# Insight into packer testing technique through numerical modelling; field implementation, effectiveness, and limitations

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## Abstract

Injection testing in packer isolated intervals is a single borehole technique widely used to characterise moderate to low hydraulic conductivity [K] rock mass in mining projects. The technique is easy to piggy-back onto resource and geotechnical drilling programmes to save time and cost. The principal advantage of packer testing is the ability to investigate rock mass hydraulic properties in narrow diameter boreholes to depths of more than 1000m. The test data allow estimation of vertical distribution of rock mass hydraulic conductivity (K), which is often needed to inform numerical groundwater models to predict water inflow and pore pressure distribution around the mine. Despite their widespread usage, there is a relatively poor understanding of the following aspects:

1. The extent of tested rock. The actual extent is unknown and, furthermore, there is uncertainty over whether or not the tested volume is representative of the surrounding rock mass.

2. The effects of undertaking testing in cumulative overlapping (successive) intervals within a limited time-period; in particular, the impact of residual pressure between tests on the results.

3. The effect of elastic storage on packer test results.

4. The degree of borehole skin effect on the packer tests results (despite this being a widely recognised issue).

The results of the present paper, which investigates the above aspects through numerical modelling, suggest that understanding of rock mass and test conditions is necessary to interpret packer testing results.

## 1 Introduction

Packer testing is a common in-situ hydraulic testing technique in which one or more inflatable bladders are used to isolate sections of a borehole. The isolated section is then tested using either water injection or extraction techniques (U.S. Bureau of Reclamation, 1977). The hydraulic conductivity of the tested interval is estimated based on the recorded pressure and flow rate data using analytical flow models, notably those developed by Thiem (1906) and Hvorslev (1951).

Packer injection testing is generally undertaken using one of two methods –testing concurrent with drilling (the ‘top to bottom’ method) and testing after completion of borehole drilling (often ‘bottom to top’ method). When testing concurrent with drilling, testing is undertaken as drilling continues, with discrete intervals tested along the borehole column. When testing after completion of drilling, numerous cumulative packer tests are run from ‘bottom to top’ of the borehole, with the results from the previous interval test used to infer the results of the subsequent test interval. In general, testing concurrent with drilling is preferred as it provides more accurate results over discrete intervals. Testing after completion of drilling is still sometimes used, however, since it is faster, more cost effective, and can be used to design more advanced testing, such as straddle packers or other, if deemed necessary. In the cumulative testing technique investigated in this paper the packer is progressively raised from the bottom-most testing position to the top-most testing position with tests run sequentially (see Figure 2). As such, the overlapping tested interval gradually increases with each test undertaken. The time needed to remove drill rods and raise the packer element between tests while testing the borehole from bottom to top can be as little as 2 hours with the use of modern testing systems such as the IPI STX-60 system (IPI, 2023).

Such cumulative testing after drilling completion is subject to known limitations, including difficulty in data interpretation due to ‘masking’ effects in which high K intervals if identified in the lower part of the borehole mask the results of lower K intervals above. This is further complicated by borehole conditions and heterogeneity in site hydrogeology due to variable, rock matrix porosity, faulting and fracturing. These factors play an important role in the reliability of the packer testing results as demonstrated further in this paper.

An introductory review of the above practical aspects of packer testing investigated by this paper is presented below.

## 1.1 Extent of rock mass tested

The actual radius of influence of a packer test (as for a pumping test) depends on the effective porosity of the rock matrix and the distribution and size of the fracture network (Houlsby, 1976). Such rock characteristics are usually unknown and their quantification from field data is often made difficult by the anisotropy and heterogeneity characteristics of the target formation. Furthermore, whether the tested volume is representative of the larger surrounding rock mass that is the focus of the investigation is also largely unknown. A radius of influence of 10m from the borehole is suggested by Bliss & Rushton (1984) for packer tests based on the results of numerical modelling using a 1m hydraulic head difference. This value is suggested for a relatively high K rock mass, with this radius decreasing significantly within lower K material.

As the radius of influence is a function of a natural logarithm, the effect of this on the transmissivity of a tested borehole is low. As such, various authors have suggested a radius of influence of between 5 and 10m producing reasonable transmissivity estimates (Meyer et al., 2008; Yihdego, 2017). Both Hvorslev and Thiem assume laminar, or 'Darcian', flow models. It is generally accepted that fine fracture networks exhibit Darcian flow, however large fracture zones may cause turbulent groundwater flow for which the above equations are not applicable (Preene, 2018). In this paper, packer test radius of influence is further investigated through numerical modelling.

The commonly used Hvorslev and Thiem equations assume laminar (or, 'Darcian') flow models. The Thiem equation (Thiem, 1906) for the effective transmissivity of an injection tested borehole is seen in equation [1]:

$$T = \frac{Q * \ln\left(\frac{R}{rb}\right)}{2\pi * Pi} \qquad [1]$$

Where T = transmissivity ($m^2$/day), Q = injection rate ($m^3$/day), R = radius of influence (m), rb = borehole radius (m) and Pi = net injection pressure. The Hvorslev (1951) equation is seen in Equation [2]:

$$K = \frac{Q}{F * H} \qquad [2]$$

Where K = hydraulic conductivity, Q = injection rate, F = shape factor and H = excess pressure. Both of these equations assume 'steady-state conditions', without taking into account the effects of storativity or skin effect.

## 1.2 Residual pore pressure effects

When packer testing following completion of drilling (refer to Figure 2), the amount of residual pressure (i.e., back-pressure) held within the tested rock mass between tests, and the effect this may have on the tests results, is unknown. Measurement of residual pressure is not practical (between successive tests) as the water level in the tested borehole does not necessarily reflect the actual pressure in the surrounding rock mass. Furthermore, the pressure gradient that builds up during packer tests and the hydraulic properties of the rock mass further complicate testing.

During a Lugeon test (an inflow test in which different pressure 'steps' are used, generating an upwards and downwards curve), a phenomenon of hysteresis between the pressure profiles is sometimes evident (Lugeon, 1933). Hysteresis is commonly thought to occur due to washing out of cavities or clay gouges within the borehole walls, wash-out between the packer inflatables or borehole walls, or movement of the rock mass during testing (Yihdego, 2017; Preene, 2018). Houlsby (1976) suggested five primary Q-H response curves produced during a Lugeon test, each of which suggests a different set of hydraulic and test conditions. A build up of pore pressure from preceding tests within the same interval are generally not considered to be the cause of hysteresis, however this has rarely been tested (Houlsby, 1976; Preene, 2018).

