ON THE SIMULATION OF SALINE INTRUSION FOR REPOSITORY PERFORMANCE ASSESSMENT

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Abstract

The objective of this paper is to assess the extent and duration of saline intrusion to a coastal nuclear waste repository located at depth in sparsely fractured Baltic Shield rocks. The underlying motive for the study is that long-term changes in the chemical environment associated with saline intrusion may affect the properties of the repository buffer zone material. The reconstruction used in this study of the hydrological conditions during the Holocene between 10,000 BP and today leads to the interpretation that the present occurrence of saline ground water reflects an ongoing but incomplete flushing of the Baltic Shield. The simulations of fifty years of dewatering followed by fifty years of resaturation suggest that the final interface between fresh and saline ground waters may be close to the conditions prior to the dewatering phase.

Introduction

Since the end of the 1970's, the Swedish Nuclear Fuel and Waste Management Company (SKB) has carried out a large number of studies at several study sites in Sweden. The investigations have been carried out from the ground surface and in boreholes down to depths of about 1,000 m. Moreover, a great deal of experimental work has been done at the Stripa mine within the framework of the international Stripa Project. The most recent large-scale project in Sweden is the construction of the Äspö Hard Rock Laboratory (HRL) in southern Sweden. The HRL provides excellent opportunities for a direct verification of the results of surface and borehole investigations by systematic observations from shafts and tunnels down to a depth of 450 m. In addition to the many laboratory and field experiments carried out by the international Task Force at Äspö, the conceptualization of ground water flow and mass transport through sparsely fractured crystalline rocks is also studied by means of numerical modeling.

This study treats the dewatering and resaturation phases associated with the construction, use and closure of a coastal nuclear waste repository located at depth in sparsely fractured Baltic Shield rocks. *Figure 1* shows a schematic cross section of the studied situation. The objective is to assess the extent and duration of saline intrusion for a set of reasonable geohydrological assumptions based on field investigations at the HRL. The underlying motive for the study is that long-term changes in the chemical environment associated with saline intrusion may affect the properties of the repository buffer zone material (bentonite).

Present-day depth-distribution of salt content in fluids residing the Baltic Shield rocks is not well known on the regional scale. For the purpose of this study, the work is therefore divided into two parts; the first part deals with model calibration and finding initial conditions for the second part, which deals with simulation of the dewatering and resaturation phases of a repository. The first part treats changes in the ground water conditions during the Holocene between 10,000 BP and today due to deglaciation and land upheaval, and the second parts treats an anticipated 50 year long period of dewatering followed by 50 years of resaturation.

Method and Limitations

The study uses the US Geological Survey computer code SUTRA (Voss, 1984). The reason for using SUTRA is its documented capability to simulate two-dimensional variable-density flow and mass transfer in saturated and unsaturated porous media under isothermal conditions. For example, Voss and Andersson (1993) used SUTRA in a related study that focused on the historical occurrence of saline ground water and regional flow patterns in the Baltic Shield during the Holocene coastal regression. The main difficulty with using SUTRA in this study, as well as in the study of Voss and Andersson (1993), is above all conceptual. Both studies address flow and transport problems through sparsely fractured crystalline rocks by using a continuum approach composed of several large zones of uniform properties. The homogeneity of each zone provides connection between any two points within a zone and flow is allowed along any pathway, whereas the actual heterogeneous fabric of sparsely fractured crystalline rocks restricts flow to distinct pathways, and hydraulic connections may not always exist between any two points.

The simulations of the dewatering and resaturation phases are approximate for several reasons. First, SUTRA cannot simulate the fully coupled variable-density problem of simultaneous heat transfer, multiphase flow and mass transport. Hence, neither the geothermal gradient nor any production of heat and gas at the repository are considered in this study while simulating the variable-density saline-intrusion problem. Second, the relationships generally considered to govern unsaturated flow are essentially unknown for sparsely fractured rock. The required relationships are the capillary head versus the saturation and the relative permeability versus the saturation. Third, the net change of the rock permeability close to a repository due to various underground activities such as blasting, excavation, grouting, etc. (excavation damaged zone) is uncertain. Fourth, SUTRA is two-dimensional, which implies an infinite extent of the conditions perpendicular to the modeled cross section.

Part 1 - Model Calibration

The purpose of *Part 1* is to provide reasonable initial and boundary conditions with regard to pressure and concentration for the simulation of the dewatering and resaturation phases (*Part 2*). *Part 1* treats the period between 10,000 BP and present.

Fourteen thousand years BP Sweden was covered with ice. The Baltic Shield was isostatically depressed by the weight of the ice cap to over 200 m below sea level, and large areas were subject to marine excursion (SNA, 1994). *Figure 2* shows the Holocene marine limit in Sweden about 10,000 years BP together with the locations of the modeled cross section (solid line) and the major upstream regional run off divide (dashed line). As indicated in *Figure 2*, more than half of the cross section falls outside the region that was inundated by sea water after the latest glaciation.

The initial ground water situation along the modeled cross section 14,000–10,000 years BP is of course unknown and must therefore be assumed. The salinity situation in the Baltic Shield was probably quite complex with high fresh water pressures under the ice cap and a simultaneous extensive marine excursion. For the purpose of this study it was assumed that the initial TDS concentration 10,000 years BP varied linearly with depth. That is, a linear concentration gradient is applied to the entire cross section as an initial condition for *Part 1*.

Figure 3 shows the modeled cross section (shaded area) and the adopted initial and boundary conditions. The cross section is assumed to be impervious at the landward and the bottom sides. This is equivalent to forcing flow to be vertical along the inland boundary, a probably acceptable boundary condition considering the location of the regional run off divide, see *Figure 2*. The chosen location of the bottom boundary at 2,000 m below sea level is found to be beyond major significance for the study.

The boundary conditions at the top and seaward sides are important for this study. A flux boundary condition must be specified at the top side in order to allow for a drawdown of the water table while the repository is depressurized. This study assumes a stationary infiltration rate at the top side. The stationary recharge is spatially adjusted to match the Holocene evolution of the hydraulic head profile of the modeled cross section between 10,000 years BP and today. Present-day heads of lakes close to the run off divide are in the range 200–300 m above sea level (SNA, 1994).

