Hydrological and Hydrogeological Effects of a Deep-Rock Repository for Spent Nuclear Fuel in Sweden: Application of a New Coupling Routine between MIKE SHE and MOUSE

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Hydrological modelling, MIKE SHE, MOUSE, nuclear waste, repository, grouted tunnels, groundwater inflow, coupling routine.

Abstract
The Swedish Nuclear Fuel and Waste Management Company (SKB) has performed site investigations for a deep-rock repository for Sweden's spent nuclear fuel at the selected Forsmark site located in the municipality of Östhammar. A ramp and different shafts will be constructed down to approximately 500 metres in the rock, where the spent nuclear fuel will be deposited. The hydrological and near-surface hydrogeological effects of the groundwater inflow to the planned repository during the construction, operation and closing phases are analysed with MIKE SHE. To model the inflow MIKE SHE is coupled with MOUSE, in which tunnels are described as a number of pipe links. In previous MOUSE applications, the coupling routine between MIKE SHE and MOUSE has primarily been used for calculating groundwater inflow to sewers. Test simulations show that the calculated inflow to a grouted rock tunnel is underestimated with up to 40% compared to an analytical solution. An improved coupling routine for the case with groundwater inflow to rock tunnels has therefore been developed. The new routine replaces part of the rock with a grouted zone, instead of adding the hydraulic properties of the grouted zone to the rock properties. Results using the new coupling routine show that the calculated inflow only differs a few percent compared to the analytical solution. The new coupling routine is used in the analysis of the hydrological and hydrogeological effects of the planned Forsmark repository. The results of the analysis will be used as an input to the Environmental Impact Assessment regarding the repository.

INTRODUCTION

The Swedish Nuclear Fuel and Waste Management Co (SKB) has performed extensive site investigations at two locations in Sweden, Forsmark and Laxemar-Simpevarp (Figure 1) for the siting of a deep-rock repository for spent nuclear fuel. In 2009 SKB selected to locate the repository to the Forsmark site. The results from the site investigations are used in a variety of hydrological and hydrogeological modelling activities. The modelling activities that are performed within the site descriptive modelling provide a description of present conditions at the site. This description constitutes the basis for other modelling activities related to repository design, safety assessment, and environmental impact assessment (EIA).

This paper describes a modelling activity that provides input to the EIA, which will be part of the permit application according to the Swedish Environmental Code. Specifically, the underground cavities (tunnels, shafts and rock caverns) of the repository will be kept drained during the long-term construction and operation. Quantifications of the magnitude of the groundwater inflow to the repository and associated hydrological and hydrogeological effects in the surroundings provide important inputs for the descriptions in the EIA of ecological and other types of consequences as well as mitigation measures.

The hydrological and hydrogeological modelling that is presented in the paper is performed using the modelling tools MIKE SHE, MIKE 11 and MOUSE. Specifically, the paper presents i) a routine for coupling the modelling tools MIKE SHE and MOUSE in applications involving grouted rock tunnels, ii) a case study in which the MIKE SHE-MOUSE coupling routine is applied to the planned deep-rock repository at Forsmark.

Figure 1: Locations of the Forsmark and Laxemar-Simpevarp sites, Sweden.

COUPLING BETWEEN MIKE SHE AND MOUSE

Description of the updated coupling routine

MOUSE is a modelling tool that originally is developed for the analysis of urban hydrology and pipe-flow hydraulics. A typical application of the coupling between MOUSE and the MIKE SHE modelling tool is calculation of groundwater inflow to sewers. In the present study, these two modelling tools are coupled to analyse groundwater inflow to a deep-rock repository for spent nuclear and associated hydrological and hydrogeological effects. The grouted tunnels of the repository are described as pipe links (segments) in MOUSE. The water flow between a saturated zone grid cell (MIKE SHE) and a pipe segment (MOUSE) intersecting the grid cell is included as a source/sink term in the governing flow equation for three-dimensional saturated flow in MIKE SHE.

Gustafsson et al., 2009 previously developed a MIKE SHE-MOUSE coupling routine (here denoted MS-M_{old}) and compared the modelling results with those obtained from an analytical solution for groundwater inflow to a grouted tunnel. They found that the MS-M_{old} coupling routine underestimated the groundwater inflow with 20–40%. This mismatch is likely due to the flow resistance of the grouted zone, which in the MS-M_{old} routine is added to rather than replacing the resistance of the original rock within the grouted zone. The MS-M_{old} routine provides realistic inflow results if there is a thin interface between the subsurface cavity (e.g. a buried sewer pipe) and the surrounding geological material. However, the thickness of the grouted zone around a rock tunnel can be several metres. This implies that the interface in this case may represent a large part of the MIKE SHE grid cells surrounding the cavity.

Mårtensson and Gustafsson, 2010 made further developments of the MIKE SHE-MOUSE coupling routine in order to adapt the routine for applications involving grouted rock tunnels. In this new coupling routine (here denoted MS-M_{new}), Equation 1 is used to calculate the water flow between MIKE SHE and MOUSE. The coupling routine and associated parameters are illustrated in Figure 2.

$$Q_{cell} = dh \cdot \frac{K \cdot 2 \cdot \pi}{\ln\left(\frac{r + d_{grout}}{r}\right)} \cdot L \qquad \text{(Equation 1)}$$

Q_{cell} Water flow between MIKE SHE grid cell and MOUSE tunnel segment (m^3/s)
dh Hydraulic-head difference (m) between MIKE SHE grid cell intersected by tunnel segment and MOUSE tunnel segment
L Length of tunnel segment intersecting MIKE SHE grid cell (m)
K Hydraulic conductivity (m/s)
r Tunnel radius (m)
d_{grout} Thickness of the grouted zone (m)

The hydraulic conductivity (K) in Equation 1 is set according to Equation 2, which compares the hydraulic conductivity of the grouted zone (K_{grout}) and the original (ungrouted) hydraulic conductivity of the rock (K_h, K_v):

$$K = \min[K_{grout}, \max[K_h, K_v]] \qquad \text{(Equation 2)}$$

K_{grout}	Hydraulic conductivity of grouted zone (m/s)
K_h	Horizontal hydraulic conductivity of MIKE SHE grid cell (m/s)
K_v	Vertical hydraulic conductivity of MIKE SHE grid cell (m/s)