## 1.3 Elastic storage effects

The effects of storativity (or, elastic storage) of the rock mass during Lugeon testing are not considered during interpretation of the hysteresis curve or in subsequent determination of K (Houlsby, 1976; BS5930, 1981). Rutqvist et al. (1998) investigated fracture storativity in a granitic rock mass, finding that most of the fracture storativity originated from fracture deformation rather than the inherent storage parameters of the fault structure, a factor itself dependant on rock mass and fracture stiffness.

### 1.4 Borehole skin effects

Prior to packer testing boreholes should be cleaned (or flushed) with freshwater or/and airlifted to remove any excess drilling fluids and drill chips, until the lifted water is clear and free of fines. However, this procedure is often not fully completed, and the borehole is flushed only over a short time period to reduce the risk of borehole collapse (particularly in weathered and fractured rock environments). In cases where borehole skin effects are suspected, a Lugeon test is recommended in order to determine if skin effects are present through hysteresis analysis, as described by Houlsby (1976).

When drilling intercepts fractured rock and weak material, such as in and around fault zones, the use of a clogging additive (or 'colmating agent') is often necessary to prevent collapse of the borehole. This chemical additive adheres to the borehole walls and expands, reducing the risk of borehole collapse and allowing the drilling to advance. This however inherently changes the hydraulic properties of the borehole walls, the effects of which may linger even after a prolonged period of borehole cleaning. In short single borehole tests, such as pack injection tests, the impact of the skin effect on packer test results is difficult to quantify accurately, especially in packer injection tests.

The above-mentioned factors will be investigated through numerical modelling in the present paper.

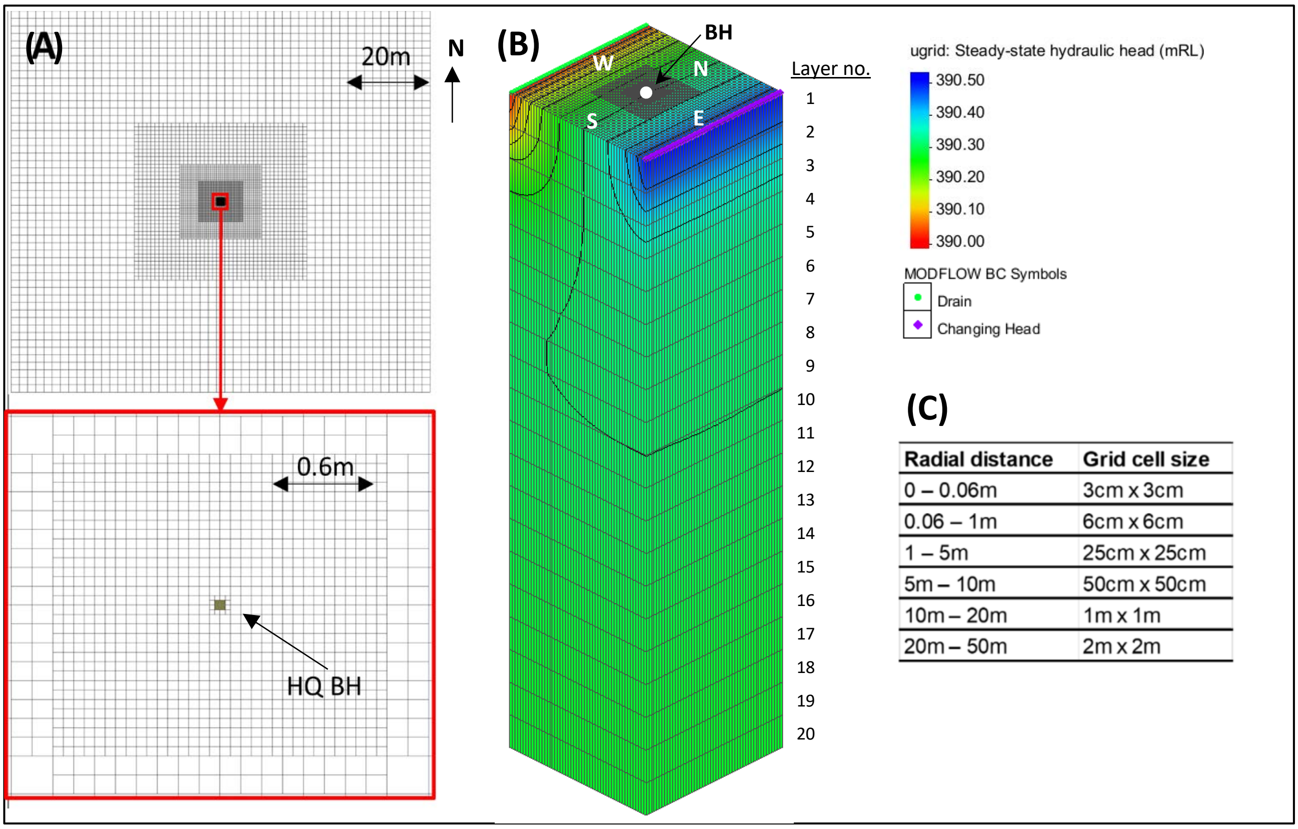
## 2 Methodology

To investigate the above packer testing aspects, MODFLOW-USG (unstructured grid) code under GMS software interface (GUI) has been used to develop various numerical models that intend to mimic the context and procedures undertaken in the field during packer testing. MODFLOW USG code was used as it provides high flexibility in terms of grid refinement that is required to accurately represent features such as hydraulic boundaries, fault zones or boreholes.

As the packer test radius of influence is expected to be limited based on literature review, all the developed numerical models are highly refined and consist of 100m-by-100m spatial grids at the center of which the packer tested borehole is located. The use of MODFLOW-USG code enabled increasing levels of refinement around the central point (representing the packer tested borehole) within the grid. All models have 20 layers (each 20 m in thickness). The grid cells are small (3cm) at the center of the model to accurately represent an HQ diameter borehole (and potential skin effect around it). Cell size then increases progressively toward the outer part of the model (see Figure 1 A). The total number of cells per model layer is 7,668, with the total number of cells in the 20-layer model totalling 153,360. Considering the number of layers and required lateral grid refinement to represent the borehole and skin effect etc., the small model extent is appropriate to keep the model size adequate for the multitude of numerical simulations required, as explained later in this paper. Plan and oblique views of the grid discretization are illustrated in Figure 1.

