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Construction of a numerical groundwater flow model in areas of intense mine drainage, as exemplified by the Olkusz Zinc and Lead Ore Mining Area in southwest Poland

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Abstract

Areas of intense mine drainage that are subjected to numerical modelling require the construction of a complex model structure that will properly reflect actual conditions. This paper presents the process and results of constructing such a structure for the Olkusz Zinc and Lead Ore Mining Area, an area situated in a cone of depression the extent of which reaches 500 km^2. This size range calls for a selection of appropriate external boundaries, properly separated from these of the mine drainage area. The complex geological structure of the Olkusz area, associated with considerable variation in the thickness of rock formations, discontinuities of rock levels and occurrence of numerous faults, must be schematised so that calculation layers can be identified. The faults in the study area have to be reflected in the regional model structure, although only those faults that actually affect groundwater flows should be selected. The model structure needs to include detailed recognition and reflection of hydraulic contacts between aquifer levels, together with a selection of hydrogeological parameters that are different for particular formations. Only a complex structure built in such a manner may be the foundation of further model studies.

Key words: hydrogeology, model structure, dewatering, Zn-Pb mine

1. Introduction

The Olkusz Zinc and Lead Ore Mining Area is characterised by complex geological structures and hydrogeological conditions. Mining operations have been conducted in the area since the 12th century (Wilk & Zuber, 1980). Development during the 20th and 21st centuries was faced with the problem of water flowing into the mines, the current rate being *c*. 200 m^3/min (Adamczyk & Motyka, 2000; Motyka et al., 2016). Drainage works have been implemented to continue ore extraction. Initially, in the 16th century, water galleries were dug out, and when the works progressed to greater depths in the rock mass, water pumps were used (Górnisiewicz, 1975; Motyka et al., 2016). Intense mine drainage caused changes in hydrogeological conditions and the occurrence of a vast depression cone around the Olkusz mines. Because zinc and lead ores have nearly been depleted, the plan is to shut down the mines in the near future. This explains why it is necessary to determine changes in water conditions that will take place after closure of the mine. The best available method to prepare a water-flow prognosis involves numerical modelling. The present paper discusses the hydrodynamic model, a structure that will allow preparation of a prognosis of flooding the Olkusz zinc and lead mines by using the numerical modelling method. Results of current work and a complex process of model structure building are outlined below.

2. Geological structure and hydrogeological conditions

The geological structure of the Olkusz Zinc and Lead Ore Mining Basin has been mapped in detail on the basis of thousands of boreholes drilled for the needs of zinc and lead ore deposit exploration and documentation. In the area occur Palaeozoic formations, of Silurian, Devonian, Carboniferous and Permian age, as well as Mesozoic (Triassic and Jurassic) and Quaternary units.

The Olkusz area contains four aquifer levels: Quaternary, Jurassic, Triassic and Carboniferous-Devonian, that are interconnected in various zones of direct and indirect hydraulic contacts (Wilk & Motyka, 1977).

The Quaternary aquifer is formed by fluvioglacial sands, with intermingled gravel and rock rubble. Locally, poorly soluble dust, clays and silts occur. That aquifer is recharged mainly by precipitation, as well as by infiltration of water from streams and rivers. The Quaternary is drained by surface streams outside the area of draining operations of the Olkusz mines and the outflow into the Triassic and Palaeozoic aquifers, within the mine drainage area (Fig. 1).

The Jurassic aquifer occurs in the eastern part of the Olkusz area (Fig. 2). It is composed of Upper Jurassic limestones, with underlying Middle Jurassic sandstones and conglomerates. The aquifer is recharged by infiltration of precipitation water either through outcrops at surface or underneath Quaternary formations. The main drainage is directed to a number of springs, surface streams and outflows to other aquifers located in the zones of mutual hydraulic connections (Wilk & Motyka, 1977; Haładus et al., 1978). Locally, the Upper Jurassic formations are drained through deep water wells that collect water for water supply pipelines. The Jurassic limestones are water reservoirs of the fissure-and-karst

