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Comparative analyses of pumping tests conducted in layered rhyolitic volcanic formations

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SUMMARY

The rhyolitic volcanic formations are modeled as multilayer flow systems composed of high permeability fractured zones separated by less permeable depth intervals referred to as matrix zones. The multilayer or linear cross flow model is applied which considers lateral flow in all units. The vertical cross flow between the model layers is calculated as the product of the head difference and the vertical inter-layer conductance. The axi-symmetrical well flow simulation software WT (i) applies either analytical or numerical drawdown simulators in the formation, (ii) assumes uniform well bore drawdown conditions in the pumping wells, and (iii) considers drawdown driven induced flow in the observation well. The interpretation of the pumping-recovery test in the well Megyaszó K-9 (Hungary) includes 7 low permeability and 6 screened water yielding zones and applies analytical method to compute the formation response. The benchmark Drill Hole Wash pumping test (Nevada) with pumped and monitoring open boreholes involves 5 fracture and 8 matrix zones. The radial formation heterogeneity is approximated by the bi-zonal flow domain and numerical method is used for drawdown simulation in the formation. Appropriate agreement with the measured drawdown data (both tests) and flow logging data (Drill Hole Wash) is achieved. Computer aided calibration is used for the parameter estimation. The results of the presented evaluations are compared with outputs of independent analyses.

1. Introduction

Rhyolitic formations comprising segments of lava flow, tuff and ash-flow may be utilized as the source of water supply (Megyaszó, Hungary) or can be selected as the geologic environment to host underground repository site for nuclear wastes (Drill Hole Wash, Nevada, USA). In such areas the volcanic rocks are frequently subject to hydrogeologic testing via pumping from screened wells or open boreholes. In thick formations several, high permeability fractured or porous depth intervals may be present, while the rest of the volcanic sequence exhibits low permeability. In this paper the low permeability sections are called matrix zones, whereas the water yielding high permeability sections are referred to as fracture zones. The location of fracture zones, the permeability variation, the availability of observation wells and flow logging survey should be considered in testing and interpretation. The presently available computer modeling tools allow for simulating well tests in layered or fissured formations by assuming unsteady, axi-symmetrical flow around the operating well using analytical solutions (Hemker and Post, 2010), numerical methods (Ruud and Kabala, 1997; Lebbe, 1999) or both techniques (Székely, 2013). The latter software is used in the present study. The WT (previously TEST) software is designed to simulate discharge/recharge/recovery, constant head, slug as well as packer tests considering linear cross flow between the model layers or diffusive cross flow through the aquitards (Hemker and Randall, 2010). It has been successfully applied to evaluate field tests conducted in sedimentary (Mukhopadhyay et al., 1994; Székely, 1992, 2013) and fissured granite (Székely, 2013a; Székely and Galsa, 2006) formations. The wellbore simulator of the WT software includes the following effects: (i) laminar and/or turbulent skin loss with depth and time variant parameters; (ii) turbulent axial friction loss; (iii) variable static level of the screened model layers; and (iv) induced flow controlled drawdown in the observation wells. The latter flow option is used in processing the second case study.

The purpose of this study is to document 3D well flow analyses in fractured formations under different hydrogeologic and testing conditions with results strongly influenced by the data availability. The WT software allowed for applying the geology conform,

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Nomenclature

b	thickness of model layers (m)
c	hydraulic resistance of model layers (d)
j	downward counter of fracture zones
k	downward counter of model layers
K_h	hydraulic conductivity in horizontal direction (m/d)
K_v	hydraulic conductivity in vertical direction (m/d)
Q_j	yield of the jth fracture zone (m^3/d)
r	distance (m)
R_{far}	distance to the circular interface between the near and far zones (m)
$s_k(r,t)$	drawdown in model layer k (m)
S_s	specific storativity (m^{-1})
S_y	specific yield, dimensionless
t	elapsed time (d)
T	transmissivity (m^2/d)
T_{near}	transmissivity of the near zone (m^2/d)
T_{far}	transmissivity of the far zone (m^2/d)
T_j	transmissivity of the jth fracture zone in the near zone (m^2/d)
δ	mean absolute deviation between the measured and simulated drawdown data (m)

