GROUNDWATER FLOW MODELLING APPLICATIONS IN MINING HYDROGEOLOGY

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Abstract
In the presented paper some specific features and problems of numerical modelling applications in mining environment are briefly discussed. The issues discussed are documented by three modelling case studies. Two of the applications are aimed at mine dewatering problems in active coal mines. The first represents the underground hard coal mining region in the Czech part of the Upper Silesian Coal Basin. The second example is focused on optimisation of the dewatering regime of open pit mining of brown coal in the Most sub-basin of the North Bohemian Coal Basin. The third example describes the concepts of mathematical modelling to be applied to solving the issues of the intensive utilisation of mine waters from flooded uranium mine Olsi-Drahonin as a source of uranium with an accompanying effect of shortening the time necessary for the purification of mine waters discharged into watercourses.

Introduction
Groundwater modelling can be a powerful tool for solving a number of groundwater related problems resulting from both mining operation and mine closure. Nevertheless modelling applications in underground and open pit mining areas have specific features which must be addressed and require a deep knowledge of the mining environment. The reasons for undertaking a modelling study in mining areas differ depending on the development stage of mining operation and whether the mine is active or under closure (typically flooded). In active mining areas they may include strategies for effective mine dewatering including the establishment of procedures for limiting the site discharge and complying with discharge requirements, particularly the control of water quality and/or the quantity of contaminants discharged from the site. The modelling applications are very useful for the evaluation of both mine exploitation and closure activity impacts on surface and ground water systems from a quantitative and qualitative viewpoint. The hydrological conditions in the areas of flooded mines can be substantially influenced by changes to both the groundwater flow pattern in the rock massif with man-made cavities (mine workings) and the natural drainage base resulting from geomorphologic changes (e.g. terrain subsidence in undermined areas). The numerical modelling can improve conceptual understanding of the processes taking place.

Specific features and problems of groundwater modelling applications in mines
Mathematical modelling of groundwater flow in a rock massif disturbed by deep mining exploitation belongs undoubtedly to very complicated modelling applications. The reasons being that, in a massif with large open mine voids, groundwater flow is often turbulent and, in the case of backfilling, mine workings represent preferential flow pathways with variable and difficult-to-estimate hydraulic properties. Moreover deep mines are typically situated in hard rocks where the existence of fractures with important hydraulic function must be expected in some cases.
The modelling approach depends on the scale of the modelling application. A strategy for modelling groundwater rebound in abandoned mine systems in relation to the scale of observation was described by Adams and Younger (2001). At the very largest scales, water balance calculations are probably as useful as any other techniques, e.g. standard porous media continuum approach models. For local scale systems, a physically-based modelling approach has been developed (Adams and Younger, 2001), in which 3-D pipe networks (representing major mine roadways, etc.) are routed through a variably saturated, 3-D porous medium. Alternatively, for systems extending from 100 to 3000 km^2, a semi-distributed model (GRAM) has been developed (Adams and Younger, 2001). This model conceptualises extensively interconnected volumes of workings as ponds, which are connected to other ponds only at discrete overflow points, such as major roadways, through which flow can be efficiently modelled using the Prandtl-Nikuradse pipe-flow formulation.
Routinely applied groundwater flow models (e.g. MODFLOW) do not enable the correct simulation of dual porosity flow with preferential flow along fractures and leakage through the rock matrix. The application of fracture flow and transport models (e.g. FEFLOW, FRAC3DVS, FRACTRAN, NETFLO, SWIFT, etc.) to mining projects has been very limited, in part due to the complexity of the models and the lack of adequate input

