Prediction of groundwater inflow into copper mines of the Lubin Głogów Copper District

T. Bocheńska · J. Fiszer · M. Kalisz

Abstract The Lubin Głogów copper district (lgom) is in an area of copper mining, where ore is mined at a depth of 600–1200 m below surface. Mine dewatering directly influences W-1 limestone aquifer of Permian (Zechstein) age and indirectly impacts a Triassic sandstone aquifer as well as water-bearing sediments interbeded with the coals. The prediction of groundwater inflow into mines has been performed using methods of mathematical modelling. In succeeding steps of the approach, the scheme of the hydrogeological framework was changed starting from the one-layer model up to the four-layer model. The evolution of this hydrogeological schematization is presented in this paper. The latest scheme characterizes such levels of details that allows the following predictions: (1) expansion of depression in all aquifers is influenced by dewatering, (2) the widest extent of depression is in the southern direction, (3) groundwater inflow to the Lubin and Rudna mines will remain at the same level, while the inflow to the Polkowice mine will increase by 25%. Reliable prediction can be achieved by incorporating the entire recharge and drainage area characteristics of the aquifer influenced by mine dewatering into the model.

Key words Mining hydrogeology · Groundwater modelling · Prediction of water inflow into mines

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Introduction

The Lubin Głogów copper district (lgom) is situated in southwestern Poland, within a large geological structure called the Fore-Sudetic Monocline (Fig. 1). It is an area with relatively well recognized geological and hydrogeological conditions due to intensive development of copper-ore mining and accompanying industry.

At present, three copper mines are in operation, i.e., Lubin, Polkowice-Sieroszowice and Rudna. The mines exploit the deposits at depths of 600–1200 m. The influence of mine dewatering is found in an area of several square kilometers. Development and selection of suitable methods of forecasting of the groundwater inflow into mine excavations in the Lubin Głogów copper district has always been one of the major tasks for hydrogeologists working in this branch of Polish mining.

Underground mining works in lgom began in 1965. Hydrogeological investigations at this time focused on predictions of groundwater inflows using boreholes from the surface and during the initial construction, designs of the mines were based on analytical calculations. The need to continually verify those early predictions was understood quite early, as the understanding of the hydrogeological conditions changed with the progress of mining work. Changes of mining plans as a result of economic factors also led to changes in the assumption for the inflow predictions. This resulted, as early as the mid-1970 s, in the application of numerical modelling methods. They allowed the complexity of natural and technical factors controlling mine inflows to be taken into account. In the same time hydrogeological parameters of drained rock mass were corrected during model calibration using solution of inverse task.

Outline of the hydrogeological conditions

A detailed location of lgom and a general description of hydrogeological conditions around the copper deposit were presented in earlier papers (Bocheńska 1984, 1988; Bocheńska and others 1995). The hydrogeological setting is schematically illustrated on the map (Fig. 1) and in cross-section in (Fig. 2).

