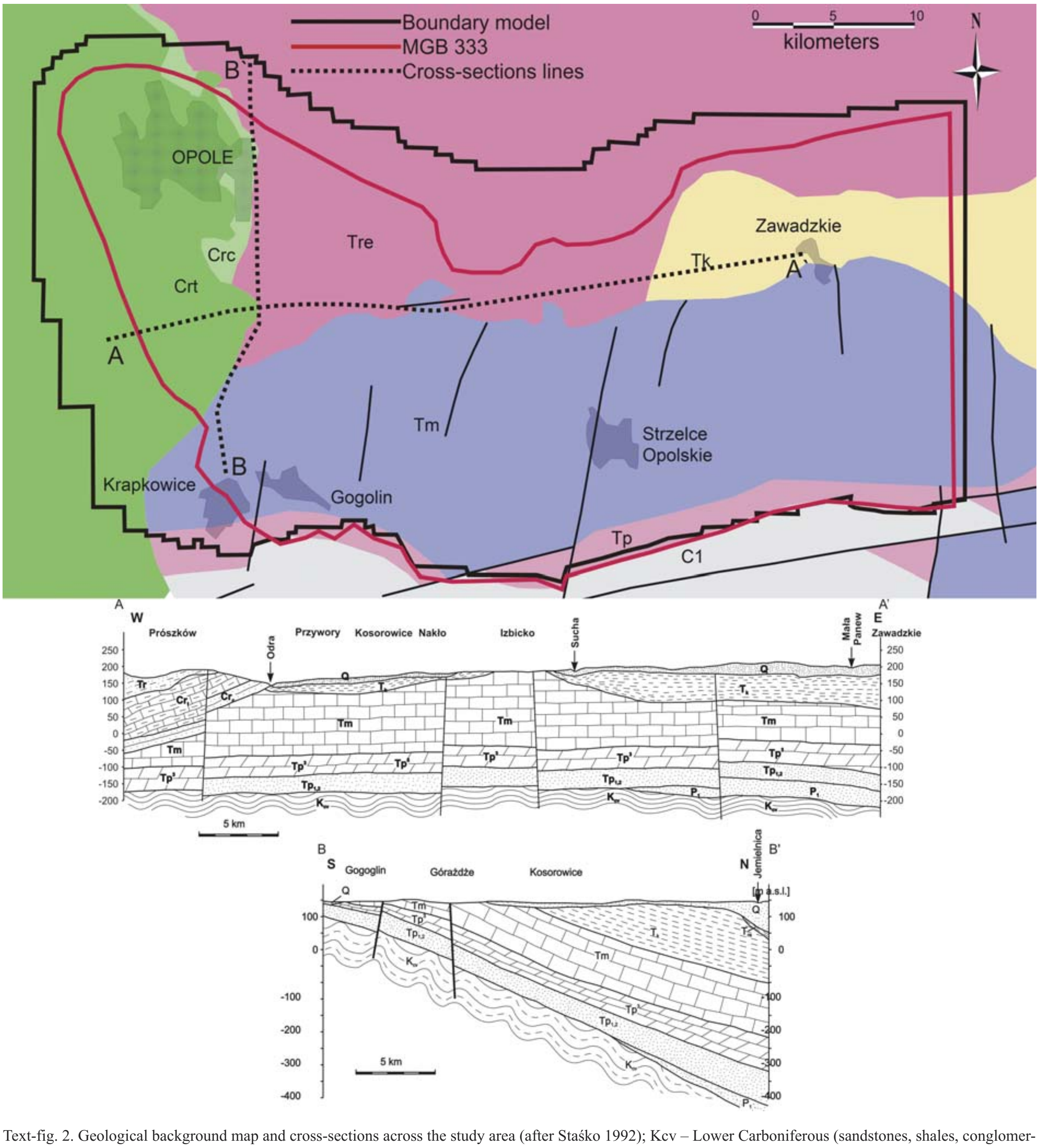
STUDY AREA

The Opole–Zawadzkie Major Groundwater Basin (MGB) is situated in the south-west of Poland (Text-fig. 1) and consist of two main aquifers: Middle Triassic carbonates -upper aquifer and Lower Triassic (Roetian marlstones, limestones)- lower one. There are two minor aquifer also: Quaternary – under Opole-Zawadzkie MGB and Permian (sandstone) – below the bottom (Text-fig. 2).

