Predictive modelling of filling with water the Bełchatów Lignite Mine final excavations

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Abstract: The U.S. Geological Survey's program MODFLOW was used to simulate the process of filling with water two post-mining excavations in the Bełchatów lignite mine. The cumulative volume of the Bełchatów and Szczerców reservoirs will reach 2.4 billion m^3 and the area about 32.5 km^2. The results obtained during simulation performed in the regional groundwater flow model has shown that the process of filling the reservoirs with water in a natural way will last for about 60 years, but the steady-state conditions will be reached after 120 years. In the case of additional recharge of both reservoirs with water from outside the cone of depression at a rate of 120 m^3/min and 240 m^3/min this process will last 28 and 18 years, respectively.

1 INTRODUCTION

The lignite open cast mine Bełchatów is the second open pit all over the world and has production capacity 38 mill T/y, overburden stripping is 110 mill m^3 yearly, the depth of operation is about 200 m and the area of the open pit is 23 km^2. At present the exploitation is conducted on the Bełchatów Field, whose area will amount to about 33.6 km^2 and the maximum depth of operation will attain 280 meters. In 2002 overburden stripping and in 2007 lignite production will start at the adjacent Szczerców Field. The designed area of Szczerców open pit will be about 21 km^2, while the depth of the open pit will reach maximum 280 meters. The dewatering system in Bełchatów open pit has been operating since 1975. The total volume of water pumped-out from the beginning to the end of 1998 is up to 4 billion m^3. The average lowering of natural groundwater table within area of mining operation is about 200 m. The cone of depression which varied from 106 km^2 in 1976 to 635 km^2 in 1993, presently is about 460 km^2. It will be increased to about 800 km^2 after starting of dewatering system on the Szczerców Field in 2000.

In 2019 it is planned to complete lignite production at the Bełchatów open pit. The depth of the final excavation will reach 280 meters, the area about 17.5 km^2 and its total volume more than 1.9 billion m^3. Adjacent Szczerców open pit, which will finish lignite exploitation in 2038 will reach the depth of about 280 meters, area of about 15 km^2 and volume more than 1.8 billion m^3. A general purpose of the management of both abandoned pits will be to shallow them with overburden and create there two huge water reservoirs, which area will reach 32.5 km^2 and volume of 2.4 billion m^3 (Figure 1).

As the slopes of Bełchatów open pit final excavation are being shaped just now and also, for reason of protection of a salt diapir situated between Bełchatów Field and Szczerców Field as well as for improvement of lignite mine management at adjacent
Szczerców open pit, the problems of final reclamation in both reservoirs require thorough analyses to be made as early as now.