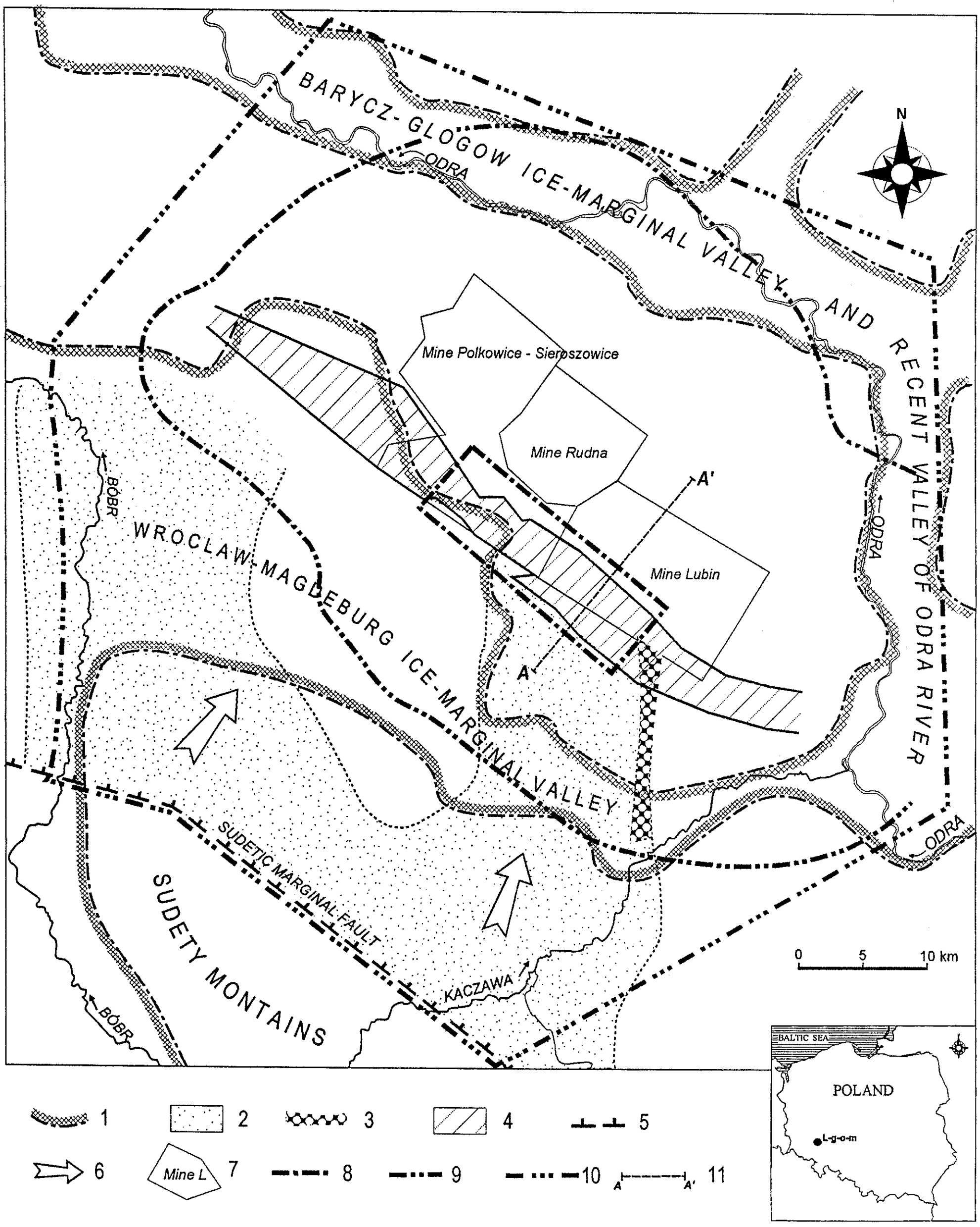
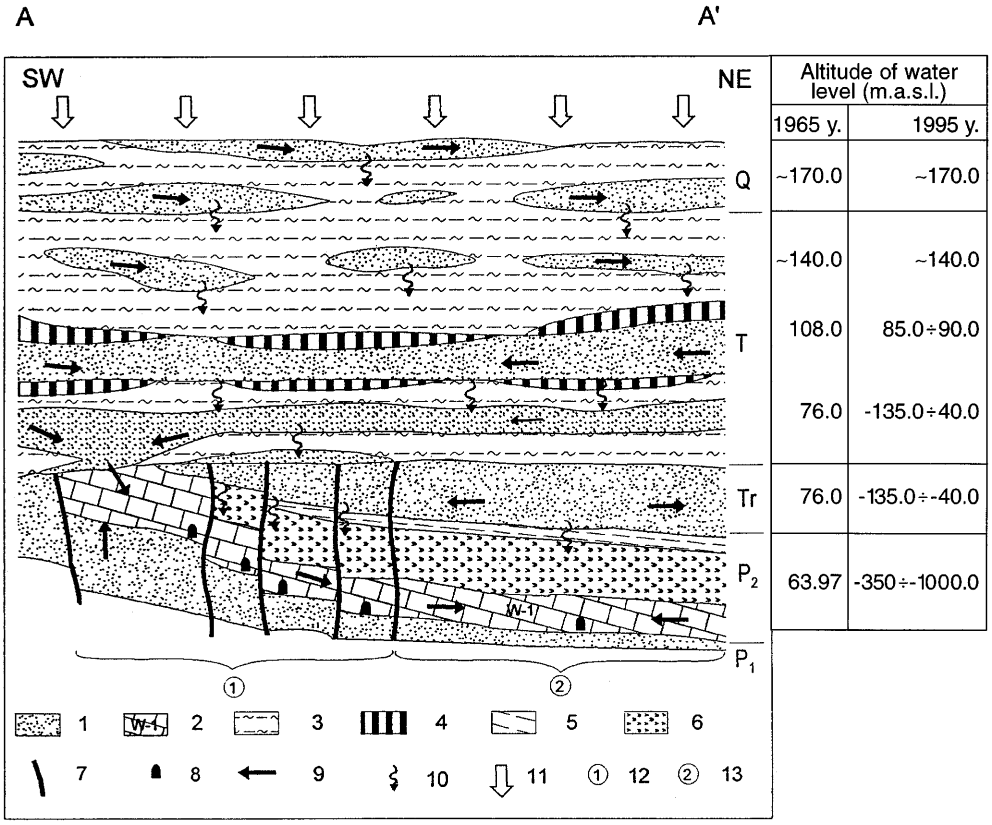