The outcrops and recharge areas of both aquifers are located in the south. The strata constitute a monocline succession dipping towards the north at an angle of about 8 degrees. The upper aquifer, on which this article focuses, consists of Middle Triassic carbonates (Muschelkalk) (Text-fig. 2), its southern part is uncovered and in the northern part it is overlapped by thick sequences of Keuper (mainly shales). The Muschelkalk aquifer is separated from the lower aquifer by layers rich in marlstones. Contact between



Text-fig. 1. Location of the Opole–Zawadzkie MGB



Text-fig. 2. Geological background map and cross-sections across the study area (after Staśko 1992); Kcv – Lower Carboniferous (sandstones, shales, conglomerates), P_1 – Lower Permian (conglomerates, sandstones), $Tp_{1,2}$ – Lower and Middle Triassic (sandstones, mudstones, conglomerates), Tp^3 – Lower Triassic, Roethian (dolomites, marls, evaporate rocks), Tm – Middle Triassic, Muschelkalk (limestones, marls, dolomites), Tk – Middle and Upper Triassic, Keuper (mudstones, marls, sandstones), Tre – Upper Triassic, Rhaetian (mudstones, breccia), Crc – Upper Cretaceous, Cenomanian (sandstones), Crt – Upper Cretaceous Turonian (marls), Tr – Tertiary (clay, sands), Q – Quaternary (sands, gravel, glacial till)

both aquifers is found locally in the south (Staśko 1992; Motyka 2005). In 2005 the annual average of groundwater exploitation for public purposes was about 30,700 $m^3 \cdot d^{-1}$. That of the mining industry (mainly open pit drainage) is much higher (about 75,000 $m^3 \cdot d^{-1}$).

GROUNDWATER MODEL

Conceptual model

The hydrogeological system comprises three aquifers: Quartenary, Middle Triassic and Lower Triassic (Roetian). The upper aquifer consists of Quaternary sands. In the Odra River valley and the Mała Panew River valley, the sands form an up to 120 m thick sequence with several intercalated clay layers. In the southern part the upper aquifer occurs locally, is much thinner (several metres) and is discontinuous. The water table is mainly unconfined or semi-confined, and is confined in the region of buried river valleys. The underlying layer (Keuper sediments) consists of fractured shale, which forms the hydraulic isolating boundary between the upper aquifer (Quaternary) and the middle aquifer (Middle Triassic Muschelkalk) forming the Opole–Zawadzkie Major Groundwater Basin. In the southern part this aquitard vanishes and the Muschelkalk aquifer is directly recharged by precipitation. An underlying thick (up to 60 m) sequence of marlstones is considered to be the hydraulic boundary that caps the lower aquifer of Roethian deposits (limestones, marlstones, gypsum). The spatial distribution of the aquifer characteristics (hydraulic conductivity K, transmissivity T, storage coefficient S, specific yield S_y and vertical conductance Vc) was obtained from analysis of samples from test holes, pumping test data for drilled water wells over the period 1960–2003, existing well-logs for aquifers and available databases of previous modelling studies (Kołaczkowski *et al.* 1980; Kryza 2001; Motyka 2005; Zalewska *et al*. 2006).

Permeability values of the Muschelkalk aquifer vary widely ($1\cdot10^{-6} – 4.8\cdot10^{-3}$ m·s^{-1}) and increase near the outcrops in the south (Kryza and Staśko 2000).

The groundwater flow pattern in the main aquifer layer (Opole–Zawadzkie MGB) is governed by conditions at the boundaries of the regional system. The boundary conditions were investigated within the scheme of previous numerical models (Kołaczkowski *et al.* 1980; Kryza 2001; Motyka 2005; Zalewska *et al*. 2006). It can be described approximately as a lack of flow in the south (aquifer outcrops), mixed boundary conditions along rivers and in the west, north and east of the model border. Along the upper model surface recharge was set as constant flow.

Numerical model

The MODFLOW program (McDonald and Harbaugh 1988) was implemented in this study to create a regional groundwater flow model. The main objective of the model is to assess the response of the karstic aquifer system to groundwater resource development scenarios for the whole of the Opole–Zawadzkie MGB area. The model was also used to test the influence of anisotropy in the prognosis of water table position and safe yield estimation.