If no fluid flow is allowed across the seaward side of the model, the modeled cross section should be stretched out to the east so that the no-flow boundary is located far enough from the region of interest (cf. Voss and Andersson, 1993). This study replaces a distant boundary by using a fixed concentration profile at the seaward side of the modeled cross section, see *Figure 3*. Thus, the pressure profile at the seaward side is hydrostatic. The reason for this approximation is to allow for an increased discretization of the region close to simulated repository in *Part 2*.

Present-day depth-distribution of salt content in fluids residing the Baltic Shield rocks is not well known on the regional scale. For the purpose of this study, the chloride measurements carried out in the deep core boreholes KLX01 and KLX02 at Laxemar were used for calibrating the simulations in *Part 1*. The locations of these boreholes coincide with the modeled cross section, with KLX01 located 500 m and KLX02 1,500 m from the seashore, respectively. KLX01 is about 1,100 m deep and KLX02 is about 1,700 m deep. The concentration profiles shown in *Figure 4* suggest that the fresh water lens is somewhat thicker in KLX02. Measurements yield that the salinity expressed as Total Dissolved Solids of the borehole fluid in KLX02 above 900 m depth is less than or equal to the present value of the Baltic Sea, which is about 0.7 % by weight (0.007 kg/kg or 7,000 ppm). At 1,700 m depth, the TDS value has increased to almost 7 % by weight, or ten times the present TDS value of the Baltic Sea (Follin, 1994). According to Laaksoharju *et al.* (1995) the bottommost water is very old.

For the simulation of *Part 1* the initial TDS concentration 10,000 years BP was assumed to vary linearly with depth between 0.7 % and 7 % throughout the modeled cross section. For an ambient isothermal temperature of +7 °C the linear TDS profile implies a linear fluid densitity profile ranging between 999,90 kg/m^3 at the top of the model to 1,049.40 kg/m^3 at the bottom.

The representation of the fractured heterogeneous shield rock as a porous medium tacitly implies that values used are in some sense mean or effective values of the heterogeneous fabric. Voss and Andersson (1993) provide a good presentation of continuum approximations and their discussion applies to the present study. For the purpose of this study different flow parameter combinations were tested based on findings from the Äspö HRL. The parameter values chosen for this study are shown in *Table 1*. The considered case consists of a heterogeneous porosity, a heterogeneous and anisotropic permeability, and a homogeneous and anisotropic dispersivity.

Table 1 *Chosen parameter values for Part 1. mbsl = meters below sea level, k = permeability, ϕ = porosity, α = dispersivity (longitudinal and transverse), D_m = molecular diffusivity. The meaning x and z is defined in Figure 3.*

Depth (mbsl)	k_x (m^2)	k_z (m^2)	ϕ (%)	α_L (m)	α_T (m)	D_m (m^2/s)
0 – 100	1.45 E–15	1.45 E–14	0.1–0.075	200	10	5 E–10
100 – 200	7.25 E–16	7.25 E–15	0.075–0.025	200	10	5 E–10
200 – 2,000	1.45 E–16	1.45 E–15	0.025	200	10	5 E–10

The solution to *Part 1* is shown in *Figure 5*. The reconstruction used in this study of the hydrological conditions during the Holocene between 10,000 BP and today leads to the interpretation that the present occurrence of saline ground water reflects an ongoing but incomplete flushing of the Baltic Shield. *Figure 5* provides the desired concentration distribution for the simulations in *Part 2*.

As shown in *Table 1* the values of the effective porosity and permeability values both decrease at depth. There is data from the Äspö HRL area to support this. For instance, Follin (1994) interpreted a long-term multi-packer interference test between KLX02 and KLX01 and concluded that both the transmissivity and storativity decrease at depth. La Pointe *et al.* (1995) analyzed packer-test and fracture data in parallel and concluded that the vertical component of the permeability tensor at Laxemar and the Äspö HRL is probably larger than the horizontal component in the east-west direction. The values of the principal components of the dispersivity tensor in *Table 1* are taken from Follin (1992), who analyzed the heterogeneity of ground water flow by means of particle tracking and Monte Carlo simulations based on the spatial variability of packer-test data from the Äspö HRL. Voss and Andersson (1993) used similar values.

Part 2 – Dewatering and Resaturation

Two cases A and B are studied. In case A the permeability of the model elements adjacent to the simulated repository is unaltered, whereas in case B it is lowered two orders of magnitude. The purpose of case B is to study the effect of a tentative excavation damaged zone close to a repository. Figure 6 shows the discretization of the simulated repository and its near-field. The distance between the center of the simulated repository and the seashore in Figure 6 is 1 km.

The simulation of the dewatering and resaturation phases requires a model for treating flow in the unsaturated zone. Unfortunately, there is no generally accepted model for unsaturated flow in sparsely fractured rock (Evans *et al.*, 1987). For the purpose of this study, van Genuchten's model (van Genuchten, 1980) is adopted. This model is implemented in SUTRA as an option by Voss (1984).

Figures 7 shows a close-up of *Figure 5* between 0–2 km from the seashore. The rectangle in *Figure 7* indicates the assumed location of the repository to be depressurized. *Figures 8 and 9* show the results of cases A and B, respectively, after fifty years of dewatering. The solid line represents zero (atmospheric) pressure (p=0). Ideally, this isobar should coincide with the dashed contour line that represents unit saturation (S=1.0). However, in order to achieve reasonable computation times it was necessary to relax the iterative convergence criterion for the nonlinear equations in SUTRA. In result, the accepted solutions are not perfect. The simulation of 50 years of dewatering required about 13 hours on a 90 MHz Pentium for a maximum model time step of 24 hours.