Fig. 1
Main elements of lgom hydrogeological conditions modelling *1* fossil valleys extends; *2* fossil alluvial fan extends; *3* Lubin – Legnica fossil valley; *4* sub-Tertiary Zechstein outcrops; *5* Sudetic Margin Fault; *6* direction of the natural groundwater flow; *7* mine areas; *8* first numerical model extend; *9* second and third numerical model extends (outline of the depression cone in the sub-lignite Tertiary sediments); *10* fourth numerical model extend; *11* hydrogeologic section

Four multi-aquifer formations are present in the lgom area: Quaternary, Tertiary, Triassic and Permian. Within these multi-aquifer formations, beds forming individual aquifers divided by layers of aquifuges and aquicludes occur. Isolation of aquifers is not continuous. Water-bearing Zechstein limestones and dolomites, the so-called “W-1” aquifer, with an average thickness of 70 m, is present in the area of the mine workings. It is underlain by the 350 m thick Rotliegendes sandstone aquifer of very low hydrogeological parameters. The W-1 bed is isolated from overlying aquifers from Triassic and Tertiary sediments by the Zechstein series of claystones-shales and anhydrides with a total thickness of approximately 200 m. In the area of Zechstein outcrops (southern part of lgom), water-bearing beds of W-1 limestones, Triassic Bundsanstein, Tertiary sands of lignite-bearing sediments are in hydraulic connection. Water inflow to the W-1 limestones and dolomites is higher there than in other regions of lgom.

Groundwater is recharged by infiltration and seepage as well as through side-inflows from mountains within the Tertiary formation. Fossil alluvial fans of the pre-Kaczawa and pre-Bóbr rivers are present in this formation. Regional drainage of the Tertiary aquifers occurs in the Barycz-Odra ice-marginal valley and contemporary Odra valley as shown on Fig. 1.



Altitude of water level (m.a.s.l.)	
1965 y.	1995 y.
~170.0	~170.0
~140.0	~140.0
108.0	85.0÷90.0
76.0	-135.0÷40.0
76.0	-135.0÷-40.0
63.97	-350÷-1000.0

Fig. 2
Schematic diagram of groundwater flow in lgom mines *1* water-bearing sands and sandstones; *2* W-1 limestone aquifer; *3* clays; *4* lignite; *5* claystone; *6* anhydrites; *7* faults; *8* mining excavations; *9* direction of groundwater flow; *10* direction of groundwater seepage; *11* infiltration of precipitation; *12* zone of higher water inflow; *13* zone of lower water inflow

Aim of model studies

The aims of the model studies were:

1. To establish rock mass permeability; parameters were previously stabilized only punctually, in the area of mining operations.
2. The quantitative determination of the conditions of aquifers recharging by infiltration of precipitation, inflow from the filtration area boundaries and recharge from the river valleys.
3. To establish the participation of each aquifer in the formation of mine global inflow, prediction of groundwater inflow into mines and of the depression cone development. These goals were achieved by carrying out four modelling stages within 30 years. Their results allowed the development of the hydrogeological model regarding the boundaries and hydrogeological parameters of the dewatered rock mass.

Description of model studies

The basis of the calculation scheme of these predictions were the assumptions that the drainage of the rock mass by the mines caused the direct discharge of groundwater from the W-1 Zechstein limestones and that, beginning in 1967, it has been recharged from aquifers occurring in the Bundsandstein and in the Tertiary sub-lignite sediments (Fig. 2) through the zones of sedimentary and tectonic contacts (Bocheńska 1979). The specification of the model patterns of the four predictions is presented in Table 1.

The calculation scheme for the first stage of studies covered a rectangular area in the region of outcrops provided for the deposit development and exploitation by 1990 (Fig. 1). The task in filtration modelling was reduced to solving the difference equations for a non-steady flow in a flat, two-dimensional filtration field, using the finite-difference method. The model reconstructed one major W-1 aquifer drained directly by horizontal mining excavations. Hydrogeological parameters of the calcareous rocks, including the ones regarding infiltration and discharge, were assumed on the basis of that recognition (Bocheńska 1979).