multi-layered hydrostratigraphic model and selecting the most appropriate solution options. The results of parameter estimation have been confirmed in two ways. The average hydraulic conductivity or the overall transmissivity of the presumably isotropic water yielding sections agree well with the data obtained by independent analytical methods developed for single aquifers or fractures. The axi-symmetrical analytical and the equivalent 3D numerical simulations of the first case study with the multilayer formation model yielded close well bore drawdown.

The low transmissivity ($T = 55.8$ m^2/d) water supply well Megyaszó K-9 (Fig. 1) is basically screened in the Sarmathian rhyolite tuff at depth 180.8–355.1 m, however, two of six permeable zones are located in the 113 m thick saturated section of the overlying Pannonian sandy-clayey formation. The Tortonian clay represents the no-flow lower boundary. The seven days long pumping-recovery test has been conducted at variable rate without flow logging measurements and observation wells. The limited data availability reduced the number of parameters and necessitated several assumptions on properties of model layers constituting the formation. By contrast the high transmissivity ($T = 381.2$ m^2/d) open borehole UE-25b#1 at the Drill Hole Wash test (Moench, 1984) discharged the Tertiary volcanic rocks at sufficiently larger depth between 471 and 1219.2 m (Fig. 3). The constant rate pumping lasted almost 3 days and the head variations in the pumping and one monitoring borehole were measured. The interpretation involved borehole flow measurements in the pumping borehole. The extended set of observation data sufficiently reduced the number of simplifying assumptions and allowed for a more comprehensive well test data analysis.

In this study the software WT applies the multilayer or linear cross flow model (Hemker, 1999; Hemker and Randall, 2010) to approximate the flow in the formation. This model assumes lateral flow along and vertical cross flow between the model layers. The anisotropic model layers exhibit depth variant hydraulic conductivities K_h and K_v m/d in horizontal and vertical directions, respectively. The vertical cross flow between layers $k-1$ and k is controlled by the hydraulic resistances c_{k-1}, and c_k with $c = b/K_v$. The specific linear vertical cross flow $q_l(r,t)$ m/d at distance r m and time t d is calculated as $q_l(r,t) = 2(c_{k-1} + c_k)^{-1}\,[s_{k-1}(r,t) - s_k(r,t)]$ where $s_{k-1}(r,t)$, $s_k(r,t)$ m denote the drawdown in layers $k-1$ and k, respectively; the term $2(c_{k-1} + c_k)^{-1}$ is called vertical inter-layer conductance.

The software WT uses the analytical technique based on the numerical Laplace inversion (Hemker, 1999a) and the axi-symmetrical numerical finite difference FD method by Székely (Székely and Galsa, 2006). In case study 2 the drawdown response of the formation is calculated with the effect of variable well radius. The method of transient, uniform (depth invariant) wellbore drawdown (uniform well-face drawdown or UWD by Hemker, 1999a) is applied in the pumping well or borehole. In both case studies water table condition is considered in the predefined 1 m thick low permeability top layer, whereas a no flow boundary is assumed at the bottom of the flow domain. Model calibration via nonlinear multi-regression analysis (Székely, 2013) is used to estimate the hydraulic parameters. All the water yielding zones are open to the pumping wellbore/borehole. This discharge option generates a close drawdown in and a limited vertical flow between the fracture zones. The absence of drawdown measurements and the low vertical flow in the interbedded matrix zones reduce the accuracy of the calibrated parameters of those intervals.

The results of the parameter estimation are compared with data obtained by independent analytical tools (Moench, 1984; Kruseman and De Ridder, 1994, software MLU by Hemker and Randall, 2010, Aquifer Test Pro by Schlumberger Water Services, 2011) as well as multilayer numerical simulation (software FLOW by Székely, 2008). The comparison confirmed base results of the multilayer analyses conducted with the software WT.

