

Use of Numerical Groundwater Modelling for Mine Dewatering Assessment

Abstract Groundwater inflow to open-pit and underground mines creates significant impacts both on mine operations and on the environment. Issues that commonly need to be addressed at different stages of engineering or environmental/permitting studies include: (a) Engineering and economic risks associated with groundwater inflow; (b) Most efficient active dewatering option that can be implemented to significantly reduce residual passive inflow to the mine; (c) Optimal regime (pumping rates and wells spacing) of the dewatering system; (d) Optimised mine to reduce both pumping costs and hydrogeological risks to a project; (e) Quality of mine-water discharge; (f) Environmental impact of mining/dewatering on the groundwater system and the surface water bodies (rivers, lakes, streams, springs, etc); and (g) Post-mining conditions (pit lake and flooded mine) after mining has ceased.

Some of these issues can be resolved at the initial stages of the minedewatering assessment by using simple analytical solutions (i.e., scoping study). However, at more advanced levels of study (pre-feasibility, feasibility, mine design or operations), those analytical solutions can be too simplistic and inaccurate. Groundwater flow in the vicinity of open pits or underground mines is three-dimensional (3-D) in most cases; consequently, 3-D numerical groundwater flow models must be based on 3-D hydrogeological data if they are to become reliable predictive tools for answering the questions listed above.

This article draws on specific project cases at different levels of study to show the advantages of using numerical groundwater modelling for mine dewatering projects with complex hydrogeological conditions. Data requirements, major phases of modelling, and practical use of the model as a predictive tool for evaluation of the mine dewatering requirements and associated environmental impacts are discussed.

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HYDROGEOLOGICAL MODEL APPROACH FOR DEWATERING MINING PROJECTS

There are three major issues related to groundwater in mining projects that need to be addressed: (1) mine dewatering requirements; (2) stability of pit walls or developments; and (3) environmental impacts on groundwater levels and on groundwater quality, during mining and post-mining periods.

Groundwater modelling has become a tool commonly used to analyse, estimate and predict those impacts. Groundwater flow in the vicinity of open pits or underground mines is three-dimensional in most cases; consequently, 3-D numerical groundwater flow models must be based on 3-D hydrogeological data if they are to become reliable predictive tools for resolving issues listed above. Three dimensional hydrogeological data in the vicinity of mine area including a lateral and vertical characterisation of hydraulic parameters, groundwater levels and water chemistry data should be collected from the ground surface to the final pit bottom or the lowest point of the underground mine or even below, depending on local hydrogeological conditions and proposed depth of the mine, in order to analyse the flow through the bottom of the pit or underground developments.

Hydraulic characterisation in the early stages of a project does not necessarily require a special hydrogeological drilling program. Good preliminary data can be obtained using simple slug testing on existing exploration holes and packer tests in some selected holes. A one-time measurement of groundwater levels (or within a short time interval) in the area once the system has recovered from the drilling and testing period can give a good understanding of the pre-mining groundwater flow direction. Water chemistry sampling should also be carried out as a part of the hydrogeological characterisation which will give a first approximation of the quality of water discharge. It is recommended that the hydrological conditions such as precipitation, evaporation, and run-off regime in the study area be evaluated at the early stages of a project as well.

The preliminary characterisation allows a first identification of the groundwater sources and potential problems for the dewatering management, stability issues, and quality of water discharge. Further hydrogeological investigation should be designed based on the analysis of preliminary data, geological and structural models, and conceptual hydrogeological model. It should be focused on specific hydrogeological units or structures that can connect water sources to the mining area.

Hydrogeological investigations must have a much larger area of influence than those considered in mining and geotechnical investigations. Mining investigations focus on the identification of ore and waste, and the radius or scale of the investigation is limited by the size and form of the ore body. Geotechnical investigations include a small distance from the boundary of the open pit or underground mine. Hydrogeological investigations, depending on the projects hydrogeological condition and vulnerabilities, can include areas of up to 10 km outside of the ore body boundary in order to have reasonable estimates of inflow to the mine, impacts of the operation on the groundwater levels and quality, and groundwater discharge to the surface water bodies during the mining and post-mining conditions. Because groundwater flow in the vicinity of an open pit or underground mine is three-dimensional, vertical field characterisation is recommended to be conducted to a depth, sufficient to characterise inflow to the bottom of the mine (regulatory agencies in some countries recommend doing this to the depth of at least 50 m below the proposed ultimate bottom of the open pit or underground mine [1]). In the same way, the numerical hydrogeological model should be vertically extended below

the bottom of final mine configuration to reasonably simulate vertical inflow to the bottom of the mine, and have an adequate vertical discretisation.

