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COMPLEX FLOW SYSTEM MODEL OF THE MUSZYNA REGION (BESKID SĄDECKI RANGE, POLISH OUTER CARPATHIANS)

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Abstract. Multilayered Muszyna regional model was constructed in the ArcGIS and the GMS environment. Among the several methods for implementing the model in the GMS system the LPF method was used to create a structure of the model. Conceptual model is a spatial arrangement of the fixed structure, which can be automatically divided in grid blocks of different densities. The studied area is located within an open hydrogeological structure in the Carpathian mountain basin. Regional model takes into account the presence of complex fold and fault structures as well as the interaction between groundwater, and surface water as well as fresh water with mineral water. Within the model were separated 10 layers with different hydrogeological characteristics. The first layer includes Pleistocene–Holocene deposits. All other layers are built of fissured-porous flysch rocks. The hydraulic conductivities in studied flysch rocks decreases exponentially with depth. The most permeable subsurface zone is about 100 m thick. The experience gained from modelling for the Muszyna region show effectiveness of the principles of the creation of regional hydrogeological models. Such a quasi 3D model seems to be a good tool to carry out the rational exploitation of fresh and mineral water in a complex groundwater flow system.

Key words: conceptual model, numerical flow model, GIS, GMS.

INTRODUCTION

This paper presents a modelling method for regional hydrogeological systems using the mountain basin example from the Polish Carpathians. The Muszyna regional model was built up and integrated into the ArcGIS and the GMS environment. It takes into account the presence of complex fold and fault structures as well as the interaction between groundwater and surface water as well as fresh water with mineral water. It was partially discussed in previous papers (Kania *et al.*, 2009a, b). The procedure of the model construction (Fig. 1) begins with the initial conceptual model of groundwater flow system. On completion of this, information about the structure of the model, hydrogeological properties and boundary conditions were included in the ArcGIS database. The data contained in the ArcGIS database is then transferred to the GMS conceptual model. The transfer process to GMS numerical model divided into blocks is done automatically. The model was therefore used, inter alia, to assess the disposable resources of medicinal and fresh waters of the studied area.

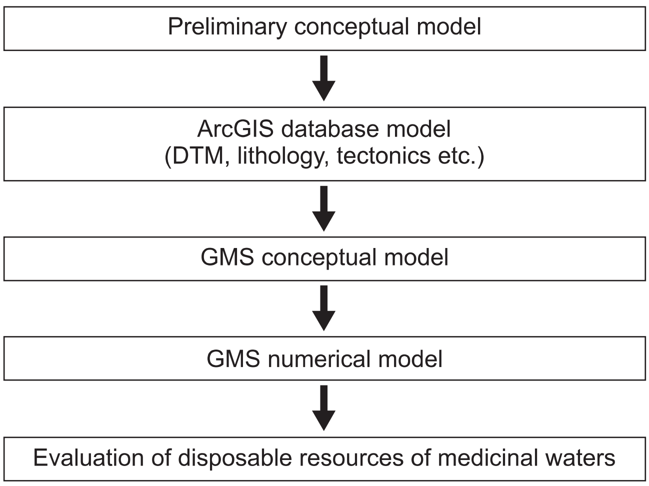

Fig. 1. Flow chart for creating the model of the Muszyna region

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PRELIMINARY CONCEPTUAL MODEL OF MEDICINAL WATERS IN THE MUSZYNA AREA

The studied area is located within an open hydrogeological structure of the common flow system of fresh and medicinal waters. The flow conditions of these waters in this structure types have been well recognized in the adjoining catchment area of the Kryniczanka River (Ciężkowski *et al.*, 1999; Witczak *et al.*, 2002). The diagram (Fig. 2) showing the conditions of water flow system was used to construct the numerical model.

The flow of groundwater take place in flysch rocks, which are composed of layers of sandstones and shales. The model adopted reveals that mainly fractured rocks determine the conditions regarding the flow of water in flysch deposits. In the regional scale, fractures included in the series of sandstones and shales, practically determine the value of the hydraulic conductivities. As a result the model behaves as a quasi continues system without distinct water-bearing strata and impermeable layers spreading through out the area. This space, however, is further complicated by existing tectonic dislocations, which may affect hydraulic barriers or zones of increased permeability. The hydraulic conductivities in studied flysch rocks decreases exponentially with depth (Oszczypko *et al.*, 1981; Witczak *et al.*, 2002). The most permeable subsurface zone is about 100 m thick. Such water-bearing zone is shown in blue in Figure 2. This is active water exchange zone recharged from the atmospheric precipitation.

When the permeability of this zone is sufficient the groundwater supplies the main streams, as shown in the given diagram (Fig. 2). When the permeability is too low, the water table intersects the terrain surface and the flow of water form the spring, which usually initiates small stream. The varied morphology makes the elevated parts, where water table is much higher than in the valleys supplying the deeper water-bearing zone. Despite the decreasing fracturing and permeability of rocks the exchange of water can reach a depth of over 1000 m, although it is less intensive. The regional groundwater flow system also return to drainage areas, which are the river valleys. The long-term regional groundwater flow and the presence in the area of carbon dioxide causes formation of the mineral waters rich in CO_2 (shchava in Polish). Penetrating to the surface in the drainage areas (the valleys) they cut through the zone of fresh water, which often creates a diverse system of mixing and very delicate balance.

