Some insights from modeling groundwater levels in open boreholes in crystalline rock in tunneling projects

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Some insights from modeling groundwater levels in open boreholes in crystalline rock in tunneling projects

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ABSTRACT: This study focuses on the importance of explicitly representing hydraulic head measurements in open boreholes in crystalline rock in numerical models. Open boreholes in crystalline rock can lead to hydraulic short-circuiting of the groundwater flow system, leading to potential misinterpretation of hydrogeological risks in tunneling projects. Such projects often rely on numerical groundwater models to assess risks, such as groundwater intrusion into tunnels and ground deformations. An example of this is studied here. A case study was conducted using MODFLOW-NWT with the Multi Node well package (MNW2) in Haga, Gothenburg, the site of a planned commuter train station, comparing simulations with and without explicit open boreholes. The findings reveal that deformation zones with higher transmissivities and connectivity that intersect open boreholes can significantly redistribute the hydraulic head, potentially affecting the estimation of pore pressure changes in overlying subsidence-sensitive clay. In addition, the study concludes that groundwater flow leakage near tunnels leads to increased short circuiting in wells and higher gradients around the tunnel.

1 BACKGROUND

Groundwater flow modeling in crystalline rock is essential for hydrogeological risk assessment in many fields, such as mining, quarrying, underground waste storage (e.g., nuclear waste repositories) and infrastructure projects. In these contexts, hydraulic heads from long, open boreholes are often used for model calibration. However, the different aquifers or fractures that intersect the well contribute to the hydraulic head based on their transmissivity that leads to hydraulic short circuit within the groundwater system (Svensson 2015; Sokol 1963).

There is a need to understand how relevant this effect is for calibrating groundwater models for hydrogeological decision support in tunneling projects. This case study aims to investigate the best methods for representing groundwater levels in open boreholes within a MODFLOW-NWT groundwater flow model, particularly in the context of the ongoing construction of a commuter train tunnel and an underground station at Haga, Gothenburg. The construction is expected to cause groundwater leakage, leading to drawdown and potential subsidence-induced damage to buildings and utilities, e.g., Sundell et al. (2019).

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This study focuses on representing groundwater levels in vertical and non-vertical open boreholes using the Multi-Node-Well package (MNW2) in various versions of MODFLOW. The calibration of the model using an infiltration test under these conditions is also investigated.

2 SITE DESCRIPTION

The case study site covers approximately 3 km^2 in central Gothenburg, Sweden, where a commuter train tunnel with an underground station at Haga is currently under construction (see, Figure 1a,c). This construction is expected to cause groundwater leakage, leading to a drawdown of groundwater. Such a drawdown poses risks of building damage and utility disruptions due to subsidence.

The topography of the site varies significantly, with a steep decline from higher elevations in the southeast (around 70 meters above sea level) to the *Rosenlund* canal at approximately sea level. The terrain then rises northward before reaching the low-lying areas along the *Göta River* (see, Figure 1b).

Gothenburg rests on crystalline, predominantly metamorphic bedrock, part of the Southwestern Swedish gneiss province. This bedrock contains water-bearing fractures with two main strike directions: northwest/north-northwest with dips of about 45 degrees, and northeast/east-northeast with dips of about 90 degrees. The overburden consists of glacial till and glacial outwash, overlain by glacial and post-glacial marine clay, and topped by heterogeneous anthropogenic fill. The fill varies in thickness from 1-3 meters, but near the Rosenlund canal, it can reach 5 to 7 meters. The clay layer's thickness ranges from 40 to 100 meters, with the deepest sections at the Rosenlund canal. The overburden soil thins towards the higher elevations in the south, where the bedrock is exposed. Three types of aquifers are present at the study site: A fractured rock aquifer, a confined aquifer in the non-cohesive soil beneath the (post-)glacial clay layer, and an unconfined aquifer in the uppermost layer of fill material above the clay (Haaf et al. 2024).

