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Groundwater and mass transport modelling for documentation and protection of groundwater resources

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Abstract. Short history of mathematical modeling of groundwater flow and transport in Poland is described. It shows brilliant and long tradition of this advanced aspect of hydrogeology. Mathematical modeling has been extensively used in Poland for years in solving practical problems concerning mainly groundwater abstraction, protection of groundwater resources and, recently, as a routine tool for environmental impact assessment whenever groundwater is involved. Use of numerical models in documenting groundwater resources and conditions of their restoration within regional water balance units are recalled. In particular – documenting admissible volumes of groundwater to be abstracted including wells operating in river valleys, determining protection zones for water supply wells and groundwater reservoirs, in particular for major groundwater basins (in Polish: GZWP), investigating optimal ways of abstracting fresh groundwater in areas where mineral waters occur, investigating alternative groundwater sources for supplying large agglomerations. Three examples: defining changes in groundwater chemical composition in conditions of intensive anthropogenic stress on the environment – impact from urban and industrial waste landfills, agriculture, transportation and municipal facilities on groundwater; coexistence of fresh and mineral waters and, finally, quantitative assessments of impacts from open-pit mines on groundwater in the mining stricken area are described in more detail. Last paragraph of the paper is a future looking assessment of aspects of mathematical modeling in Polish hydrogeology that need to be further developed. The aspects concern scientific issues like: scale problem, inverse problems and chemical reactions in subsoil. Also a need of developing specialized software, setting hardware infrastructure and training staff are addressed as the necessary conditions for keeping pace with world's hydrogeology.

Keywords: *mathematical modeling, groundwater flow, mass transport in groundwater, groundwater protection, groundwater abstraction, documentation of water resources*

Numerical modelling methods have been used in Poland for many years for solving various practical hydrogeological problems. Numerical models became an indispensable tool used for designing groundwater supplies; investigations and calculations of interactions between surface waters and groundwater; water balance calculations; determination of impacts resulting from groundwater abstractions by public utilities and mining; assessing volume and dynamics of groundwater resources; impact assessment of engineering structures and other forms of anthropogenic activities at the soil surface and subsoil on the groundwater environment. In particular, mathematical modelling methods have been used in Poland for numerous investigations and calculations regarding:

- documenting groundwater resources and conditions of their restoration within regional water balance units;
- documenting admissible volumes of groundwater to be abstracted including wells operating in river valleys;
- determining protection zones for individual large water supply wells and groundwater reservoirs, in particular for major groundwater basins (in Polish: GZWP);
- investigating optimal ways of abstracting fresh groundwater in areas where mineral waters occur;
- investigating alternative groundwater sources for supplying large agglomerations;
- defining changes in groundwater chemical composition in conditions of intensive anthropogenic stress on the environment – impact from urban and industrial waste landfills, agriculture, transportation and municipal facilities on groundwater;
- quantitative assessments of impacts from deep and open-pit mines on groundwater and surface waters;
- investigating processes of groundwater discharge to the Baltic Sea.

Below we present selected examples of case studies in which numerical modelling played a key role in solving important issues related to the protection of groundwater resources in Poland.

Mathematical modelling of groundwater resources from glorious history to the demanding present day

In Poland, conformity of hydrogeological documentations with national regulations is exercised by the Commission for Hydrogeological Documentations, which is a state authority established in 1955 and acting to present times, i.e. for the last 55 years. There are only a few similar bodies in the geological services all over the world. The commission consists of professional hydrogeologists appointed from two groups, i.e. academics and highly competent practitioners.

Historically, rules for documenting groundwater resources in Poland were collected in two important and overlapping acts of 1960, namely in the *Geological Act*, which governs the rules for prospecting, recognition and partially also for exploitation of groundwater resources and in the *Council of Ministers Resolution No. 29*, which binds investment activities related to intake of groundwater with the degree of their recognition and requirements regarding their documentation. In the following years, an increasing demand for groundwater abstractions to meet the needs of

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developing urban, rural and agricultural areas as well as new industrial plants had brought an urgent need for developing field investigation and calculation methods for defining groundwater resources. Problems occurred with documentations requiring consideration of interoperable multiple wells (well fields); supply wells drawing waters from complex hydrogeological conditions; defining and computing water balances incorporating all recharge inputs and with the development of qualitative and quantitative forecasts for resources. In this respect, development and use of mathematical modelling methods for evaluation of groundwater flow and water balance proved to be very helpful. The beginning of the practical use of numerical modelling in the 60s was primarily due to a demand for forecasting for mining needs, specifically for draining of open-pit mines. Application of mathematical modelling for documenting admissible volumes of extracted groundwater for water supply wells started in 1965.

In the first phase of the development of mathematical modelling methods in hydrogeology, the key role was played by analogue equipment (discrete models – hydraulic integrators, electrical integrators – mesh, continuous models – AEHD using electro conducting paper and electrolytic baths). In 1972, a national symposium was held in Poznań, which concerned the usability of analogue models to model filtration conditions in areas of water supply wells, during which a publication containing results of tests from seven large groundwater supplies studied between 1966–1970 was presented (Brylska et al., 1972). The 70s brought continuous development of modelling techniques (Auer, 1976) and a substantial amount of hydrogeological documentation occurred in which these techniques and procedures were successfully applied for quantification of groundwater supplies (Flisowski & Wieczysty, 1979). However, in parallel to that and increasingly, a tendency to develop numerical modelling appeared. This was first reflected in Wieczysty (1970) and then a special section regarding numerical methods (Pazdro, 1977) in the national engineering hydrogeology and general hydrogeology books appeared. An important and inspiring role in this was played by publications by Szymanko (1972) and Macioszczyk (1973). In those times *Przedsiębiorstwo Hydrogeologiczne* from Poznań received permission to translate a French handbook by Emsellem (1971 – *Construction de modeles mathematiques en hydrogeologie*). The publication was published in Polish in 1975, translated by Rogoż and edited by Dąbrowska, Dąbrowski and Sachy (Emsellem, 1975).

