ANALYTICAL ASSESSMENT OF MINE WATER REBOUND. CASE STUDY RUHR COAL BASIN

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This study aims to assess key factors that influence mine water rebound on the example of a large amount of hard coal mines flooded or being flooded in Europe. Three German mines have been selected for a detailed study. A mathematical model based on analytical formulae of seepage theory has been employed to calculate time-dependent radial inflow to the shaft simulated as a big well in vertically heterogeneous rocks. The results of modelling showed good conformity with measurements for all studied mines. Besides, we evaluated the sensitivity of the model output to parameter variations for mine water level and initial inflow to the mine.

Introduction

Germany is rich in resources and looks back at a long tradition of mining. Currently, approximately 180 Mt/a of lignite and 500 Mt/a of different minerals are extracted [1]. Coal, salt and ores have been mined for centuries at different depths in underground mining. For centuries, hard coal has been mined in the coalfields located in Saarland, Ruhr area and Ibbenbüren; in the 1950s, more than 600,000 people were employed in coal mining in the Ruhr area alone who produced around 115 Mt/a of hard coal [2]. Since 1960s, the costs for hard coal mining in Germany have been significantly higher than the world market price. For this reason the exploitation of mines has to be subsidized by the German government; the subsidy will be discontinued at the end of 2018. In parallel, last decades new energy sources have been introduced. So, in December 2018, the last two collieries in Germany will close; as a consequence, the wide-range and controlled raise of the mine water table in the underground workings is planned.

Shut-down of hard coal extraction encompasses a number of diverse tasks for which the operator of the coal mine continues to be responsible. Three major tasks, often referred to as "perpetual tasks" or "perpetual burdens" include [3]

- long-term mine water drainage,
- polder measures to regulate the ground water table close to the surface,
- decontamination of ground water at formerly contaminated colliery sites (in particular coking plants).

The sustainable funding of the tasks mentioned is handled by a foundation set up exactly for that purpose: by the RAG Stiftung based in Essen. Current estimates calculate an amount of €220 Mio required annually. The most crucial and cost-intensive task will be long-term pumping of mine water at a volume of up to 80 Mio m^3 per year. The compensation of mining damage caused by active mining, however, is not one of the perpetual tasks.

Last years a number of experts have reported how rising mine water level impacts the environment. Copious studies have been made into ground heaving [4,5], gas migrations and changes in the quality of both mine water and ground water caused by the mine water rebound [6,7,8,9]. A recent study published by the University of Applied Sciences Georg Agricola compiles the relevant experiences gained in European coal mining areas [10,11].

This study is supposed to contribute to a better understanding of the complex processes caused by rising mine water level and its impact on the objects worth of protecting first of all human beings, the environment and the infrastructure. As part of an evaluation process a systematic and comprehensive overall assessment will be done of a number of completed as well as on-going mine water rebounds in European coal mining areas.

Analytical Assessment of Mine Flooding in Europe

In many hard-coal mining areas in Europe (Figure 1) collieries have already been abandoned and flooded. Often, the space-time course of the mine water rebound was measured in shafts and at mine water measuring points and documented accordingly. The records of such courses draw a picture that strongly varies (Figure 2) and provides evidence that hydrogeological and mining properties of the deposit significantly influence the rise of mine water level.