3 GROUNDWATER MODEL

3.1 *Modeling approach*

USGS MODFLOW-NWT was used to simulate groundwater flow at the study site. MODFLOW-NWT is based on MODFLOW-2005, which uses a block-centered finite-difference approach, however the groundwater flow equations are solved using the Newton-Raphson formulation. For simulating open boreholes, the Multi-Node Well package (MNW2) in MODFLOW is used, while the WEL package is used for passive piezometeres. The site has two open boreholes in the crystalline rock, with specified flux boundaries (HH4324H and HH4323H) as well as three passive piezometers (HH4302U, HH4107U, and HH4297B) which were installed in the confined layers at varying distances from the open boreholes. In a finite difference grid, the hydraulic head in a cell differs from that in a wellbore due to variations in volume, hydraulic properties, and surroundings. If the well's open length exceeds the cell's thickness, the head in the well relates to multiple cells. Water levels in multi-node wells are calculated by representing the well as interconnected nodes, each representing a section of the well screen. This integrates the well into the model grid, with flow between the well and surrounding media controlled by the head difference at each level of the open borehole, weighted by hydraulic conductivity (Konikow et al. 2009).

3.2 *Model design*

The grid resolution is set to 10x10 m, with a local grid refinement to 2x2 m in the infiltration test area. The model consists of 18 numerical layers: the topmost layer represents coarse-grained filling material, followed by clay and coarse-grained filling material, glaciofluvial material and glacial till, fractured upper bedrock, and bedrock with vertical and inclined deformation zones (see, Figure 1). Stratification modeling used a Kriging-based method informed by borehole log data and bedrock outcrops (Sundell et al. 2016).