Based on pre-mining and mining data collection, a 3-D hydrogeological numerical groundwater model can be built. Modelling is an iterative process that includes: grid construction and assignment of properties and boundary conditions; steady state and, if there is data available, transient calibration; validation of calibrations; predictive simulations; and sensitivity analysis. The reasonableness of results in each step should be checked before proceeding to the next step. It is common that multiple parameter combinations (hydraulic conductivity, recharge, storage parameters, conductance in rivers and drain cells, etc.) can reproduce measured values. Those multiple combinations should be reduced by validating the model calibration. Sometimes, if predictive simulations results are unreasonable, it is necessary to go back through steady state and transient calibrations to check and/or modify parameters or extension of models, or even to change the conceptual model. This iterative process is necessary in order to keep predictions within an acceptable range of error according to the level of study, and not to receive disproportionate over- or under-estimated values.

Groundwater quality predictions can be done either using a solute transport model based on the 3-D numerical groundwater flow modelling or a simple water chemistry mixing model by using the different flow components from the numerical groundwater model.

EXAMPLES OF GROUNDWATER MODELLING APPLICATIONS ON MINE PROJECTS

Two actual cases of mine dewatering projects are described below to show how a 3-D groundwater numerical model can be used as a predictive tool on open pit and underground mine projects.

Case 1: Open pit mine at site A

Case description

Dewatering requirements and possible hydrogeological impacts of two proposed pit excavations for Project A were evaluated by a 3-D groundwater numerical model of about 1,000 km² and a thickness of 750 m, including 300 m below the final bottom pit.

The hydrogeology of the project area is essentially comprised of two groundwater systems: (a) shallow upper sands, silts/clays, till and a basal boulder/gravel unit; and (b) deep sandstones and underlying carbonates. Both water-bearing systems are separated by a shale unit; a confining layer of low permeability.

Infiltration from precipitation recharges the shallow groundwater system. A significant part of this water discharges back into creeks and ravines through the layer of upper sand. The deep groundwater system also receives recharge from the shallow groundwater system due to the differences in hydraulic head and the existence of a vertical downward gradient. The River A is the major surface water body within the hydrologic study area, with the riverbed being located within the lower till. Groundwater discharges into the river during pre-mining conditions.

A developed conceptual hydrogeological model has shallow and deep groundwater systems subdivided by a confining layer. Infiltration from precipitation recharges the shallow groundwater system. A significant part of this water

discharges back into creeks through the layer of surficial sand. The deep groundwater system also receives recharge from the shallow groundwater system due to differences in hydraulic heads and the existence of a vertical downward gradient. The River A is a major surface water body within the hydrologic study area with the riverbed being located within the till unit. Groundwater discharges into the river during pre-mining conditions.

During mining conditions the major sources of inflow to the proposed pits would be: (a) groundwater storage of the shallow groundwater system (during initial stages of pit excavation); (b) groundwater storage of the deep groundwater system (during late stages of pit excavation); (c) direct inflow from precipitation; and (d) inflow from River A (most likely limited) through the lower till and by recharge to the sandstone groundwater system through overlying shale.

Both pits will be excavated from the ground surface through the lower portion of the sandstone unit to the depth of 320 m. A dewatering well system was simulated as a total of 22 pumping centres on the perimeter of each pit, pumping water from the sandstone groundwater system. The water level for each dewatering well was specified to be 30 m below the elevation of the pit bottom at the end of each year, according to the yearly mine plans.

Constructed 3-D numerical groundwater flow model was calibrated to pre-mining water levels measured in numerous monitoring wells and to results of four long term pumping tests. The model was developed by using *MODFLOW-SURFACT* code [2] to simulate two water tables in predictive calculations.

Predictive modelling results

Predictive simulations of: (a) passive inflow to proposed pits; (b) dewatering requirements and residual passive inflow; (c) propagation of drawdown during proposed dewatering; (d) pit lake infillings; and (e) impacts to groundwater discharge creeks and River A (during both pit excavations and pit lake infillings), were done for the simultaneous excavation of both pits.

Predicted passive inflow, dewatering requirements, residual passive inflow and pit bottom depths in time for both pits are shown in **Figures 1 and 2**.