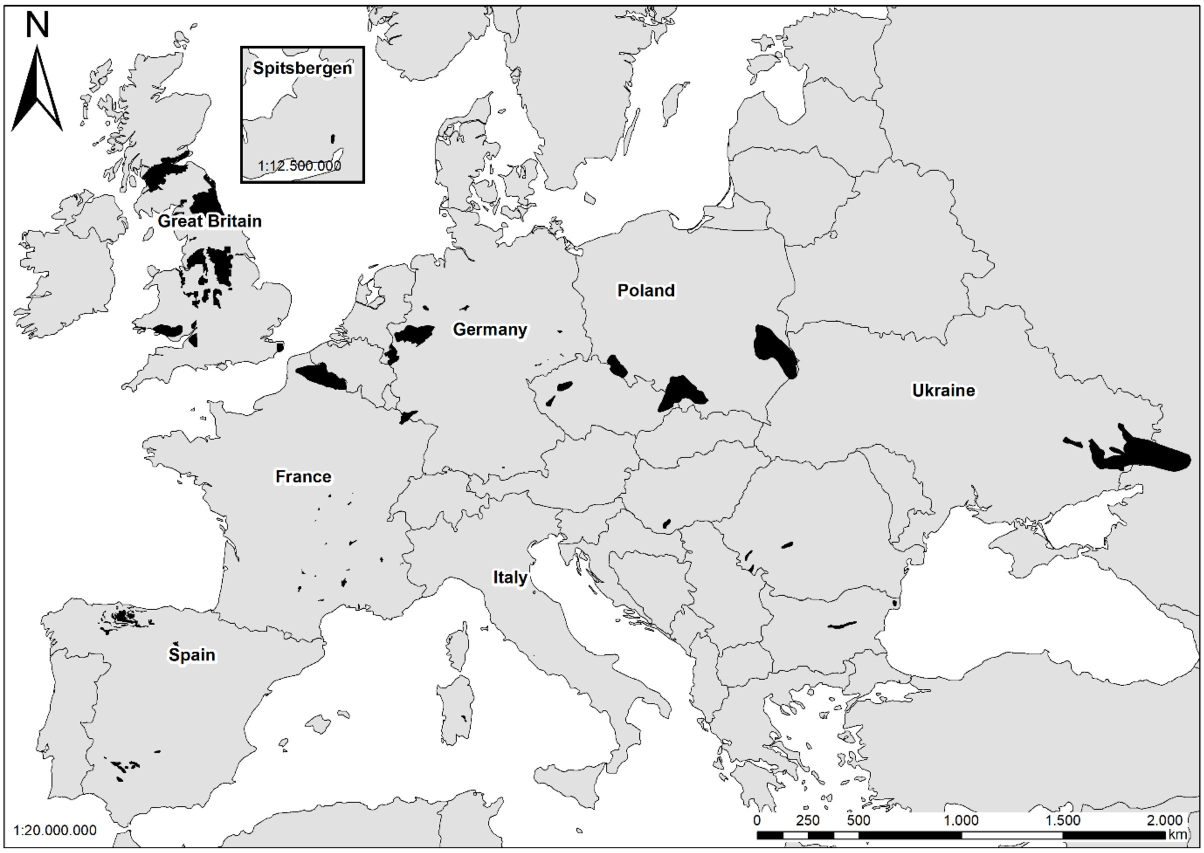

Figure 1. Hard-coal deposits in Europe [12].

The first results of the current study have been published in [12].

The mine water rebounds in the European hard-coal mining regions have been assessed in detail regarding the experiences made with the processes of mine water rebounds. The targeted regions included Ruhr area, Saar area, Ibbenbüren, Aachen, Erkelenz, Saxony in Germany, East Fife, Northumberland, East Pennines in the United Kingdom, Lorraine in France, Asturia in Spain, and Upper Silesia in Poland and the Czech Republic. More than 100 different courses of mine water rebounds were identified.

The evaluation aims to analyse the space-time course of mine water rebound and related influences as well as the correlations on both quantitative and qualitative changes of mine water drained; the ground movements caused by flooding processes, and gas migrations close to the ground surface. This overall evaluation intends to identify generally applicable causal relations of mine water rebound; separate locally specific conditions, and transfer the insights to other hard-coal mining areas where mine water rebounds are imminent.

The space-time rise of mine water level mostly depends on the hydro-geological and mining conditions of the colliery, so the rise is specific for each location. This essay introduces the factors which decisively influence the space-time course of the mine water rebound. A rather simply structured model would allow for a prompt and efficient simulation of the mine water rebounds in three abandoned German underground hard-coal mines.