It was assumed that the elastic storage coefficient, calculated on the basis of the volume of the regional multi-level depression cone, general for the whole rock mass in the southern parts of the Lubin and Polkowice mines, presents quantitatively the value of recharge of the aquifer drained directly by the excavations from the overlying horizons. The model was balanced in relation to the inflows due to the absence of reliable data from, at the time, a small number of piezometers in the W-1 limestone aquifer in the outcrop area.

During the second stage, hydrogeological recognition for the year 1979 was taken into account. The studies of the fourth stage were made in 1980. They resulted in specifying the hydrogeological parameters and the prediction made until the year 2000. The prediction was prepared for the variant of wide range of development and mining operations in the area of Zechstein outcrops. Model studies were carried out using FNN4 software (Fisher 1978), using the finite-element method. Filtration was still modeled as non-steady, two-dimensional, flat, and in the W-1 carbonate bed. The participation of the other aquifers in the model was taken into account as the extra recharge. This stage of the studies allowed the solution of a number of methodological problems typical for numerical modelling, as well as the correction and amendmention of the calculation scheme applied during the first stage. The progress in the calculation scheme development is shown in the Table 1. The essential innovation of this stage was taking indirectly into account, in the calculation scheme, the participation of the Tertiary inter-lignite aquifer in recharging the W-1 limestones. Piezometer measurements were used.

The recharge coefficient of the W-1 limestone aquifer, with water from the overlying water-bearing complex,

Table 1

Evolution of hydrogeological schematization for model studies

Numerical model	I stage	II stage	III stage	IV stage
Calculation scheme	One-layer: W-1 limestones aquifer	One-layer: W1-limestones aquifer	Four-layer: aquifers: W1 limestones Triassic Boundsandstein sub-lignite Tertiary inter-lignite Tertiary	Three-layer: aquifers: W1 limestones Triassic Boundsandstein and sub-lignite Tertiary inter-lignite Tertiary
Calculation method	Rectangular grid – finite-difference	Triangular grid – finite-element	Triangular grid – finite-element	Rectangulat grid – finite-difference
Software	Own author – A. Szaciło	Own FNN4 author – J. Fisher	Own FKWL author – J. Fisher	MODFLOW (ModCad)
Modelled area	Fragment of the area covered by the depression cone in W-1 Zechstein carbonates	Area within the depression cone in W-1 Zechstein carbonates	Area within the depression cone in the Tertiary formation	Area bigger than the depression cone, outlined by natural boundaries of recharge and drainage
Calibration period	1965–1975	1965–1979	1965–1991	1990–1996
Forecast period	1975–1990	1990–2000	1991–2000	1996–2013
Boundary conditions	Outer $Q=0$ and $H=f(t)$ inner $H=\text{const}$	Inner and outer $H=F(t)$	Outer $H=f(x,y)$; $Q=0$ inner $H=f(t,x,y)$	Outer $H=f(x,y)$; $Q=f(H)$ $Q=f(x,y)$ inner $H=f(t,x,y)$
Hydrogeological parameters	Transmissivity of W-1 limestones $T=m*k=f(x,y)$	Permeability coefficient of W-1 limestones k storage coefficient of W-1 limestones μ elastic storage coefficient of W-1 limestones μ^* recharge of W-1 limestones q	W-1 limestones k, μ^* Boundsandstein k, μ^* sub-lignite Tertiary k, μ^* inter-lignite Tertiary k, μ^* leakage coefficient for separating beds	W-1 limestones T, μ^* Boundsandstein sub-lignite Tertiary T, μ^* inter-lignite Tertiary T, μ^* leakage coefficient for separating beds
Calibration basis	Mine inflows	Mine inflows, pressures in W-1 Zechstein limestones	Mine inflows and pressures in four aquifers being in the hydraulic connection	Mine inflows and pressures in four aquifers being in the hydraulic connection
Results	Inflows forecast	– Inflows forecast, – New distribution of k Values in W-1 limestones, – Spatial diversity of inflows	– Inflows forecast, – Participation of each Aquifer in the inflows Formation, – Leakage coefficients for separating beds	– Inflows forecast, – Participation of each Aquifer in the inflows Formation, – Leakage coefficients for separating beds

was determined. The model studies confirmed the importance of the outcrop areas and the Tertiary under-lignite aquifer, in total inflows to the lgom mines. The model was calibrated with reference to the measurements in piezometers installed in the W-1 limestones and to inflows, correcting the hydrogeological parameters in the selected parts of the rock mass.