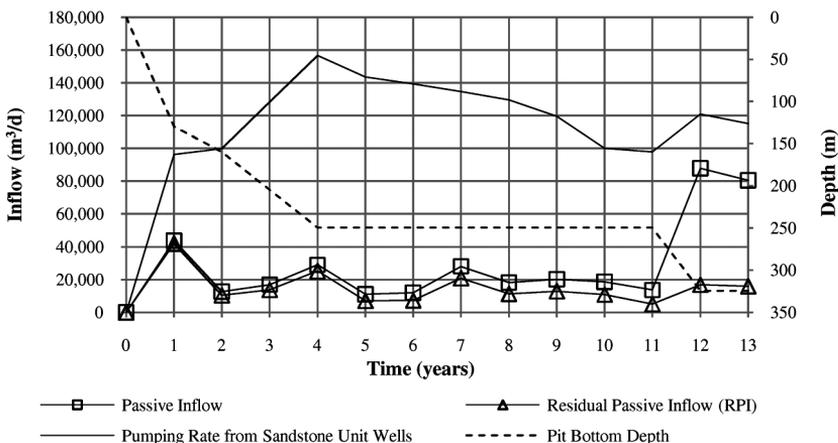


Figure 1 Open pit A inflow predictions.

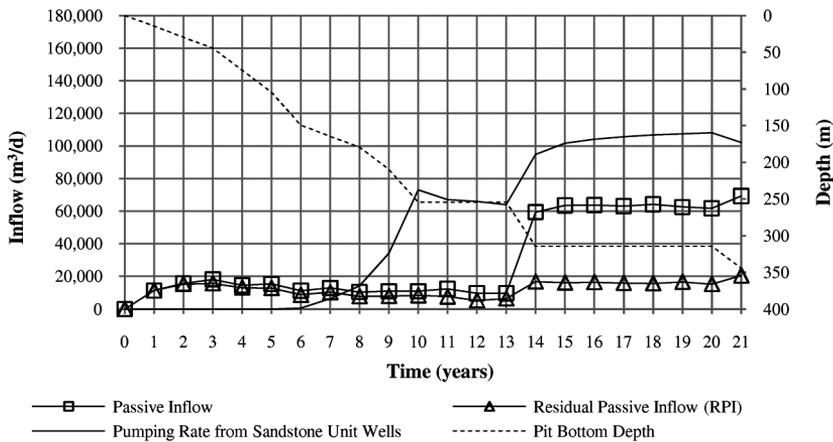


Figure 2 Open pit B inflow predictions.

Results of predictive simulations are summarised as follows:

- Maximum passive inflow is predicted to be between 18,000 m³/d and 44,000 m³/d during first three years of excavation of surface sand, and between 69,000 m³/d and 81,000 m³/d during excavation of the lower sandstone unit and carbonates.
- Maximum total pumping from the dewatering wells will be between 157,000 m³/d and 108,000 m³/d.
- Residual passive inflow (RPI) is predicted to be between 15,700 m³/d and 42,000 m³/d during the excavation of the upper aquifer and between 16,800 m³/d and 20,500 m³/d during the excavation of the sandstone unit.
- The 1-m contour of drawdown resulting from dewatering will propagate to a maximum distance of more than 10 km away from both.
- Maximum impacts to the surface water bodies are predicted to be between 200 m³/d and 6,000 m³/d, and will occur about 40 years after the end of pits excavation; and
- During the pit infilling with groundwater, pit lakes water elevations will reach 95% of recovery after 310 years and 315 years of the end of mining, for Pit A and B respectively. Pit lakes will have a water level elevation within 50 m below the pre-mining groundwater elevation in the pit area. The pits influence on both deep and shallow groundwater systems will continue throughout the period of pit infilling for more than 360 years.

Case 2: Underground mine at site B

Case description

Dewatering requirements, potential impacts on rivers due to mining, and quality of mine water discharge were evaluated using a 3-D numerical model as a part of a pre-feasibility level study. The model domain encompasses 420 km² and has an average thickness of 1,700 m, including 800 m below the bottom of the final mine plan.

The conceptual hydrogeological model consists of two major components: (a) an aquifer of unfrozen alluvial sediments, developed in a valley of large rivers and creeks; and (b) a groundwater complex of fractured rock, characterised by an extensive but depth-dependent jointing of host rocks and the varied thickness of permafrost.