The hydrodynamics of a mine water rebound are a complex process influenced by a number of factors listed below:

- *underground workings* (geometry such as spatial layout of roadways and shafts, mining level and mining methods, hydraulic power capacity and long-term stability of roadways to carry the water; remaining cavity volumes created by mining, positions of water transfer points, occurrence of standing water areas).
- *geology* (deposit conditions, tectonics such as structures of upfolds and depressions, faults and occurrences of remoulding, volumes of geogenic voids and fractures than can be used for storage, and tectonic elements)
- *hydrogeology* (permeability, porosity of voids and fractures, storage coefficient, water level in the surroundings of the mine, spatial extension of the depression cone , natural mine water level after the flooding has been completed).
- *inflows* (infiltration and seepage water, depth or formation water, inflow from or outflow into adjacent underground workings).
- *Regulating measures* (water retention due to pump operation, drainage adits, dams).

For the detailed numerical analysis three collieries in the Ruhr area were selected (Table 1). All collieries are under management of the German mining company RAG AG (based in Herne) and were partly already abandoned and flooded in the 1970s. In the collieries selected, the mine water rebound has already developed a lot or even finished and has been supervised by measurements. The collieries selected differ mostly by the thickness of their overburdens and the height of the seepage water flowing in from the overlying strata.

The collieries Westfeld Ibbenbüren and Westfalen are hydraulically isolated underground workings without open roadways to adjacent collieries. Thus, any inflow from or outflow into neighbouring collieries is not to be expected. Although Königsborn colliery has a roadway towards its northern colliery neighbours, this is closed by a dam. However, the fissured overburden of the Upper Cretaceous is of higher porosity and, contrary to the other two collieries, allows for an outflow.

Table 1. Parameters of mine water rebound in the collieries selected for the analysis

Colliery name	**Abandoned in**	**Thickness of overburden, m**	**Flooding period**	**Flooding**
Westfeld Ibbenbüren	1979	< 10	1980-1982	finished
Königsborn	1980	approx. 300	since 1996	almost finished
Westfalen	2000	approx. 800	since 2000	much advanced

To carry out the analysis, knowledge as precise as possible is required on the input data listed below:

- depth position of the layer boundaries of lithological units; m at SL
- vertical distribution of the geogenic effective cavity volume (porosity) useful for storage $n_{e,n}$ in m³
- vertical distribution of volume created by mining (underground working) $n_{e,a}$ in m³ (Figure 3a),
- conductivity k_f, per lithological units; m/s (Figure 3b),
- infiltration $\dot{h}_{inf}$ in m³/min,
- inflow from and discharge into neighbouring underground workings in m³/min,
- spatial extension of the cone of depression R in m.

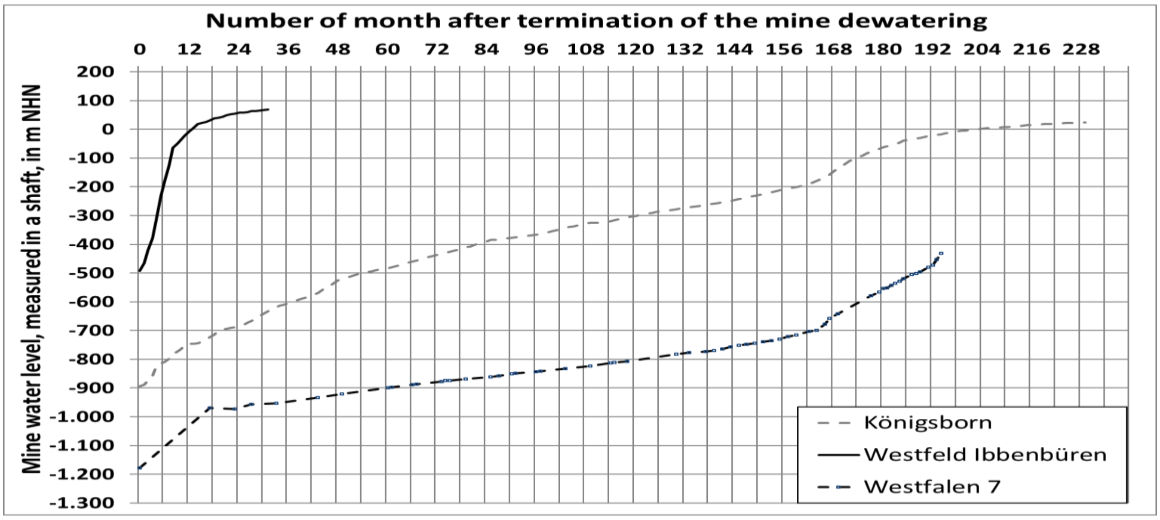

Figure 2. Rising mine water level in the collieries Westfalen, Königsborn, and Westfeld Ibbenbüren