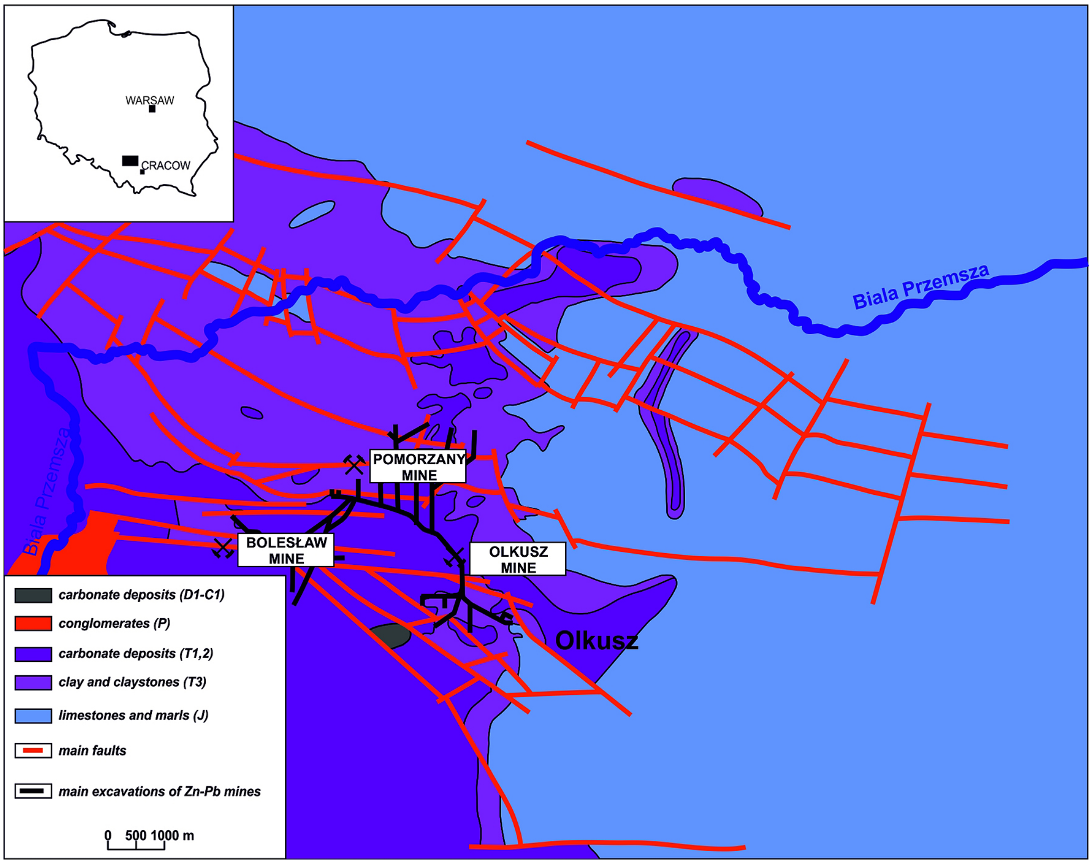

Fig. 1. Geological map of the Olkusz region (after Adamczyk & Motyka, 2000).
Stratigraphical symbols: D1 – Lower Devonian, C1 – Lower Carboniferous, P – Permian, T1, T2, T3 – Lower, Middle and Upper Triassic, J – Jurassic.