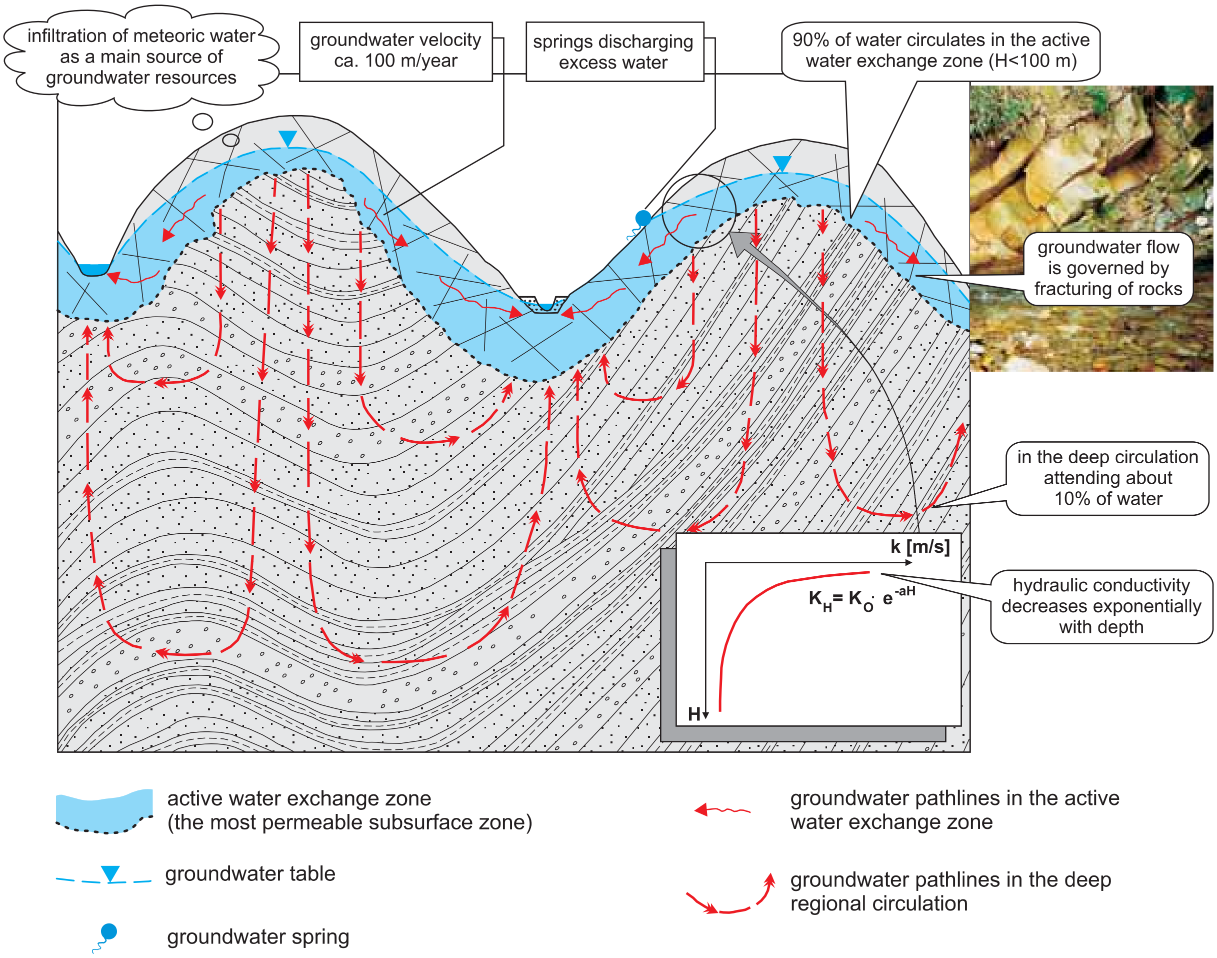


Fig. 2. Conceptual model of groundwater flow system in the studied area

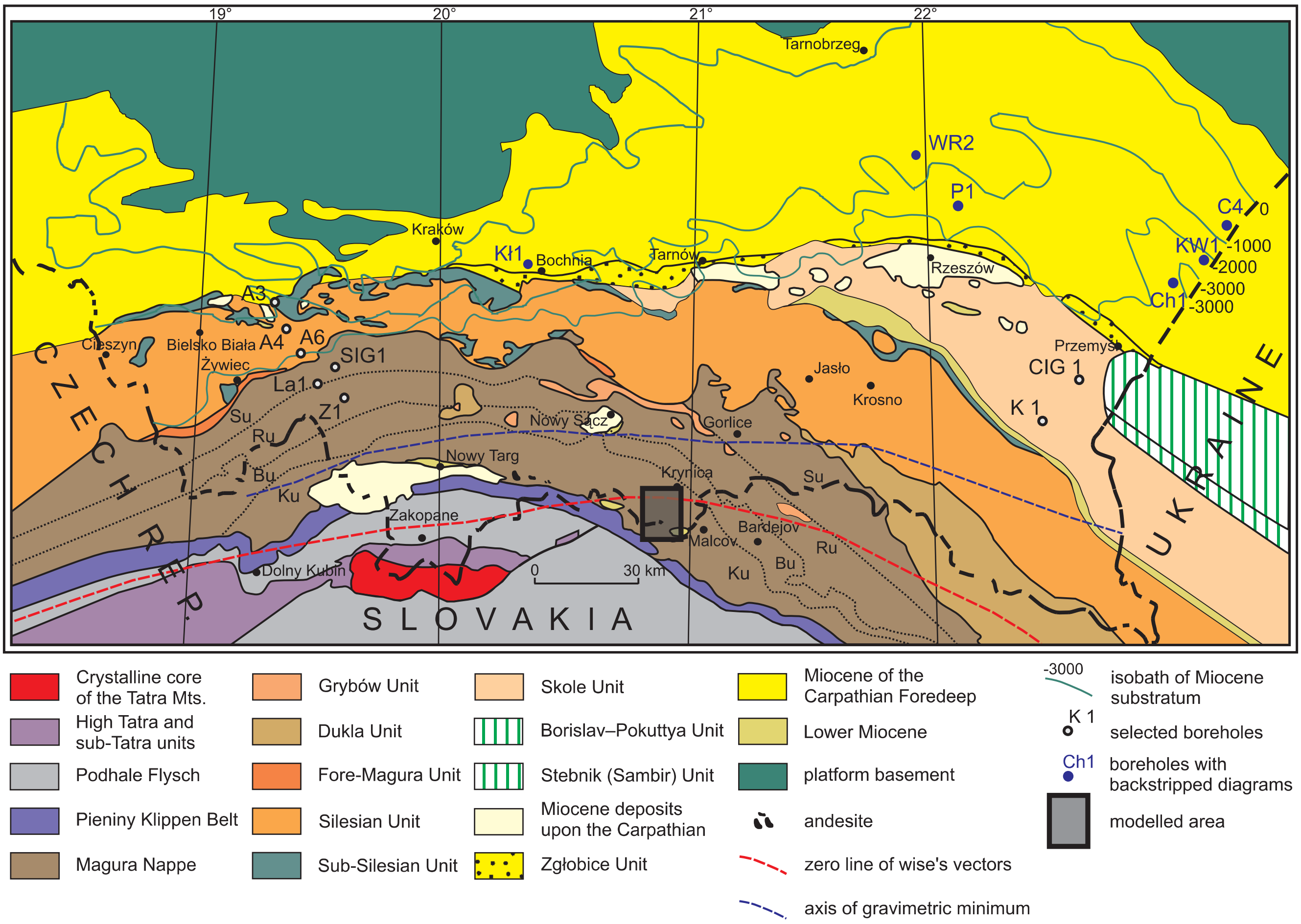
STRUCTURE OF CONCEPTUAL MODEL IN THE ArcGIS AND GMS ENVIRONMENTS

Conceptual and numerical model of Muszyna hydrogeological region is based on the GMS software package – Groundwater Modeling System (Jones, 2005), working in close cooperation with the GIS environment, and using a software package ESRI ArcGIS (McCoy, 2004). Among the several methods for implementing the model in the GMS the LPF (Layer Property Flow) method was used to create a structure of the model. It involves the separation of the model space for many layers of varying thickness, within which zones of different hydraulic conductivities are separated.

GEOLOGICAL SETTING

The Muszyna region is located in the southern part of the Polish Outer Carpathians (Fig. 3). The Outer Carpathians fold and thrust belt is mainly composed of the flysch (turbiditic) sediments deposited through the Late Jurassic to the Early Miocene. The flysch sequences consist of sandy-clayey sediments, deposited by gravitational flows in a deep-sea environment. The Polish Outer Carpathians (POC) were built up from a stack of nappes and thrust-sheets, completely uprooted from their