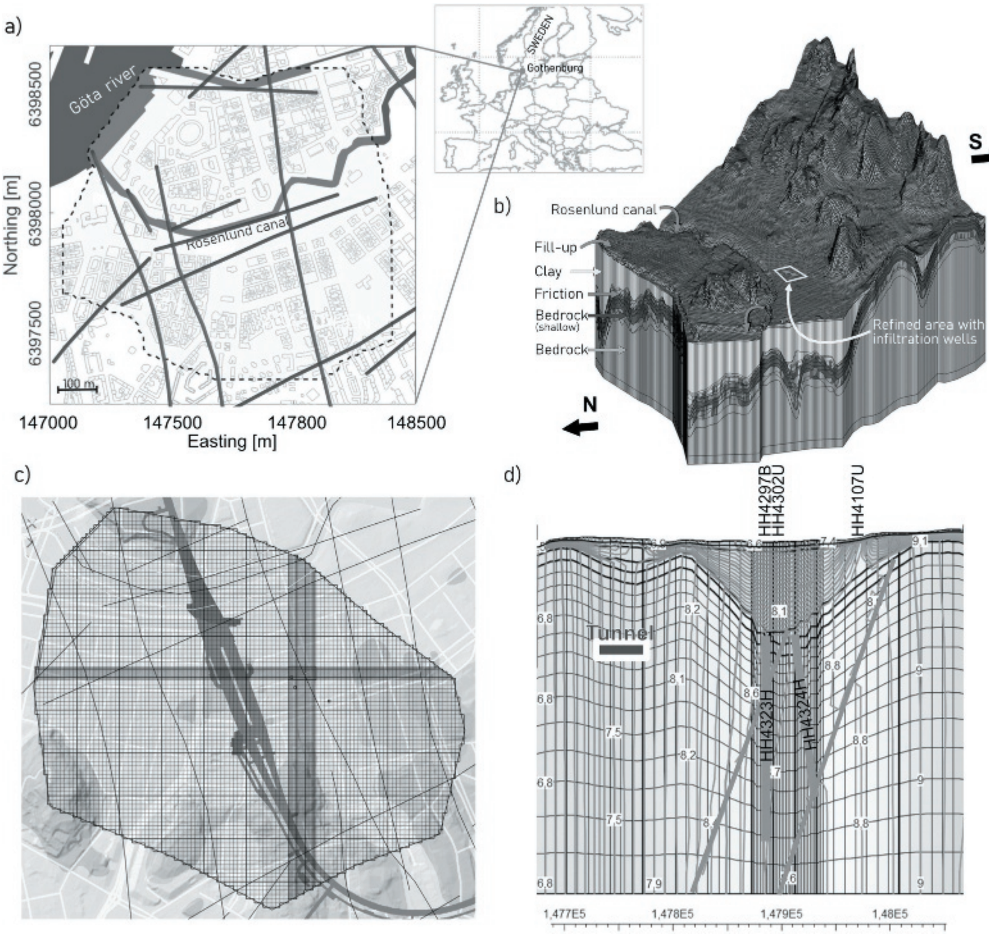

Figure 1. a) Map of downtown Gothenburg, Sweden. Model domain indicated by dashed line. Black lines indicate deformation zones. b) Stratigraphic model of study area (vertical scale ten times exaggerated). Area of grid refinement with open borehole locations in groundwater model indicated by square. c) Numerical finite difference grid with grid refinement. d) Cross section with equipotential lines (m.a.s.l.) through the area where open boreholes HH4323H and HH4324H are located and which are intersected by deformation zones.

The model area is defined by topographic and groundwater gradients, with general flow from south to northwest. Constant head boundaries are set along the northwestern, northeastern, and a small southwestern edge. A previous calibrated groundwater model at a larger scale defined the heads along these boundaries (Haaf et al. 2024). Rosenlund canal is represented by a drain in the topmost layer. Hydraulic conductivity for bedrock between deformation zones is $4 \cdot 10^{-8}$ to $2 \cdot 10^{-7}$ m/s, and within deformation zones and upper fractured bedrock is $2 \cdot 10^{-7}$ to $5 \cdot 10^{-6}$ m/s, based on pump tests (Lithén and Wadsten 2016).

The confined aquifer's hydraulic conductivity varies from 10^{-7} to 10^{-4} m/s, with higher values along Rosenlund canal and lower values in glacial till areas. The clay layer's hydraulic conductivity is expected to be 10^{-10} to 10^{-9} m/s but was set higher due to convergence issues. Shallow coarse-grained materials, including drains, are highly heterogeneous with high hydraulic conductivity. General literature values were used for specific yield and specific storage Woessner and Poeter (2020). Net precipitation is about 420 mm/year, with expected recharge between 100-170 mm/year (Lissel 2016). Estimating actual recharge is difficult due to system disturbances; leakage from drinking and sewage systems can increase recharge, while runoff to civil drainage can reduce it.

4 RESULTS

4.1 *Calibration*

A total of five wells were implemented to calibrate the model on: two open boreholes in the crystalline rock with specified flux boundaries, using the MNW2 package (HH4324H and HH4323H), and three passive piezometers in the coarse-grained confined layers (HH4302U, HH4107U, and HH4297B) at varying distances from the open boreholes. Calibration starts with a steady-state simulation and then advances to transient simulations, requiring multiple iterations to refine the model. For example, in a steady-state simulation, the model is calibrated to match observed groundwater levels, while in transient simulations, it is calibrated to match time-varying data, such as seasonal fluctuations in groundwater levels. The initial steady-state model calibration aimed to align pressure gradients between the confined aquifer and various bedrock layers by refining the hydraulic properties of the aquifers using the three observation wells.

Based on this, the model was calibrated in transient mode using an infiltration test conducted between September and October 2021 as seen in Palmenäs (2023), to refine the initial calibration by adjusting storage parameters. Infiltration in HH4324H lasted six days, immediately followed by a 14-day infiltration in HH4323H, both maintaining a stable flow with 0.5 bar overpressure. Levels in HH4302U dropped after one day, stabilizing lower than initial levels; hence, early observations were excluded from calibration. Peaks and subsequent drops in HH4302U's levels were due to pressure transducer adjustments and were disregarded. Post-infiltration, HH4323H's levels stabilized at approximately 11.5 m.a.s.l. after 2.5 days, but as other observations returned to initial levels, these were not included in calibration.

Initially, after achieving numerical stability and a conceptually reasonable model, a significant offset in magnitude and timing between the time series in the five wells and simulations was observed. To better capture the dynamics indicated by the pump test, the hydraulic conductivity was adjusted throughout the confined aquifer. Figure 2a) shows that the simulation results were satisfactory, although the model still does not fully capture the system dynamics. The main differences are that simulated levels in the open boreholes did not stabilize with reduced infiltration, and hydraulic heads at HH4297B are underestimated by at least 2-3 decimeters. Increasing model complexity in bedrock and soil layers and exploring alternative loss functions for the MNW2-package could improve results. However, the current results were deemed satisfactory to allow for predictive modeling and sensitivity analysis with regards to the relevance of representation of open boreholes when constructing a tunnel in crystalline bedrock.

