Application of Detailed Interval Flow Data Measured in Drillholes with PFL Tool in Hydrogeological Conceptualization and Numerical Flow Modelling for Mine Feasibility Scoping

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Abstract

Hydraulic drillhole measurements with the Posiva Flow Logging method have been performed at a planned open pit mining site in Northern Finland to acquire input data for numerical groundwater modelling. The high spatial resolution and low detection limit of the method enabled determining the hydraulic conductivity of bedrock, its depth dependence, and differences between two pit locations on a level sufficient for the numerical modelling. Separate FEFLOW models for two planned open pits were compiled and used to calculate groundwater inflow into the pits and effects on the water table in projected mining phases.

Keywords: Flow Logging, Hydraulic Conductivity, Groundwater Modelling

Introduction

In the Suhanko area in Ranua, Northern Finland, a few open pit mines are being planned for the exploitation of deposits of platinum-group metals in an Archaean mafic layered intrusion. We report hydrogeological field measurements and numerical groundwater modelling of two planned open pit locations at Ahmavaara and Konttijärvi. The goal of the measurements was to acquire hydraulic conductivity data of the bedrock that could then be used as an input in the modelling phase. The main aim of the modelling was to estimate the inflow rate of groundwater into the planned open pits in several stages.

Hydrogeological measurements

Prior to the reported study, data concerning the hydraulic conductivity of bedrock in the pit locations was only available from a few 24-hour crosshole pumping tests. Therefore, a better coverage was required before numerical modelling could be carried out. Downhole wireline hydrogeological measurement using Posiva Flow Logging (PFL) was chosen for data acquisition (Komulainen 2017) based on earlier good experiences elsewhere (Picken *et al*. 2017) and in the Suhanko area. Hundreds of exploratory and inventory drillholes were available for measurements. Information on fracturing and lithology in them was reviewed to define the most interesting locations for measurements, both within and outside of the planned pit shells, and two or three candidate drillholes from each location were selected. Some new holes were also drilled. In the selection of measured drillholes, the aim was to find ones extending below the bottom level of the pit, and to include intersections with modelled fault structures, the ore-hosting formation, the hanging wall, and the foot wall lithologies. A steep inclination was necessary to ensure smooth probe movement. Measurements in the field consisted of 20 drillholes during a time of two months. The flow logging of one 200–300 m long drillhole was typically performed overnight in 10–15 hours.

The PFL method is based on pumping a stable drawdown in an open drillhole, starting several hours before measurement, and running a flow logging with dense depth steps while continuously pumping. Elastic flow guides isolate the measurement section from the rest of the drillhole, so that the measured flow represents groundwater flow from the rock into the measurement section only. From the drawdown and flow, transmissivity associated with the measurement section can be calculated. The method is more sensitive to low transmissivities than spinner or thermal pulse in-line measurements, usually detecting dozens of flow locations in a drillhole with transmissivities ranging from 10^{-9} to 10^{-5} m^2/s, whereas spinner could typically indicate 3 to 5 flow locations with higher than 10^{-6} m^2/s transmissivity (Figure 1). The low background transmissivities are necessary in determining the hydraulic conductivity of the rock mass.

Compared with packer measurements, the measurable transmissivity range is similar, but PFL is quicker to implement, does not require a drill rig nor the expansion and deflation of packers, and yields a much denser set of observations along a drillhole in a shorter measurement time. Moreover, there is no need to decide beforehand which sections of the drillhole to test. The radius of influence in PFL is larger than in a packer survey due to typically longer pumping time, which leads to a lower interpreted transmissivity for a given fracture (Aalto *et al.* 2019).

Results

Interval transmissivity was calculated from the measurement data at a dense spacing along each drillhole. Each value represents a single hydraulically conductive fracture or a set of closely located fractures. Figure 2 presents the acquired results in the Ahmavaara pit location as disks along the studied drillholes, coloured according to the transmissivity value. Fractures with the largest hydraulic transmissivities are more abundant in the upper part of the bedrock to the depth of about 100–150 m.