An important moment in the application of numerical models in Polish hydrogeology by academia and in practice was the introduction by the Central Office of Geology of a research paper titled: *Determination of IT system for hydrogeological assessments with a specific focus on prognoses of groundwater resources*. Within the framework of the project, a library of numerical programmes called HYDRYLIB was created (Dąbrowski, 1978), and its first publications were published in print in 1977. With an increasing access to PCs, programmes of the HYDRYLIB library were quickly incorporated into the modern technological applications. The HYDRYLIB library consists of a group of computer programmes intended for groundwater flow simulations, which allow researchers to undertake identifications and prognoses with respect to quantification of groundwater resources on regional scales as well as water supplies of single or multiple water layering systems. The library was a magnificent achievement on the European and the worldwide scale and it can be said that it preceded, in time and in its quality, computer programmes offered by the major IT corporations, as the first documentation by the U.S. Geological Survey, which developed the most common application used for groundwater modelling – MODFLOW, was published in 1988 (McDonald & Harbaugh, 1988).

As shown in statistics of Polish hydrogeological publications (Felkel & Kasztelan, 2006), the majority of programmes used in practical and academic applications in the last ten years of the past century, were programmes from the HYDRYLIB library list (among others: Przybyłek & Ryszkowska, 1989; Kowalczyk & Rubin, 1995; Haładus et al., 1995; Dąbrowski et al., 1999 and many other publications). In parallel, starting from 1994, publications regarding application of the MODFLOW package used for examining groundwater flows, balancing groundwater resources as well as mass transfer modelling (Duda et al., 1997) started to appear in Polish literature. In the past decade (2001–2010), a definite increase in publications showing results of modelling using other programmes offered by *Waterloo Hydrogeologic Inc.*, *Environmental Modelling Systems Inc.*, *Danish Hydraulic Institute – Water Environment* has been noted. This is related to the development of user friendly interfaces.

Rules for determining admissive volumes of groundwater resources using mathematical modelling have been incorporated into methodological guidance, which was developed by the order of the Minister of the Environment (Dąbrowski et al., 2004a), and for academic needs a textbook titled *Modelling of filtration processes* by Kulma and Zdechlik was published in 2009.

Generally, in Polish practice, hydrogeological modelling of mass transfer in groundwater has been induced by the need of protecting national groundwater resources against pollution, whose primary source lies in anthropogenic activities. In situations requiring legal intervention (environmental protection) or in relation to the existence of a direct or potential risk to the quality of groundwater resources, Polish hydrogeologists usually employ the most modern commercial numerical models available on the market.

Modern groundwater flow models discussed in this overview (e.g. MODFLOW) have appropriate *overlays* which allow the designation of areas and concentrations of contaminants being modelled. Issues of mass transport modelling within a groundwater flow stream and in substantially heterogeneous rocks is, however, far more complex than modelling of groundwater flow itself. In the last chapter of this article, a group of issues and modelling aspects that still wait for theoretical solutions is discussed. Most of these problems are known to hydrogeologists worldwide and there is a general agreement that the currently available numerical models for mass transport processes in groundwater should be treated as the *first approximation* only. Examples of the usability of numerical models in Polish hydrogeology are discussed below and the focus of this work is on modelling of groundwater flows. In this field, Poland represents a good European level and has significant achievements (Fig. 1).

Example 1. Calculating groundwater resources in terms of regional resources and designation of protection zones for Major Groundwater Basins – GZWP

The purpose of these modelling tests was to establish the dynamics and the amount of disposable resources of the major groundwater basin GZWP 333 (called: Triassic of Opole Region), and to define the extent of its protection