The model was completed for public administration as a tool in groundwater management. MODFLOW was chosen for this study because the code is well documented, it is used worldwide and for this reason it is preferred by the main user – public administration.

Based on the available data describing the hydrogeological conditions and the present studies, three aquifers isolated by two aquicludes were delineated. The regional model was divided into 139 columns and 124 rows (the total number of grid cells was 86,180). Grid spacing in both the x and y directions alternates between 1000 m in the peripheral region and 100 m in an open pit. On the basis of available historical data, the year 2005 was selected as the representative period in terms of hydrogeological stresses, which could be assumed to be typical of a long-term period. This approach allowed the model to be developed for steady state conditions.

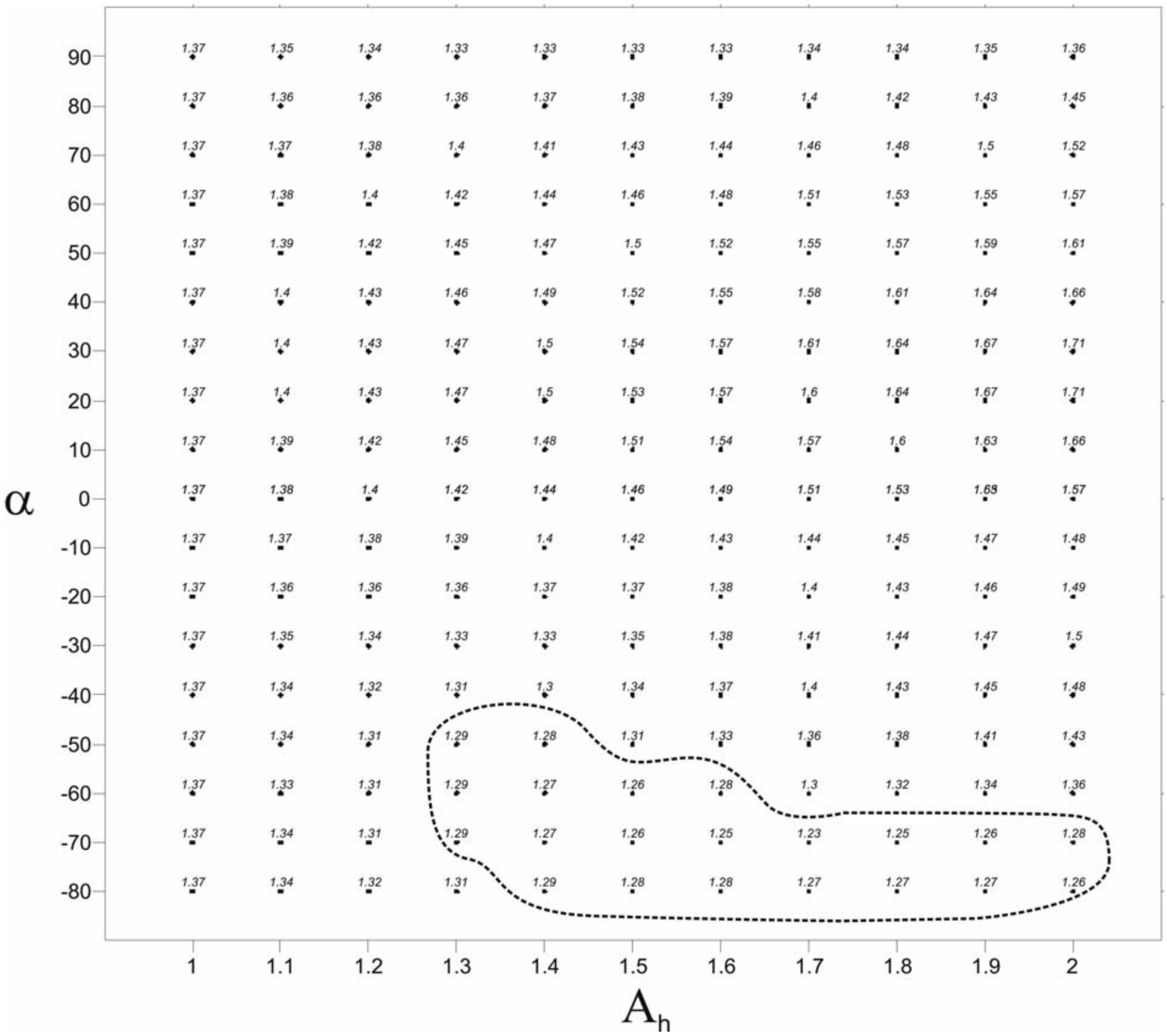
ANISOTROPY OF HYDRAULIC CONDUCTIVITY

Horizontal anisotropy (A_h) is considered to be an important factor for (i) capture zone modification, (ii) water table depletion and (iii) water balance changes of intake in karstic aquifer areas. The anisotropy of hydraulic conductivity is not easy to assess by way of simple hydraulic tests or laboratory investigation. In the case of field investigation, pumping tests with several observation wells are necessary. Laboratory analysis provides only local-scale data. Both methods in large flow systems are limited by efficiency and costs.

The authors have adopted a mixed methods approach based on the multi-scale analysis of (i) aquifer parameter distribution (specific capacity [S_c] of wells), (ii) fracture orientation in outcrops and (iii) micro-scale observation. The Opole–Zawadzkie GMB is well represented in open pits and water wells. For this reason, the described research offers the optimal source of data for anisotropy investigation.

