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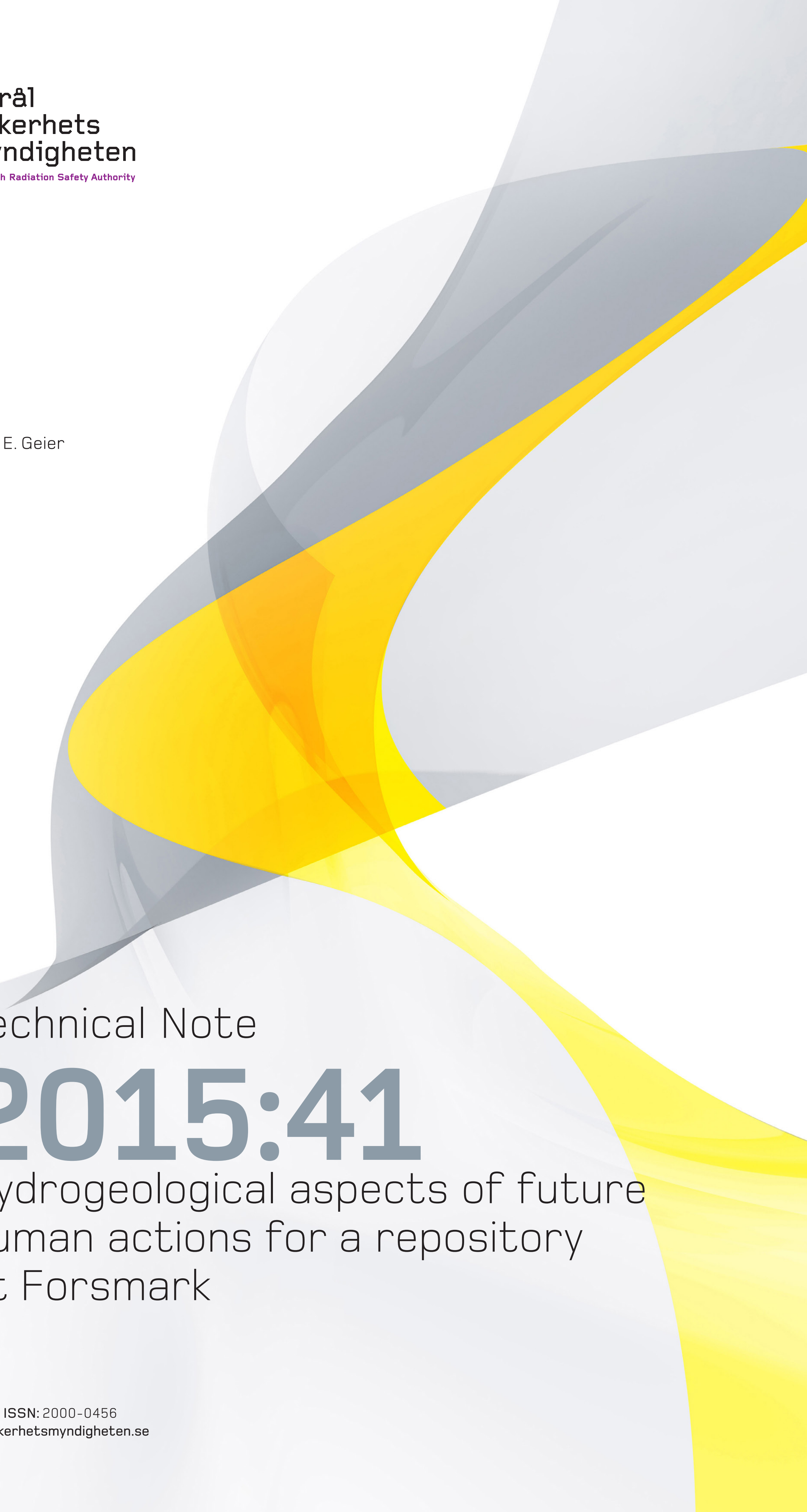
Swedish Radiation Safety Authority



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Technical Note

2015:41

Hydrogeological aspects of future human actions for a repository at Forsmark

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Syftet med projektet är att utvärdera SKB:s hydrogeologiska beräkningar i samband med redovisningen av framtida mänskliga handlingar i säkerhetsanalysen SR-Site.

Författarsammanfattning

SKB har i säkerhetsanalysen SR-Site använt hydrogeologiska beräkningar som underlag för analysen av framtida mänskliga handlingar (”future human actions”, FHA). Denna granskning undersöker resultaten av dessa beräkningar med hänsyn till hantering av osäkerheter och hur SKB integrerar resultaten i konsekvensanalysberäkningarna.

SKB: s hydrogeologiska modeller för ett öppet förvar under driftskedet och ett övergivet icke fullständigt förslutet förvar är väl beskrivna och trovärdiga givet sina ursprungliga syften. SKB:s bedömningar i samband med scenarier för framtida mänskliga handlingar är dock i huvudsak baserade på kvalitativa hydrogeologiska argument, med undantag för fallet med ett övergivet delvis förslutet förvar. När SKB hänvisar till specifika modelleringsresultat har dessa baserats på modeller som har utvecklats och tillämpats för andra hydrogeologiska situationer.

SKB tillämpar modellen för ett övergivet, delvis öppet förvar som underlag för att bedöma scenariot med en tunnel som uppförs ovanför ett förslutet förvar. Modellen innefattar dock öppna (vattenfyllda) tunnlar på förvarsdjup som är anslutna till ytan via schakt i anläggningen, vilket kan vara en betydelsefull skillnad till situationen i det antagna scenariot. Modellen ger mycket låga tryckgradienter i deponeringstunnlarna vilket inte helt stämmer överens med scenariot där en tunnel på grundare djup kortsluter utströmningsvägarna för grundvatten som strömmar genom ett förslutet förvar.

SKB redovisar inga hydrogeologiska modeller som specifikt beräknar konsekvenserna av underjordiska anläggningar, gruvor, eller borrhål som oavsiktligt skär genom förvaret. Scenarier som innefattar uppförandet av undermarksanläggningar på djup mer än 150 meter har inte beaktats. De redovisade modelleringsresultaten och skillnaderna mellan olika modelleringsmetoder föranleder frågor om hur väl processerna som styr inflöden till tunnlar har representerats i modellerna.

Sammanfattningsvis bör begränsningarna i SKB: s bedömning av de hydrogeologiska aspekterna av framtida mänskliga handlingar beaktas i samlade utvärderingen av säkerhetsanalysen liksom de låga sannolikheterna för dessa scenarier

Projektinformation
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Diarienummer ramavtal: SSM2011-3629
Diarienummer avrop: SSM2014-1403
Aktivitetsnummer: 3030012-4091

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The objective of the project is to evaluate SKB's hydrogeological calculations related to the future human action scenarios that are part of the safety analysis SR-Site.

Summary by the author

The Swedish Nuclear Fuel and Waste Management Co. (SKB) has used hydrogeological calculations as input for the analysis of future human actions (FHAs). This review examines the results of these calculations in view of the uncertainties and how SKB integrates the results in consequence analysis.

SKB's hydrogeological models of an open repository during the operating phase and of an abandoned repository are well described and credible for their original purposes. However, except for the case of an abandoned but partly sealed repository, SKB's higher-level evaluation of FHAs related to hydrogeology is mainly based on qualitative arguments. Where specific modelling results are cited, these refer to models that were developed and applied for different hydrogeological situations.

The model of an abandoned, partly open repository is used to assess the FHA scenario of tunneling above a closed repository. A potentially important distinction is that the model of a partly open repository includes open (water-filled) tunnels at repository depth which are connected to the surface via shafts. Thus this model has very low head gradients through the deposition tunnels compared with what might result from the FHA scenario in which a tunnel at shallower depth short-circuits the discharge path for groundwater flowing through a closed repository.

No hydrogeological models are presented that specifically demonstrate the consequences of subsurface facilities, mines, or inadvertent borehole penetration of the repository. Scenarios involving construction of caverns at depths deeper than 150 m have not been considered. Additionally the modelling results that have been presented, and the discrepancies between different modelling approaches, leave questions regarding their representativity for the processes governing inflow into tunnels.

The limitations of SKB's evaluation of hydrogeological aspects of FHAs therefore is recommended for consideration in higher-level review of the SR-Site safety case, taking into consideration the low probabilities associated with these scenarios.

Project information

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Contents

1. Introduction

SKB has used hydrogeological calculations as input for the analysis of future human actions (FHA). The goal of this task was to assess if the results of hydrogeological calculations concerning FHAs are reasonable, considering the given uncertainties and how SKB integrates the results in subsequent consequence analysis calculations.

The main reports considered in this review were:

- SKB R-10-41, Groundwater flow modelling of an abandoned partially open repository. SR-Site Forsmark.
- SKB R-10-18, Hydrological and hydrogeological effects of an open repository in Forsmark.
- SKB TR-10-53, Handling of future human actions in the safety assessment SR-Site.

In addition relevant sections of SR-Site main report (SKB TR-11-01, main Section 14.2) were considered to see how the results were used in the safety case.

2. Hydrogeological Calculations to Assess Future Human Actions

2.1. SKB’s presentation

Future human actions are addressed in Section 14.2 of the SR-Site main report (SKB TR-11-01). Two main categories of scenarios related to future human actions, FHA are distinguished:

- Scenarios related to a sealed repository, and
- Scenarios related to an unsealed or incompletely sealed repository.

Hydraulic impacts of scenarios in the second category are addressed mainly in Section 4.5 and Sections 6.3 through 6.5 of the Future Human Actions (FHA) report (SKB TR-10-53). In addressing these scenarios, SKB also refers to an analysis of the hydrogeological effects of an open repository by Mårtensson and Gustafsson (2010; SKB R-10-18). Scenarios in the second category are addressed in Section 6.6 of the FHA report, based in large degree on the results of hydrogeological modeling of an abandoned partially open repository by Bockgård (2010; SKB R-10-41).

SKB's presentation of these two categories of scenarios is summarized in Sections 2.1.1 and 2.1.2, respectively. Relevant aspects of the hydrogeological analysis of an open repository are described in Section 2.1.3.

2.1.1. Scenarios involving a sealed repository

An inventory of possible human actions that could affect a deep repository are listed in Table 14-1 of SKB (2011; TR-11-01, p. 743). The following actions are judged not to be able to directly affect the technical barriers and the containment of the fuel, due to the likelihood that they would be restricted to shallow depths of at most a few tens of metres:

- T4: Build plant that generates heating/cooling on the surface above the repository
- H2: Build dam
- H3: Change the course or extent of surface water bodies (streams, lakes, sea) and their connections with other surface water bodies
- H4: Build hydropower plant
- H5: Build drainage system
- H6: Build infiltration system
- H7: Build irrigation system
- H8: Change conditions for groundwater recharge by changes in land use

- M3: Excavate open-cast mine or quarry

- M4: Construct dump or landfill

- C2: Construct sanitary landfill (refuse tip)

- C3: Acidify air, soil and bedrock

- C4: Sterilise soil

- C5: Cause accident resulting in chemical contamination (though some of them could include drilling of relatively deep wells).