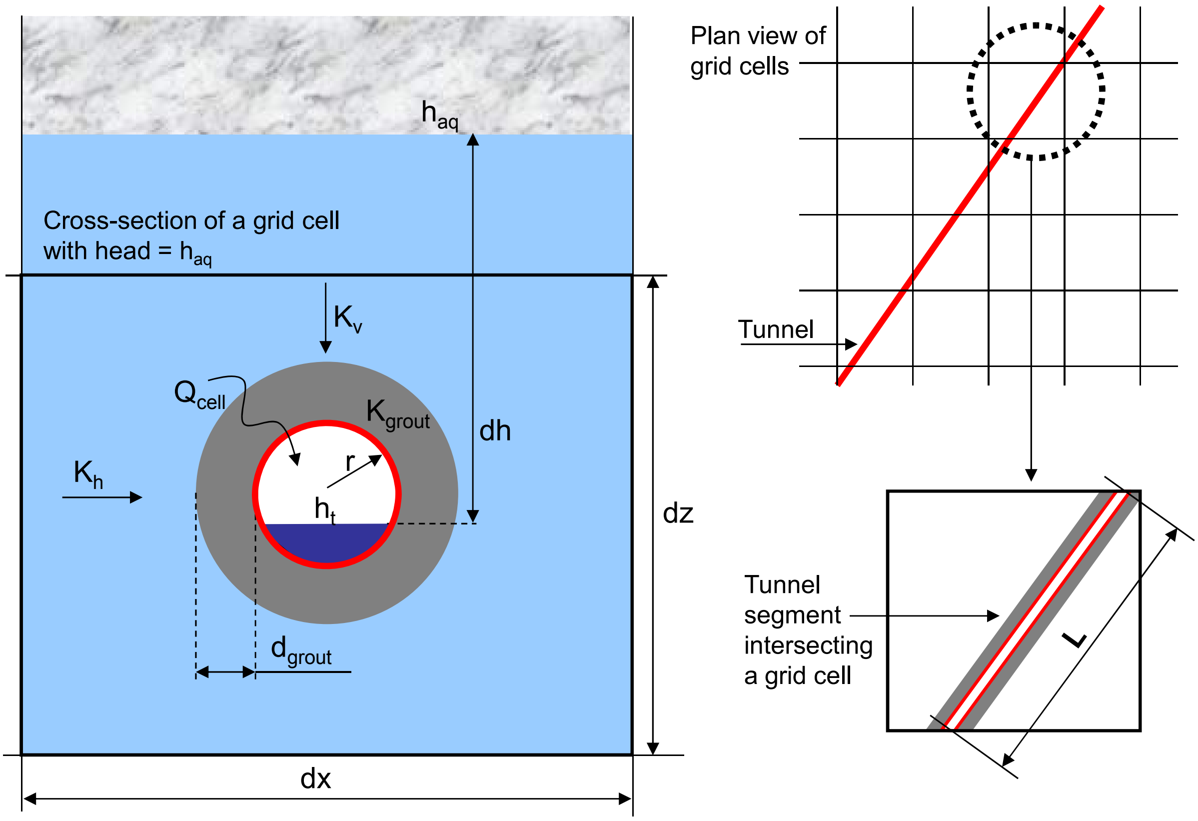

Figure 2: Illustration of the new MIKE SHE-MOUSE coupling routine (MS-M$_{new}$) and associated parameters.

In the new coupling routine, the condition in Equation 2 determines whether the hydraulic conductivity of the grouted zone (K_{grout}) or that of the ungrouted rock (K_h or K_v) is used in Equation 1 to calculate the groundwater inflow to the tunnel segment. If there is a higher flow resistance (i.e. a lower hydraulic conductivity) in the grouted zone compared to that of the ungrouted rock, $K = K_{grout}$ is used to calculate the inflow. On the contrary, if K_h or K_v of the rock is lower than K_{grout}, the highest of K_h and K_v is used for K in Equation 1. Essentially, Equation 2 mimics a real situation in which no rock grouting is performed if the original hydraulic conductivity of the rock around the tunnel periphery is below a certain hydraulic conductivity threshold. Note that in MIKE SHE-MOUSE model applications, the parameters r (the tunnel radius), K_{grout} and d_{grout} (the thickness of the grouted zone) may have different values for different tunnel segments.

Neither MS-M$_{old}$ nor MS-M$_{new}$ allows calculation of groundwater inflow to vertical cavities (e.g. vertical shafts). Instead, the inflow to such cavities is calculated by assigning a specified hydraulic head in the corresponding MIKE SHE grid cells, equal to the atmospheric pressure for a fully drained cavity (see Figure 3). The total groundwater inflow to a specific vertical cavity is calculated as the sum of the individual inflows from all intersected MIKE SHE calculation layers, based on a specified total conductance, C, for each calculation layer:

$$Q_{cell} = dh \cdot C \qquad \text{(Equation 3)}$$

Q_{cell} Water flow from MIKE SHE grid cell with cavity (m^3/s)
dh Hydraulic-head difference (m) between MIKE SHE grid cell with cavity and a specified boundary, equal to lower level of calculation layer when cavity is deeper than this level and equal to cavity bottom if above this level
C Total conductance (m^2/s)

The total conductance C in Equation 3 is calculated as follows:

$$C = \frac{K \cdot 2 \cdot \pi}{\ln\left(\frac{r + d_{grout}}{r}\right)} \cdot dz \qquad \text{(Equation 4)}$$

K Hydraulic conductivity (m/s)
dz Height of MIKE SHE calculation layer, alt. height of cavity segment if segment bottom is above lower level of calculation layer (m)
r Cavity radius (m)
d_{grout} Thickness of grouted zone (m)

In Equation 5, a condition is set for the hydraulic conductivity K in Equation 4 that compares the hydraulic conductivity of the grouted zone and the ungrouted horizontal hydraulic conductivity of the rock. Note that there is no vertical inflow to a vertical cavity, and Equation 5 only considers the horizontal hydraulic conductivity of the rock.

$$K = \min[K_{grout}, K_h] \qquad \text{(Equation 5)}$$

K_{grout} Hydraulic conductivity of grouted zone (m/s)
K_h Original horizontal hydraulic conductivity of MIKE SHE grid cell (m/s)

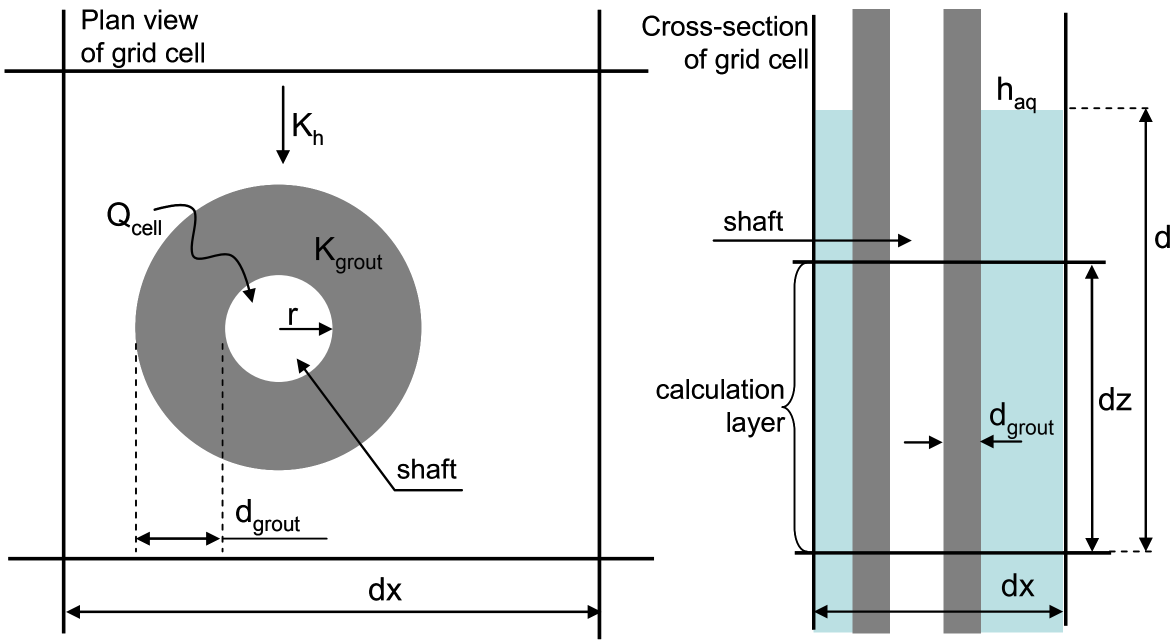

Figure 3: Calculation of groundwater inflow to a vertical cavity and associated parameters.

Test of accuracy: Comparison with analytical solution

A number of model simulations were performed in order to test the accuracy of the new MIKE SHE-MOUSE coupling routine when applied to grouted rock tunnels. Following Gustafsson et al., 2009, the test methodology includes comparison with an analytical solution for groundwater inflow to a grouted tunnel (Equation 6). The solution assumes that the rock can be interpreted as a homogenous porous medium and that the location of the groundwater table is fixed.

$$q_{an} = \frac{2\pi \cdot K_0 \cdot H}{\ln(\frac{2H}{r}) + (\frac{K_0}{K_{grout}} - 1) \cdot \ln(1 + \frac{d_{grout}}{r})} \qquad \text{(Equation 6)}$$

q_{an} Groundwater inflow ($m^3/(s \cdot m)$)
K_0 Hydraulic conductivity of rock (m/s)
K_{grout} Hydraulic conductivity of grouted zone (m/s)
H Vertical distance from groundwater table to tunnel centre (m)
r Tunnel radius (m)
d_{grout} Thickness of grouted zone (m)

Figure 4 shows the layout of the MIKE SHE test-model domain, representing such idealized conditions for which Equation 6 is applicable. The model domain has dimensions 4,000 m in one horizontal direction (x) and 2,000 m in the vertical direction (z). Down to the level z = -600 m the grid size is set to 40 m in all three dimensions. In the second horizontal direction (y) only three grid rows are used, of which two form the model boundary. A fixed hydraulic head is applied at the top boundary at ground level (z = 0), whereas all other boundaries are no-flow boundaries. A MOUSE tunnel segment representing a hypothetical tunnel with a radius of 2.5 m and atmospheric pressure is located with its centre at z = -500 m.