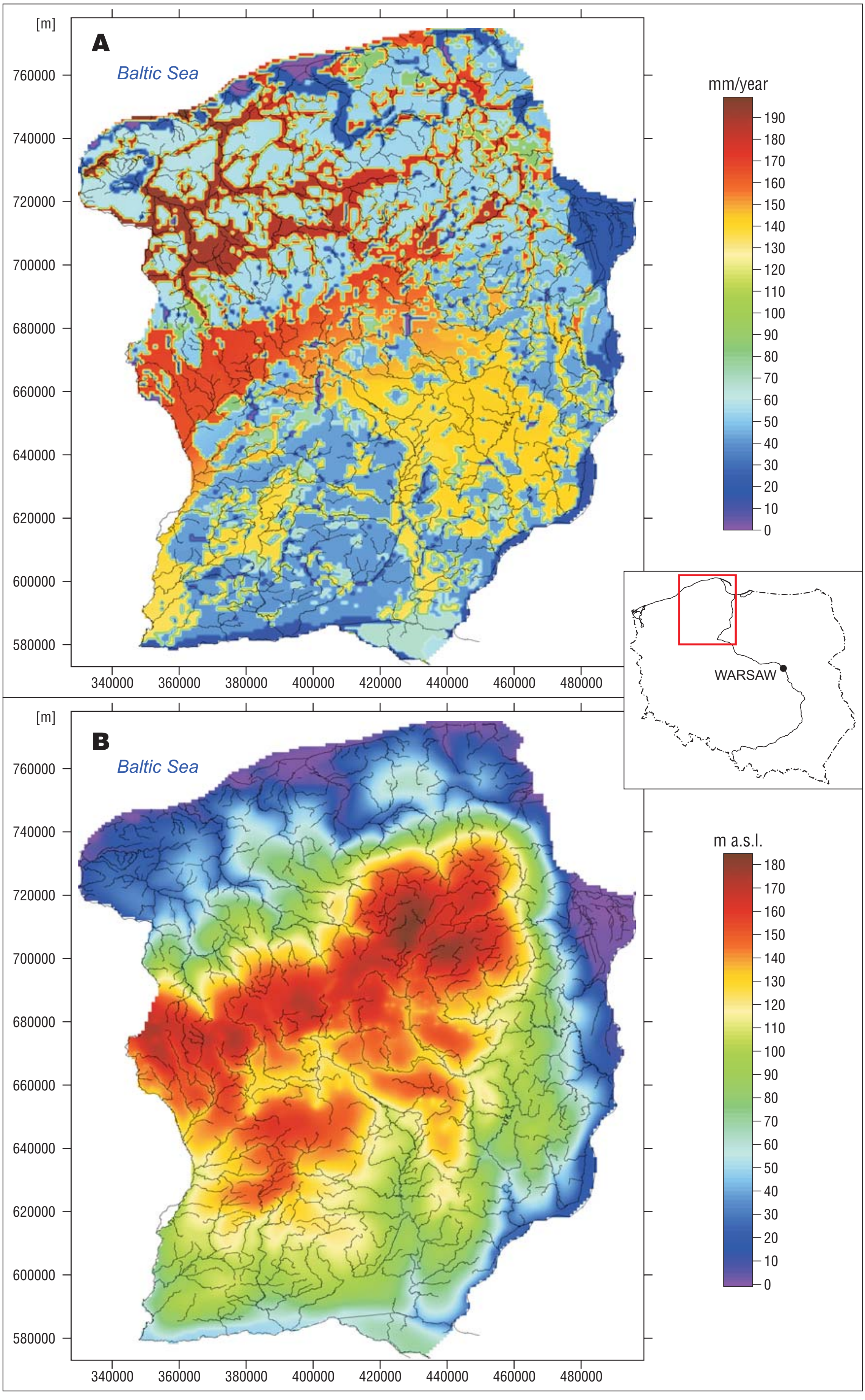

Fig. 1. Regional model of groundwater flow for east part of the Pomerania Lakeland (Śmietański & Lidzbarski, unpublished); **A** – groundwater recharge, **B** – piezometric surface of Quaternary aquifer

zone. This is a basis for defining the principles of sustainable use of water resources and the numerical modelling method is recommended for this type of research (Paczyński et al., 1996). The numerical model of the basin was created using the MODFLOW package (McDonald & Harbaugh, 1988). The modelled hydrogeological system had an area of 1401.8 km^2 and was characterised by a high degree of complexity in hydrogeological conditions. The model of the groundwater reservoir comprised three aquifers and two isolating layers. The upper layer consisted of Quaternary and Cretaceous sediments, the middle, limestones and dolomites of the Middle Triassic age, and the lower one, sediments of the Perm and Lower Triassic ages. The upper and the lower aquifers showed relatively stable hydrogeological parameters while the middle layer was heterogeneous.

The karst-fissured aquifer showed high instability of parameters with well yields ranging from 10 to 246 m^3/h (Staśko, 1992; Kryza & Staśko, 2000), thus it was accepted to use models described by Motyka (1998) and Bakalovic (2005). There are over 30 groundwater intakes in the study area, including one that supplies water to Opole city. There are numerous open-pit mines operating in the southern parts of the reservoir, in the area where limestone bedrock crops out. Exploitation of limestone is accompanied by groundwater drainage. Groundwater inflow to the mines is high and ranges from 10 000 to 65 000 m^3/d. Pumping of groundwater induces steep cones of depressions having limited impacts. The water exchange time within the limestone outcrop area, determined by isotopic methods, is short and ranges from 10 to 25 years, in the central zone it ranges from 25 to 100 years and in the northern parts it reaches the age of thousands of years. The basic materials for constructing a numerical model of the basin included data from Bank HYDRO, information from hydrogeological maps and numerous data collected during field investigations. For constructing the model, water level data from groundwater observation and measuring points as well as surface water level from rivers and lakes were used (Anderson & Woessner, 1991). From over 300 well records, data from 198 pumping tests and drilling tests were analysed in detail.

High drainage of the Triassic aquifer within mining areas resulted in a great calculation instability and in a prolonged iterative calibration process. Work on the model posed difficulties in reflecting strongly concentrated karstic flows and extremely high recharge to the mines. To reflect the complexity of flows in the preferential flow zones, a stochastic approach was taken (Berkowitz, 2002).

Generally, a zone decrease of disposable resources was observed in the model which included preferable flow zones (Fig. 2). One of the conclusions of the demonstrated approach was that ignoring heterogeneity can lead to overestimation of disposable resources (Staśko & Wcisło, 2008).

Example 2. Coexistence of fresh and mineral waters

The objective of modelling in this case was determination of renewable and disposable resources of mineral waters used for therapeutic purposes and fresh waters in Tylicz in the Carpathians. It was important to establish the principles of sustainable use of ordinary (fresh) waters so that their exploitation did not interfere with resources of mineral waters. An important aspect was to recognize the hydrodynamics of the mixing mechanism of fresh and mineral waters. A numerical model was created using the Visual MODFLOW model. The model's boundaries were defined using the topographical surface water divides. In structuring of the model and its calibration, a prominent role was played by data from over 420 springs and 15 hydrogeological bores reaching up to 125 m depth. To calibrate the model, hydrometric measurements from major rivers and streams were used. In order to render hydrogeological conditions, seven layers with decreasing values

