Numerical forecast of groundwater inflow to the mines of the Legnica-Głogów Copper District with a particular emphasis on the "Polkowice-Sieroszowice" mine

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Abstract: The paper presents the results of work on the numerical hydrogeological model of the mines of the Legnica-Głogów Copper District (LGCD) in Poland. Due to the extensive impact on the rock mass and the multi-layer depression cone caused by drainage, the model covers an area of 3,049 km^2. The complicated, mutual hydraulic connections of the multi-aquifer hydrogeological system required the model to cover the area beyond the range of mining areas, and to separate 17 numerical layers. The research was carried out in the GMS software environment using Modflow computing modules. The model was updated successively, since its structure, parameters, and boundary conditions are subject to change. It was also additionally calibrated based on new data from measurements in piezometers and changes recorded in inflows to the excavations. The simulations made it possible to determine the exact water balance, with a particular emphasis on the Sieroszowice mining area, where sudden unexpected inflows were noted. Subsequently, two prognostic simulations were performed to estimate dynamic water inflows to mine workings in the years 2020 and 2025.

Keywords: numerical model update, regional model, complex aquifer system, mine dewatering

INTRODUCTION

The extensive experience to date related to the implementation and several verifications of the numerical regional model for the Legnica-Głogów Copper District (LGCD) indicates that it can be successfully used as a permanent simulation tool for both the entire area and selected mining sites. In addition, it is possible to effectively analyze local issues in specific mine water hazard zones. The current problems with groundwater concern in particular the "Polkowice-Sieroszowice" mine, where increased inflows appeared related to the Main Dolomite aquifer (Ca2).

The concept of a regional numerical model, covering the entire mining area of the LGCD, was developed on the basis of archival materials and the results of previous model research (Bocheńska 1979, Kalisz et al. 1996, Bocheńska & Kalisz 2003a, 2003b, Fiszer et al. 2005, Fiszer & Kalisz 2008). This original model, implemented in 2010 and later modified (Staśko et al. 2011, 2012, Gurwin et al. 2014, 2022), was further updated as part of the work related to documenting the Radwanice-Gaworzyce deposit and other tasks related to excavation water hazard. Another major modification, which is the basis of this publication, took place in 2016, when the geological survey of the mine provided new measurements of the bottom surface of the Basic Limestone (Ca1) and a map of subsidence.

The model covers an area of 3,049 km^2 in order to best represent the natural boundaries of the aquifer system and limit the impact of constraints on side inflows. In this way, natural groundwater recharge areas in the Cenozoic formation, drainage bases in the form of major rivers and watersheds were included in the model. The range of the model is shown in the Figure 1.

The study was based on the assumption that a former regional model can be used as a permanent tool in solving various scale tasks (Gurwin & Wcisło 2018). However, it must be emphasized that the entire model was developed on the basis of long-term average recharge parameters, without taking into account extraordinary situations. This means that simulations cannot predict the threat of sudden water inrush or increased water inflow caused by, for example, rock bursts and rock mass movements.

The view of many authors regarding the maximum simplification of groundwater flow conditions when schematizing the model should be considered (e.g. Bredehoeft 2005, Voss 2011a, 2011b). However, in such a complex aquifer system, it was necessary to map it on a regional scale, separating 11 aquifers and 6 insulating layers (17 model layers). The layers adopted in the model can be divided into two complexes: Cenozoic, in which sedimentary series are generally horizontally deposited, and Sub-Cenozoic, formed by Permian and Triassic deposits dipping to the NE (Fore-Sudetic monocline). Sub-Cenozoic outcrops of these formations form a zone of high drainage in the south and good hydraulic contact with the Cenozoic complex.

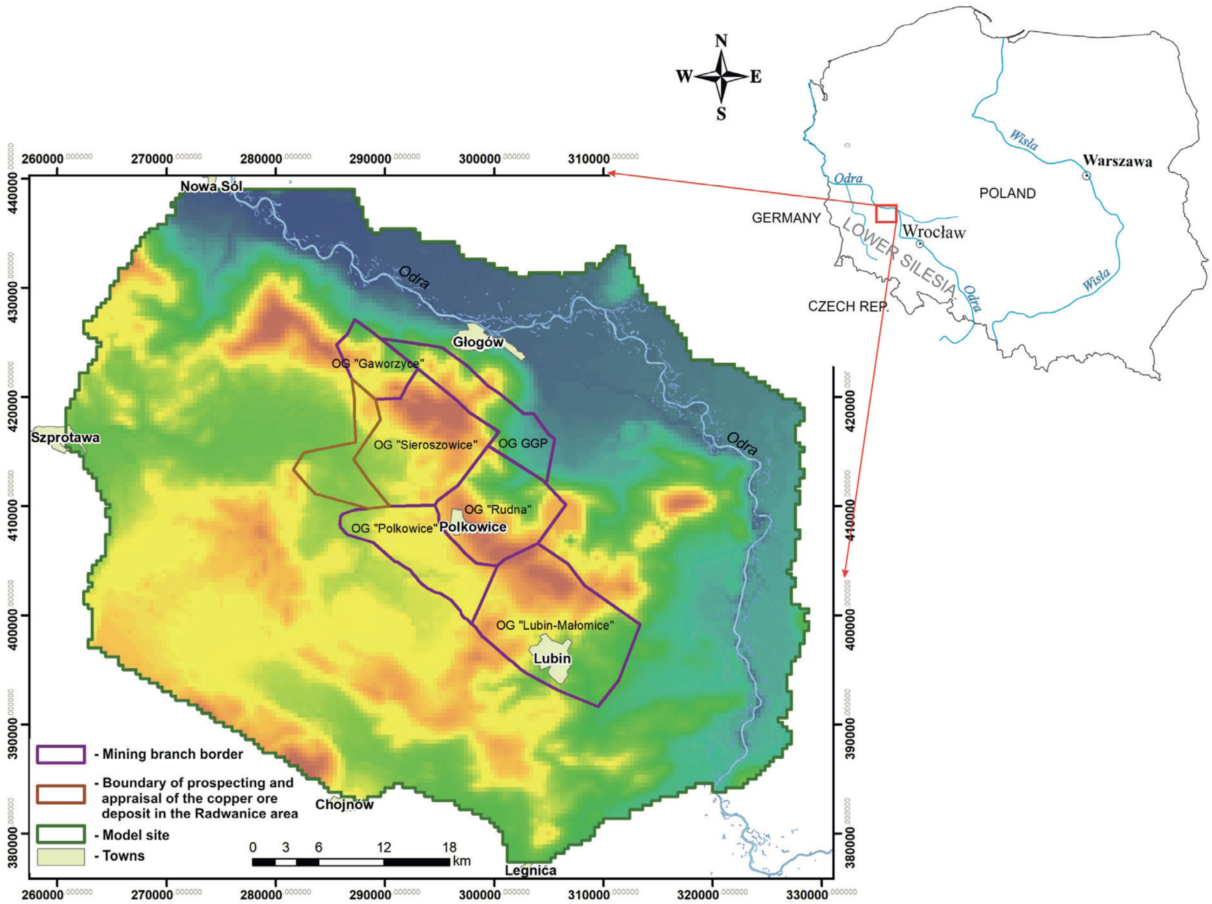

Fig. 1. Location of the study area

Therefore, the problem of high inflows concerns mainly the Polkowice and Lubin-Małomice mining areas (MA) (Fig. 1). The structure and parameters of the regional filtration model have been described in more detail in earlier papers (Staśko et al. 2012, Gurwin et al. 2022). Other articles have highlighted the possibility of a permanent model playing a role in which various simulations and forecasts resulting from the current problems of the mine can be implemented (Gurwin et al. 2014, Gurwin & Wcisło 2018). Progressive exploitation required updating the model in order to represent new batches of excavations and drainage boreholes not previously taken into account. New data collected by the mine's hydrogeological survey indicated the possibility of an approximate separation of inflows into different zones, especially with regard to the most important, due to the size and nature of the inflow, the Sieroszowice MA and Polkowice MA. Along with the progress of mining and pre-emptive dewatering in precisely defined zones, local changes in parameters and boundary conditions had to be defined in such a way as to achieve compliance of the inflow with accuracy to individual zones, not only to the entire mine area, improving the model in this manner.