The test simulations include totally nine simulation cases, including the combinations 10^{-7}, 10^{-8} or 10^{-9} m/s in terms of K_0 (= K_h = K_v) and K_{grout}. In the test simulations, the thickness of the grouted zone (d_{grout}) was set to 4 m. In order to reach steady-state conditions, all MIKE SHE simulation cases were run for a minimum time period of 10 years.

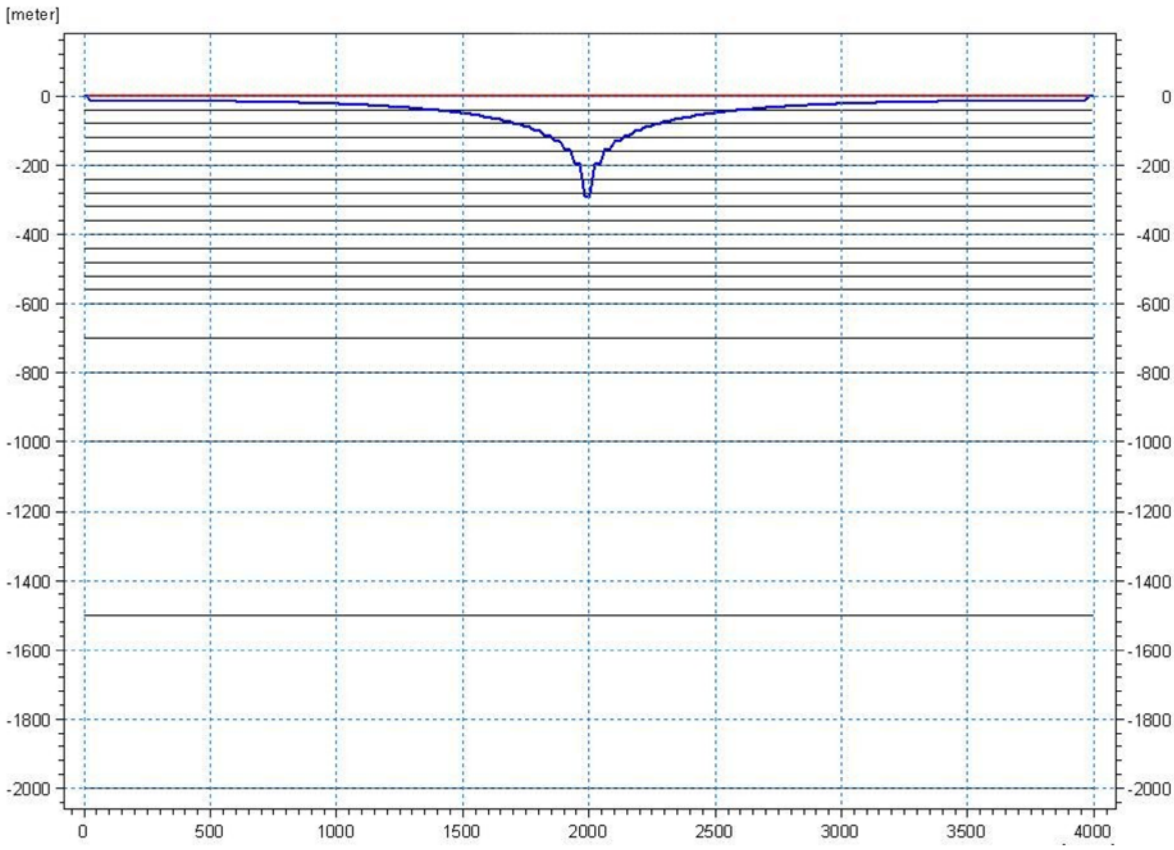

Figure 4: Cross-section of the MIKE SHE test-model setup. At the top boundary (z = 0) the hydraulic head is fixed at 0 m. The horizontal black lines show the lower level of each MIKE SHE calculation layer. The blue line represents the calculated hydraulic head in the layer where the hypothetical tunnel is located (tunnel centre at z = -500 m) for one of the simulation cases.

Table 1 presents calculated groundwater inflows for the nine simulation cases, using MIKE SHE with the new coupling routine (MS) and the analytical solution (Eq. 6). Moreover, the table shows ratios between MIKE SHE-calculated and analytically calculated inflows, using the old (MS-M_{old}) and the new (MS-M_{new}) MIKE SHE-MOUSE coupling routine. As has also been mentioned previously the old coupling routine, which was used and tested by Gustafsson et al., 2009, yields an inflow that is 20–40% smaller than the analytically calculated inflow. The new coupling routine yields more accurate results, with an inflow that differs by only a few percent compared to those obtained using Equation 6. This improved match is due to that the new routine (Equations 1 and 2) does not include a grouted zone if the hydraulic conductivity of the rock surrounding the tunnel is lower than K_{grout}. In the opposite case, the grouted zone replaces the rock in the MIKE SHE grid cells within the grouted zone.

Table 1: Calculated groundwater inflows using MIKE SHE (MS) and an analytical solution (Eq. 6) for the nine test simulation cases.

	Test case								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	Hydraulic conductivity (m/s)								
Rock	10^{-7}	10^{-7}	10^{-7}	10^{-8}	10^{-8}	10^{-8}	10^{-9}	10^{-9}	10^{-9}
Gr. zone	10^{-7}	10^{-8}	10^{-9}	10^{-7}	10^{-8}	10^{-9}	10^{-7}	10^{-8}	10^{-9}
	Calculated inflow (10^{-5} $m^3/(s\cdot m)$)								
MS (MS-M_{new})	4.9	2.2	0.31	0.61	0.54	0.22	0.063	0.061	0.054
Eq. 6	5.2	2.2	0.31	0.61	0.52	0.22	0.062	0.061	0.052
	Ratio between MS and Eq. 6 (%)								
MS-M_{new}	93	101	101	100	103	102	101	100	103
MS-M_{old}	71	64	61	73	71	64	77	77	74

FORSMARK CASE STUDY

Site description

This section presents a case study in which the new MIKE SHE-MOUSE coupling routine is applied for calculation of the groundwater inflow and associated hydrological and hydrogeological effects at the planned deep-rock repository for spent nuclear fuel at Forsmark in mid-eastern Sweden.

The Forsmark site is characterised by a small-scale topography, with a strong correlation between the topography and the elevation of the groundwater table. Granite is the dominating rock type and the rock is overlain by Quaternary deposits (average thickness 5 m), dominated by glacial till. Rock outcrops constitute c. 5% of the area. Measurements indicate that the hydraulic conductivity of the till is anisotropic (the vertical hydraulic conductivity is lower than the horizontal) and that it decreases with depth. There are no large streams at the site, and most of the lakes in the area are small (sizes < 1 km^2, average depth 0.1–1 m) and underlain by fine-grained sediments.

The conceptual model of the hydrological and near-surface hydrogeological conditions at Forsmark is illustrated in Figure 5. The upper c. 200 m of the rock contains high-conductive sheet joints that are connected over long horizontal distances. The sheet joints are primarily connected to the Quaternary deposits at locations where the upper part of the rock contains fracture zones with high vertical hydraulic conductivity.