Figure 3 shows the depth-oriented distributions of underground working volume (left) and hydraulic conductivity (right) using the example of Königsborn colliery.

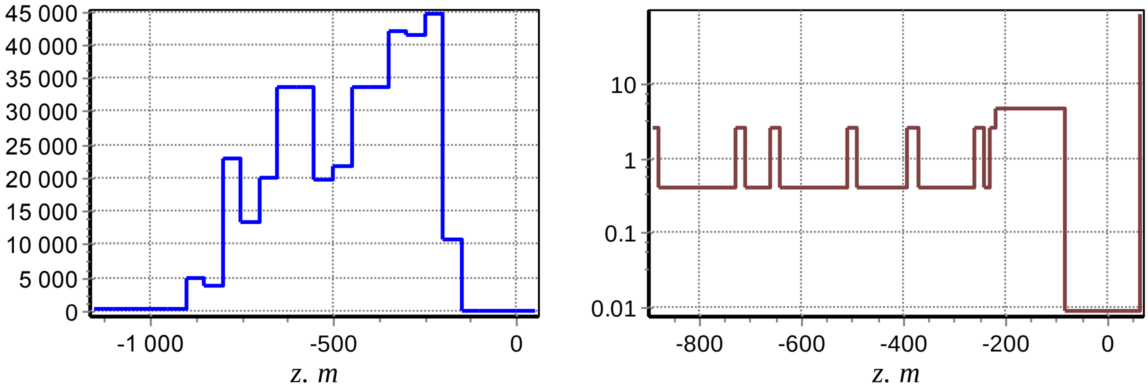

Figure 3. Vertical distribution of underground workings of Königsborn colliery, expressed as the surface of a horizontal cross-section of all workings $A_h(z)$ (a) and hydraulic conductivity of rocks $k_{f,2}$ (b)

However, the process of input data collection has shown that many geological and hydrogeological records are often incomplete or is no longer available; in addition, available data were found to be contradictory and ambiguous. Therefore, this analytical assessment focused to examine the sensitivity of the influencing factors for which sufficient and reliable data are available. Using the variation of the input data, the mine water balances were calibrated for the selected collieries.

Model development

The developed model to simulate flooding of the mines is based on the following assumptions:

- As a general case, an isolated mine is simulated; however, hydraulic connections to neighbouring mines can be taken into account in mine water balance.
- The draining effect of the mine is simulated by a single well located in a geometrical centre of the flow domain of circular shape.
- Underground workings within the mine are interconnected; the mine water level goes up in all workings simultaneously.

- Rocks within the drained area are vertically heterogeneous due to geological settings and mining operations.
- The volume of voids which occurred due to mining operations is uniformly distributed over each horizontal section within the mine.