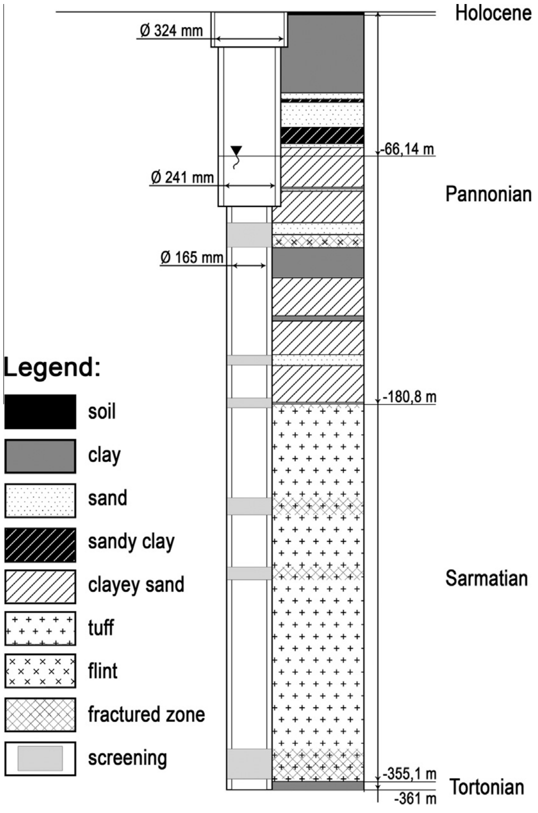

Fig. 1. Hydrostratigraphic section of the well Megyaszó K-9.

2. Case study 1: the Megyaszó K-9 pumping test

The detailed interpretation of the Megyaszó K-9 pumping test is performed in the framework of the Well aHead project (Madarász et al., 2013). The investigated region is located in North-East Hungary. The area has numerous tourist attractions and is the homeland of the famous Tokaj wine. The main rock of this volcanic area comprises andesite, rhyolite and volcanic tuff. Although some mineral prospecting projects have been conducted in the 1960s and 1970s, the groundwater resources remained unrevealed. The regional water budget and the groundwater flow systems were not known before the complex hydrogeologic investigations carried out in the framework of the Well aHead TÁMOP project. It was believed earlier that there is no chance to find thermal water in this volcanic area since the average hydraulic conductivity of the subsurface formations is very low. The objective of the presented well test data evaluation is to get reliable hydraulic parameters of multi-layered formations to support evaluation of the geothermal potential of the region.

The water supply wells of the village Megyaszó discharge basically the Sarmathian rhyolite tuff and are also screened in sandy layers of the overlying Pannonian clastic sediments. The deep volcanic formation is exposed at land surface in the nearby Tokaj mountain range. The covering sandy clayey formation has been deposited in the prequaternary Pannonian lake. In the well K-9 the static level at depth of 67.3 m marks the water table or upper boundary at assumed specific yield of $S_y = 0.1$, whereas the top of the Tortonian clay at depth of 355.1 m represents the presumably impermeable bottom of the flow system. Fig. 1 shows the hydrostratigraphic section of the well. The top of the first water yielding section is located at depth of 97.0 m, the last fractured zone is found at the bottom of the rhyolite tuff formation, the overall thickness of water yielding model layers is 57.2 m. The well is screened at the diameter of 165 mm and the 200 mm borehole diameter is used in calculations. Six screens are installed in the depth intervals 97.0–108.4, 158.2–162.8, 178.0–186.0, 224.0–232.6, 256.0–262.6 and 340.0–354.5 m, respectively. 13 model layers are used to simulate the axi-symmetrical flow to the well. The lack of wellbore flow logging and observation well data necessitates the introduction of the following three assumptions: (i) the screened fine sands and the fractured rhyolite tuff have equal hydraulic conductivities and specific storativity; (ii) uniform hydraulic conductivity and specific storativity is also assumed for the cased low permeability sections (clayey-silty layers in the upper sedimentary part and matrix zones in the lower volcanic formations); and (iii) the low permeability model layers are considered as isotropic. The limited hydraulic information and the above assumptions allow for conditional evaluation of the pumping/recovery test under consideration.