basement. From the South to the North there are: the Magura Nappe, the Fore-Magura-Dukla group of units, the Silesian Nappe, the Sub-Silesian Unit, and the Skole Nappe. The POC are flatly overthrust onto the Middle Miocene deposits of the Carpathian Foredeep. The thickness of the Carpathian accretionary wedge is documented by boreholes and varies from a few hundred metres at the front of the orogeny to more than 5–7 km in the contact with the Pieniny Klippen Belt.

The Muszyna region is located in the south-eastern part of the Magura Nappe at the Krynica facies zone (Figs. 3 and 4). The Krynica facies zone subunit is composed of the Upper Cretaceous to Oligocene deposits (Oszczypko and Oszczypko-Clowes, submitted). The oldest deposits are known from the Muszyna–Złockie area. They consist of the Turonian–Maastrichtian, deep-water variegated shales (Malinowa Fm.) with sporadic intercalations of thin-bedded sandstones. That formation passes upwards into strongly tectonized, medium to thin-bedded turbidites of the Paleocene and Lower Eocene (Szczawnica Fm.). Higher up in the succession, thin-bedded



Sub-units of the Magura Nappe: Su – Siary, Ru – Raca, Bu – Bystrica, Ku – Krynica

Fig. 3. Tectonic sketch map of the Polish Carpathians and their foredeep (based on Oszczypko, 2006)