Distribution of the specific capacity of wells

Specific capacity is the best recognized parameter of aquifers in the research area. The possibility of parameter interpolation was analysed. Kriging was selected as the method for testing as it is an optimal tool in geological spatial analysis (de Marsily and Delay 2005). Two main parameters of interpolation in the kriging method were considered: anisotropy level and orientation. The goal was to give data points in a specific direction more weight in determining the value of a grid node. These two values (anisotropy level and orienta-



Text-fig. 3. Contour map of estimation error for specific capacity interpolation (sqm·h^{-1}·m^{-1}).

tion) were investigated in a probe of 101 points (wells) by the trial and error method under the condition of minimal error of estimation (Chiles and Delfiner 1999). As a result, the matrix of error of estimation is presented in Text-fig. 3.

Text-fig. 3 shows the distribution of estimated error versus horizontal anisotropy value A_h (x axis) and horizontal anisotropy direction α (y axis). Minimum values of error occur for anisotropy A_h = 1.7 and for the azimuth –70 degrees (290 deg.). The zone of low error (<1.30) is between 280 and 310 degrees.

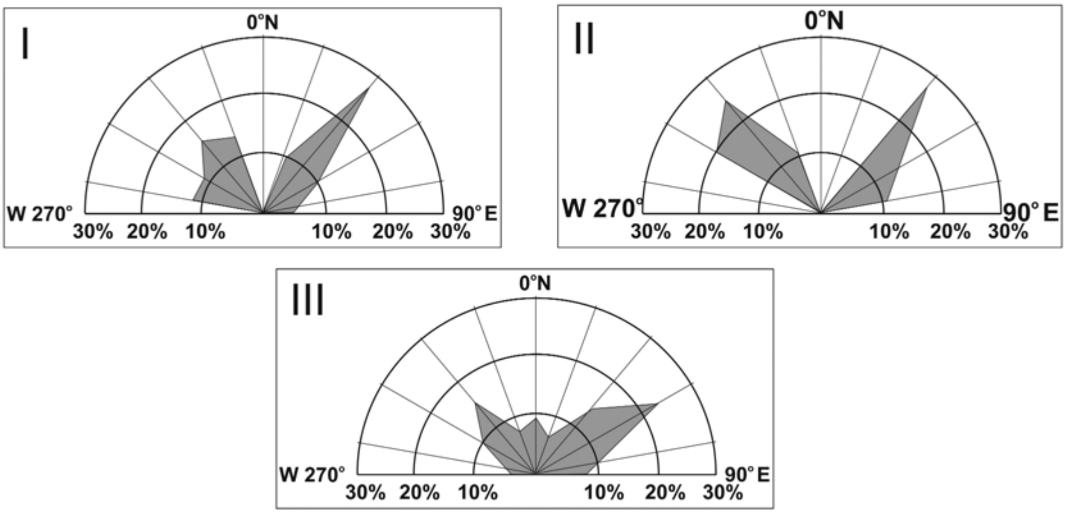
Fracture orientation in outcrops

Three areas were available for the measurement of fracture orientation: the towns of Gogolin (I), Sucha (II) and Tarnów Opolski (III) and their surroundings (Staśko 1992). Research was conducted on the Triassic limestone in open pits. The fracture orientation data were compiled as rose diagrams (Text-fig. 4).