MATERIALS AND METHODS

Schematization of hydrogeological conditions

The area of modelling research is located, according to the regional division of groundwater, in the region of the middle Odra River (Paczyński & Sadurski red. 2007), within a complex multilayer aquifer system under the influence of long-term mining drainage. In the Cenozoic complex with a total thickness of 350 m in the south to 500 m in the north, there are pore waters in the Quaternary and Neogene aquifers. The Triassic-Permian complex, with a total thickness of several dozen meters to over 1,000 m, collects fissure-porous and fissure-karst waters. In the case of the Triassic aquifer, the variegated sandstone formations and, more northerly, the carbonate series of Muschelkalk also determine the water supply. The Permian aquifer consists of Zechstein limestones and dolomites and Rotliegend sandstones. The implementation of a conceptual model on a regional scale requires the appropriate aggregation of hydrogeological units. A combined Quaternary aquifer (layer 1) was separated, isolated from the underlying overcoal aquifer (3) by a complex of boulder clays and clays (2), then inter-coal aquifer (5) and sub-coal aquifer (7) isolated by clay series (4, 6, 8). Under the Miocene and Oligocene sediments, there are monoclinal formations of Muschelkalk (9), Rhetium (10), Middle and Lower Variegated Sandstone (11 and 12), which are underlain by a sequence of insulating Permian gypsums, anhydrites, and shales (13). Within them, the Zechstein horizon of the main Ca2 dolomite (14) with a thickness of several to over 30 m is isolated, while limestones and dolomites of the Ca1 (16) deposit series with a thickness of several to several dozen meters are of key importance for the direct watering of the excavations. Rotliegend sandstones occur below the bottom of these series (17). Taking into account the appropriate schematization of hydrogeological conditions for the model areas, Figure 2 presents the hydro-stratigraphic conceptual model of the LGCD mine.

Model update and calibration

The study area was discretized with a uniform square grid of elementary blocks with dimensions $x = y = 400$ m. Quasi-steady state conditions were adopted for the calculations. The GMS system package was used, in which calculations of groundwater flow are performed by MODFLOW (McDonald & Harbaugh 1988), which has been proven in many regional studies. The next stage of updating and calibrating the model consisted in adjusting its parameters in such a way as to obtain inflows to the excavations in line with the currently observed ones, and the compliance of heads on the model and in reality. The hydrodynamic state of April 2016 was selected for the calculations.

The structure of the regional model was updated based on a new digital terrain model, which was integrated in the GIS system in the form of averaged values in a grid of 100 m points. Then, the converted average values were entered into blocks of the model's discretization grid, thus producing a new elevation map (Fig. 1).

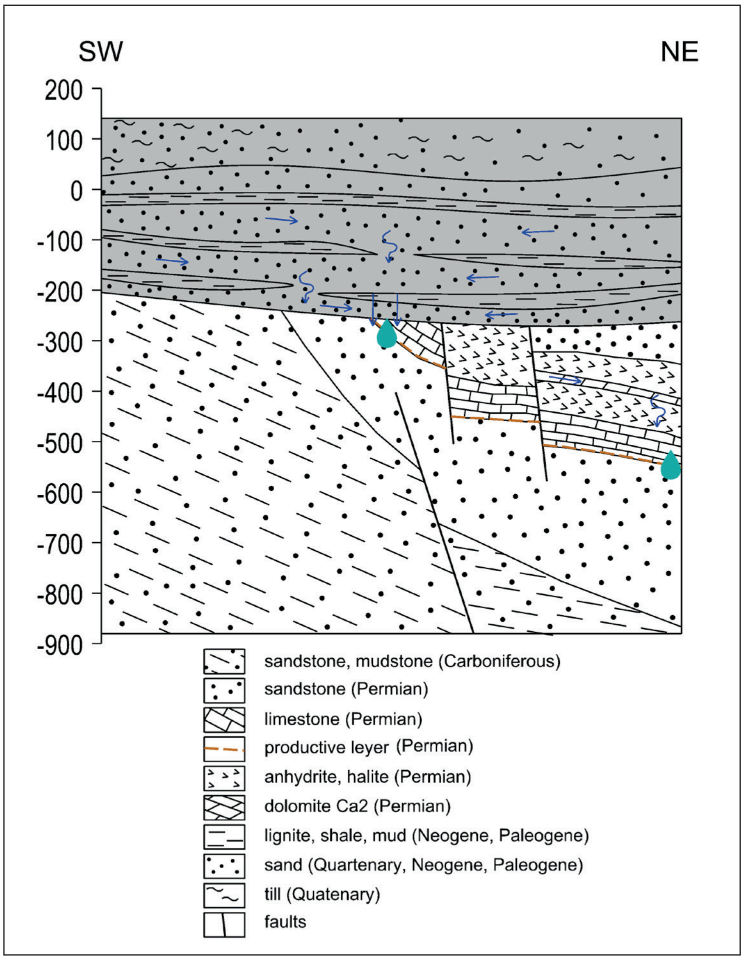

Fig. 2. *Hydro-stratigraphic conceptual model of the LGCD mine. Cenozoic complex is dimmed. High-yield water inflow to the excavations is symbolized with the blue drops. Navy blue arrows reflect the flow direction. Straight tail means relatively high velocity, the waved one – groundwater seepage*

Significant changes result from land subsidence under the influence of mining activity. The introduction of the updated topography also entailed the verification of the parameters of the 3d type boundary conditions (BC) responsible for rivers. All RIVER type BC were adapted to the terrain configuration, mainly lowering in many sections, which improved the consistency of the obtained results of the water table in the first layer, i.e. for the Quaternary aquifer.

Verification of the Zechstein bottom surface was based on the submitted isoline maps for individual mining areas, which, however, did not have any height attributes. These files had to be connected within each isoline and given values (Fig. 3). First of all, the calculation blocks within the area already explored by cutting the ore deposit were checked in this respect. The maps clearly show that in the area not yet excavated, the shape of the isolines drawn is adapted to the recognition points, which results in the "bull's eye" effect, while in the areas already explored, this effect does not exist. Therefore, the geostatistical kriging method originally adopted on the model (especially dedicated to the exploration of raw material deposits) interprets the point exploration in the best possible way (Fig. 3). Additionally, taking into account the adopted grid step, the variability of the values of a few dozen meters is frequent within one block, so the correction in the range of several meters does not change anything. Therefore, the changes were mainly made in the zones indicated as the regions of the current inflows, where the hydrogeological survey encounter water hazard problems. The raster model obtained (Fig. 3) allowed the direct import of values to the model grid.