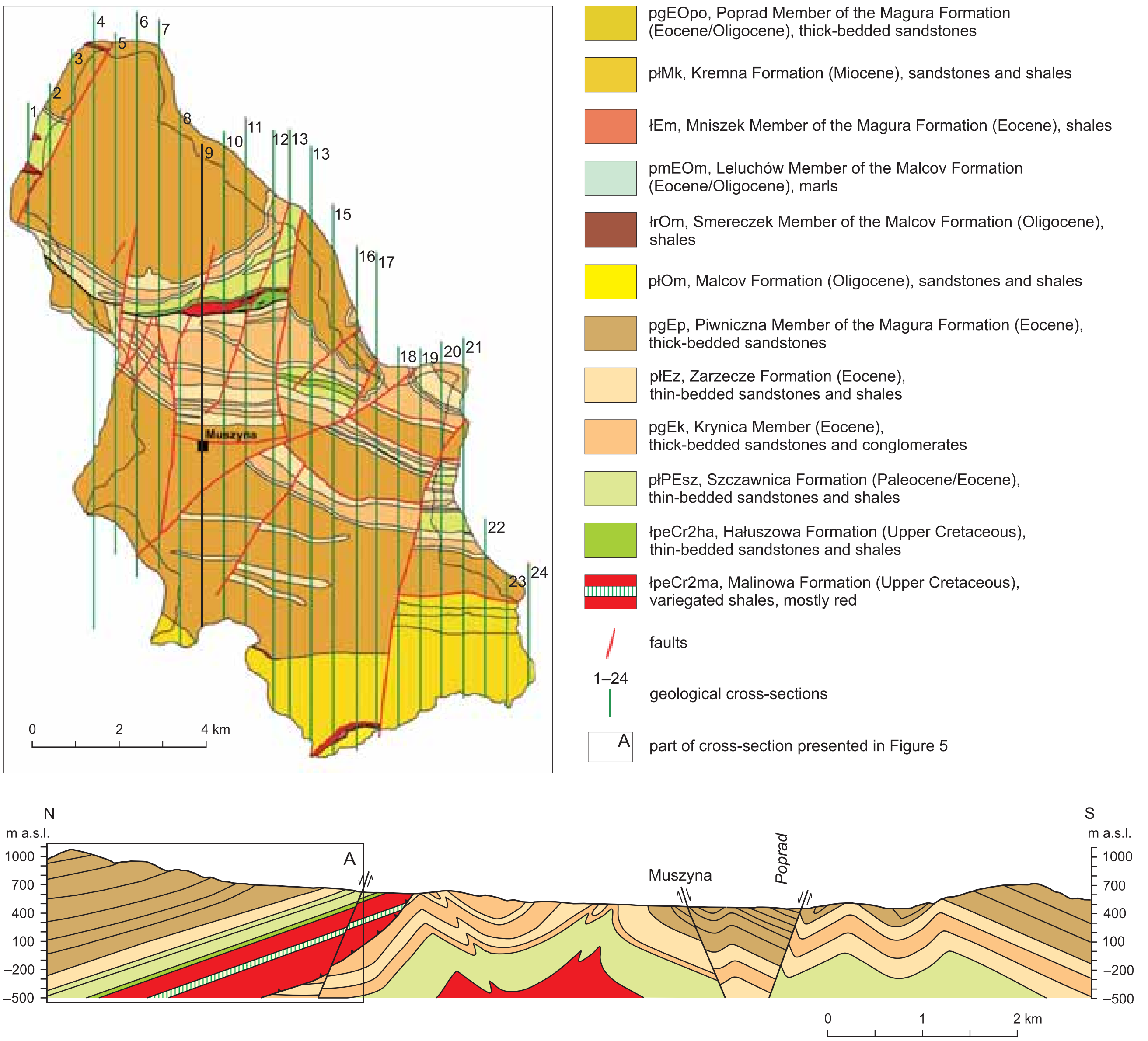


Fig. 4. Geological map of the Muszyna region and an example of geological cross-section 9–9 (based on Oszczypko, Oszczypko-Clowes, submitted)

turbidites occur, with intercalations of thick-bedded sandstones and conglomerates of the Lower–Middle Eocene (Zarzecze Fm.). In the Muszyna region the youngest deposits of the Krynica subunit belong to the thick-bedded sandstones of the Magura Fm. (Middle Oligocene). The stratigraphic thickness of the Magura Nappe reaches at least 2.6 km. During the folding and overthrust movements and tectonic repetitions, the total thickness of the flysch deposits in the Krynica subunit increased up to 5.5–7.5 km. The several NE–SW trending transversal faults cut the Krynica subunit into several blocks.

The structure of the hydrogeological model is based on detailed geological map 1:10,000 by Oszczypko and Oszczypko-Clowes (submitted) and prepared by these authors 24 meridian trending geological cross-sections, constructed every 500 m intervals (Fig. 4).

BREAKDOWN OF THE MODEL INTO LAYERS

Within the model were separated 10 layers (Fig. 5) with different hydrogeological characteristics. The top of the structure is a digital terrain model (DTM), whereas the first layer simulates the Quaternary deposits. Deepest layers of the model has been separated in reference to the depth from the surface. In the Muszyna model layers have not be treated as separate aquifers. According to the definition (Dowgiałło *et al.*, eds., 2002) these layers can be treated as water-bearing zones, which depends mainly on the permeability of the rock fracturing, decreasing with depth as well as increasing the tectonic zone engaged.

The first layer includes Pleistocene–Holocene deposits. All the other layers are built of flysch. Second layer (down to 30 m below surface) is characterized to be the most permeable

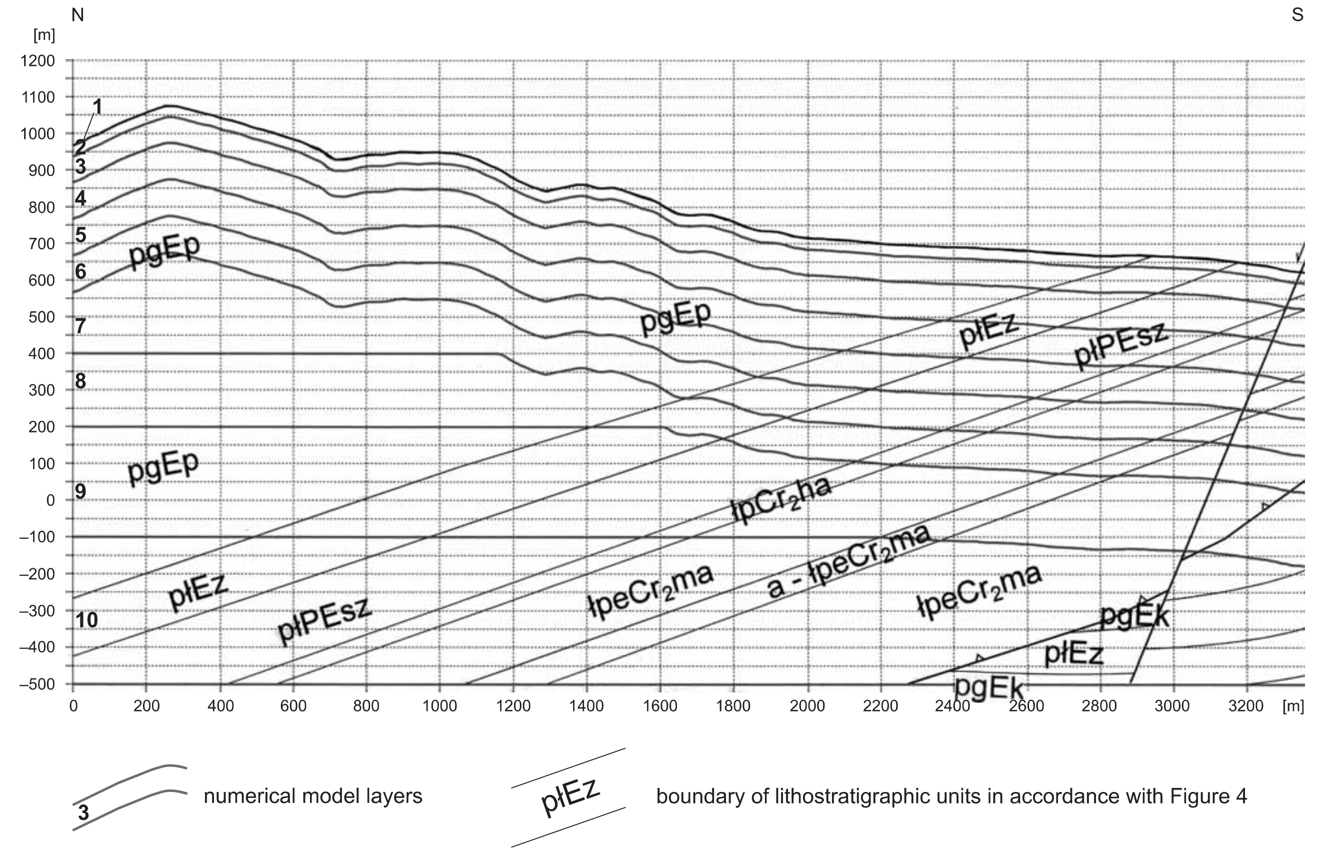


Fig. 5. Model partition into ten layers. An example of geological cross-section 9–9