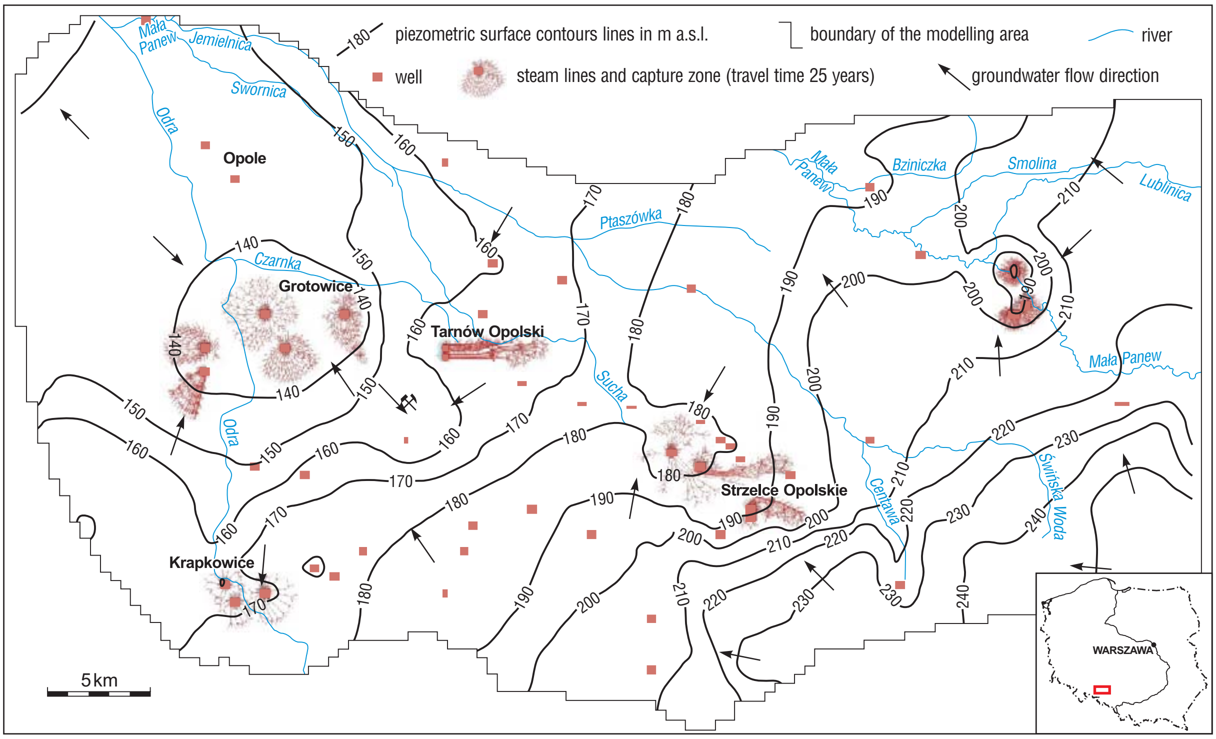

Fig. 2. Calculated contour map of the piezometric surface in Triassic aquifer in the Opole area (Lower Silesia) and selected capture zones under exploitation condition 106 000 m^3/d

of permeability from 1.3×10^{-7} to 2.3×10^{-11} m/s were defined. Hydraulic conductivity of fissure-pore layers that was obtained from modelling ranged from 1.25×10^{-9} to 1.13×10^{-4} m/s (Jetel, 1986; Nałęcki et al., 2004).

Intensity of water exchange was decreasing with depth, but distribution of pressure resulting from morphological diversification of the terrain showed the potential for water exchange also at greater depths reaching even 1500 m (Witczak & Duńczyk, 2004). The complicated layout of flysch deposits, involved tectonically, were defined by a deterministic model analogous to a porous model. This approach stems from limitations with the current state of poor identification of hydrogeological conditions.

Groups of small fissures were treated as a porous rock whereas larger tectonic structures were defined as zones with increased or reduced and often isotropic hydraulic conductivities. A similar approach was applied when documenting the adjacent groundwater basin of *Kryniczanka*.

The best infiltration properties were determined in tectonic zones, where increased hydraulic conductivity in directions parallel to slopes were determined, while in the perpendicular zones they were lower by one degree of magnitude. It was assumed that water movement within the upper, more fissured flysch layers was in hydraulic continuity with the underlying layer of less fissured rocks.

Restrictions of the MODFLOW model related to changes in thickness, permeability and dimensions of modelling blocks created a difficulty to precisely model the discontinuous and highly heterogeneous water bearing horizons. Therefore, on a regional scale, it was not possible to precisely map the actual composition of the hydrogeological system of flysch. Nevertheless, it was possible to establish (on a regional catchment scale) the dynamics and the amount of disposable resources, which is helpful for the proper management of normal waters.

Example 3. Application of groundwater modelling in deep mining

Numerical modelling of the copper mines in SW Poland has a long history and started in 1975. The first models of the Lubin-Głogów Copper Region (LGOM) recognised and analysed the existence of 1 up to 4 layers. They relied on programs written by Fiszer and their purpose was to forecast groundwater inflow volumes to the mines. In 1996, the MODFLOW program was introduced which allowed the modelling of groundwater circulation inside mines. As a result of this work, nine numerical models were developed, with varying accuracies, which forecast groundwater inflows and the extent of cones of depressions for individual mines or mining areas (Fiszer, 2003, 2005). Characterisation of hydrogeological conditions identified in the multi layered water bearing horizons and isolating layers between them were described, *inter alia*, in the work of Bocheńska (1988, 2003), Bocheńska et al. (1995, 2000), Becker et al. (2007) and Kleczkowski et al. (2007). As a result of this work, groundwater inflows into areas proposed for mining in the future were established and the impact of dewatering on adjacent groundwater dependent terrestrial ecosystems was assessed. Numerical modelling methods have become an important assessment method for conducting safe exploitation of copper.

The currently modelled area covers 2500 km^2; the modelled system reaches a depth of 1200 m and comprises nine layers. The most advanced and modern modelling package of the GMS was used for this modelling. The scope of modelling is much wider than normal and includes most of the natural and artificial barriers and boundaries within the system. Further hydrogeological aspects of the LGOM system are also discussed in work by Kowalczyk and others of this volume.

Example 4. An integrated information system for the protection of groundwater within open pit mining areas

One of the adverse effects of mining operations is the lowering of groundwater level in the vicinity of pits. Generally, the decline of groundwater in the vicinity of open pit mines is caused by intensive dewatering of excavations and municipal water consumption by wells. In such situations, entities seeking permits for abstraction of groundwater resources (e.g. food industry, pharmaceutical holdings, agricultural farms), may face refusal by local authorities. When groundwater resources are close to exhaustion, local authorities may reduce the already permitted abstraction rates through a permit renewal process.

In the area of coal mines in Konin District (Fig. 3), shared use of groundwater resources causes a number of conflicts. A solution to the problems was a prototype of a Decision Support System (DSS) proposed by the Warsaw University of Technology (Nawalany et al., 2003). It is an integrated set of IT tools, whose function is to minimize the number of conflicting situations, resulting from decisions made by private users and regional state managers of groundwater resources. For example, in the area of lignite mines in the vicinity of Konin, sharing of groundwater resources results in two major types of conflicts with dissimilar character:

- ❏ a conflict between the Brown Coal Mines (KWB) and the local governor's office in Konin (US) regarding protection of the environment, specifically lakes and water resources,
- ❏ a conflict between the Brown Coal Mines (KWB) and the local communities regarding the common use of water resources and damage caused by mining operations.