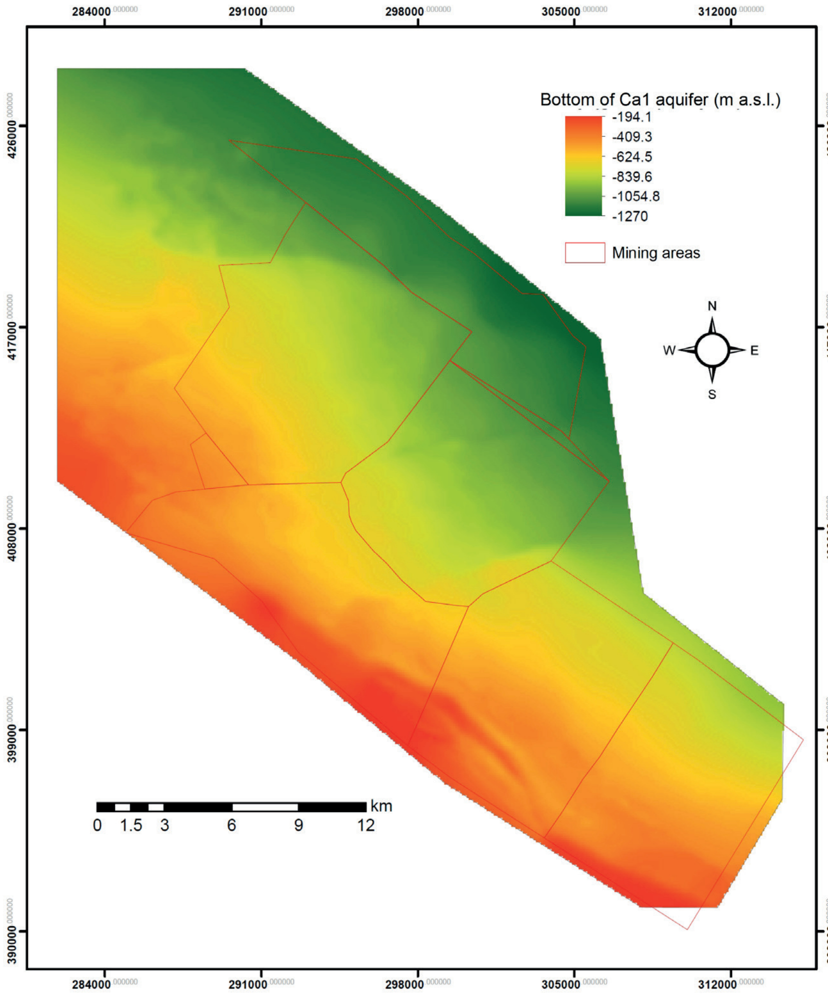

***Fig. 3.** Mapping of the Ca1 aquifer bottom introduced into the model structure*

The calibration consisted of comparing the inflow from the rock mass observed in the excavations and obtained from the model, and comparing the hydraulic heads. The comparison was made on the basis of 20 designated subzones (Table 1). The method of these calculations was presented on the example of the Sieroszowice MA by Gurwin & Wcisło (2018). In most cases, the difference between the inflows measured and those obtained in model studies does not exceed 10%. Cases of greater differences concern relatively low inflows (400–500 L/min). The obtained differences in hydraulic heads ranging from 3 m to 16 m (Table 2) should be considered relatively small, taking into account the fact that the hydraulic gradients reach the value of 500 m/km, and the head variation in individual blocks of the model is approx. 25–200 m. The remaining calibration points also indicate a good level of agreement. The mean absolute error for the whole model domain was 4.6 m, and for the key aquifers: Oligocene (16.4 m), Main Dolomite (Ca2 – 16.5 m), Basic Limestone (Ca1 – 11.6 m).

Water balance calculations were performed for all separated mining areas. However, due to the complicated 17-layer structure, a partial aggregation of model layers was made for practical reasons and flows between selected compartments were analyzed. The following divisions were adopted: (1) Cenozoic complex (1–7 model layers), (2) Sub-Cenozoic complex without Basic Limestone and Main Dolomite (8–13 model layers), (3) Main Dolomite (14–15 model layers), (4) Basic Limestone + Rotliegend (16–17 model layers).

Table 1
Comparison of actual and model inflows

No.	Mining area (MA)	Particularly important areas	Observed inflow from the orogen (Q1 2016)		Inflow calculated by the model		Difference [%]
			[m³/min]	[m³/d]	[m³/min]	[m³/d]	
1	Lubin-Małomice	W-520a; branch G-5/PUGIB; ramp AW-13a	2.827	4,071	2.694	3,879	–5
2	Lubin-Małomice	Ramp S-1	2.020	2,909	2.011	2,896	0
3	Lubin-Małomice	G-1	5.488	7,903	5.512	7,937	0
4	Lubin-Małomice	G-4	1.320	1,901	1.401	2,017	6
5	Polkowice	Level C, K6&7W, C6E, K7W	1.918	2,762	1.931	2,784	1
6	Polkowice	Level H10W	1.323	1,905	1.338	1,928	1
7	Polkowice	Level H9W	0.317	456	0.332	478	5
8	Polkowice	Field H, I on ramp J-43	0.500	720	0.499	719	0
9	Polkowice	Level G-9E	0.284	409	0.279	402	–2
10	Polkowice	G9W+G7&8W	16.265	23,422	16.301	23,474	0
11	Polkowice	G6W	1.037	1,493	0.985	1,419	–5
12	Sieroszowice	GG-5	0.354	510	0.397	571	12
13	Sieroszowice	(GG-6) Level F1W	1.595	2,297	1.463	2,107	–8
14	Sieroszowice	(GG-6) Block CI-CVI (branch G-61)	0.678	976	0.661	925	–5
15	Sieroszowice	(GG-6) Level F2W	0.280	403	0.286	412	2
16	Sieroszowice	(GG-6) The rest part	0.921	1,326	0.981	1,413	6
17	Rudna	Rudna MA	2.055	2,959	2.026	2,917	1
18	Lubin-Małomice	Total area	12.197	17,564	12.586	18,124	3
19	Polkowice	Polkowice MA	24.371	33,444	22.584	32,523	–3
20	Sieroszowice	Sieroszowice MA (without Gaworzyce)	3.838	5,527	3.766	5,423	–2

Table 2
Comparison of hydraulic heads calculated and observed in piezometers located in the vicinity of high-water inflow zone in the Sieroszowice mining area

Measuring point	Aquifer	Model layer	Hydraulic head		Difference [m]
			observed [m]	calculated [m]	
SS-11	Main Dolomite (Ca2)	14	30.61	23.15	7.46
Ra-10 G-31		14	–425.60	–419.36	6.24
S-431		14	–38.33	–17.32	21.00
H-18	Sub-coal (Oligocene)	7	–134.95	–118.61	–16.34
S-365		7	–21.26	–30.89	9.63
S-69		7	–40.97	–38.27	–2.70
SS-10		7	–39.82	–32.03	–7.79
G-14		7	–18.79	–26.84	8.05

RESULTS

Hydrodynamic conditions according to the model simulation

The basic result of the model is the distribution of pressures in the entire multilayer aquifer system. As a consequence of the mine activity, a multi-layer depression cone has been formed and the inflows are concentrated towards the center of the area. The reductions in hydraulic heads are confirmed by observations from the monitoring network installed in all aquifers. The map of the Basic Limestone aquifer (Ca1) gives a picture of the head distribution in the most intensively directly drained deposit horizon (Fig. 4).