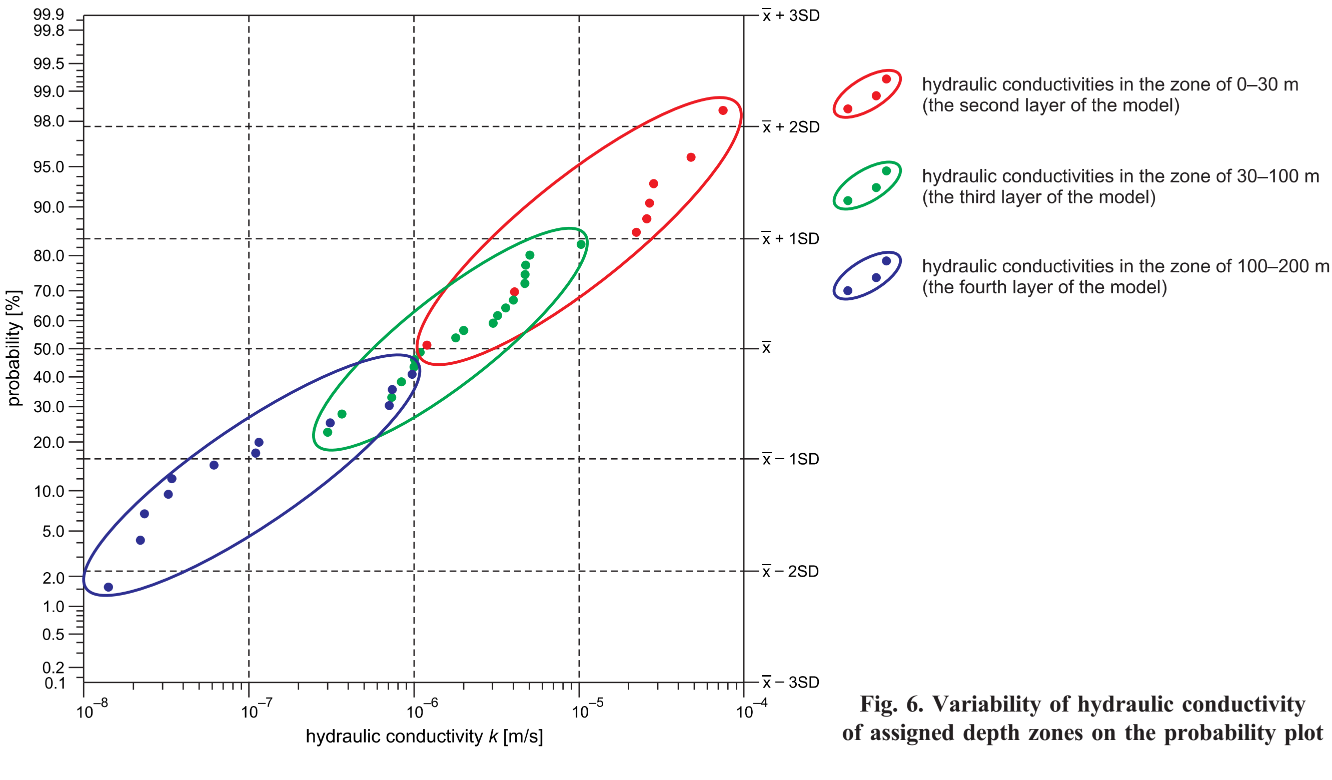


Fig. 6. Variability of hydraulic conductivity of assigned depth zones on the probability plot