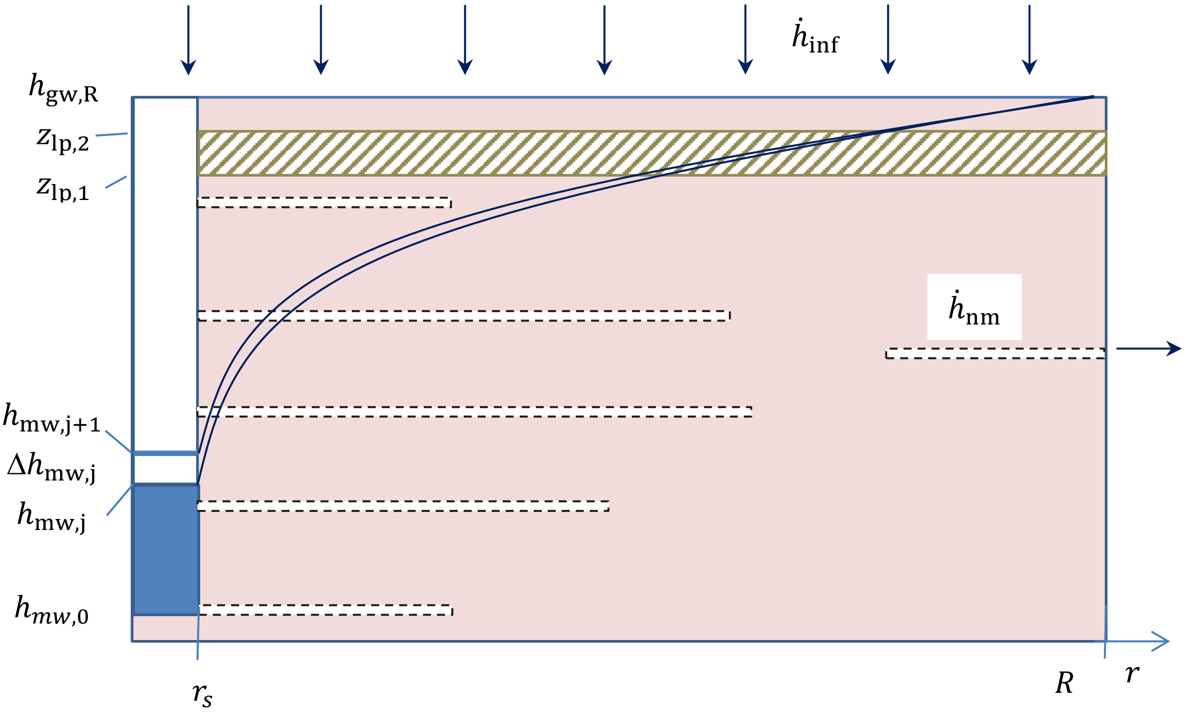

Figure 3. Vertical section of the flow domain

The groundwater flow was simulated to the shaft represented by a big quasi-well with the time-dependent mine water level [13] using the equation of radial convergent inflow to a single well:

$$\frac{\partial(n_{\text{e}}h_{\text{gw}})}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(k_{\text{f}}h_{\text{gw}}r\frac{\partial h_{\text{gw}}}{\partial r}\right)+\dot{h}_{\text{inf}}+\dot{h}_{\text{nm}} \tag{1}$$

Here n_e is the total effective porosity of rocks; $n_e = n_{e,n} + n_{e,a}$, $n_{e,n}$ is the natural floodable porosity, $n_{e,a}$ is the porosity of anthropogenic origin generated by mining operations (underground workings and occurred voids like new fractures), h_{gw} the groundwater head, k_f the rock conductivity, r the radial coordinate, t is time, $\dot{h}_{inf}$ the specific inflow of infiltration water to the drained area, $\dot{h}_{nm}$ the specific outflow (related to the drained area) to neighbouring mines through connective galleries. The groundwater head is to be calculated in the range $r_s \le r \le R$, where r_s is the inner radius, and R is the flow domain radius.

The groundwater head on the inner boundary changes simultaneously with the mine water level. The radius r_s is evaluated as the square root of the average horizontal section area A_h of underground workings in the flooded interval divided by π. The parameter A_h is calculated as

$$A_h(z) = V_{w,12}/(z_2 - z_1) \tag{2}$$

where $V_{w,12}(z)$ is the volume of all underground workings in the layer limited by two horizontal sections $z = z_1$ and $z = z_2$, $(z_1 \le z \le z_2)$. The groundwater head on the outer boundary $r = R$ remains constant during flooding; the parameter R is evaluated by analogy to r_s.

Solving Eq. 1 we divide the total time of flooding by a number N of equal time steps; thus, instead of solving the initial non-steady flow problem, we solve a series of N successive steady-state flow problems that differ from each other by the mine water level at the inner boundary $r = r_s$. For each steady-state flow problem we calculate the water balance and apply the Dupuit-Thiem formula to radial free surface flow with the average conductivity of rocks within the minimum and maximum water levels for each time interval.