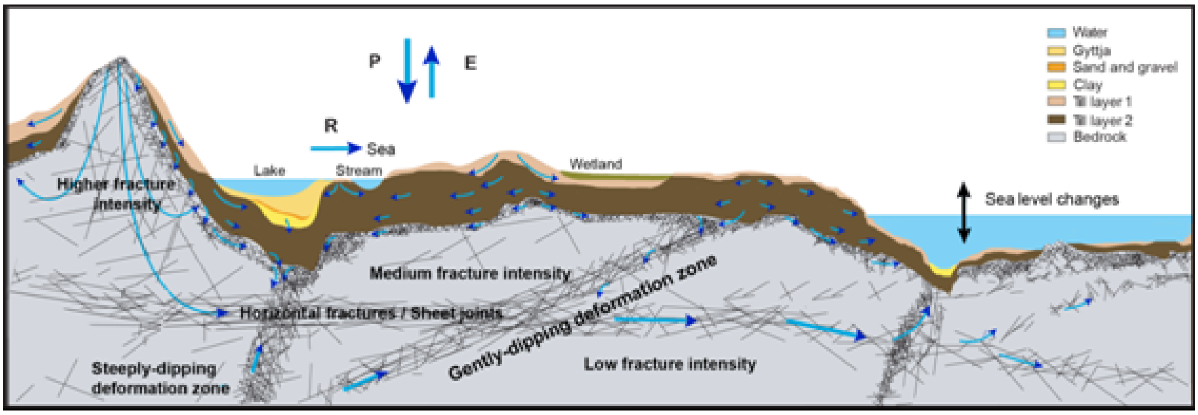

Figure 5: Illustration of the conceptual model of the hydrology and near-surface hydrogeology at the Forsmark site.

MIKE SHE model setup

A site-specific MIKE SHE model, coupled to the channel flow code MIKE 11, has been developed to quantify the groundwater inflow to the planned Forsmark repository and associated hydrological and hydrogeological effects. The codes used in the project are software release version 2009 SP4. The MIKE SHE model area has a size of 56 km^2 (Figure 6) and a horizontal grid resolution of 40 m by 40 m. The model domain extends from the ground surface down to the level 1,200 m.b.s.l. (metres below sea level). It is assumed that groundwater and surface-water divides coincide. Accordingly, the on-shore parts of the model-area boundary, which follows surface-water divides, are also set as no-flow boundaries for groundwater flow. The sea forms the uppermost calculation layer in the off-shore part of the model area. Due to that substantial overland flow in MIKE SHE may lead to numerical instabilities, the sea is defined as a geological layer with a very high hydraulic conductivity.

Based on measured sea levels, a transient head boundary condition is used in the sea part of the uppermost calculation layer and along the outer sea boundary for all calculation layers. The top boundary condition is expressed in terms of a time series of measured (actual) precipitation and calculated potential evapotranspiration (PET). It is assumed that both the precipitation and PET have uniform spatial distributions. The bottom boundary of the model domain is defined as a no-flow boundary. For further details of the Forsmark MIKE SHE model setup, see Mårtensson and Gustafsson, 2010.

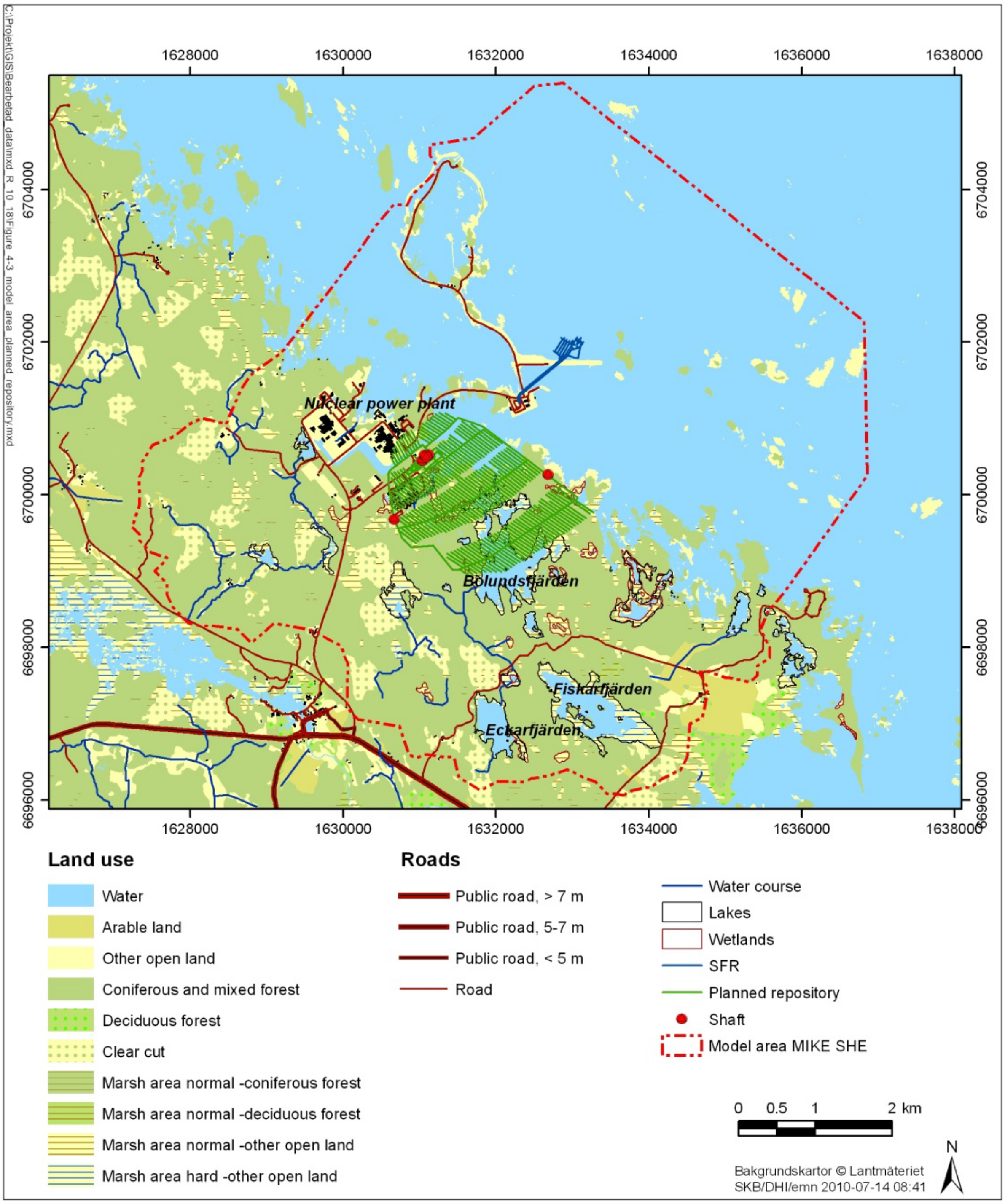

Figure 6: The Forsmark MIKE SHE model area and the layout of the planned deep-rock repository (layout D2, version 1.0).

Prior to implementing the deep-rock repository in the MIKE SHE model, the model was calibrated using long-term (several years) measurements of groundwater levels from a large number of groundwater monitoring wells (installed in the Quaternary deposits) and percussion boreholes (drilled in the rock), lake-water levels and stream discharges. Moreover, the model performance was tested using results from a long-term pumping (interference) test, including diversion of groundwater from the rock. Extensive model calibration and tests show that the model performance is very good in terms of its ability to reproduce actual measurements at the site, including both undisturbed and disturbed conditions. Current groundwater diversion in Forsmark includes the underground facility SFR (final repository for short-lived radioactive waste) and a groundwater-drainage system installed below the Forsmark nuclear power plant (Figure 6). The MIKE SHE-calculated groundwater inflow to SFR is 5.7 L/s (the measured inflow is approximately 6 L/s), whereas the calculated drainage flow below the nuclear power plant is 1.3 L/s (the measured flow is c. 1.5 L/s).