information (structural data and transport parameters). However, these models are expected to become more widely used. Several models have been developed for the specific task of simulating the flooding of large underground mines and the associated rebound of the groundwater table. The main difference to the conventional groundwater flow models is the provision for turbulent flow in the large, man-made voids typical of underground mines. Several models have been developed to suit the scale of the underground mine (from a few hundreds m^2 to thousands km^2). Mine reflooding models are typically used to predict the timing and/or location of groundwater discharge after mine reflooding. Reliable model must be based on reliable input data. It is essential to describe the spatial variability of rock massif hydraulic parameters and the function of boundary conditions. The realistic description of heterogeneity and anisotropy of hydraulic parameters is a general problem of groundwater modelling applications, solved through model calibration and validation. Under the conditions of hydraulically stressed mining environment, groundwater flux has a significant vertical component, which requires 3-D model application. The requirements on the complexity of input data rise in such a case, especially in relation to the knowledge of rock massif anisotropy. The feasibility of natural anisotropy determination in the mining environment is debatable due to the disturbance of natural conditions by mining activities. Tracer tests, which could verify conceptual assumptions, are very demanding and rare in the mining environment (in Czech Republic documented by Halir, 2002). Moreover their performance in the mines reflects a significant anthropogenic component and it is not feasible to distinguish natural conditions.

Geological exploration performed in former mining areas started in the period when the advanced hydrogeological exploration methods were not available. Therefore, at present there is a lack of reliable data, and available information is variable with the highest density in the areas already exploited, where the natural state has been already disturbed. Moreover some types of data represent an expert judgement and are of relatively low reliability, e.g. uncontrolled dewatering discharges. Each reliably calibrated groundwater model must be based on the well-established mine water balance. The water balance of the entire mine has a number of components; the majority are difficult to quantify since they represent directly immeasurable values. The water balance of a mine is the basis of the general assessment of the deposit saturation. Hitherto hydrogeological assessment of mines is based on observation of discharges pumped to the surface. These values are mistakenly regarded as "mine inflows". The problems connected with the solution of the water balance equation of a mine are complicated by a variety of unknown or directly immeasurable values. The water balance equation has substantially more components than those obtained by geologists during the assessment of hydrogeological conditions of a mine. Generally, the equation can be formulated in the following form ($m^3 \cdot period^{-1}$):

$$Q_p = Q_{op} + Q_{en} - Q_v - Q_t \pm Q_l \pm Q_r$$

where Q_p = amount of water pumped to the surface, Q_{op} = amount of operational water put into a mine, Q_{en} = amount of water recharged from rock environment:

$$Q_{en} = Q_{in} + Q_{aq}$$

where Q_{in} = amount of infiltrated water from precipitation, Q_{aq} = amount of water recharged from aquifers, Q_v = amount of water led off the mine by mine air, Q_t = amount of water transported out of the mine with mineral resources production, Q_l = amount of water of unspecified losses and gains, Q_r = amount of water accumulated in or released from reserves (gob water). Of the aforementioned components of the water balance equation, only the values of Q_p are observed in most cases and they are frequently presented as an equivalent of Q_{en}. In many cases, due to non-acquaintance or complete absence of data, it is necessary to accept certain simplifications.

During mine flooding Q_p, Q_{op}, Q_v , Q_t and Q_r become zero, and Q_{en} (specifically the component Q_{aq}) decreases in time in relation to the hydraulic gradient decrease. After groundwater rebound in situations that the drainage base is below groundwater level of the mining area, the left side of the water balance equation will represent groundwater flux naturally drained from the area.

Case studies

1. Dewatering in the Czech part of the Upper Silesian Coal Basin

The Upper Silesian Coal Basin represents the mining area of traditional deep hard coal exploitation shared by Poland and Czech Republic. The principal part of the basin situated in the Czech Republic, called Ostrava-Karvina Coalfield, is divided into three sub-basins; two of them are flooded and groundwater is kept at specified level to prevent overflow to the third Karvina sub-basin which is still being exploited.

Within the depressions of Carboniferous paleorelief, which had been formed by Post-Carboniferous selective erosion, the basal Lower Badenian clastics were deposited on the base of the Lower Miocene overburden units.

The Lower Badenian basal clastics, which are called "detritus" in the Czech part of basin, form a confined geohydrodynamic structure of fossil marine water.