SKB judges that near-surface activities belonging the mechanical and hydrological categories M and H will have less influence on the repository than natural changes in conjunction with future climate change. Two bomb-related scenarios are considered briefly:

- M5: Bomb or blast on the surface above the repository
- M6: Subsurface bomb or blast

The first is dismissed on the reasonable grounds that only a nuclear bomb would be capable of impacting a repository at depth, and in such a case the devastation and residual radiation at the surface would likely exceed leakage from the repository. The second is dismissed on the grounds that a society that conducts subsurface nuclear bomb testing would likely have the technology to detect and respond to radiation leakage.

The remaining future human activities in the list considered by SKB all involve some degree of drilling and/or construction in the rock, based on present-day technology:

- T1: Build heat store
- T2: Build heat pump system
- T3: Extract geothermal energy (geothermics)
- H1: Construct well
- M1: Drill in the rock
- M2: Build rock cavern, tunnel, shaft, etc.
- C1: Store/dispose hazardous waste in the rock

SKB argue that scenarios that involve large-scale underground excavations are unlikely to be undertaken without prior investigation by drilling. They further argue that it would be technically implausible “to build a rock cavern, tunnel or shaft or to excavate an open-cast mine which leads to penetration of the copper canister ... without having investigated the rock in such a way that the repository is discovered.”

Therefore, they analyse only a reduced set of cases:

- Canister penetration by drilling
- Rock facility in the vicinity of the repository
- Mine in the vicinity of the Forsmark site

as representative cases for scenarios related to a sealed repository. SKB's treatment of each of these cases is summarized below.

Canister penetration by drilling

SKB's assessment of canister penetration by drilling is described in Section 6.3 of TR-10-53, and in Section 14.2.5 of TR-11-01. The two accounts are basically the same, except that TR-10-53 includes additional tables of data concerning radionuclide inventories, solubility limits etc. which are covered by the SR-Site Data Report, and TR-11-01 contains a few additional explanatory paragraphs and explicitly lists the safety function indicators that were considered. TR-10-53 also includes a somewhat more detailed discussion of uncertainties than were carried into the main report.

The scenario considered by SKB assumes that drilling to repository depth is done for the purpose of exploration, using diamond core-drilling bits similar in size to those used for deep core-drilled holes in SKB's site investigations at Forsmark. This scenario leads to a likelihood that drill core would be recovered and examined by a geologist. This leads to a risk of direct exposure from recovery of part of fuel rod, although it also leads to a high likelihood that this would be recognized.

The alternative possibility, that deep holes could be drilled for other purposes (e.g. creating a path for fluid circulation as part of a heat extraction facility) is mentioned but then dismissed as less likely than the exploratory drillhole scenario.

The analysis of this scenario as summarized by SKB 2011 (p. 746-747) is based on the pessimistic assumption that a canister is penetrated by drilling, and that the borehole above the penetrated canister is grouted so that the buffer does not expand into the borehole and prevent advective transport. SKB notes that this situation is likely to change over time as the grout degrades, allowing the buffer and backfill to expand into the borehole. They also consider that the loss of buffer and backfill will not be sufficient to affect nearby deposition holes in the same deposition tunnel as the penetrated canister.

The data used for quantitative assessment of this scenario, as listed in table 14-2 of SKB (2011), include only a few items that come from hydrological monitoring or analyses:

- Runoff 0.186 m/y (Löfgren, 2010).
- Well capacity 82,502 m3/year (Löfgren, 2010).
- Water flow through deposition hole at a rate of 0.1 m^3 per year (FHA report, Appendix B).

According to Löfgren (2010, p. 345) the runoff parameter represents the total mean annual runoff for the SDM-site model area. The calculation was based on the final SDM-site model of Bosson et al. (2008).

The well capacity figure, according to Löfgren (2010, p. 345), is based on the values from 22 percussion boreholes located in the area close to or directly above the repository. They note that, "the median value for the well capacity of the data set for the percussion boreholes is about 20 times greater than the values for the surrounding domestic wells outside the candidate area. The reason for this is that these wells penetrate sheet joints located deep within the investigation area. Drilled wells located farther away could result in elevated activity concentrations in the well water."

The magnitude of water flow through the deposition hole with the penetrated canister was chosen, as described in SKB (2010, Appendix B, p. 85-86), based on consideration of the volumetric flows predicted by the base-case model of Joyce et al. (2010) for present-day temperate conditions. SKB (2010) regard the chosen value of 0.1 m^3/year as a cautious value, as this exceeds the 95th percentile value of 0.076 m^3/year calculated by Joyce et al. (2010) for the case in which deposition holes that do not meet the full-perimeter criterion (FPC) are excluded, and because “higher flow implies a higher release rate from the fuel of radionuclides that are not solubility limited.” If deposition holes that do not meet the extended full-perimeter criterion (EFPC) are also rejected, then the chosen value of 0.1 m^3/year exceeds the corresponding 95th percentile value (0.020 m^3/year) by an even greater margin.

SKB's choice of 0.1 m^3/year as the magnitude of flow through a fracture intersecting a deposition hole is based on flows for a model (Joyce et al., 2010) in which flows and head gradients are regulated by the discharge path through bedrock to the surface. A borehole would be expected to reduce the resistance to flow along the discharge path, resulting in higher fluxes, but this does not seem to have been taken into account.

The impact of the drilled hole on the hydrological situation in the remainder of the repository is assumed to be limited to just the penetrated canister, based on an assumption that the hole would be grouted upon reaching the backfill and buffer (TR-11-01, p. 747). The likelihood that the grout will degrade is considered, but it is argued that the expansion capabilities of the backfill and buffer will lead to re-establishment of “favorable” hydrological conditions in the repository, including in the deposition hole with the penetrated canister. It is concluded that “even though drilling a borehole that penetrates a canister will severely affect the deposition hole hit by drilling, the impact of the borehole on the containment potential of other parts of the repository as well as on the retardation potential of the geosphere is negligible” (TR-11-01, p. 751-752).

Rock facility in the vicinity of the repository

SKB's assessment of an underground rock facility in the vicinity of a repository is described in Section 6.4 of TR-10-53, and in Section 14.2.6 of TR-11-01. The two accounts are basically the same, except that TR-10-53 includes additional tables of data concerning radionuclide inventories, solubility limits etc. which are covered by the SR-Site Data Report, and TR-11-01 contains a few additional explanatory paragraphs and explicitly lists the safety function indicators that were considered. TR-10-53 also includes a somewhat more detailed discussion of uncertainties than were carried into the main report.

SKB's analysis of an underground rock facility (TR 11-01 p 752) is based on consideration of a tunnel at moderate depth (50 m) with a cross section of 100 m^2. The purpose of the tunnel or rock excavation is not specified. The operational period of the tunnel is assumed to be “a couple of hundred years” after which the tunnel/excavation is abandoned and is resaturated with groundwater. It is assumed that the construction of the facility takes place at least 300 years after repository closure.

The assumption that the tunnel would be at 50 m depth, and directly above the proposed repository at Forsmark, places it within what has been described as the "shallow bedrock aquifer" within which groundwater flow is assessed as being dominated by highly transmissive, nominally horizontal sheet joints. SKB notes (TR-11-01, p. 753) that construction in this zone would require extensive grouting that would limit the impact of the tunnel on the hydrogeology in the surrounding superficial rock. This, together with the relatively low hydraulic conductivity of the deeper bedrock, would mitigate any tendency for upconing that could affect groundwater chemistry of flow patterns at the repository depth of 450 meters.

The future uplift due to ongoing postglacial isostatic rebound is discussed. As this uplift is only projected to be about 7 m over the next 1000 years, it is not expected to significantly affect the hydrogeological importance of the sheet joints in the shallow bedrock.

SKB argues (TR-11-01, p. 753) that while an abandoned tunnel could become a conductor for near-surface flows, it would not significantly affect the magnitude of water flow at repository depth. As support for this argument, SKB cites the results of hydrogeological analyses of an abandoned, partially open repository (Bockgård 2010), which is summarized in Section 2.1.2 of this technical note. The situation considered by Bockgård (2010) includes open tunnels at repository depth which are connected to the surface via shafts that have only nominal resistance to flow.

SKB asserts that "similar arguments could be made for tunnels located down to at least the 150 m level ," although they do not make these arguments explicitly. In conclusion, they note that the upper 150 m of the bedrock would be an unfavourable location for a tunnel from an engineering point of view. Despite this observation, SKB does not present an analysis of the consequences of a tunnel at greater depths, where the bedrock would be more favourable from an engineering point of view. Their reason for excluding such a case from consideration is based on the observation that tunnels down to 50 m depth are more typical, based on current practices in Sweden, in which "the depth is generally as shallow as possible with regard to the geology and purpose of the facility." (TR-11-01, p. 752).

Mine in the vicinity of the Forsmark site

The possibility of a mine in the vicinity of the Forsmark site has been considered (TR-10-53, p. 60-62, with arguments repeated nearly verbatim in TR-11-01) in the context of an evaluation of ore potential, which concluded that in an area south-west of the Forsmark site (Figure 1), a felsitic to metavolcanic rock has potential for iron oxide mineralisation (Lindroos et al., 2004). The mineral deposits were assessed to be not worthwhile for exploitation, under present economic circumstances. However the possibility of mining becoming feasible at some future date was considered.

SKB's consideration of this scenario did not consider any specific design, based on an argument that under current mining standards, a mine exploiting the mineralisation would not be feasible. Possibilities mentioned could range from a quarry or open-cast mine with depth from tens to hundreds of metres, or for an (underground) mine, depth of a thousand metres or more.

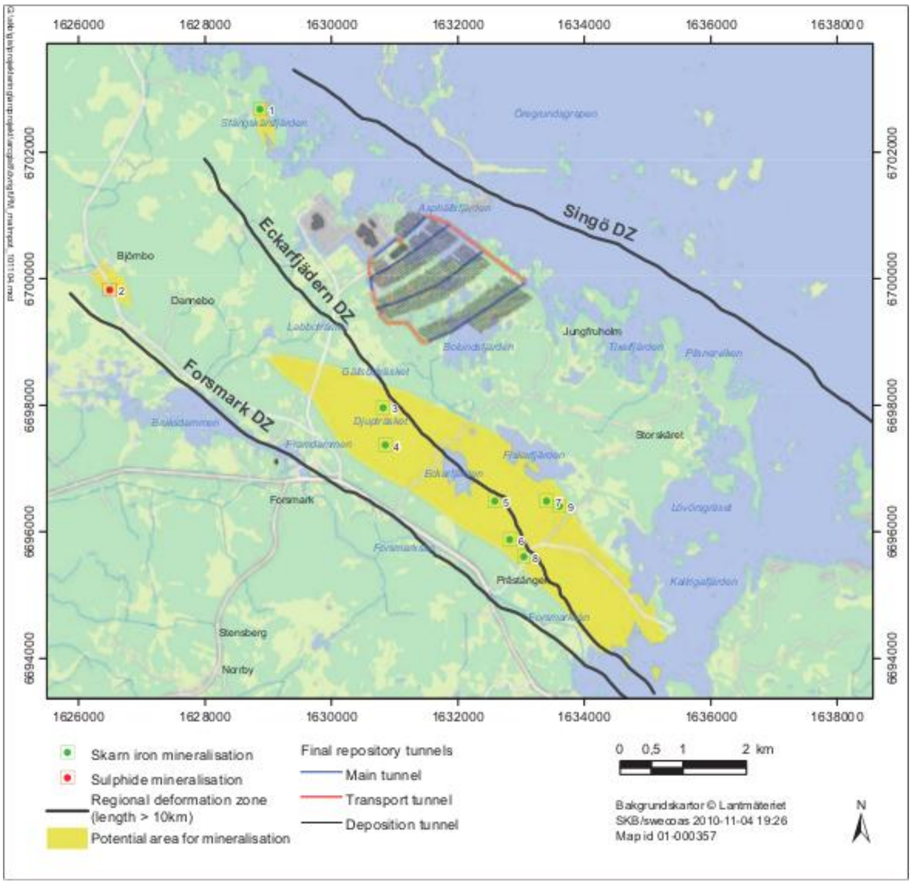


Figure 1: Map showing the areas on the surface that are judged to have some exploration potential for mineral deposits ((SKB TR 11-01, Figure 14-4; also Figure 6-5 in the FHA report).