4.2 *Simulation with and without open boreholes*

The effects of modeling open boreholes with the MNW2 package in the presence of the commuter train tunnel are investigated by comparing the hydraulic heads during drawdown with and without open boreholes in the surrounding crystalline bedrock. The tunnel and station are modeled with the drain package (DRN) included in MODFLOW-NWT. The geometry of the modeled commuter train tunnel and station in the X- and Y-directions follows the base shape of the top view as seen in Figure 1c), with a depth set at -20 m.a.s.l. This means that the tunnel and station are mainly located in layers 7, 8, 9, and 10 in the bedrock with thicknesses of 8-10 m. In the southern part of the model area, the structure intersects deeper layers down to layer 12 and may reach a total thickness of up to 15 m. In the northern section, the tunnel intersects the clay and may have larger thicknesses. The conductance of the tunnel is set to 1×10^{-9} m/s, resulting in an average drainage in the structure of about a third of the outflow from the model. The drawdown in layers 3, 7, and 14 is shown in 2b). The coarse-grained material of layer 3 exhibits a maximum drawdown of 2.2 m, with a larger extent to the east of the tunnel due to blocking bedrock levels. Layers 7 and 14, both in the bedrock, exhibit drawdowns of up to 5.2 m and 7.4 m, respectively. The cone of depression in the bedrock is more focused on the sections directly at or underneath the tunnel. The two open boreholes are very close at the surface level and show drawdowns in the three layers in a range of about 1-3 meters.

Removing the MNW2 package shows differences in head distribution in cells intersected by the open boreholes, ranging from 7.5 cm to -6 cm. Comparing the absolute difference between the measured long-term average of the open boreholes with water levels in the open boreholes open only to one layer at a time shows a similar result. Figure 3a) shows differences in hydraulic head in grid cells that intersect HH4323H or the non-vertical HH4324 and some surrounding areas. The extent of the differences due to the omission of open boreholes is rather limited and lies within tens of meters. This is because the open boreholes are placed in an area of intermediate flow without large, natural vertical gradients. Although water flows through the open borehole (in the case of HH4224H upward, resembling a discharge zone, and HH4223H downward, resembling an intermediate zone), the exchange does not induce large water level differences compared to hydraulic head without open boreholes.