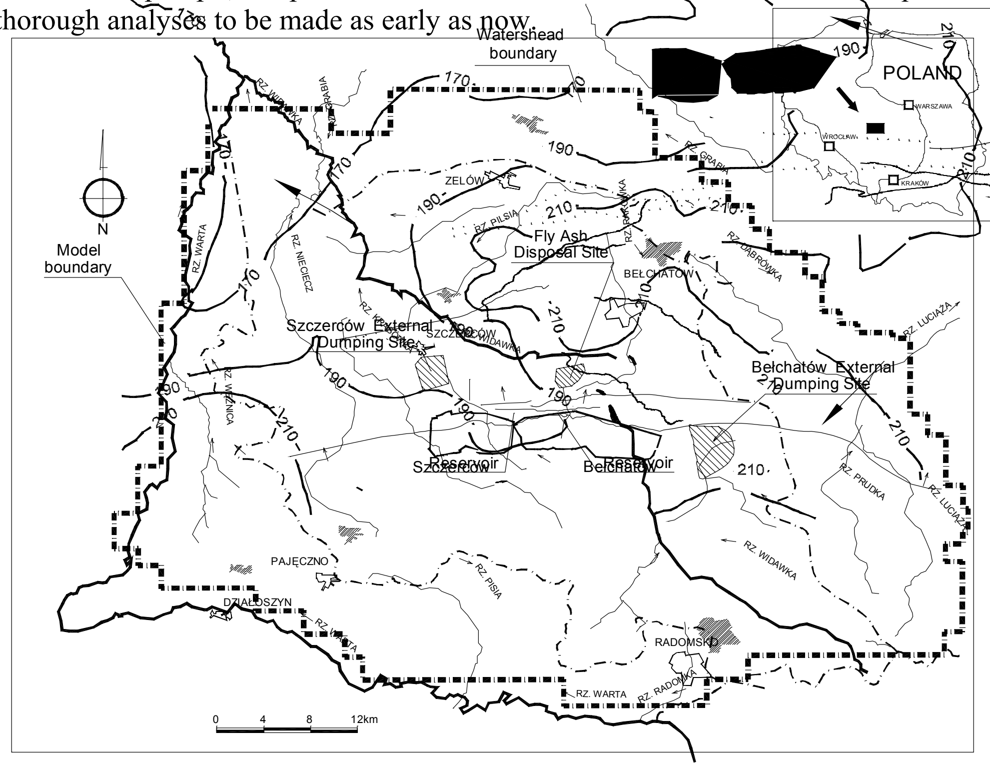


Figure 1 The range of the numerical model in the area of the Bełchatów lignite mine with groundwater contours for postmining condition

2 HYDROGEOLOGICAL CONDITIONS

The Bełchatów Lignite Basin is deposited in the tectonic rift valley having length of 60 km and width of 0.5 - 2 km. Its maximum depth amounts to 500 m. In the central part of the rift valley the „Dębina" salt dome divides the lignite basin into the Bełchatów Field and Szczerców Field.

The Mesozoic base is formed by Jurassic and Cretaceous rocks. Mesozoic aquifers are: fractured limestone, marls and sandstone. This aquifer occurs at the depth about 40 to 100 m around rift valley, but within the rift valley at the depth of about 400 m. The average hydraulic conductivity for this fissured aquifer is about 5 m/day, but is very diversified; the highest permeability occurs in karstified limestones.

Tertiary formations occur within the rift valley at the depth 90 to 400 m. Permeable sand strata have the hydraulic conductivity of about 1 to 3 m/day and are about half of all Tertiary formations. The other half are clays and lignite - both impermeable.

Quaternary formations occur in the whole area. Their maximum depth amounts to 300 m occur in the northern part of Bełchatów Field in post glacial buried valley. In the other parts of the region the depth of Quaternary formation is about 90 m. It consists of sand-gravel about 70 percent and 30 percent of clays. The average hydraulic conductivity for sand-gravel series is about 20 m/day.

The aquifers occurring in the particular stratigraphic series have many geological and hydraulic connections, so the whole complex of the permeable rocks create one huge and heterogeneous aquifer in the whole region.

The lignite basin and its surroundings are in the south part of Widawka River basin with area of 1525 km^2. The natural groundwater table occurred 2 to 5 m below the terrain surface with flow towards N-W direction. The water balance for the Widawka River basin, before dewatering of the mine resulted in that for total sum of precipitation feeding this region - 620 mm/y, total runoff has taken 29 percent, but 71 percent has been evaporated. The baseflow was 3.53 $l/s/km^2$ (Sawicki, 1977). In the most part of the area the potentiometric pressures in both layers were similar or the same.

3 CONCEPTUAL MODEL AND COMPUTER CODE SELECTION

The numerical model used for simulation of the ground-water flow system was USGS modular three-dimensional finite-difference ground-water flow model MODFLOW (McDonald & Harbaugh, 1988).

To determine the dimensions of the numerical model and the design of the grid the conceptual model was built. The lateral boundaries were beyond the radius of influence of the measured and predicted cone of depression. It was based on physical boundaries - rivers and hydraulic boundaries that include groundwater divides and streamlines (Figure 1).