The "detritus" has been a source of hydrogeological complications since the beginning of mining activity in the Ostrava-Karvina Coalfield (hereafter OKR), as both for water inrushes and dangerous increased water inflows into underground mine workings. Also the penetration and migration of methane and carbon dioxide from "detritus" water into underground mines occurred frequently. Groundwater flow modelling became an important tool for the revision of mine safety legislation concerning the protection of underground mines against water inrushes (Dvorsky et al., 2006). The impact of groundwater rebound in flooded Czech and Polish mines on water inflows to active deep mine in Karvina Basin and risk of water inrushes endangering mining activity were assessed by means of mathematical modelling. Since the model was built on a regional scale (about 1200 km^2) the utilisation of MODFLOW 2000 code (Harbaugh et al., 2000) was fully justified.

Initially a database of geological and hydrogeological data was compiled by means of revision of final reports of surface boreholes which were completed after the Second World War in OKR and in its surrounding territory for purposes of deposit, hydrogeological and mine gas prospecting. The piezometric levels have been measured periodically at a quarter year frequency in the boreholes which were preserved for long-term monitoring. Measurements of the longest period monitored borehole NP 611 in Jistebník nad Odrou started in 1963.

Furthermore, the database of total water inflows into active as well as abandoned underground mines of OKR was dealt with; it was compiled from results of half-year water inflow measurements which had been completed on underground mines according to mine safety regulations.

Very favourable results of model calibration on 28 calibration targets (example on Fig. 1) with regard to known regime of piezometric levels in monitoring boreholes enabled us to create a relatively reliable model prediction of "detritus" dewatering as a consequence of water drainage into active or abandoned underground mines. The predictions have been extrapolated until 2015 in the form of piezometric level contour maps and flow vectors. The scenario of water inrushes into the mine workings was simulated as well.

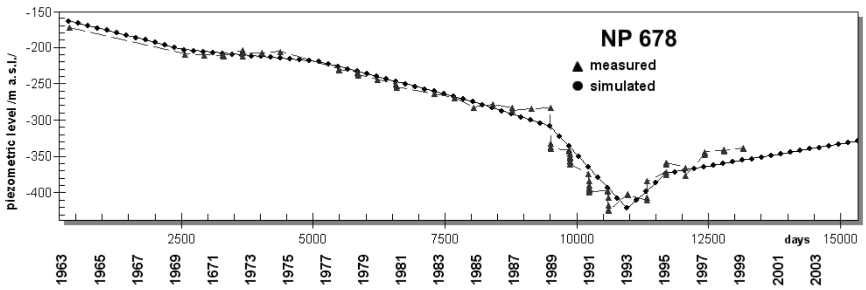

Figure 1. Comparison of measured and simulated piezometric heads on observation borehole NP 678.

2. Optimisation of dewatering in the North Bohemian Coal Basin

The area of interest (Most sub-basin) is situated in the North-western part of the Czech Republic within the North Bohemian Brown Coal Basin. The lower boundary of productive coal seam formation is formed by so called "underlying sands", which represent the most extensive aquifer of the basin reaching the thickness up to 100 m. It forms the continuous hydraulic system with the recharge area on the slopes and at the foot of the Krusne Hory Mountains, where it outcrops. The system is fed by water from the Quaternary slope debris.

The medium to coarse sands are well permeable with hydraulic conductivity values of 10^{-4} to 10^{-5} m.s^{-1} and original piezometric level of 230 to 235 m a.s.l. The pressure on the coal seam bottom reached the values up to 0.2 to 0.8 MPa and endangered open cast mining by water inrushes. To ensure the mining safety the piezometric level in "underlying sands" was lowered by dewatering to the level below pit base. The pumping hydraulic barrier with 6 boreholes was built in the zone in the front of the face to keep the piezometric head at required level. With opencast mine advance of Jan Sverma Mine the system became insufficient and required optimisation in the terms of locations of pumping centres as well as discharge rates. Dewatering regime had to be optimised taking into consideration the opencast advance plans. Numerical modelling of groundwater flow (MODFLOW code) together with spatial analyses done in ArcGIS became the tools to solve the above given problem. The combination of these methods brought particular results and recommendations.