Using the hydrogeological data as an input to numerical modelling required generalization of the results (Komulainen *et al.* 2018). The obtained transmissivities were examined with respect to their spatial distribution, lithology, depth, and coincidence with interpreted interceptions of faults and their zones of influence, as well as to fracturing indicators in drill core data (RQD, fracture frequency, breccia, faults, and core loss). For each drillhole interval in a

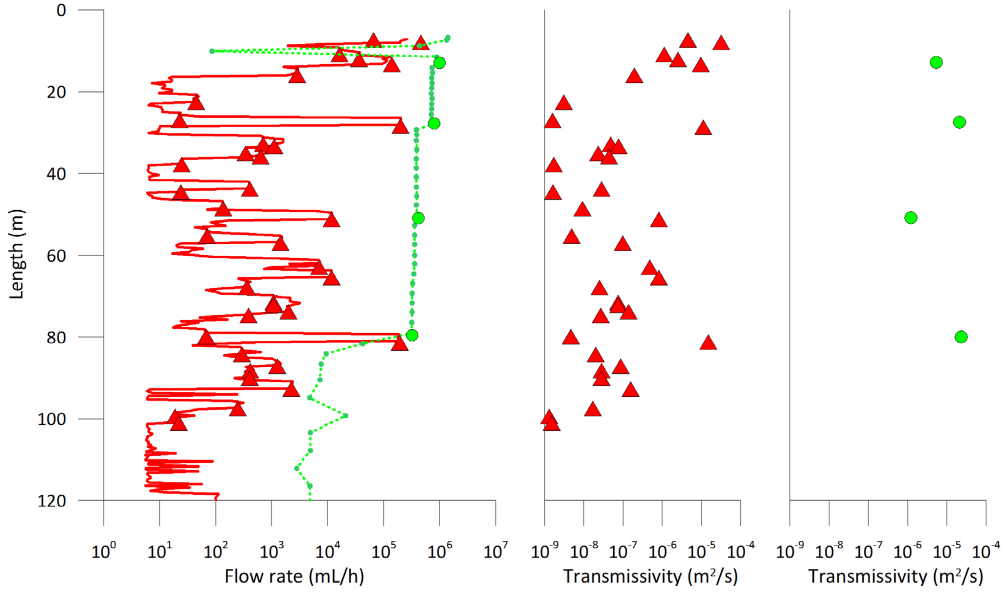

Figure 1 *Measurement data at the upper 120 m part of drillhole AHM-41 in Ahmavaara. Measurement continues to 267 m. In the graph on the left, the red line presents PFL flow data at 0.4 m intervals, red triangles the measured fracture flows (stepwise change in the flow data), the green line flow along the drillhole at 0.5 m to 5 m steps (spinner-type), and the green circles the detected fracture flows. The graph in the middle presents the transmissivities interpreted from the PFL data, and the graph on the right transmissivities interpreted from the flow along the hole. Both measurements were made with the PFL tool, on different runs and settings.*

certain geology, transmissivities were summed and divided by length. The obtained hydraulic conductivity was plotted versus the elevation of the interval centre (Figure 3). Practically impermeable intervals occurred also, shown using a hydraulic conductivity value of 10–11 m/s in the graph. Variability is high, and rock mass heterogeneous. There is no reliable indication of hydraulic conductivity difference between lithological domains. Hanging wall

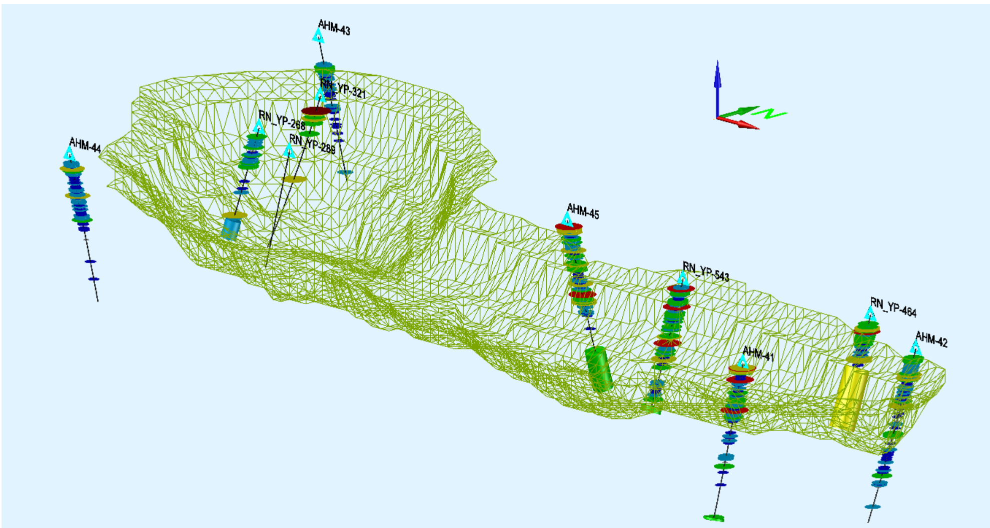

Figure 2 *Measurement data from Ahmavaara shown in 3D view, with the planned open pit shell, and results along drillholes. Size and colour of each disk depends on transmissivity (larger and red for greater values, small and blue for lower).*

