Mine Water Environ (2007) 26:264–270
DOI 10.1007/s10230-007-0017-1

TECHNICAL COMMUNICATION

Ground Water Flow Modelling Applications in Mining Hydrogeology

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Received: 3 September 2007 / Accepted: 27 September 2007 / Published online: 16 October 2007

Abstract Some specific features and problems of numerical modelling applications in mining environment are briefly discussed and three modelling case studies are presented. 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 focussed 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 how mathematical modelling can be applied to solve issues associated with the intensive use of mine waters from the flooded Olsi-Drahonin mine as a source of uranium to shorten the time necessary for the purification of mine waters discharged into watercourses.

Introduction

Models can be a powerful tool for solving a number of ground water related problems associated with mining and mine closure but have specific features that must be addressed and that require a deep understanding of the mining environment. The reasons for modelling differ depending on the development stage of the mining operation and whether the mine is active, closed, or being closed and, typically, flooded. At active mines, they may be used to develop strategies for effective mine dewatering including procedures for limiting the site discharge and complying with discharge requirements, particularly control of water quality and/or the quantity of contaminants discharged from the site. At closed flooded mines, numerical modelling can improve conceptual understanding of the hydrogeological processes taking place due to changes to the ground water flow pattern in the rock massif and to the natural drainage base due to geomorphologic changes, e.g. terrain subsidence in undermined areas.

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Specific Features and Problems of Ground Water Modelling Applications in Mines

Mathematical modelling of ground water flow in a disturbed rock massif (deep mining) can be very complicated because ground water flow in large open voids (mine workings) is often turbulent. Even when these voids are backfilled, they represent preferential flow pathways with variable and difficult-to-estimate hydraulic properties. Moreover, underground mines are often situated in hard rock where fracture flow is important and must be accounted for.

The correct modelling approach depends on the scale of the modelling application. A strategy for modelling ground water rebound in abandoned mine systems relative to the scale of observation (modelling) 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 more than 100–3,000 km^2, a semi-distributed model (GRAM) has been developed (Adams and Younger 2001). This 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 ground water 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 such models and the lack of adequate input information (structural information and transport parameters). However, these models are expected to become more widely used.

Several models have been developed specifically to simulate the flooding of large underground mines and the associated rebound of the ground water table. The main difference to the conventional ground water 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 hundred meter square to thousands of kilo meter square). Mine reflooding models are typically used to predict the timing and/or location of ground water discharge after mine reflooding (Wels 2007).

Models require reliable input data, including the spatial variability of rock massif hydraulic parameters and the nature of boundary conditions. Realistic description of the heterogeneity and anisotropy of hydraulic parameters is a general problem of ground water modelling applications, solved through model calibration and validation. In a hydraulically stressed mining environment, ground water flux has a significant vertical component, which requires 3-D model application. The complexity of the required input data rises in such a case, especially with respect to 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). Use of tracer tests in flooded mines was reviewed by Wolkersdorfer (2001). A possible reason for the small number of published mine water tracer tests might be that many tracer tests in underground mines were not, or only partly, successful (Davis 1994). It should be noted that their performance in mines reflects a significant anthropogenic component and does not distinguish natural conditions.

Geological exploration of former mining areas started in the period when advanced hydrogeological exploration methods were not available. Therefore, information density and reliability is variable, with the highest density in areas already exploited. Moreover, some types of data simply reflect an expert judgement and may be of relatively low reliability, e.g. uncontrolled dewatering discharges.

Each reliably calibrated ground water model must be based on a 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. Hitherto, hydrogeological assessments of mines have been based on observation of discharges pumped to the surface. These values are mistakenly regarded as “mine inflows”.

The problems connected with solving the water balance equation of a mine are complicated by the 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}/:

$$Q_\text{p} = Q_\text{op} + Q_\text{en} - Q_v - Q_t \pm Q_1 \pm Q_r$$

where Q_p is the amount of water pumped to the surface; Q_op is the amount of operational water put into a mine; Q_en is the amount of water recharged from rock environment; Q_en = Q_in + Q_aq (where Q_in is the amount of infiltrated water from precipitation and Q_aq is the amount of water recharged from aquifers); Q_v is the amount of water led off the mine by mine air; Q_t is the amount of water transported out of the mine with mineral resources production; Q_l is the amount of water of unspecified losses and gains; and Q_r is the 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 $Q_\text{p,}$ Q_op, Qv, $Q_\text{t,}$ and Q_r become zero and Q_en (specifically component Q_aq) decreases over time relative to the hydraulic gradient decrease. After ground water rebound in situations where the drainage base is below the ground water level of the mining area, the left side of the water balance equation will represent ground water flux naturally drained from the area.