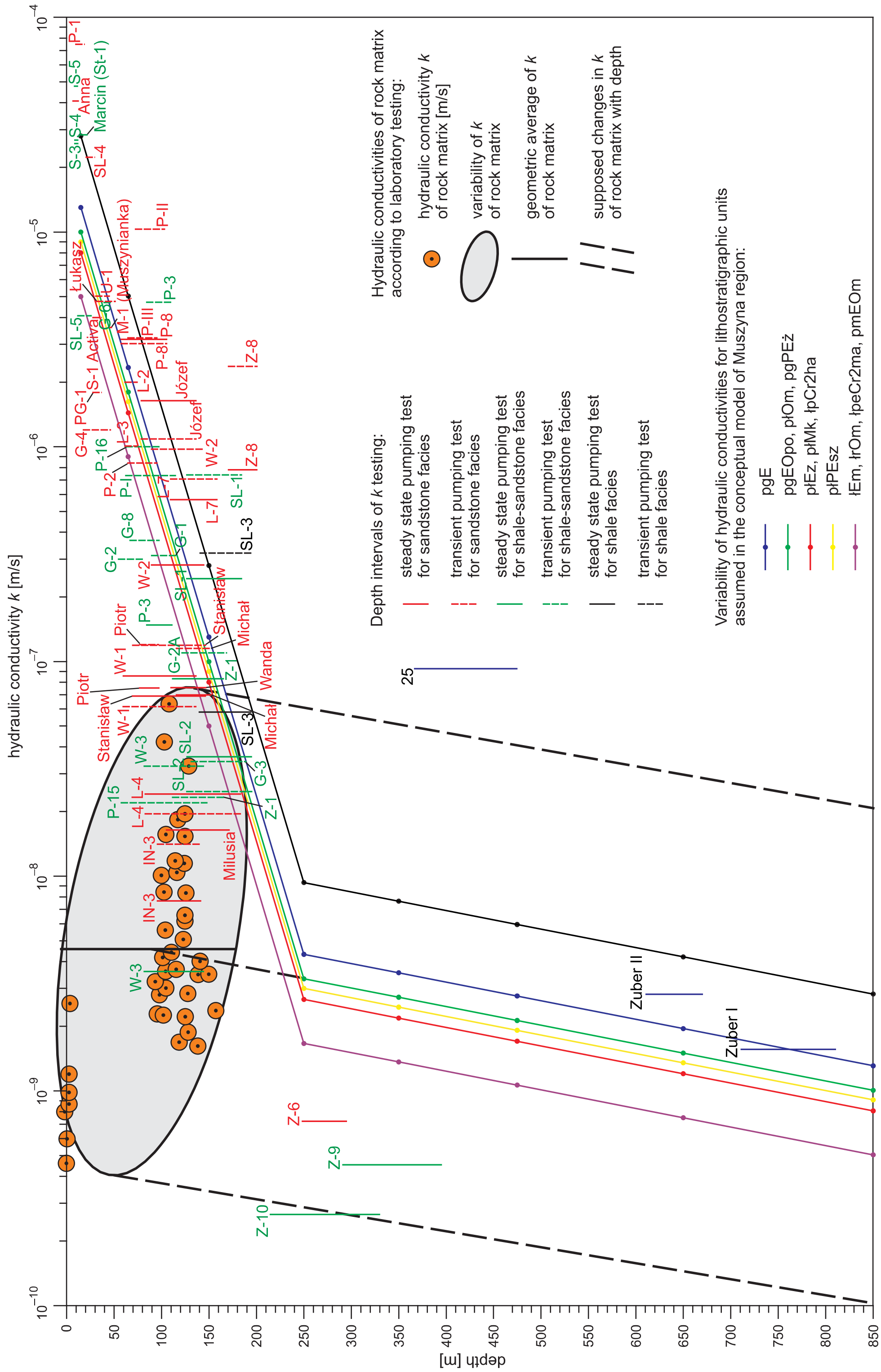


Fig. 7. Variability of flysch rock hydraulic conductivity against the experimental data

within flysch profile. Hydraulic conductivity in this zone is controlled mainly by fracturing, induced by relaxation of rock massif by erosion. Layers 3 to 10 (from 30 to 500 m beneath the surface) includes a zone of gradually decreasing permeability. Separation of lithostratigraphic units within the various layers of the model is based on interpretation of cross-sections and takes into account the characteristics of the structure. This resulted in GIS quasi 3-D image build up of different lithostratigraphic units from surface down to altitude 500 m below sea level.

HYDROGEOLOGICAL PROPERTIES OF THE STRUCTURE

Hydrogeological parameters, variable with depth, have been assigned to the lithostratigraphic units adopted in the model. These rocks properties applied to the model have been based on the water-pressure tests of the Magura sandstones (Oszczypko *et al.*, 1981), as well as on the results of pumping test and their interpretation and reinterpretation. These results confirmed that hydraulic conductivity vary with depth according to a preliminary conceptual model (Fig. 2). The variation in the hydraulic conductivity with depth (0–30, 30–100 and 100–200 m below surface) allowed the separation of layers of a hydrogeological model (respectively, 2, 3 and 4 – Fig. 6) which are illustrated in the probability plot. The deeper layers of the model are very little recognized during the geological research.

This part of the modelling is mainly based on the literature and experiences of the authors (Ciężkowski *et al.*, 1999; Witczak *et al.*, 2002). As in the Kryniczanka River catchment the authors adopted two trends showing the permeability change with depth. A stronger decline, occurring to a depth of 250 m below the surface, is based on a number of pumping test results (Fig. 7). In the deeper zone, the permeability is determined mainly by the rock matrix. This is based on the laboratory tests and is confirmed by data from fewer wells (mainly in Krynica Zuber). As a result, each assigned lithostratigraphic units have its own hydraulic conductivities (Fig. 8).

These hydrogeological properties create the structure stored in the ArcGIS environment and the GMS conceptual model. This structure is transferred to the GMS numerical model automatically divided into individual blocks of fixed size, which can be defined depending on your needs. GMS conceptual model is a spatial arrangement of the fixed structure, which can be automatically subdivided in grid blocks of different densities. This is an important advantage of the GMS software package with other software.

