R-05-56

The Simpevarp repository

Modelling changes in the flow, pressure and salinity fields, due to a repository for spent nuclear fuel

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December 2006

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Abstract

Water inflow to an open repository will change the pressure and salinity in a large volume around the repository. The effect will reach the surface and may cause a drawdown of the ground water table and very salt water from below the repository may be transported up to repository level.

A numerical simulation model which simulates these effects is developed and tested. By employing a number of advanced modelling techniques (unstructured grids, free surface algorithm, matrix exchange, etc) it is demonstrated that realistic simulations can be performed. An application to the Simpevarp repository is carried out and site specific results are discussed.

As a conclusion one may state that the methodology introduced is promising, but further work is needed before the realism of the results can be assessed.

Sammanfattning

Inflöde till ett djupförvar ger förändringar i tryck- och saltfältet i en stor volym runt förvaret. Vid markytan kan en sänkning av grundvattenytan bli resultatet. Under förvaret kan en uppåtgående transport, som kan öka salthalten på förvarsnivå, förväntas.

En numerisk modell som beskriver dessa effekter har utvecklats och testats. Genom att utnyttja en rad avancerade tekniker (ostrukturerade beräkningsnät, algoritm för fri grundvattenyta, matrisutbyte, m m) kan realistiska simuleringar erhållas. En tillämpning på ett tänkt förvar i Simpevarp visar detta.

Som en allmän slutsats kan säjas att den utvecklade metodiken är lovande, men mer utvecklingsarbete krävs innan realismen i resultaten kan fastställas.

Contents

1 Introduction

1.1 Background

A repository for spent nuclear fuel will have atmospheric pressure in the tunnels during the excavation and operational phases. In order to reduce the resulting water inflow grouting will be carried out. Unless the inflow is totally eliminated (which is not feasible) a disturbance in the pressure and salinity fields will result.

From several points of view it is of interest to be able to predict these disturbances:

- The ground water table will be lowered due to the tunnel inflow. The water level in lakes and wells is thus affected as well as the flow rate in streams.
- The engineered barriers are known to be affected by the salinity of the surrounding water. It is expected that water from below the tunnel will be transported to the tunnel, carrying water with high salinity (upconing). Also the oxygen saturated water from the ground surface may affect the engineered barriers.
- From a construction point of view it is essential to know the expected inflow to the repository; this in order to perform suitable grouting, design pump systems, etc.

After the closure of the repository a resaturation phase starts. Also this phase and the coupling to the host rock is of interest to simulate. Finally, one needs to consider the possible transport of radionuclides from the repository to ground level.

Considering all these aspects and the complex geometry of a repository it is realized that the simulation task is far from trivial. A model that resolves the processes around the tunnels (on a metre scale) as linked to regional scales (on the km scale) is needed.

1.2 Objectives

The main objectives of the study are:

1. Method testing using site data.
2. Inflows to the tunnel (for different grouting efficiencies).
3. Near-surface drawdown (including influence area).
4. Upconing of saline water to the tunnels.

A secondary objective is to demonstrate new methodology, as embodied in the code DarcyTools Version 3.0.

1.3 Scope

In order to meet the objectives a number of advanced modelling techniques are needed. The most important of these are:

- A computational grid that can resolve the geometry of the repository, as embedded in a regional scale model. In this report an unstructured grid will be introduced as a solution to this problem.
- A method to handle a free ground water surface.
- The repository geometry is given in form of high resolution CAD files. These files need to be imported to the code and the computational grid is to be constructed in a way that resolves the geometry.
- The salinity distribution is in focus in the study. The gravitational effects due to the varying salinity as well as the exchange with immobile volumes (including the rock matrix) should be accounted for.
- Grouting will reduce the hydraulic conductivity close to the repository walls. This skin effect needs to be simulated in a realistic manner.

These features are considered to be essential parts of a realistic problem formulation and the modelling task is therefore also a feasibility study.

Some issues that are not considered in this study include: the resaturation phase, thermal effects and transport of radionuclides from the repository to ground level. It should further be noted that calibration and sensitivity studies are outside the scope of the present project.

2 Site description

2.1 General

The Simpevarp area is located near the Oskarshamn nuclear power plant on the east cost of Sweden, see Figure 2-1. In this figure also the Regional Model domain is introduced; this domain is also the largest one considered in this study. The dimensions of the Regional Model area are: 21 km (west-east), 13 km (south-north) and 2.1 km (depth).

An outline of the repository is shown in Figure 2-2. The repository is located at a depth of about 500 metres, the total tunnel length is about 60 km and the number of deposition holes is about 6,600. The layout of the repository is done with respect to major fracture zones in the area.