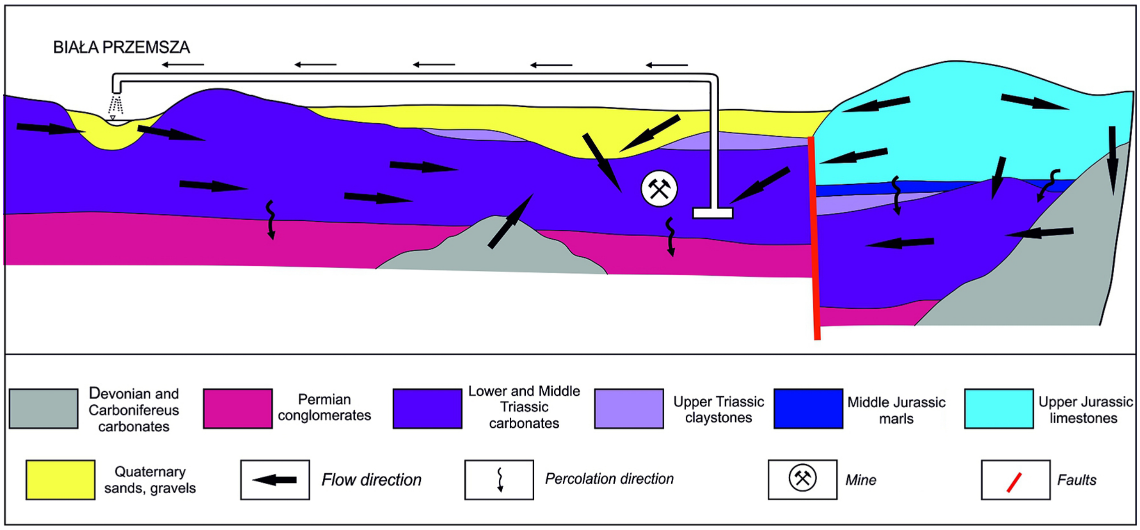

Fig. 2. Groundwater flow diagram for the Olkusz region (after Haładus et al., 1978).

type, with sandstones and conglomerates of the porous-and-fissure type.

Zinc and lead ores occur in carbonate rocks of Middle Triassic age and locally also in Lower Triassic rocks. Owing to a high porosity of cell dolomites of the Upper Variegated Sandstone (Rhaetian) and *Diplopora* dolomites (Middle Muschelkalk), the Triassic carbonate rocks contain aquifers of the fissure-and-karst (limestones) and porous-and-fissure (dolomites) types (Motyka, 1998; Krajewski & Motyka, 1999). The Triassic aquifer is supplied in various ways, with precipitation infiltration through outcrops. Under conditions that are distorted by mine drainage, the Triassic level is fed by water infiltration from the River Biała Przemsza and its tributaries, reaching either the Triassic rocks or the Quaternary formations, with Triassic dolomites and limestones underlying. Another essential compo-

