Kittilä Gold Mine dewatering assessment: benefits of a new approach

Päivi Picken[1], Tuomo Karvonen[2], Eero Heikkinen[3], Tiina Vaittinen[3], Ville-Matti Seppä[3], Jaakko Saukkoriipi[4],

[1]Pöyry Finland Oy, Koskikatu 27 B, 96100 Rovaniemi, Finland, paivi.picken@poyry.com
[2]Waterhope, Munkkiniemen Puistotie 20 A 6, 00330, Helsinki, Finland
[3]Pöyry Finland Oy, Jaakonkatu 3, 01620, Vantaa, Finland
[4]Pöyry Finland Oy, Elektroniikkatie 13, 90590, Oulu, Finland

Abstract Water inflows into Kittilä Gold Mine underground workings were predicted over a selected time period, as the mine expands to deeper regimes. A new approach enabled effective studying of large regional datasets and complex underground workings, which are constantly changing. Posiva Flow Log was used for hydraulic testing. Generalizations of soil and bedrock were carried out. RQD-values (rock quality designation) were worked into a RQD-voxel model using geostatistics. Dependency between K-values and RQD values was determined, simplification of the underground space was carried out and a numerical groundwater model generated (continuous time-lapse simulation). Inflow during past mining was used for calibration.

Key words mine dewatering, hydrogeology, modelling

Introduction

Agnico Eagle Finland Oy Kittilä Gold Mine is located in Finnish Lapland, Kittilä municipality. Mining operations started in 2008 with two open pits Suurikuusikko and Roura. Underground operations started 2010. Since November 2012 mining has taken place only underground. Currently Kittilä Gold Mine production rate is 1.6 Mt/year and underground operations are gradually reaching deeper. A hydrogeological study was carried out 2015-2016 to support the mine operations and permitting. The objective of the study was to define the inflow quantities to the underground workings during 2014-2035. Primary focus was set for the time period 2016-2020. As a part of the survey inflow qualities in the different parts of the mine were assessed, as well as mass balances of certain water quality variables. This paper focuses to the inflow quantities, to the methodology behind the results, the benefits of the approach and uncertainties.

Methods

Background data, case conceptualization and model definition

Several data sources were used for conceptualization and defining the extent of the hydrogeological model. Initial available data included water courses and catchment areas, elevation model, climatic and hydrological data. Modeling volume was large enough to include the complete catchment area, so the source of water was net precipitation and recharge from soil layers to bedrock. Lateral recharge was neglected. Some prior hydraulic conductivity data was available, concerning one part of the study area. Soil cover, types and thickness were generalised. Bedrock was generalized into four main categories: mafic volcanic tuff, mafic graphitic tuff, tholeiitic basalt and shear zone (Figure 1), which was mainly containing the ore. Other data included ground water monitoring data and dewatering rates which were used in calibration using groundwater table, and geometry of the planned underground workings for the years 2014 – 2035. Leakage records from drilling were also available. Stress field was not used in modelling. Data sources included Geological Survey of Finland, Finnish Meteorological Institute, Finnish Environment Institute, National Land Survey of Finland and Agnico Eagle.

Processing of rock fracturing data

Rock fracturing was used for hydraulic characterization of rocks. Rock Quality Designation (RQD) available from drill core logging was processed with inverse distance squared method to a voxel model and extrapolated to cover areas without data, using depth position and lithological and deformation models. The volume of the model covers 8 x 13 x 1,3 km with cell size 40 m x 40 m in horizontal direction, and in vertical direction increasing from 1.0 to 10 m at the top 20 m, then being 40 m below depth of 20 m.