Fig. 2 shows drawdown evolution during the pumping-recovery test performed in July 1984. Airlifting at the rate 410 m^3/d was applied first. A discharge pipe of 127 mm diameter was submerged at 230 m depth, the air pipe of diameter 50 mm was operated at depth of 121.7 m. The pump was installed between 2.91 and 3.00 days. The first stage of pumping started at the rate of 65 and gradually increased to 125 m^3/d. A constant rate pumping at 276.5 m^3/d was conducted between 4.25 and 5.25 days and the test was completed with a recovery. Circles show the measured drawdown data.

The analytical option of the WT software was used for the multilayer well flow simulation. The model calibration yielded 0.976 and 0.000650 m/d hydraulic conductivity for high and low permeability sections, respectively. Specific storativity values of $S_s = 0.0000234$ and 0.0000363 m^{-1} were obtained for the above units. The mean absolute deviation between the 102 measured and simulated drawdown data δ is 0.0986 m. The solid line in Fig. 2 exhibits result of this simulation. The reliability of parameters is affected by many factors and may be quantified through the confidence intervals. The 95% confidence intervals of the calibrated parameters were defined by means of the software PEST (Doherty, 2000). The first parameter shows the narrowest confidence intervals of 0.968–0.983 corresponding to the highest reliability. The last parameter shows the widest interval of 0.0000288–0.0000459 indicating the lowest reliability. Intermediate values are found for the remaining two parameters: 0.000615–0.000687 and 0.0000203–0.0000270.

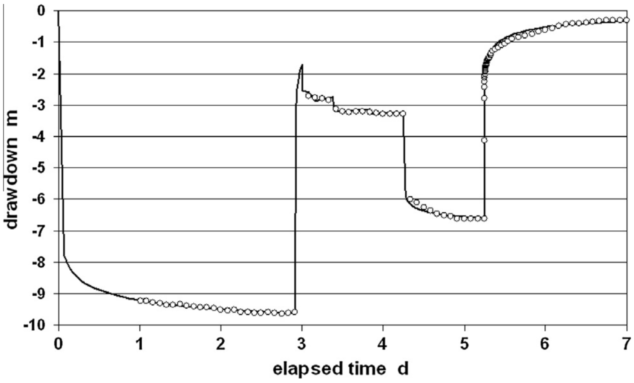

Fig. 2. Measured (circles) and simulated (lines) drawdown-recovery data in the well Megyaszó K-9.

Two additional analyses with different simulation techniques were also conducted.

The results obtained by the analytical WT simulation under linear cross flow conditions have been checked through finite difference (FD) groundwater flow modeling based on 3D rectangular mesh using the same 13 model layers and parameters. The software FLOW (Székely, 2008) based on the point centered numerical scheme generated low mean absolute deviation of $\delta = 0.109$ m and the simulated drawdown-time curve exhibits negligible deviation from the solid line in Fig. 2. Earlier the FLOW along with the MODFLOW-MNW software proved also useful in numerical simulation of the Fairborn pumping test (Szűcs et al., 2013).

The performance of the simplest hydrostratigraphic model of a single, 57.2 m thick, confined, homogeneous aquifer was also investigated. The software Aquifer Test Pro (Schlumberger Water Services, 2011) was applied in the parameter estimation. The average hydraulic conductivity of 0.899 m/d is close to the previous two values. However evaluation of the expected future pumping tests in the well involving flow logging will require application of the more complex multilayer model better fitting to the geology of the site and the actual screening of the well.