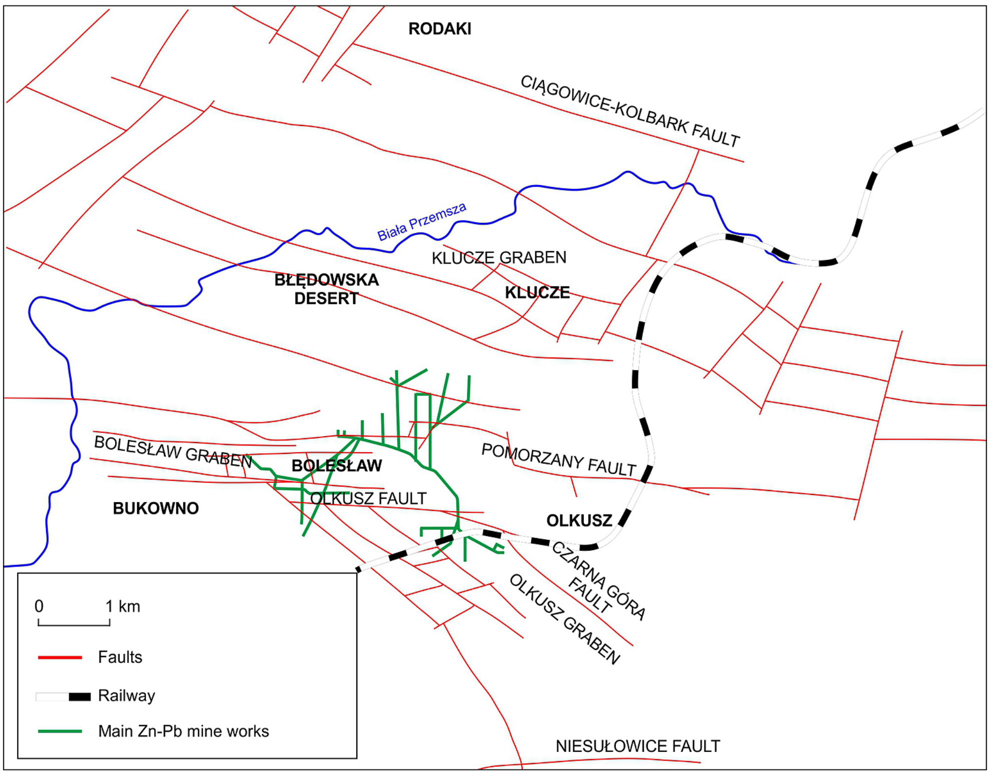

Fig. 3. Diagram of tectonics in the Olkusz region.

nent of the Triassic aquifer supply involves recharge from Jurassic and Palaeozoic formations that are located in the zones of hydraulic connections (Fig. 2).

The Carboniferous-Devonian aquifer is composed of limestones and dolomites and is of the fissure-and-karst type, although water-bearing cavern and fissure zones occur sporadically there. For that reason, their water-bearing capacity is much less than that of the Jurassic limestones and Triassic carbonates. The aquifer under discussion is supplied from the zones of hydraulic connections with Jurassic and Triassic carbonates (Wilk & Motyka, 1977). Across the area covered by mine drainage operations, groundwater flows from the Carboniferous and Devonian formations to the Triassic carbonate rocks (Fig. 2).

The complex geological structure and hydrogeological conditions are also associated with local tectonics. In the northeastern section of the area occurs a boundary between the tectonic zones: the Upper Silesian and Małopolska Region Blocks, belonging to the Kraków-Lubliniec tectonic zone (Habryn et al., 2014).

The following tectonic structures are essential from the point of view of groundwater flow conditions on the Olkusz Zinc and Lead Ore Mining Area, starting from the south (Fig. 3):
- Niesułowice Fault,
- Olkusz Trough,
- Olkusz Horst, switching into the Bolesław Graben in the west,
- Pomorzany Fault,
- Klucze Trough,
- Ciągowice-Kolbark Fault.

It should be mentioned that these structures have not been taken into consideration in previous models.

3. Description of aquifers

At present, numerical modelling constitutes the best available tool for conducting prognostic calculations of groundwater inflow into the mine corridors and the future mine flooding operations. However, for such calculations to be feasible, it is necessary to build a conceptual model of the water-bearing system, followed by construction of the model structure. That process requires collection of a data base and a detailed data analysis of geological structures and hydrogeological conditions, in particular of hydrogeological rock properties. The next step will involve schematisation of the water-bearing system, intended to simplify the complex geological structure and recharge conditions. The most important elements of that stage include selection of proper boundaries of the area being modelled and a subdivision of the model into calculation layers. Consequently, the groundwater flows can be reflected accurately (Zdechlik, 2017).

During research in the Olkusz area, a large number of geological and hydrogeological data were collected, in the form of studies, documentation and publications. These documents are related to studies conducted during recent decades, intended mainly to document the zinc and lead ore deposits and to identify drinking water sources for local residents. Such data were obtained from the former Geological Enterprise in Kraków, Polish Geological Institute – National Research Institute (Upper Silesian Branch in Sosnowiec), Water Supply and Sewage Management Company in Olkusz and the “Bolesław” Mining and Metallurgy Plant at Bukowno.

During the first step in the current model, the external boundaries of the area intended to be modelled were determined. That process was quite complicated, because a large area of zinc and lead mine drainage system affected and the relatively poor knowledge of groundwater flows in the peripheral sections of the study area. That issue was analysed previously by Motyka (1975) and Haładus et al. (1978), who conducted modelling studies in the same area. However, to represent the groundwater flows within the cone of depression in a credible manner, the model boundaries had to be moved away from the area affected by the mining operations. We took the model boundaries along natural separations occurring on land, i.e., along surface streams and surface water divides. The northern model boundary was based on the River Biała Przemsza, the Pilica divides and the River Czarna Przemsza. The eastern boundary was marked along the divides of the rivers Biała Przemsza, Prądnik and Szklarka. To ensure a credible representation of real conditions, the southern model boundary was based on the River Rudawa. For that purpose, the MODFLOW software package was supplemented with a module of a distant model boundary GHB. Considering the existing mine drainage system and a backfilled sand pit, the western model boundary was set partially at the place of the lateral hydraulic contact of the Triassic aquifer level with the Quaternary formations (Fig. 4).