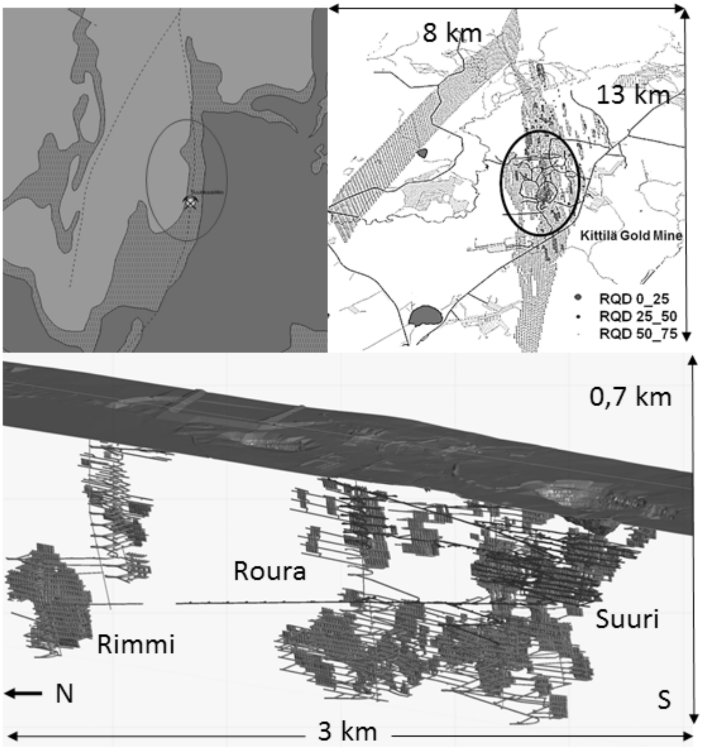

Figure 1. *Modelling area and volume of Kittilä Gold Mine together with regional geology. Upper on the left: Tholeiitic basalt (dark grey), mafic volcanite (light grey) and graphitic volcanite (medium grey), regional shear zones with dash lines, and mine area with a circle. Upper on the right: RQD values 0-75 % (grey voxels) modelled at borehole covered volumes, and generalised from deterministic regional shear zone model elsewhere. RQD values 75 – 100 % excluded. Below: mine geometry on a side view from the West.*

Composite files from core RQD data (5 m cells) were generated inside bedrock domains and calculated to voxel model at four stages within each bedrock domain, increasing the search distance at 50m, 100m, 200m and 500m to fill empty blocks. Search ellipsoid directions were based on geostatistical investigation and on the mine staff knowledge and experience of the site. Fracturing is more typically encountered in the upper part of the bedrock and in deeper parts of the site in the major shear or fault zones. Layer thickness of the more intensely fractured surficial rock was also based on the drill core data, and was defined for each bedrock category separately, studying the median of composites as function of depth (Figure 2).

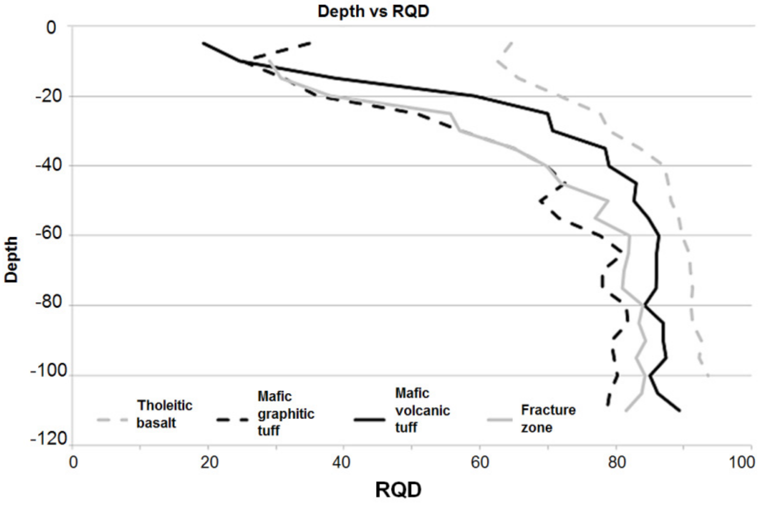

Figure 2. *Median RQD in lithology classes and shear zone vs. depth.*

A generalised dependency was derived between measured hydraulic conductivity from boreholes and the RQD from the same boreholes and depth levels. The model was transferred to numerical hydrological modelling. Hydrological model area was defined based on catchment areas, the elevation model, water courses, and geometry of the shear zones. Preliminary modelling was carried out to test suitability of the chosen model extent and available data sets – and to support planning of field investigations. Preliminary and final modelling used the same approach. The model is described later in this paper.