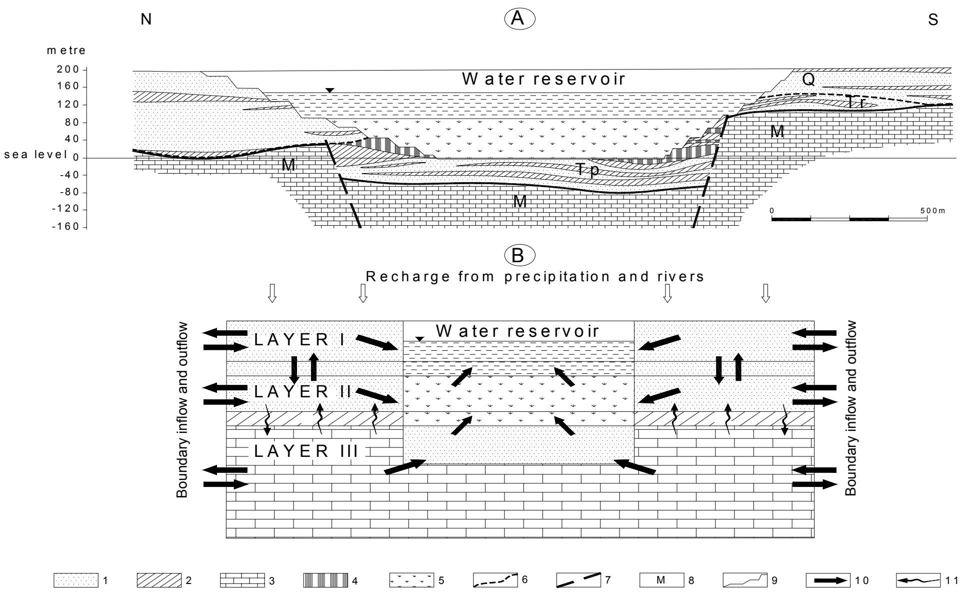
In case of premining and mining conditions the study area was vertically divided into two hydrostratigraphic units: the first one consists of a porous Quaternary and Tertiary aquifer, and the second one consists of a Mesozoic fissured-karstic aquifer together with Tertiary lignite underlying aquifer (Szczepiński & Libicki, 1999).

After the final reclamation of the Bełchatów abandoned pits related to its partial backfilling, the process of filling the pits with water will start. The postmining excavations of the Bełchatów and Szczerców open pits will become a new element in the regional groundwater circulation system. In the whole area a new hydrogeological system will be formed, with reservoirs filling with water being a part of it. To simulate the new groundwater flow system the two - layered conceptual model has been changed to three - layered model. It consists of:

- layer I – represented by upper part of Quaternary aquifer [Q] and Tertiary aquifer [Tr] outside of the pits and water reservoirs inside of the pits,
- layer II – represented by lower part of Quaternary aquifer [Q] and Tertiary aquifer [Tr] outside of the pits and overburden inside of the pits,
- layer III – represented on the whole area by the Mesozoic fissured-karstic aquifer [M] together with Tertiary lignite underlying aquifer [Tp] (Figure 2).

The vertical expansion of layers varies in space. The top of the layer I in the area of water reservoirs equalled to the water level in premining condition, while the bottom was determined with the originate of the top of the overburden used for shallowing the

Figure 2 Simplified N-S geological cross-section through the reservoirs area (A) with the



conceptual model suitable for numerical modelling (B).

1- porous, permeable formations, 2- impermeable and slightly permeable formations, 3- fissured-karstic formations, 4- lignite, 5– overburden, 6- boundary of the Quaternary aquifer, 7- faults, 8- symbols of aquifers, 9- open-pit limits, 10- direction of groundwater flow, 11- direction of groundwater percolation

excavations; +90 m above sea level. The top of the layer II corresponded to the bottom of layer I, while the bottom of this layer was equal to the ordinates of final excavations directly after lignite production.

Outside of the water reservoirs layers I and II have been created within the limits of the layer I existing for premining and mining conditions. Hydraulic parameters and the cumulative thickness of both layers was equalled to these of layer I assumed for two-layered model. The layers I and II contact directly in every place.