Subsequent to model calibration, the model was applied to simulate undisturbed conditions, i.e. the conditions without the planned repository. The results from this simulation were used as reference for the simulations that include the repository. Both for undisturbed and disturbed conditions, simulations were done using meteorological data and sea levels measured at the site during the two-year period 2005–2006. Specifically, year 2005 was used as an initialisation period whereas results were derived from the year 2006. Meteorologically, this year was relatively normal, however with unusually intense snowmelt during April and dry conditions during the summer (July–August).

The planned deep-rock repository (layout D2, version 1.0 from April, 2008) was implemented in MOUSE (Figures 6 and 7). The repository consists of an access tunnel (ramp) and six vertical shafts that extends from ground surface down to repository level (c. 450 m.b.s.l.), where the access ramp and four of the shafts are connected to a central area. At repository level there are various types of tunnels, including main tunnels, transport tunnels, and so called deposition tunnels, from which deposition holes will be drilled and used for deposition of canisters containing the spent nuclear fuel.

In the repository layout used in the present simulations the total length of tunnels and shafts is approximately 84 km, of which the largest part is located at repository level. Modelling results are here presented for three grouting cases, $K_{grout} = 10^{-7}$, 10^{-8} and 10^{-9} m/s, denoted case A, B and C, respectively. The thickness of the grouted zone (d_{grout}) was set to 5 m. All the simulation cases for disturbed conditions consider a fully open repository, which implies that all deposition tunnels (see Figure 7) are open at the same time. This will not be the case in reality, which implies that the presented modelling results represent a hypothetical worst-case scenario. Further simulation cases, including simple representations of the actual step-wise construction, operation and backfilling sequence for the deposition tunnels, see Gustafsson et al., 2009; Mårtensson and Gustafsson, 2010.

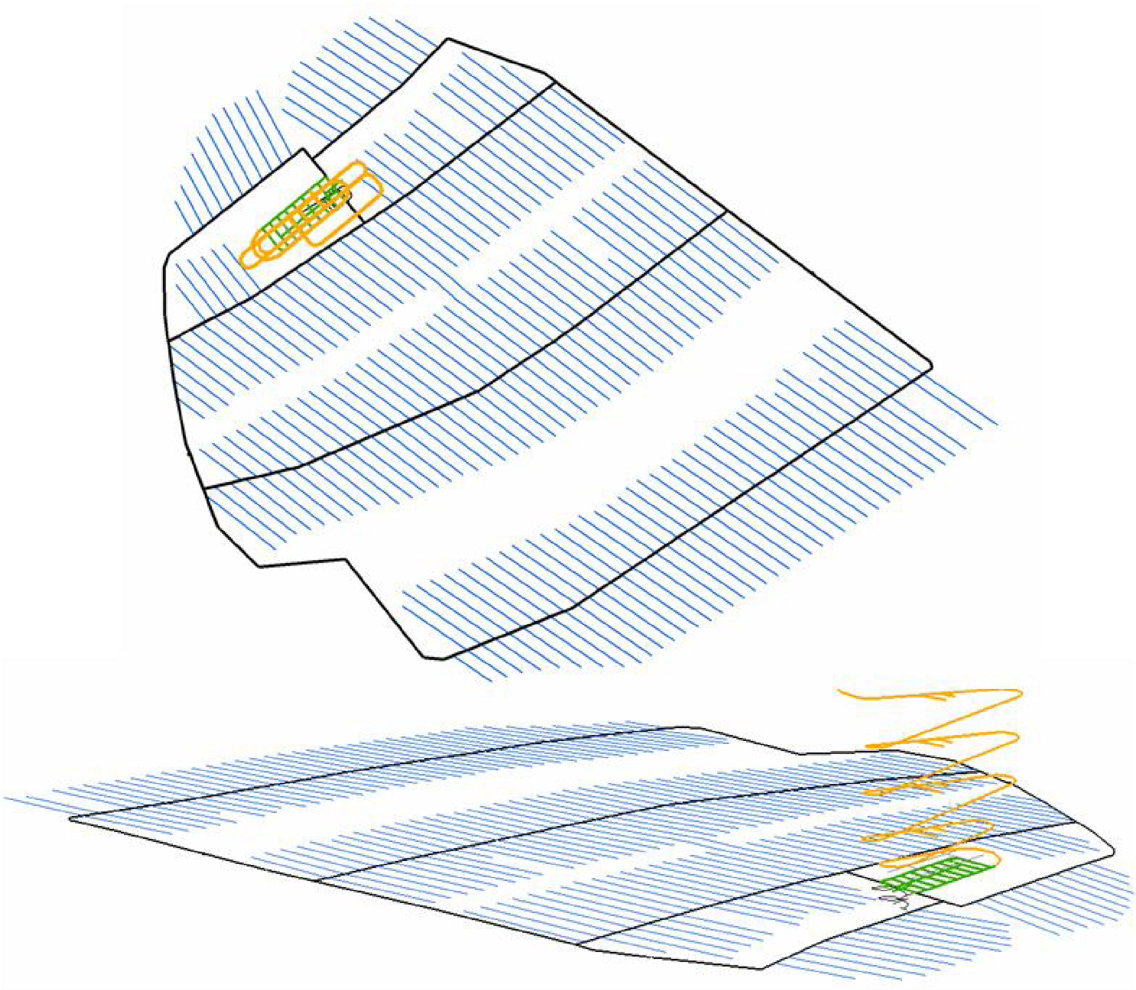

Figure 7: Layout of the planned deep-rock repository in Forsmark that was implemented in MOUSE. The yellow line is the access ramp, extending from ground surface down to repository level (c. 450 m.b.s.l.). At repository level, green lines are tunnels and rock caverns in the central area, black lines are main and transport tunnels, and blue lines are so called deposition tunnels, from which deposition holes will be drilled.

CASE-STUDY MODELLING RESULTS

Groundwater inflow

Table 2 shows the MIKE SHE-calculated annual average groundwater inflow to the repository for the three studied grouting cases A, B and C. The results are divided into tunnels and shafts, and are shown in terms of the total inflow and separately for each MIKE SHE calculation layer. As expected, the calculated inflow is largest for grouting case A (c. 47 L/s) and smallest for grouting case C (c. 15 L/s). The largest part of the total inflow occurs at repository level in calculation layer 15, i.e. the layer with the largest part of the total length of tunnels and shafts. Between ground-surface level and repository level, the largest inflows to the access ramp and the shafts occur in calculation layers 4, 6 and 8, which contain sheet joints with high horizontal hydraulic conductivity (Figure 5).

According to Table 2, the hydraulic conductivity of the grouted zone (K_{grout}) has a relatively large influence on the inflow in the "sheet-joint layers" 4, 6 and 8, whereas the inflow at repository level (layer 15) is not very sensitive to K_{grout}. In particular, at repository level there is only a small inflow difference between grouting cases A (K_{grout} = 10^{-7} m/s) and B (K_{grout} = 10^{-8} m/s). At repository level, the hydraulic conductivity of the rock is generally lower than 10^{-8} m/s and therefore controls the inflow (cf. Equations 1 and 2). On the other hand, the high hydraulic conductivity of the sheet joints implies that K_{grout} has a large influence on the inflow in the calculation layers that contain such joints.

Figure 8 shows the spatial distribution of the annual average inflow at repository level for grouting case B. The largest inflow occurs along fractures zones (yellow areas) that are in contact with the repository. The figure also illustrates what could be described as a "cage effect". This effect implies that large part of the inflow at repository level occurs at the transport tunnels that form boundaries of the repository, in particular to the transport tunnels towards the sea.

Table 2: MIKE SHE-calculated annual average groundwater inflow (L/s) to tunnels and shafts in each MIKE SHE calculation layer, for grouting cases A, B and C.