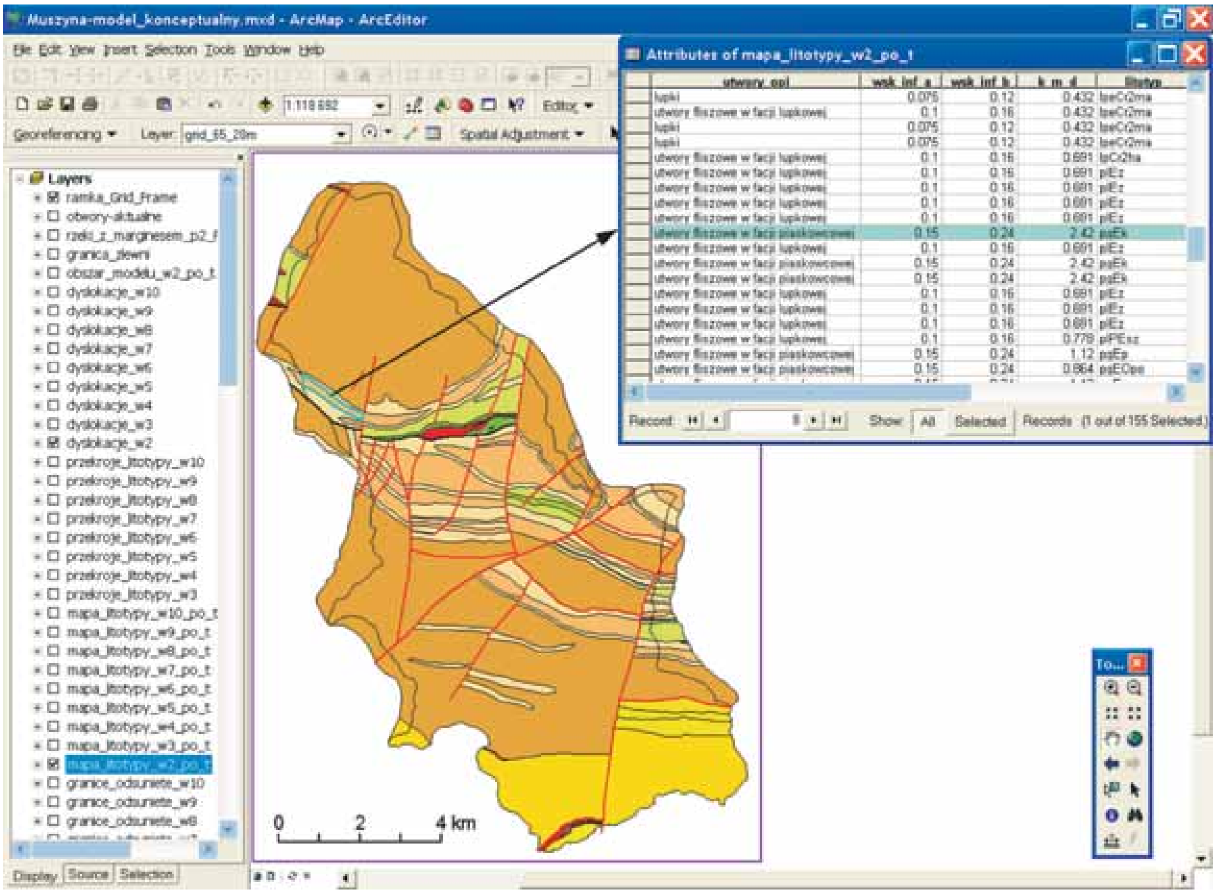


Fig. 8. Example of hydrogeological characteristics of lithostratigraphic units in the second layer of the model (Kania *et al.*, 2009b)

GMS NUMERICAL MODEL

Transition from a conceptual model, to discretely divided into blocks GMS numerical model, has been carried out automatically. Adopted by authors the division into equal sized square blocks of 50×50 m allowed for accurate mapping of geological structures identified in the modelled area. It should be noted that the GMS suite in the adopted modelling scheme allows for smooth change in the density distribution of the blocks in the transition from the conceptual to numerical model.

BOUNDARY CONDITIONS

The area of the model has been adapted to flow budget evaluation of the groundwater catchment. Appropriate representation of the groundwater fluxes in the catchment requires that the model boundary is not strictly based on the topographic watershed. This forced a priori assumption that groundwater fluxes between catchments non exist (the boundary condition Q = 0 on the watershed). To avoid this the authors adopted a model based on catchment boundary, plus a strip of about 300–500 m in the adjacent catchments. In addition, the outer contour of the model was bound by the terms of the General-Head Boundary (GHB) – which is linked with streams of adjacent catchments. This approach does not exclude the possibility of flows between cachments and formation of natural grounwater divide. The basis for defining the watershed was the hydrographic map.

The simulation of rivers is an interesting task (Kania *et al.*, 2009b). In most cases, rivers are simulated by the head-depended

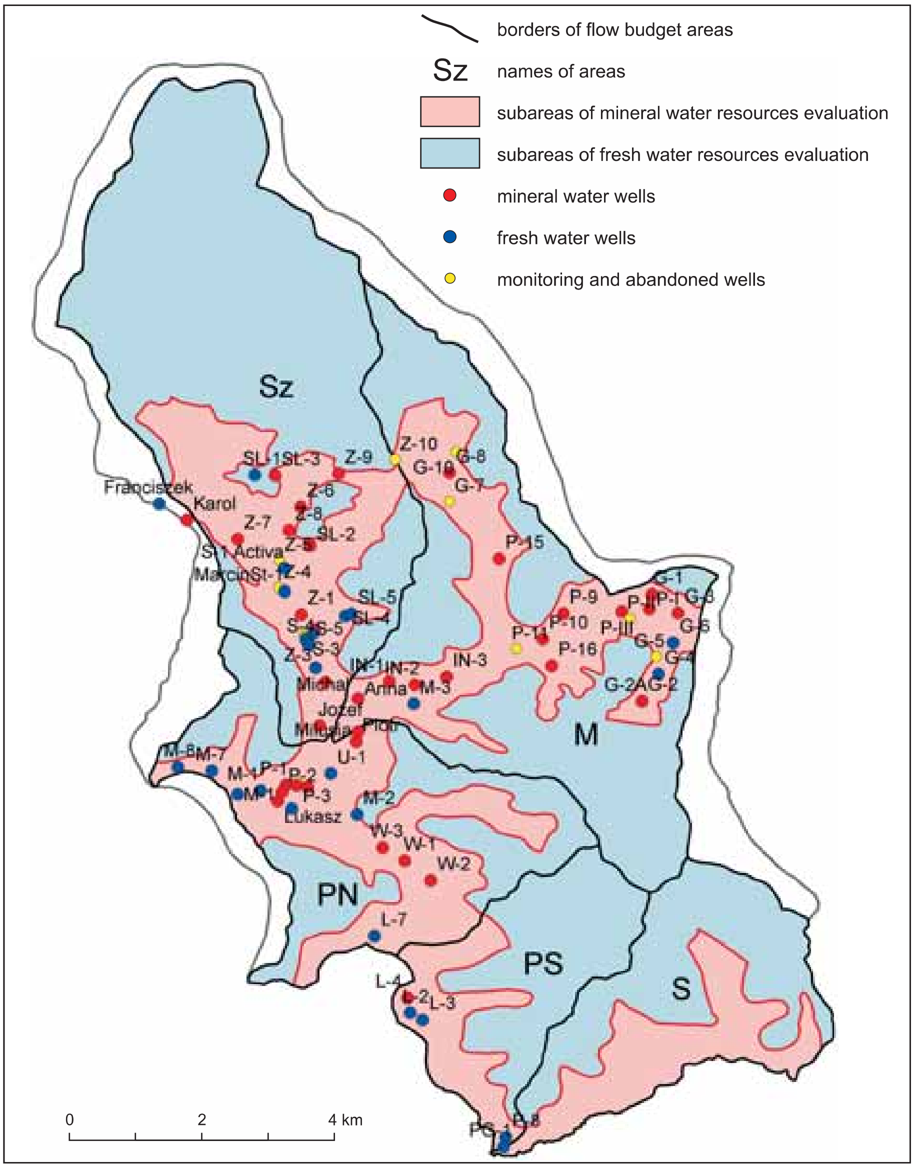


Fig. 9. Exploitation wells on the flow budget areas and subareas of mineral and fresh water resources evaluation (Kania *et al.*, 2009a)

flow boundary conditions. For the stability of the model, the Poprad River was simulated as constant-head boundary condition in the first layer of the model. The specific nature have the source sections of the streams. Depending on the groundwater discharge, spring location of the streams can be moved. During the dry season the source sections are drying up. To enable the modelling of river under varying conditions such source sections were simulated as the drains.