The extent of the water table decline is considerable for case A. As shown in *Figure 8* the entire region between the top side and the simulated repository is more or less unsaturated at the end of the simulation period. Most of this drawdown develops during the first two years of dewatering. Despite the closeness to the seashore, *Figure 8* suggests that the question of saline intrusion to a coastal repository may be a phenomenon that is dominated by vertical upconing rather than lateral infiltration from the sea. Moreover, in *Figure 8* the occurrence of saline ground water in the unsaturated zone above the repository is notable. The TDS value at the level of the simulated repository has increased about five times.

Field pressure data from the tunnel at the Äspö HRL yields that the hydraulic head at 450 m depth is close to hydrostatic right behind the tunnel wall (Rhén, 1995) and that the drawdown of the ground water table above the tunnel does not exceed 60 m at any location. This implies a low-permeability of the excavation damaged zone around the HRL tunnel. In *Figure 9*, the effective permeability of the most adjacent model elements is lowered two orders of magnitude compared to *Figure 8*. The decrease in drawdown is quite significant. This figure supports the standpoint that the excavation damaged zone has strong skin effect.

Figure 10 shows the simulation results for case A after fifty years of recovery. The location of the closed repository is indicated with a rectangle. Again, the solid line represent zero (atmospheric) pressure and for a perfect numerical solution this isobar should fall on top of the dashed contour line that represents unit saturation. *Figure 10* suggests an extensive residual drawdown of the ground water table for case A. The incomplete recovery may to some extent be due to the small fixed infiltration rate prescribed at the top side of the model. Notwithstanding, the interface between fresh and saline ground waters after fifty years of closure is close to the conditions prior to the dewatering phase (cf. *Figure 7*) despite the incomplete pressure recovery, which is an interesting result considering the objective of the study.

Conclusions

This study treats the question of saline intrusion to a deep coastal repository in Baltic Shield rocks. The motive is that long-term changes in the chemical environment associated with saline intrusion may affect the properties of the repository buffer zone material (bentonite). The reconstruction used in this study of the hydrological conditions during the Holocene between 10,000 BP and today leads to the interpretation that the present occurrence of saline ground water reflects an ongoing but incomplete flushing of the Baltic Shield. The simulations of fifty years of dewatering followed by fifty years of resaturation suggest that the final interface between fresh and saline ground waters may be close to the conditions prior to the dewatering phase.

Aknowledgments

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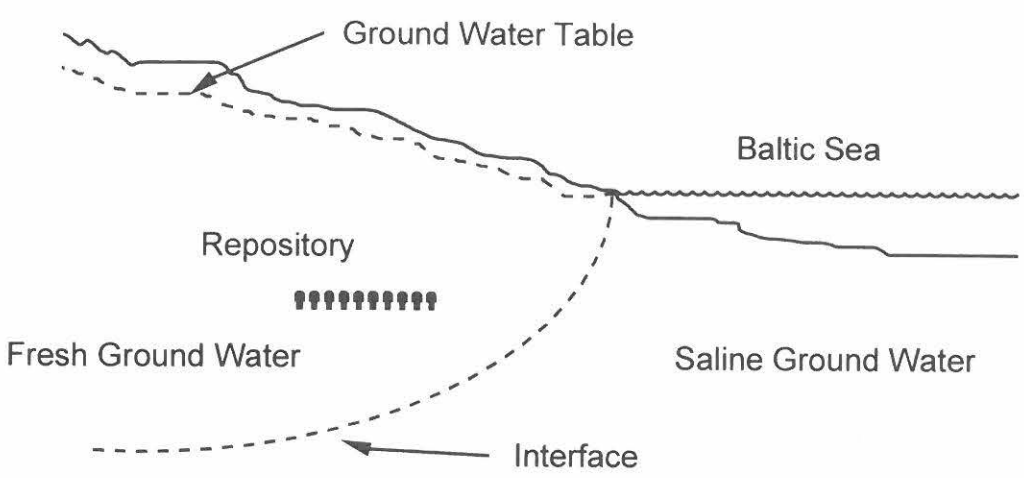

Figure 1 *Schematic cross section of the studied scenario.*

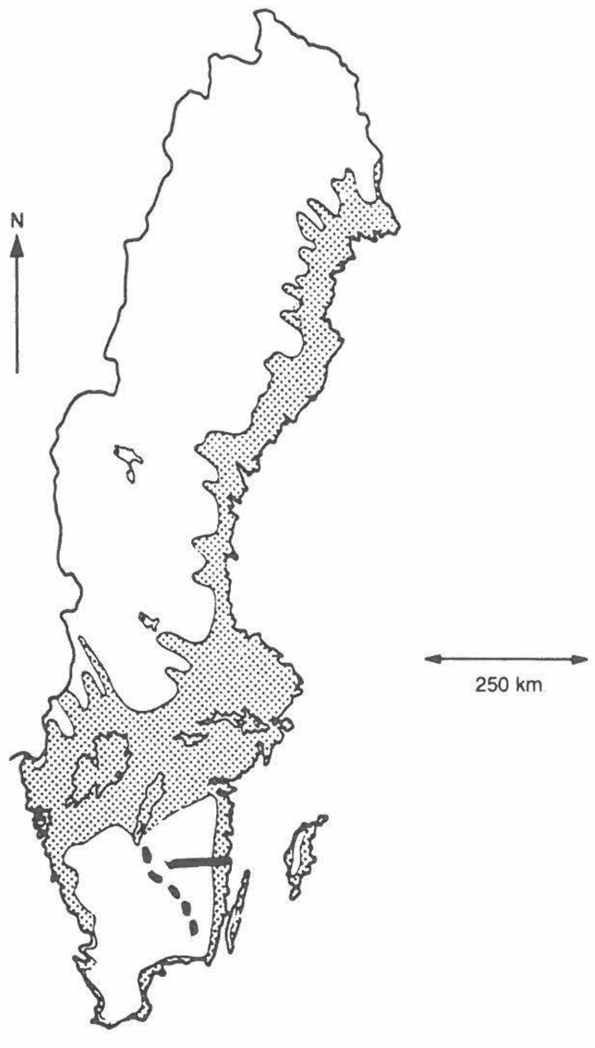

Figure 2 *Holocene marine limit in Sweden, about 10,000 years BP. Shaded region was inundated by sea water. The solid line shows the location of the modeled cross section. The dashed line shows an interpretation of the location of the major run off divide for the region of interest. Modified after Lindewald (1985).*