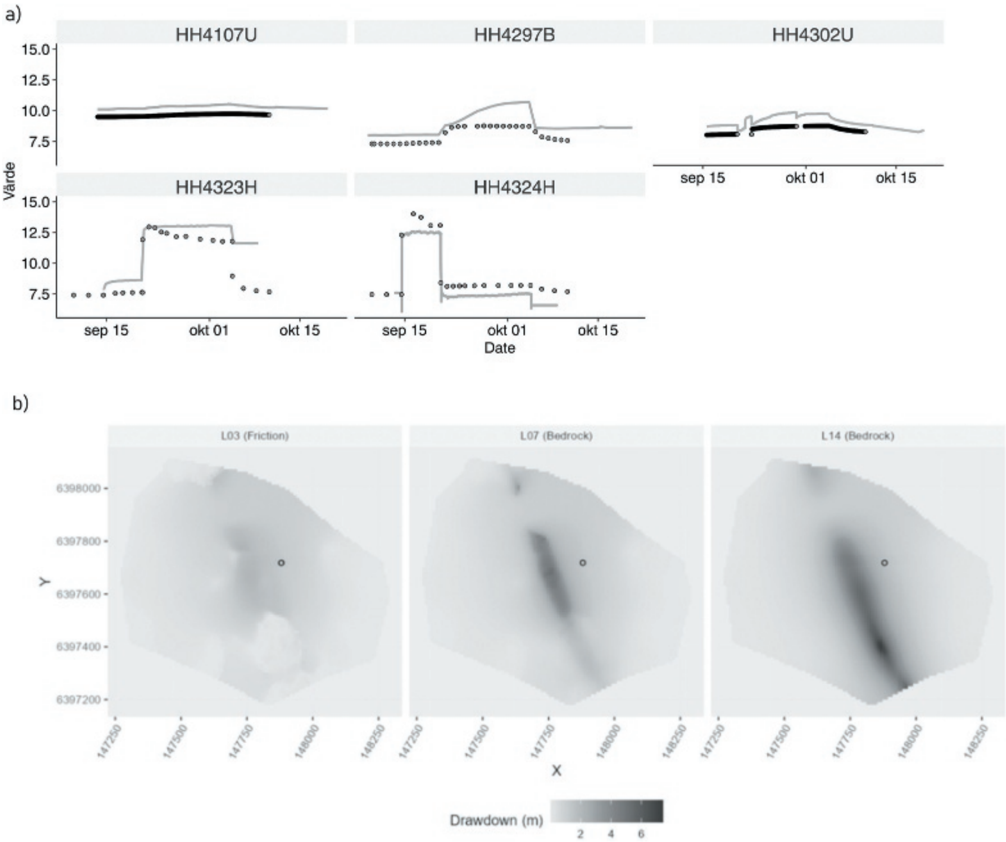

Figure 2. a) Calibration of infiltration test, black dots are observations, grey lines are simulations. b) Drawdown due to tunnel in different layers. Black dot is location of open boreholes (infiltration well).