Case Study: Dewatering in the Czech Part of the Upper Silesian Coal Basin

The Upper Silesian Coal Basin is an area of traditional deep hard coal exploitation in both Poland and the Czech Republic. The principal part of the basin situated in the Czech Republic, called the Ostrava-Karvina Coalfield, is divided into three sub-basins; two of them are flooded and ground water 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 were 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 (Fig. 1).

The detritus has been a source of hydrogeological complications since mining began in the Ostrava-Karvina Coalfield (hereafter OKR), causing water inrushes and dangerous increased inflows into underground mine workings. Detritus water also frequently caused the migration of methane and carbon dioxide into underground mines. Ground water flow modelling became an important tool as mine safety legislation regarding the protection of underground mines against water inrushes was revised (Dvorsky et al. 2006). The impact of ground water rebound in flooded Czech and Polish mines on water inflows to active deep mine in Karvina Basin and the risk of water inrushes endangering mining were assessed by means of mathematical modelling. Since the model was built on a regional scale (about 1,200 km^2), the use of MODFLOW 2000 code (Harbaugh et al. 2000) was fully justified.

Initially, a database of geological and hydrogeological data was compiled from final reports of surface boreholes that had been completed after the Second World War in the OKR and in its surrounding territory. The piezometric levels have been measured periodically at a quarter year frequency in the boreholes that had been preserved for long-term monitoring. The longest period of measurements was at borehole NP 611 in Jistebník nad Odrou, which started in 1963.

In addition, a database of total water inflows into active as well as abandoned underground mines of OKR was compiled from the semi-annual water inflow measurements that had been conducted at underground mines according to mine safety regulations.

Very favourable results of model calibration on 28 calibration targets (example on Fig. 2) 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 as piezometric level contour maps and flow vectors (example on Fig. 3). The simulated ground water flow pattern was confirmed by comparison with the long-term hydrogeochemical measurements of ground water. The scenario of water inrushes into the mine workings was simulated as well.

Case Study: Optimisation of Dewatering in the North Bohemian Coal Basin

The area of interest, the Most sub-basin, is situated in the northwestern part of the Czech Republic within the North

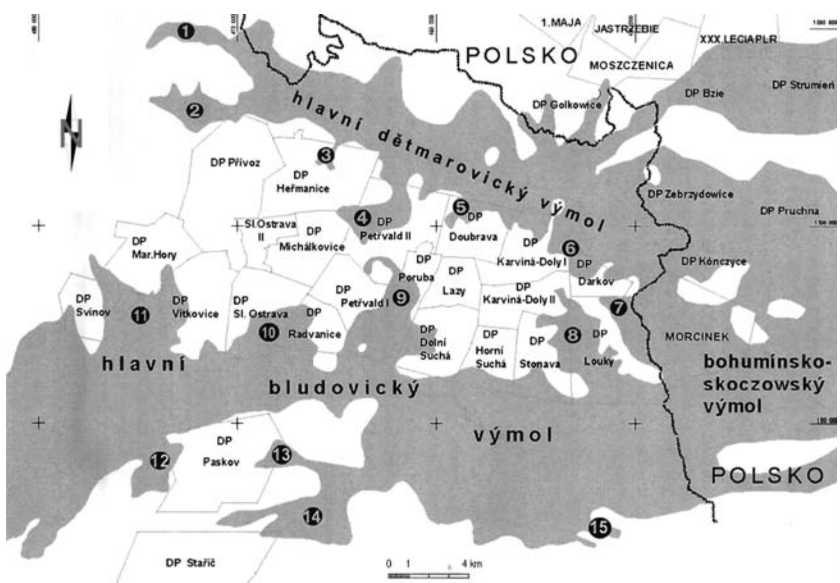

Fig. 1 The regional extent of the structure of Carboniferous relief depressions

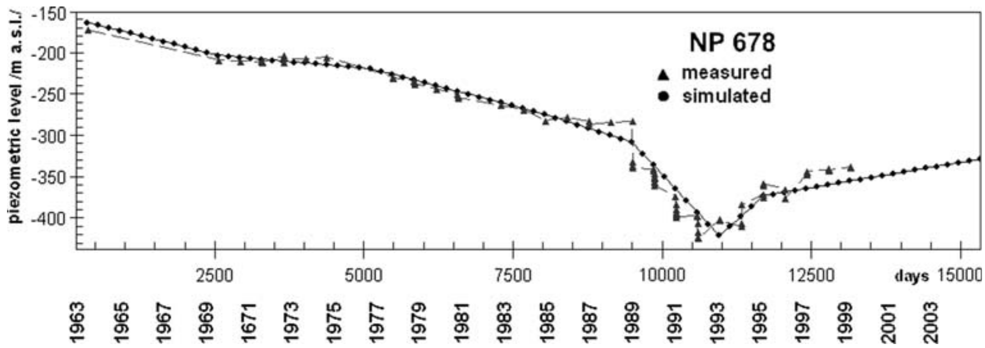

Fig. 2 Comparison of measured and simulated piezometric heads on observation borehole NP 678