The basic idea behind creating the DSS was an assumption that an agreement between parties of various conflicts can be, nonetheless, achieved once the main obstacles are removed, as follows:

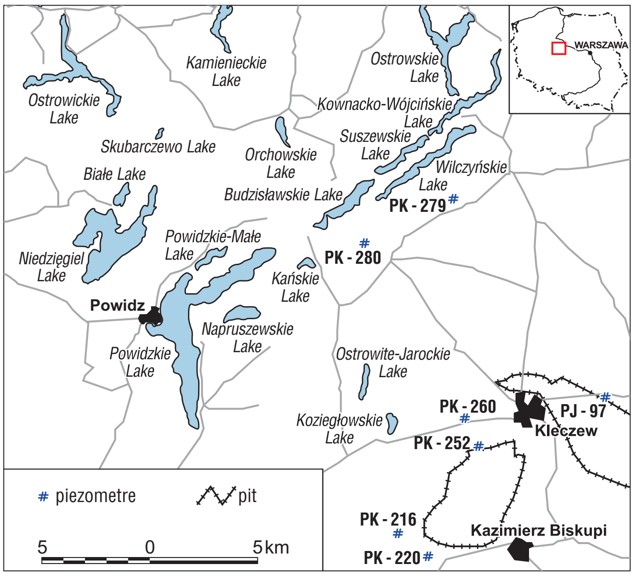

Fig. 3. Location of open pits of Brown Coal Mines (KWB) in Konin District and lakes in the vicinity of open pits (situation in 2003)

- lack of the common knowledge within the Brown Coal Mines and the governor's office regarding regional hydrogeological conditions and the lack of exchange of information between the two institutions;
- lack of tools approved by both institutions used for predicting losses and benefits of deploying some solutions for the management of water resources by both the mine and the governor's office; and finally
- unwillingness to take collective decisions regarding the local water management issue, which results primarily from various criteria used by the two institutions.

The decision support system was developed using the latest generation of GIS programmes. The DSS uses a graphical interface and data collection and processing systems with a spatial resolution, as available in GIS. In addition, the DSS model has a regional, two-dimensional, numerical groundwater flow model (MODFLOW) together with relevant GIS procedures for analysing the modelling results. Apart from that, the DSS allows the creation of reports and figures directly from the DSS.

Figure 4 shows the schematic organisation of the DSS structure. The system consists of programs and procedures forming interrelated modules, the most important of which are:

- interface for intercommunication between the program and a user;
- inter-related databases – a collection of tables and maps containing information about water resources, topography, land use, weather, etc. in the region of open pit coal mines in Konin. In addition to storing historical data, the database is capable of storing temporary information, such as for example, modelled hydroizohips which are plotted on maps; a database of applications containing programs that process information stored in particular databases and information supplied by a user during his communication with the DSS to determine parameters which are necessary to run algorithms of the decision-making process. The most important procedures include programs of the decision support system, GIS and the mathematical model together with tools for modelling and analysing the modelling results;
- results module, which is responsible for a neat presentation of the results of decision-making algorithms e.g. in the form of maps, charts, tables and reports.

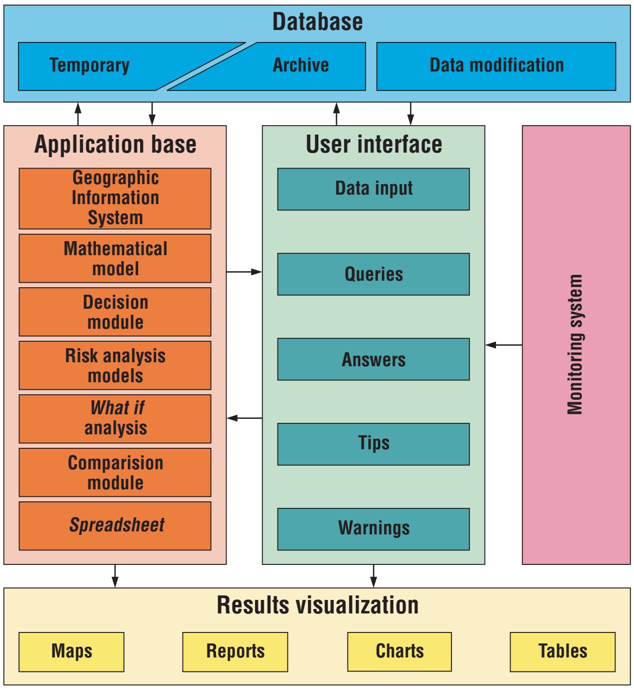

Fig. 4. Schematic organisation of the Decision Support System for water management in the vicinity of open pit mines (Kochanek, unpublished)

Since the individual stages of the decision-making process are organised in a specific order, the menu of the DSS is designed to reflect the subsequent steps in the process of resolving a problematic situation. To this end, all procedures are grouped according to their functions and are gathered in the main menu of the interface in four expandable lists:

- data – tools for creating, editing and presenting input data and modelling simulations gathered in the DSS database;
- scenarios – procedures for creating and editing scenarios used in mathematical modelling of groundwater flows;
- decision analysis – programs used in analysing results of the mathematical modelling;
- risk analysis – tools allowing the calculating of risks associated with the decision-making process.

Analysis of the decision-making process regarding water management involves numerical simulations of numerous scenarios representing different variants of groundwater exploitation within the mines' regions. A decision-maker obtains information on probable losses or benefits which will happen by application of a given solution in practice (analysis of the *what if*? type). For analysis of the *what if?* type, decision support systems are usually equipped with one or several mathematical models (e.g. a model that simulates steady state conditions and a model simulating a transitional state) and processors which help to prepare data for numerical simulations. The number of combinations between pits moving in time and space; mathematical models and recharge scenarios gives the applied DSS a choice of many potential situations that could potentially occur in nature. These are a function of the way nature works (recharge) and the planned mining operations (movement of pits in time), as well as availability of several different numerical models (e.g. steady-state and unsteady-state models). A decision-maker cannot create data regarding recharge and movement of pits; however, he has complete freedom to create, from scratch, his own groundwater abstraction scenarios to be used in computer simulations (locating and establishing abstraction rates for wells). When a scenario analysis of *what if?* is ready, a decision-maker can run a mathematical model directly from the DSS.