In the third stage, due to the subsequent recognition of the rock mass dewatering and its results, like deeper and wider depressions of the groundwater table in each aquifer, an attempt was made to quantitatively evaluate the role of the hydraulic connections (Bocheńska 1988, Bocheńska and Fiszer 1988). The studies were carried out on a multi-layer model, taking into account the hydraulic connection between the four aquifers. Calculations were done using FKWL software, based on the finite-element method with an irregular, triangular, and digitized grid. Hydrogeological parameters of all four aquifers, with arising depression of the water table and of the separating beds, were included in the calculation scheme.

The prediction of the third stage was made in 1990 for the Lubin and Polkowice mines, for the period of 1991–2000 according to the up-to-date design for the deposit development and mining. The calculation scheme prepared in 1988 (Bocheńska and Fiszer 1988) was used, implementing small corrections of hydrogeological parameter distribution due to the better recognition of the tectonics around the mining excavations.

The fourth stage of studies gave the inflow prediction for the years of 1996–2013, i.e. the period including the maximum development of mining excavation compatible with approved mining designs. The aim of the studies was to prepare the final prediction of the groundwater inflow as well as to determine the influence of mine dewatering on the environment by defining the quantity of groundwater recharge. It was performed in order to establish the influence of the mine dewatering on the Quaternary complex, regarded previously as isolated from deeper aquifers.

While making this prediction, the modeled filtration area was substantially enlarged (Fig. 1). Its boundaries were established along the natural hydrographic and geomorphological elements. The calculation scheme included the following assumptions and facts:

1. Rock mass drainage due to mining operations affects the aquifers of: W-1 Zechstein limestones. Triassic Bundsandstein, sub-lignite and inter-lignite Tertiary deposits.
2. Sub-lignite Tertiary aquifer is in close hydraulic connection with the Bundsandstein level and they both can be regarded as one water-bearing horizon.
3. Tertiary aquifers: inter-lignite and sub-lignite occur on the whole modelled area.
4. The southern boundary of W-1 limestone aquifer is the natural extension of this layer and the northern one is the Odra valley.
5. There is a possibility of the hydraulic connection between all aquifers by water seepage through separating beds having different degrees of permeability. In the area of the W-1 Zechstein limestone outcrops, contacts have increased activity – especially between W-1 layer and sub-lignite Tertiary sediments.
6. The participation of the Quaternary and Tertiary over-lignite aquifers is reconstructed by assuming the vertical recharge corresponding with 2% of the precipitation. The velocity and its spatial distribution were modified, while balanced, during the model studies.
7. According to the applied methodology, i.e. finite-element method (MODFLOW), the area of the model was digitized by the rectangular grid of 80 rows and 80 columns. The boundaries of the model are irregular. The modeled area has 12413 active blocks.
8. Aquifers are reconstructed by giving their hydrogeological parameters by the coefficient of transmissivity $T=k^{*}m$. The average transmissivities between the blocks were calculated as a harmonic means. The participation of the beds separating aquifers was taken into account by giving them corresponding values of the leakage coefficient. The values of the parameters assumed in the model are given in the Table 2.
9. Groundwater flow in such a calculation scheme is in the confined regime, in quasi-steady state conditions.

Table 2
Aquifer transmissivities

Aquifers and *separating beds*	Hydraulic transmissivity [m2/d]	Vertical seepage l/d
1 – Tertiary inter-lignite	13–44	
1/2 separating bed		*0.000001*
2 – Tertiary – sub-lignite	26.5–56	
2/3 separating bed		*0.000251*
3 – W-1 limestones and dolomites (zone of increased saturation)	30–55	
2/3 separating bed		*0.0000001*
– W-3 limestones and dolomites (zone of weak saturation)	1	

The outer boundaries of the model of the fourth stage were based, if at all possible, on natural elements influencing the aquifers recharge or discharge (Fig. 1). For the Tertiary aquifers, on their southern and northern boundaries of the model, boundary conditions of the first type $H=\mathrm{const.}$ were assumed. The rivers together with their valleys included in the model, were mapped using the third type boundary condition $Q=f(H)$.

The direct mine drainage occurring in the aquifer of W-1 limestones and dolomites was mapped in the model by introducing within the outline of the deposit development in every mining area, boundary conditions of the first type – $H=\mathrm{cost.}$ – of values corresponding with the deposit bottom ordinates.