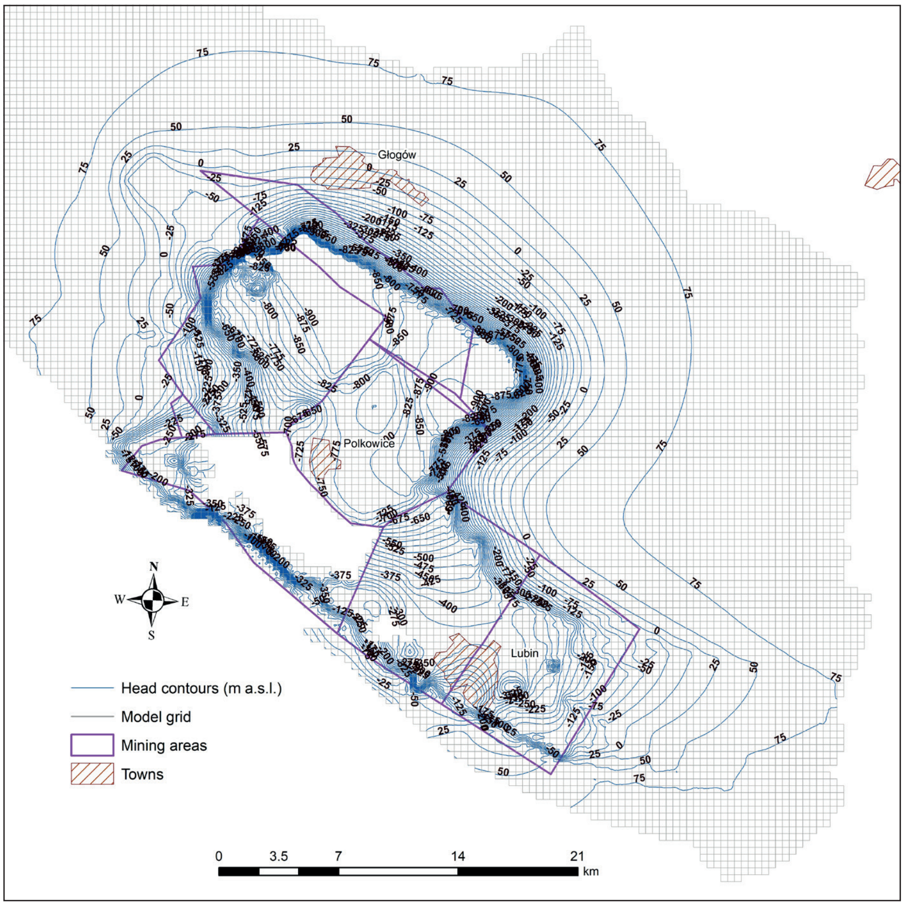

Fig. 4. *Head contour map of the Ca1 aquifer*

The map of the Main Dolomite (Ca2) introduces the effects of transferring the impact of this drainage to the upper aquifers.

The Basic Limestone aquifer in the LGCD area forms an extensive depression cone with the center defined by the area being cut by excavations. It is basically completely or almost completely drained from free water in this part. The exceptions are highly water supplied zones on the outskirts, where the static resources have not been drained or there is a direct supply from the Oligocene aquifer. Within the mining area or in the adjacent strip, the filtration parameters increase in relation to the distant undisturbed rock mass. At the border of this zone, hydraulic gradients are the highest and reach 300 m/km, especially in the northern zones. The head contour map of the Main Dolomite aquifer shows a greater diversity than that of the Basic Limestone. Despite maintaining the general flow direction from the outcrop towards the NE, local deformation zones are clearly visible. Generally, this aquifer should be considered only partially drained. There are several such zones where Ca2 aquifer is clearly influenced by drainage, but only in the area of the G-63 branch in the Sieroszowice MA it is associated with a clearly increased inflow to the excavations. There is a high probability that this inflow comes from dynamic resources. The analysis of the hydrodynamic field indicates that the supply is not only via inflows from Ca2 outcrops, but from higher formations – e.g. variegated sandstone, which has its Sub-Cenozoic outcrops in the analyzed area. These observations are consistent with the results of the water balance calculations.

Inflows to the mines and water balance components

An analysis of the overall water balance for the entire LGCD area was presented by Gurwin & Wcisło (2018), so now the focus is on the results of inflow forecasts for individual mining areas.

However, the key area of hydraulic connectivity of the Ca1 and Ca2 aquifers in the Sieroszowice MA was particularly taken into account. The size of the inflow here depends mainly on seepage from the upper layers (Fig. 5A). The Sub-Cenozoic complex is inflowed from the Oligocene aquifer with about 4,000 m^3/d and a similar amount of water flows further downwards to the Main Dolomite aquifer (Ca2). On the other hand, the analysis of the lowest aquifer (Ca1) leads to the conclusion that the inflow of water from the Main Dolomite (4,441 m^3/d) accounts for 80% of the total supply, the rest comes from lateral inflow and upward flow from Rotliegend formations.

The interpretation of the Polkowice MA water balance (Fig. 5B) leads to slightly different conclusions due to the fact that it covers the Ca1 outcrop zone. The supply through this zone (20,389 m^3/d) should be considered the main source of inflows, which is supplemented by a lateral inflow in the Ca1 aquifer. The analysis of the hydroisohypse map shows that this inflow is primarily associated with the areas located in the north-western part of the Polkowice MA (area of the G7&8W and G9W sections), where the inflow is also associated with the outcrop zones and has basically the same origin as (on the model) "seepage from above". In light of this, it can be estimated that 99% of the inflows are associated with direct seepage from the Oligocene aquifer in or near the mining area itself.

The total inflow from the system to the excavations in the Lubin-Małomice MA (Fig. 5C) is approx. 18,000 m^3/d. The structure of its water supply is analogous to the Polkowice MA. Water seeping from the Oligocene aquifer (19,111 m^3/d) is drained in excavations (18,124 m^3/d) with a slight influence of side inflows/outflows. The structure of the inflow to the Rudna MA (Fig. 5D) indicates that the main source is slow seepage through the overlying aquifer complexes, supplemented by about 10% of inflow from the Basic Limestone and Rotliegend aquifers. Such a relationship is not confirmed, as direct observations in the mine indicate that Rotliegend aquifer is responsible for about 50% of the inflow. It should be noted that the model (representing only dynamic inflows) inflow from static resources is not properly simulated. It can be concluded that in the current situation, about 10% of the sum of inflows to the excavations are dynamic inflows (effectively reflected by the model as an inflow from Rotliegend and Basic Limestone aquifers), and 90% are static resources. With such a methodology, we obtain the correct amount of total inflows, while their forecasting is subject to considerable uncertainty. However, this problem only concerns areas with relatively little change and low inflow (Rudna MA, GGP MA). Water balances for two more northerly areas – called Głogów Głęboki-Przemysłowy MA – are presented below, divided into zones belonging to the Sieroszowice MA and Rudna MA (Fig. 5E, F). Their analysis leads to the conclusion that the structure of inflows is also significantly influenced by static resources, so determining the sources of supply is burdened with a significant degree of error.