3. Case study 2: the Drill Hole Wash pumping test

3.1. Site description and previous analyses

Moench (1984) reports results of the Drill Hole Wash pumping test conducted in August–September 1981 on the east flank of the Yucca Mountain at the Nevada test site (USA). The Tertiary volcanic formation is composed of a sequence of high permeability fracture zones (called aquifers) and low permeability matrix zones (referred to as blocks). The detailed information on the geology, borehole and testing is available at Lobmeyer et al. (1983).

The hydrostratigraphic section of the 1219.2 m deep test borehole UE-25b#1 is shown in Fig. 3, the depth data on the right hand side refer to the bottom of the low permeability matrix zones. The radius of the open section is 0.111 m, whereas a perforated casing

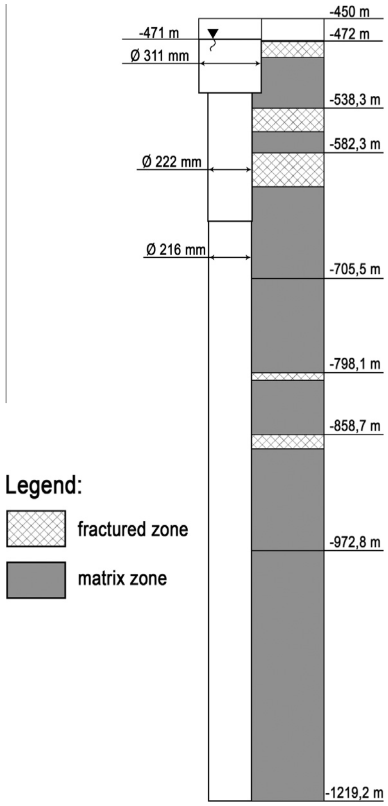

Fig. 3. Hydrostratigraphic section of the borehole UE-25b#1.

of radius 0.1555 m is applied at the top of the saturated part of the formation. The latter condition increases the yield of the uppermost fracture zone. The static level of groundwater is located at depth of 471 m. The 762.2 m deep open observation borehole UE-25a#1 of radius 0.0375 m is drilled at distance $r = 110$ m. The test borehole was pumped at a rate of 3093 m^3/d (35.8 l/s). The water yielding ability of the five fracture zones at depth between 477 and 875 m was characterized by borehole flow surveys conducted during and at the end of drilling operations (Lobmeyer et al., 1983 Fig. 8, Moench, 1984 Fig. 9). This plot was used to read the approximate depth intervals of the water yielding fracture zones as follows: 472.0–488.4, 538.3–561.5, 582.3–615.5, 798.1–805.6 and 858.7–872.8 m. The estimated thickness of the fracture zones ranges between 7.5 and 33.2 m.

Moench (1984) developed an analytical method for the double porosity fractured aquifer with sphere- or slab-shaped blocks. The model comprises a fissure, an associated block (matrix) and an optional skin zone between them. Pseudo steady-state (called linear) or transient flow in low permeability slab-shaped block are assumed (Moench, 1984). The author applied this model to this benchmark field test and obtained transmissivity of $T = 345.6$ m^2/d of the equivalent single fracture scheme.

Hemker and Randall (2010) followed the previous concept of single fracture analysis and applied it to this well flow problem. The option of linear inter-porosity flow with fracture skin was found to produce the best fit considering drawdown measurements in both pumped and observation boreholes. Calibration of the flow model resulted in transmissivity of $T = 378.2$ m^2/d.

Kruseman and De Ridder (1994 Example 17.1) applied the conventional straight line method to the drawdown data in the pumping borehole. Based on the slope of the late time part of the semi-log plot of drawdown versus time the authors recommended $T = 333$ m^2/d for the formation transmissivity and $S_y = 0.15$ for the specific yield. The latter value was used as the initial guess in WT calibration.