SKB argues (TR-10-53, p. 61-62 and TR-11-01, p. 755) that the impacts of a mine extending to the same depth as the repository, and located 1 to 1.5 km from the closest part of the repository, would be minimal. This assertion is based on an observation that modelled drawdowns in simulations of an open repository (Mårtensson and Gustafsson, 2010, discussed here in Section 2.1.3), in directions west of the repository, are limited due to the low hydraulic conductivity of rock around the repository. SKB states that “this constraining hydraulic condition is valid also for a potential future mine outside the tectonic lens.”

2.1.2. Scenarios involving an unsealed or incompletely sealed repository

SKB's treatment of scenarios involving an unsealed or incompletely sealed repository is introduced in SKB TR-11-01 (p. 744). The case selected for analysis represents an incompletely sealed repository rather than an unsealed repository, which is justified by the premise that the repository will be developed in stages, such that deposition tunnels are successively filled with canisters and then backfilled and sealed as soon they are filled. SKB argue that “abandoning the repository in the middle of this process is unlikely because this would mean that canisters are left at the surface where they would constitute a larger risk than if emplaced in the repository.”

Therefore for analysis of a case in which the repository is abandoned, SKB assume that this occurs after all canisters are deposited and all deposition tunnels backfilled and sealed, but all other repository volumes are still open. SKB's treatment of this case is outlined in the following paragraphs.

Incompletely sealed repository

Only one situation of an unsealed or partially sealed repository has been evaluated, this being the situation in which all canisters are deposited and all deposition tunnels have been backfilled and sealed, but other repository openings are left open (Figure 2).

In the analysis of this case (TR-11-01, p. 757) the starting point is that the when the plug is lost from a given deposition tunnel, the plugs are also lost from neighbouring tunnels. This assumption limits the volume that is available for backfill to swell into the openings that have not been backfilled, and in turn limits the extent and degree of density reduction for the backfill.

The quantitative analysis of the backfill expansion is reportedly given in Section 22 of Åkesson et al. (2010). This report has not been evaluated as part of the present review.

On p. 757 of TR-11-01, SKB briefly discuss the alternative case in which the plug in one tunnel fails but the plug in a (singular) neighbouring tunnel does not. They note that such a situation will allow a larger volume for backfill to expand into, and hence the length of deposition tunnel over which backfill drops below the allowable density will be greater than for the quantitatively analysed case.

SKB speculate that this could lead to “a few additional deposition holes” that experience a backfill with a density below the acceptance criteria. However they state that “the exact number of such deposition holes is not important for the approach selected for analysis of the dose consequences of this case.”

From SKB's brief discussion of this situation (TR-11-01, p. 757), it is not clear as to whether they have consider the case in which the plug for just one deposition tunnel fails far in advance of the plugs for all of its neighbours.

The consequences for canister corrosion by oxygen dissolved in the water in the open tunnels in the repository were assessed by means of simple calculations, based on the assumption that the water in the backfilled deposition tunnels above a deposition hole is saturated with dissolved oxygen, and that oxygen reaches the canister lid by by diffusion through a 1.5 m thickness of bentonite buffer (TR-11-01, p. 757-758; TR-10-53, p. 69-70 and Appendix B). The assumption that the buffer is fully saturated with oxygen is regarded as pessimistic provided that transport of oxygen along the deposition tunnel is by diffusion without advection.

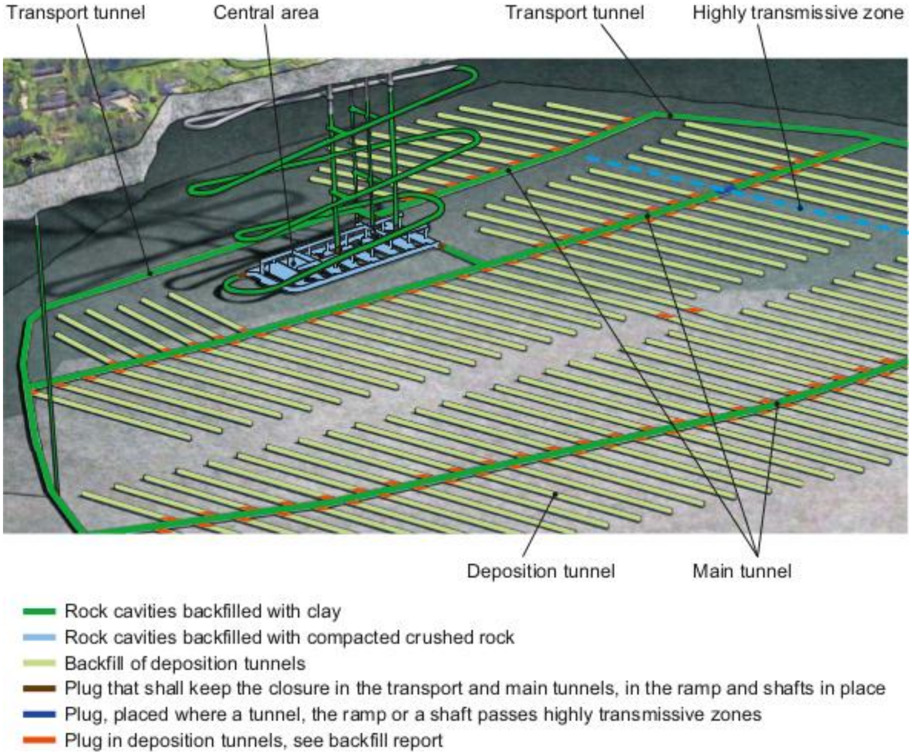


Figure 2: Reference design for repository closure. For the case of incomplete closure it is assumed that only the deposition tunnels are backfilled and plugged towards the main tunnels, and the darker green tunnels are left open (based on SKB TR-10-53, Figure 6-6).

Groundwater flow to a partially open, abandoned repository was evaluated using a numerical model by Bockgård (2010). The analysis makes use of the DarcyTools model of Svensson and Follin (2010) which uses an equivalent-continuum representation of the bedrock. The following changes are introduced in comparison with the model of Svensson and Follin (2010):

- The flow-wetted surface of the bedrock was specified for sub-domains of the model according to the specification of Vidstrand et al. (2010).
- The size of grid cells at the tunnel walls of the repository was reduced (except for deposition tunnels and deposition holes which are considered to be backfilled);
- No grouting was simulated (consistent with a future situation in which grout has been degraded);
- Hydraulic and transport properties of backfilled repository parts (hydraulic conductivity, kinematic porosity, and flow-wetted surface) were set according to the reference closure as specified by Joyce et al. (2010);
- The density of the groundwater was fixed to fresh-water density, i.e. density variations were ignored;

- Due to the constant-density assumption, the head at the sea bottom was specified corresponding to fresh water density rather than corresponding to the salinity of the Baltic Sea.

- Tunnels treated as open or having low flow resistance in the abandoned repository were simulated using internal specified-head boundaries in the tunnels.

- For the glacial simulation cases, a specified-head boundary condition of 220 m was applied at the top surface of the model.

The model was applied to two different climate situations: a temperate climate with present-day boundary conditions, and a generic future glacial situation with the ice front above the repository. For each of these situations, calculation cases were carried out both for a partially open repository and for the reference case with a closed repository, resulting in a total of four calculation cases.

The required hydraulic properties for the bedrock (hydraulic conductivity and kinematic porosity) were calculated from the same stochastic DFN model produced by Joyce et al (2010), but using the upscaling methodology in DarcyTools as was used by Svensson and Follin (2010). The flow-wetted surface was assigned for each fracture domain and depth interval following the specification in Vidstrand et al. (2010).

Backfilled tunnels were simulated by assigning a hydraulic conductivity of 10^{-10} m/s and porosity of 0.45 to the grid cells representing the backfilled volumes. Backfilled deposition holes were assigned the same values as for the deposition tunnels.

For the upper parts of the ramps and shafts (above -200 m elevation), for which the reference specifications indicate a high hydraulic conductivity $K = 10^{-1}$ m/s, a constant-head boundary condition equal to that at the surface of the model was used on the grounds that the hydraulic gradient would be negligible. For the central area tunnels, for which the reference design implies $K = 10^{-5}$ m/s, a slightly lower value $K = 10^{-7}$ was used to avoid numerical stability problems in the flow solution, and based on previous studies indicating that this would not affect results for tunnels closed at both ends, in a system controlled by the much less conductive rock mass.

The hydraulic role of open tunnels was scoped using the EPANET 2 pipe network model (Rossman, 2000). Results indicated that, for present-day conditions, head losses along the open portions of the tunnel system would be negligible, so use of constant-head boundary conditions equal to the drainage level of these tunnels was justifiable as a simplification to allow stable numerical solutions.

However for glacial conditions, the head losses along tunnels and in bends, tunnel crossing etc. would be significant. Therefore the pipe network model was used to calculate the head distribution in the tunnels for this case. The flow through the tunnel system at repository level for this case was estimated to be about 250 m^3/s. The head distribution in the tunnel system for this situation is shown in Figure 3. These heads were then applied as specified heads along the open tunnels in the DarcyTools model of the partially open repository in the glacial situation.