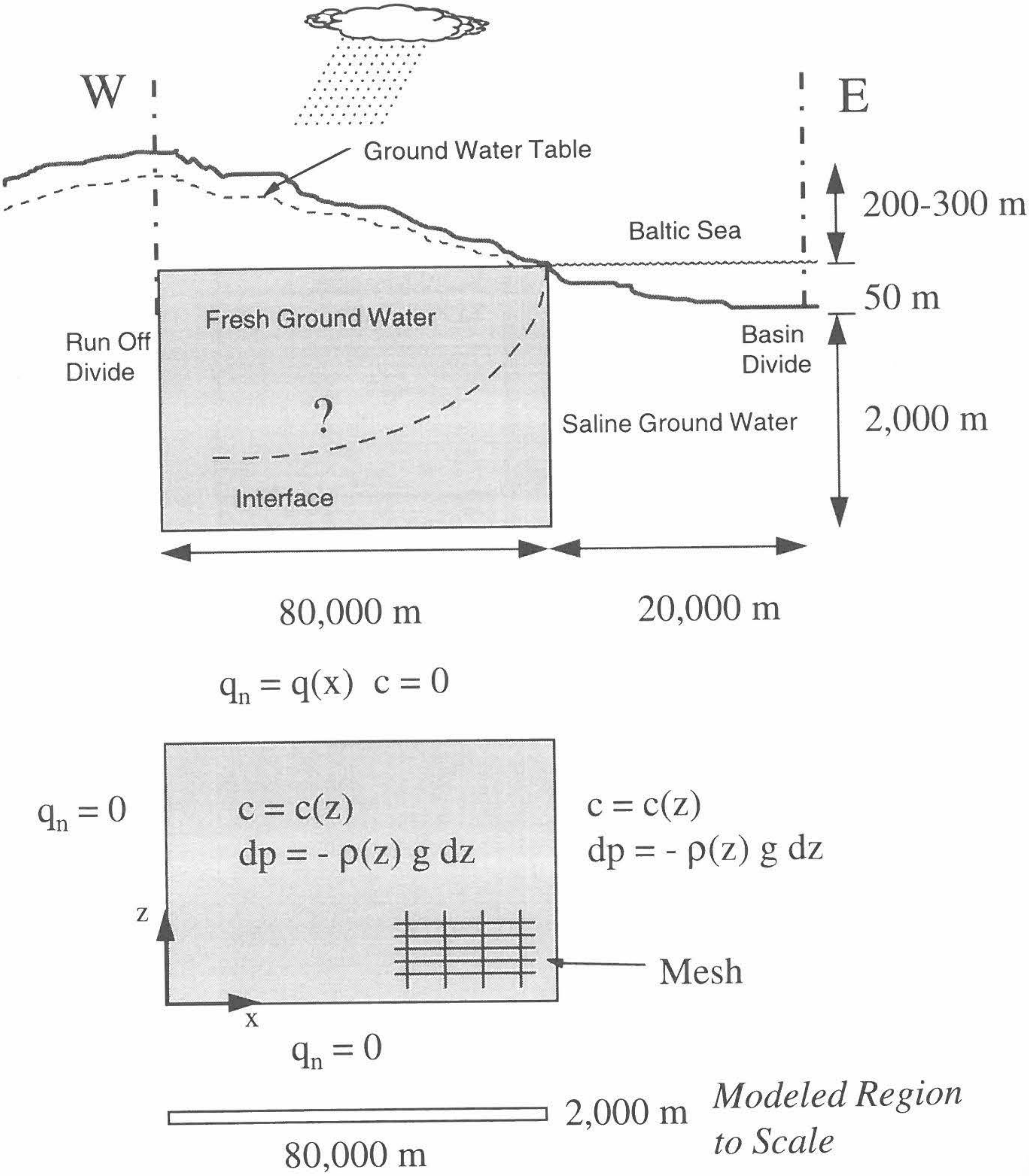

Figure 3 *The conceptual-numerical model used for Part 1. Model discretization mesh has 861 nodes and 800 elements (shaded area). Each element is 2 km long and 100 m deep.*