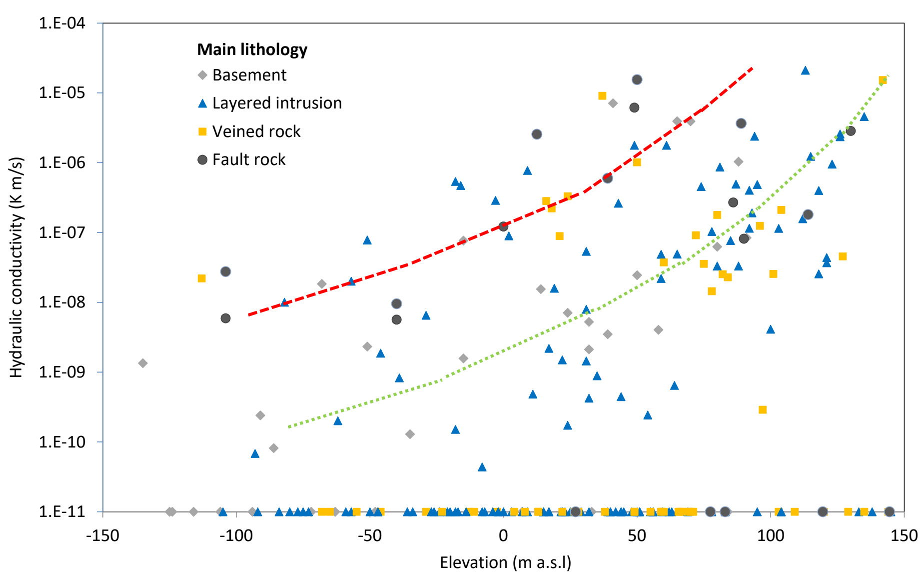

Figure 3 *Hydraulic conductivity versus elevation in Ahmavaara according to main lithological and fault interception intervals. Depth trends are sketched by the broken lines. Lower background conductivity (green) applies to average rock, and the scattered elevated values (red) about one order of magnitude higher to faults and fracturing intervals, which occupy a small fraction of total rock volume.*

is closer to surface, and it may indicate higher conductivity than the marginal series, which consisted of less fractured rock mass.

For modelling, transmissivities were converted to hydraulic conductivities of 10-metre elevation intervals, including also the contribution of fault interceptions. A distinct depth trend of lowering hydraulic conductivity was observed (Figure 4). There is a difference between the hydraulic conductivity depth distribution between Ahmavaara and Konttijärvi open pit locations.

Data from Konttijärvi shows a lower hydraulic conductivity in comparison with Ahmavaara. Lateral hydraulic conductivity differences between drillholes within the pit areas were negligible. The hydraulic conductivity was generalized to a depth trend, separately for each pit. Fault conductivities are heterogeneous in drillhole interceptions, typically one order of magnitude greater than for average rock and indicating depth dependence. According to the results, both pit locations represent typical Finnish bedrock.

Groundwater modelling

Separate groundwater flow models of the two open pits were made with FEFLOW. Ground topography was obtained from National Land Survey of Finland databases. Figure 5 presents the modelling approach for the pit models on a conceptual level. In general, the overburden in the area consists of two layers, glacial till directly on top of the bedrock and above that, a peat layer. According to weight sounding and GPR, the average peat layer is 1 m, and up to 6–7 m thick in the lower mire areas and almost absent on the surrounding hills. Bedrock topography was obtained from drilling close to the planned pits and supplemented with geophysical data. The till cover is typically 0–30 metres thick. Bedrock outcrops are scarce. Hydraulic conductivity of the peat layer is based on composition studies in laboratory and corresponding values from literature. Hydraulic conductivity of the till layer was obtained from slug tests in observation wells.