For the layer III all hydraulic parameters as well as thicknesses were the same as for layer II in premining and mining conditions.

4 GROUNDWATER FLOW MODEL CONSTRUCTION

The study area of about 2500 km^2 was represented by a grid consisting of 86 rows, 151 columns and 3 layers. The grid was irregularly spaced. Node spacing ranged from 100 m in area of excavations to 1000 m near the model boundaries. The model simulated horizontal flow within each layer and vertical flow between layers through the confining bed. The layer I and II were simulated as unconfined aquifer and the layer III as a confined/unconfined aquifer with variable transmissivity.

For simulation of groundwater flow system the identical lateral limits of the model and the external boundary conditions as for preminig and mining model were used. The internal boundary conditions simulating the open pit dewatering system have been removed. The heads from the end of 2049 were used as initial conditions.

The numerical model developed for simulating mining conditions was adapted for filling conditions by making additional modifications. They were made to the mining input data to reflect the changes caused by mine reclamation.

The water reservoirs will be placed over areas represented by nodes where the layer I and impermeable lignite seam had previously been simulated. In stage of filling conditions the water reservoirs space in layer I was simulated by constant hydraulic conductivity of 10000 m/d and specific yield of 1. The leakage parameter was changed to 1 d^{-1} simulating direct hydraulic contact between layers.

Assuming that in the Bełchatów area the precipitation is equalised by potential evapotranspiration (Stachy, 1987), lack of recharge from precipitation was assigned in the reservoirs area. Furthermore, in the cone of depression the elements of natural water balance have been changed. As shown in modelling study the amount of effective infiltration from precipitation increases, even twice with the lowering of groundwater table (Szczepiński & Libicki, 1999). At the stage of water table reconstruction it will return again to its natural values. The dried water courses will be recreated.

5 POSTMINING

The final reclamation of the Bełchatów open pit related to its partial backfilling by the overburden from Szczerców open pit will start in 2020 (Kozłowski et al., 1999). The end of this work is planned in 2030, when the Bełchatów final excavation will reach depth of about 110 meters. The dewatering system working in the Szczerców open pit will result in the lowering of groundwater table in the area of the Bełchatów final excavation. However, the modelling studies indicate that groundwater table reconstruction in this area will exceed the rate of overburden storing in the final excavation, so it will still be necessary to maintain the dewatering system around it. It will allow safe storage of overburden.

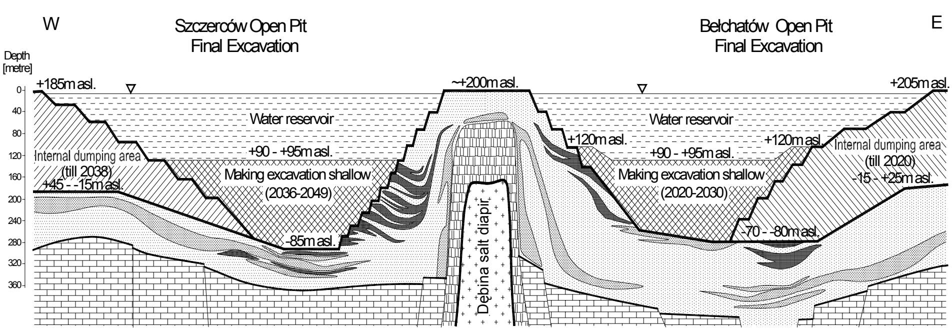
The works related to shallowing the Szczerców final excavation by the overburden from Szczerców external dumping site will be started in 2036 and completed in 2049. The final depth of reservoir will attain about 100 meters. To allow safe storage of overburden, it will be required to maintain dewatering system around it. Furthermore, in order to avoid earlier filling of the Bełchatów reservoirs with water and make impossible to increase the hydraulic gradient over the salt diapir up to 0.004 (Seweryn & Wojtkowiak, 1995), the dewatering system of the Bełchatów open pit will still have to operate. The main goal of this is elimination of water flow through the stock zone and prevention of the washing out of the salt diapir and protection of the water against pollution with saline water from the stock area.