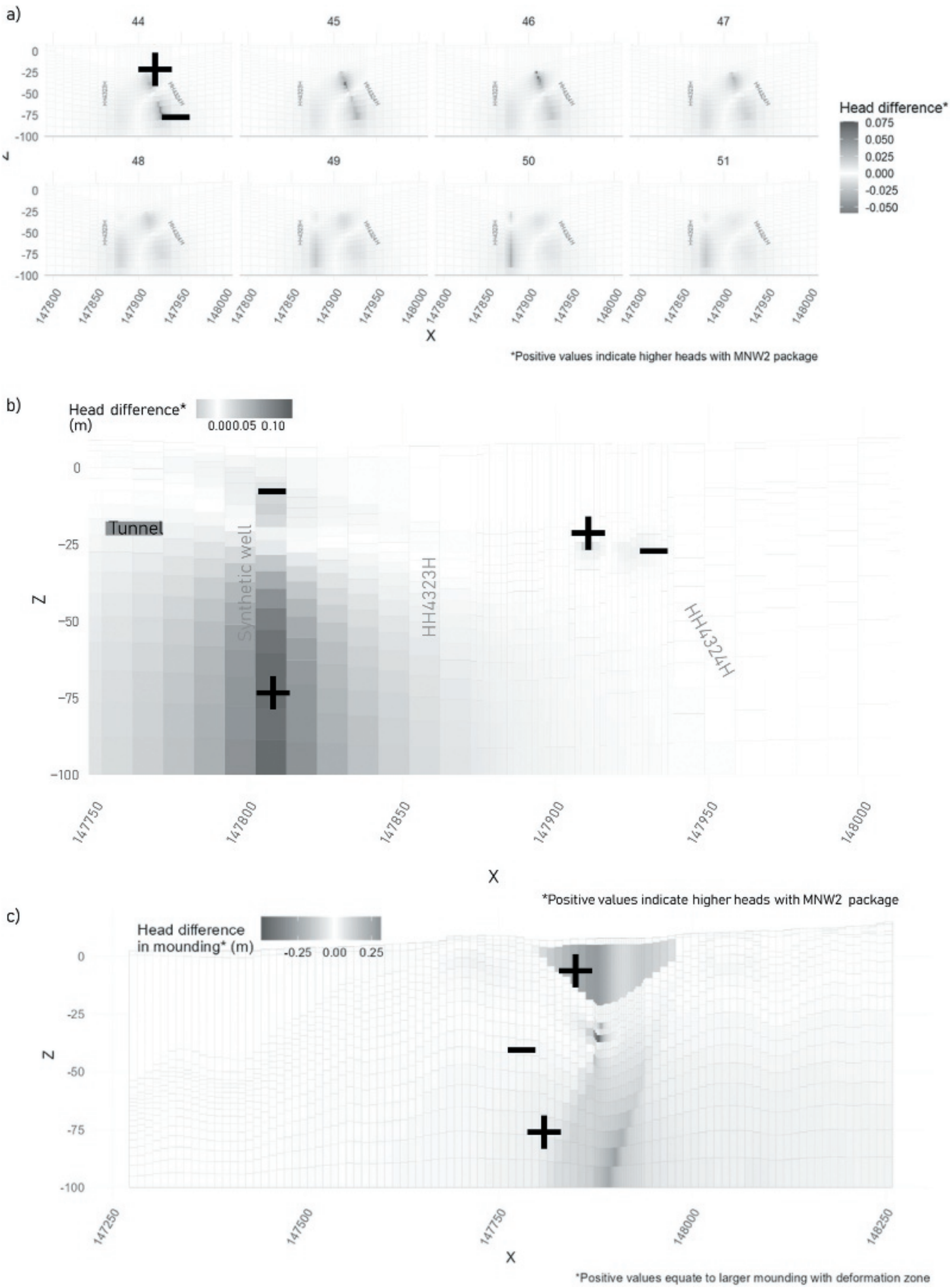

Figure 3. a) Difference between model with calibrated open boreholes and without boreholes. b) Difference with and without calibrated and synthetic open borehole. c) Difference with and without discrete deformation zone intersecting open boreholes. Areas of plus indicate higher heads with an implementation of an open borehole with MNW2 and minus lowered heads.

To investigate if the head difference increases in open boreholes in locations with stronger vertical hydraulic gradients, a synthetic well with the same dimensions as HH4323H was placed close to the tunnel, as shown in Figure 3b), which shows that head difference in this area with larger vertical gradients reaches multiple decimeters.

Finally, simulations were run with and without deformation zones. One of the deformation zones intersect HH4323H in layers 5-7 and another intersects HH4324H in layers 14-15, see Figure 1d). The distribution of the infiltration mound can be seen when comparing the head increases of models with and without discrete deformation zones. In Figure 3c) the differences in mounding due to the infiltration test in HH4323H are shown. Generally, higher hydraulic heads can be observed without deformation zones, although the largest absolute differences can be seen in the immediate vicinity of the deformation zones and in the clay layer. This is due to the redistribution of infiltrated and recharged water within the bedrock that with deformation zones could be more easily transported through the deformation zones into the confined aquifer. For the same reasons, the areas where the discrete deformation zones were located show increased heads once these are removed. This also leads to higher head at the interface of bedrock and the confining clay layer which propagates into the clay layer with a head increase of about 0.2-0.3 m. The effect in the clay is not as clear, where the fracture zone interfaces with the soil layers. With deformation zones present, the hydraulic head is significantly higher around the location where the deformation zone intersects the open borehole and in the higher conductivity layers in the coarse-grained confined aquifer and the surficial bedrock down to below the intersection point of the deformation zone.

5 CONCLUSIONS

This study investigated the implementation of the MNW2 package for MODFLOW-NWT to model open boreholes under transient conditions. The model was calibrated using infiltration tests in two open boreholes, matching observation wells in both the open borehole and the confined aquifer above the bedrock. The MNW2 package allows straightforward implementation of open boreholes.

Post-calibration and predictive modeling was conducted to examine (i) the effect of discrete deformation zones intersecting the open boreholes and (ii) the impact of open boreholes on hydraulic head distribution during groundwater leakage to a tunnel. The results indicated that intersecting deformation zones can significantly redistribute hydraulic head due to higher transmissivities and connectivity, potentially affecting pore pressure estimates in subsidence-sensitive clay. For (ii), when evaluating the effect groundwater leakage to a tunnel on open boreholes showed minimal head differences compared to volume-weighted cells, smaller than the typical error margin of a head-calibrated groundwater flow model (< 10 cm). However, previous research (e.g., Poulsen et al. 2019; Zhang et al. 2018) suggests that the borehole's location within the flow regime (recharge, intermediate, or discharge) influences the occurrence of significant vertical gradients. After implementation of a synthetic open borehole significant effects of open boreholes could be identified, emphasizing the importance of correct representation with e.g., the MNW2 package in MODFLOW.

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