Infiltration water inflow is evaluated depending on the permeability of overburden and the area of surface water catchment for the simulated mine. The outflow to neighbouring mines is calculated for each case individually; an example of outflow to the neighbouring drained mine is given below for the Königsborn colliery.

The volume of water that flows in the mine $\Delta V_{\Sigma,j}$ during the time interval Δt_j is distributed between underground workings of the volume $\Delta V_{uw,j}$ and floodable natural voids of the volume $\Delta V_{fnp,j}$

$$\Delta V_{\Sigma,j} = \Delta V_{uw,j} + \Delta V_{fnp,j} \tag{3}$$

Following the assumption on the interconnectivity of all underground workings

$$\Delta V_{uw,j} = A_{h,j} \Delta h_{mw,j} \tag{4}$$

where $\Delta h_{mw,j}$ is the mine water level rise during the time interval Δt.

The volume $\Delta V_{fnp,j}$ of floodable natural voids is calculated as the volume of rocks limited by the positions of ground water head within the depression cone at the beginning and the end of the time interval Δt_j multiplied by natural floodable porosity $n_{e,n}$. The value $\Delta V_{fnp,j}$ is calculated based on the formula for free surface ground water flow.

The rise of the mine water level during the time interval Δt_j is calculated as follows

$$\Delta h_{mw,j} = \frac{\Delta V_{\Sigma,j} - \dot{V}_{nm,j} \Delta t - \Delta V_{fnp,j}\left(\Delta h_{mw,j}\right)}{A_{h,j}} \tag{5}$$

Because of non-linearity Eq. 5 is solved numerically using an iterative procedure. The mine water level at the moment t_{j+1} is calculated by adding $\Delta h_{mw,j}$ to its value at the previous moment t_j

$$h_{mw,j+1} = h_{mw,j} + \Delta h_{mw,j} \tag{6}$$

Eqs. 3-6 define the time-dependent cycle; after its completion we obtain the mine water level and water balance constituents for the period of mine flooding.

To validate the model, we first minimize the difference between the calculated and measured initial inflow to the mine, then we minimize the deviation between the calculated and measured mine water level during mine flooding using the mean square root of the difference between these values. Minimizing this deviation, we simultaneously evaluate plausible intervals for model parameters and model sensitivity.

The developed mathematical model based on analytical relations of ground water flow theory and adapted to the availability of hydrogeological and mining parameters has been tested on the examples of three case studies in Germany mentioned above.

The calculation results include nine variants of modelling with one of them as the most plausible with the minimum deviation between measured and calculated values, and the others demonstrating model sensitivity to the variations of four major model parameters which are:

- recharge area identified by the radius R; m,
- groundwater recharge $\dot{h}_{inf}$; m³/min,
- scaling factor to vary the volume of underground workings identified by the reference parameter ξ_V; 1,
- hydraulic conductivity k_f; m/d.

Results and discussion

The individual temporal developments of the mine water level and the inflow were modelled based on nine variants that included one basic variant with minimum deviation from measured data and eight variants with different input data combinations. Generally, the modelled curves showed good congruence with the actual measured curves as seen from the excerpt below related to the Westfeld Ibbenbüren (Figure 5), Königsborn colliery (Figure 6) and Westfalen colliery (Figure 7).