There are two perpendicular directions of preferential fracturing: NW–SE and NE–SW. One of these indicates the direction of anisotropy, depending on its fracture density. In areas I and III the NE component is dominant, while in area II it is the NW component that is dominant.

Fracture density analysis

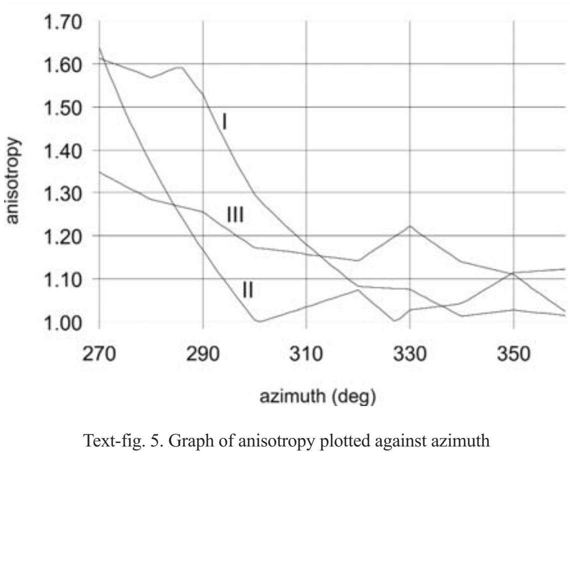
The mechanical parameters and stress field are strictly connected to the hydraulic properties of karstic and hard rock (Macpherson 1983; Jaquet *et al.* 2004).



Text-fig. 4. Rose diagrams for fracture orientation in the Opole–Zawadzkie MGB area in locations I, II and III

In this case, the fracture density in different directions can be a good source of information about the anisotropy of hydraulic conductivity. Using data collected in open pit mines (Text-fig. 4), the analysis of anisotropy value depends on the direction of the fracture measurements made. Three curves (Text-fig. 5) show the variability of anisotropy in different areas shown in Text-fig. 6. All of the curves indicate that the highest anisotropy is typically in the direction of 270–285 degrees. The azimuth obtained remains in general accord with the conclusions from the interpolation analysis of specific capacity.

The anisotropy values (Text-fig. 5) for three areas of fracture measurements were estimated. The maximum value (A = 1.6) was observed for areas I and II. Lower values were typical of area III (A = 1.35). All of the results correspond to anisotropy interpreted from the map (Text-fig. 3).



Text-fig. 5. Graph of anisotropy plotted against azimuth

Micro-scale observations

In the area of the Opole–Zawadzkie MGB micro-scale investigation has been conducted by other researchers (Wojewoda 1983). Wojewoda proved that the horizontal anisotropy of rock conductivity in the Triassic formation was between 1.67 and 2.7. Cube-shaped samples (side length ca 25 cm) were collected in an abandoned open pit. The results obtained indicated higher values of anisotropy and different directions, which did not appear to be random and disagreed with previously described results. The explanation for this discrepancy can be found in the different processes responsible for conduit formation. Sedimentation processes were indicated as a source of anisotropy at the micro-scale (Wojewoda 1983). As mentioned above, the distribution of hydraulic conductivity remains under the influence of the tectonic background rather than the lithology. Small samples did not include enough fractures to analyse flow phenomena in the karstic aquifer of the Opole–Zawadzkie MGB (Choquette and Pray 1970).

Water table for safe yield

The model was initially calibrated for the isotropic condition. In the next step, the investigated anisotropy of hydraulic conductivity was applied to the model. After this operation, the quality of the calibration remained at the same level and differences in the elevations of the water tables were less than 0.5 m. Scenarios of safe yield were tested using the model for isotropic conditions. The value of safe water depletion was investigated in detail, taking many aspects into account; however, its description is not the goal of this paper and for this reason it is omitted. After the estimation of the safe yield for all the wells, the new water table elevation was obtained in the isotropic model (Text-fig. 6). The same values of water rates were applied to the model of anisotropic conditions. The main goal of the new simulation was to analyse how the application of anisotropy would affect the water table and well capture zones for prognostic simulations of safe yield.

For this reason, the water tables for safe yield were compared and a map of the differences between them was drawn (Text-fig. 6). This map allows the area of the Opole–Zawadzkie MGB to be divided into two sub-regions: south and north.