The schematisation of the water system, designed to obtain calculation layers, involved about 7,000 geological sections of boreholes containing detailed lithostratigraphical data, as well as documentation and research papers that provided data on the hydraulic conductivity at particular levels. Our data analysis has allowed us to conclude that

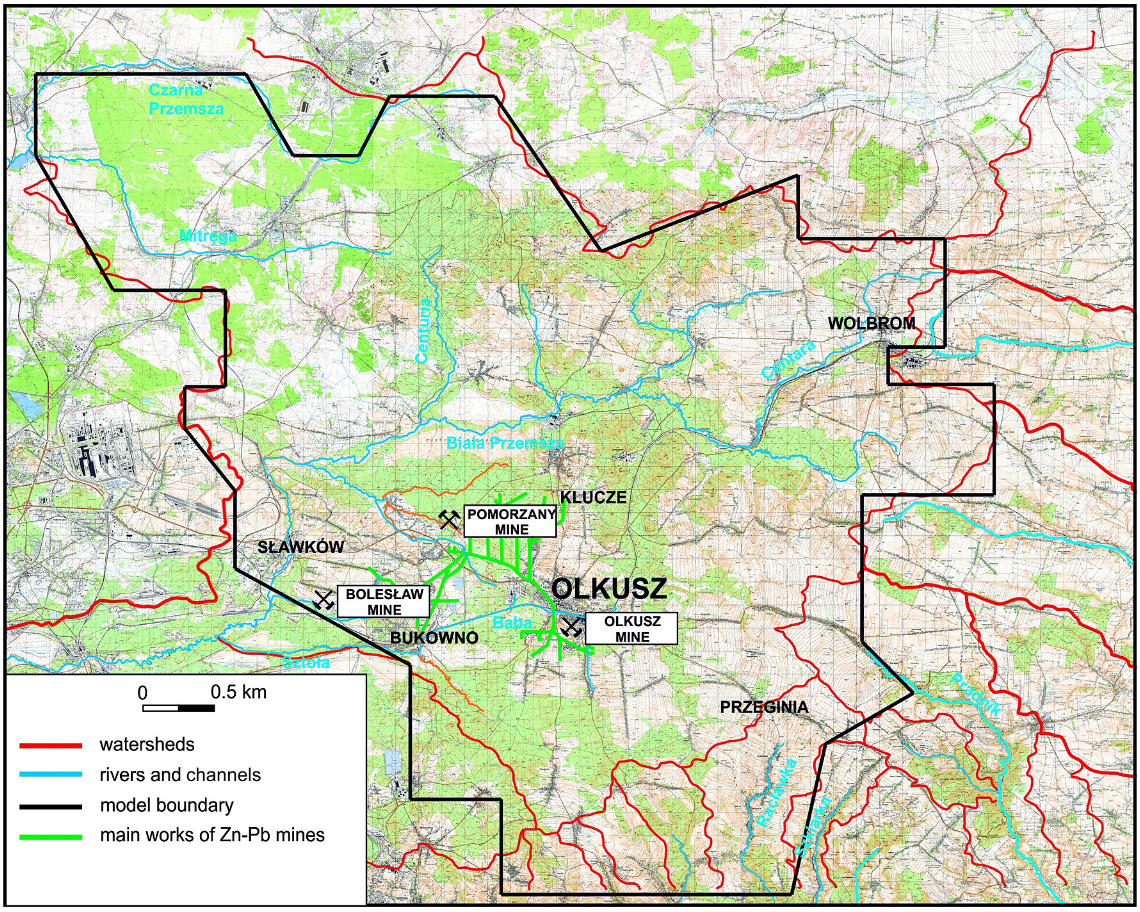

Fig. 4. Model boundaries.

there was no continuity of geological levels in the research area, which constituted a problem in the schematisation process. Moreover, the majority of the rock units in the Olkusz area had very good filtration properties, with the exception of the Upper Triassic (Keuper) and Permian formations. At first, our data analysis has enabled us to separate the layers representing high and low permeability. On that basis, our schematisation of the geological structure was developed to be represented in the model of a nine-layer system (Table 1).