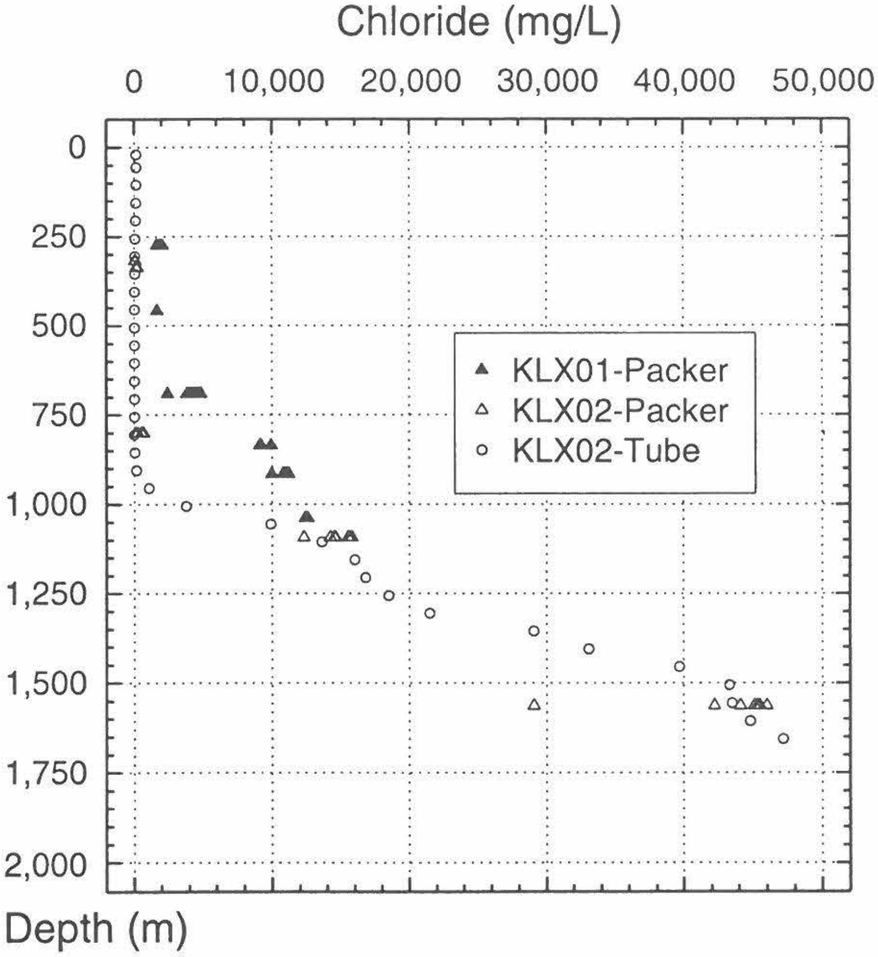

Figure 4 *Concentration profiles (chloride) from KLX01 and KLX02. Modified after Laaksoharju et al. (1995).*

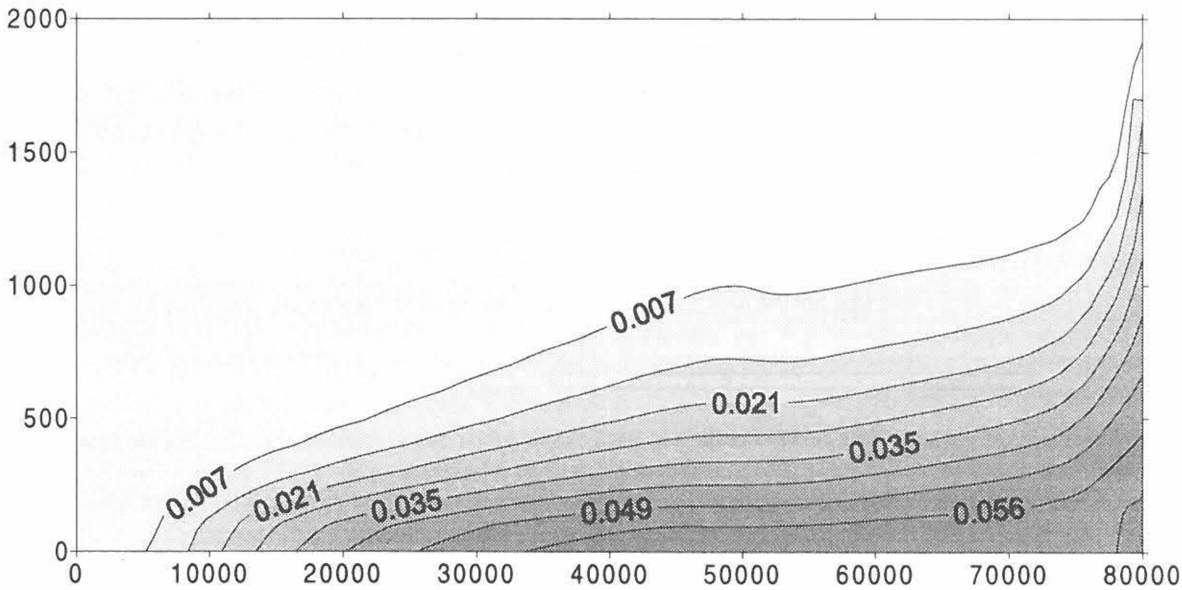

Figure 5 *Result of the model calibration in Part 1 for the parameter values and hydraulic conditions specified in Table 1 and Figure 3. The salinity contours are in kg TDS/kg solution. The conceptual locations of the (Chloride) contration profiles in Figure 4 are at 78,500 m (KLX02) and 79,500 m (KLX01).*