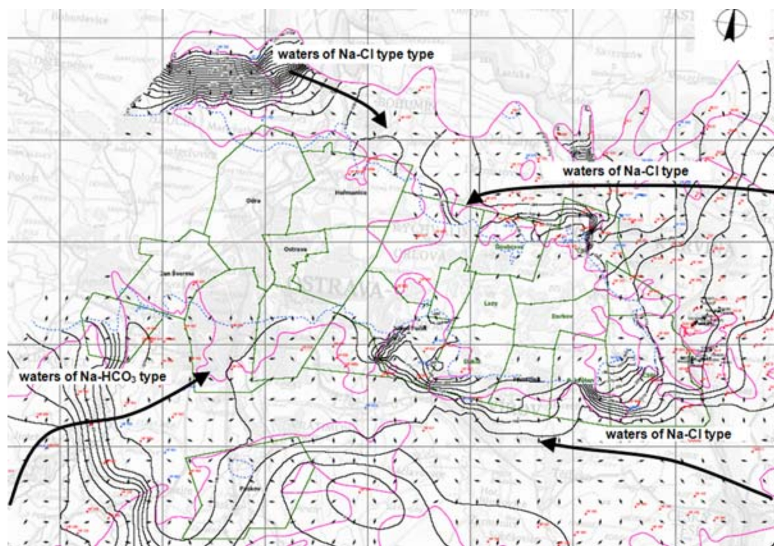

Fig. 3 Ground water flow pattern in the simulated structure of the Lower Badenian basal clastics

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, up to 100 m thick. It forms a continuous hydraulic system with the recharge area on the slopes and at the foot of the Krusne hory mountains, where it comes to the Earth's surface. The system is fed by water from the Quaternary slope debris.

The medium to coarse sands are quite permeable, with hydraulic conductivity values of 10^{-4}–10^{-5} m s^{-1} and original piezometric level of 230 to 235 m above sea level (a.s.l.). The pressure on the coal seam bottom reached values up to 0.2 to 0.8 MPa and endangered open cast mining by water inrushes. To ensure mine safety, the piezometric level in the "underlying sands" was lowered by dewatering to the level below the pit base. A pumping hydraulic barrier was developed with six boreholes in the zone in the front of the face to keep the piezometric head at the required level. With the Jan Sverma opencast mine advancing, the system became insufficient and required optimisation in terms of locations of pumping centres and discharge rates. The dewatering regime had to be optimised, taking into consideration the opencast advance plans. Numerical modelling of ground water flow (MODFLOW) and spatial analyses using ArcGIS were used to solve the problem.

The numerical model was built within natural geological and hydrogeological boundaries. They were defined by the extent of the aquifer; this boundary was described by a no flux-II kind boundary condition. In the distant parts of geological boundary of aquifer, undisturbed static hydraulic conditions in the structure of artesian wedge were assumed and the boundary was then described by specified head boundary condition. The aquifer is not spatially recharged from precipitation due to impermeable overlying layers. The quasi-homogeneous aquifer zones were identified based on information from geological profiles of the exploration boreholes; the transmisivity 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 a relatively unique solution to the selected and geologically well-founded conceptual model. The weakness of the solution lies in the insufficient number of calibration targets and a narrowing calibration parameter (hydraulic conductivity), requiring more extensive field testing.

The model, calibrated with an average absolute error of 33 cm (piezometric heads residuals), was used to optimise the location and pumping regime of the dewatering boreholes. Simulated piezometric levels for each individual variant were subjected to spatial analyses in ArcGIS (Fig. 4). The piezometric head, ground water drawdown, and 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 the numerical modelling study undoubtedly represent a 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.

Case Study: Non-traditional Use 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 the 1980s, the production of uranium has gradually reduced, due to the exhaustion of the deposits or the marked drop in sales resulting from political-economic changes during the turnult of the 1990s. At present, mining operations only continue in one underground mine in the Rožná deposit with the planned termination of mining there at the end of 2010.