### 2.1 Steady-state model

An initial steady-state model was developed, representing a simple and realistic hydrogeological system in which the packer tests are undertaken. As shown in Figure 1, a lateral hydraulic gradient of 0.5% was implemented between a constant head (CHD package) boundary condition (BC) along the eastern border of the grid (set at an elevation of 390.5 m) and a drain boundary condition (DRN package) along the western border of the grid (set at an elevation of 390 m). In the real world, this could represent a section of an aquifer system between a lake/river at the eastern boundary and an open pit or drain along the western boundary. The predicted hydraulic head from this model is used as the starting head for the following transient models that simulate the packer tests.



| Radial distance | Grid cell size |
|---|---|
| 0 – 0.06m | 3cm x 3cm |
| 0.06 – 1m | 6cm x 6cm |
| 1 – 5m | 25cm x 25cm |
| 5m – 10m | 50cm x 50cm |
| 10m – 20m | 1m x 1m |
| 20m – 50m | 2m x 2m |

Figure 1. Model grid. A – Plan view, B – Oblique view showing steady-state hydraulic head and boundary conditions (as well as equipotential isobars-black contour lines), C – Grid refinement parameters

## 2.2 Transient models

Various transient models were developed, each with a total of 40 stress periods representing 20 cumulative packer tests. In the model, each test consists of a 30-minute period of injection followed by a 120-minute ‘recovery period’, thus each full injection-recovery cycle lasted a total of 150 minutes. 10-minute time steps were used in the model to simulate both ‘injection’ and ‘recovery’ phases. A schematic of the packer testing sequence is shown in Figure 2.

A total of eight transient models were developed under different scenarios. Table 1 summarises the model configuration, structures, hydraulic parameters, and BCs used in the various numerical models developed.

When rock permeability is relatively low (i.e., <1E-7 m/s), a field packer test is typically carried out using constant injection pressure for a limited period (say, 20 minutes) during which the water injection flow rate is measured. The pressure and injection flow rate are recorded and used to calculate the hydraulic conductivity of the tested rock interval using the flow equations described above.

Using IPI packer systems (IPI, 2023), 100 psi pressure (around 70 m of hydraulic head differential) is generally used during injection testing to limit rock mass fracturing whilst still achieving injection of water into the surrounding rock mass. The maximum pumping rate achievable by drill rig injection pumps is no more than 15 l/s, with most commonly available pumps generally between 1 and 2 l/s capacity (Drillmaster, 2023). Two constraints have been used accordingly; 15 l/s injection rate and 100 psi injection pressure. As such, depending on the controlling factor in each model, either General Head (GHB) or Specified Flow (WEL) BCs were used to simulate packer injection tests.

These two constraints have been used as limiting factors during model simulation, ensuring that neither the 15 l/s injection rate or 100 psi pressure were exceeded (at the four central cells of the model grid representing the test borehole). The total horizontal length across the four central cells of the model is 62 mm and the diagonal length 89mm, mimicking an HQ borehole.

Keeping the same model structure and outer boundary conditions, a number of models were developed to investigate various packer testing scenarios, including homogeneous rock mass and faulted environments, and scenarios where skin effects are present. Paired models with different K and Ss characteristics have then been constructed for each of the rock mass scenarios with a total of 8 models developed in all. Table 1 summarises the hydraulic characteristics of each model.

The faults introduced into models 3 and 4 were set up as 12 m thick features to ensure oblique continuity between grid cells across layers (refer to Figure 3). These two breached both the injection and pressure limits during different time steps. For these models the GHB was used at a lower pressure, replicating what would typically occur in the field.

Each of the groundwater models described is designed to investigate one or more of the aspects introduced in Section 1. Generally, only one variable was changed per model to assess the influence of this variable on the results of a packer test.

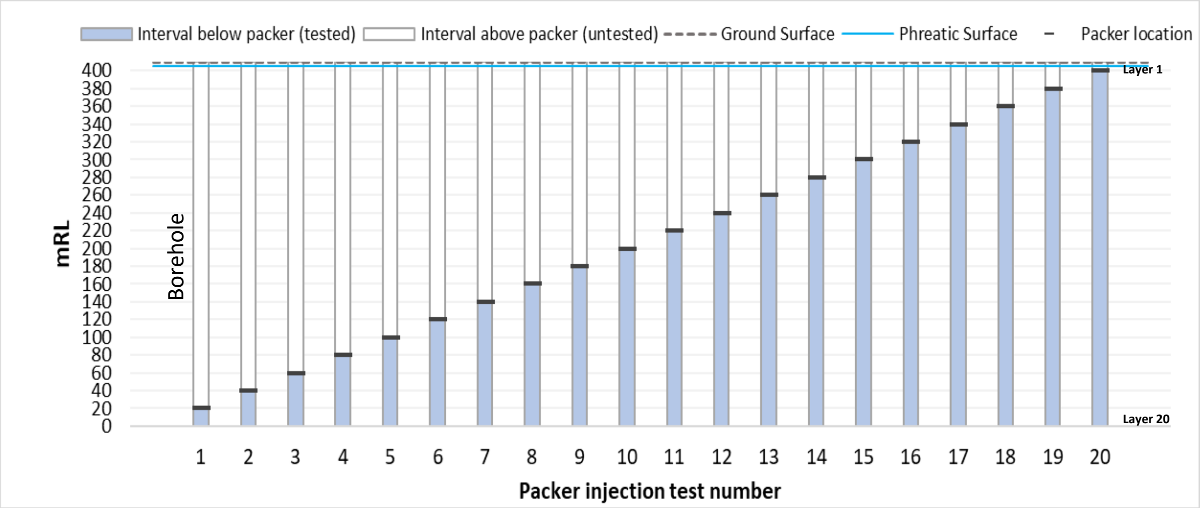


Figure 2. Cumulative packer testing following completion of drilling. Interval tested increases as testing progresses. The interval overlapping with the previously tested interval also increases over time.