In the south sub-region a relative increase in the height of the water table of about 0.5–2.0 m can be observed. Lowering of the water table is noted in the north sub-region and is much less intense, locally achieving 1.5 m. The decrease in the elevation of the water table is typical of regions of large intake with extensive depressions. The results obtained prove that two prognoses are given for safe yield, that is, for anisotropic and isotropic conditions. The observed changes can be attributed to different azimuths of anisotropy. Lower hydraulic conductivity in the N–S direction results in the limitation of flow from the recharge area in the south.

The reduction of depression in the proximity of well fields (Text-fig. 6) suggests that safe yield assessed for the isotropic conditions model (M1) is no longer valid for the new, anisotropic conditions model (M2). For the M2 model, new well rates were applied, which guaranteed the water table elevation characterized for safe yield. The general total rate of water exploitation was reduced from 110,000 $m^3 \cdot d^{-1}$ to 98,000 $m^3 \cdot d^{-1}$, which is 11% less.

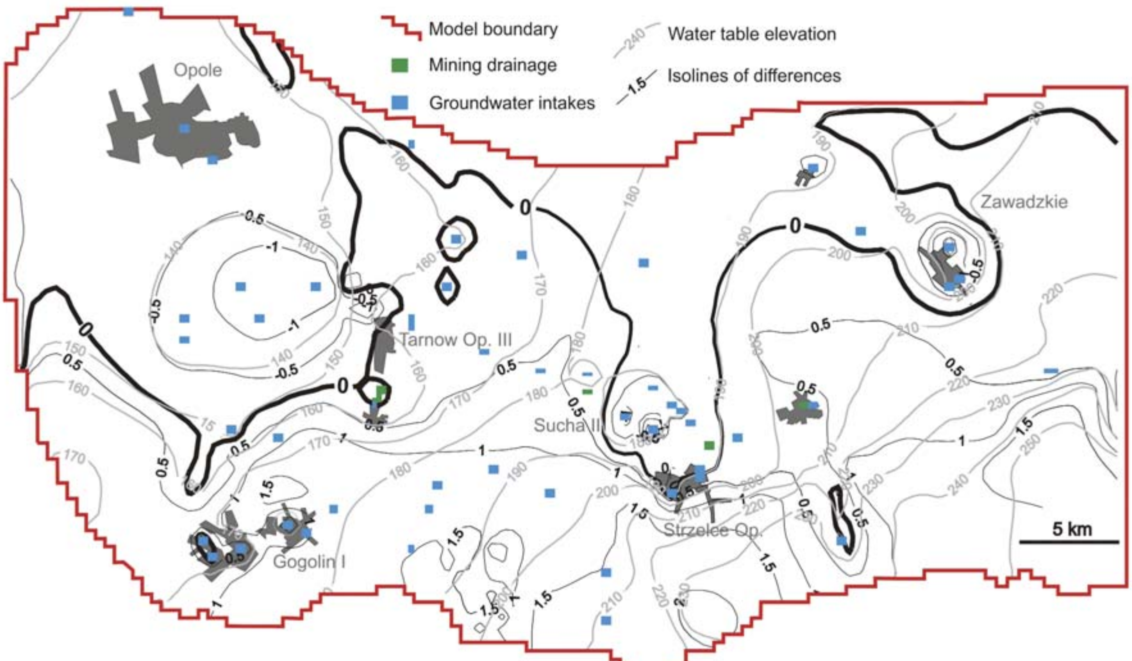
CONCLUSIONS

The results of the investigations described in this paper allow conclusions to be drawn concerning the role of horizontal anisotropy in regional groundwater flow patterns in the karstic aquifer of the Opole–Zawadzkie MGB. Observations at many scales provide evidence of a significant level of anisotropy of hydraulic conductivity ($A = kx/ky = 1.3 \div 2.0$).

The magnitude and direction of anisotropy assessed from fracture orientation in outcrops was confirmed on a regional scale in the analysis of specific capacity distribution.

Different results obtained on a micro-scale remain in accordance with the opinion that fractures and channel network development are determined mainly by tectonic background, and to a lesser extent by lithology and sedimentary processes (Motyka 1998).

Testing of anisotropy by the regional groundwater model indicates that the anisotropy value exerts a significant influence on water table prognosis. Increases in the elevation of the water table were observed in



Text-fig. 6. Map to show differences in water table position for safe yield (Q-110000 $m^3 \times d^{-1}$) for the M1 and M2 models recharge areas, while decreases characterized drainage zones.