Field investigations

New rock hydraulic conductivity data was produced during the project, covering the ore and the shear zone – and surrounding host rocks. New borehole studies included four deep holes from the ground surface, three deep characterisation holes from the research tunnel and six underground production holes. For these holes, PFL (Posiva Flow Log) measurements were carried out, including fracture transmissivity, hydraulic head, flow direction and water electrical conductivity. The method is quick to apply, and is providing well covering information along boreholes on fracture specific transmissivities, which was converted for modelling to larger scale hydraulic conductivity (K-values of depth intervals and lithological and deformation domains). Measurement took place in natural status and under pumping (using achievable constant drawdown in each borehole, for example 10 m). The measurement procedure was adjusted to gain efficiency so that largest transmissivities (T $>10^{-8}$ m^2/s) could be detected and generalised in five meter blocks to average hydraulic conductivities (K-values, m/s) by summarizing fracture transmissivities and dividing the sum with the length of the assessed interval. Field investigations included also measurements of electrical conductivity of groundwater. Borehole measurements from ground level provided information about the hydraulic head and its variation which made it possible to assess the mine dewatering impact on the hydraulic head in the mine surroundings, as the measurements are showing which fractures are currently connected to the underground workings. Monitoring programme was designed for gathering up information of both seasonal and spatial variation of hydraulic head. Shut-off interference testing was carried out between five underground production holes sealed with packers at collar and equipped with logger installations for hydraulic head measurement. Zones having highest transmissivity were assumed to be associated with the changes in hydraulic head. Suggested installation of permanent vibrating wire piezometers was replaced with these shut-off tests and subsequent temporary monitoring due to mine production related time and site availability limitations. During the course of time the monitoring and progress of dewatering will indicate possible effects of stress field or discharging the aquifer, and modelling can be revised accordingly. A structural geology logging was carried out for the measured boreholes. Drill cores were assessed with Q'-method, where Q' is calculated with Equation 1 (Barton 2014):

$$Q' = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \quad \text{(Equation 1),}$$

where J_n is joint set number, J_r is joint roughness number and J_a is joint alteration number. Special attention was paid to such fracture zones were investigated where Q' –values were typically small (<0.1). Necessarily Q' does not correlate with hydraulic conductivity, as an open individual fracture (like a fault core zone) may alone cause a high hydraulic conductivity. A leakage survey was carried out in the tunnels by Agnico Eagle staff. Stopes were classified to leakage groups including 1) dry stopes (<10 % of wall/sealing was moist), 2) dripping stopes (10-50 % of wall/sealing was moist), and largely dripping stopes (10-50 % of wall/sealing was moist) and leakages with flow (> 5 l/min).

Modelling approach

A new method was adopted for predicting the underground leakage. The key challenges in this type of work are the complicated underground geometry and its changes over time. New tunnels and stopes are opened every year and former workings will be closed after ore extraction. From this perspective, finite volume modelling method was chosen instead of finite element or finite difference method. The cell size was kept unchanged around the open underground workings, using same cell size everywhere and accounting the flow proportional to the total volume of open underground space for each cell, allowing flexible modelling of constantly developing underground workings. The method consisted of three sub-models:

1. Predicting the entire rock volume K-values (log (K)), based on voxelized RQD and lithogical model
2. Simplification of the complex geometry of the underground mine
3. Predicting the leakage amounts at twice a year steps based on the results from the sub-models 1 and 2

In the sub-model 1 the average K-values and the average RQD value were compared and their site specific large scale interdependence was assessed. Information on fractures intersecting the boreholes, their orientation, or length and connectivity distribution was not available. Based on the interdependence the RQD voxel model was used in the hydrogeological numerical modelling as the hydraulic conductivity information source. Interdependency of RQD and log (K) was assumed to be linear (Equation 2):

$$\log(K) = A \cdot RQD + B \qquad \text{(Equation 2)}$$

Above 500 m depth the modeling volume was divided into three regions with different coefficients A and B, and below 500 m constant values were applied. A vertical anisotropy was introduced for the depths below 500 m, based on interpretation of depth and log (K) relation. Because of the fractured zone, a horizontal anisotropy was included in the model. The degree of anisotropy (2.1) was defined in the calibration context.

In the sub-model 2, effective tunnel length L_{eff} and radius R_{eff} were calculated using average tunnel cross section, the average radius derived from average cross section width (3.1 m in this case) and information about tunnel lengths opened each year. Effective tunnel lengths opened each year are presented in Figure 3.