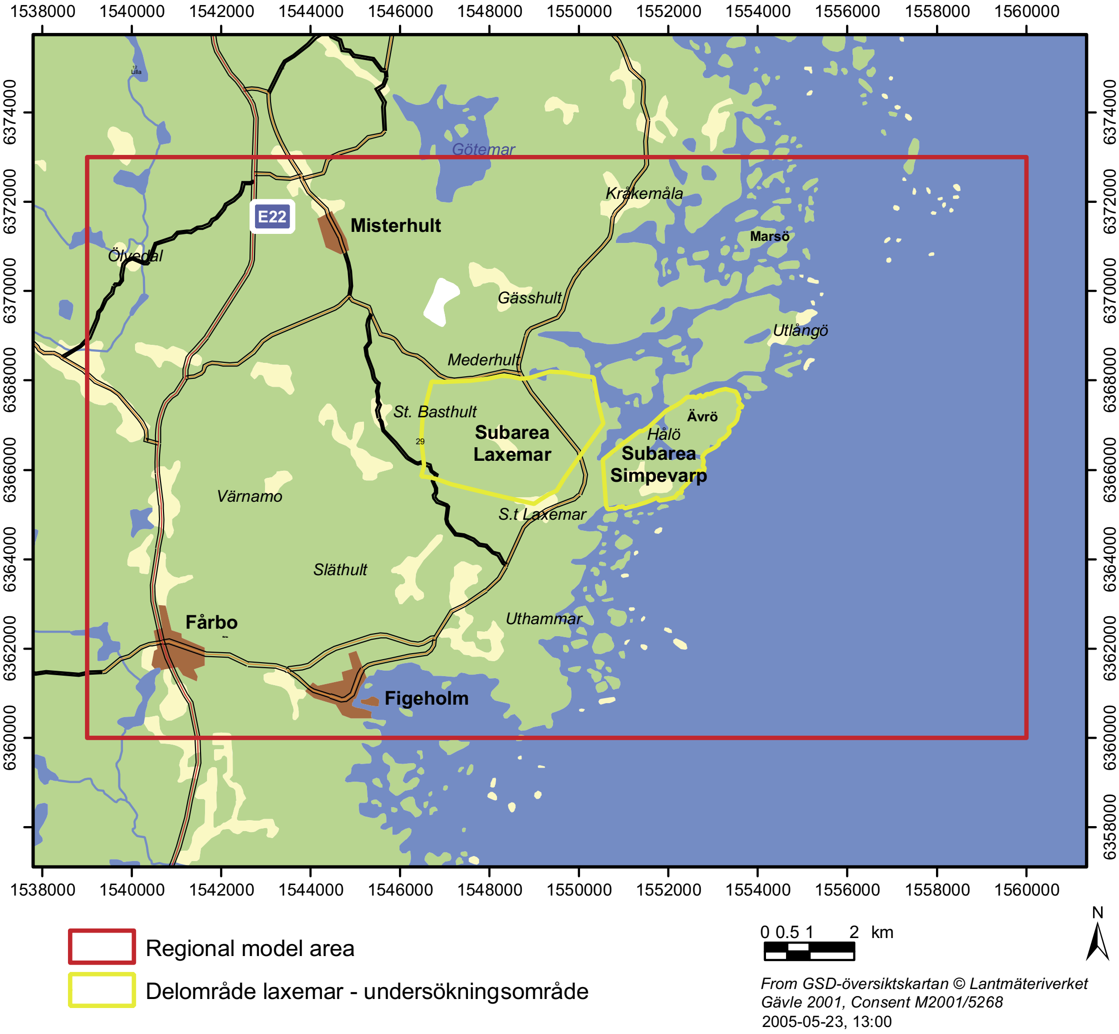

***Figure 2-1.** Overview of the Simpevarp area and identification of the Simpevarp and Laxemar subareas.*

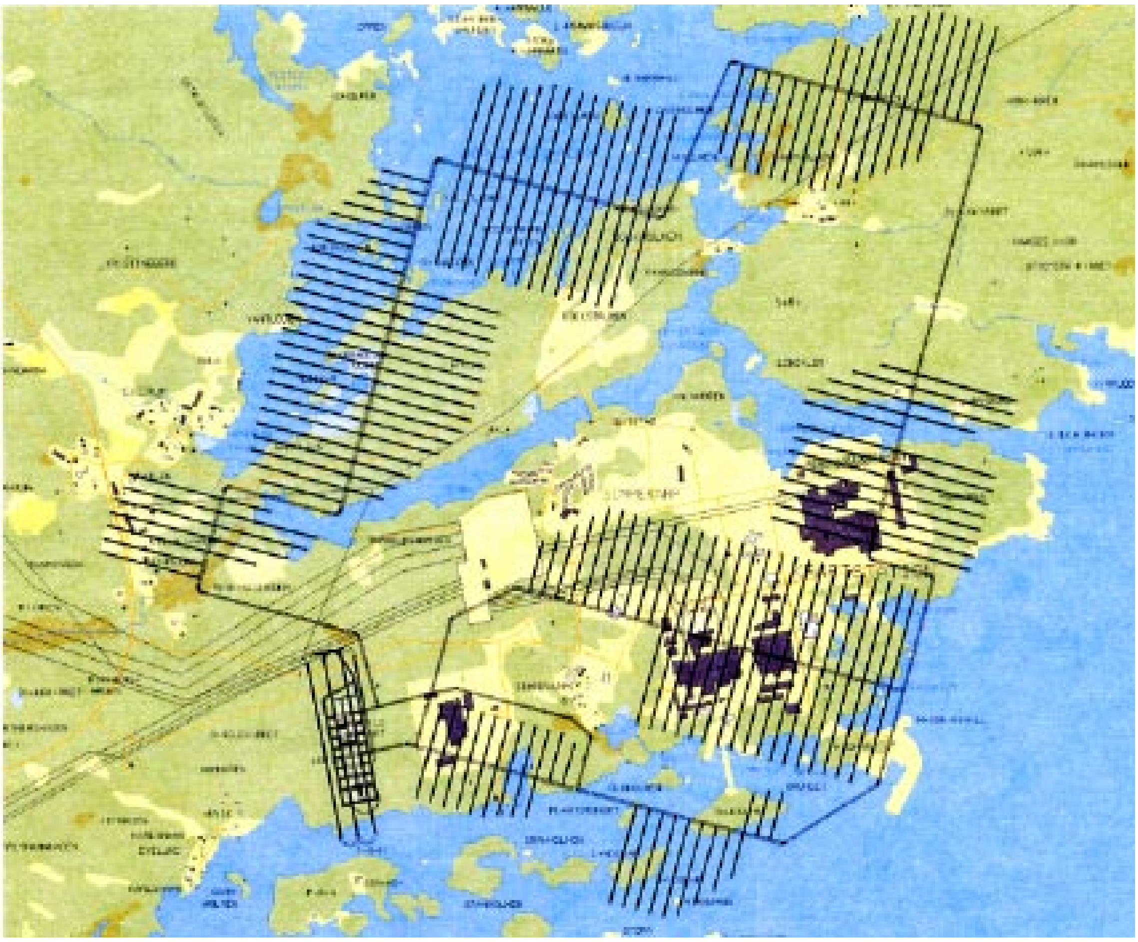

Figure 2-2. *Layout of the repository.*

2.2 Site data

The general conditions and data for the model set-up are given in /Follin et al. 2005/. Some of the main points are:

- The model domain coordinates are those of the Regional Model.
- The elevation of the top surface of the model should match Metria's 2300 DEM coupled with bathymetric data for the sea floor.
- The fracture network, deterministic and stochastic, should be identical with the network used in the Site-descriptive model.
- The tunnel layout is presented in /SKB 2006/ and is provided by SKB in form of a CAD file (STL-format).
- Initial conditions should be based on the results from the Site-descriptive model.
- Boundary conditions:
  - Prescribed net precipitation (165 mm/year) above sea level, fixed pressure and salinity below.
  - Salinity at bottom boundary fixed to 10%.
  - Hydrostatic conditions on all lateral boundaries.
  - Atmospheric pressure in tunnels.

3 Mathematical model

For a general description of the basic assumptions and mathematical formulation of DarcyTools, the reader is referred to /Svensson et al. 2006/. In this section some problem specific settings and assumptions will be discussed.

3.1 Properties

As mentioned, the fracture network should be the same as used in the Site-descriptive model and will for this reason not be discussed here. The present set-up, in contrast to the models used in the Site-descriptive model, employs a free surface algorithm. As a consequence the near ground properties need to be calibrated, in particular the hydraulic conductivity. Also the drawdown above the repository requires some considerations regarding the conductivity. In Table 3-1 the settings used are summarized. It should be emphasised that this study has not included any "fine trimming" of the surface hydrology part of the model and the values adopted are therefore mainly based on earlier experience and some test simulations.

Table 3-1. Properties. As the basic fracture network is imported from the Site-descriptive model, only additional properties are given here.

Property	Depth	Values
Porosity (–)	0 → 20 m	$n = 0.05 \times 10^{-depth/20}$ min value = 10^{-3}
	20 m →	min value = 10^{-5}
Conductivity (m/s)	0 → 20 m	$k = 5 \times 10^{-3} \times 10^{-depth/3}$ min value = 10^{-6} $k_{river} = 2$ $k_z = 5 \times 10^{-6}$, constant
	20 m →	min value = 5×10^{-11} Above repository (down to 300 m) $k_{z,min} = 5 \times 10^{-9}$
Specific storativity (m^{-1})	above sea level	$S_s = 10^{-3}$
	below sea level	$S_s = 10^{-3} \times 10^{-depth/20}$ min value = 10^{-6}

3.2 Equations

The following equations and algorithms are employed:

- Conservation of mass, including the effects of a variable density and specific storativity.
- A transport equation for salinity.
- A transport equation, used as a tracer, for precipitation water.
- The Darcy equation, including the gravitational term.
- The subgrid model FRAME, based on the multi-rate diffusion model, is used for both salinity and the precipitation tracer.
- The ground water table is tracked with a free surface algorithm that can handle both natural conditions and the drawdown due to the repository.
- A tunnel routine puts atmospheric pressure in all computational cells in contact with the repository. All cell walls of these cells have reduced conductivities with a specified factor (skin factor).