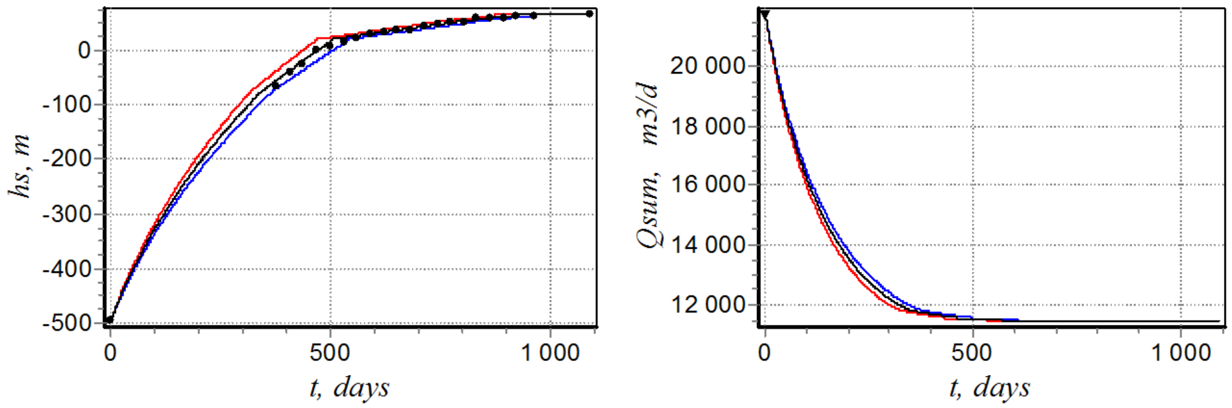

Figure 5: Mine water level (left) and inflow (right) versus time in the Westfeld Ibbenbüren for three different variants (markers – measured; lines – calculated; black line = basic variant with minimum deviation; blue line = variant with lower volume of underground workings than basic variant; red line = variant with higher volume of underground workings than basic variant).

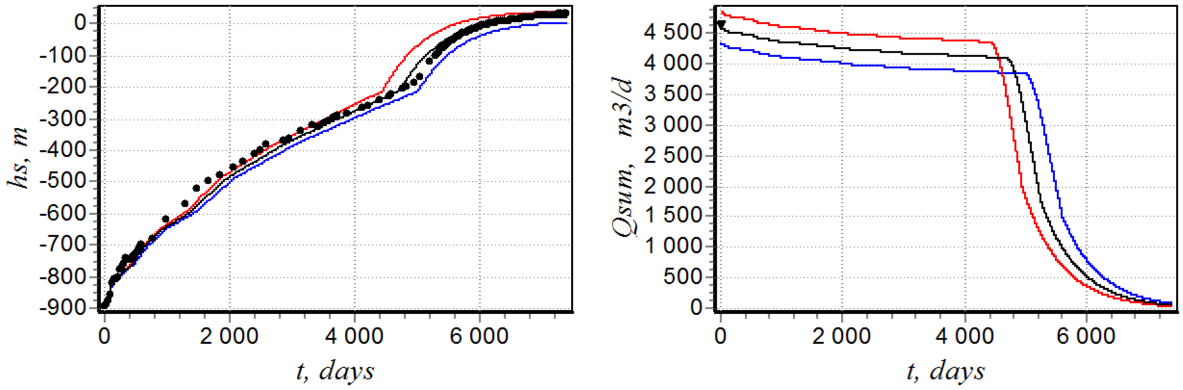

Figure 6: Mine water level (left) and inflow (right) versus time in the Königsborn colliery for three different variants (markers – measured; lines – calculated; black line = basic variant with minimum deviation; blue line = variant with lower infiltration rate than basic variant; red line = variant with higher infiltration rate than basic variant).