Table 1. Summary of transient models and corresponding input parameters: (a) investigating the extent of rock mass tested, (b) residual pore pressure between tests, (c) elastic storage effect, and (d) the borehole skin effect on packer test results.

| ***Model #*** | ***Rock mass structural configuration*** | | **Hydraulic parameters** | | **BC** | **Aspect investigated** |
|---|---|---|---|---|---|---|
| | | | **K (m/d)** | **Ss (/m)** | | |
| *1* | Homogenous | | 0.01 | 1E-04 | GHB | a, b, c |
| 2 | Homogenous | | 1 | 1E-04 | WEL | a, b, c |
| 3 | Faulted | Host rock | 0.01 | 1E-04 | GHB | a, b |
| | | Fault | 1 | 1E-04 | | |
| 4 | Faulted | Host rock | 1 | 1E-04 | WEL | a, b |
| | | Fault | 0.01 | 1E-04 | | |
| 5 | Homogenous | | 0.01 | 1E-06 | GHB | c |
| 6 | Homogenous | | 1 | 1E-06 | WEL | c |
| 7 | Skin | Host rock | 0.01 | 1E-04 | GHB | d |
| | | Skin | 1E-04 | 1E-04 | | |
| 8 | Skin | Host rock | 1 | 1E-04 | GHB | d |
| | | Skin | 1E-04 | 1E-04 | | |

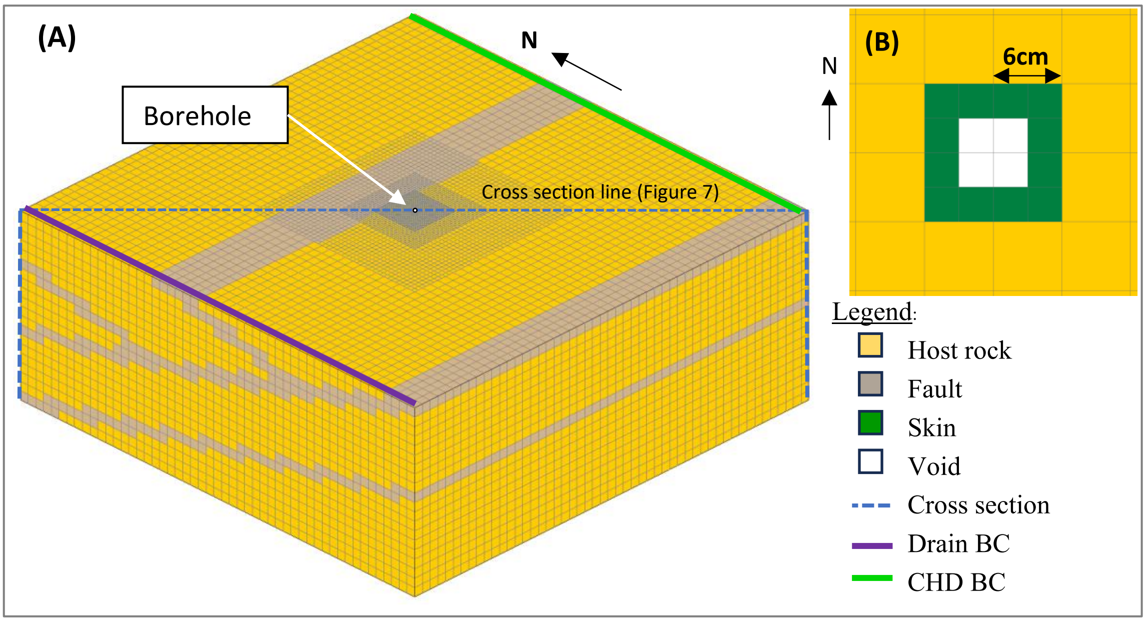


Figure 3. Configuration of Models with Faulting and Skin Effects: (A) block diagram of Models 3 & 4 including faults; (B) plan view of central portion of Models 7 & 8 illustrating skin effect simulation

# 3 Results and discussion

For ease of comparison, the model simulation results are presented in pairs in the following sections i.e., Models 1 and 2; Models 3 and 4; Models 5 and 6; and Models 7 and 8. 'Observation points' refer to fictitious water level monitoring points built into the model and located at variable distances from the center of the model grid (i.e., from the test borehole) to assess how significant and over what distance the effect is observed. Vertical and horizontal anisotropy are both assigned a value of 1 in all models.

Models 1 and 2 simulate packer tests in homogenous media that have the same elastic aquifer storage but different K values (model 1 low K and model 2 high K). These two models assess the effect of K on the extent of the radius of influence of packer tests and could be considered baseline models to which models 5 and 6 (investigating elastic storage effect, the former exhibiting low K and the latter high K) and models 7 and 8 (investigating skin effects, the former exhibiting low K host rock and the latter high K host rock) can be compared. Models 3 and 4 investigate the effects of faulting and will be discussed in Section 3.3. In model 5 and 6 a lower elastic storage value is assigned to the aquifer compared to models 1 and 2, whilst in models 7 and 8 a low permeability skin (3 cm thin, with a K value of 1E-6 m/s) is added around the borehole without changing the elastic storage coefficient.

## 3.1 Skin effect and storativity

The simulated water injection rate into the borehole for models 1, 2, 5, 7 and 8 during packer injection testing is shown in Figure 4. The injection rate for model 6 is not plotted as it is identical to that of model 2. The y axis of the graph is limited to 5 l/s, however model 2 (and model 6) exhibit inflows of 15 l/s during every injection test. The predicted hydraulic heads over time (over the cumulative 20 packer tests period) from models 1, 2, 5, 6, 7, and 8 at observation points 0.5 m, 5 m and 50 m east of the center of the packer tested borehole are shown in Figure 5 (top, middle and bottom graphs respectively). In both Figure 4 and Figure 5, time zero corresponds to the start of the first packer test in which only the lowest 20 m interval of the borehole was tested. Each inflow peak and hydraulic head peak (in Figure 4 and Figure 5 respectively) corresponds to a 30-minute injection test, with the trough in between these peaks corresponding to a 120-minute recovery period during which injection is stopped and the packer deflated (and section of drill rods pulled out to position the packer for the next test).