In the course of the development and exploitation of particular uranium deposits, the chemistry of mine waters changes depending on the extent of the infiltration area, the total volume of worked-out mineral, its mineralogical composition, and the depth of mining. In the course of flooding an underground mine after its closure, many important changes occur in water chemistry; in general, the total dissolved solids (TDS) increase several times (with increased concentrations of uranium, radium, iron, and others). Mine waters of flooded former uranium mines thus represent, with reference to their considerable volumes, a potentially significant source of uranium. The increase in the TDS is induced by the total oxidation of rock minerals in the mine space and/or by the fact that the water comes in contact, to a much higher degree, with the rock, and/or by a change in the hydrologic regime in the deposit. In this way, uranium can be obtained from closed and flooded uranium mines long after classic exploitation has been completed.

Of course, parameters cannot exceed prescribed values when the mine water is discharged into watercourses. The solution to that situation in particular deposits is based on minimizing the TDS values from the flooded mine so that water purification can be as simple as possible. However, in all likelihood, mine water treatment will be necessary for more than 30–40 years. An alternative approach (Rapantova et al. 2007) deals with the problem by increasing the TDS values, favouring extraction of uranium, while shortening the time necessary for mine water treatment.

Ground water modelling of the flow and reactive transport is the principal tool for fulfilling the following tasks:

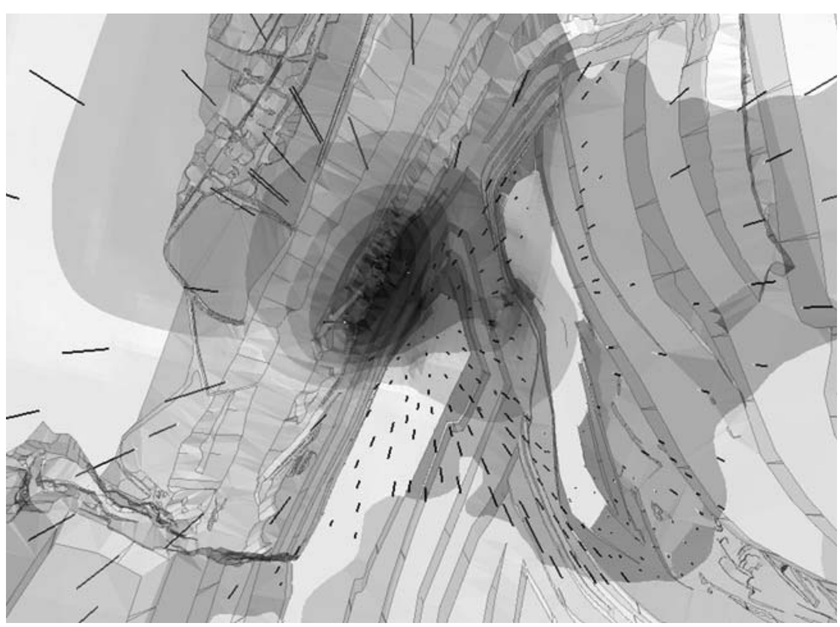

Fig. 4 Visualisation of simulated ground water depression cone resulting from open pit mine dewatering

- Emphasizing the natural stratification process in deep parts of abandoned mines to favour zones where extraction of uranium would be economical.
- Controlling geochemical reactions taking place along flow paths so as to minimize the time or extent that the other mine water contaminants exceed determined values, reducing the time that mine water treatment is necessary.

Mathematical modelling should provide answers to two basic questions. First, ground water flow pattern and fluxes (whether there is a stagnant, non-flowing mine water area in the flooded mine or not), and second, the theoretical uranium concentration in the mine water. A mathematical model is being prepared by collecting the necessary data, preparing a conceptual model, and verifying suitable software for this purpose.

The task to be solved by this project is demanding, due to the high level of uncertainty and a minimal amount of calibration data, of water quality at various levels and/or flow rates within the simulated structure. That is why it is necessary to base the model solution on a reliably calculated water balance of the deposit. We begin by assuming that the mine's sole source of recharge is precipitation. Therefore, it is essential to determine correctly the hydrologic balance of the partial river catchment area: direct runoff (overland and overburden runoff), evapotranspiration, and effective infiltration into the modelled structure.

The undisturbed rock mass usually has interstitial or dual (interstitial-fissure) type of porosity. Commonly used models of ground water flow do not enable hydraulically correct simulation of dual porosity. As soon as the rock mass is mined, the workings creates a karst-type porosity, so that the flow patterns and rates are determined by the secondarily produced, hydraulic inhomogeneities, and anisotropic environment. The main problem in the simplification of this type of environment (anthropogenic pseudokarst) is to describe changes in the hydraulic properties of preferential flow paths.

The project being done on the former already flooded uranium mine Olsi-Drahonin requires the application of a modelling code that could simulate dual porosity flow as well as preferential flow along mine workings.