Groundwater recharge was simulated by the boundary condition Q = const at highest active cells of the model. The infiltration has been obtained in accordance with the adopted algorithm takes into account the rate of rainfall infiltration and additional leakage from water supply network (Kania *et al.*, 2009b). Exploitation of groundwater is simulated as boundary condition Q = const. The particular wells were located in the ArcGIS environment (Fig. 9) together with attributes specifying basic data: water table, depth of top and bottom of the screen, discharge and drawdown of the well etc. The data prepared in the ArcGIS environment were transferred into the GMS conceptual model and next to the GMS numerical model.

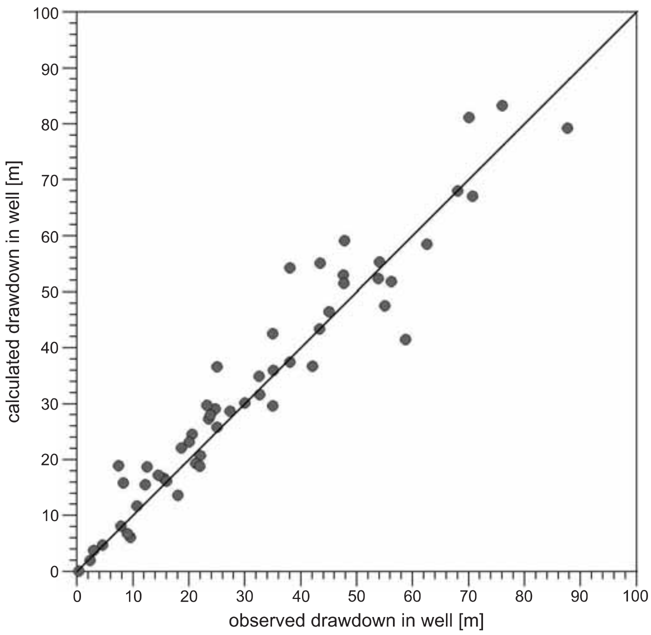


Fig. 10. Simulation of groundwater exploitation – calculated versus observed drawdown in wells with discharge equal to exploitation concession

CALIBRATION OF NUMERICAL MODEL

Numerical model calibration process takes place by trial and error method (Kania *et al.*, 2009a). The model was calibrated by adjusting the discharge of groundwater from particular subcatchments simulated by the model to hydrological measurements as well as simulated and observed hydraulic heads at the observation points (wells and source sections of the streams). During calibration process regional changing of hydraulic conductivities in the particular layers of the model was conducted, in keeping with accepted ratio between the particular lithostratigraphic unit.

In the next step of calibration, the hydraulic conductivities in the direct vicinity of wells were changed to adjust the simulated discharge of wells to the admissible discharge from pumping tests. The comparison of drawdown obtained by the model with the drawdown observed during pumping tests for individual wells indicates a satisfactory agreement (Fig. 10). An important result obtained by 3D modelling is the ability to provide three-dimensional nature of cone of depression around the wells (Fig. 11). This requires a new approach to assess the conditions of water inflow into the well and mixing of shallow fresh water and mineral water fluxes. Zones of depression around the well across model layers interfere with each other both vertically and horizontally (Kania *et al.*, 2009a).

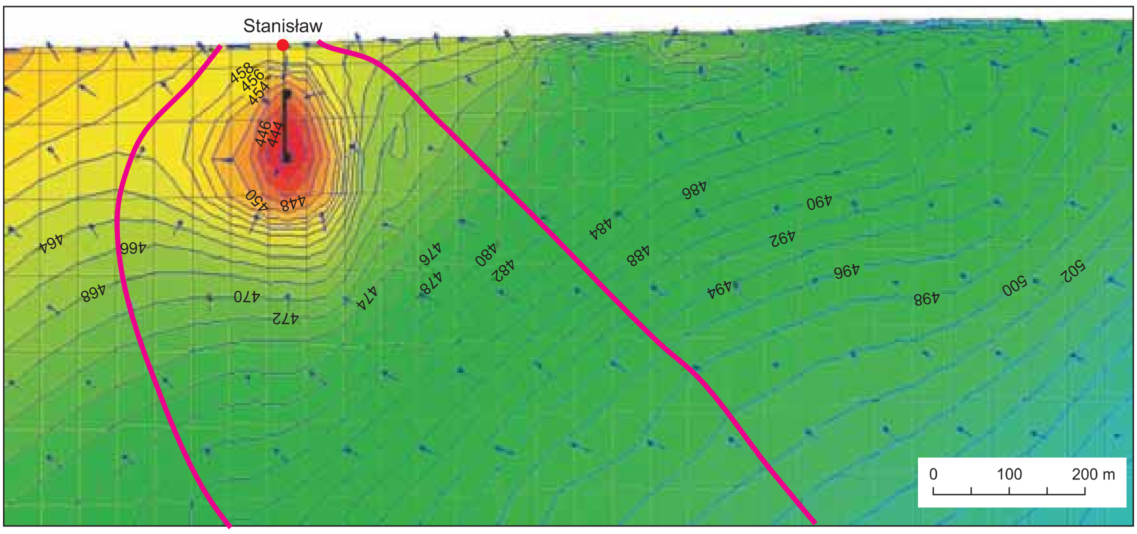


Fig. 11. Cross-section showing 3D character of the capture zone of the Stanisław well (Kania *et al.*, 2009a)

APPLICATION OF THE MODEL

Undoubtedly, an important advantage of the presented procedure is to store the structure and properties of the system in the ArcGIS and GMS conceptual model. It also enables automatic transfers to a GMS numerical model. Conceptual model is a spatial arrangement of the fixed structure, which can be automatically divided in grid blocks of different densities.

The experience gained from modelling for the Muszyna region show effectiveness of the principles of the creation of regional hydrogeological models. Such a model seems to be a good tool to carry out the rational exploitation of fresh and mineral water in a complex groundwater flow system.

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