3.2. WT simulation

The objective of the presented simulation is to enhance the previous analyses. Thus the modeling (i) applies a geology conform, multilayer well flow model of the axi-symmetrical drawdown evolution, (ii) involves the flow metering data into model calibration, and (iii) achieves a satisfactory fit to the drawdown data measured in both boreholes (Moench, 1984 Table 2). The WT software enables one to simulate bi-zonal formation model. This option is used to assess the effect of lateral heterogeneity present in this rhyolitic formation.

The well flow model extends over the full 748.2 m saturated thickness penetrated by the pumping borehole. The formation is split into 13 model layers or segments including the top water table unit with the calibrated specific yield of $S_y = 0.163$ and the 5, presumably isotropic permeable fracture zones. The flow logging data indicate that these units provide the total pumping rate of 3093 m^3/d. In the model the fracture zones have different hydraulic conductivities but equal specific storativity. The separating and underlying low permeability anisotropic matrix zones or blocks are assigned low horizontal hydraulic conductivity of $K_h = 0.0001$ m/d to prevent sufficient flow into the borehole. In the analysis these units also have equal vertical hydraulic conductivity and specific storativity. Both boreholes are open to the full drilling depth.

The FD solver of the WT software (Székely and Galsa, 2006) was utilized to simulate the axi-symmetrical transient flow. The WT-FD simulation applies the model of induced flow controlled drawdown (IFD) in observation borehole (Székely, 2013). The latter is calculated as the effect of the axial cross flow in the observation wells/boreholes due to the vertical drawdown difference caused by the pumping well at the observation point. The process is known as the "short-circuiting" effect (Kruseman and De Ridder, 1994 page 103).

The parameters of the presumably laterally homogeneous formation model were calibrated first. This includes 6 parameters (five conductivity and one specific storativity values) for fracture zones and 2 parameters (vertical conductivity and specific storativity) for matrix zones. The analysis resulted in 377.8 m^2/d overall transmissivity value for the 5 fracture zones. As shown above a close value was obtained by Hemker and Randall (2010). Thin lines in Figs. 4 and 5 exhibit results of this simulation.

The significant discrepancy between the measured and simulated drawdown values necessitated sufficient model

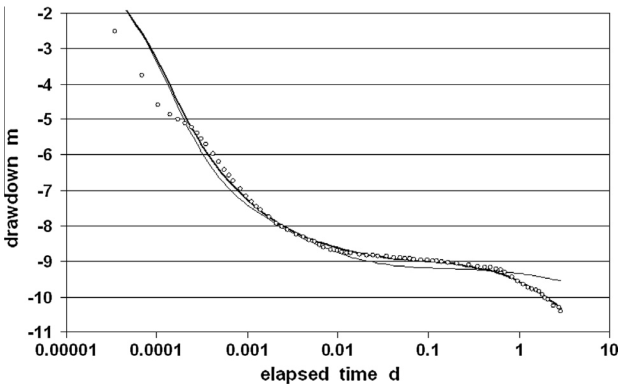

Fig. 4. Measured (circles) and simulated (lines) drawdown-time data in the pumped borehole UE-25b#1 (thin and bold lines correspond to laterally homogeneous and bi-zonal formation models, respectively, circles mark observation data).

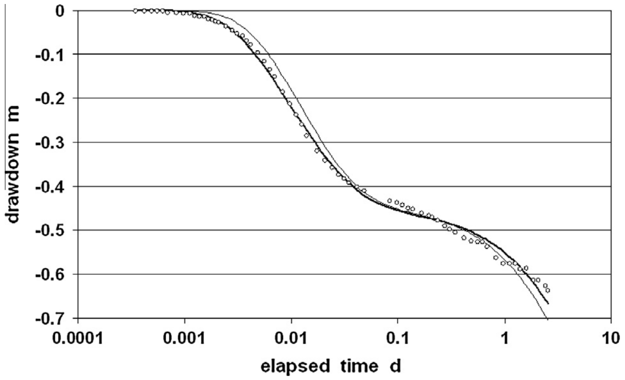

Fig. 5. Measured (circles) and simulated (lines) drawdown-time data in the observation borehole UE-25a#1 (thin and bold lines correspond to laterally homogeneous and bi-zonal formation models, respectively, circles mark observation data).