		Inflow to tunnels			Inflow to shafts		
Calc. layer	Lower level (m.b.s.l.)	A	B	C	A	B	C
1–3	20	0.1	0.0	0.0	0.1	0.0	0.0
4	40	2.2	0.5	0.1	0.9	0.2	0.0
5	60	0.7	0.4	0.1	0.3	0.1	0.0
6	80	7.5	1.7	0.3	1.7	0.3	0.0
7	100	0.4	0.7	0.2	0.6	0.2	0.0
8	120	9.1	4.5	0.7	1.6	0.4	0.1
9	140	0.4	0.3	0.1	0.1	0.1	0.1
10	160	0.2	0.3	0.2	0.2	0.2	0.1
11	180	0.2	0.3	0.2	0.3	0.2	0.1
12	200	0.2	0.4	0.3	0.4	0.2	0.1
13	300	0.1	0.1	0.2	0.6	0.5	0.2
14	400	0.1	0.1	0.1	0.7	0.6	0.2
15	500	18.9	18.0	12.2	0.0	0.0	0.0
16	600	0.0	0.0	0.0	0.0	0.0	0.0
17	700	0.0	0.0	0.0	0.0	0.0	0.0
18	800	0.0	0.0	0.0	0.0	0.0	0.0
19	900	0.0	0.0	0.0	0.0	0.0	0.0
20	1,000	0.0	0.0	0.0	0.0	0.0	0.0
21	1,100	0.0	0.0	0.0	0.0	0.0	0.0
22	1,200	0.0	0.0	0.0	0.0	0.0	0.0
Sum		40.2	27.3	14.7	7.2	3.2	0.8

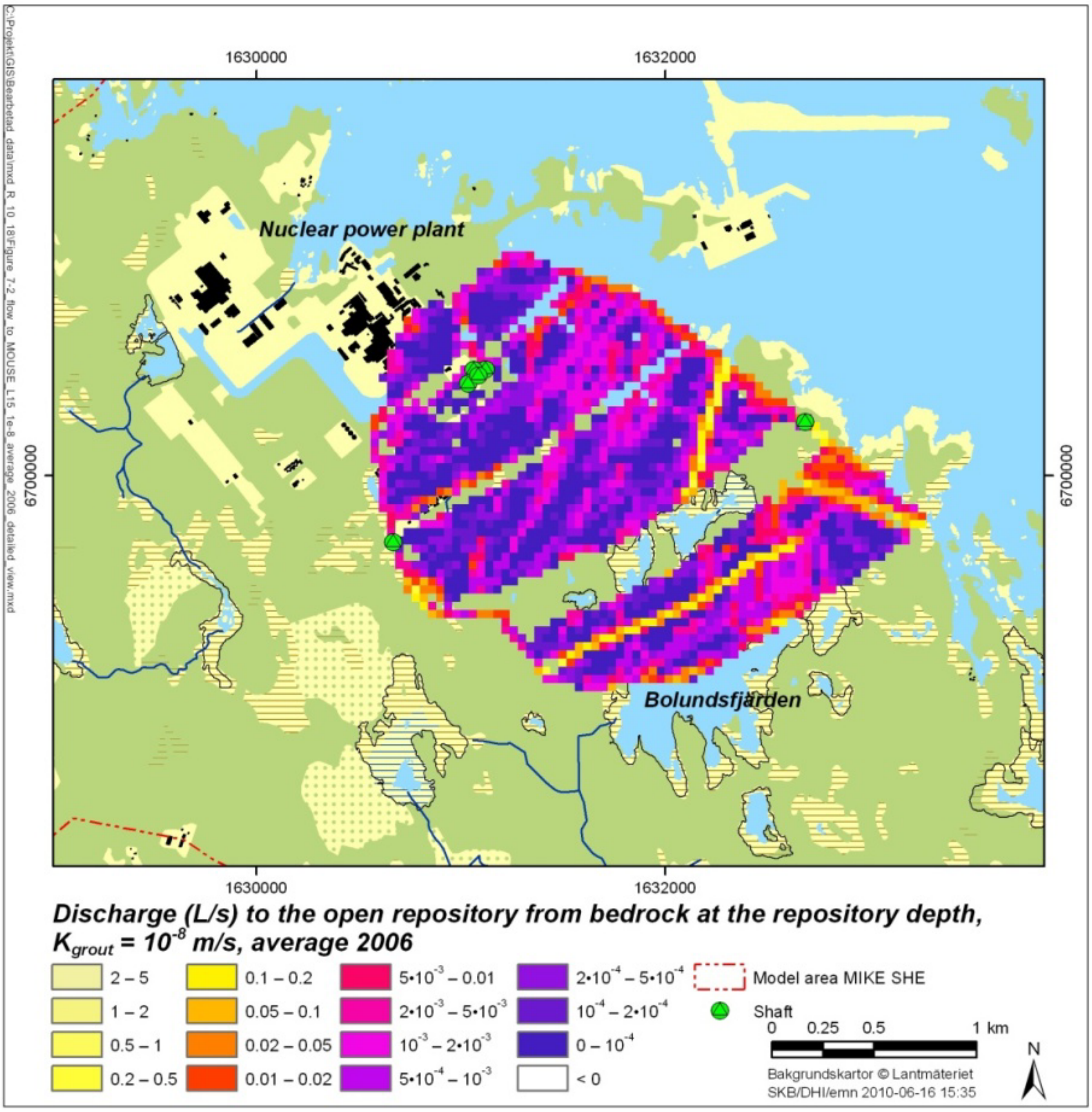

Figure 8: MIKE SHE-calculated annual average groundwater inflow (L/s) to the repository from each MIKE SHE grid cell at repository level (450 m.b.s.l., calculation layer 15) for grouting case B.

Effects on water balance and hydrological conditions

According to the MIKE SHE modelling results the groundwater inflow to the repository will affect the total water turnover in the model area. Table 3 summarises annually accumulated water-balance components (year 2006) for the land part of the model area. Results are shown for undisturbed (i.e. without the repository) and disturbed conditions (with the repository) for the three studied grouting cases A, B and C. All water-balance components are expressed in the form of area-normalised accumulated flows (mm/y). Observe that part of the repository at repository level is located below the sea (cf. Figure 6), which implies that this specific part of the repository is not included in the results that are shown in Table 3.

For grouting case A ($K_{grout} = 10^{-7}$ m/s) the annual runoff is 124 mm, which can be compared to 158 mm/y for undisturbed conditions and hence corresponds to a runoff reduction of 34 mm/y. For this grouting case the groundwater inflow to the repository is 45 mm/y. The residual (45 – 34 = 11 mm) is due to subsurface storage changes and a slight reduction of the evapotranspiration. The inflow hence represents 28% (45/158) of the annual runoff for undisturbed conditions. The corresponding ratios for grouting cases B and C are 18% (28/158) and 9% (14/158), respectively.

The inflow to the repository also influences the runoff to the streams. This runoff component is reduced by 13 mm (-14%) in grouting case A. In particular, the inflow leads to a reduction of the overland flow to the streams, which in grouting case A is reduced by 11 mm (-19%). According to the modelling results the largest effects on the water balance will occur downstream from Lake Bolundsfjärden (Figure 6). In this area, the depth to the groundwater table is small for undisturbed conditions and the inflow leads to a large drawdown of the groundwater table (see further below).

Considering water flows across the boundary between land and sea, both the net subsurface inflow and the overland inflow are higher in the disturbed case. Specifically, for grouting case A the net overland inflow increases with 4 mm (23%) and the net subsurface inflow with a factor of five, respectively. In relative terms, the latter is the runoff component that is most affected by the groundwater inflow to the repository.

Table 3: Annually accumulated water balance (mm/y) for the land part of the model area, presented for undisturbed conditions and disturbed conditions for grouting cases A, B and C.