For a detailed account of equations and algorithms, see /Svensson et al. 2006/.

3.3 Software

DarcyTools Version 3.0 is used in the study. This is the first major project using Version 3.0 and the project thus also serves as an evaluation of Version 3.0. The reason for using this software is that the unstructured grid option (not available in earlier versions) is needed to resolve the geometry of the repository. Version 3.0 also allows direct import of CAD files in STL format, which is utilized in the present study.

4 Results

4.1 Properties and grid

It is perhaps a bit unusual to include properties and grid in the result section. However, as the study is partly a feasibility study and the grid resolution is a major new element of the model, it can be justified. As will be shown, also the representation of properties can be classified as a result in itself.

The grid in the horizontal plane at sea level is shown in Figure 4-1. The largest cell size is 128 metres, the surface topography is resolved by a cell size of 64 metres and streams by cells with a dimension of 32 metres. Around the repository a grid size of 32 metres is used. In Figure 4-2 this area is enlarged and one can see the tunnel system. Figure 4-3 gives a further enlargement and one can now discern the smallest cell size used, which is 2 metres. This high resolution is needed to resolve the deposition holes individually. A vertical section through the repository is shown in Figure 4-4. From a depth of 1,500 metres a cell size of 64 metres is used; however from 600 metres depth and upwards the maximum size is 32 metres. The vertical resolution close to the top boundary is 2 metres and below this boundary down to a depth of 20 metres (the soil and weathered layer) the maximum vertical cell dimension is put to 4 metres. In total about 1.6 million cells are required to specify the problem as outlined.

All parts of the tunnel system above a depth of 300 metres below sea level were disregarded in the analysis. The reason for this is that the algorithm for the determination of the ground water table, can not handle a volume with atmospheric pressure that crosses the water table.

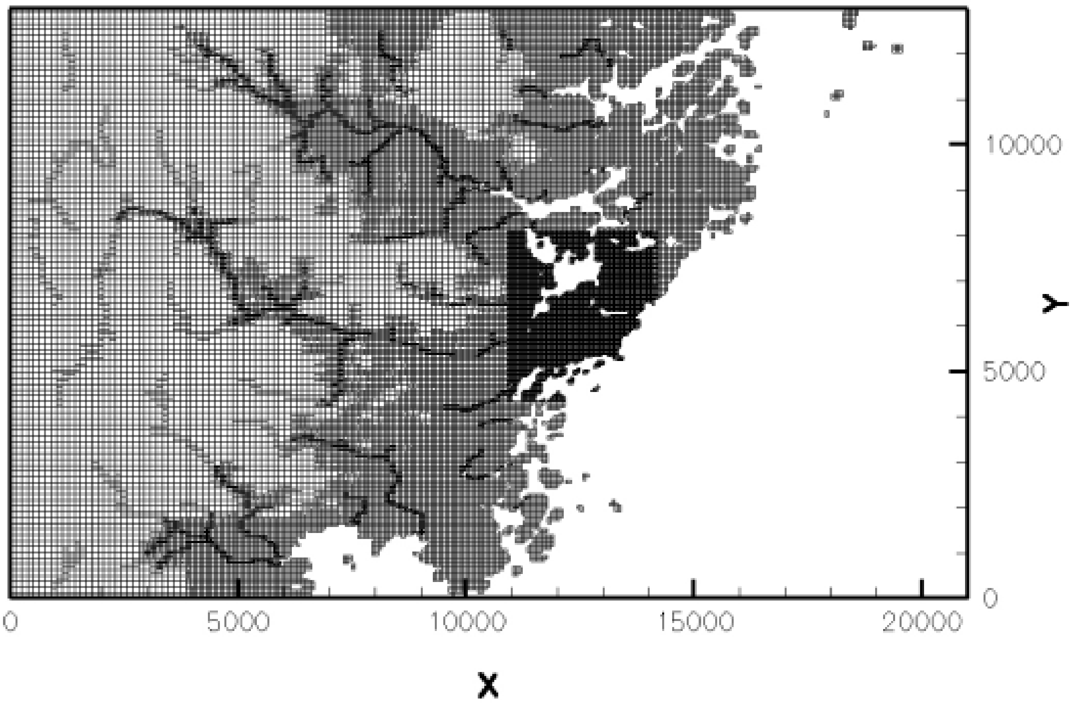

Figure 4-1. Computational grid. Horizontal plane at sea level.

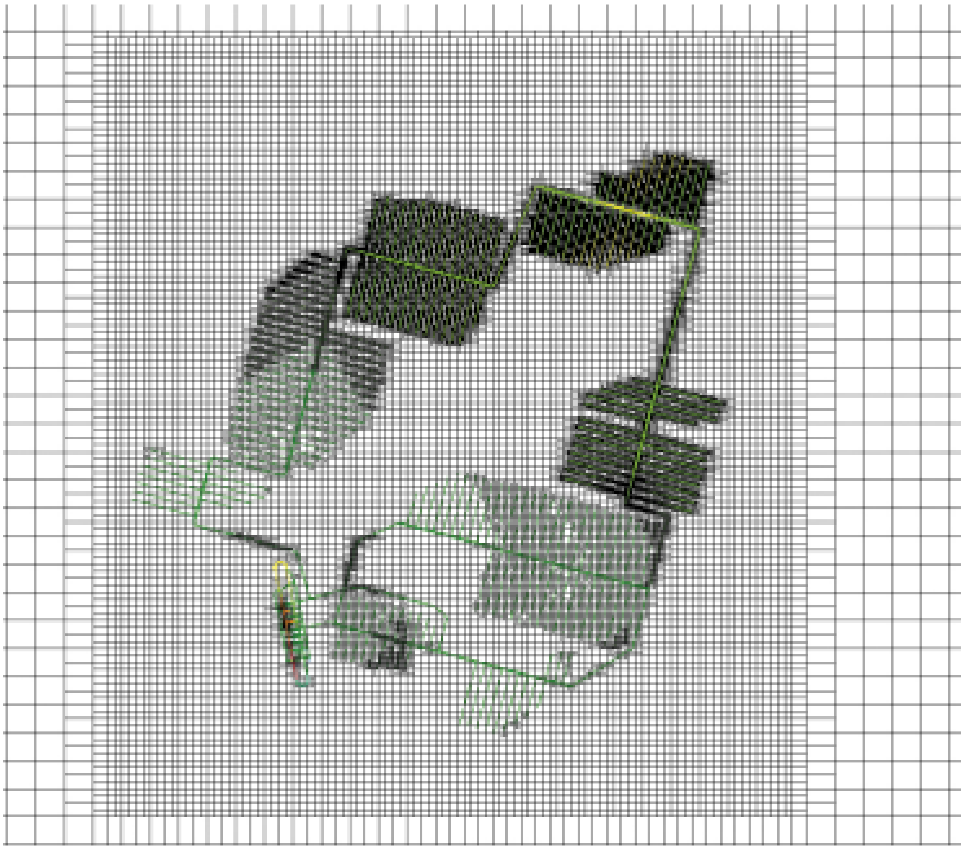

Figure 4-2. *Enlargement of Figure 4-1, with focus on the repository. Depth = 515 metres (m.b.s.l.).*