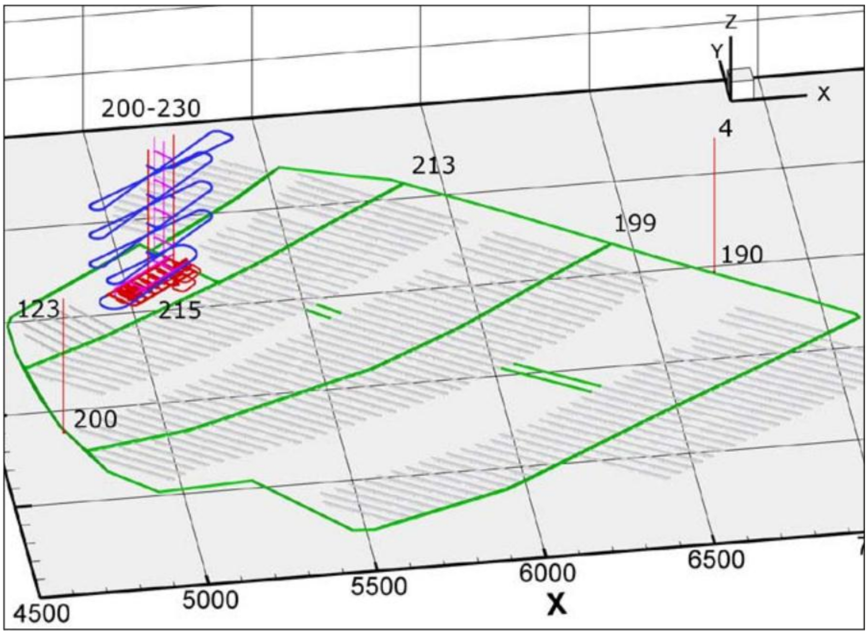


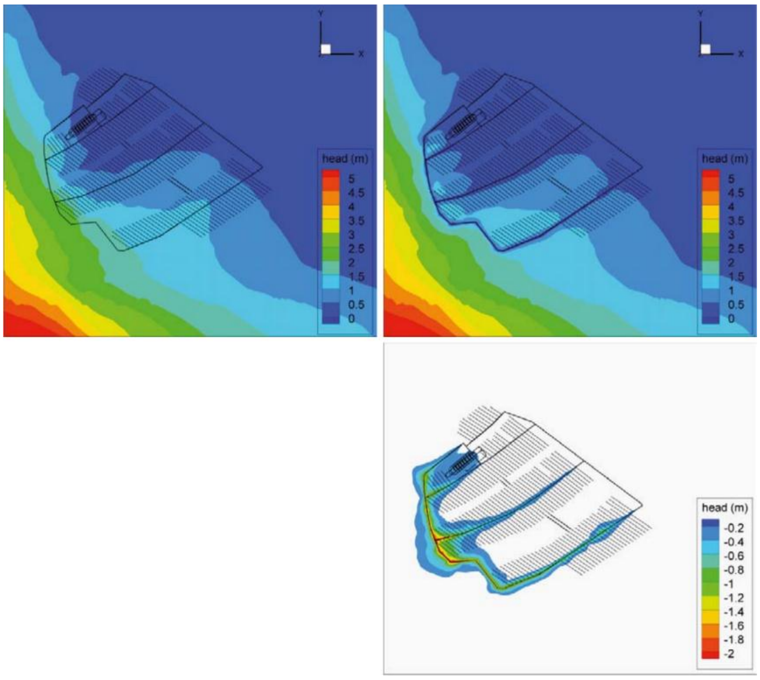
Figure 3: Schematic illustration of the head distribution (in meter above sea level) in the open tunnel system for the glacial case calculated by EPANET 2 (from SKB R-10-41, Figure 3-3).

The resulting head distributions at the repository level are shown for the two climate situations in Figures 4a and 4b, in each case comparing the heads for the reference case with the case of an unsealed, partially open repository. It can be seen that for the temperate case, the influence on head gradients within the repository is comparatively small, whereas for the glacial case, the open tunnels produce high head gradients between the open transport tunnels and the nearest portions of the deposition tunnels.

The calculated flow fields for each case, together with particle tracking, were used to obtain cumulative distribution functions (CDFs) of performance measures including Darcy flux at the deposition positions, advective travel times, and flow-related transport resistance (F-factor), for the set of possible deposition positions along the tunnels. The methods used for this part of the modelling are essentially identical to those used by Vidstrand et al. (2010) for calculating flow-related performance parameters for the evolution of the reference-case repository.

The most important performance measures for safety assessment are the Darcy flux (which is closely related to the equivalent flowrates through deposition holes that affect the potential for buffer erosion and canister corrosion as well as transport from failed canisters) and the transport resistance (F-factor). From Figure 5 it can be seen that the open-repository case has only a minor effect on Darcy flux for the temperate case. However for the glacial case an open repository leads to an increase of nearly half an order of magnitude in the CDF.

(a)



(b)

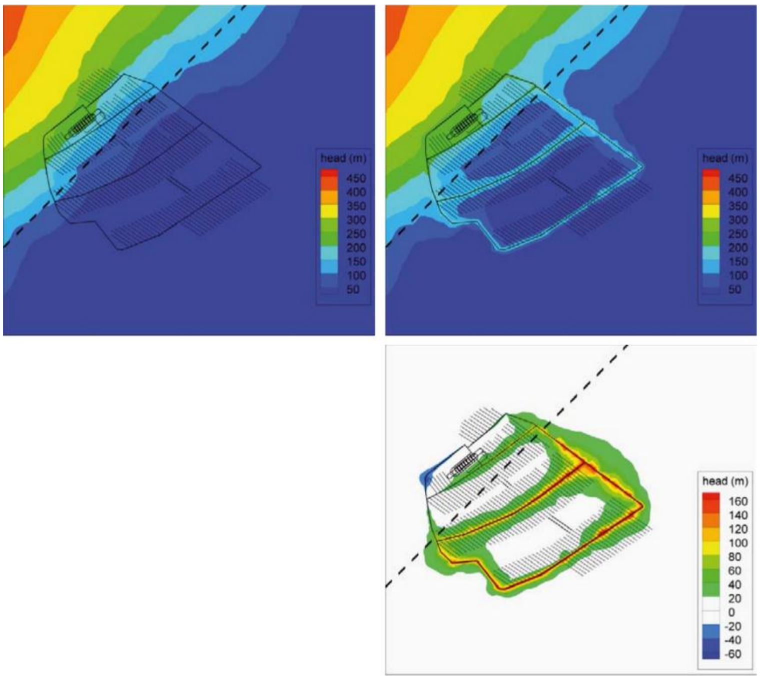


Figure 4: Hydraulic head field at repository depth (Z = –465 m RHB 70) during (a) temperate conditions and (b) glacial conditions. For each set of conditions, heads are shown for the reference closure case at upper left, for the open tunnel case at upper right, and the change in hydraulic head caused by the open tunnels is shown at lower right. The datum level for head is 0 m RHB 70 (from SKB R-10-41, Figure 4-1 and Figure 4-13).

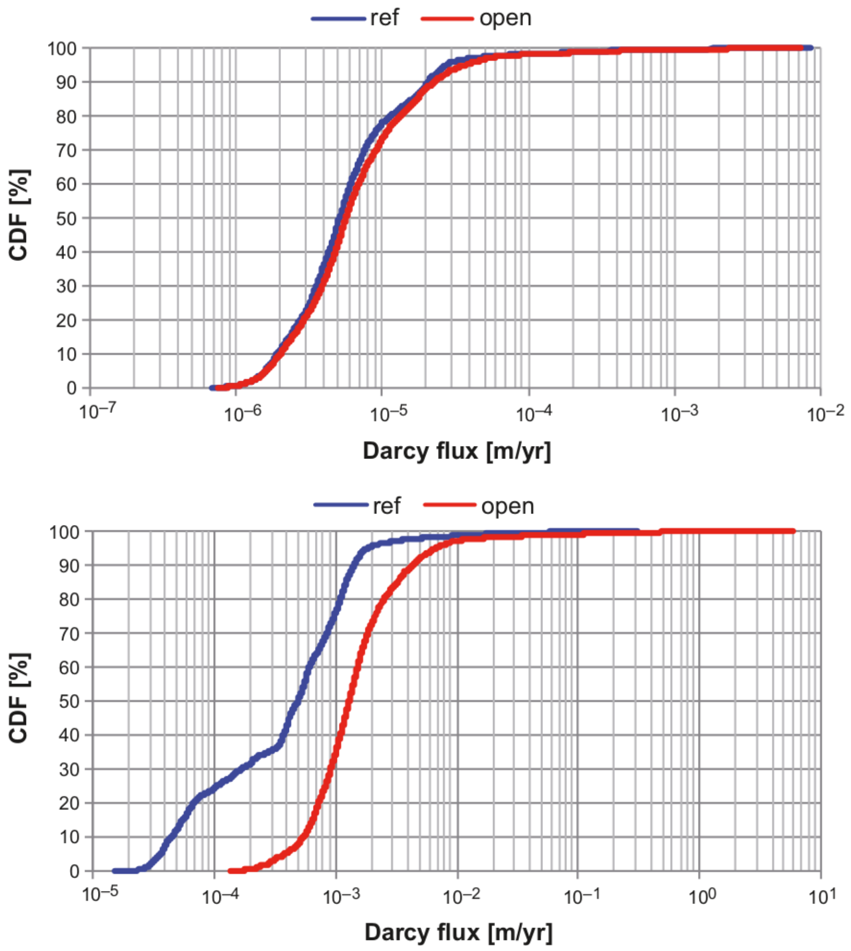


Figure 5: Cumulative density function of simulated Darcy flux at the 6,916 deposition hole positions (top) during temperate conditions and (bottom) for glacial conditions. In each plot the results for the reference closure case are shown in blue and those for the open tunnel case are shown in red (from SKB R-10-41, Figures 4-9 and 4-20). Note that the horizontal scales are different.

For both climate situations, the open-repository case leads to a reduction of transport resistance by up to half an order of magnitude (Figure 6). The dashed line in Figure 6 indicates the distribution of transport resistance for the fraction of particles that reach the surface at least partly by way of open tunnels. This line coincides with the overall distribution for low values of F, but diverges for higher values.

This implies that all of the low-F transport paths below 10^6 yr/m make use of the tunnel system. It does not necessarily imply that particles released from positions with higher F values do not travel through the tunnel system, but travel through the tunnel system becomes less prevalent for higher-F positions.

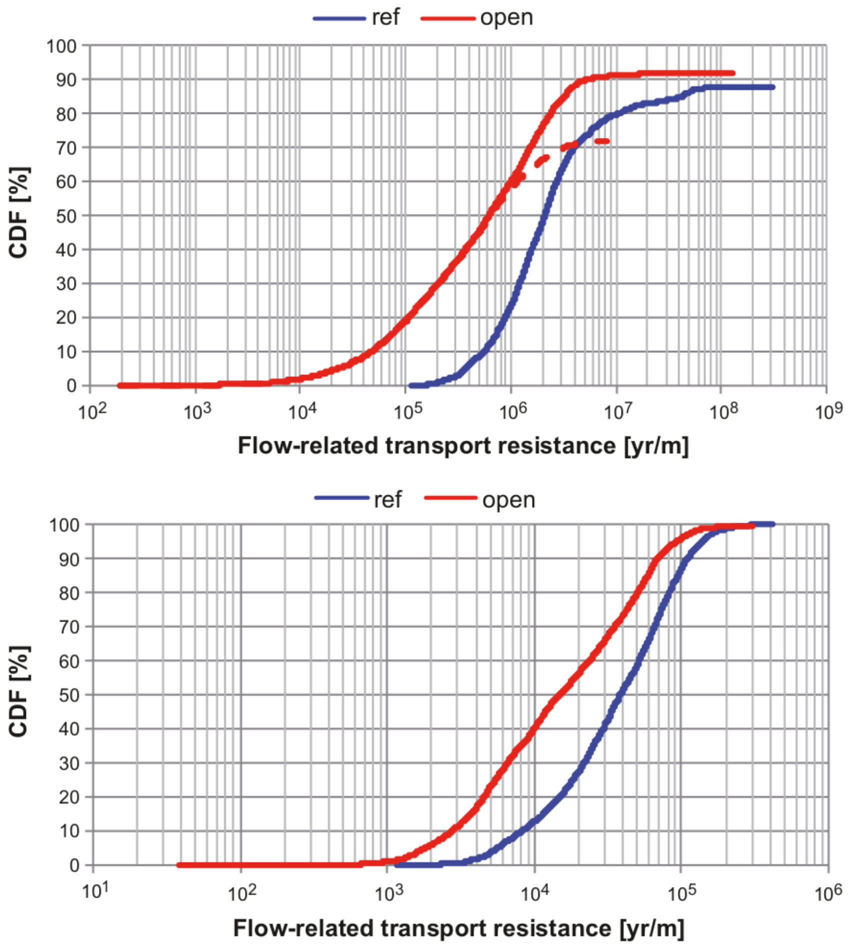


Figure 6: Cumulative density function of simulated flow-related transport resistance (F-factor) for particles released at the 6,916 deposition hole positions during (top) during temperate conditions and (bottom) for glacial conditions. In each plot the results for the reference closure case are shown in blue and those for the open tunnel case are shown in red. For the temperate case, the solid red line represents all particles that reached surface and the broken red line represents the fraction of these particles that reached the surface at least partly via open tunnels (from SKB R-10-41, Figures 4-12 and 4-23). Note that the horizontal scales are different.