The model reproduced identifies the following levels: three Quaternary levels, reaching 70 metres in the central part of the area; the Upper Jurassic (layer 4) and Middle Jurassic (layer 5), Upper Triassic (layer 6), Middle Triassic (layer 7), Lower Triassic (layer 8) and Palaeozoic (layer 9), taking into account the Permian, Carboniferous and Devonian sedimentary rocks, with various hydrogeological parameters with respect to hydraulic conductivity. The hydraulic conductivity of the Olkusz area was recognised in detail on the basis of numerous test pumping operations performed in exploratory boreholes.

The Quaternary formations were characterised by a very good permeability, and the geometric average of the hydraulic conductivity amounted to 2.5×10^{-4} m/s (Motyka & Wilk, 1976).

The Jurassic formations were characterised by diverse lithologies which was also reflected by hydrogeological parameters of these rocks. The carbonate formations of the Upper Jurassic displayed slightly better hydraulic conductivity than those of the Middle Jurassic marl and silt units. The geometric average of the hydraulic conductivity of the Up-

Table 1. Description of aquifers

Layer	Permeable	Impermeable
1	Quaternary	–
2	Quaternary	–
3	Quaternary	–
4	Upper Jurassic	–
5	–	Middle Jurassic
6	–	Upper Triassic
7	Middle Triassic	–
8	Lower Triassic	–
9	Devonian/Carboniferous	Permian

per Jurassic limestones amounted to 1.6×10^{-5} m/s (Motyka & Wilk, 1976), while those of the Middle Jurassic ones were in the order of 1.5×10^{-7} m/s.

The Upper Triassic formations were composed of silt, with very low hydraulic conductivity. The hydraulic conductivity of the Keuper formations was not analysed on the Olkusz area and, for that reason, typical values of the Krakowieckie silts were adopted for them, reaching values in the order of 4×10^{-10} m/s (Pająk & Dobak, 2008).

The geometric average of the hydraulic conductivity of the Triassic carbonate rocks amounted to 6.5×10^{-5} m/s, with notable differences between the values concerning the Lower and Middle Triassic. The modal value of the hydraulic conductivity concerning the Middle Triassic dolomites and limestones ranged from 9.6×10^{-5} to 8.7×10^{-5} m/s, while that of the Rhaetian units reached 7.2×10^{-6} m/s (Motyka & Wilk, 1976). These differences have contributed much to the identification of the Lower and Middle Triassic formations as two separate levels in the model structure.

Hydraulic conductivity was analysed with respect to Devonian formations, using the samples collected from two exploratory boreholes, and the results were 7.6×10^{-6} m/s and 7.0×10^{-5} m/s, respectively, while in the case of the Permian formations, the results ranged from 2.5×10^{-8} to 1.6×10^{-5} m/s (Motyka & Wilk, 1980). Palaeozoic units were poorly recognised in the study area, owing to the small number of deep wells and, for that reason, such formations were not distinguished as individual layers.

Tectonics was a complex component of the model structure as well. The number and complexity of faults occurring in the Olkusz area called for a far-reaching schematisation that allowed the model structure to take into account only those faults which had a realistic impact on groundwater circulation.

4. Discussion

The model structure, presented here, was worked out on the basis of the most recent geological and hydrogeological data on the Olkusz area, although the peripheral sections of the study area were recognised rather poorly. The model boundaries were based on natural hydrographic and geological boundaries in order to represent groundwater flows in the most accurate manner. The assumptions made here were somewhat different from those applied in structures of previous models completed for the Olkusz area. The application of numerical modelling software for groundwater flows allowed us to achieve a much better representation of the hydrogeological conditions (aquifer layers) in the model structure, and that was reflected in the nine-layer system applied here. That system will also be used in subsequent calculations.