The hydraulic conductivity values were estimated from more than 200 tests in open boreholes installed within groundwater complex of fractured rock and indicated that they decrease with depth and depend on the thickness of permafrost (decrease from river valleys where open taliks exist along inter-stream areas where thickness of permafrost exceeds 100 m).

Groundwater quality decreases with depth. TDS concentrations within the talik (unfrozen) zones and below shallow permafrost at the bottom of the proposed mine are predicted to be within the maximum contaminant level (MCL) limits. TDS concentration in groundwater below thicker permafrost (100 m and more) is predicted to exceed the MCL limits at the bottom of the proposed mine.

The proposed underground mine plan has an extension of about 19 km east to west, located beneath four of the five major rivers, and the simulated bottom of the ultimate underground mine is at a depth of 800 m under the rivers. The simulated schedule assumes 21 years of mining of four individual underground mines.

Two major sources of inflow to the proposed underground mines are: (a) groundwater storage; and (b) recharge from the river and creeks through unfrozen alluvium during the six month period when surface water bodies are unfrozen.

Two scenarios of distribution of the hydraulic conductivity values (K), were used for model calibration and predictive simulations to evaluate a possible range of inflow to the underground mine and associated environmental impacts: Scenario I uses the arithmetic mean of the hydraulic conductivity values; and Scenario II uses the geometric mean of the hydraulic conductivity values. Based on our experience, geometric mean values give better predictions for radial inflow to the mine. Arithmetic mean values better represent one-dimensional vertical flow (recharge to groundwater from a river, for example). Both components of flow will occur during mining of the deposit. Thus, two sets of hydraulic conductivity numbers (arithmetic and geometric means) were used to simulate the possible range of predicted inflows.

The model for both scenarios was constructed in *Visual MODFLOW* with *MODFLOW-SURFACT* capability [2, 3] and calibrated to pre-mining water levels and groundwater inflows to two trail underground mines, developed at two different levels during a five year period, and to associated changes in water levels in four alluvial and 39 bedrock monitoring wells.

Predictive modelling results

Predictive numerical simulations were conducted assuming only passive inflow conditions, and no active dewatering was implemented in the model. Predictive inflows and TDS concentration on water discharge are shown in **Figures 3, 4 and 5**.

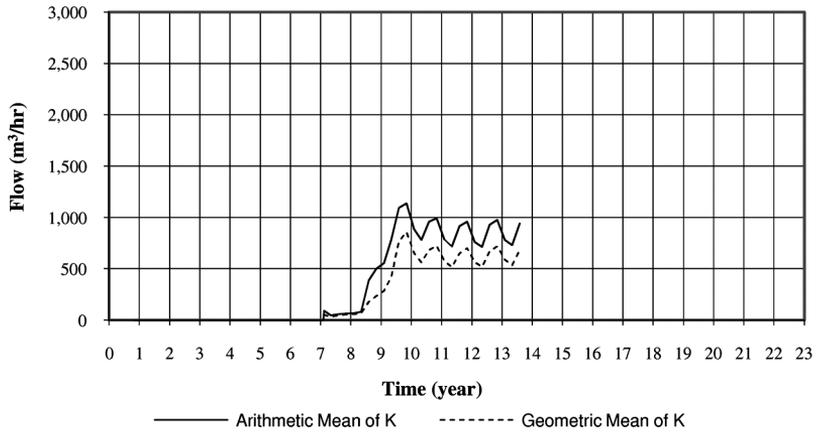


Figure 3 Predicted inflow to underground mine A.

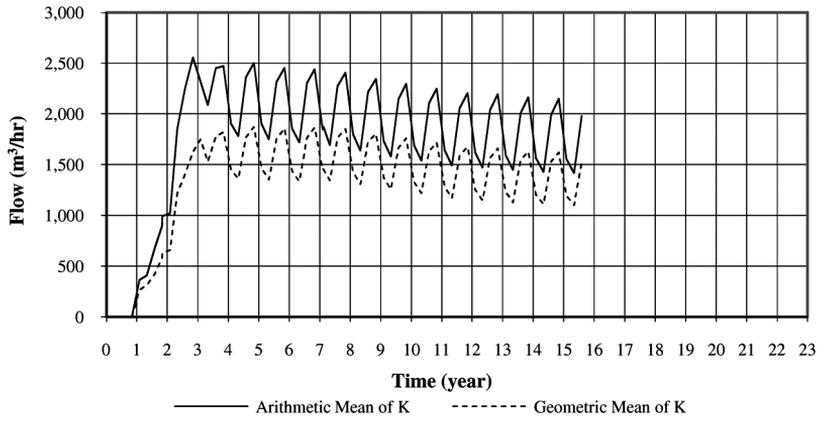


Figure 4 Predicted inflow to underground mine B.