The prediction of the inflow to the mines was made for the periods up to 2000, 2005 and 2013.

Table 3
Groundwater table depression in LGOM Cenozoic and Mesozoic aquifers

Aquifer	Number of observation Boreholes	Groundwater table ordinate in m above sea level		Groundwater table depression (m)
		Before mining operations	For XII 1996	
Over-lignite Tertiary	4	127.50÷148.80	126.85÷150.20	none
Inter-lignite Tertiary	12	99.10÷111.32	54.14÷108.80	2.42÷45.86
Sub-lignite Tertiary	18	73.18÷80.00	−164.71÷41.80	53.03÷242.21
Boundsandstein	10	67.80÷92.00	−107.37÷76.15	8.85÷177.35
Main dolomite(W-2)	2	78.00	−198.50÷19.80	58.20÷276.5
Limestones and dolomites (W-1)	9	75.00÷91.70	−198.50÷10.00	80.30÷485.80

Discussion of the study results

The first three stages of model studies allowed the precision of the model of lgom hydrogeological conditions, regarding hydrogeological parameters of the aquifers and their participation in the value of the mine inflows. Simultaneously, they were the basis for elaborating, during the fourth stage, the regional model, allowing preparation of the prediction of the depression cone development and mine inflow velocity, till the end of their operation, as well as establishment of the influence of mine drainage on the dynamic groundwater resources of the lgom area. The fourth stage of modelling showed that the continuous dewatering of the deposits would result in further changes of hydrodynamic conditions in the aquifers being dewatered. There will be an increase of the groundwater table depression in every aquifer and the increase of the depression extension. The latest development of the depression extension will be in the southern direction towards the Sudetic Marginal Fault (Fig. 1). It will cause intensification of the groundwater flow from the south towards Zechstein outcrops area in the Tertiary aquifers. The model studies show also that in the northern and eastern direction, the Odra valley with its ice-margin valley structures will probably be within the range of the depression cone in the Tertiary sediments. The increase of the depression extension will be towards the west as well, and from this side the inflow in the Tertiary aquifer will

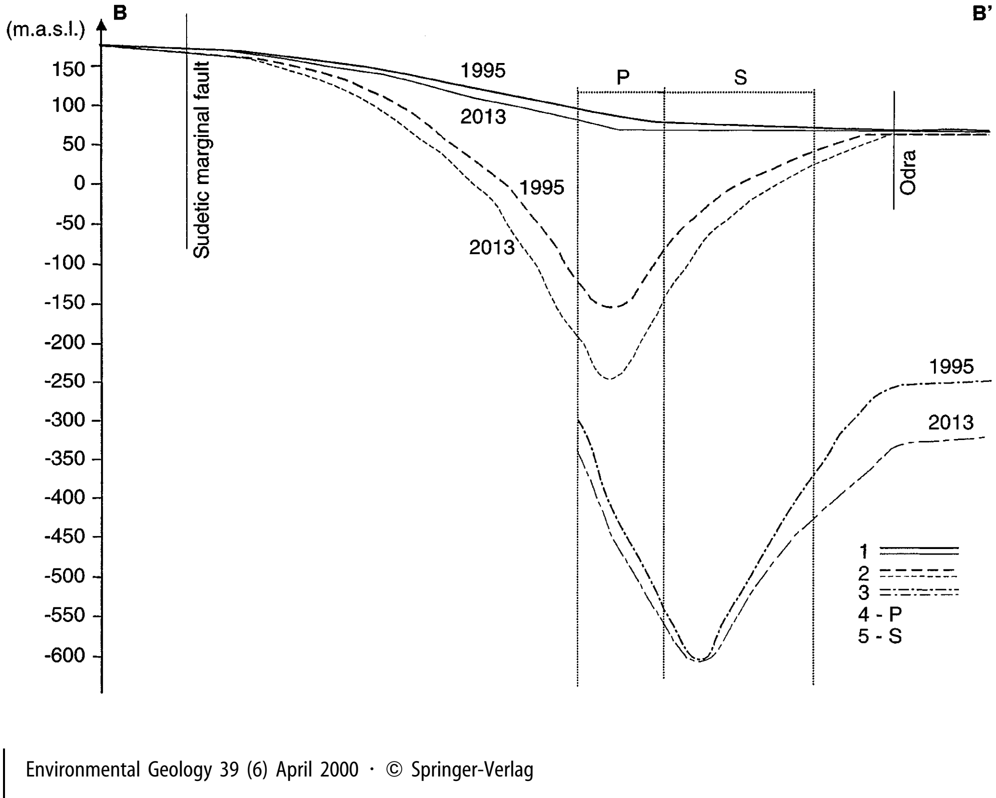


Fig. 3
Progress of depression in dewatering aquifers. Aquifers: *1* inter-lignite Tertiary; *2* sub-lignite Tertiary; *3* W-1 limestones; *4* mine Polkowice; *5* mine Sieroszowice