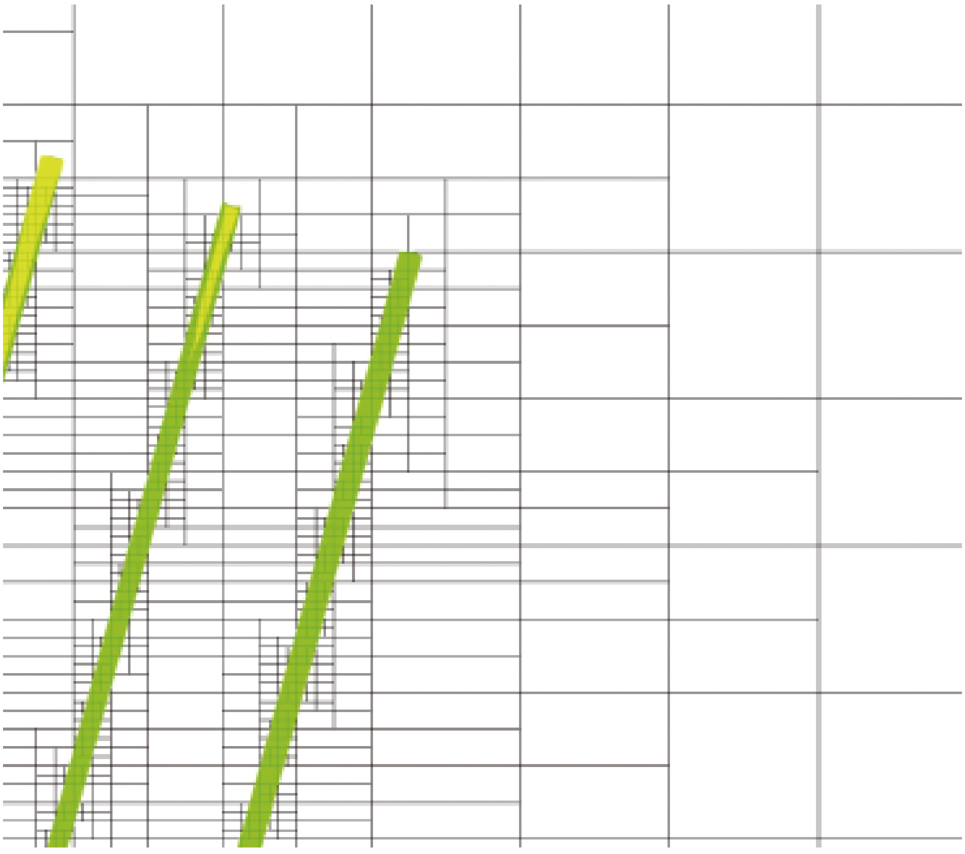

Figure 4-3. *Enlargement showing the north-east part of the repository. Depth = 515 metres (m.b.s.l.).*

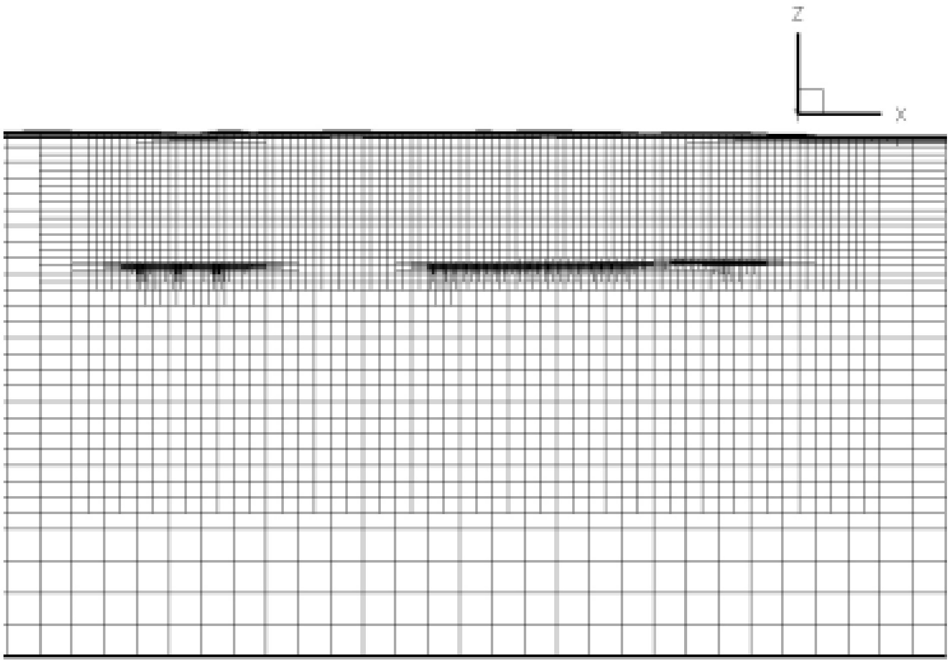

Figure 4-4. *Vertical section (west-east) through the repository area.*

This grid will allow an individual representation of all deposition holes (about 6,600) and all tunnels (about 60 km). It is then straight forward to calculate how many contact points there is between the connected fracture network and the tunnel system (including the deposition holes). Of all cells that are in contact with the walls of the tunnel system about 7% are also in contact with the connected fracture network. It should be stated that this figure is most likely very sensitive to the specified properties of the fracture network. Here the minimum size in the stochastic part of the network is set to 100 metres; a smaller value should certainly increase the number of contacts. In Figure 4-5, an illustration of the distribution of the contact points is found.