FEFLOW code (Diersch 2006) was selected as the best available software since the flexibility of finite elements mesh design enables the geometrisation of the uranium ore deposit on an acceptable level of simplification. In addition to 3D elements, it is possible to work with a 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 based on Darcy's law for porous media, the Hagen-Poiseuille law for fracture flow, or the Manning-Strickler law for channel flow. The problem in conceptualisation and modelling of the mining environment consists of correctly describing and quantifying the hydraulic properties of preferential pathways. Depending on the site, one can decide to use either the Darcy or Manning-Strickler equations for mine workings.

A geological model of the area of interest was built (Fig. 5) as well as a conceptual model of ground water flow. Table 1 describes the assumed hydrogeological zoning in the vertical profile, prevailing flow component, and numerical code applied.

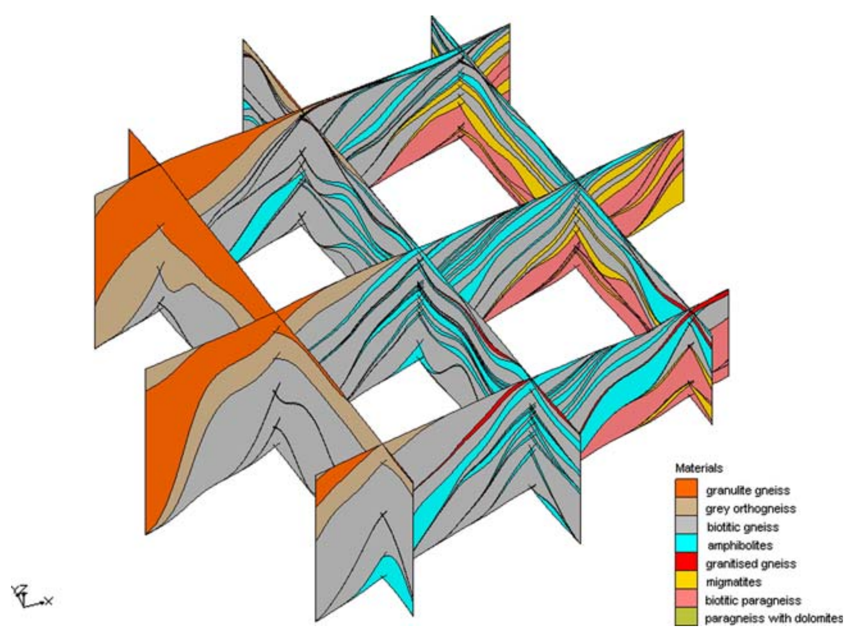

Fig. 5 Geological model of the area of interest (Groundwater Modelling System v. 5.2)

Table 1 Hydrogeological concept

Type of rock/ thickness		Hydrogeological zones		Simulated component /numerical code
Gneiss, amphibolite	Serpentinite			
1.5 m	Up to 2.5 m	I. Zone	Unconsolidated eluvial and aluvial sediments	Well permeable-recharge HELP
3–5 m	Up to 7 m	II. Zone	Intense weathering zone	Vertical recharge-HELP
7–20 m	Up to 30 m	III. Zone	Weathering zone	Horizontal ground water flow-MODFLOW
		IV. Zone	Bedrock	Fracture flow-FEFLOW

As stated earlier, we assumed that the deposit is recharged only from precipitation. Much of this water remains in shallow circulation, and drains into local streams; only a part of the ground water reaches the deeper parts of the deposit to flow along preferential pathways, the mine workings and some fractures. The ground water level in the deposit is kept at a specified level by pumping. In order to validate those two components of ground water circulation, the hydrologic balance of the partial watershed has to be done carefully. The rainfall-runoff model HEC-HMS and water balance model HELP (Hydrologic Evaluation Landfill Performance) are being used for this purpose.

Conclusion

In spite of the problems and uncertainties involved in applying ground water modelling to mining problems, these case studies document the various roles that modelling can play in solving complicated mining hydrogeological tasks. Ground water modelling, based on realistic assumptions of hydrogeological structure, boundary conditions, recharge and discharge areas, is a valuable tool to verify the validity of conceptual models. Mathematical modelling is the only applicable tool to assess the impact of hydraulic stresses (and especially their interference) on aquifers. The modeller must be aware of specific features of ground water flow in the environment disturbed by mining activities, and must factor such knowledge in an appropriate way in their modelling study.

Acknowledgments This work was supported by the Czech Science Foundation in the framework of research project 105/06/0127 and by the Ministry of Education, Youth, and Sports of the Czech Republic in the framework of research project MSM 4456918101.

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