Safe yield assessment was modified after anisotropy was introduced into the model. Ignorance of horizontal anisotropy of hydraulic conductivity leads to a significant error in safe yield approximation for the Opole–Zawadzkie MGB (ca 11%).

The presented results indicate that anisotropy of hydraulic conductivity should be considered as an important factor that determines regional groundwater resources.

REFERENCES

Chiles, J.P. and Delfiner, P. 1999. Geostatistics: modeling spatial uncertainty, pp. 1–734. Wiley; New York.

Choquette, P.W. and Pary, L.C. 1970. Geological nomenclature and classification of porosity in sedimentary carbonates. *AAPG Bulletin*, **54**, 207–250.

De Marsily, G. and Delay, F. 2005. Dealing with spatial heterogeneity. *Hydrogeology Journal*, **12**, 161–183.

Jaquet, O., Siegel, P., Klubertanz, G. and Benabderrhamane, H. 2004. Stochastic discrete model of karstic networks. *Advances in Water Resources*, **27**, 751–760.

Kołaczkowski, M., Kryza, J. and Raczmański, J. 1980. The hydrogeological documentation of groundwater intake located in Mushelkalk sediments together with the research project of groundwater resources (category B and C) of Opole – Grotowice – Utrata intakes for Municipal Water Service in Opole. Central Geological Archive, Warsaw. [In Polish]

Kryza, J. 2001. Numerical model of Opole Triassic region. In: T. Bocheńska and S. Staśko (Eds), Współczesne Problemy Hydrogeologii, tom 2. Wydawnictwo Sudety, Wrocław, pp. 363–378. [In Polish with English summary]

Kryza, J. and Staśko, S. 2000. Groundwater flow rate and contaminant migration in fissure – karstic aquifer of Opole Triassic System due to man activity. *Environmental Geology*, **39**, 384–389.

Macpherson, G.L. 1983. Regional trends in transmissivity and hydraulic conductivity, Lower Cretaceous sands, north-central Texas. *Ground Water*, **21**, 577–583.

McDonald, M.G. and Harbaugh, A.W. 1988. A modular three –dimensional finite-difference ground –water flow model In: Techniques of Water-Resources Investigations of the United States Geological Survey, Denver, pp. 1–586.

Motyka, J. 1998. A conceptual model of hydraulic network in carbonate rocks, illustrated by examples from Poland. *Hydrogeology Journal*, **6**, 469–482.

Motyka, J. 2005. The documentation defining hydrogeological conditions in connection with the exploitation and influence of dewatering of Triassic limestones deposit in Tarnów Opolski on the environment. Central Geological Archive, Warsaw. [In Polish]

Staśko, S. 1992. Groundwater in carbonate Triassic rocks in Opole region. *Prace Geologiczno-Mineralogiczne*, **32**, 1–74. [In Polish with English and Russian summaries]

White, W. 2002. Karst hydrology: recent developments and open questions. *Engineering Geology*, **65**, 85–105.

Wojewoda, J. 1983. Water flow anisotropy in carbonate rocks from Opole region - attempt to explain. Proceedings of National Symposium. Modern Problems of Regional Hydrogeology, Lądek Zdrój, pp. 184–191. [In Polish]

Zalewska, M., Bieroński, J., Kempiński, G., Panek, D., Wojciechowicz, D., Bajcar, D. Wcisło., M. Szyszkowska B. and Szyszkowski P. 2006. The hydrogeological documentation of disposable resources of groundwater in the Kłodnica river catchment. Central Geological Archive, Warsaw. [In Polish]

Zimmerman, D., De Marsily, G., Gotaway, C., Marietta, M., Axness, C., Beauheim, R., Bras, R., Carrera, J., Dagan, G., Davies, P., Gallegos, D., Galli, A., Gomez-Hernandez, J., Grindrod, P., Gutjahr, A., Kitanidis, P., Lavenue, A., McLaughlin, D., Neuman, S., Ramarao, B., Ravenne, C. and Rubin, Y. 1998. A comparison of seven geostatistically-based inverse approaches to estimate transmissivities for modeling advective transport by groundwater flow. *Water Resources Research*, **34,** 1373–1413.

Manuscript submitted: 25th August 2013
Revised version accepted: 25th April 2014