The third sub-model predicted the leakages in each cell. A modification of a function for equilibrium stage for a long tunnel was used. Initial equation for calculating the leakage quantity to tunnel q ($m^3/s/m$) can be presented in following format, Equation 3 (Goodman et al. 1965, Gustafson 1986, Sievänen 2001):

$$q = \frac{2\pi K H}{\ln\left(\frac{2H}{R}\right)} + f_{skin} \qquad \text{(Equation 3)}$$

where K is hydraulic conductivity (m/s), H is hydraulic head (m), R is tunnel radius (m) and f_{skin} is an empirical coefficient allowing taking into consideration not fully radial flow. Cell specific leakage $Q_{(I,j,k)}$ (m^3/s) was calculated according to following function, Equation 4:

$$Q_{(i,j,k)} = \frac{2\pi K_{eff} L_{eff} (H_a - H_n)}{\ln\left(\frac{H_a - H_n}{R_{eff}}\right)} + f_{skin} \qquad \text{(Equation 4)}$$

L_{eff} and R_{eff} were calculated as explained above. K_{eff} was calculated as the geometric average of current node's and the surrounding nodes' K-values. H_a is hydraulic head around the leaking node as computed by the model and H_n is estimated hydraulic head in the leaking node. The hydrogeological modelling was carried out using numerical solution of the Richards equation (Eymard, 1999, Tracy, 2007, Karvonen 2008, Warsta 2011), which allows calculating simultaneously flows in both soil and bedrock. Moreover, computation of transport of substances was included in the model, taking into account density differences of groundwater.

Model calibration

Modelling was carried out for the period 2008 – 2035, calibrating the model using monitoring and dewatering data from 2008 – 2015. A snow accumulation and melting model was generated to support hydrogeological model calibration in addition to precipitation and evaporation.

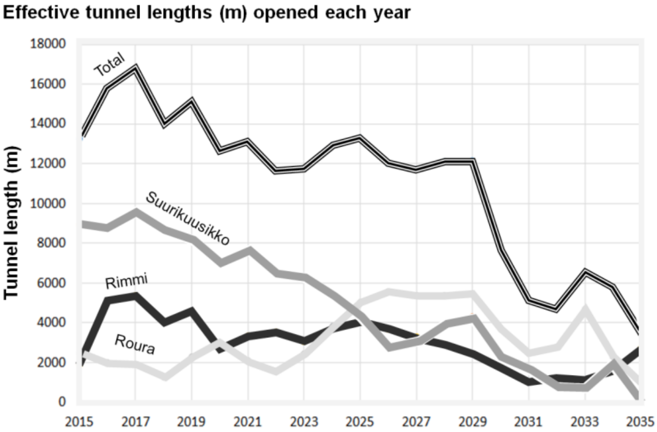

Figure 3 *Effective tunnel lengths opened each year: total, Suurikuusikko, Roura and Rimmi.*

Final model

Two alternatives were calculated for water leakages, where Alternative 1 was the primary (actual) alternative. Alternative 2 served partially a purpose rather similar to sensitivity analysis, with 50 % higher hydraulic conductivity in bedrock and differing treatment in stope backfills. Mass balance of certain elements and compounds were calculated as transport model for the Alternative 1. The transport model results did not include impacts of any chemical reactions like sulphide oxidation or attenuation. They simply present the water qualities from the rock transported to the underground workings. Outside the scope of this paper, it should be mentioned, that long term impacts of sulphide oxidation and other chemical processes were assessed in a separate geochemistry study and the results were used to support final conclusions and recommendations.

Results

According to the model, dewatering quantity pumped out of the underground workings in 2016 was estimated to be 4.22 M m^3/year (482 m^3/h). The actual quantity was confirmed to be 4.02 M m^3/year at the end of the year 2016. In 2020 the quantity is forecasted to reach

4.77 Mm³/year (545 m³/h). The summary of the water development according to the short term prediction is presented in the Figure 4 below.

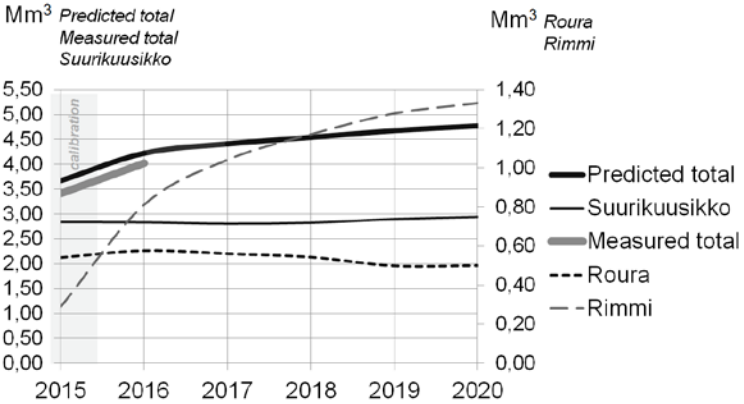

Figure 4. *Water amounts to be pumped, Alternative 1. Horizontal axis: time (year). Left vertical axis: predicted total inflows, measured total inflows and Suurikuusikko predicted inflow (million m³/year). Right vertical axis: Roura and Rimmi predicted inflows (million m³/year).*