In the bedrock, the hanging wall volumes of the intrusion were modelled separately from the rest of the rock volume because of the conductivity differences indicated by the measurements. In all the bedrock, conductivity was assumed to decrease with depth. Vertical or dipping fault zones were included as discrete planar features with additional hydraulic conductivity. Their locations and extensions were interpreted from existing geological and geophysical information. As various waste rock dumps, temporary storage piles, water basins, and tailings areas are planned to be constructed

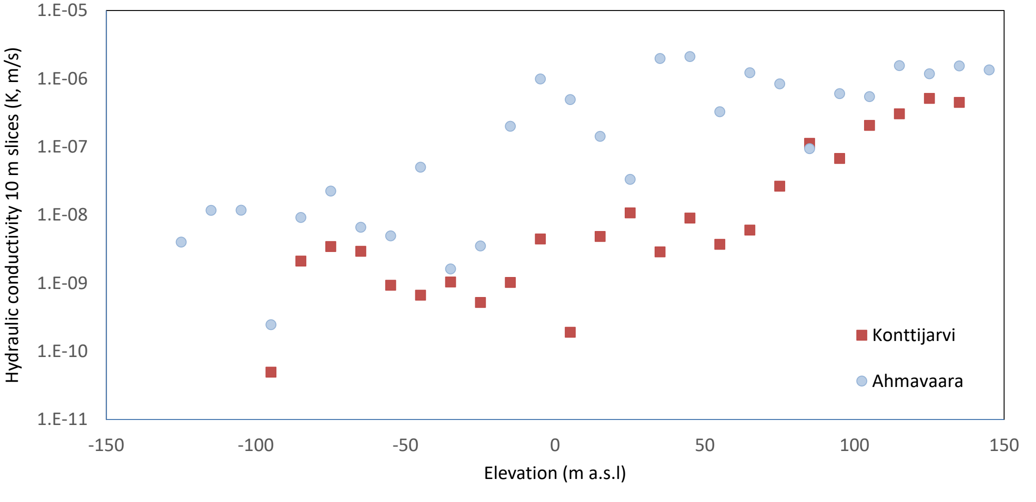

Figure 4 Measured transmissivities converted to hydraulic conductivity in 10-metre elevation intervals, plotted separately for the two studied pit locations. Konttijärvi appears less permeable.

close to the pits, they were included in the models. On the surface, natural rivers and brooks as well as artificial ditches were modelled using boundary conditions allowing the removal of groundwater from the model if hydraulic head of groundwater is higher that the assumed level of the body of surface water. Groundwater recharge on the top surface, or infiltration, adds groundwater to the budget of the model. On the sides of the modelled volume, a constant-head boundary condition was set, based on the assumption that the drawdown effect from the open pit will not extend to the model boundary, but head will remain at the value obtained from a regional MODFLOW model compiled earlier.

Figure 6 shows a three-dimensional view of the model geometry for the Ahmavaara open pit in its largest modelled extent. The highest surface elevations, presented in red, are waste rock dumps around the pit. A sector has been cut away from the modelled volume for better visibility of the open pit in the middle.

Modelling results

The main result of the groundwater modelling was the inflow of groundwater into the planned open pit mines. Figure 7 presents a