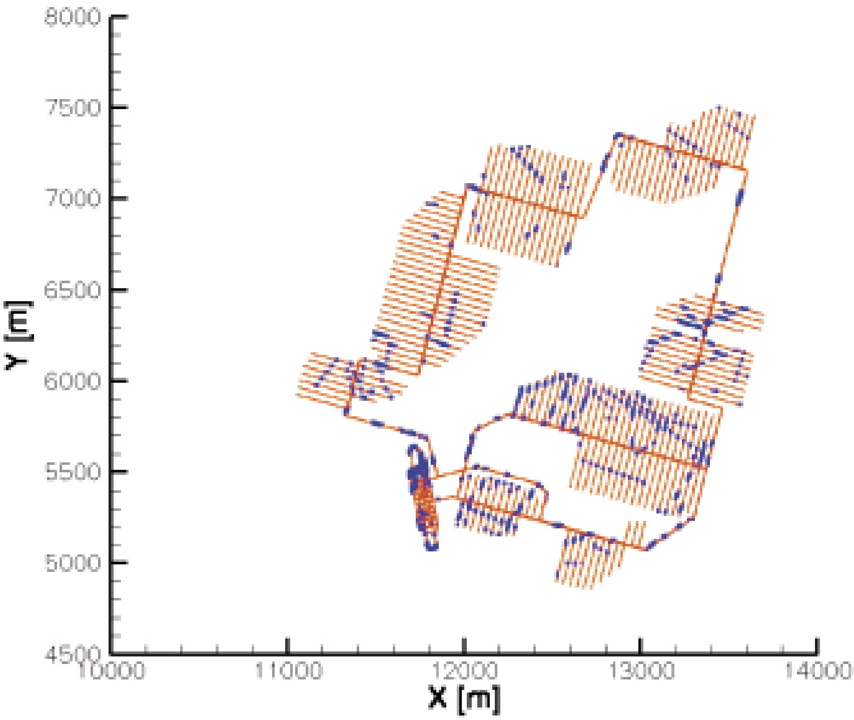

Figure 4-5. *Contact points (blue) between the tunnel system and the fracture network.*

We can also analyze the distribution of the conductivities in the contact points. In Table 4-1 the vertical conductivity distribution is shown. Grouting will affect this distribution and in the simulations to be presented we will multiply all conductivities with a skin factor. In Table 4-1, the effect on the distribution is illustrated. The skin factors 0.1, 0.01 and 0.001 will be used in the simulations to be presented.

4.2 Natural conditions

The natural, or undisturbed, conditions are needed as a reference when the tunnel effects are estimated. Another argument for studying the undisturbed situation is that the surface hydrology part of the model should be calibrated for undisturbed conditions. Due to time constraints this will however not be undertaken in the present study, instead some estimates based on earlier experiences are used.

The saturation level slightly above sea level is shown in Figure 4-6. This figure is mainly shown for reference purposes as the drawdown due to the repository will be illustrated in similar figures. The two black lines in the figure show the positions of the vertical sections through the repository, used for illustrating results.

Table 4-1. Distribution of vertical cell conductivities in contact with both the tunnel system and the fracture network. Effect of skin factor illustrated.

Skin factor	Distribution of log_{10} $Cond_z$, in %								
	> –5	–6 → –5	–7 → –6	–8 → –7	–9 → –8	–10→ –9	–11→ –10	–12 → –11	–13 → –12
1.0	1.9	34.5	32.9	20.5	6.3	3.9			
0.1		1.9	34.5	32.9	20.5	6.3	3.9		
0.01			1.9	34.5	32.9	20.5	6.3	3.9	
0.001				1.9	34.5	32.9	20.5	6.3	3.9

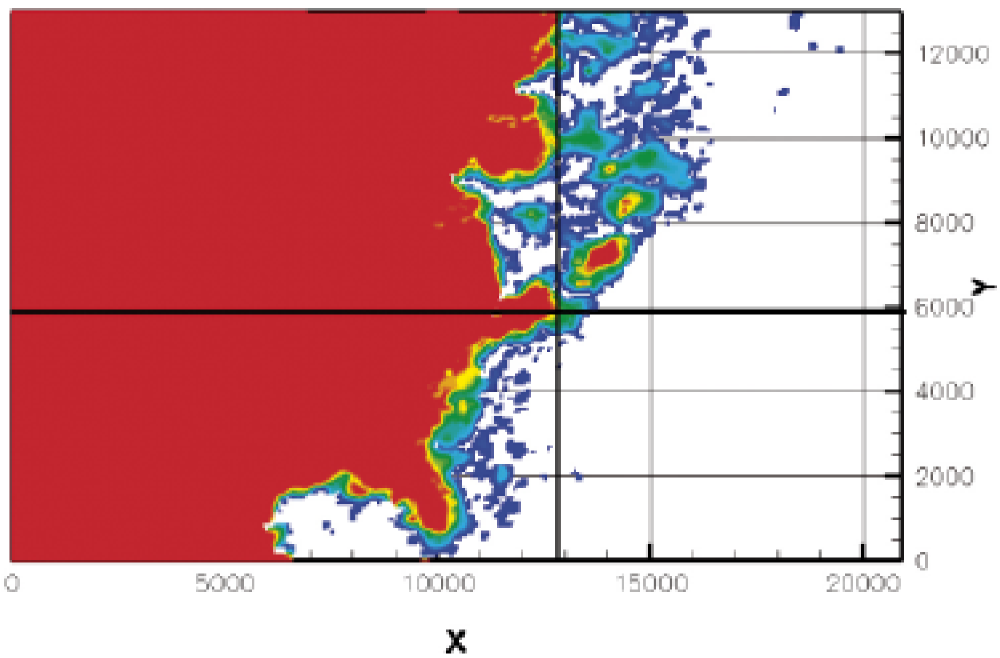

__Figure 4-6.__ The saturation level slightly above sea level. The two black lines show positions of vertical sections. Red colour indicates fully saturated conditions.

The salinity distribution in these two sections is shown in Figure 4-7. The depth of the fresh water is found to increase towards west. In the north-south section we see that the fresh water lens in the repository area ($y \approx 6,000$ m) has a depth of about 200 metres.

Near surface processes include the flow in streams. In Figure 4-8, the flow in streams is shown together with a contour plot of the pressure distributions at sea level. It is found that Laxemarån has the highest flow rate.