Model studies relating to the Olkusz Zinc and Lead Ore Mines have previously been carried out by several authors. The initial model studies, with the use of the Lukyanov apparatus, were conducted by Motyka (1975) and Haładus et al. (1978); Haładus (1988) continued such model studies. They covered an area in excess of 950 km^2, comprising both the Olkusz and Zawiercie districts. Haładus performed model studies, using an analogue AP-600 apparatus in a single-layer system, owing to limitations of equipment applications. The initial model boundaries assumed by Haładus exceeded those of the model structure that has been presently assumed by us and extended to Myszków. The author of the analogue model struggled with similar problems when constructing his conceptual model, including proper determination of the external boundaries of the model. Technological development allowed Haładus & Kulma (2003) to build the first digital model. The schematisation of hydrogeological conditions was presented on a two-layer system, onto which the Quaternary-Jurassic and Quaternary-Triassic-Devonian aquifer layers were placed. That model was developed in the HYDRYLIB software library and was generally applied, for example, to forecasts of water inflows into the Olkusz mines (Haładus & Kulma, 2003, 2004). The model boundaries were similar to those of the present model structure, although they were only partially based on natural boundaries such as water divides or surface streams. Owing to technical limitations, it has not been possible previously to represent the multi-layered aquifer system in detail, in contrast to the present capabilities of software applied to groundwater flow modelling.

Subsequent modelling in the Olkusz area was conducted by Kret et al. (2017). Their purpose was similar to ours and concentrated on the preparation of a prognosis of hydrogeological conditions following the closure of the Olkusz Zinc and Lead Ore Mines. Those authors assumed, however, quite different boundaries of the study area since their area reached as far as the River Biała Przemsza in the north and the town of Jaworzno in the south. The area being modelled was limited to the north and west of the River Biała Przemsza, which was controversial, if the current range of the depression cone around the Olkusz Zinc and Lead Ore Mining Area is taken into account; this extends considerably beyond the River Biała Przemsza, as has been confirmed by water-flow studies determining water escaping to rock mass (Motyka & Różkowski, 2003). Based on this study, it is not possible to obtain any details on the role of faults in affecting the Triassic water flows.

5. Conclusions

Model studies are currently the best available tools for determination of groundwater resources, mine water inflow and prognoses of changes in water relationships after mine closure by flooding. The first stage of such studies is to build the structure of a hydrodynamic model, which process is complicated and time consuming. It requires collection and analysis of a large geological and hydrogeological data set relating to the study area. The construction of the model structure is one of the initial research stages during which considerable difficulties can be met with, especially when studying the areas with modified groundwater conditions as a result of intense mine drainage operations.

We have applied the most recent data concerning the geological and hydrogeological conditions of the Olkusz district to allow to build a model structure that would be used in subsequent stages of model studies. The authors recognised about 7,000 borehole logs, together with other geological and hydrogeological data, to build the first detailed structure of the hydrodynamic model of the Olkusz Zinc and Lead Ore Mining Area. The major difficulties that occurred during model building were associated with the selection of external boundaries, owing to a very vast range of local impact by the Olkusz Zinc and Lead Ore Mines. The main assumption was that the external boundaries were based on natural formations. For that reason, the boundaries were placed along water divides and surface streams, rivers and other geological features. Another major problem concerned the subdivision of the study area into calculation layers. This was performed on the basis of our knowledge of the geological structure of the area, as well as differences between hydrogeological parameters of particular lithological units and aquifer layers. The degree of complication of the Olkusz area model structure was also affected by numerous hydraulic contacts occurring between particular aquifer layers. In the final version of the model, the schematisation of the geological structure of the study area was performed in a nine-layer system. Besides, tectonics (rather complex) was also considered at the stage of model structure building. Following analysis of available data, it was decided to represent in the model structure only the main faults that realistically affected groundwater flows in the study area.

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