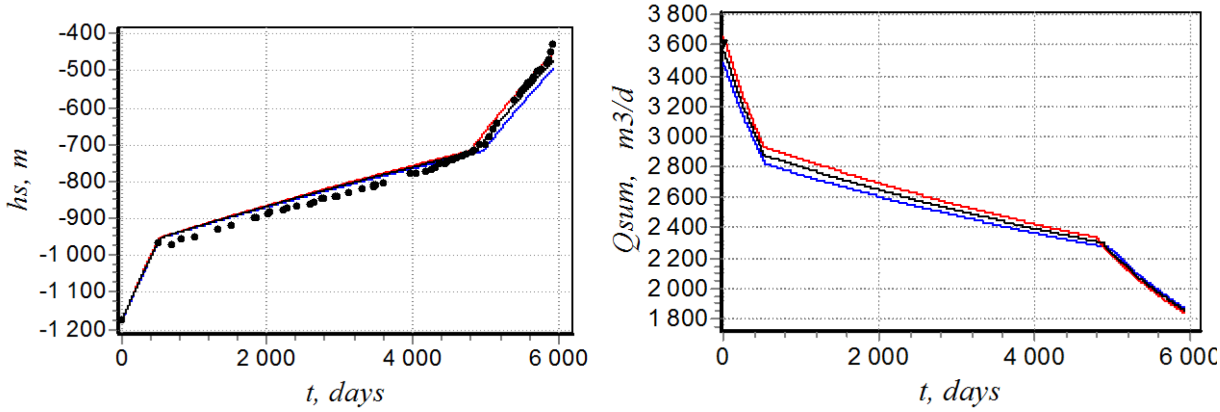

Figure 7: Mine water level (left) and inflow (right) versus time in the Westfalen colliery for three different variants (markers – measured; lines – calculated; black line = basic variant with minimum deviation; blue line = variant with lower hydraulic conductivity than basic variant; red line = variant with higher hydraulic conductivity than basic variant).

In Table 2 we evaluated the significance of each factor for mine flooding simulation by evaluating the model response to specific parameter variations. We obtained the deviations as the mean-square root between the calculated and measured mine water levels and the difference between calculated and measured initial inflow to the mine.

As the reference values we took the figures calculated for the variant with minimum deviations of these parameters for each colliery. Then we classified the extent of model sensitivity using the following intervals

- Negligible influence if the deviation is less than 5,
- Moderate influence if the deviation is higher than 5 and less than 10,
- Considerable influence if the deviation is higher than 10.

Table 2. Evaluation of model sensitivity of depending on parameter variations

Mine	**Variation / response**	**Infiltration rate**	**Depression cone radius**	**Volume of under-ground workings**	**Hydraulic conductivity**
Westfeld Ibbenbüren (no overburden)	Parameter variation, %	8	9	10	25
	Increase of mine water level deviation (times n)	**2.5**	**2-3**	**3**	**2**
	Increase of initial inflow deviation (times n)	**30**	**50**	**No influence**	**80**
Königsborn colliery (low to medium overburden thickness)	Parameter variation, %	6	3	8 – 17	20-25
	Increase of mine water level deviation (times n)	**2**	**1.5-1.8**	**2-4**	**Low influence**
	Increase of initial inflow deviation (times n)	**10**	**8-10**	**No influence**	**2-5**
Westfalen colliery (high overburden thickness)	Parameter variation, %	8	3	10	35-100
	Increase of mine water level deviation (times n)	**2**	**1.15**	**3**	**No influence**
	Increase of initial inflow deviation (times n)	**3-5**	**3.5**	**No influence**	**2-4**

A first sensitivity analysis shows that mine water rebound, disregarding the type of deposit, depends most certainly on the infiltration rate, the depression cone radius and the volume of underground workings available (

Table *2*). The changes of hydraulic conductivity do not influence significantly the mine water rise at deposits of a medium to thick overburdens. The analysis of the sensitivity of the initial inflow rate, however, shows that the infiltration rate, the depression cone radius and hydraulic conductivity influence increasingly more the thinner the overburden is.

The results obtained so far show that the model provides a useful tool to simulate the finished or developing mine water rebounds.

Conclusion

The process of mine water rebounds in underground hard-coal mines is essentially influenced by the hydrogeological and mining factors of the deposit. A large number of factors influence its evolution in space and time.

The study described here created the models of flooding underground workings for three German collieries to analyse numerically how selected factors really influence this process. The developed model based on the analytical formulae for time-dependent radial inflow in a quasi-isolated flow domain with a big well takes into account vertical heterogeneity of rocks and decreasing inflow rate due to rising mine water level. The model curves show a very good congruence with the actual measured curves. Thus, it can be concluded that the water balance of the mines is appropriately simulated. The first sensitivity analysis showed that the infiltration rate, the dimension of the depression cone and the hydraulic conductivity coefficient have a larger influence on the inflow rate than on the mine water level rebound.

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