The preparation of both excavations for filling with water will be completed in 2049. Since 2050 the process of filling the post-mining excavations with water will start. The cumulative volume of the reservoirs will reach 2.4 billion m^3 and the area 32.5 km^2.

The existing, calibrated numerical model, which successfully operates for the determination of the water inflow to mine dewatering system was used in forecasting the dynamics and duration of the reservoirs water filling after the operation of dewatering system is ceased. Calculation for final reservoirs filling with water were made for two alternatives:

For first one – hereinafter referred to as version 1 – the assumption was that the water inflow will proceed in a natural way, i.e. through the slopes and bottom of reservoirs. For this purpose, the internal boundary conditions of constant head simulating operation of dewatering systems at abandoned pits were neglected.

For second – hereinafter referred as version 2 – the assumption was that the reservoirs will be filled with water in a natural way, but aided by additional recharge with water from outside the cone of depression at a rate of 120 m^3/min and 240 m^3/min for version 2a and 2b, respectively. For this purpose, within area



of reservoirs, recharge boundary Q = const was added, thus simulating

Figure 3 Final excavation at Bełchatów/Szczerców open pits

constant water inflow independent of hydrogeodynamic conditions in the region. The simulation was carried out in transient condition.

5.1 Results for reservoirs filling with water in natural way (version 1)

For version 1, the water will inflow to the reservoirs from cone of depression created by the mine dewatering system, as a result of natural groundwater drainage. The increment of water table in the reservoirs will grow less with time due to decrease of hydraulic gradient and increase of area of the reservoirs.

The essential stage of reservoirs flooding will come to an end after about 60 years, i.e. in 2110. The water table will become stabilized finally in 2170. The final ordinates of water table in the Bełchatów and Szczerców reservoirs will be +187.05 m and 183.14 m asl., respectively (Figure 4A).

The rate of groundwater inflow to the reservoirs will be up to 209 m^3/ min when reservoirs filling will begin, in 2050 and up to 2 m^3/min in 2120. In the remaining years, the total inflow to the reservoirs will be lower than 2 m^3/ min and will come to an end in 2170 (Figure 4B).

5.2 Results for reservoirs filling with water with additional recharge (version 2)

The version 2 provides for water inflow to the reservoirs as a result of natural drainage of groundwater and additional recharge of both reservoirs with water from outside the cone of depression at a rate of 120 m^3/min (version 2a) and 240 m^3/min (version 2b).