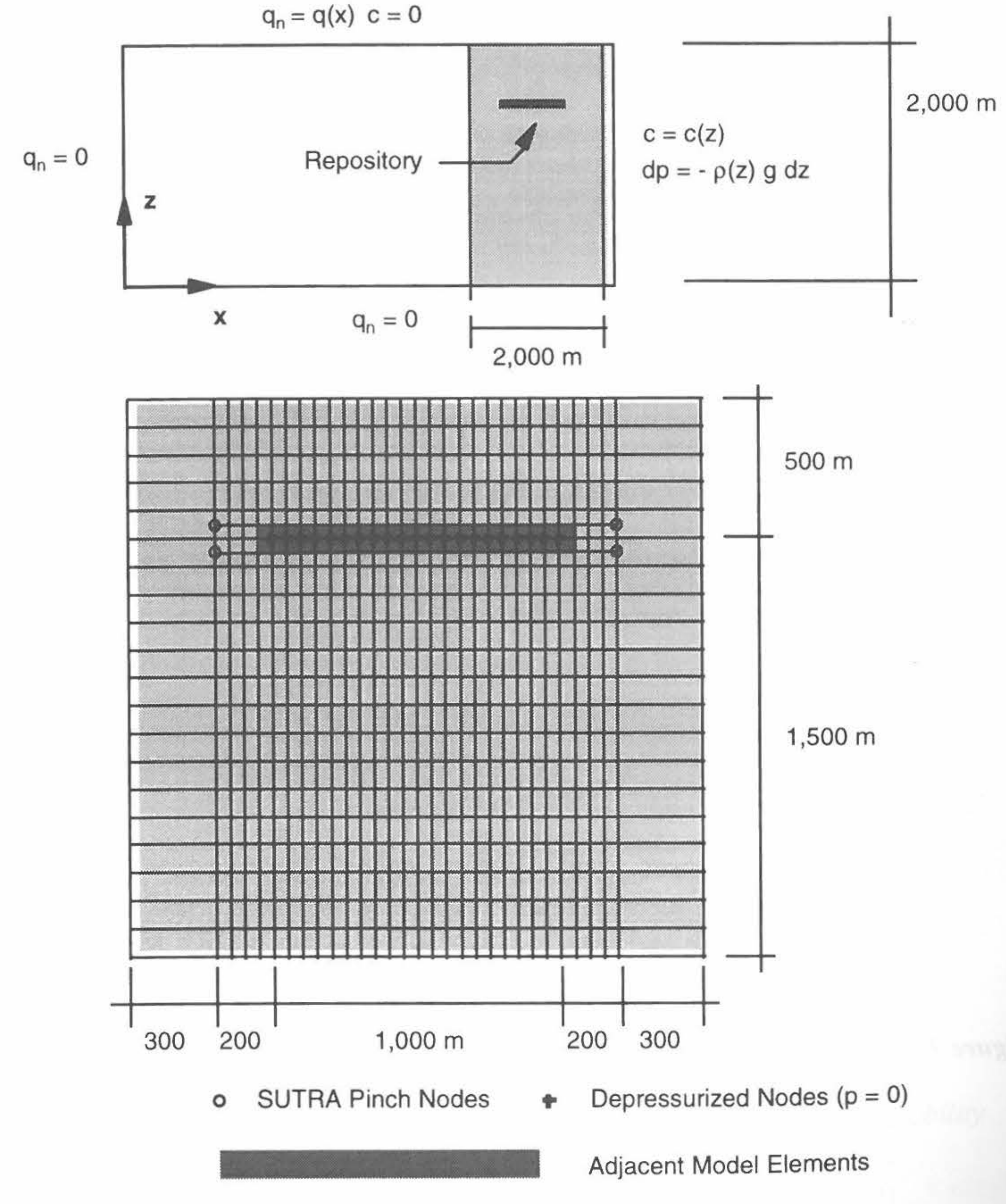

Figure 6 *Finite-element discretization for simulation of saline intrusion to a repository. The complete mesh consists of 1,528 nodes and 1,436 elements.*

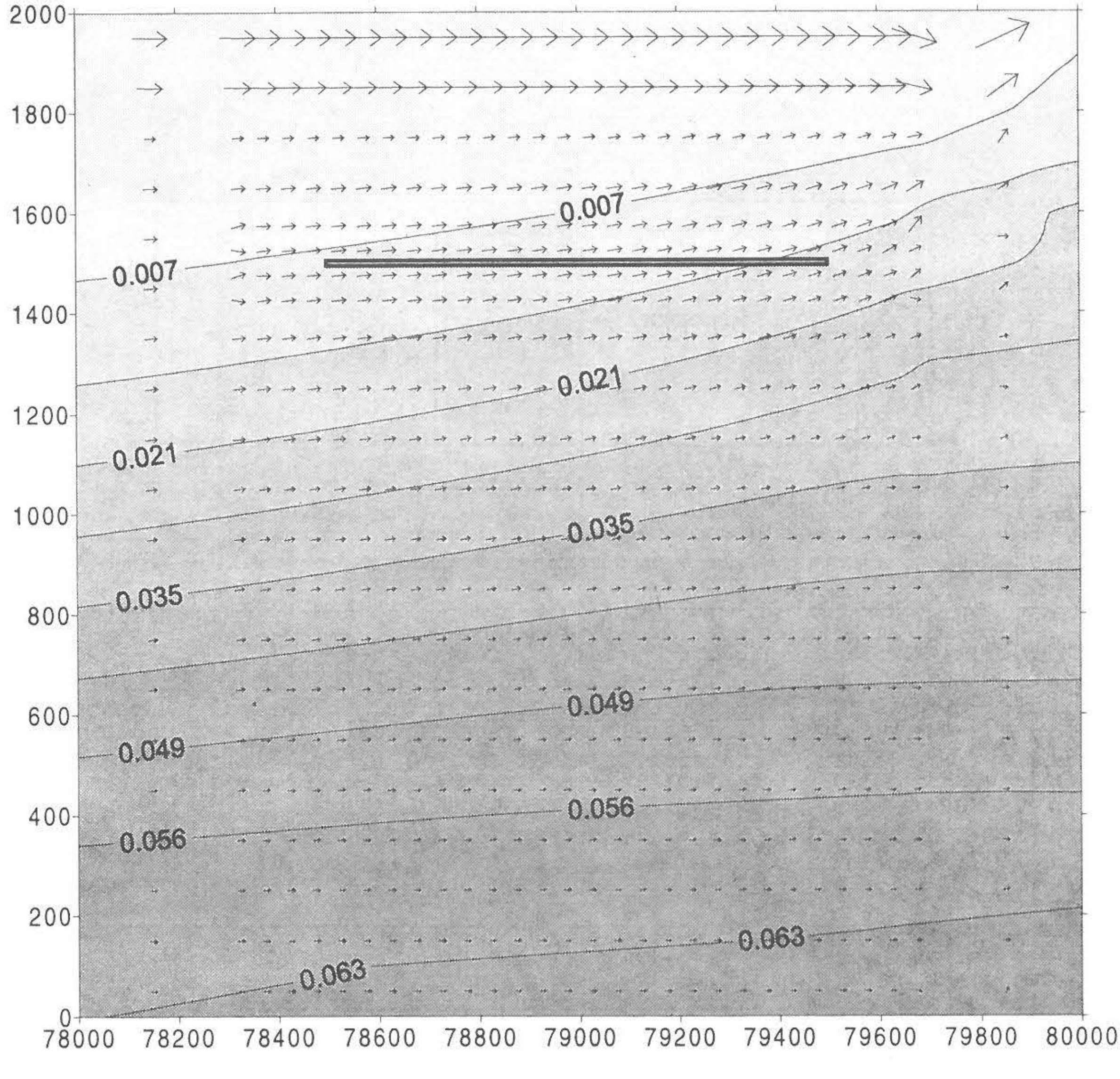

Figure 7 *Close-up of Figure 5 - Situation prior to the start of the dewatering phase. The forthcoming location of the repository is indicated with a rectangle. The magnitudes of the velocity vectors are relative only. The salinity contours are in kg TDS/kg solution. The conceptual locations of the (Chloride) contration profiles in Figure 4 are at 78,500 m (KLX02) and 79,500 m (KLX01).*