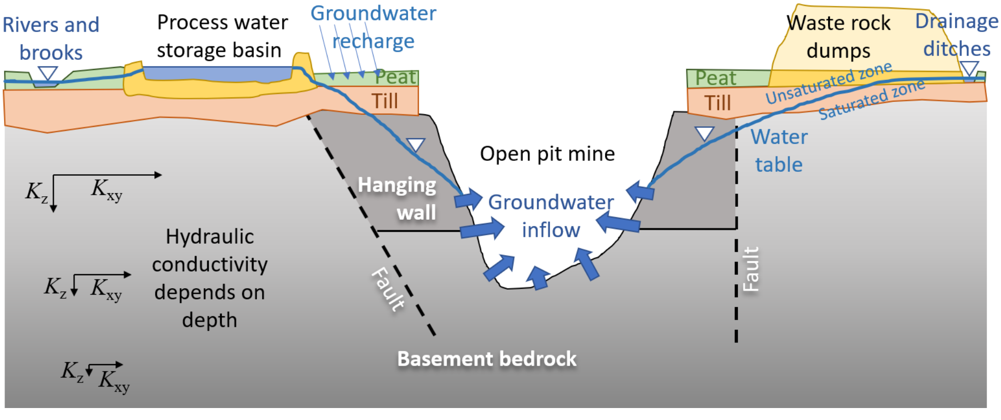

Figure 5 *The conceptualization of the modelled open pit mines.*

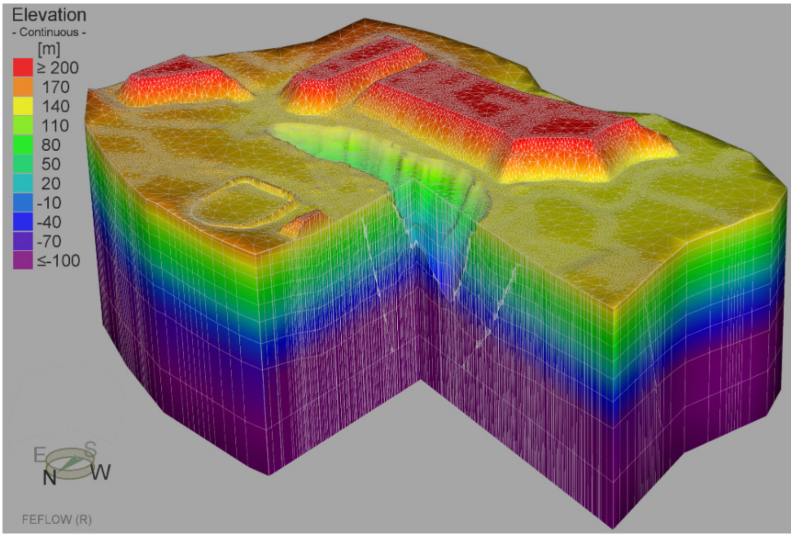

Figure 6 *3D view of the model of the Ahmavaara open pit in the final mining phase. A sector in the foreground has been cut away to show a cross section of the pit. Vertical dimension exaggerated 3-fold.*

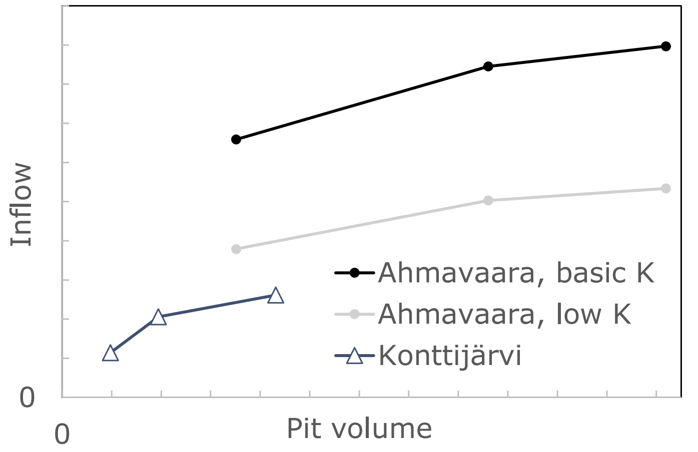

Figure 7 *Relative comparison of calculated groundwater inflow in three mining phases of the planned open pit mines, presented as a function of the volume.*

plot of the relative difference of the calculated inflows as a function of excavated pit volume. For the larger Ahmavaara pit, there are two curves, one for the basic assumption on the hydraulic conductivity of bedrock and the other for low conductivity (one-third of the basic values) calculated for sensitivity analysis. The comparison clearly shows the consequence of the observed difference in the hydraulic conductivities of bedrock in the two pit sites: even with the lower conductivity assumption for Ahmavaara, a larger inflow can be expected for about the same pit size. Especially in the case of the Ahmavaara pit, the increase of inflow as a function of pit volume is rather gentle. This results from the decrease of hydraulic conductivity of bedrock with depth.

Besides the inflow into the pits, the groundwater models yielded estimates of the drawdown of water table and hydraulic head. According to the results, the effect of the pits on the water table will be tolerable, extending mainly to areas around them that will also be altered by surface construction and other activities related to the mining. The models are expected to be useful in future modelling tasks, e.g., for the assessment of environmental effects after mine closure.

Conclusions

Hydrogeological measurements in the field with the PFL method, and generalization of the results for the numerical groundwater flow modelling proved to be a fruitful approach for the task of estimating the groundwater effects of planned open pit mining. The spatial and depth coverage of the measurements was sufficient to obtain the necessary hydraulic conductivity input for the numerical model. A decreasing trend of hydraulic conductivity as a function of depth was confirmed and found to differ in the two studied pit locations, and an increased conductivity related to the known faults was indicated.

The reported investigation was part of preliminary and detailed feasibility studies for the mine project, but it is likely that the obtained conductivity data and the compiled models are also useful in the future for e.g., the assessment of post-closure environmental impact.

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