The result of the DSS is a useful interpretation of results obtained by numerical modelling for the analyzed scenario involving a feasibility analysis of the *what if?* type; a sensitivity analysis for the aquatic environment with respect to changing hydrogeological parameters and changing input data for a model; a risk analysis as well as a visual analysis in the form of a map, showing hydraulic heads in areas under the influence of mining activities. The DSS has significant capabilities of spatial data analysis in both vector and raster form. The DSS platform has a built-in calculator for maps, tools allowing the creating and editing of vector layers as well as mapping layouts allowing printing in any size.

The future of the hydrogeological modelling

Over the past decade, Polish hydrogeology has undergone rapid transformation induced by a technological development enabling fast and reliable processing of large amounts of information about systems, structures, natural processes and anthropogenic impacts on the groundwater environment. Documenting and forecasting of groundwater resources dynamics, the exploitation and protection of groundwater reservoirs in Poland are being exercised by numerous research institutes, universities and companies that apply modern hydrogeological instruments and IT tools. The most modern databases, geographical information systems, numerical models, and software packages used for interpretation and visualization of measured and computed data are extensively applied. From the perspective of the progress made so far (and still being made) in the field of making Polish hydrogeology IT-oriented, it can be clearly stated that Polish hydrogeological institutions are already (or will soon become) equal and valuable partners for similar institutions in Europe. Achievements in the field of mathematical modelling of water flow in fissure and sedimentary rocks as well as of mass transport (groundwater pollution) modelling are on solid levels. Two major and recurring Polish conferences in this area – the *Groundwater Flow Modelling* and the *Current Challenges in Hydrogeology* – show considerable progress in this domain. Four basic classes of studies related to mathematical modelling in hydrogeology have clearly developed. These are: studies on water filtration models in rocks and drift deposits; studies on mass transport models (groundwater pollution); studies on groundwater resources models and studies on models regarding interaction between groundwater and groundwater dependent terrestrial ecosystems.

Modelling becomes an important tool in the decision-making process used in water resources planning, remediation of contaminated aquifers (e.g. Nemeček et al., 1995; Nawalany, 1995b, c) and in integrated river basin management. Generally, all mainstream hydrogeological studies carried out in Poland use numerical models and all serve objectives of the EU *Water Framework Directive* (2000/60/EC). A review of works published and presented at conferences in recent years by Polish hydrogeologists leads to the conclusions that can be summarized as follows:

- ❏ extensive research needs to be undertaken in the field of mathematical modelling in directions specified by the world's science (see below);
- ❏ human resources with high skills must be even more developed and supported;
- ❏ appropriate financial means need to support upgrading computing infrastructure for Polish hydrogeology.

Requirements of the EU *Water Framework Directive* to achieve good status of groundwater by 2015 and then to maintain this status means that obtaining information about the status of waters (groundwater monitoring) and then processing the measured data (mathematical models) for proper exploitation of groundwater will require models that will include three-dimensional (3D) nature of flows in strongly heterogeneous rocks. Also, surface and groundwater interactions, which are intrinsically 3D, should be modelled using 3D models, (e.g. Nawalany, 1993). The required computational effort for 3D modelling describing groundwater flow and mass transport (of groundwater contaminants) in realistic heterogeneous rocks greatly exceeds the calculation capacities of commonly available PCs. Although, at present, cheap and user-friendly software for hydrogeological mathematical modelling (MODFLOW, FEFLOW etc.), is easily accessible on the market (Diersch et al., 2005), this situation will not last long; the future definitely belongs to 3D models with high requirements for number crunching and pre- and post-data processing.

Academic centres and geology-oriented institutions which undertake research in hydrogeology in Poland, have already developed good hardware facilities, gathered accessible software and educated highly motivated young staff and are in the process of switching to advanced *methods of numerical computing* and data processing techniques in groundwater modelling. The driving force is, in many instances, the *Water Framework Directive*. For instance, the WFD requires monitoring of groundwater parameters, which have not been routinely monitored so far. Many of them are substances whose densities are different from the specific weight of water (petroleum substances, tri- and tetra-chloroethane). Interpretation of monitoring data with respect to these substances requires using numerical models of density flows. So far, only a small group of Polish hydrogeologists have applied numerical models describing such flows. A separate issue, also under the general philosophy of the *Water Framework Directive*, regards the ecology of groundwater dependent terrestrial ecosystems. Examples of these are wetland ecosystems and the entire area of agricultural issues. In both cases, the assessment of the vertical component of groundwater flow and mass transfer is a considerable challenge for professionals specialising in the hydrogeological numerical modelling (Nawalany, 1987, 1989; Zijl & Nawalany, 2004; Getchachew, 2009).

A research field which still requires more research in Polish hydrogeological mathematical modelling is the issue of scale (Nawalany, 1999). Especially in (what is considered a well researched area in hydrogeology) the processes of sorption and chemical reactions of substances moving together with water in porous rocks, identification of the appropriate scale and the right sorption or chemical reaction model is crucial for interpretation of the modelled processes (Szymkiewicz, 2004; Nawalany, 2008). Another research field open to Polish hydrogeology is the entire area of inverse hydrogeology i.e. identification of hydrogeological parameters (e.g. Sinicyn, 1998; Małecki et al., 2006), estimation of groundwater recharge (e.g. Nawalany & Stachurski, 2005), estimation of initial conditions (Nawalany, 1995a) or determination of reverse trajectories (Zijl & Nawalany, 1993). There is also an issue that rarely occurs in the Polish hydrogeological modelling – the mathematical modelling of groundwater flow in nonstationary subsoil systems.