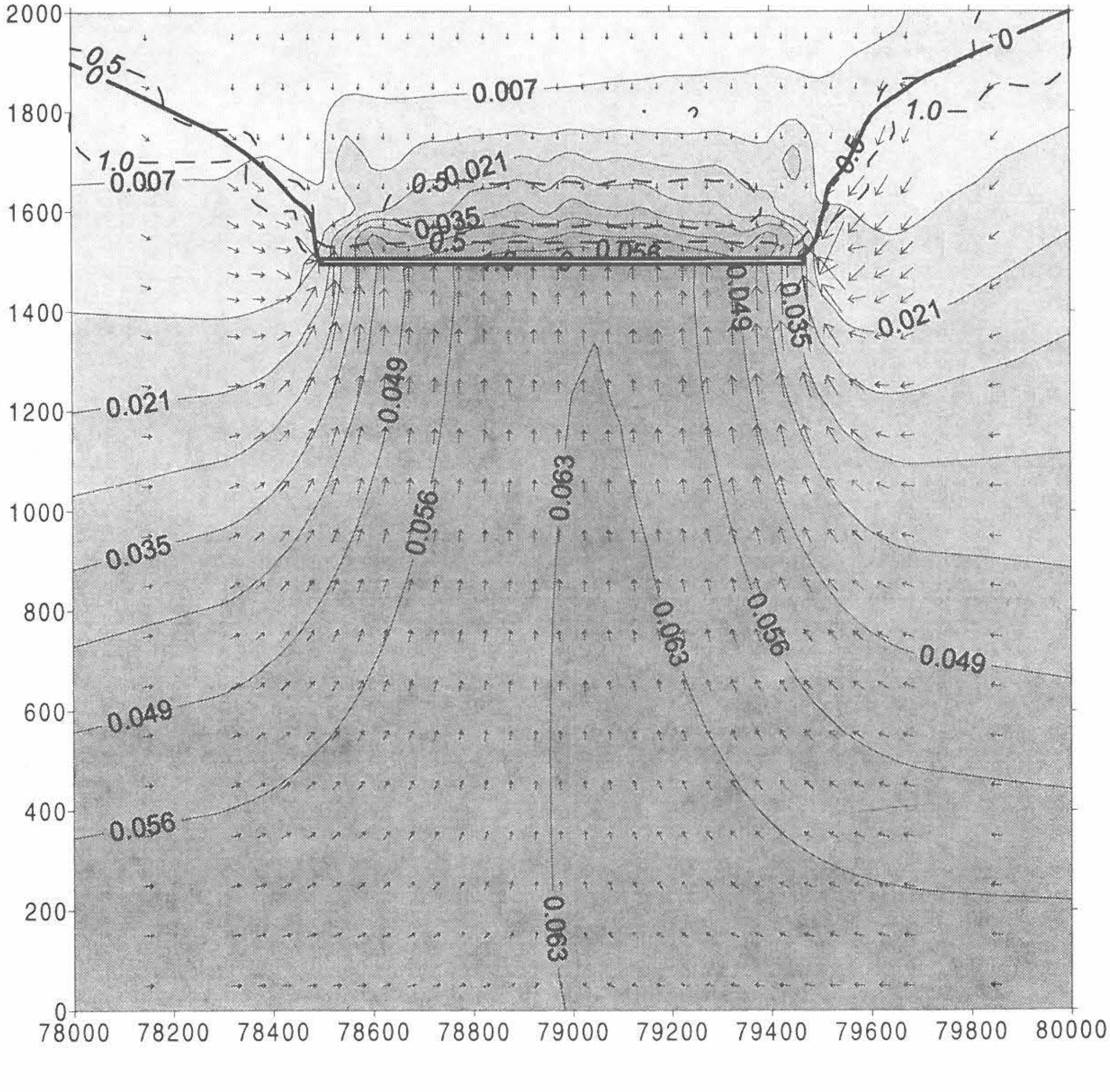

Figure 8 *Situation after 50 years of dewatering for case A (unaltered permeability close to the depressurized repository nodes).*