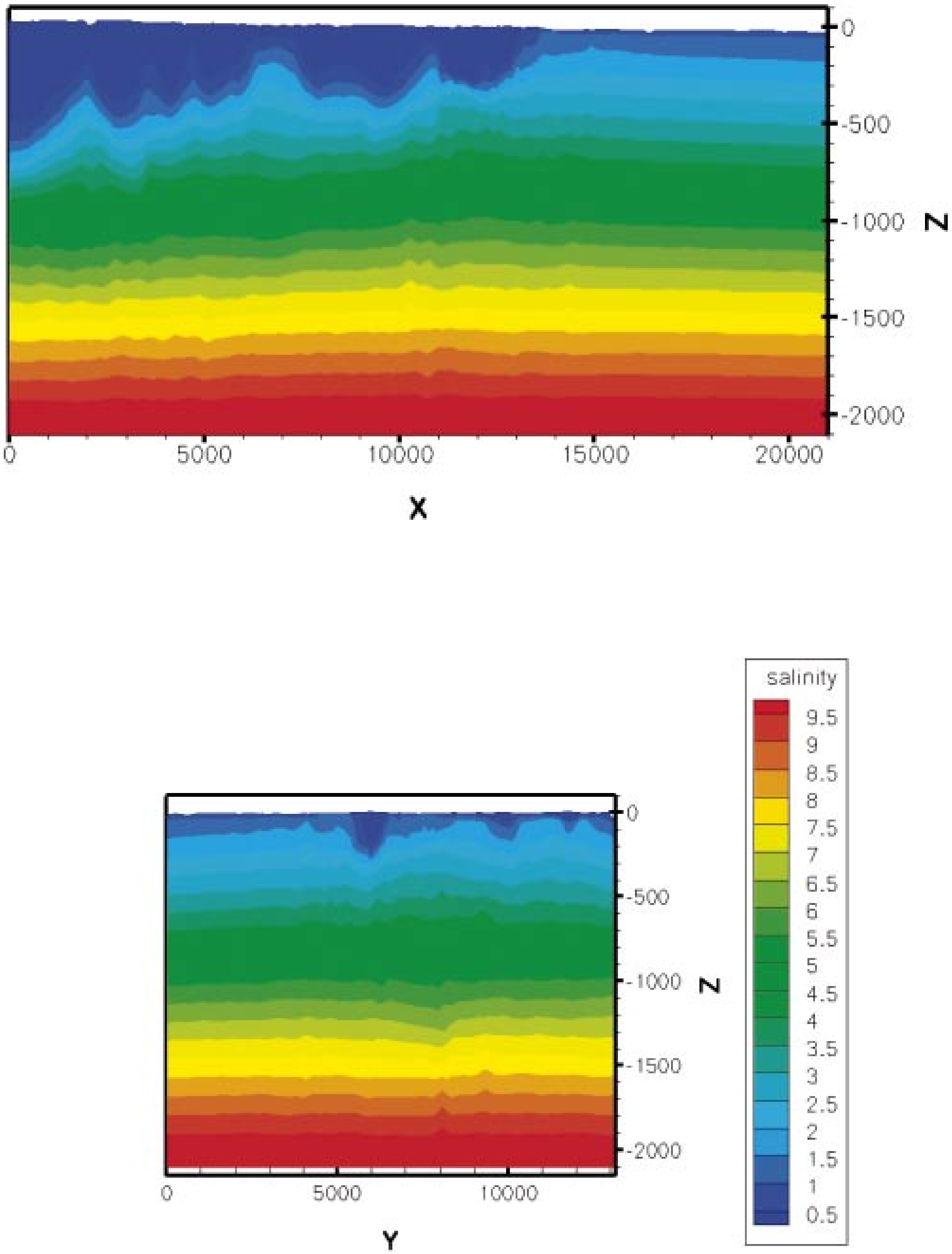

__Figure 4-7.__ Salinity (in %) distribution in a west-east (top) and south-north vertical section through the repository.

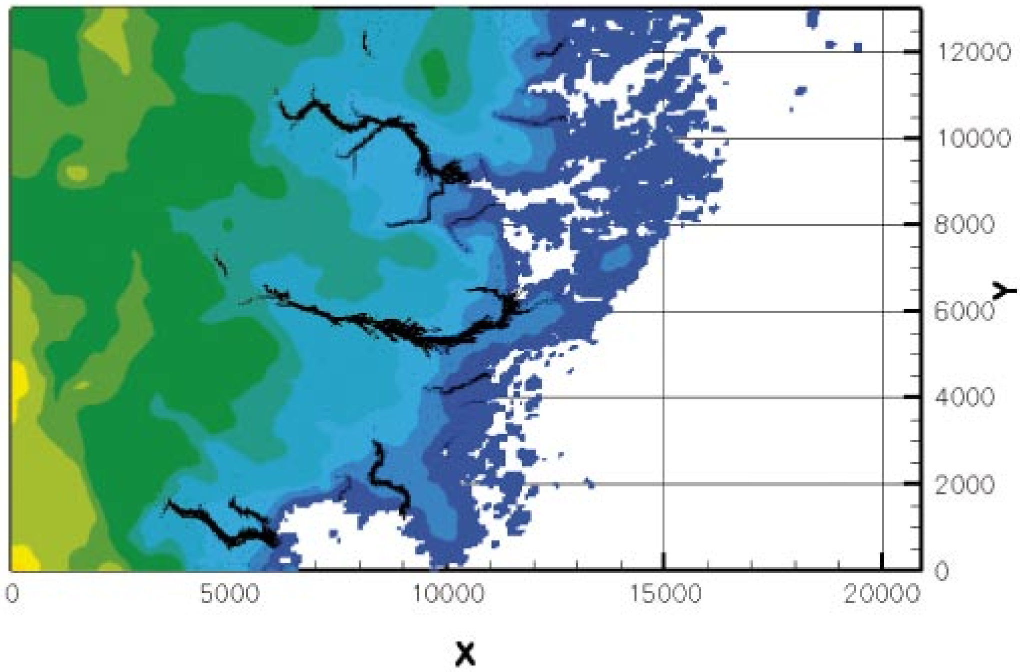

Figure 4-8. *Flow in streams and pressure contours at sea level. Only flow vectors from sea level up to eight metres above sea level are shown. The pressure contours indicate a pressure head that ranges from zero (blue) to about 50 metres (red).*

4.3 Open repository

The main objective of the report is to estimate the effects on an open repository, with respect to “inflow”, “upconing”, “precipitation” and “drawdown”. It will be assumed that the tunnel construction is instantaneous and that the duration of the operational phase is forty years. Hence, we are to simulate a transient process, starting from initial conditions given by the steady state natural situation, discussed above. Results are reported for three skin factors 0.1, 0.01 and 0.001 respectively.

Starting with the total inflow to the tunnel system, we find that it ranges from 7 to 180 l/s, see Table 4-2. Once again, it should be emphasized that these figures will vary with the properties assigned to the fracture network. It should also be remembered that the upper 300 metres of the repository are removed.

The upconing of the salt water to repository level can be studied in Figure 4-9. For a skin factor of 0.001 there is hardly no upconing, while the effect is significant for a skin factor of 0.1.

Table 4-2. Total inflow, as a function of applied skin factor.