The numerical model was built within natural geological and hydrogeological boundaries. They could be defined by the extent of the aquifer; this boundary was described by no flux II kind boundary condition. In the parts of distant geological boundary of aquifer, undisturbed static hydraulic conditions in the structure of artesian wedge were assumed and the boundary then was described by specified head boundary condition. The aquifer is not spatially recharged from precipitation owing to impermeable overlying layers. The quasi homogeneous aquifer zones were identified on the basis of information from geological profiles of the exploration boreholes and their transmissivity coefficient represented the only calibrated parameter estimated from the results of aquifer testing. From this viewpoint the modelling study has a good prospect of obtaining relatively unique solution to the selected and geologically well-founded conceptual model. The weakness of the solution lies in insufficient number of calibration targets and narrowing calibration parameter (hydraulic conductivity) by more extensive field testing. The model calibrated with average absolute calibration error of 33 cm (piezometric heads residuals) was utilized for optimisation of location and pumping regime of dewatering boreholes. Simulated piezometric levels for each individual variant were subjected to spatial analyses in ArcGIS (Fig. 2). The piezometric head, groundwater drawdown as well as the height of piezometric head above the top of aquifer were calculated for various scenarios depending on the opencast mine advance in time. Alternative measures, to preserve the specified thickness of confining protective layer on the bottom of coal seam formation, were assessed by spatial analyses as well. The results from numerical modelling study represent undoubtedly the considerable contribution to opencast mine dewatering optimisation. It is possible to verify the efficiency of the designed system and minimise the costs needed for dewatering system construction and operation.

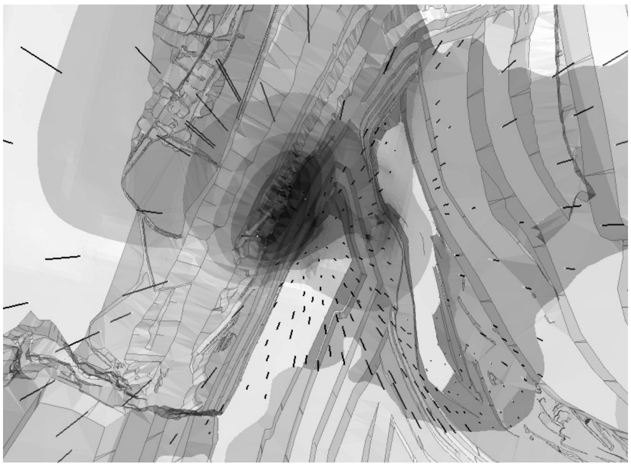

Figure 2. Visualisation of simulated groundwater depression cone resulting from open pit mine dewatering.

3. Non-traditional utilisation of uranium deposits after underground mining completion

For a long time, the Czech Republic held one of the foremost positions in the world in uranium mining. However, since the end of 1980s the production of uranium has been gradually reduced due to either the deposits exhaustion or the marked drop in sales resulting from political-economic changes in the 1990s. At present, mining operations are only continued in one underground mine in the Rožná deposit, with closure planned at the end of 2010.

In the course of development and exploitation of particular uranium deposits, the chemistry of mine waters changes depending upon the extent of the infiltration area, the total volume of worked-out mineral, its mineralogical composition and also the achieved depth of mining. In the course of underground mine flooding after its closure, the content of dissolved substances (uranium, radium, iron and others) in waters increases several times. Mine waters of flooded former uranium mines thus represent, with reference to their considerable volumes, a significant source of uranium. The increase in the content of solutes in waters is induced either by the oxidation of rock minerals in the mine space or by the more intensive water-rock interaction, as well as by a change in the hydrologic regime in the deposit. In this way uranium continues to be obtained from closed and flooded uranium mines as an accompanying effect even long after completing the classic exploitation of the deposit.