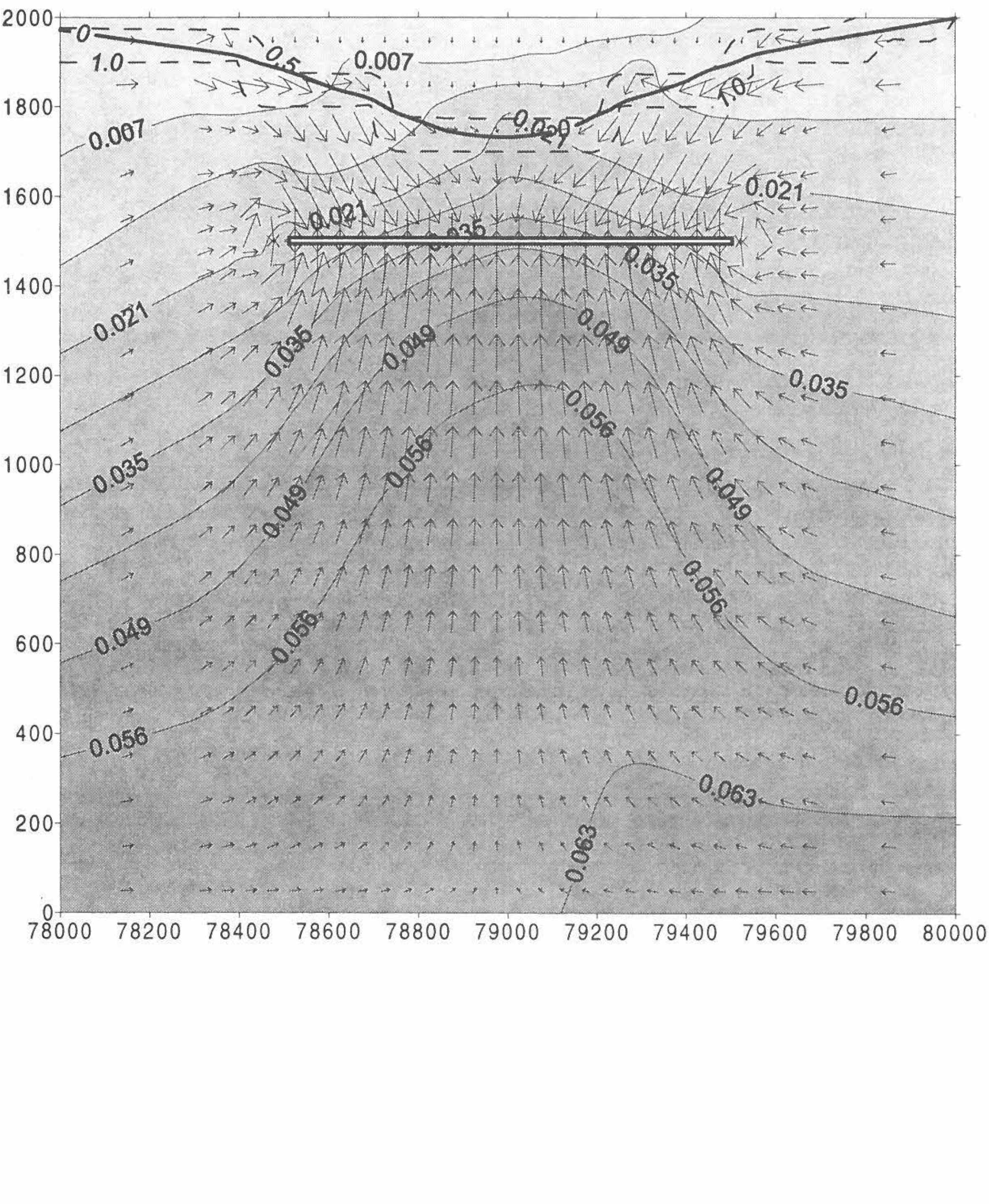

Figure 9 *Situation after 50 years of dewatering of case B (the permeability of the model elements adjacent to the repository is decreased 2 orders of magnitude with regard to case A).*

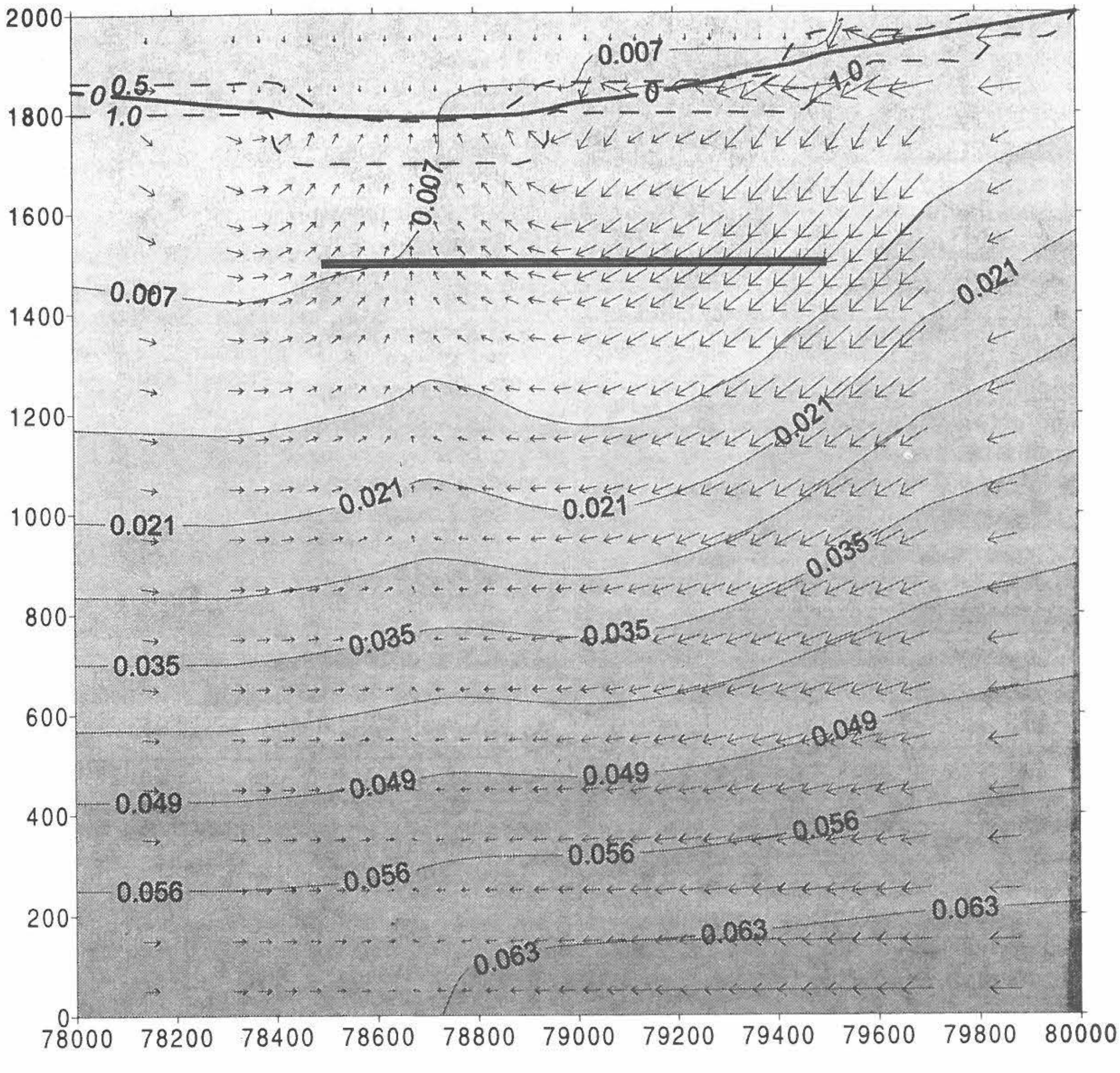

Figure 10 *Situation after 50 years of dewatering and 50 years of resaturation for case A.*