2.1.3. Hydrogeological effects of an operating repository

Hydrogeological effects of an open repository were analysed by Mårtensson and Gustafsson (2010; SKB R-10-18). This analysis was primarily aimed to support the Environmental Impact Assessment (EIA) that was part of the permit application according to the Environmental Code, rather than as part of the safety assessment. However as noted above, some result are referred to in SKB's assessment of future human actions that involve mines, tunnels, or other excavations in the vicinity of the proposed repository.

The analysis makes used of a suite of modelling tools that were previously used in the evaluation of surface hydrology and coupling to bedrock hydrogeology, for the Forsmark site-descriptive modelling (SDM). The following coupled tools were used:

- MIKE SHE (DHI, 2010a): simulates water flows from rainfall to river flow, including overland flow, vertical flow through the unsaturated zone in Quaternary deposits, and 3D flow in the saturated zone;
- MIKE 11 (DHI, 2010a): simulates flow through networks of rivers and surficial channels;
- MOUSE (DHI, 2010b): models inflow into and flow through underground pipe-like conduits, taking into account leakage from groundwater.

The saturated zone is represented in MIKE SHE as a heterogeneous equivalent porous medium (ECPM) continuum.

The network of tunnels in the repository is based on the Forsmark D2 layout (Version 1.0). The tunnels are represented as linked pipes. Geometrical details are given as tables in Section 4.3.1of SKB R-10-18. Deposition holes (whether utilized or abandoned and backfilled based on deposition-hole acceptance criteria) are not included in the representation.

The exchange flow from groundwater into a grouted tunnel as represented in the MOUSE module is calculated based on a simple formula that is consistent with steady-state radially-convergent flow (SKB R-10-18, p. 17, Eq. 2-4), idealizing the tunnels as circular cylinders, and considering the grouted zone to be of uniform thickness and hydraulic conductivity. Inflow of water to vertical shafts could not be represented explicitly in the coupling between MIKE SHE and MOUSE, so inflow of water to the shafts is calculated in MIKE SHE only, using equivalent assumptions regarding radially-convergent flow and properties of the grouted zone.

The SDM version of the model (Bosson et al., 2008) was updated:

- to refine the bedrock hydrogeological portion of the model of the bedrock using hydraulic conductivity and specific storage coefficient values as calculated from the CONNECTFLOW model of Joyce et al. (2010),
- to increase the vertical and horizontal extents of the model domain,
- to include a representation of the SFR (final repository for short-lived radioactive waste), and
- to include the subsurface-drainage system at the nearby nuclear power plant.

The modelled area (Figure 7) covers 56 km^2 and generally corresponds to the Forsmark regional model area as considered for the bedrock hydrogeological modelling (Joyce et al., 2010). One main difference is that that the upstream (inland) boundary follows the surface-water divide towards the catchment of the river Forsmarksån rather than the inland boundary of the Forsmark regional model area. The bottom of the model is at 1200 m below sea level.

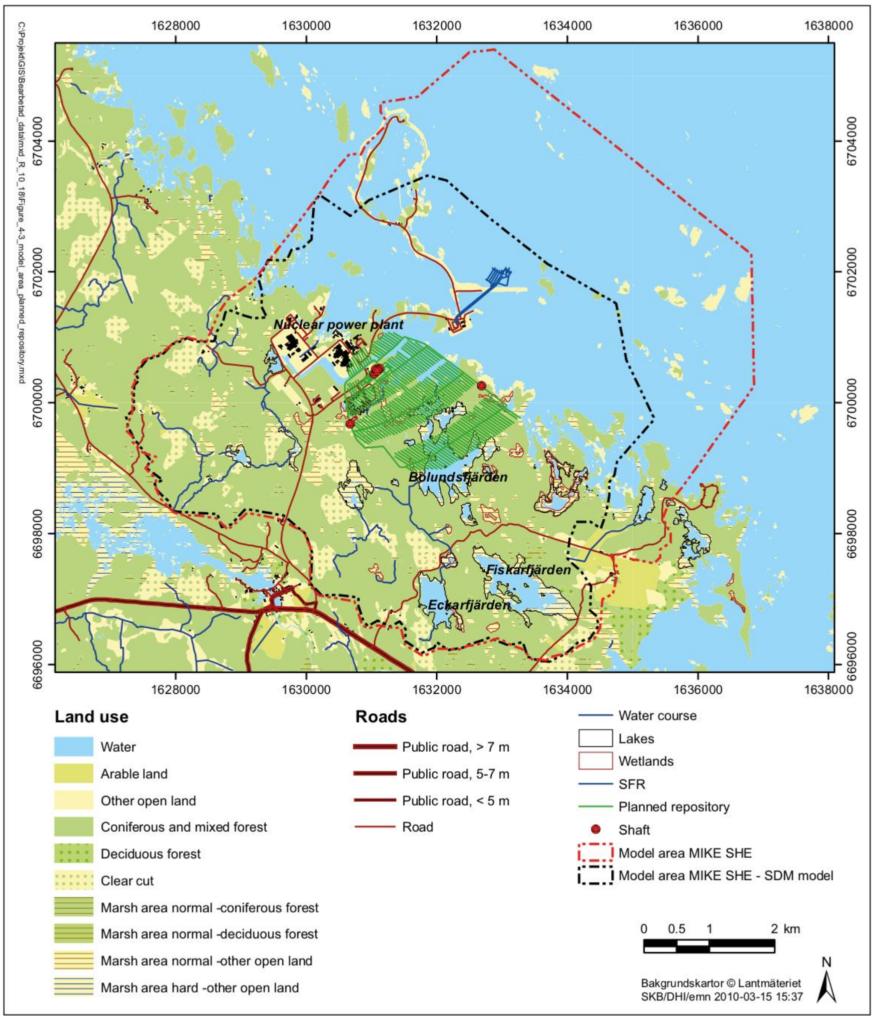


Figure 7: MIKE SHE model area, SFR and the planned repository (based on SKB R-10-18, Figure 4-4).

The updated model was calibrated with respect to measured groundwater levels in the Quaternary deposits and the bedrock, water levels in lakes, and stream discharges, as well as to the responses observed in monitoring wells during pumping in HFM14. The calibrated model was then used to simulate undisturbed conditions (i.e. prior to repository constructions) and compare with modelling results obtained for disturbed conditions (with the repository). The latter case requires representation of the underground tunnel network and effects of grouting.

As a first step in the calibration process, the time constant that governs the rate of subsurface drainage in the MIKE SHE model was increased by a factor of 5 compared with the previous model of Bosson et al. (2008), resulting in slower subsurface drainage and hence increased the surface-water discharge (SKB R-10-18, p. 35). Subsequent calibration starting from the properties calculated Joyce et al. (2010) led to the following changes in the bedrock hydraulic properties:

- The horizontal hydraulic conductivity was increased by a factor of 5 in the upper 200 m of the bedrock.

- The vertical hydraulic conductivity was decreased by a factor of 5 in the upper 200 m of the bedrock.
- The specific storage coefficient was set to $5 \cdot 10^{-8}$ m^{-1} in all bedrock layers.

Thus the upper bedrock was assessed to be even more strongly anisotropic than in the model of Joyce et al. (2010).

The modelling cases considered are specified in Table 4-5 of SKB R-10-18. These can be summarized as follows:

- No repository or SFR ("natural conditions");
- No repository but with extended SFR;
- Construction phase (low and medium grouting effectiveness);
- Fully open repository excluding main and deposition tunnels (medium grouting effectiveness);
- Development phase 3 (medium grouting effectiveness);
- Fully open repository (low, medium and high grouting effectiveness);
- Fully open repository with extended SFR (medium grouting effectiveness);
- Repository resaturated after closure (medium grouting effectiveness persisting)

where low grouting effectiveness implies a hydraulic conductivity $K_{grout} = 10^{-7}$ m/s for the grouted zone around each tunnel, medium grouting efficiency implies $K_{grout} = 10^{-8}$ m/s, and high grouting efficiency implies $K_{grout} = 10^{-9}$ m/s . The case of an extended SFR reflects a proposal to extend the existing SFR which is being considered as a separate license application by SKB. Two additional "reference" cases are included for checking the model results.

The modelling results for undisturbed conditions as presented in Chapter 6 of SKB R-10-18 are similar to those that were produced using the earlier version of this model for SDM-Site Forsmark (Bosson et al., 2008). The calculated results for runoff when compared with data for 2006 (SKB TR-10-18, p. 47-48) give a generally good match in terms of runoff dynamics, although spring peak is overestimated and the mid-autumn response after a long dry period in summer is too slow.

The predicted areas of recharge and discharge under present-day conditions (Figure 8) are characterized by upward flow in the vicinity of and below the lakes, and to a lesser degree topographical depressions at the ground surface, and strong downward flow in the areas around SFR and the nuclear power plant, due to the inflow to SFR and the subsurface drainage below the power plant. The authors state (but do not present results to show) that for natural conditions without groundwater diversion at these facilities, there is no downward flow in the bedrock in these areas.

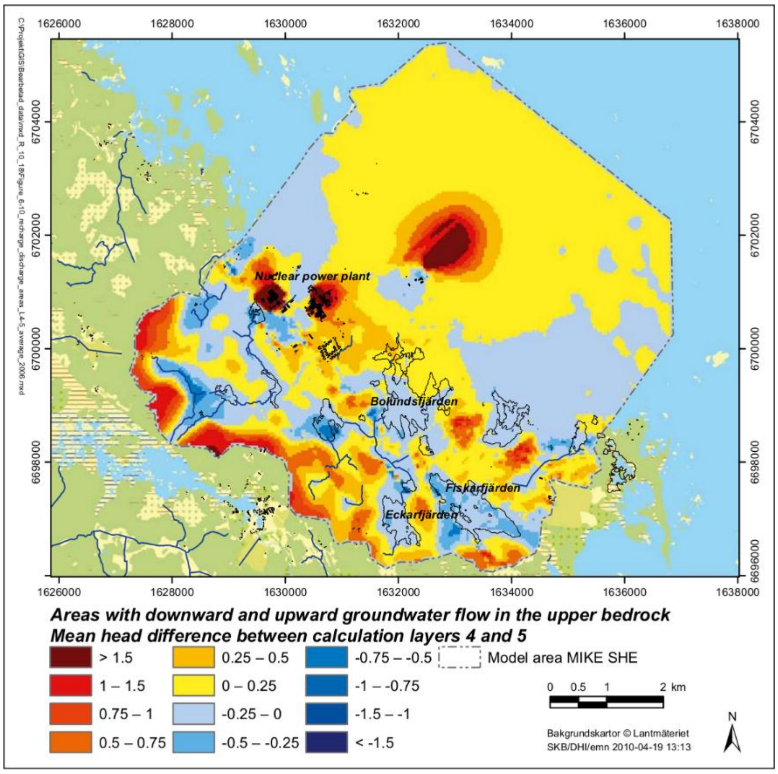


Figure 8: Calculated annual average hydraulic-head differences (m) between two computational layers in the upper part of the bedrock, showing areas with downward and upward groundwater flow in the upper part of the bedrock. Blue colours indicate upward flow and yellow/red colours indicate downward flow for present-day conditions. (From SKB R-10-18, Figure 6-10).