improvement. This was achieved by switching to the better performing bi-zonal flow model. This composite radial flow domain exhibits different parameters around the pumped borehole (near zone) and beyond a distance R_{far} called far zone. This option of the WT software was applied earlier to a fissured granite formation (Székely and Galsa, 2006). Manual calibration based on trial and error was used to find the optimum radius R_{far} delineating the circular interface between the near and far zones. Parameter estimation at the optimized $R_{far} = 20$ m provided the best model fit. Bold curves in Figs. 4 and 5 visualize the simulated drawdown variation, the average absolute deviation δ between the measured and calculated drawdown are 0.125 m (pumping borehole) and 0.009 m (monitoring borehole). The drawdown data in the pumping well show good fit and lower deviation of $\delta = 0.063$ at elapsed time of $t > 15$ s (Fig. 4). The simulated relative water yield data 11.99%, 19.98%, 18.99%, 19.00% and 29.99% of the five fracture zones are close to the values 12%, 20%, 19%, 19% and 30% based on the earlier flow meter survey (Lobmeyer et al., 1983 Fig. 8, Moench, 1984 Fig. 9). The optimized overall transmissivity values for the near and far zones are $T_{near} = 381.2$ and $T_{far} = 469.3$ m^2/d, respectively. The calibrated transmissivity values T_j of the jth facture zones ($j = 1$–5) in the near zone are as follows: 79.3, 65.7, 54.5, 69.0 and 112.8 m^2/d. For both zones the magnitude of S_s varies in the range of 10^{-4}–10^{-6} m^{-1}, whereas the vertical hydraulic conductivity K_v for the matrix zones is 0.099 and 0.030 m/d.

The open section of the observation borehole penetrates the fracture zones 1–3 and provides a channel for the axial borehole flow. This flux is induced by the vertical drawdown difference at that distance due to the pumping the deeper borehole. The IFD simulation resulted in low induced inflow/outflow of ±10.92 m^3/d between the formation and the open borehole. This constitutes only 0.35% of the pumping rate and, thus, the hydraulic feedback between the observation and pumping boreholes can be ignored.

4. Conclusions

The fractured rhyolitic volcanic formations exhibit high and low permeability sections called fracture zones and matrix zones, respectively. The high permeability sections are supposed to be isotropic. The low permeability model layers have assumed horizontal hydraulic conductivity, this approximation has little effect on the results. Radial flow in and linear vertical cross flow between the model layers are considered.

Interpretation of results of the pumping-recovery test in the well Megyaszó K-9 with no flow logging data yielded average hydraulic conductivity and specific storativity for fracture and matrix zones. The linear cross flow model and the option of single confined aquifer were used in the analyses. These models produced close hydraulic conductivities for screened units with an overall transmissivity of 55.8 m^2/d. 3D numerical groundwater flow modeling was applied to confirm the formation parameters derived by the axi-symmetrical linear cross flow model.

Evaluation of the benchmark Drill Hole Wash pumping test involves all the drawdown and borehole flow measurements data in pumping and monitoring boreholes. Linear cross flow between the model layers, bi-zonal formation model and induced flow controlled drawdown (IFD) in observation borehole are considered in simulation. The computer calibration provided acceptable fit between the measured and simulated data in both boreholes. The transmissivity values obtained by the earlier single fracture interpretation models vary in narrow range of 333 and 378.2 m^2/d. The WT-FD simulation assumed depth variant hydraulic conductivity of fracture zones. The calibration concluded with the overall transmissivity of 381.2 m^2/d around the pumping borehole.

At present the single aquifer or double porosity analytical solutions are frequently used to parameter estimation in multilayer environments. However the parameters should be considered as approximate and these values can be used only as initial guess in parameter optimization of more realistic, geology conform, multilayer models.

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