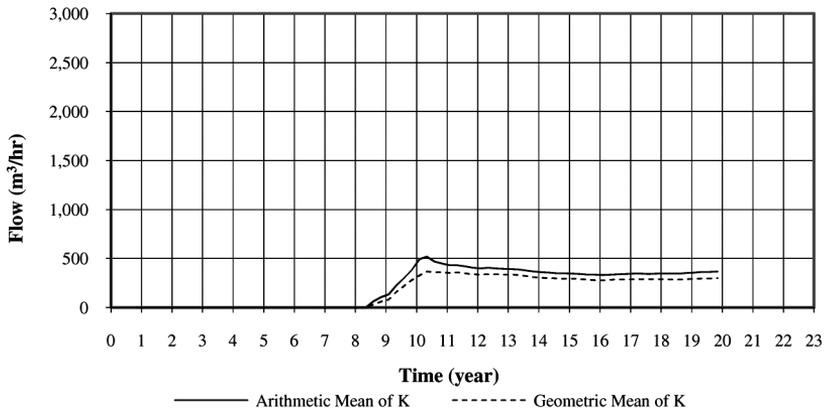


Figure 5 Predicted inflow to underground mine C.

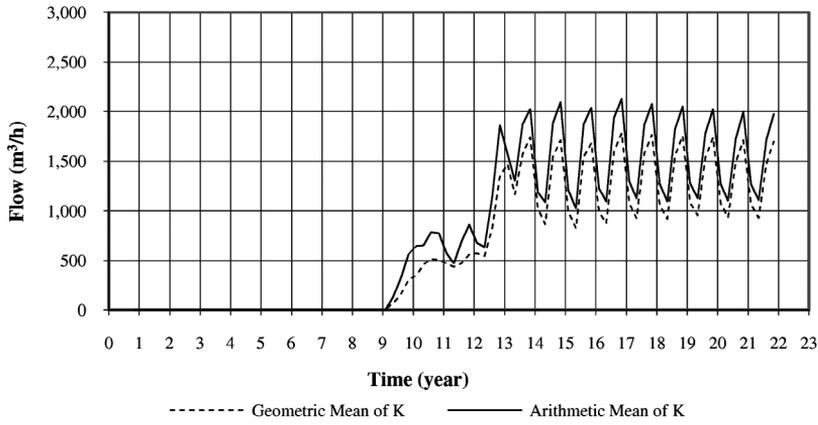


Figure 6 Predicted inflow to underground mine D.

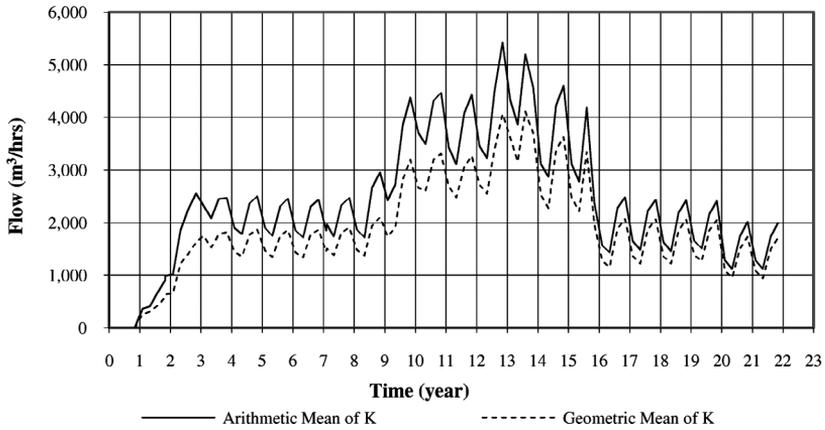


Figure 7 Predicted total inflow to underground mines.