In conclusion, it should be noted that when it comes to practical aspects of mathematical modelling, Polish hydrogeology follows worldwide standards and represents a good level. However, some theoretical issues, such as, for example, the issue of scale, reverse modelling, non-stationary subsoil systems, density flows, do occur rather rarely in the Polish mathematical modelling. Also, indissociable from groundwater flow modelling, numerical aspects of the 3D groundwater flow and mass transport, the requirement of high accuracy vertical flow modelling and, resulting from mineralogical heterogeneity of rocks, numerical models describing aspects of sorption and chemical reactions are just being tackled by Polish researchers. These issues are serious challenges for Polish hydrogeology and set high academic and organisation standards for the nearest future but... also offer good prospects for international research collaboration with Poland.

References

ANDRESON M.P. & WOESSNER W.W. 1991 – Applied groundwater modelling. Academic Press Inc. New York.

AUER A. 1976 – Analogue modelling of processes of distributed constants [in Polish]. PWN, Warszawa.

BAKALOVIC M. 2005 – Karst groundwater: a challenge for new resources. Hydrogeol. Journ., 13: 148–160.

BECKER R., FISZER J. & KALISZ M. 2007 – Hydrogeology [in Polish]. [In:] Monografia KGHM Polska Miedź S.A. Wyd. KGHM Cuprum, Wrocław: 82–90.

BERKOWITZ B. 2002 – Characterizing flow and transport in fractured geological media: A review. Advances in Water Resources, 25: 861–884.

BOCHEŃSKA T. 1988 – The development of hydrodynamic conditions in the Lubin-Głogów copper-bearing area due to mine dewatering [in Polish]. Acta Univ. Wratisl. Pr. Geol.-Miner., 14: 1–148.

BOCHEŃSKA T. 2003 – The hydrogeology of mineral deposits and water problems of copper mining. Fore-Sudetic Monocline [in Polish]. [In:] Hydrogeologia polskich złóż kopalin i problemy wodne górnictwa, 2: 20–56. Wyd. AGH, Kraków.

BOCHEŃSKA T., FISZER J. & KALISZ M. 2000 – Prediction of groundwater inflow into copper mines of the Lubin-Głogów Copper District. Environ. Geol., 6: 587–594.

BOCHEŃSKA T., LIMISIEWICZ P. & POPRAWSKI L. 1995 – Long-term changes in the shallow water table in a mining area: The Lubin-Glogow Copper Region, Southwestern Poland. Hydrogeol. Journ., 3: 41–52.

BRYLSKA E., DĄBROWSKI S., PLECZYŃSKI J., PRZYBYŁEK J. & SZCZEPAŃSKI A. 1972 – Groundwater flow modelling of areas near water catchment sites [in Polish]. Wyd. Geol., Warszawa.

DĄBROWSKI S. 1978 – Assessment of the use of mathematical modelling for predicting admissible volume of extracted groundwater [in Polish]. [In:] Rozpoznawanie wód podziemnych dla potrzeb gospodarki narodowej. Wyd. Geol., Warszawa.

DĄBROWSKI S., GÓRSKI J., KAPUŚCIŃSKI J., PRZYBYŁEK J. & SZCZEPAŃSKI A. 2004a – Methodology for determination of admissible volume of extracted groundwater in catchments. Methodology guidebook [in Polish] Ministerstwo Środowiska, Warszawa.

DĄBROWSKI S., RYNARZEWSKI W. & PAWLAK A. 1999 – Groundwater renewal in Górna Warta catchment in modelling investigation [in Polish]. Współczesne Problemy Hydrogeologii, 9: 29–36.

DIERSCH H.J.G. & PERROCHET P. 2005 – FEFLOW finite element subsurface flow & transport simulation system. Manual book, WASY GmbH, Berlin.

Directive 2000/60/EC of 23 October 2000, establishing a framework for Community action in the field of water policy. Official Journal EC L 327/1 (EU Water Framework Directive).

DUDA R., ZDECHLIK R. & KANIA J. 1997 – Contaminant transport modelling as a tool for endangering assessment and protection of groundwater in the region of Żelazny Most disposal site [in Polish]. Współczesne Problemy Hydrogeologii, 8: 213–218.

EMSELLEM Y. 1975 – Construction de modeles mathematiques en hydrogeologie. ZPH, Przedsiębiorstwo Hydrogeologiczne w Poznaniu, Poznań (Polish translation).

FELKEL B. & KASZTELAN D. 2006 – Review of groundwater numerical modelling use to hydrogeological research in Poland [in Polish]. Geologos, 10: 57–63.

FISZER J. 2003 – Lower Silesian Coal Basin [in Polish]. [In:] Wilk Z. (ed.) Hydrogeologia polskich złóż kopalin i problemy wodne górnictwa, 1: 338–392. Wyd. AGH, Kraków.

FISZER J. 2005 – Modelling studies of regional groundwater circulation system in areas affected by mines of the LGCB [in Polish]. Pr. Nauk. Gł. Inst. Górn. Ser. Konf., Zagadnienia interdyscyplinarne w górnictwie i geologii: 111–121.

FLISOWSKI J. & WIECZYSTY A. 1979 – Analogue discrete modelling of groundwater catchments [in Polish]. Wyd. Geol., Warszawa.

GETACHEW A.M. 2009 – Modelling groundwater-surface water interaction and development of an inverse groundwater modelling methodology. Doctoral thesis, Frije Universiteit Brussels (VUB), Brussels.

HAŁADUS A., KULMA R. & JÓZEFKO I. 1995 – Groundwater resources of the Żabnica-Breń drainage area according to model testing [in Polish]. Współczesne Problemy Hydrogeologii, 7: 155–163.

JETEL J. 1986 – Vertical variations in permeability of flysch rocks in the Czechoslovak Carpathians. Geol. Quart., 29: 167–178.

KLECZKOWSKI A.S., DOWNOROWICZ S., ZIMNY W. & BECKER R. 2007 – Hydrogeology of mineral deposits [in Polish]. [In:] Monografia KGHM, Polska Miedź S.A. Wyd. KGHM Cuprum, Wrocław: 133–142.