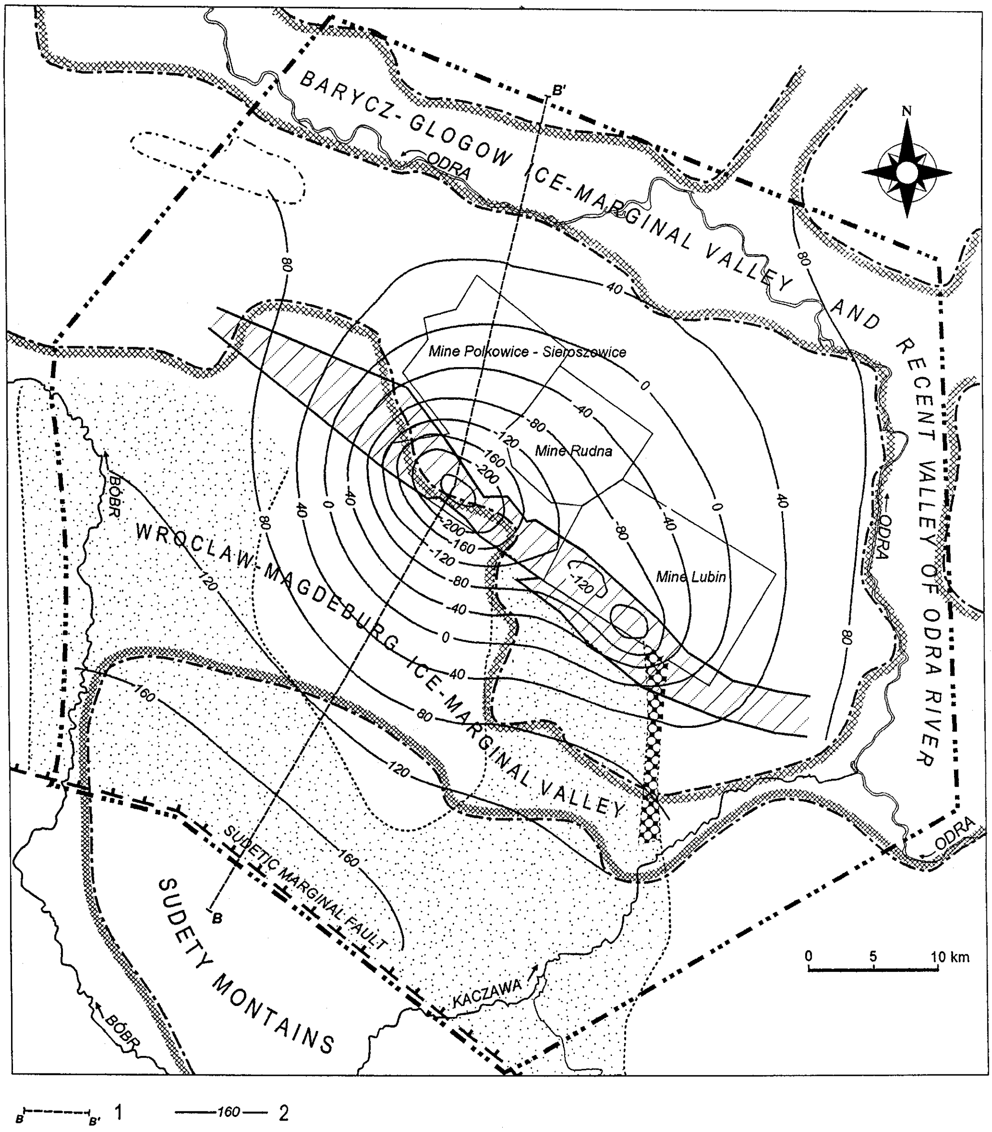


Fig. 4
Prognosis of depression in sub-lignite Tertiary aquifer in 2013 year. *1* section B-- B (Fig. 3); *2* hydroizohypse

rise towards mining areas. The development of the depression cone in the aquifers from 1995 to 2013 is presented on Fig. 3, and the maximum extension of the depression cone in the Tertiary sub-lignite aquifer is presented on Fig. 4.