### 3.1.1 Skin effect

The volume of water injected into model 2 is almost three orders of magnitude higher than that injected into model 8 during the first injection cycle. This discrepancy decreases as testing continues, however the predicted injection rate between the two models remains almost 2 orders of magnitude different by the final injection cycle. Furthermore, models 1 and 7 show that skin effect simulation injection flow rate results are one order of magnitude lower than without skin effect by the end of last injection cycle.

In the Hvorslev Equation [2], the injection rate is directly proportional to the hydraulic conductivity (K) of the tested rock mass. As such, a three order of magnitude decrease in injection rate would result in a three order of magnitude decrease in the estimated hydraulic conductivity of the rock mass. Therefore, if a borehole is not cleaned properly and skin effect is present, this could lead to large underestimation of the hydraulic conductivity of the tested rock mass, resulting in incorrect site hydrogeological characterization and potential underestimation of inflow rates into either a planned open pit or underground mine. These findings highlight the need for pumping tests using observational wells to be included in field programmes, in order to detect and quantity borehole skin effect.

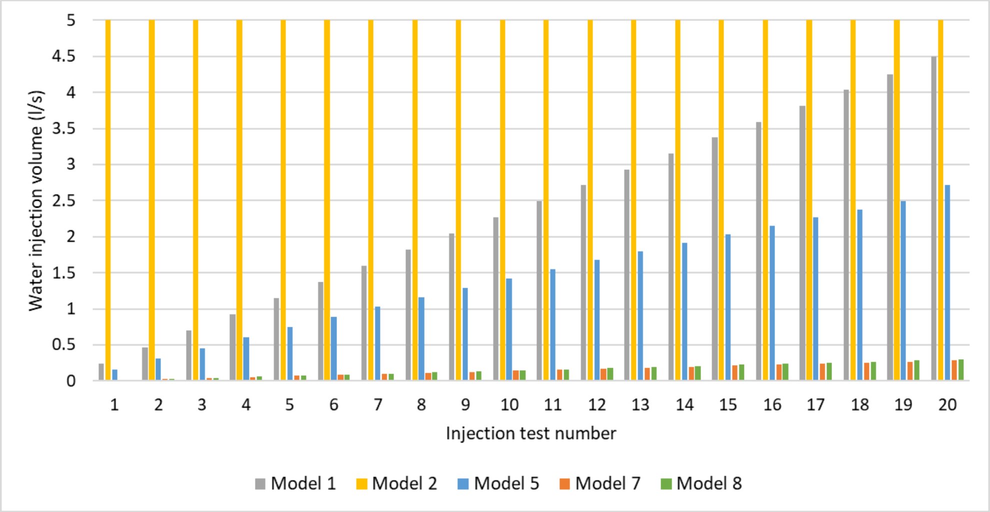


Figure 4. The impact of borehole skin on predicted inflows into the packer tested section of the borehole: Note: Model 2 inflows are 15 l/s throughout injection tests. Values above 5 l/s are not shown on graph.

At 0.5m distance from the center of the borehole, the maximum difference in hydraulic head between model 7 and model 1 is around 27 m. At 5 m horizonal distance from the borehole, the maximum difference between these models decreases to around 7 m and at 50 m horizontal distance from the borehole the maximum difference is less than 2 m. Comparison of Model 2 and 8 shows a maximum difference of around 36 m head at 0.5 m horizontal distance from the borehole, decreasing to 14 m at 5 m distance, and 2 m difference at 50 m distance from the borehole. The inclusion of a borehole skin layer is thus seen to alter the predicted hydraulic head surrounding an injection tested zone, with this difference increasing closer to the tested borehole. This will again have implications on site hydrogeological characterization and mine groundwater inflow predictions.

The hydraulic heads predicted by models 7 and 8 also exhibit high similarity across the cumulative testing period, with little change between the start and end of the packer injection testing period. The predicted hydraulic head between different observation points within these two models also remains largely the same throughout the injection testing sequence. Borehole skin is thus seen to effectively ‘mute’ the effect of a packer injection test on the surrounding rock mass, with very little change in hydraulic head occurring during a test, even at distances as close as 0.5 m from the injected borehole. The hydraulic head of model 8 at 0.5 m from the borehole showed less than 0.5 m change in hydraulic head throughout the testing period, indicating that the borehole skin is insulating the borehole from the surrounding rock. When a drilling additive has been used, a diagnostic for borehole skin effect and application of an equation taking this into account (such as Dougherty-Babu) should be used to estimate K. If skin issues are suspected, operators can switch to multi-pressure methods (e.g., Lugeon testing) for diagnostic evaluation of borehole skin effect.

The large discrepancy between the predicted water intake during injections simulated in models 1 and 7 and models 2 and 8, would lead to significant underestimation of the rock mass K if skin effect is not considered, which is often the case as this cannot be quantified from packer test data alone. Importantly, the degree to which borehole skin effect will impact the results of a packer test (and subsequently the rock mass K estimates) is dependent on the hydraulic conductivity and thickness of the borehole skin. The hydraulic conductivity and thickness assumed for the skin layer in the present paper are 1E-04 m/d and 3 cm respectively. The assumed hydraulic conductivity of the skin corresponds to that of a clay and is a lower end estimate. The thickness of the skin could also exceed 3 cm and the predicted effects are deemed reasonable.

### *3.1.2 Storativity*

The results for models 5 and 6, both with lower aquifer elastic storage characteristics, are compared to models 1 and 2 (refer to Table 1) to assess the impact lower storativity has on the results of a packer test. The water intake predicted by models 1, 2 and 5 are shown in Figure 4. The achieved water injection rate in model 1 varies between 0.2 and 5 l/s, increasing as the tested interval increases in length over the cumulative testing period. By comparison, the injection rate in model 5 (in which elastic storage is 2 orders of magnitude lower) varies between 0.15 and 2.9 l/s over the testing period, with the volume of water injected again increasing as the interval of the borehole tested increases in length. The borehole water intake (injection) in model 5 is consistently between 60 and 75% of that in model 1. This difference, relating solely to the lower storativity characteristics of the rock mass (not usually recognised or considered in packer test data analysis) would lead to an underestimation of the K of the rock mass. As the Hvorslev equation assumes a linear relationship between hydraulic conductivity and the injection rate and as such hydraulic conductivity may be underestimated by 25 to 40% due to a two order of magnitude lower storativity of the rock mass. Thus, if only packer test data are used in estimating the aquifer parameters, mine groundwater inflow would be underestimated. If borehole skin is suspected, a solution that takes borehole skin effect into account should be used instead of the Hvorslev or Thiem equation (e.g., the Dougherty-Babu equation) to better constrain the storativity of the tested rock mass. Pumping tests employing observation wells is also suggested to better constrain storativity.