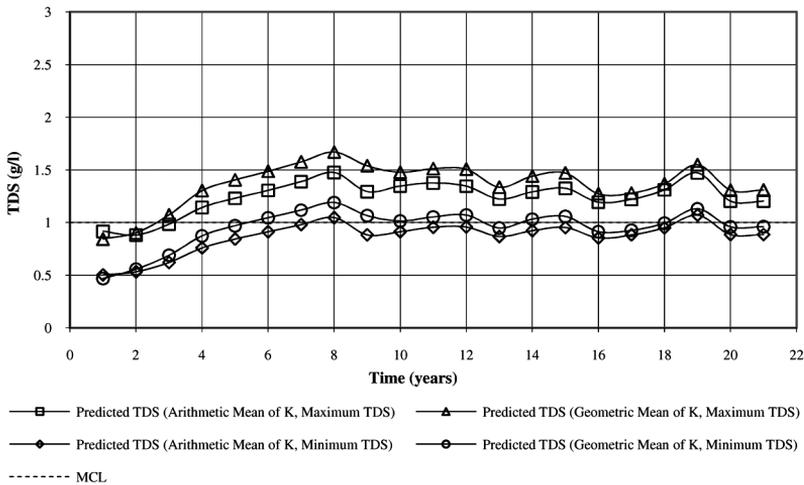


Figure 8 Predicted TDS in combined mine water discharge.

Results of predictive simulations are summarised as follows:

- Maximum inflows to individual mines are predicted to be between 500 m³/hr and 2,600 m³/hr, while the total combined maximum inflow is predicted to be about 5,400 m³/hr.
- Fluctuations of inflow in time, depending on river regime (unfrozen/frozen), will be between 700 m³/hr and 1,000 m³/hr as a result of recharge from rivers during the unfrozen period. Differences in mine inflow simulated for the two scenarios (arithmetic and geometric means of K values) are between 100 m³/hr and 700 m³/hr at the end of year 12, when all mines will be simultaneously operating.
- Predicted drawdown of 25 m within the uppermost saturated layer of the model were calculated to occur at a maximum distance of between 5 km and 9 km, for both simulated scenarios at the end of development of the mines.
- Maximum impact on the flow of rivers and creeks in the vicinity of the mines is predicted to be between 0.3 m³/s and 0.5 m³/s; and
- TDS concentrations of the mine water discharge, using the water chemistry mixing model and different flow components from the numerical groundwater model, are predicted to be between 1 g/L and 2.8 g/L for the different mines separately and with a maximum of 1.7 g/L for all combined water.

SUMMARY

Groundwater generally flows into open pit and underground mines three-dimensionally and variably through time. Collection of 3-D groundwater data, and commonly, the development of 3-D numerical groundwater and solute-transport models are required in order to fully characterise the groundwater system and to predict dewatering requirements and mining impacts. Hydrogeological data necessary for 3-D characterisation should primarily be collected in the area adjacent to the orebody and at a depth of at least 50 m below the proposed ultimate bottom of the open pit or underground mine. Data might include:

- A vertical profile of horizontal hydraulic conductivity (K_h) values within different hydrogeological units.
- The vertical hydraulic conductivity (K_v) value for specific units.
- A profile of water chemistry with depth.
- The hydraulic connection between the groundwater system and surface water bodies; and
- Water levels in plan-view and at various depths, to estimate lateral and vertical groundwater gradients.

We emphasise that vertical hydraulic gradients and vertical hydraulic conductivity are very important components of a conceptual hydrogeological model and predictive simulations of mine inflows and post-mining conditions (pit lake chemistry, for example), and are commonly missed during even advanced-level hydrogeological investigations.

Three-dimensional numerical groundwater modelling developed on geological and hydrogeological data, and on proposed mine plans, can be used for sensitivity analyses and planning of field work as well as for predictive purposes. There are numerous numerical codes and techniques now available; however, the commercially available and most frequently used finite-difference codes are *Visual MODFLOW* with *MODFLOW-SURFACT* [2, 3] and finite-element code

FEFLOW [4]. These codes have good modelling features to simulate the open pits and underground mines, are very well accepted by regulatory agencies and international experts and could be considered as the first choices in groundwater modelling of mine dewatering projects.

The fully developed 3-D numerical groundwater model should be calibrated to steady-state pre-mining and transient (initial mine dewatering, pump tests, etc.) conditions. After calibration, the model might be used to predict: (a) passive inflow to the mine (both in space and time); (b) active dewatering options (if required); (c) pore pressures, as input for slope/roof stability analysis; (d) potential environmental impacts to water levels and surface water bodies; and (e) post-mining conditions (including formation of a pit lake or flooding of the underground mine).

If necessary, a simple geochemical mixing model or a more comprehensive solute transport model can be developed based on the 3-D numerical groundwater model to predict quality of water discharge during the mining or pit-lake water chemistry for post-mining conditions.

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