The results of the model studies carried out during each stage, regarding the quantity of the groundwater inflow to the copper mines, are presented on the summary chart (Fig. 5). From the forecast calculations of the fourth stage show that groundwater inflows for the Lubin and Rudna mines will remain at the same level and for the Polkowice mine they will increase by about 25% from 1995 to 2013.

The balance of the groundwater inflows to the mines, which completes the fourth stage of the model studies, showed that 11% of the inflows are from groundwater storage of the aquifers dewatered during mining operations and 89% of the inflows are from the dynamic groundwater resources of the modeled area, i.e. infiltration, precipitation, recharging aquifers from watercourses and their valleys as well as the underground inflow in the Tertiary sediments from the area of the Sudetic Marginal Fault. Only a small part of this inflow goes through the Tertiary deposits from the southwest boundary of the filtration area. The participation of the groundwater storage in the mine inflow will be smaller and smaller, reaching 1% in 2013.

Final remarks

1. The lgom area can be regarded as a good testing ground for application and development of the numerical modelling methods while forecasting the effects of mining drainage.
2. The model study results presented in the paper were used not only to prepare the designs of mine dewatering, but also to obtain the exact hydrogeological recognition in the area of the deposit.

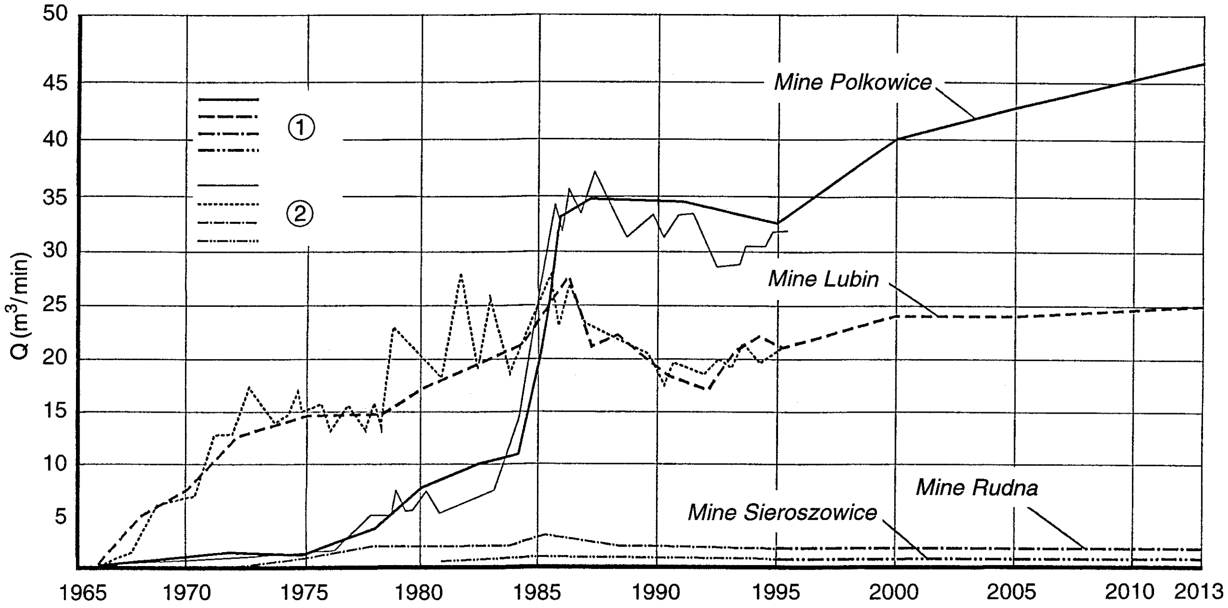


Fig. 5
Lgom mine inflows; *1* inflows according the model studies; *2* real inflows

3. The numerical modelling method, having as a rule only a few piezometers in the mine areas, is often the one which can verify the hypothesis advanced by hydrogeologists and dewatering designers, regarding underground water circulation in the rock mass changed by the antropopression.
4. The predictions about mine inflows made using numerical modelling should always be verified using the results of mines dewatering.
5. The reliable prediction of the depression cone development and mine inflows can be guaranteed if the model of the filtration area, outlined with natural boundaries, places of drainage and recharge of aquifers under the influence of mine dewatering are included.

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