KOWALCZYK A. & RUBIN K. 1995 – The effects of groundwater exploitation in the Bibiela well field based on mathematic modelling results [in Polish]. Współczesne Problemy Hydrogeologii, 7: 227–234.

KRYZA J. & STAŚKO S. 2000 – Groundwater flow rate and contaminant migration in fissure – karstic aquifer of Opole Triassic system due to man activity. Environ. Geol., 39: 384–389.

KULMA R. & ZDECHLIK R. 2009 – Modelling of groundwater flow processes [in Polish]. Wyd. AGH, Kraków.

MACIOSZCZYK T. 1973 – Model methods of evaluating groundwater resources and balances [in Polish]. Prz. Geol., 10: 555–558.

MAŁECKI J., NAWALANY M., WITCZAK S. & GRUSZCZYŃSKI T. 2006 – Determination of parameters of migration of pollutants in a porous medium [in Polish]. Wydz. Geol. Uniw. Warsz., Warszawa.

MCDONALD M.G. & HARBAUGH A.W. 1988 – A modular three-dimensional finite-difference ground-water flow model. U.S. Geol. Survey Open-File Report, Washington.

MOTYKA J. 1998 – A conceptual model of hydraulic network in carbonate rocks, illustrated by examples from Poland. Hydrogeol. Journ., 6: 469–482.

NAŁĘCKI P., REŚKO D., SCHMALZ A. & WITCZAK S. 2004 – Hydrogeological parameters description of fissured-porous therapeutic groundwater basin in Krynica [in Polish]. Biul. Państw. Inst. Geol., 404: 145–164.

NAWALANY M. 1987 – FLOSA 3D, Introduction to system analysis of three-dimensional groundwater flow. Report TNO IAG OS 86–07, Delft.

NAWALANY M. 1989 – FLOSA-FE finite element model of the three-dimensional groundwater velocity field. Report TNO IAG OS 89–12, Delft.

NAWALANY M. 1993 – Mathematical modelling of river-aquifer interactions. Report SR 349, HR Wallingford.

NAWALANY M. 1995a – Inverse problems of hydrogeology – basics. [In:] Troisi S. (ed.) Lectures of European Training Course on Parameter estimation in groundwater flow and pollution modelling, Cosenza.

NAWALANY M. 1995b – Introduction to the Integrated System for Controlling and Monitoring Groundwater Remediation. Report TNO IAG OS 95–15B, March 1995, Delft.

NAWALANY M. 1995c – Hydraulic Isolation of Uncontrolled Waste Disposal Sites. [In:] Gambolati G. & Verri G. (eds.) Advanced Methods for Groundwater Pollution Control, Springer Verlag, Wien, N.Y.

NAWALANY M. 1999 – Scale problem in hydrogeology [in Polish]. Biul. Państw. Inst. Geol., 388: 179–190.

NAWALANY M. 2008 – Modelling transport of substances undergoing physical-chemical processes and chemical reactions in groundwater flow [in Polish]. Biul. Państw. Inst. Geol. – Hydrogeologia, 431: 169–177.

NAWALANY M., SINICYN G., KOCHANEK K. & CZYŻKOWSKI B. 2003 – A decision support system for groundwater: water management issues for opencast mining. [In:] Rosenbaum M.S. & Turner A.K. (eds.) New paradigms in subsurface prediction. Springer, Berlin.

NAWALANY M. & STACHURSKI M. 2005 – Inverse problems in hydrogeology [in Polish]. Współczesne problemy hydrogeologii, 12. Wyd. Uniw. Mikołaja Kopernika, Toruń.

NEMEČEK J., MYL J. & NAWALANY M. 1995 – Optimization of pollution plume containment using management models. Proc. Int. Conf. on Groundwater Quality: Remediation and Protection, 15–18.05.1995, Praha.

PACZYŃSKI B., MACIOSZCZYK T., KAZIMIERSKI B. & MITRĘGA J. 1996 – Establishing of groundwater disposable resources – methodological guidebook [in Polish]. Wyd. TRIO, Warszawa.

PAZDRO Z. 1977 – Basic hydrogeology [in Polish]. Wyd. Geol., Warszawa.

PRZYBYŁEK J. & RYSZKOWSKA J. 1989 – A numerical model of the MGWB of the Opole Monocline and Opole Depression [In:] Problemy hydrogeologiczne południowo-zachodniej Polski. Pr. Nauk. Politech. Wrocł., 58: 247–253.

SINICYN G. 1998 – The effect of uncertainty on the accuracy of groundwater quality estimates near landfills [in Polish]. Politech. Warsz., Warszawa.

STAŚKO S. 1992 – Groundwater in Triassic carbonates of the Opole region [in Polish]. Acta Univ. Wratisl., 1407.

STAŚKO S. & WCISŁO M. 2008 – The influence of the heterogeneity of the aquifer on the assessment of groundwater disposable resources [in Polish]. Biul. Państw. Inst. Geol. – Hydrogeologia, 431: 195–201.

SZYMANKO J. 1972 – Concerning methods for planning and carrying out hydrogeological research in establishing groundwater resources [in Polish]. Prz. Geol., 11: 517–522.

SZYMKIEWICZ A. 2004 – Modelling of the unsaturated water flow in highly heterogeneous Soils. Doctoral thesis, Joseph Fourier University and Gdańsk University of Technology, Grenoble.

WIECZYSTY A. 1970 – Engineering hydrogeology [in Polish]. PWN, Warszawa-Kraków.

WITCZAK S. & DUŃCZYK L. 2004 – Regional multilayer model of a groundwater flow system in the Carpathians Flysch; example of the Kryniczanka watershed [in Polish]. Biul. Państw. Inst. Geol., 404: 263–290.

ZIJL W. & NAWALANY M. 1993 – Natural groundwater flow. Lewis Publ. Comp., Boca Raton, London.

ZIJL W. & NAWALANY M. 2004 – The edge based face element method for 3D-stream function and flux calculations in porous media flow. Transport in porous media, 55: 361–382.