The impact of storativity on packer test results is illustrated in Figure 5, which shows the head difference produced by models 1 and 5 (in the case of a low K rock mass) and models 2 and 6 (in the case of a high K rock mass). Comparing the hydraulic head results of models 1 and 5 in Figure 5, the discrepancy between the two curves increases with the distance from the borehole center (i.e., from 0.5m to 50m lateral distance from the borehole center).

The above features point to complex interactions between storativity and skin effect within a borehole in terms of packer testing results. A careful and considered approach to results interpretation is critical to achieving an accurate set of results.

The combined low K low storativity nature of model 5 has potentially resulted in the boundary conditions at the perimeter of the model being reached, resulting in an increase in head within the entire model domain. The sharper, more pronounced hydraulic head peaks seen during injection phases of the lower storativity models are attributed to the storage capacities of these models being ‘saturated’, with additional pressure added during injection phases being quickly distributed further from the injection point. In a high K, low storativity rock mass (model 6), these rapid changes in head are seen even at distances as far as 50m from the central borehole. Model 6 may also explain the behaviour of hydraulic conductivity features such as faults that often represent preferential groundwater flow pathways, as demonstrated later in this paper. These results suggest that differing storativities may cause large changes to the K estimated from packer testing for otherwise identical rock masses.

Figure 4 shows an increase in inflows over the course of cumulative testing in model 5, whereas in model 6 inflows are seen to be constant over the model run. The higher K used in model 6 means that even with a maximum injection (realistically achievable) rate of 15 l/s, the hydraulic head increase remains limited to the area adjacent to the borehole (i.e., smaller radius of influence). The lower K value used in model 5, on the other hand, quickly translates into an increase in hydraulic head, even at low injection rates. As injection continues during the cumulative tests, the pressure increase is transferred to farther distances from the borehole.

Packer testing of a lower storativity aquifer, therefore, results in greater hydraulic head changes. Head change in a lower storativity system is also seen to propagate further from the tested borehole than in a higher storativity system. If the tested rock mass is expected to exhibit low storativity (based on the results of pumping testing, for example), a more nuanced solution taking storativity into account should be used in this case. These results also point to the necessity of including pumping tests with the use of observation wells within a hydrogeological field program.

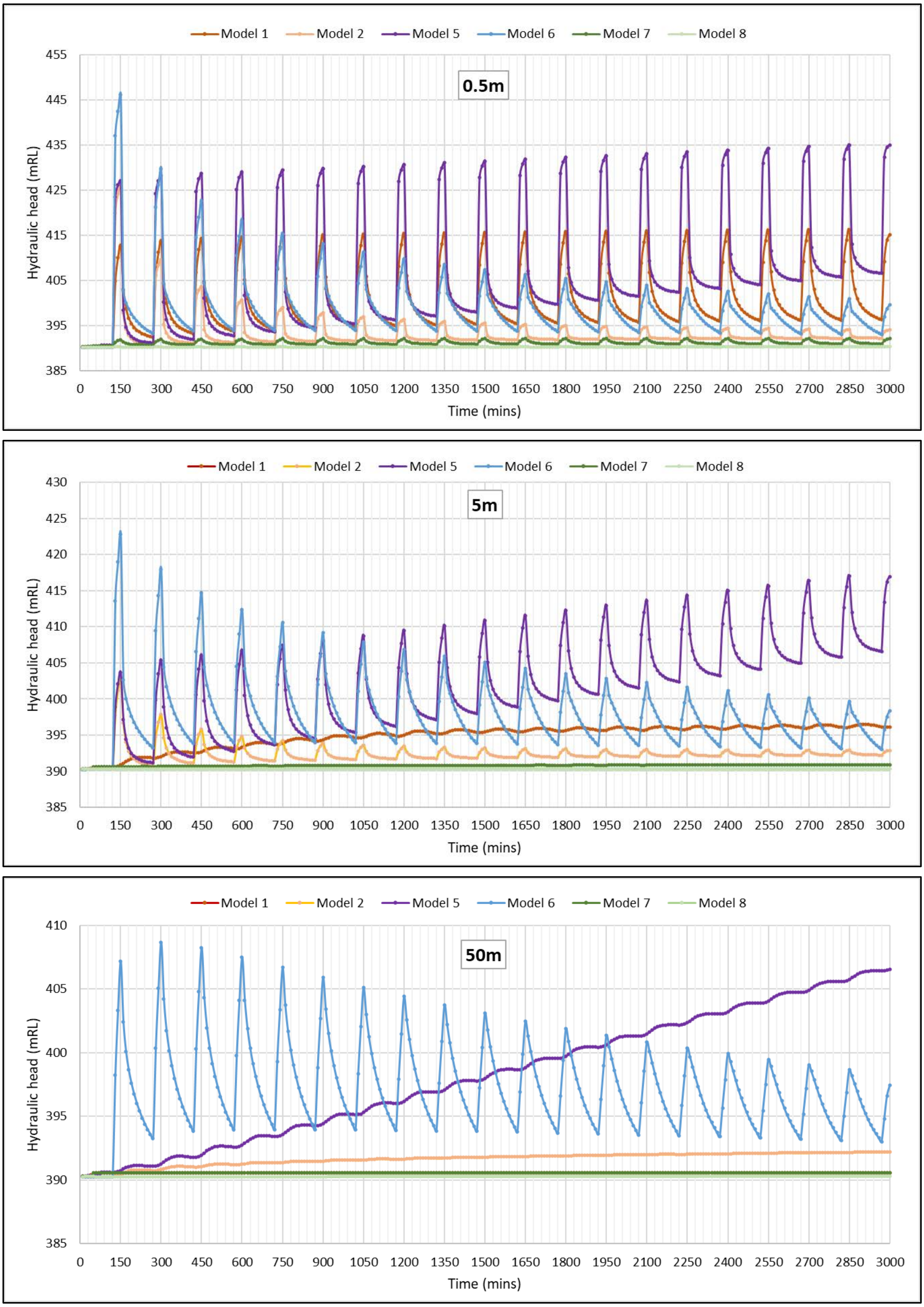


Figure 5. Hydraulic head predicted by Models 1, 2, 5, 6 and 7, at 0.5 m (top), 5 m (middle) and 50 m (bottom) horizontal distance within layer 20, during cumulative packer tests.