	Undisturbed conditions	Gr. case A	Gr. case B	Gr. case C
Precipitation	534.1	534.1	534.1	534.1
Evapotranspiration	406.6	401.1	404.4	405.3
Canopy storage change	0.1	0.1	0.1	0.1
Snow storage change	-29.8	-29.8	-29.8	-29.8
Overland storage change	7.6	7.0	6.9	9.1
Subsurface storage change	-11.3	-15.0	-12.9	-12.0
Net overland sea inflow	16.0	19.6	19.9	19.9
Net subsurface sea inflow	3.6	20.3	12.9	7.2
Drainflow to sea	85.2	84.1	84.6	84.9
Overland flow to river	57.4	46.7	50.0	53.7
Drainflow to river	28.9	26.9	27.3	27.7
Net baseflow to river	5.9	5.7	5.8	5.9
Gw. inflow to repository	-	44.5	28.0	13.7

Hydrogeological effects

The overview map in Figure 9 shows the MIKE SHE-calculated annual average (year 2006) groundwater-table drawdown for grouting case B ($K_{grout} = 10^{-8}$ m/s). As can be seen in the figure, the relatively small and band-shaped influence area is located above the repository around Lake Bolundsfjärden. The influence area primarily coincides with locations where the Quaternary deposits are in contact with rock containing fracture zones with high vertical hydraulic conductivity. The area with the largest annual average groundwater-table drawdown (c. 9 m for $K_{grout} = 10^{-8}$ m/s) is located north of Lake Bolundsfjärden.

Figure 10 illustrates the importance of the hydraulic conductivity of the grouted zone on the groundwater-table drawdown. Specifically, the figure shows MIKE SHE-calculated influence areas (here defined as areas with an annual average drawdown exceeding 0.3 m) for the studied grouting cases. The shape of the influence area is relatively similar for all three grouting cases. Grouting case A yields the largest groundwater inflow (see above) and therefore also the largest influence area and groundwater-table drawdown (locally up to c. 16 m).

The upper part of Figure 11 shows the calculated annual average hydraulic-head drawdown in the rock at the level 50 m.b.s.l. for grouting case B. Compared to the groundwater-table drawdown (Figures 9 and 10), the size of the influence area of the hydraulic-head drawdown in the rock is considerably larger. This can be explained by the sheet joints in the rock (Figure 5). Their high horizontal hydraulic conductivity and long-distance connections act to distribute the hydraulic-head drawdown in relatively large areas in the rock around the repository. The lower part of Figure 11 shows calculated annual average hydraulic heads at different levels along a west-to-east profile across the model area for grouting case B. As can be seen in the figure, the magnitude of the drawdown is largest at repository level (c. 450 m.b.s.l.).

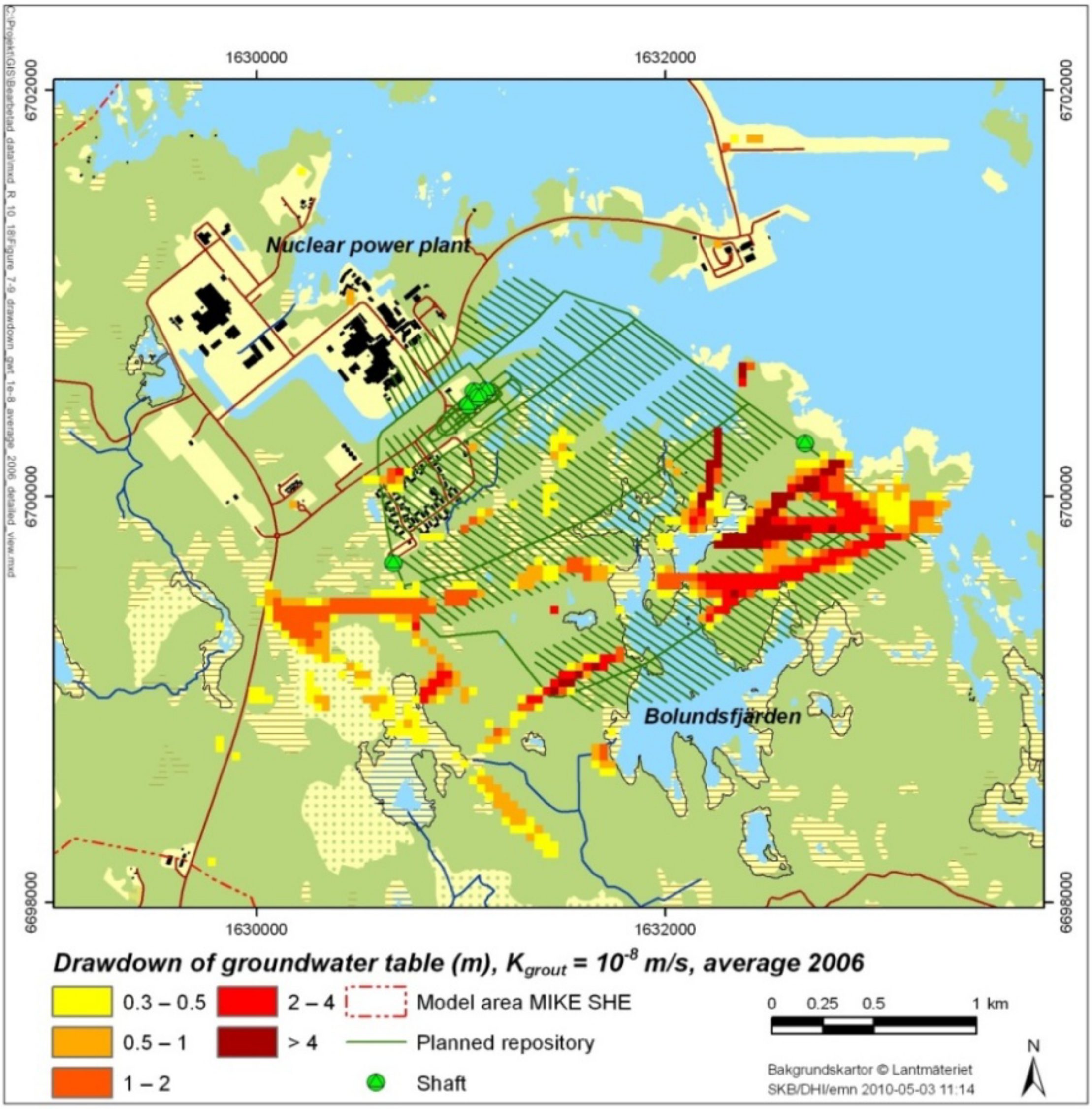

Figure 9: MIKE SHE-calculated annual average groundwater-table drawdown for grouting case B.