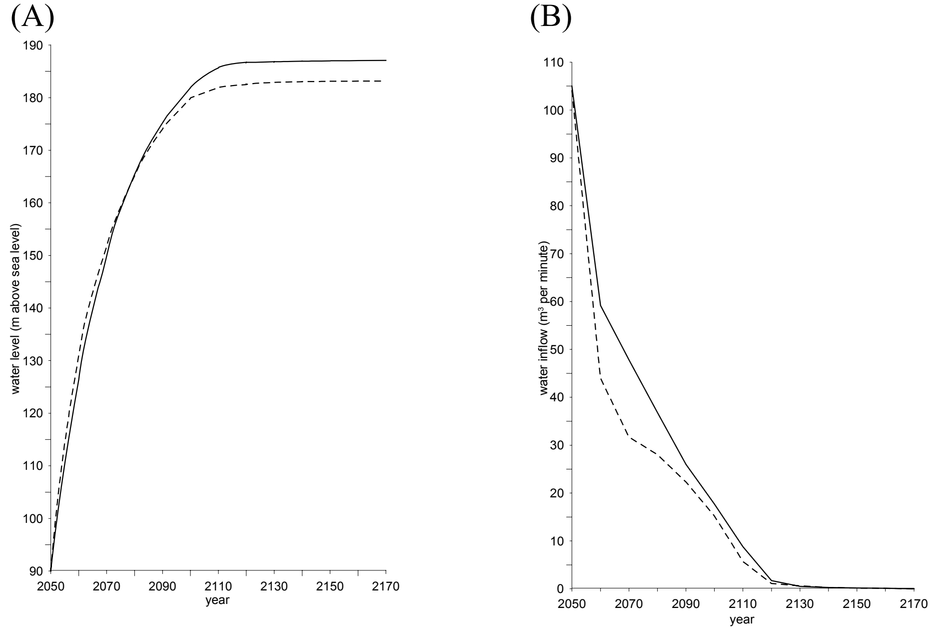


Figure 4 The water table increment in the Bełchatów and Szczerców reservoirs (A) along with the inflows to the reservoirs (B) – version 1

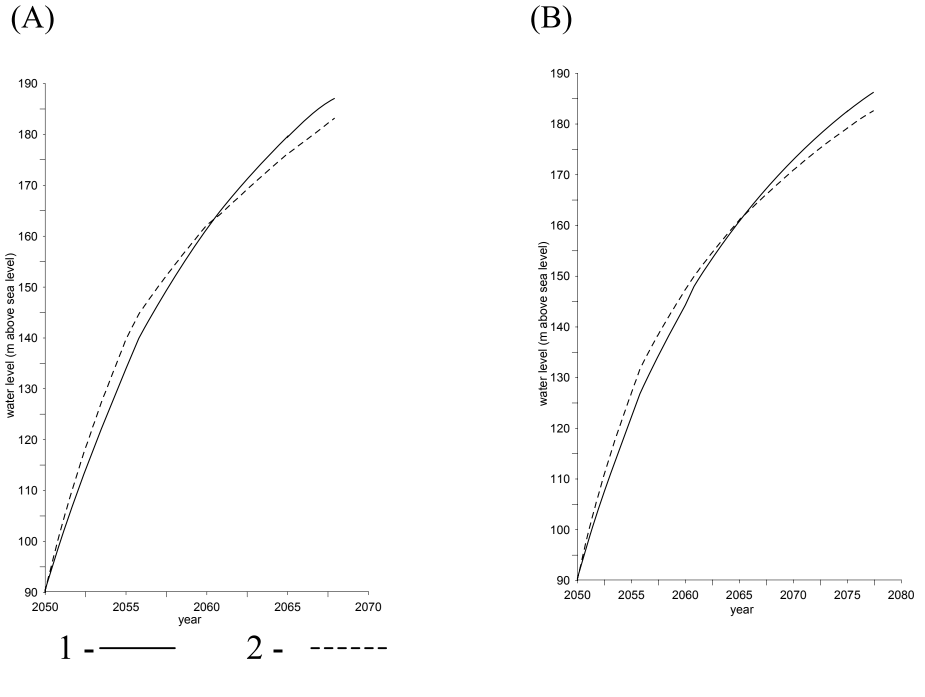


Figure 5 The water table increment in the Bełchatów and Szczerców reservoirs for version 2a (A) and 2b (B) *1 – Bełchatów reservoir, 2 – Szczerców reservoir*

For version 2a, an additional inflow to the Szczerców and Bełchatów reservoirs was assumed to be 54.6 m^3/min and 65.8 m^3/min, respectively. At the end of each stages, the inflow from outside of the cone of depression will exceed the natural inflow. After 2070, the hydraulic gradient in the region of reservoirs will be reversed, and process of aquifer recharge with water from reservoirs will start (Table 1). The duration of both reservoirs filling with water will be 28 years (Figure 5A).