Modelling results for disturbed conditions (with the repository) indicate that the magnitude and the geographical extent of the drawdown for the groundwater table (Figure 9) will be smaller than for the drawdown of hydraulic head in the bedrock (Figure 10). The influence area for the groundwater-table drawdown mainly coincides with locations where Quaternary deposits are in contact with high-conductivity fracture zones. Otherwise the low hydraulic conductivity of the deeper bedrock in relation to the surficial deposits and shallow bedrock apparently limits the effects of the facility on the water table. Lower grouting effectiveness (K_{grout} = 10^{-7} m/s) as discussed in Section 7.5.3 of SKB R-10-18 leads to somewhat higher drawdowns of the water table, but with a similar spatial pattern controlled by the high-conductivity fracture zones.

For the hypothetical case of a fully open repository, the model-calculated inflow is in the interval 15–47 L/s, depending on the assumed level of grouting effectiveness. The associated influence area for the groundwater-table drawdown (defined as the area with annual average drawdown exceeding 0.3 m) covers 1.4 km^2 for K_{grout} = 10^{-7} m/s (low grouting effectiveness) and less than half of that for K_{grout} = 10^{-9} m/s. (high grouting effectiveness).

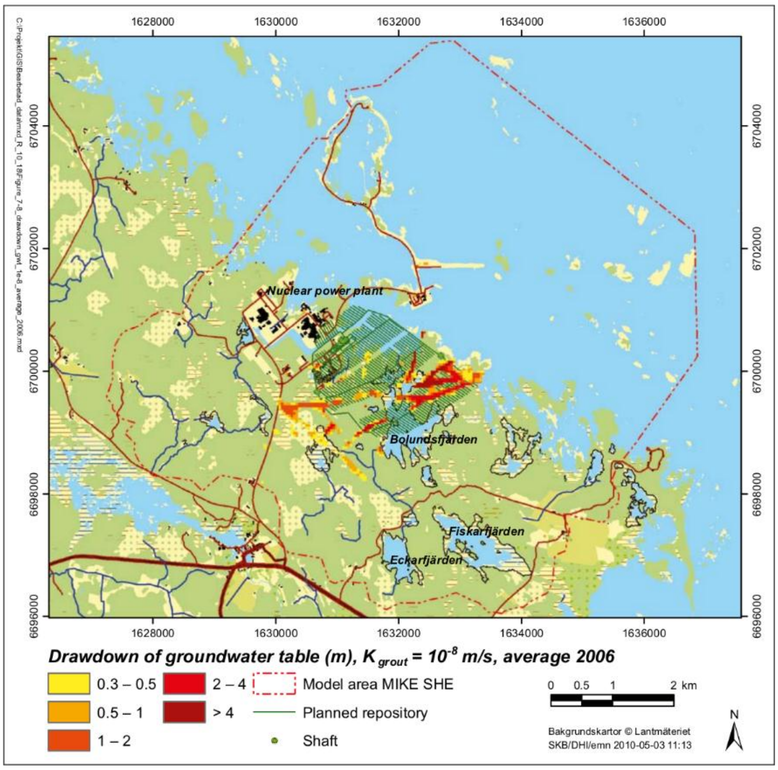


Figure 9: Calculated groundwater-table drawdown, medium grouting effectiveness (K_{grout} = 10^{-8} m/s). Areas with less than 0.3 m drawdown are left in the same color as the base map. (From R-10-18, Figure 7-16).

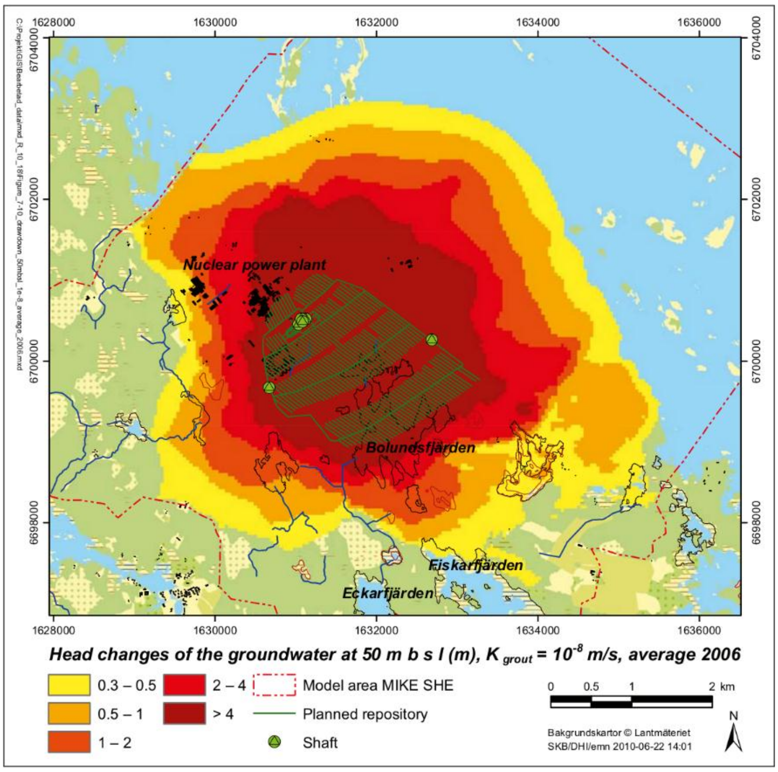


Figure 10: Calculated drawdown of hydraulic head at the level 50 m below sea level, medium grouting effectiveness (K_{grout} = 10^{-8} m/s). Areas with less than 0.3 m drawdown are left in the same color as the base map. (From R-10-18, Figure 7-18).

Sensitivity analyses (described in Chapter 8 of SKB R-10-18) were carried out to test the effects of:

- Reverting to the values of hydraulic conductivity and specific storage for the bedrock as calculated by CONNECTFLOW, without the adjustments from the MIKE SHE calibration (Case *BRO-HV-Ss*);
- Reverting to the values of hydraulic conductivity as calculated by CONNECTFLOW, but applying a constant value of specific storage $S_s = 5 \times 10^{-8}$ m^{-1} in all bedrock layers as in the calibrated model (Case *BRO-HV*);
- Increasing the horizontal hydraulic conductivity and decreasing the vertical hydraulic conductivity of the upper bedrock by a further factor of 2 compared with the calibrated model (Case *BR-HV*);
- Applying specified-head rather than no-flow boundary conditions on the vertical, on-shore boundaries of the model (Case *BR-boundary*);
- Adjusting the parameterisation of the uppermost 20 m to match that used in a related study using DarcyTools by Svensson and Follin (2010) (Case *Darcy-20m*).
- Performing explicit calculations for each grid cell in the unsaturated zone, rather than using a lumped approximation for cells with similar soil columns (Case *UZ-all*);
- Increased sea level (by 0.56 m), also using the explicit approach for grid cells in the unsaturated zone (Case *Sealevel-high*).

The results indicate that neither groundwater inflow to the repository nor the size of the area over which the water table is influenced are very sensitive to the hydrogeological properties of the upper 200 m of the bedrock and the boundary conditions (including the sea level). However the influence area is somewhat sensitive to the method for calculating water flow in the unsaturated zone, and also to the specific model for hydrogeological properties in the upper 20 m of the model domain.

The planned extension of the SFR is predicted to have at most a very limited impact on the inflow to the repository or on the groundwater table, compared to a situation with the repository and the present SFR layout.

A simplified approach was used for modelling of the backfill saturation and the groundwater-level recovery subsequent to the operational phase of the repository. As described in Appendix 4 of SKB R-10-18, the pore volume of the backfill is represented in a lumped fashion as a cylindrical void in the centre of the pipe segments that represent the tunnels of the repository, and the remaining solid portion of the backfill is effectively modelled as a sealing layer, inside of the grouted layer, with hydraulic conductivity based on the backfill properties. Resaturation is considered to take place until the cylindrical void is filled. The pore volumes of the bentonite buffer in deposition holes and in tunnel plugs are not taken into account.

Simulations of resaturation using this model by Mårtensson and Gustafsson (2010, p. 117) developed problems with numerical instability after 10.5 months, at which point the repository was 66% saturated. Based on this they projected that full saturation would be achieved after 14.5 months.

The time for full recovery of the groundwater table was then calculated by applying the groundwater levels and heads from the resaturation model after 10.5 months, to a model in which the repository was entirely removed. After two years (Figure 11) the residual influence area is approximately 20% of the influence area at the start of the recovery. Six years after full saturation (Figure 12) the influence area is limited to an area between the nuclear power plant and Lake Bolundsfjärden. The authors suggest that a few more years would be required for the hydraulic-head at repository level compared to the recovery of the groundwater table, although this was not directly demonstrated.