With regard to high concentrations of solutes in the mine water, the waters from flooded mines with parameters exceeding prescribed values must be purified and contaminants retained before discharging into watercourses. However, the solution to a situation in particular deposits is based on the requirement to drain mine waters with the minimum contents of dissolved substances from the flooded mine so that water purification may be as simple as possible. In all likelihood, this solution implies mine water purification for more than 30-40 years. The project being solved (Rapantova et al., in print) deals with possibilities of the intensive utilisation of mine waters from flooded uranium mines as a source of uranium with an accompanying effect of shortening the time necessary for the purification of mine waters discharged into watercourses.

Groundwater modelling of the flow and reactive transport will be the main tool for fulfilling the following tasks:

- Emphasize the natural vertical zoning of mine waters in deep parts of abandoned mines with a possibility to utilise intensively mine waters of the flooded uranium mines as a source of uranium.
- Control the geochemical reactions taking place along paths for pumping the mine waters having parameters exceeding determined values so that the effect may be a decrease in the degree of contamination and thus a shortage of the time necessary for the purification of mine waters discharged into public watercourses.

The project being done on the former already flooded uranium mine Olsi-Drahonin requires the application of the modelling code which could simulate double porosity flow as well as preferential flow along mine workings. FEFLOW code (Diersch, 2006) was selected as the best available candidate since the flexibility of finite elements mesh design enables the geometrisation of uranium ore deposit on an acceptable level of simplification. In addition to 3D elements it is possible to work with combination of planar and linear elements applicable for simulation of fractures and vertical and horizontal mine workings. Within these elements there is a choice of hydraulic calculations after either Darcy law for porous media or Hagen-Poiseuille law for fracture flow or Manning-Strickler law for channel flow. The problem in conceptualisation and modelling of the mining environment consists in the ability to describe and quantify the hydraulic properties of preferential pathways. Depending upon the type of liquidation the decision can be made using either the Darcy equation or the Manning-Strickler equations for mine workings.

The task being solved is demanding due to high level of uncertainties, following from minimum number of calibration data, which could be groundwater heads and fluxes within simulated geohydrodynamic structure. Therefore the reliable model solution must be based on water balance of the deposit which is recently under processing. As far as model inputs are concerned, we assume that the deposit is recharged only from precipitation. Significant part of water in shallow circulation drains into the local streams and only a part of groundwater recharges to the deeper parts of the deposit along preferential pathways (mine workings and some fractures). The groundwater level in the deposit is kept on the specified level by pumping. In order to validate those two components of groundwater circulation, water balance of partial watershed has to be done carefully (i.e. calculation of hydrologic water balance components: overland flow, evapotranspiration and net recharge to simulated structure). The rainfall-runoff model HEC-HMS and water balance model HELP (Hydrologic Evaluation Landfill Performance) are being used for this purpose.

Conclusions

In spite of the above discussed arguments, dealing with problems and uncertainties involved in groundwater modelling applications to mining problems, presented case studies could document the non-replaceable role of mathematical modelling for solving complicated mining hydrogeological situations. Groundwater modelling, based on realistic assumptions on hydrogeological structure, boundary conditions, recharge and discharge areas, is a valuable tool for verification of the conceptual models accepted. Mathematical modelling is the only applicable tool for impact assessment of hydraulic stresses imposed on the aquifers and their interference on the level of reliability which can be reached in this kind of applications. The modeller must be aware of specific features of groundwater flow in the environment disturbed by mining activities and that fact must be in appropriate way reflected in modelling study.

Acknowledgements

This work was supported by the Czech Science Foundation in the framework of the research project No. 105/06/0127 and by the Ministry of Education, Youth and Sports of the Czech Republic in the framework of the research project No. MSM 4456918101.

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