## 3.2 Effects of residual pore pressure and the extent of rock mass tested

The effects of residual pore pressure and the extent of rock mass influenced during a packer test will be illustrated using the results of model 5, exhibiting low storativity and low K model. The results of this model have been used for illustrative purposes as the characteristics of this model resulted in the most pronounced changes to injection rates and predicted hydraulic head results, representing a 'worst-case'. The hydraulic head predicted by Model 5 at various lateral distances (0.5m to 50m) from the borehole, is shown for model layer 20 in Figure 6. The latter also shows the volume of water that has been injected into layer 20 to maintain 100 psi pressure in the borehole during injection tests. The hydraulic head within the test borehole itself is consistently at 460 mRL (i.e., 70 m or 100 psi of additional hydraulic head above SWL) during the tests, mimicking a packer test procedure in the field.

Notably, because the GHB BC was used to simulate packer injection testing, an absolute 70 m pressure (equivalent to 100 psi) above the Static Water Level (SWL) measured prior to testing was implemented for every injection test. Since residual pressure increases with every injection and the hydraulic head pressure in the borehole doesn't recover to the starting static level, in each successive injection phase the actual differential pressure decreases and by the end of the last test the applied pressure during injection is no more than 56 m. This issue is purely a numerical modelling limitation that doesn't reflect actual packer tests where the 100 psi pressure is applied in each injection phase.

Although the simulated decreasing packer injection pressure does not reflect how an actual packer test is carried out in the field, the model results are still useful and reasonable for analysis. Notably, the predicted hydraulic head at all six fictitious observation points display a consistent increase with time over the cumulative tests. The hydraulic head at the observation points adjacent to the borehole during the injection tests is also seen to increase with each successive packer injection cycle. These results indicate that the residual pore pressure from the cumulative tests is increasing with each additional test and affecting both the static water level of the surrounding rock mass (up to 50 m distance) prior to an injection test, and subsequent pressure distribution within the adjacent rock mass. As illustrated in Figure 6, the volume of water that is injected into layer 20 to maintain the 100 psi packer test pressure during an injection cycle is seen to drop from 0.177 l/s during the first injection test to 0.127 l/s by the last (20th) injection test, likely due to the increased initial pressure at the start of each test since groundwater flow is proportional to hydraulic head (Darcy's law).

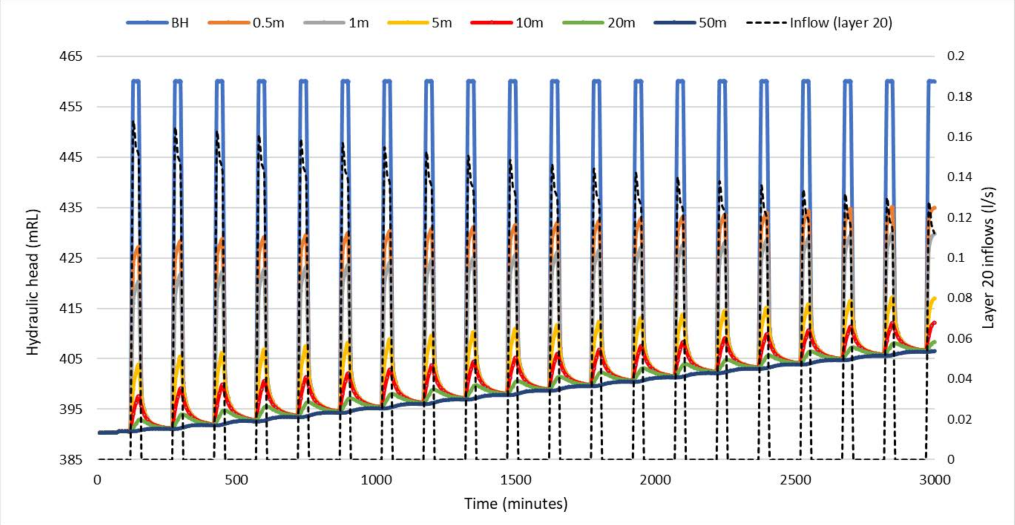


Figure 6. Model 5 predicted hydraulic head at 7 observations points (left vertical axis) within layer 20 at various distances from the injection well and volume of water injected into layer 20 (right vertical axis).

Using the Hvorslev Equation [1] to estimate the K based on the measured inflow (water injection) of the first and last injection tests could result in an underestimation of hydraulic conductivity by approximately 10% in the last injection phase compared to the first injection phase. This is a relatively small difference, with packer testing generally given accuracy ranges within an order of magnitude. This difference is also dependent on the K and storativity of the rock mass, with a potentially larger discrepancy possible dependent on rock mass conditions. These results suggest that residual pore pressure from cumulative packer injection testing does not seem to greatly affect water injection rates and as such hydraulic conductivity estimates.

A new pressure equilibrium is established in all the fictitious observation points within the two hours after each injection phase. If tests are undertaken with a shorter recovery time between each test, the pressure in some of the observation points could be different from that of the borehole, and therefore could affect the injection rate as this is proportional to the hydraulic gradient. In such case the packer test data would no longer be reliable to estimate K. As such, given the hydraulic parameters of model 5, the 2-hour 'recovery' period between tests is deemed marginally sufficient to ensure residual pressure does not impact packer testing results. As model 5 exhibits low K and low storativity, the effects of residual pore pressure will be most pronounced in this case. The effect of residual pore pressure may be deemed negligible in the other scenarios.

## 3.3 Effects of faulting

Models 3 and 4 are designed to simulate the extent and effectiveness of packer testing in hydrogeological settings where faults are present; with model 3 exhibiting a low K rock mass with a high K fault system and model 4 exhibiting a high K rock mass with a low K fault system (refer to Table 1, see Figure 3). The predicted pressure distribution in the model layers at the end of the model run (end of testing of the full borehole length) is illustrated in the cross section in Figure 7 for model 3, which also shows the position of the fault network as well as the water intake (injection/absorption rate) per model layer maintaining 100psi packer test pressure.