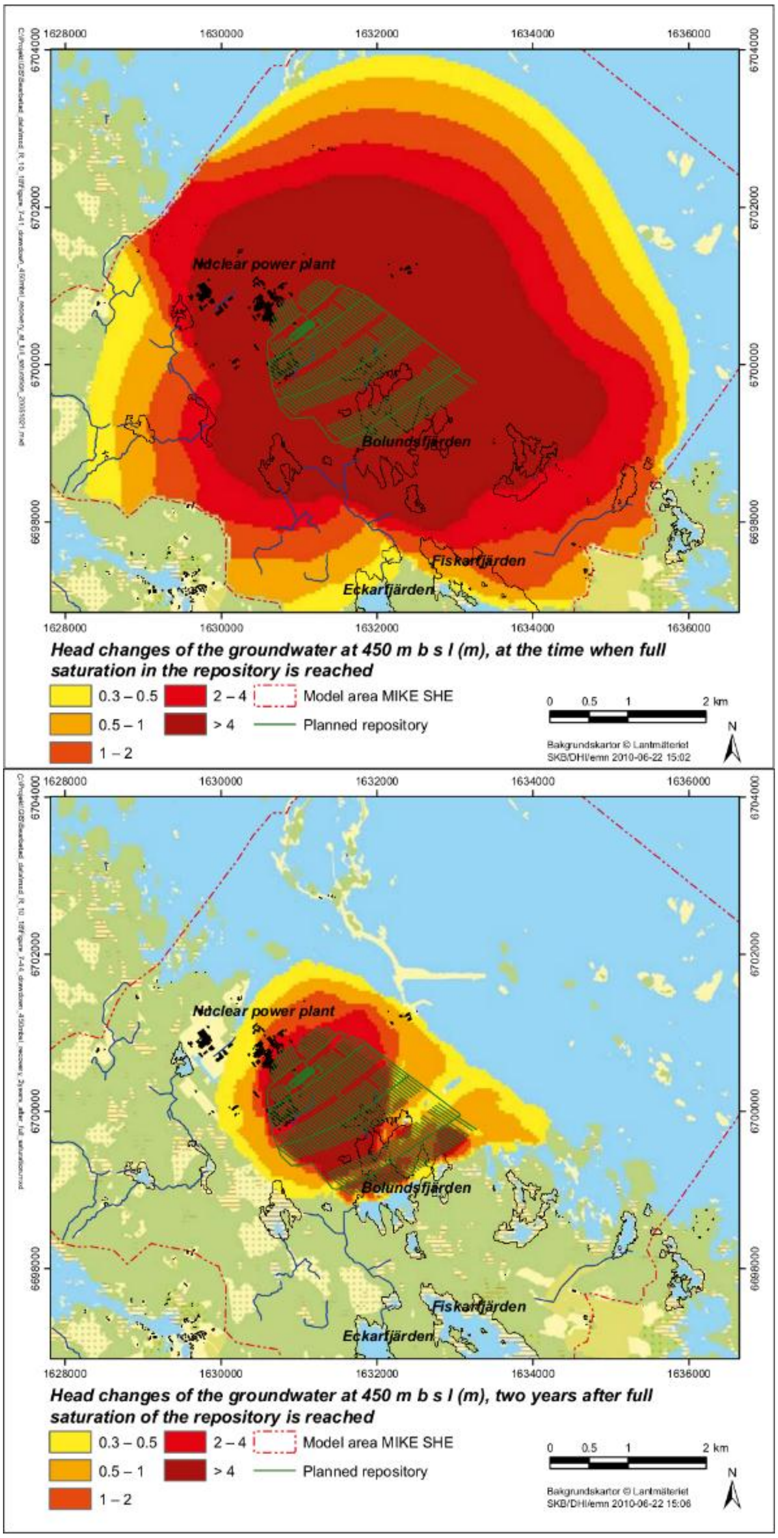


Figure 11: Residual hydraulic-head drawdown at the level 450 m.b.s.l. (top) at time of full backfill saturation, and (bottom) two years after full saturation, and (c) six years after full saturation (from SKB R-10-18, Figures 7-51, 7-52 and 7-53).

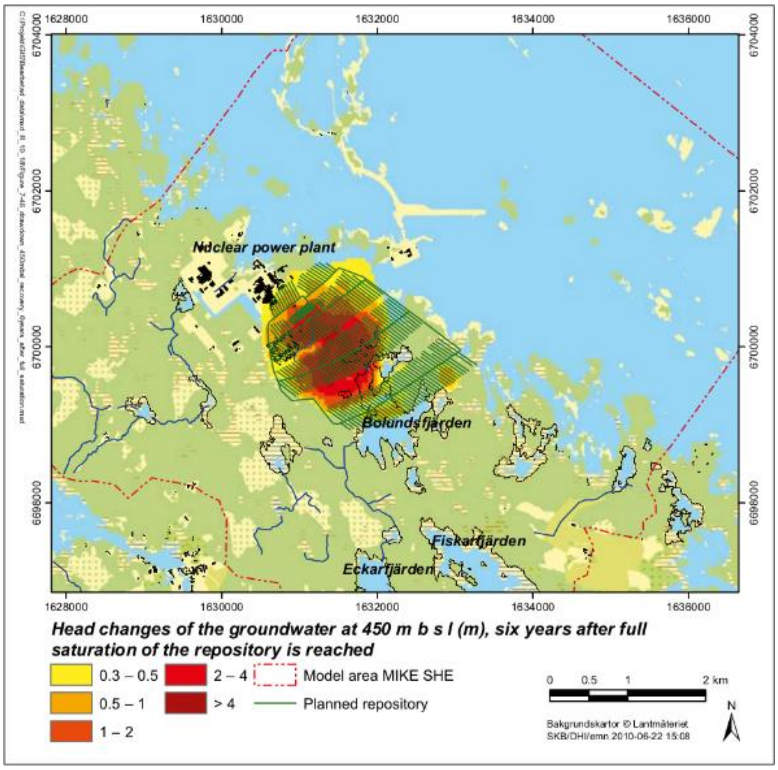


Figure 12: Residual hydraulic-head drawdown at the level 450 m.b.s.l. six years after full saturation (from SKB R-10-18, Figures 7-51, 7-52 and 7-53).

2.2. Motivation of the assessment

Future human actions and their impact on the repository are evaluated separately from SKB's analysis of the main scenario (reference evolution), and are not included in the summation of risk. The scenarios involving future human actions to some extent are to be regarded as illustrative rather than likely scenarios. Due to the largely unforeseeable range of possibilities concerning future human societies that could occupy the Forsmark area in the future, their level of technical development, and needs in terms of natural resources and landscape utilization, the chosen FHA scenarios are to be regarded as illustrative rather than comprehensive.

For these reasons, the quantitative demands on the analysis of FHA scenarios are not as stringent as for the reference evolution scenario. However there is still a need to ensure that the FHA scenarios have been evaluated with a sufficient degree of rigour to support their use in the safety case.

This review thus focuses mainly on whether the results of hydrogeological calculations concerning FHAs are reasonable in view of their application in subsequent consequence analysis and safety assessment.

2.3. The consultant’s assessment

This assessment is structured within the same framework as SKB's presentation in the FHA and SR-Site main report, focusing on the two main categories of scenarios related to future human actions:

- Scenarios related to a sealed repository, and
- Scenarios related to an unsealed or incompletely sealed repository.

The hydrogeological modelling of an open repository by Mårtensson and Gustafsson (2010) and of an abandoned, partially open repository by Bockgård (2010) are discussed within the context of their application to scenarios within these categories.

2.3.1. Assessment of sealed-repository scenarios

The analysis of scenarios involving a sealed repository rely only indirectly on the hydrogeological modelling of an open, operational repository and its subsequent resaturation after backfilling, as carried out by Mårtensson and Gustafsson (2010). This modelling study was primarily focused on providing information for biosphere modelling and assessment of the environmental impacts of an open repository. The model appears to have only been used for limited purposes in the overall safety assessment. Selroos and Follin (2010) discuss it only briefly in comparison with the model of Svensson and Follin (2010), as a model that entails a more detailed treatment of the Quaternary layers and surface hydrology. However, due to the more detailed treatment of the uppermost bedrock and regolith, and of surficial hydrology, the model is useful for the assessment of surface-groundwater interactions, including the effects of an operational repository and its resaturation.

Effects of an operational repository and resaturation

The report on hydrogeological modelling of an abandoned, water-filled partially open repository by Mårtensson and Gustafsson (2010) is straightforward and clearly written, including calibrations that give confidence in the model at least as a description of the surface hydrology and shallow bedrock hydrogeology response to perturbations.

The representations of the bedrock and backfilled repository sections are simplified in two important respects. First, the bedrock is modelled as a continuum – although using equivalent continuum properties upscaled from a discrete-fracture network representation, and thus equivalent to the simplification used by Svensson and Follin (2010). Second, the backfill is treated as a conductive layer on the inside of tunnels, rather than as an initially unsaturated porous-medium

The simplified treatment of resaturation by Mårtensson and Gustafsson (2010) does not take into account the details of unsaturated flow within the backfill as it recharges. As the hydraulic conductivity value used for the backfill is the saturated hydraulic conductivity, this may result in overestimating the rate at which the repository resaturates. Also as noted by the authors, the pore volumes of the bentonite buffer in deposition holes and in tunnel plugs are not taken into account. Furthermore the representation of the surrounding bedrock as a continuum may not adequately represent the effects of convergent flow that would be expected in an irregularly connected fracture network, or even more so in a sparse channel network. Thus it seems likely that the calculated times for resaturation are underestimated due to the modelling methods and simplifications.

The predicted groundwater recovery time of "a few years " as stated in the abstract of the report by Mårtensson and Gustafsson (2010) can be regarded as a misstatement, as the presented results show that recovery is incomplete after six years. A more reasonable description of the results would be around ten years.

The resaturation time of 14.5 months as estimated by Mårtensson and Gustafsson (2010) differs by two orders of magnitude from the resaturation time of 150 years for all tunnels in the DarcyTools model of Svensson and Follin (2010).

This significant discrepancy is not commented on by Selroos and Follin (2010). However they do compare the models in terms of the area of influence for drawdown of the water table. They argue that the area of influence predicted by Svensson and Follin (2010) may be too large by a factor of two due to the simplified treatment of the surface hydrology and near-surface hydrogeology, and therefore that the simulated changes in chemical composition around the repository are also overestimated. This argument was used as the basis for arguing that, in SR-Site "that the uncertainty in groundwater chemistry (salinity) during the excavation and operational phase does not need to be propagated to further analyses." (Selroos and Follin, 2010, p. 55).

Selroos and Follin (2010, p. 55) also argue that the inflows to an open repository, calculated using DarcyTools, are overestimates both due to use of the ECPM approach and because the MIKE SHE model (which also relies on an ECPM approach) indicates lower total inflows based on a more detailed model of surface and near-surface hydrology.

Considering the highly simplified representation of the open tunnels in the MIKE SHE model (i.e. uniform hydraulic conductivity related to different assumed levels of grouting effectiveness), and also for the backfilled/post-closure state, it is not clear that the MIKE SHE model results should be viewed as strong support for these arguments. The large difference in calculated resaturation times, between these two models, suggest that the representation of variably-saturated flow processes in the backfill may also be important. In addition, neither model includes a discrete representation of the inflow points in tunnels (either DFN or channel network).

The process of calibrating the near-surface portion of the MIKE SHE model led to a conclusion that the anisotropy in hydraulic conductivity (K_h/K_v) needed to be increased by a net factor of 25 in order to match surface water discharge data. This suggests that the Hydro-DFN representation of the upper bedrock which was used to produce ECPM values of hydraulic conductivity for these models is not well bounded, despite relatively strong data support for this portion of the bedrock, in numerous shallow boreholes.

The significance of neglecting chemical perturbations on the basis of the arguments mentioned above should be considered in the ongoing review.

Canister penetration by drilling

The evaluation of consequences of canister penetration by drilling makes only limited use of hydrogeological modelling results. The value used for well capacity is well-supported by direct measurements from the area above the repository.

The assumed magnitude of water flow through the deposition hole with the penetrated canister is based on consideration of the volumetric flows predicted by the base-case model of Joyce et al. (2010), and can be regarded as conservative if the deposition-hole criteria using either the FPC or EFPC are applied.

One non-conservative aspect however is that the model of Joyce et al. (2010) represents a situation in which flows and head gradients are regulated by the discharge path through bedrock to the surface. A borehole would be expected to reduce the resistance to flow along the discharge path, resulting in higher fluxes, but this does not seem to have been taken into account. In such a case, flow would still be regulated by the recharge path through the bedrock, even if the flow resistance of the borehole is negligible. Hence the consequences of neglecting the effect of a borehole short-circuiting the flow system are not likely to be worse than a factor of two increase in the calculated fluxes through deposition holes.

Rock facility in the vicinity of the repository

SKB cites the results of hydrogeological analyses of an abandoned, partially open repository (Bockgård 2010), in arguing that an abandoned tunnel at shallow depth would not significantly affect the magnitude of water flow at repository depth.

However the situation considered by Bockgård (2010) is a different hydrogeological situation, as it includes open (water-filled) tunnels at repository depth which are connected to the surface via shafts that have only a nominal resistance to flow. Although superficially this may seem to be a more extreme situation, the open transport tunnels may act as a “hydraulic cage” that partially shields the deposition tunnels from hydraulic gradients. This hydraulic-cage effect would not be present for the case of an abandoned tunnel due to a rock facility at shallow depth, and thus it would not mitigate any increase in the hydraulic gradient due to short-circuiting of discharge paths by a shallow tunnel.