Forecast of the impact of the progress of mining excavations on groundwater

On the numerical model calibrated as of 2016, two prognostic simulations were performed to estimate dynamic water inflows to mine workings in the years 2020 and 2025. At the same time, the simulation for 2020 could be treated as a verification, because data for this period are already available. However, this consistency is disturbed due to the described sudden inflows which could not have been exactly predicted. In order to make such forecasts, maps of planned mining excavations for these periods were imported. Then, the distribution of boundary conditions of the 3d type (DRAIN) in the 16th layer of the model was modified so that by locating them in subsequent calculation blocks, the modeled arrangement of excavations was obtained in accordance with the maps (Fig. 6). In this way, in each active block in a given period, a drain with a fixed elevation ordinate operated. The conductivity of the drains was introduced by analogy with the values of the drains already existing in a given area, determined at the calibration stage. Forecasting simulations were conducted in the following directions:

- changes in the hydrodynamic system,
- development of inflow to mining excavations,
- formation of a depression cone in aquifers.

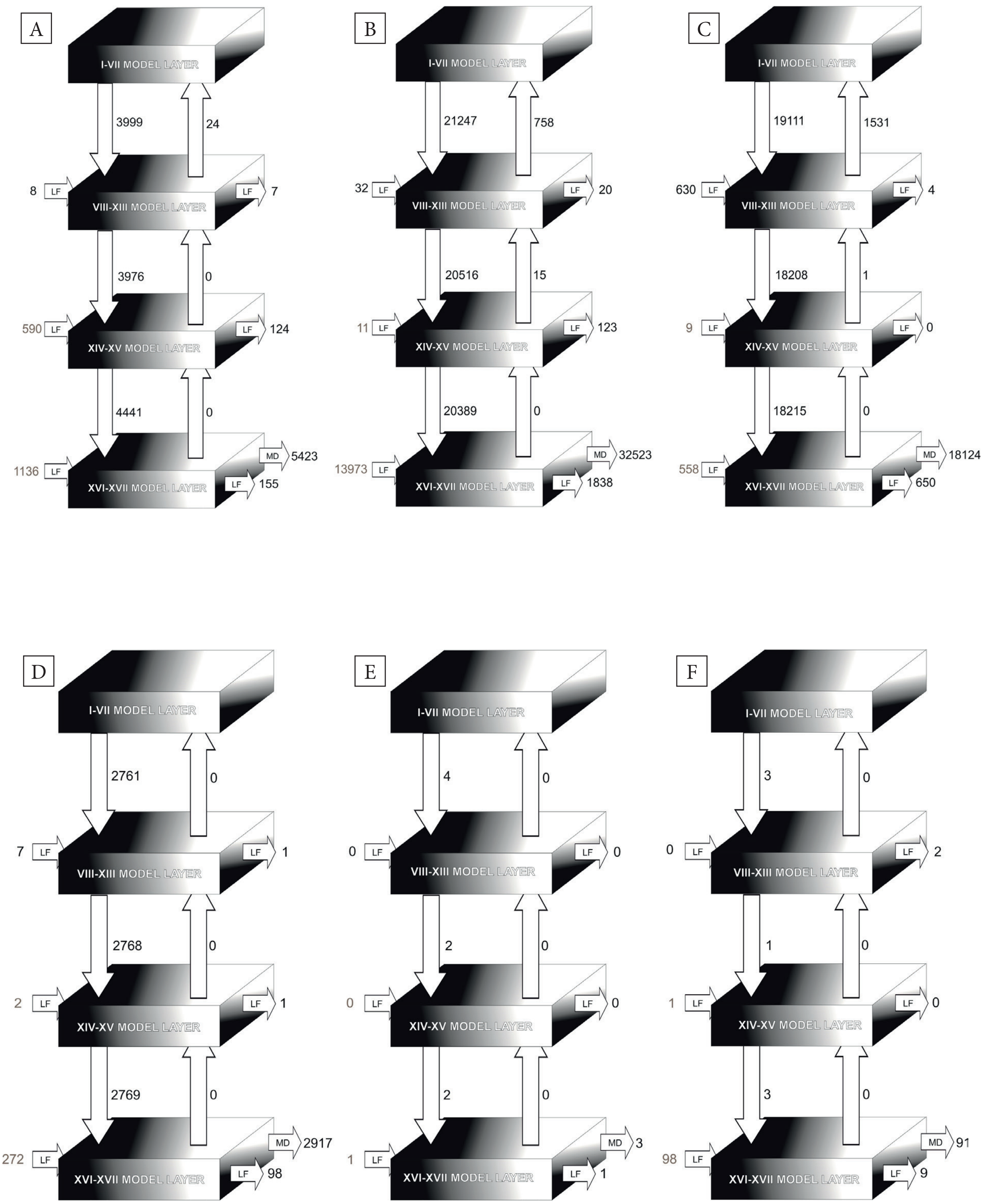

Fig. 5. *Water balance components for: A) Sieroszowice MA; B) Polkowice MA; C) Lubin-Małomice MA; D) Rudna MA; E) GGP MA (W); F) GGP MA (E) [m^3/d]. LF – lateral flow, MD – mining drainage*

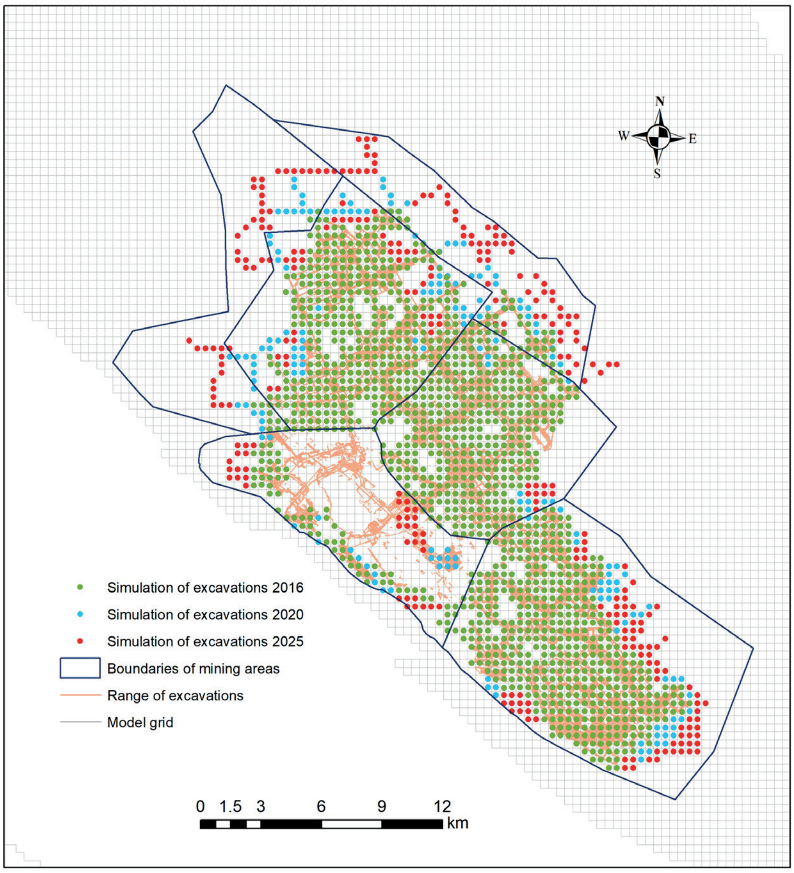

Fig. 6. *Distribution of the 3rd type boundary conditions simulating excavations in the model grid*

Changes in the hydrodynamic system

As a result of the simulations carried out in the following years, a layout of hydroisohypses was obtained for each aquifer. In the case of the Ca1 aquifer, subjected to the direct influence of drainage, very clear changes are visible, adapted to the expected distribution of new excavations. Hydraulic heads as of 2020 vary from −850 m a.s.l. to −1,050 m a.s.l. in the north-western part and from −200 m a.s.l. to −600 m a.s.l. in the south-eastern part up to 25–50 m a.s.l. in the outer regions of the deposit. Very high hydraulic gradients within even single computational blocks are characteristic. According to the calculations for 2025, the head contours layout is similar to the previous one, but the depression cone has been shifted and lowered by several dozen meters, and even several hundred meters locally in the areas of new excavations.