As can be seen from Figure 7, the increase in hydraulic pressure is higher along the fault zones where the hydraulic conductivity and storativity are higher compared to the surrounding host rock. The higher hydraulic conductivity along the fault zones allows easier transfer/propagation of hydraulic pressure through these features. The increase in pressure within the faults seems to be limited to around 30 m distance from the borehole. Beyond 30 m the initial head distribution remains unaffected (ellipse A, Figure 7). Notably, an increase in pressure is also evident within the 'host rock' model cells immediately adjacent to the 'faults. The region of 'host rock' affected, however, seems to extend to only 1 cell in vertical thickness (ellipse B in Figure 7). Similar trends of increased pressure within the high K units were seen in model 4 compared to model 3, with these trends more pronounced in model 3. As such, only figures and discussion on model 3 have been provided in the present paper. The host rock away from the faults (layers 10-12, ellipse C in Figure 7) does not exhibit any significant increase in pressure around the injected borehole. The lowest faulted layer in the model, layer 15, exhibits a greater radius of increased pressure than the upper faulted layers (i.e., layers 2-3 and 7-8) indicating that, over time, pressure increase propagates along the zones of increased K and is maintained despite prolonged intervals of no water injection between tests (ellipse B vs ellipse D, Figure 7). The upper faulted layers are also seen to 'take in' more water in the last injection phase than the lower faulted layers (right-hand graph, Figure 6), indicating that the pressure within the lower faulted layers is being maintained between injection tests causing a lower lateral hydraulic gradient. The much higher percentage of inflows into faulted layers would cause a significant masking effect of the host rock. As a result, packer testing data of the host rock units above the lowest fault would be largely unreliable.

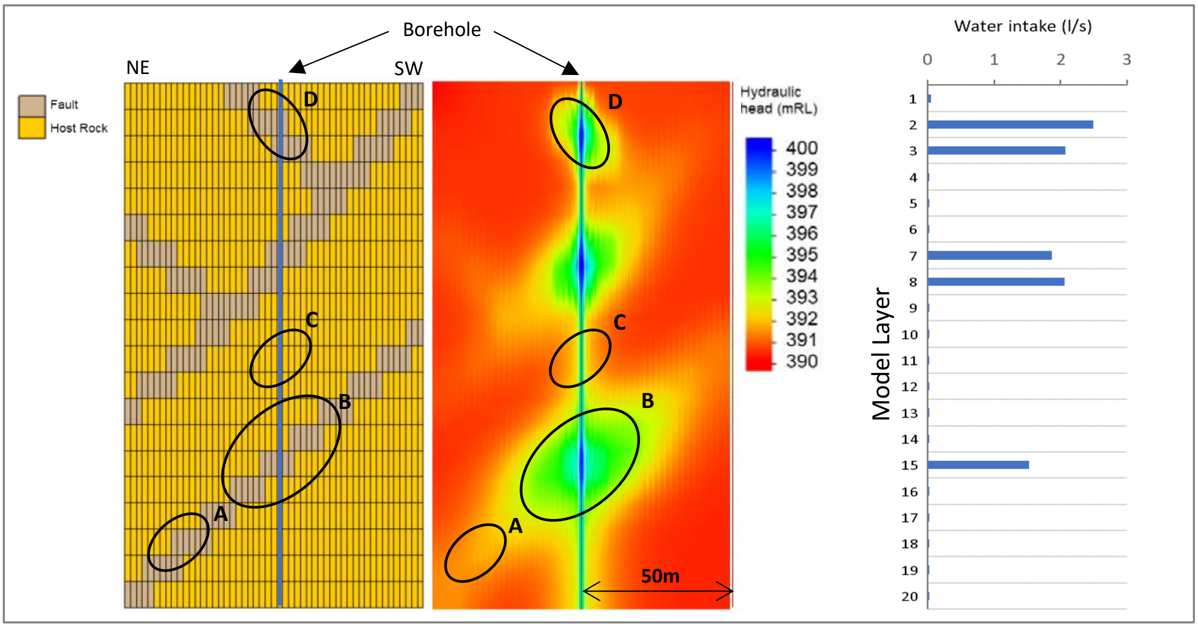


Figure 7. Cross sections of Model 3 fault configuration and predicted pressure distribution, as well as water intake per layer at end of the cumulative packer tests. Refer to Figure 3 for cross section line.

## 4 Conclusions

Literature review and numerical modelling methods have been used to investigate the applicability of commonly used equations and the effect of residual pressure during cumulative injection packer testing following completion of drilling.

The effects of residual pressure from previous tests seem insignificant. In a low K low storativity rock mass (conditions which often prevail at hard rock mine sites), K values derived from packer test data using the Hvorslev Equation [2] could be underestimated by a maximum of around 10% due to residual pore pressure from cumulative testing. Furthermore, modelling showed that the two-hour recovery time between injection tests used in the model is the minimum time that should be allowed between tests for the pressure to recover to acceptable levels before undertaking further injection.

Numerical modelling suggested an up to three order of magnitude difference in injection rates between models with and without borehole skin effect simulated using the Hvorslev equation, leading to an equivalent underestimation of hydraulic conductivity. Such results motivate altering the constant pressure test to a multi pressure approach and/or the use of a more nuanced equation to analyse packer test data when borehole skin effects are identified/suspected.

Storativity is a largely unconsidered factor during packer test data analysis, however the results of the present paper suggest significant differences in test results may occur due to differing storativities of a rock mass. This highlights the need for pumping tests including the use of observation wells to be included in a field programme.

In summary, the present paper demonstrates that the use of cumulative overlapping packer testing method (used following completion of borehole drilling) should be implemented with caution with a full understanding of the limitations demonstrated here. Cumulative testing provides a fast and effective method for ‘screening’ of boreholes, particularly in a low K environment. High importance is given to the test pressure approach and the equations used to estimate K. The effects of borehole skin and rock mass storativity should also be carefully considered during both cumulative and concurrent packer injection testing, underlying the need for pumping tests to confirm and quantify these aspects.

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