Skin factor	Inflow [l/s]
0.1	180
0.01	50
0.001	7

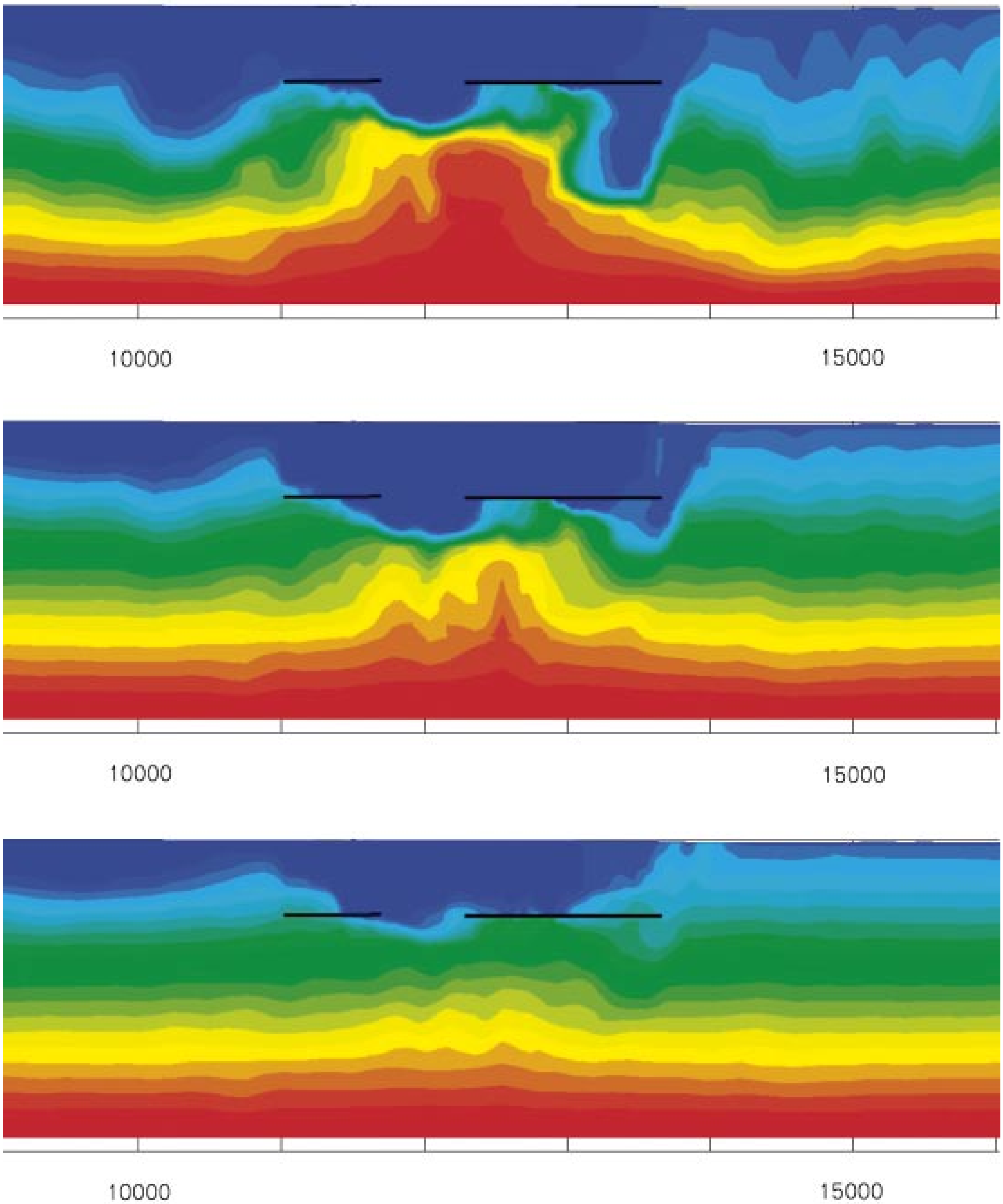

Figure 4-9. *The upconing of salt water. Skin factor put to 0.1 (top), 0.01 (middle) and 0.001. West-east section, specified in Figure 4-6. Salinity legend given in Figure 4-7.*

A similar set of figures is shown in Figure 4-10, where the distribution of precipitation water is found. The figures give the distribution after forty years of tracking of the precipitation water. Once again we find that the strength of the process is related to the skin factor applied.

The effect on the ground water table, the drawdown, can be studied in Figures 4-11, 4-12 and 4-13. It was found that the drawdown for skin factor 0.001 is hardly noticeable and only the results with the two larger skin factors are therefore shown. Two horizontal views of the ground water table, for a skin factor of 0.1, are shown in Figure 4-11. At one metre depth we find that the drawdown is quite extensive. This depth will be used as an indication of "the influence area". At 100 metres depth the area is smaller, as expected. In Figure 4-12, two vertical sections show that the maximum depth of the drawdown is in fact about 250 metres. Reducing the skin factor to 0.01 will have a dramatic effect on the drawdown, as can be seen in Figure 4-13; the maximum depth is now only 10 metres.

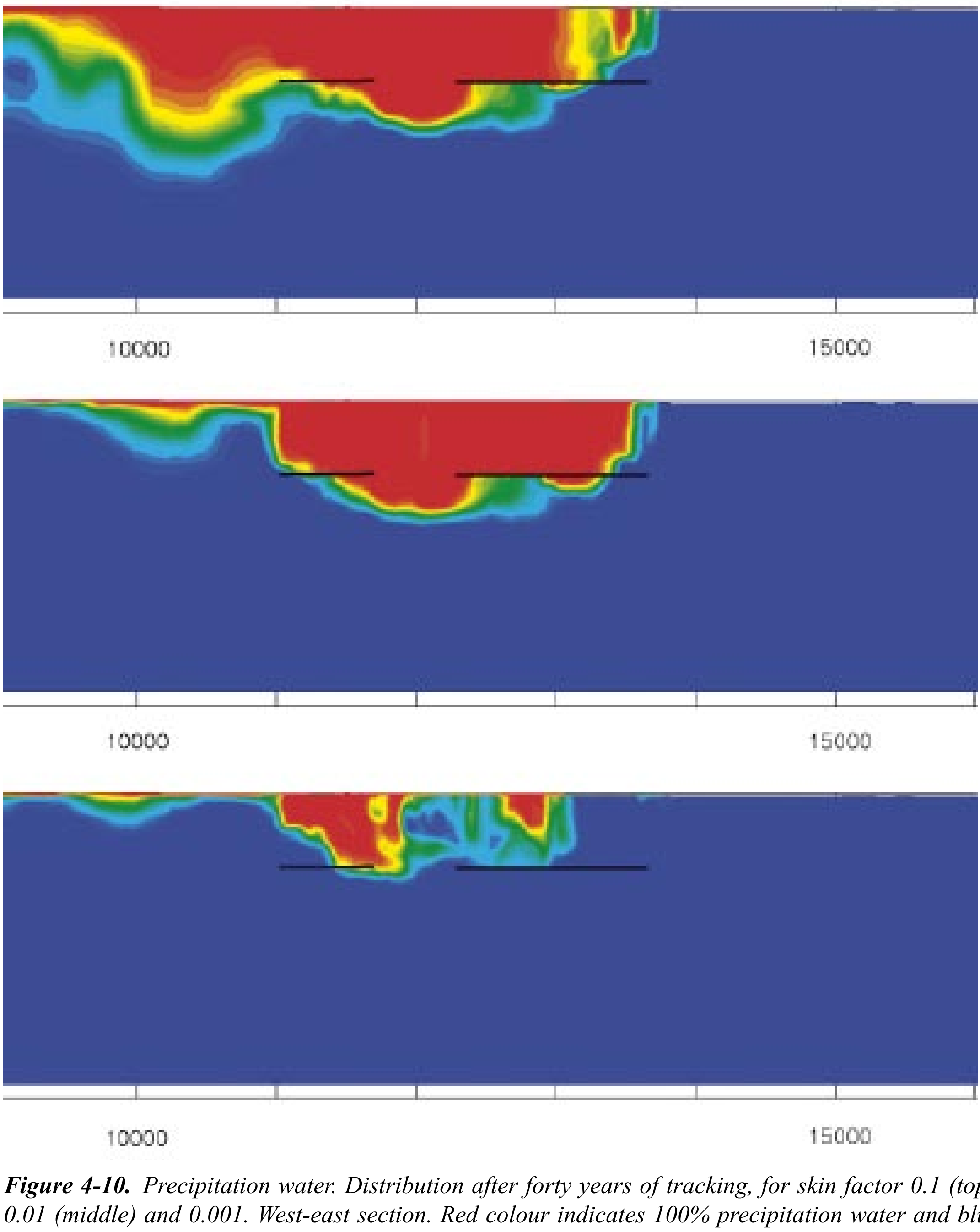

Figure 4-10. *Precipitation water. Distribution after forty years of tracking, for skin factor 0.1 (top), 0.01 (middle) and 0.001. West-east section. Red colour indicates 100% precipitation water and blue colour 0%.*