Taking into account the gradual increase in drainage excitations, the propagation of the depression cone is of key importance for the impact on the water abundance of the upper aquifers. The depression cone has an oval shape, elongated in the NW-SE direction and is successively shifted, in the northern part in 2020–2025 over a distance of 300–700 m. In the NW, the depression cone widened much more, within 2 km, and on the SE by about 0.5–1.0 km on average. The transverse size of the cone is approx. 29–30 km for the assumed periods. This causes the effect of lowering the pressure also in the Ca2 aquifer, which is also clearly visible, but with a smaller range, which across the cone is approx. 28.5–29.0 km, respectively. The effect of reduced pressures is also observed in the Oligocene sub-coal horizon, for which the depression cone is widened NE by about 850–950 m, and SW by 300–500 m by 2025. Changes in the longitudinal axis are more visible from approx. 54–57 km for the Basic Limestone aquifer, 49–51 km for the Main Dolomite aquifer and 63–64 km for the Oligocene aquifer.

Changes in the size and extent of individual depression cones are shown in Table 3.

Table 3
Projected changes in the area of depression cones according to model forecasts [km^2]

Year	Oligocene aquifer	Ca2 aquifer	Ca1 aquifer
2016	2,387	1,081	1,180
2020	2,402	1,104	1,203
2025	2,489	1,169	1,265

Changes in the water balance

Changing the mining drainage system in subsequent years will result in changes in the total inflows to the area covered by the model (Table 4). There will be an expected increase in inflows at the expense of outflows from 732,056 m^3/d (2016) to 732,622 m^3/d (2020) and 733,929 m^3/d (2025), which is manifested in small percentage increases of 0.1% and 0.3%, respectively. This is the result of the increase in the extent of the mines, so the most important element of the balance is the total outflow to the excavations, which will increase, respectively: from 59,097 m^3/d (2016) to 60,463 m^3/d (2020) and 63,881 m^3/d (2025). At the same time, a slight reduction in the drainage of surface watercourses is observed from 601,538 m^3/d (2016) to 601,178 m^3/d (2020) and 600,178 m^3/d (2025), i.e. around 2.5%.

Total inflows to mining excavations will therefore increase in subsequent periods by approx. 3% (2020) and 9% (2025) compared to the initial period. Expanding the mining drainage system will cause slight changes in the amount of seepage both from and to the Basic Limestone aquifer (Tab. 5).

Table 4
Water balance of the LGCD area according to model forecasts for assumed average conditions

Balance components		2016		2020		2025	
		[m^3/d]	[%]	[m^3/d]	[%]	[m^3/d]	[%]
Inflows	Lateral inflow/outflow	+61,161	8.4	+61,697	8.4	+62,922	8.6
	Rivers	+29,498	4.0	+29,528	4.0	+29,610	4.0
	Recharge	+641,397	87.6	+641,397	87.6	+641,397	87.4
	Drainage by excavations	0	0	0	0	0	0
	Pumping wells	0	0	0	0	0	0
	Total	+732,056	100.0	732,622	100.0	733,929	100.0
Outflows	Lateral inflow/outflow	−52,913	7.3	−52,471	7.2	−51,361	7.0
	Rivers	−601,538	82.2	−601,178	82.1	−600,178	81.8
	Recharge	0	0	0	0	0	0
	Drainage by excavations	−59,097	8.0	−60,463	8.2	−63,881	8.7
	Pumping wells	−18,500	2.5	−18,500	2.5	−18,500	2.5
	Total	−732,047	100.0	−732,613	100.0	−733,920	100.0
Difference		9	0.01	9	0.01	9	0.01

Table 5
Groundwater balance of the Basic Limestone aquifer according to model forecasts [m^3/d] for assumed average conditions

Balance components		2016	2020	2025
Inflows	Lateral inflow	65.0	92.3	124.4
	Seepage from the upper aquifer	62,272.7	63,579.6	66,868.9
	Seepage from the lower aquifer	1,529.5	1,550.1	1,631.5
	Total	63,867.2	65,221.9	68,624.8
Outflows	Lateral ouflow	3,223.4	3,189.8	3,090.9
	Seepage to the upper aquifer	17.7	18.8	21.2
	Seepage to the lower aquifer	1,529.5	1,550.1	1,631.5
	Drainage with mining excavations	59,096.6	60,463.2	63,881.3
	Total	63,867.2	65,221.9	68,624.8

An increase in the inflow from the bottom is expected from the value of 1,530 m^3/d in 2016 to 1,550 m^3/d in 2020 and 1,631 m^3/d in 2025. The low value of the lateral inflow to the Basic Limestone aquifer will increase by about 50% (from 65 m^3/d to 124 m^3/d in 2025). The lateral outflow will decrease from 3,223 m^3/d up to 3,091 m^3/d. Seepage from the upper layers to the Basic Limestone aquifer will change from 62,273 m^3/d in 2016 to 63,579 m^3/d in 2020 and 66,869 m^3/d in 2025.

Forecast simulations of water inflow to the mines

According to the calibrated state (2016), groundwater inflows to the excavations are at the level of approx. 59,000 m^3/d. The forecast of total inflows for individual mining areas (Table 6) indicates a general increase with the progress of exploitation. Apart from the Rudna MA, where, according to data from that period, stabilization was expected.

Table 6
Groundwater inflows to the excavations in 2016, 2020 and 2025 according to model forecasts

Inflows	Mining area											
	Polkowice			Sieroszowice			Rudna			Lubin-Małomice		
	2016	2020	2025	2016	2020	2025	2016	2020	2025	2016	2020	2025
Per day [m^3/d]	32,523	32,480	34,313	5,423	5,817	5,894	2,917	2,941	2,865	18,124	18,964	19,868
Per minute [m^3/min]	22.585	22.556	23.828	3.766	4.040	4.093	2.026	2.042	1.990	12.586	13.169	13.797