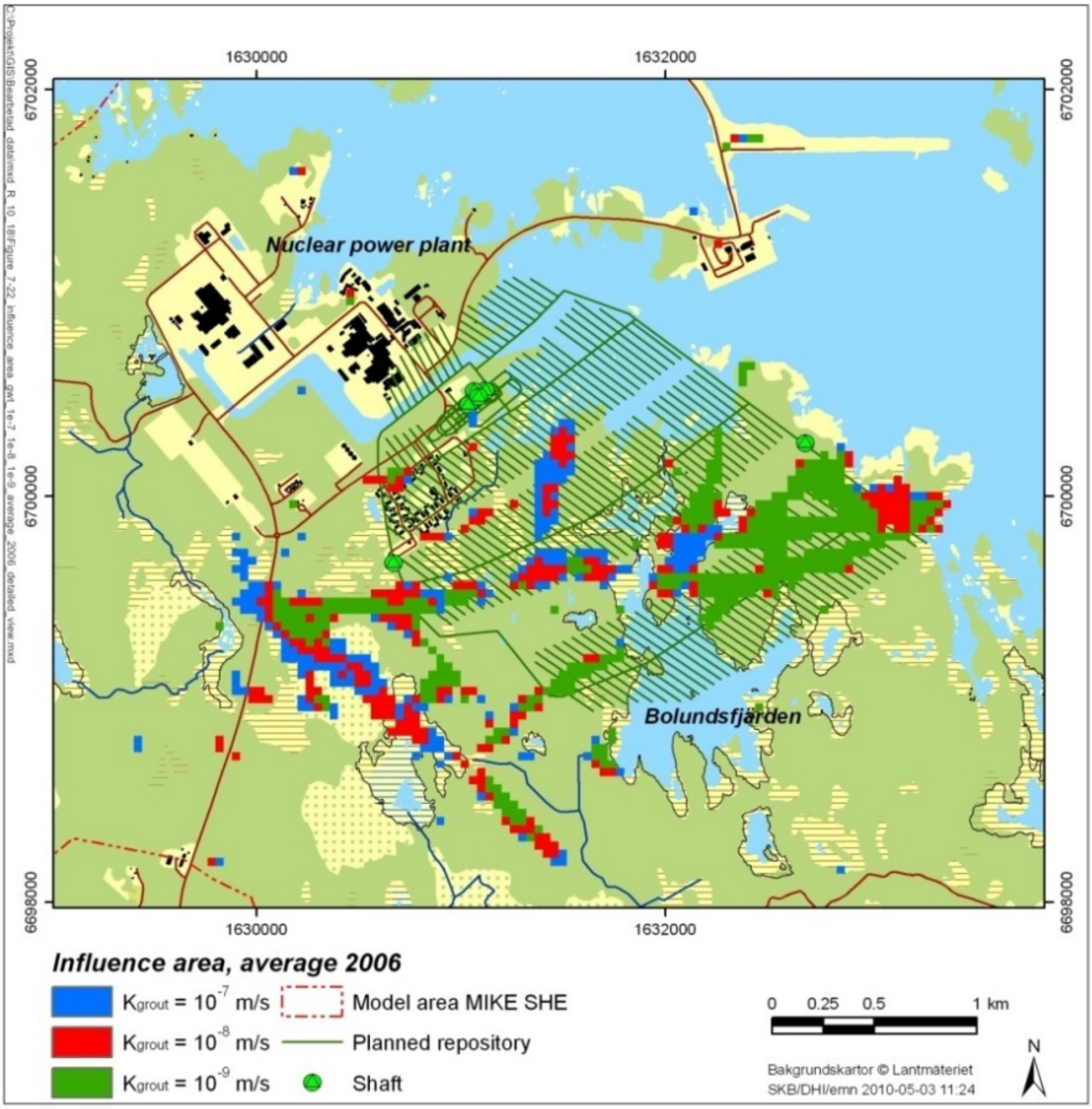

Figure 10: Comparison of MIKE SHE-calculated influence areas (annual average groundwater-table drawdown > 0.3 m) for grouting cases A (blue, red and green), B (red and green) and C (green).

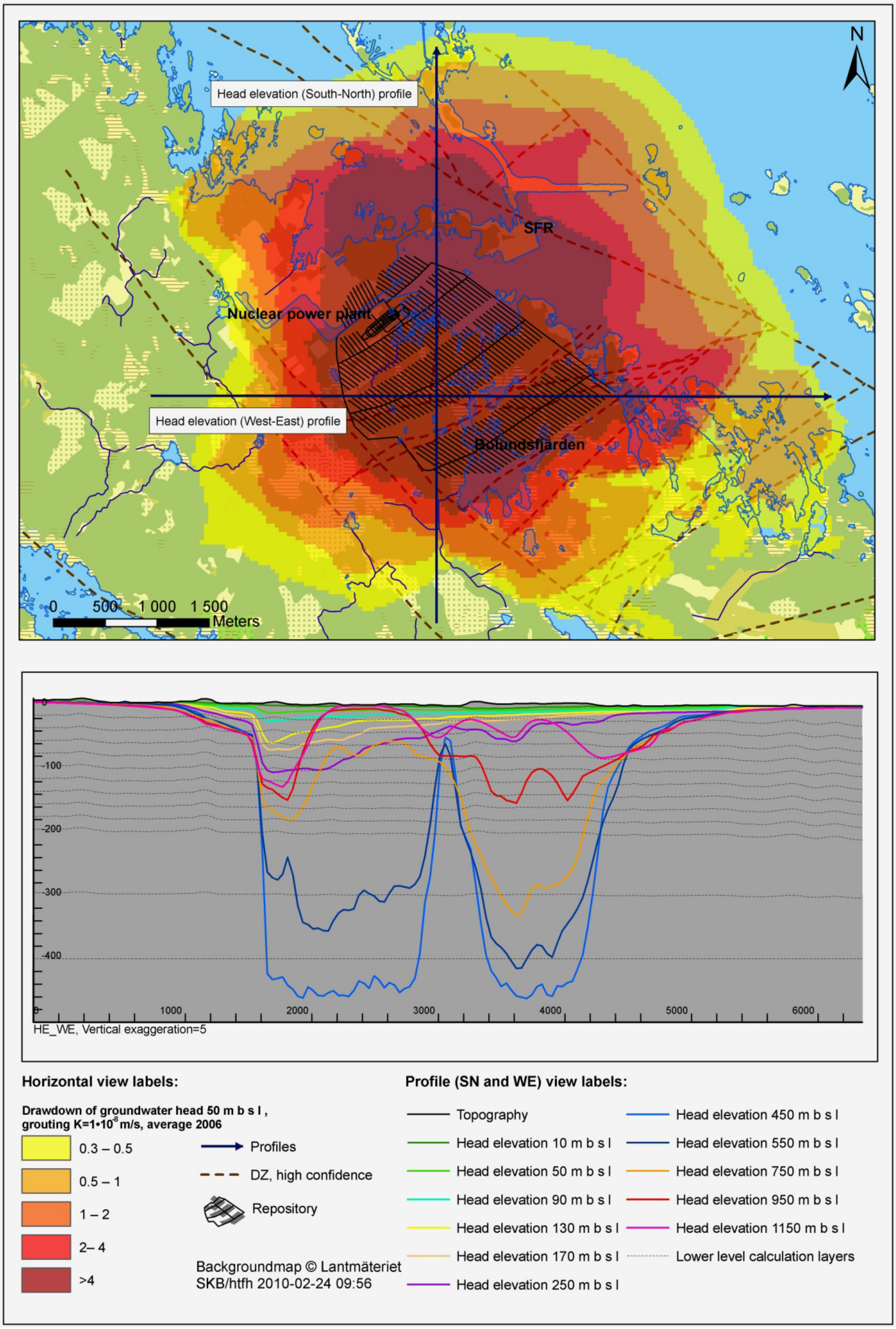

Figure 11: MIKE SHE-calculated annual average hydraulic heads in different calculation layers (coloured lines) along a west-to-east profile across the model area and the repository. The geographical location of the profile is shown in the upper map, which also shows the calculated hydraulic-head drawdown in the rock at the level 50 m.b.s.l. The results refer to grouting case B.

CONCLUSIONS

A new routine for coupling the modelling tools MIKE SHE and MOUSE has been developed. The new routine is specifically adapted for calculation of groundwater inflow to grouted rock tunnels. Tests of the new routine shows that removal of the rock within the grouted zone yields a close match between MIKE SHE-calculated inflows and results obtained using an analytical solution. For applications involving grouted rock tunnels, it is therefore recommended that the new routine is used instead of the typical MIKE SHE-MOUSE coupling routine, according to which the flow resistance of the geological material and that of its interface with an underground cavity are added.

The new coupling routine was implemented in a site-specific MIKE SHE model (which is also coupled to the modelling tool MIKE 11) and applied to the planned deep-rock repository at Forsmark in mid-eastern Sweden. For a hypothetical worst-case scenario (a fully open repository), the results of the case study show that the groundwater inflow to the repository will be in the range 15–47 L/s, for values of the hydraulic conductivity of the grouted zone (K_{grout}) in the range 10^{-9}–10^{-7} m/s. Depending on the value of K_{grout}, the inflow corresponds to 10–30% of the total undisturbed (without the repository) runoff from the land part of the model area.

The model-calculated inflow to the repository yields hydraulic-head drawdown in the rock in a relatively large area around the repository. This phenomenon is in agreement with the conceptual hydrogeological model of the Forsmark site, according to which the upper 200 m of the rock contains high-conductive sheet joints that are connected over long horizontal distances. The model-calculated influence area of the groundwater-table drawdown is considerably smaller. Specifically, drawdown of the groundwater table primarily occurs at locations where the Quaternary deposits are in contact with rock containing fracture zones with high vertical hydraulic conductivity.

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