A robust assessment of the consequences of a rock facility would require evaluating the consequences of an isolated tunnel short-circuiting the discharge path, at whatever depths can be considered feasible for such a facility. Because SKB has not presented such an analysis, this review needs to be based on simple reasoning. As the uppermost 150 m of rock are assessed as having very high hydraulic conductivity relative to the deeper bedrock, it seems unlikely that an open tunnel from a rock facility at shallow depth would significantly affect flows at repository depth. More significant effects could result from an open tunnel at greater depth.

SKB recognizes that upper 150 m of the bedrock would be an unfavourable location for a tunnel from an engineering point of view, but they do not present an analysis of the consequences of a tunnel at greater depths, where the bedrock would be more favorable from an engineering point of view. Their reason for excluding such a case from consideration is based on the observation that tunnels down to 50 m depth are more typical, based on current practices in Sweden, in which "the depth is generally as shallow as possible with regard to the geology and purpose of the facility." Considering the fairly rapid recent evolution of underground technology and the likelihood that future societies will find use for rock facilities at greater depths (as illustrated, for example, by recent research on CO_2 sequestration), it seems that a wider range of cases could have been considered, including tunnels or galleries closer to repository depth.

Mine in the vicinity of the Forsmark site

SKB's consideration of the mining scenario did not consider any specific design, based on an argument that under current mining standards, a mine exploiting the mineralisation would not be feasible. They argue that the impacts of a mine extending to the same depth as the repository, and located 1 to 1.5 km from the closest part of the repository, would be minimal. This assertion is based on an observation that modelled drawdowns in simulations of an open repository (Mårtensson and Gustafsson, 2010), in directions west of the repository, are limited due to the low hydraulic conductivity of rock around the repository. SKB states that "this constraining hydraulic condition is valid also for a potential future mine outside the tectonic lens."

The basis for this argument is somewhat unclear, as drainage to a nearby mine in more conductive rock, with higher storage capacity, is not obviously reciprocal to drainage to an opening in very tight rock. The drawdown cone from a mine in relatively conductive rock would presumably affect a larger area, particularly in the case of a deep open-cast mine that intersects one or several major deformation zones.

As noted above, the MIKE SHE model of Mårtensson and Gustafsson (2010) has significant discrepancies with the DarcyTools model of Svensson and Follin (2010), in terms of the area over which significant drawdown of the water tables is predicted. The MIKE SHE model also is based on the ECPM properties of just a single realization of the Hydro-DFN as provided by Joyce et al. (2010), so stochastic uncertainties governing the probability of a connective path between the repository and a hypothetical mine have not been explored.

An illustrative model would have given more assurance in the applicability of this argument. However, from general hydrogeological principles and considering the inferred very low permeability of the bedrock around the proposed repository, contrasting with higher permeability in the bedrock nearby, SKB's argument can be regarded as reasonable in general terms.

2.3.2. Assessment of unsealed-repository scenarios

The report on hydrogeological modelling of an abandoned, water-filled partially open repository by Bockgård (2010) is straightforward and clearly written. Despite that the model is limited by the assumption of an effective continuum representation for the sparsely fractured bedrock around the repository, the presentation of comparison cases using the same model, but with a sealed repository consistent with the reference evolution scenario, facilitates an evaluation of the consequences.

Only one situation of an unsealed or partially sealed repository has been evaluated, this being the situation in which all canisters are deposited and all deposition tunnels have been backfilled and sealed, but other repository openings are left open.

Therefore for analysis of a case in which the repository is abandoned, SKB assume that this occurs after all canisters are deposited and all deposition tunnels backfilled and sealed, but all other repository volumes are still open. They do not discuss the possibility that one deposition tunnel in use at the time of abandonment (for example, due to a security crisis) could be left unsealed and not completely backfilled.

In the analysis of this case (SKB TR-11-01, p. 757) the starting point is that that when the plug is lost from a given deposition tunnel, the plugs are also lost from neighbouring tunnels. This assumption limits the volume that is available for backfill to swell into the openings that have not been backfilled. This in turn limits the extent and degree of density reduction for the backfill.

Although assessment of the longevity of engineered barriers from an engineering perspective is outside the scope of this review, it seems likely that failure of the tunnel plugs will be distributed in time, rather than simultaneous. The inflow to backfilled tunnels is expected to be spatially variable according to the Hydro-DFN model, and hence the times required for the backfill to resaturate, for water pressure to build up against the seals, and various processes contributing to deterioration of the seals will also vary from one tunnel to the next. Further temporal variability in these processes can be expected due to the variable influence and longevity of grouting of water-bearing fractures or minor deformation zones that intersect the tunnels.

Thus it seems likely that the first deposition tunnel for which the plug fails will have a larger volume for backfill to expand into, than has been considered based on SKB's assumption that all seals fail simultaneously. Accordingly this tunnel will have a greater loss of backfill density, extending further along the length of the deposition tunnel, than SKB has considered in their quantitative analysis.

SKB's qualitative discussion of this situation (SKB TR-11-01, p. 757) is not clear as to whether they have considered the case in which just one deposition tunnel plug fails far in advance of the plugs for all neighbouring tunnels. The discussion only mentions “a” (singular) nearby tunnel for which the plug did not fail. No quantitative statements are given respecting the volume into which backfill could expand in such a case, nor is there any supporting evidence for how they reached the conclusion that only “a few additional deposition holes” would experience backfill with a density below the acceptance criteria.

However they state that “the exact number of such deposition holes is not important for the approach selected for analysis of the dose consequences of this case.” This statement deserves further evaluation.

In the discussion of uncertainties for the analysis of this situation (SKB TR-11-01, p. 760) SKB mentions that the friction angle used to calculate the expansion of backfill into unfilled repository openings is likely conservative. To some degree this may mitigate the consequences of what otherwise seems to be a non-conservative assumption, regarding the space available for expansion. However only one of these two assumptions – the one that can be regarded as conservative – is mentioned in the discussion of uncertainties.

This assumption may be relevant for assessing SKB's assertion that the boundary conditions used for assessing canister corrosion by oxygen are pessimistic because it is assumed that the water in the backfilled deposition tunnels above a deposition hole is saturated with dissolved oxygen, as this could not occur if transport of oxygen along the deposition tunnel is by diffusion without advection. This assumption could be realistic rather than pessimistic if the backfill from a single deposition tunnel can expand into a larger space in the transport tunnel.

3. The consultant’s overall assessment

The models of Mårtensson and Gustafsson (2010) and Bockgård (2010) are well described by the reports, and can be regarded as scientifically credible. However the representations of the processes that govern flow into tunnels in fractured rock leave doubt as to the representativity of the models.

In the case of the models of an abandoned repository by Bockgård (2010), this problem is assuaged by the presentation of comparisons between cases that represent the reference state, and cases in which the reference state is not fulfilled.

In the analysis of future human actions for the SR-Site safety case, SKB have placed minimal weight on the specific results from these models. Except for the case of an abandoned but party sealed repository as analyzed by Bockgård (2010), SKB's evaluation of FHAs related to hydrogeology is mainly based on qualitative arguments. Where specific modelling results are cited, these refer to models that were developed and applied for other hydrogeological situations.

Overall it must be concluded that SKB's hydrogeological analysis of FHAs, as presented in SR-Site, is only cursory. No hydrogeological models are presented that specifically demonstrate the consequences of subsurface facilities, mines, or inadvertent borehole penetration of the repository. The modelling studies that were reviewed as part of this assignment are only marginally relevant to the scenarios considered, other than the case of repository abandonment.

Additionally the modelling results that have been presented – and large discrepancies between different modelling approaches – leave questions regarding their representativity for the processes governing inflow into open or backfilled tunnels. These questions are pertinent, for example, for assessing the potential impacts of piping erosion. Improvement in this area should be expected, possibly as a licensing condition.

Overall, SKB's assessment of the hydrogeological aspects of FHAs is very limited, and omits at least a few scenarios that could be regarded as plausible for the foreseeable future. The results of this limited evaluation may be acceptable in view of the low probability that more significant events could occur, but further attention on this issue by SSM is recommended.

4. References

Bockgård, N., 2010. Groundwater flow modelling of an abandoned partially open repository. SR-Site Forsmark. SKB R-10-41, Svensk Kärnbränslehantering AB.

Bosson, E., Gustafsson, L-G., and Sassner, M., 2008. Numerical modelling of surface hydrology and near- surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-09, Svensk Kärnbränslehantering AB.

DHI Software, 2010a. MIKE SHE – User Manual. DHI Water, Environment & Health, Hørsholm, Denmark.

DHI Software, 2010b. MOUSE PIPE FLOW – Reference Manual. DHI Water, Environment & Health, Hørsholm, Denmark.

Joyce, S., Applegate, D., Hartley, L., Hoek, J., Simpson, T., Swan, D., Marsic, N., and Follin, S., 2010. Groundwater flow modelling of periods with temperate climate conditions – SR-Site Forsmark. SKB R-09-20, Svensk Kärnbränslehantering AB.

Löfgren, A. (ed.), 2010. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. SKB TR-10-01, Svensk Kärnbränslehantering AB.

Mårtensson, E., and Gustafsson, L-G., 2010. Hydrological and hydrogeological effects of an open repository in Forsmark. Final MIKE SHE flow modelling results for the Environmental Impact Assessment. SKB R-10-18, Svensk Kärnbränslehantering AB.

Rossman, L.A., 2000. EPANET 2 user's manual. EPA/600/R-00/057. U.S. Environmental Protection Agency, Washington, D.C.

SKB, 2010. Handling of future human actions in the safety assessment SR-Site. SKB TR-10-53, Svensk Kärnbränslehantering AB.

SKB, 2011. SR-Site main report. SKB TR-11-01, Svensk Kärnbränslehantering AB.

Selroos, J-O., and Follin, S., 2010. SR-Site groundwater flow modelling methodology, setup and results. SKB R-09-22, Svensk Kärnbränslehantering AB.

Svensson, U., and Follin, S., 2010. Groundwater flow modelling of the excavation and operation phases – SR-Site Forsmark. SKB R-09-19, Svensk Kärnbränslehantering AB.

Vidstrand, P., Follin, S., and Zugec, N., 2010. Groundwater flow modelling of periods with periglacial and glacial climate conditions – Forsmark. SKB R-09-21, Svensk Kärnbränslehantering AB.

Åkesson, M., Kristensson, O., Börgesson, L., Dueck, A., and Hernelind, J., 2010. THM modelling of buffer, backfill and other system components. Critical processes and scenarios. SKB TR-10-11, Svensk Kärnbränslehantering AB.

APPENDIX 1

Coverage of SKB reports

Table A1: Coverage of SKB reports

Reviewed report	Reviewed sections	Comments
SKB TR-11-01, SR-Site main report	Section 14.2	Focused on hydrogeological aspects
SKB R-10-18, Hydrological and hydrogeological effects of an open repository in Forsmark	All	
SKB R-10-41, Groundwater flow modelling of an abandoned partially open repository. SR-Site Forsmark	All	
SKB TR-10-53, Handling of future human actions in the safety assessment SR-Site.	All	Focused on hydrological and hydrogeological aspects.
SKB R-09-22 SR-Site groundwater flow modelling methodology, setup and results.	Sections 4.5 and 5.4.	Previously reviewed in full as part of hydrogeological review. Used here mainly to provide context for review of more detailed models.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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