Horizontal and vertical Darcy flow velocities were extracted from the model. Horizontal flow velocities (maximum year) at far ends of the model were extremely low, confirming the model area extent is adequate. Also modelled depth was large enough based on small vertical flow velocities at bottom of the model. Some up-coning of higher density groundwater can take place from the deeper regimes due to density gradient. The most important uncertainties were related to the amount and representativeness of measurement data and to interdependence between RQD and log (K), especially deeper down. There were also uncertainties concerning the hydraulic conductivities at the contact of the stope backfill and bedrock, and the mathematical treatment of flow at mechanic failure in Suurikuusikko open pit floor. Changes above the ground, which might take place over time, were not included to the model inputs. Settings for the horizontal and vertical anisotropy were based on a small number of measurements. Other identified uncertainties were related for example to a specific monitoring points unexplained groundwater table variations, and reliability of measured pumping volumes. There were substantially larger uncertainties related to the long term prediction. Two different underground dewatering water streams were preliminary proposed, though water management design is still an ongoing work. A simplified spread-sheet style calculation basis was generated for calculating water quantities and qualities from the different depths and spatial parts of the mine, when applying different water quality criteria.

Conclusions

Two different time frames were applied for the utilisation of the results. For the short term, years 2016-2020, uncertainties were smaller as the measured data was considered rather well representative. Results of the short term prediction are currently being used for planning and permitting the next phases of the operations. This far, after a short period, modelled and measured inflows are rather well in the same order of magnitude. In the deeper regime, no open tunnel workings exist and information was gathered from few boreholes. Therefore the long term forecast (2014-2035) has a higher degree of uncertainty and those results are taken as indicative. Concerning long-term forecasting, it should be also noted, that the model was based on 2014 mine planning status and these plans are updated. This study provided an effective and flexible approach to forecast development of inflows to an underground mine over a long time period, though quantity and representativeness of input data steer the reliability of the results. In the used approach, water quantity impacts of opening new underground workings and backfilling them can be assessed in a flexible and rather detailed way. This approach also "recycles" effectively data collected for other purposes. PFL measurements and their interpretations provide information of hydraulic transmissivity variation in rock mass to be used as input in numerical hydrologic modelling. This allows rather detailed dewatering design, taking into consideration different regimes within the mine and gradual changes over time.

Acknowledgements

The authors thank the rest of the project team for their valuable input and Agnico Eagle Finland Oy and Kittilä Gold Mine staff (Andre Wageningen, Pasi Kreivi, Jukka Välimaa and Leena Rajavuori) for co-operation and on-site support during the study.

References

Barton N, Grimstad E (2014) Forty years with the Q-system in Norway and abroad. Fjellsprengningsteknikk, NFF, Oslo, 25 pp

Eymard R, Gutnic M, Hilhorst D (1999) The finite volume method for Richards equation. Comput Geosci 3(3–4):259–294

Goodman RE, Moye DG, van Schalkwyk A, Javandel I (1965) Ground water inflows during tunnel driving. Engineering Geology 2:39—56

Gustafsson G (1986) Hydrogeological pre-investigations in rock (In Swedish). Swedish Rock Engineering Research Foundation, Report BeFo 84:1/86, 125 pp

Karvonen T (2008) Surface and near-surface hydrological model of Olkiluoto Island. Posiva Working Report 2008-17, 88 pp

Sievänen U (2001) Leakage and groutability. Posiva Working Report 06/2001, 82 pp

Tracy FT (2007) Three-dimensional analytical solutions of Richards' equation for a box-shaped soil sample with piecewise-constant head boundary conditions on the top. Journal of Hydrology 336: 391– 400

Warsta L (2011) Modelling water flow and soil erosion in clayey, subsurface drained agricultural fields. Aalto University publication series, Doctoral Dissertations 82/2011. Aalto Print, Helsinki, 211 pp