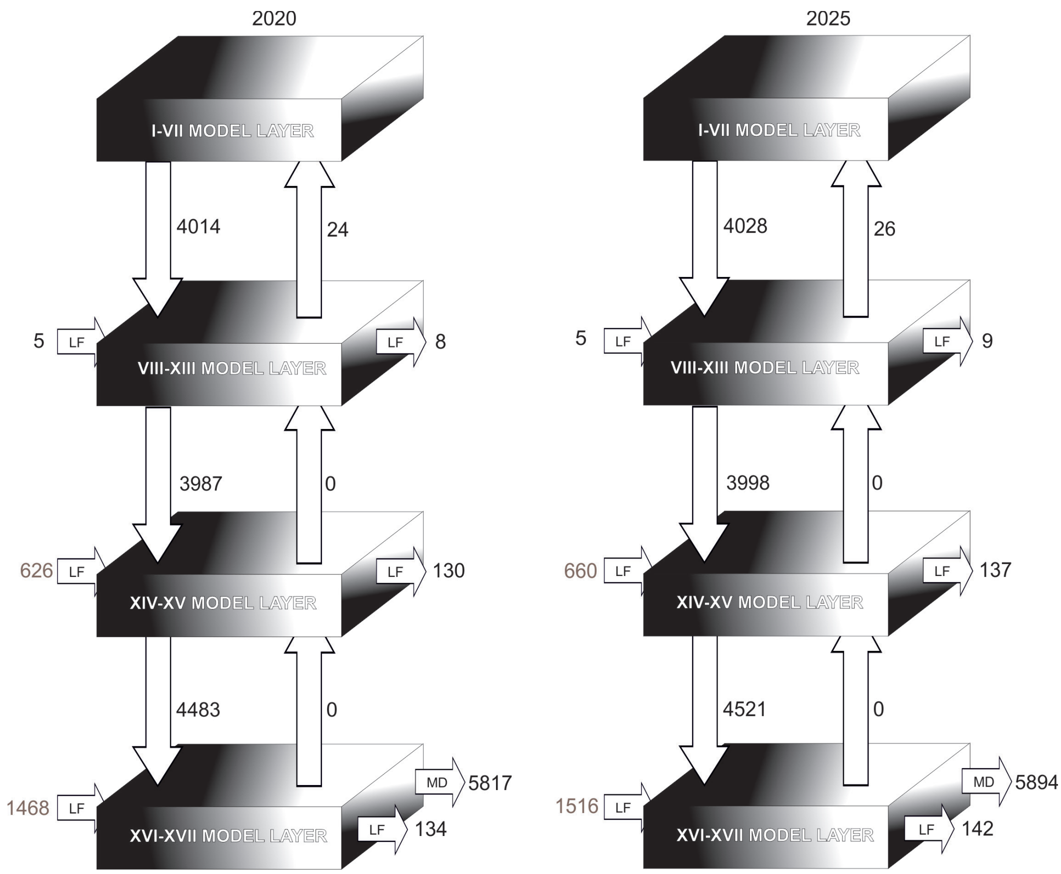

Fig. 7. *Water balance components according to the forecast for the Sieroszowice MA*

However, it should be borne in mind that a direct comparison of forecasts with actual total inflows, e.g. for 2020, is difficult, because the model solves dynamic inflows, and this is compounded by the described problems of sudden inflows that cannot be predicted.

For the Sieroszowice MA, the forecast scenario assumes (Fig. 7) that by 2020 there will be an increase in inflows by approx. 400 m^3/d (0.27 m^3/min, 7%), and by 2025 it will be a slight increase by approx. 80 m^3/d (0.06 m^3/min). The main source of supply will still be seepage from upper formations, which will increase only slightly in the case of the Oligocene aquifer (by 15 m^3/d in subsequent periods), remaining at the level of approx. 4,000 m^3/d (2.8 m^3/min). A similar amount of water flows downwards to the Main Dolomite aquifer (3,987 m^3/d and 3,998 m^3/d, respectively). In the Main Dolomite (Ca2) aquifer, seepage from above supplemented by a lateral inflow forms the main source of supply for the Basic Limestone (Ca1) aquifer, which increases from 4,441 m^3/d (3.08 m^3/min in 2016) to 4,483 m^3/d (3.11 m^3/min in 2020) and 4,521 m^3/d (3.14 m^3/min in 2025).

Forecast simulations for the Polkowice MA (Fig. 8) indicate that after initial stabilization at the level of 32,480 m^3/d (22.6 m^3/min), mining drainage will increase by 1,833 m^3/d to the level of 34,313 m^3/d (23.8 m^3/min), i.e. by approx. 6%.

In the Lubin-Małomice MA, an increase in the total inflow to the excavations by 2020 by approx. 800–850 m^3/d was demonstrated – to the level of 18,964 m^3/d (13.16 m^3/min), while until 2025 there will be a further similar increase of 900 m^3/d – to the value of 19,868 m^3/d (13.79 m^3/min).

In the Rudna MA, the inflows will be at a stable level with the possibility of slight decreases in subsequent years from 2,917 m^3/d up to 2,865 m^3/d. It is expected that, in accordance with the regional distribution of the hydrodynamic field, along with the progress of works in the GGP MA (E), there will be a slight reduction in inflows to the "Rudna" mine, after a slight increase previously, i.e. generally stabilizing in the assumed periods at the level of 2,900 m^3/d (2.01 m^3/min).

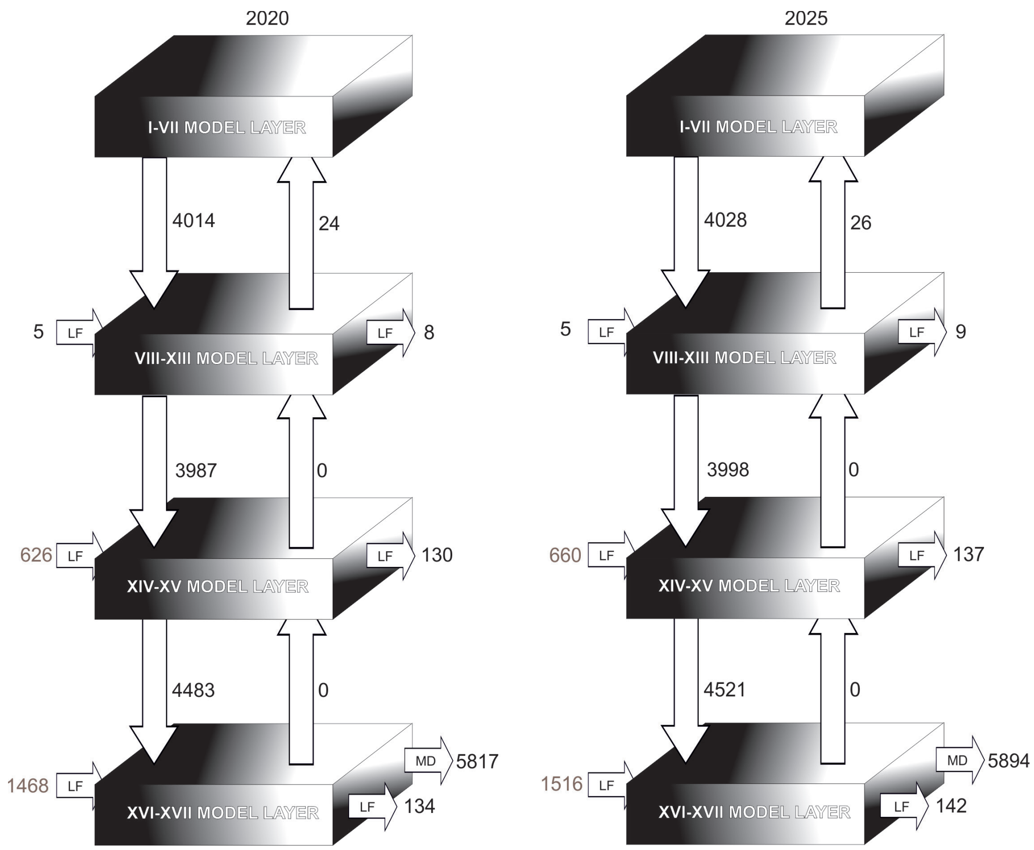

Fig. 8. *Water balance components according to the forecast for the Polkowice MA*

DISCUSSION

Inflows to the mines were determined by analyzing the inflow to the DRAIN type boundary condition in the model area. It should be noted that, despite the fact that this is a steady-state model, the inflow value was close to the total value. Therefore, for areas with a large share of static resources (Rudna MA and GGP MA), forecasts should be treated with caution. Inflows to the GGP MA were verified with actual values due to their static nature i.e. the modeled values of dynamic inflows were added to the observed values. A dynamic increase in inflows is also presumed in the coming years in connection with the mining plans in various parts of the deposit areas. The actual inflows will mainly be influenced by factors related to the geological conditions of the contacts of the Oligocene and Basic Limestone aquifers as well as the Oligocene and Miocene aquifers in the areas of the planned extension of exploitation towards SE and W, and the grade of fissuring within the Ca1 aquifer. Due to the difficulties in predicting the described phenomena, the presented forecasts should be treated with great caution, assuming that they are highly credible, but according to the current degree of recognition of hydrogeological conditions. As a result of dewatering, the rock mass becomes stronger and stiffer, hence mining tremors occur more often, and as a result, compressed and loosened zones appear, which may result in a sudden strong inflow from the overburden.