Table 1 Values of final reservoirs recharge for version 2a; [m^3/min]

	Szczerców reservoir			**Bełchatów reservoir**		
Year	**Recharge outside of the cone of depression**	**Inflow from aquifer**	**Total inflow**	**Recharge outside of the cone of depression**	**Inflow from aquifer**	**Total inflow**
2050	54.6	104	158.6	65.8	105	170.8
2055	54.6	29.8	86.2	65.8	43.6	109.5
2060	54.6	7.6	64	65.8	30.4	96.2
2065	54.6	0.6	57	65.8	18.6	84.4
2070	54.6	0.5	56.9	65.8	3	68.8
2075	54.6	-9.5	46.9	65.8	-11	54.8
2078	54.6	-31.1	25.1	65.8	-29.4	36.4

For version 2b, the amount of water inflowing to the reservoirs from beyond the cone of depression is increasing two times and works out at 109.2 m^3/min and 131.6 m^3/min for Szczerców and Bełchatów reservoirs, respectively. The water inflow resulting from the natural drainage of groundwater takes place in the first years of filling only. After 2055, the water from reservoirs will start to recharge the aquifer (table 2). The duration of both reservoirs filling with water will be about 18 years (figure 5B)

Table 2 Values of final reservoirs recharge for version 2b; [m^3/min]

	Szczerców reservoir			**Bełchatów reservoir**		
Year	**Recharge outside of the cone of depression**	**Inflow from aquifer**	**Total inflow**	**Recharge outside of the cone of depression**	**Inflow from aquifer**	**Total inflow**
2050	109.2	104	213.2	131.6	105	236.6
2055	109.2	3.2	112.4	131.6	18.7	150.3
2060	109.2	-25	84.2	131.6	-4.5	127.1
2065	109.2	-27.9	81.3	131.6	-29.6	102.0
2068	109.2	-48	61.2	131.6	-54.3	77.3

6 SUMMARY

The project for management of Bełchatów Mine final excavations is first to such an extent, not only in Polish lignite mining as regards his depth and volume. Solution can be performed with use of the existing, calibrated numerical model. It will be a great importance not only for this mine but also for other big surface mines. It will allow to obtain the information related to:

- optimum depth of water ponds, the dynamics and duration of the reservoirs water filling and groundwater table reconstruction in natural conditions and with enhancement of recharge of waters from outside the cone of depression,
- changes of hydrogeodynamical, hydrological and hydrochemical conditions in the region of the mine during the course and on completion of water filling, particularly groundwater flow circulation and groundwater balance,
- stability of slopes and edges of ponds during filling with water (waves effect).

The calculated times of filling with water the liquidated post-mining excavations will allow to use options which will make possible to take correct actions aiming at the minimisation of harmful environmental impact of the undertaken project. Furthermore, it enable to estimate costs relevant to the stage of controlled water filling of such a type of excavations.

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Wypełnianie wodą wyrobisk poeksploatacyjnych po zakończeniu eksploatacji węgla brunatnego w KWB Bełchatów

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Streszczenie: W artykule omówiono konstrukcję modelu numerycznego dla rozwiązania procesu wypełniania wodą zbiorników poeksploatacyjnych kopalni węgla brunatnego w Bełchatowie. Zakończenie eksploatacji węgla brunatnego w odkrywce Bełchatów planowane jest w roku 2020, natomiast w sąsiadującej z nią odkrywce Szczerców w roku 2038, gdy oba wyrobiska osiągną głębokość 280m. Etap wypłycania obu wyrobisk do rzędnej +90 m npm zakończy się w roku 2050, kiedy oba zbiorniki osiągną głębokość ok. 90 – 110 m. Objętość zbiornika końcowego bełchatowskiego wyniesie około 1.0 mld m^3, a szczercowskiego 1.4 mld m^3. W artykule przedstawiono prognozę zmian warunków hydrodynamicznych w czasie napełniania zbiornika bełchatowskiego i szczercowskiego m.in. szybkość przyrostu zwierciadła wody w zbiornikach oraz wielkości dopływów dla założonych wariantów napełniania zbiorników. Określono długość procesu napełniania zbiorników wodą na około 80 lat i rozpatrzono możliwości jego skrócenia do około 17 lat poprzez dostarczenie dodatkowej ilości wody spoza leja depresyjnego.