Considering the most important mine due to the actual water hazard i.e. the Sieroszowice MA, the water balance of the lowest aquifer (Ca1) indicates that in the coming years, the inflow of water from the Main Dolomite (Ca2) aquifer will remain at a level slightly below 80% of the total supply – the rest comes from the Ca1 and Rotliegend aquifers. A slight increase in the share of lateral inflows will be observed from 20.0% to 21.4% and 21.7%, which is: 1,136 m^3/d (2016), 1,468 m^3/d (2020) and 1,516 m^3/d (2025).

Thus, the hydrodynamic system will be maintained, in which the Ca2 aquifer is recharged primarily from the Sub-Cenozoic complex (a slight decrease from 87% to 86.4% and 85.8%), and the Sub-Cenozoic complex – practically exclusively from the Oligocene aquifer. Thus, the inflow from the Oligocene aquifer will remain the main source of water drained by the workings of the Sieroszowice MA, and the remaining approx. 20% is formed in the Main Dolomite unit. However, as noted earlier, in such a complicated system of multilayer flows, the Ca2 aquifer, due to low filtration and capacity parameters, is not a good resource collector and is also indirectly supplied from the Oligocene aquifer.

Considering the Polkowice MA this area includes the Ca1 outcrop zone, so changes in the balance components have slightly different characteristics. The recharge through this zone should be considered as the main source of inflows, which will increase from 20,389 m^3/d (2016) to 20,398 m^3/d (2020) and 21,452 m^3/d (2025), remaining at the level of approx. 60% of the total sum of inflows, and will be supplemented by a lateral inflow in the Ca1 aquifer (change from 13,973 m^3/d (2016) to 13,900 m^3/d (2020) and 14,202 m^3/d (2025), also associated with the outcrop zones. Therefore, 99% of the inflows are associated with direct seepage from the Oligocene aquifer within or near the mining area.

Having the forecasts for the Rudna MA, the assessments from the 2016 calibration phase can be upheld that the main source of water in this mine is slow seepage through overlying aquifers, supplemented in about 10% by inflow from the Basic Limestone and Rotliegend aquifers. However, one should bear the earlier explanation in mind that the inflow from static resources plays a major role, something which is only indirectly simulated in the model.

The obtained results can be related to the approximate analytical calculations contained in the hydrogeological documentation (Stochel et al. 2013, 2014a, 2014b). In the case of the Lubin-Małomice MA, the values of the inflows are consistent with those presented in the aforementioned study. For the years 2020–2034, 15–25 m^3/min is expected, which means that the model calculation results, equal to 13.17 m^3/min (2020) and 13.8 m^3/min (2025), are slightly below the stated minimum values. For the Polkowice MA for the years 2021–2025, the study provides a range of inflows from min. 20 m^3/min to max. 30 m^3/min (avg. 23–26 m^3/min). This means that the inflows from the model calculations (22.56 m^3/min and

23.83 m^3/min) are fully in line with the low average values given. Inflows to the Rudna MA were only roughly estimated at 2.05 m^3/min and this is fully consistent with the model simulations (2.04 m^3/min – 2020 and 1.99 m^3/min – 2025).

In the case of the Sieroszowice MA, the documentation provides a range from min. 2.2 m^3/min to max. 2.8 m^3/min. However, this is due to the fact that at the stage of preparation of the documentation, the phenomenon of water inflow from the Ca2 aquifer to the Ca1 aquifer was much less intense (no inflow in the F1W, F2W areas). Its dramatic growth was impossible to predict. The calculations of the model showed that the inflows should be at the level of 3.8–4.0 m^3/min in the years 2016–2025, i.e. above the ranges quoted in the documentation. However, this was revealed after the latest exploration of the deposit and the model's reflection of these updated conditions (2016), additionally assessed by sub-areas.

CONCLUSIONS

The numerical model, the base version of which was created in 2010, has been the subject of significant updates as part of this work, involving: (i) introduction of the bottom of the Ca1 aquifer in accordance with the results of new measurements; (ii) introduction of a new DTM, taking into account mining subsidence; (iii) update of river parameters; (iv) calibration based on monitoring points and inflow data from the first quarter of 2016.

The results of numerical simulations showed that in the Polkowice MA and Lubin MA, 99% of the inflows come from dynamic resources, mainly from the Cenozoic complex. In the case of the Sieroszowice MA, water supply comes mainly (approx. 80%) from the Main Dolomite aquifer. This horizon is also fed by a lateral inflow, which can be interpreted as a recharge at Sub-Cenozoic outcrops.

A key zone in the vicinity of the G-63 section (due to technical difficulties in dewatering) has its source of water in the Main Dolomite aquifer, which is supplied from above, not by lateral inflow from the outcrops. It is proven by the generally low filtration parameters, i.e. very low hydraulic conductivity and poor water storage capacity. Also, the high heterogeneity of the Ca2 aquifer makes the attempt to identify it as a source of inflow rather dubious. When estimating the renewability of the Ca2 aquifer in unrecognized areas (thus influencing the forecasts), it was considered that the discussed area in the G-63 section is unique. Its genesis is related to tectonic factors, but mining activity, including the method of liquidation of excavations, induces mining tremors and causes the destruction of the rock mass. As a result, a privileged zone for the flow is created and this zone probably also extends to the variegated sandstone series. Thus, the Ca2 aquifer is rather a transmission zone for waters coming from the upper layers, finally being recharged from the Oligocene aquifer.

Forecasts of total inflows have been developed for the years 2020 and 2025. In most cases, slow increases in inflows are expected for the periods mentioned. Considering the Lubin MA, the average inflows in 2019–2020 were 16.35 m^3/min, which gives 13.8 m^3/min in terms of dynamic inflows, which is only slightly more than predicted in the model. The summarized inflow in the "Polkowice-Sieroszowice" mine projected for 2020 is 26.6 m^3/min, which has been also confirmed by the latest measurements. Data obtained from the mine for 2020 indicate the total inflow of 31.2 m^3/min, and considering that dynamic resources constitute in this region approx. 85% (i.e. 26.5 m^3/min), the compliance achieved is more than satisfactory. Unfortunately, however, a significant increase in these sudden inflows is still being recorded, so further attempts will be made to reproduce and calibrate the value of inflows on the model in future research. In the light of the mining exploitation to date, it seemed that this was an exceptional situation.

An attempt to rebuild the entire model to the unsteady conditions seems to be an overly complex task but, if necessary, such a forecast can be made for a strictly selected region, which would allow inflows from specific storage to be included in the water balance.

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