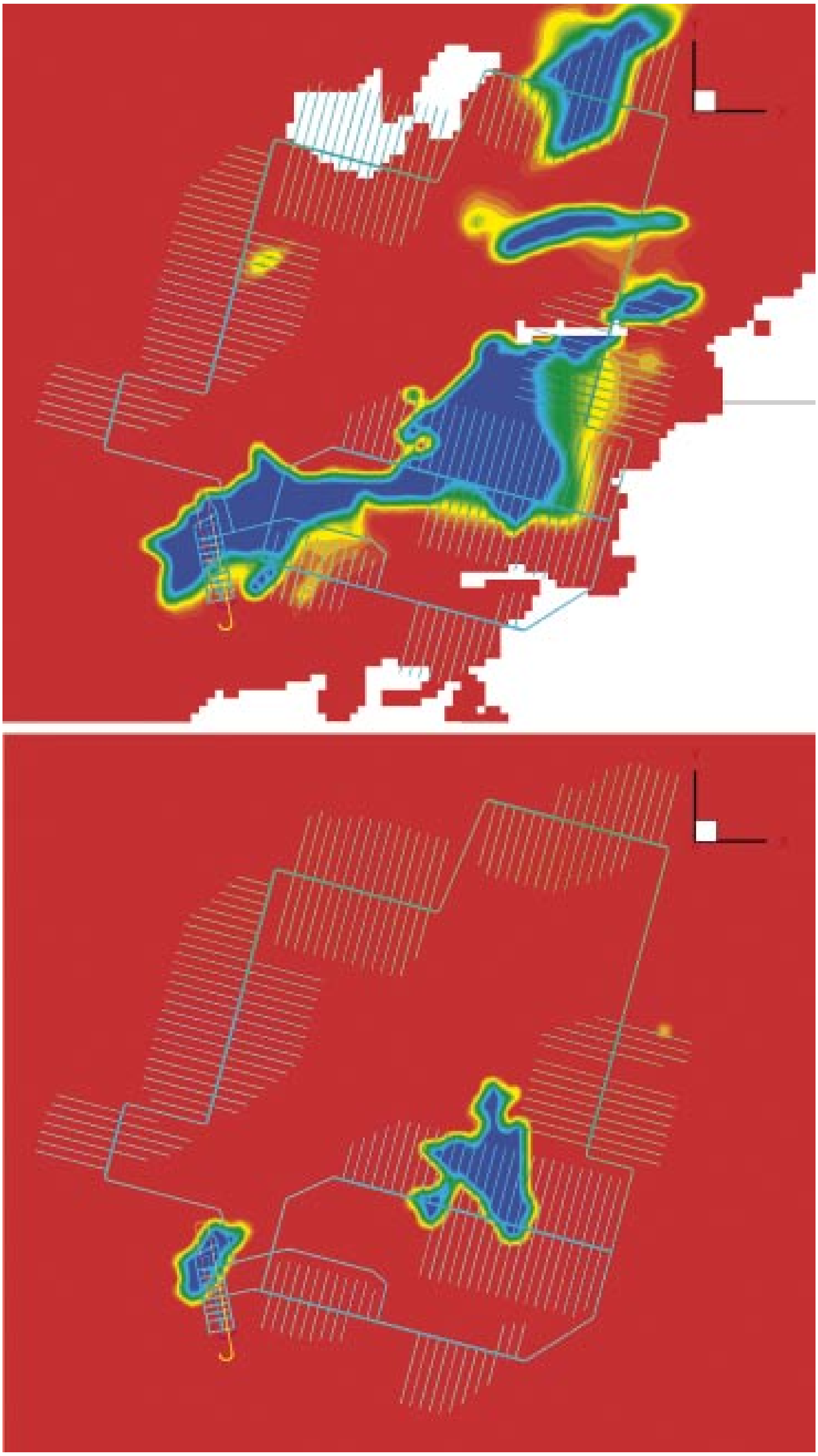

Figure 4-11. *Groundwater table for a skin factor of 0.1. Saturation levels at a depth of 1 metre (top) and 100 metres (m.b.s.l.). Red colour indicates fully saturated conditions and blue fully unsaturated.*

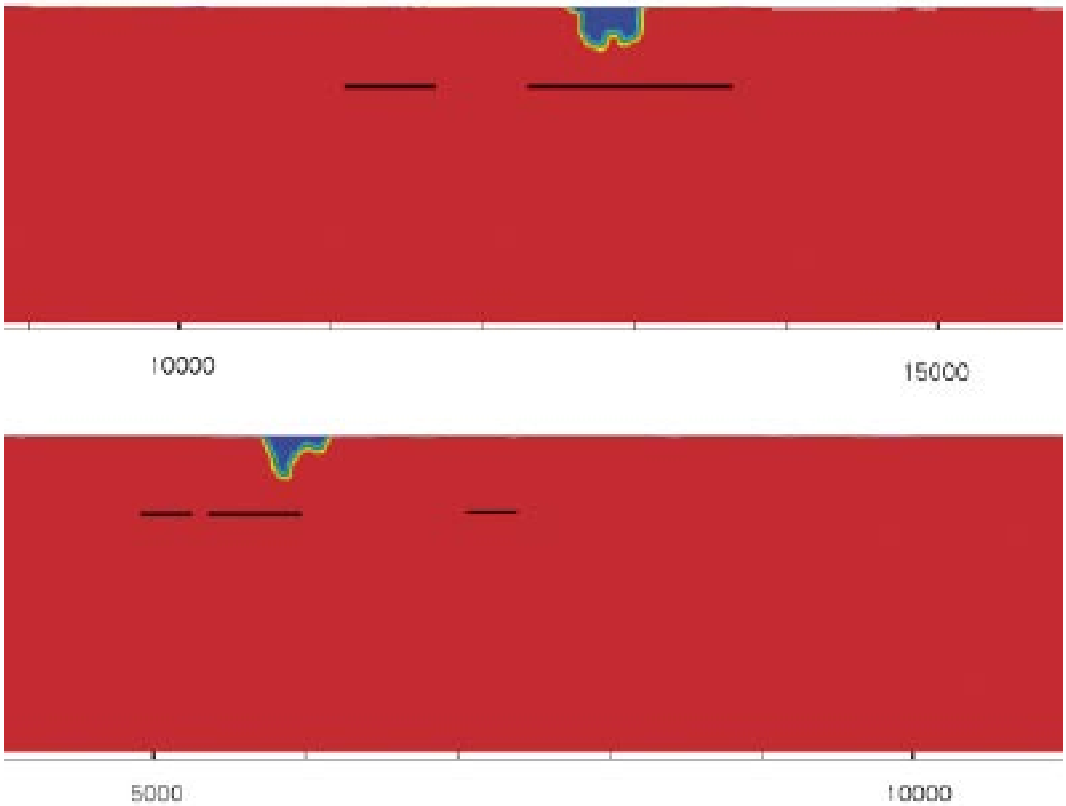

Figure 4-12. Groundwater table for a skin factor of 0.1. West-east (top) and south-north sections through the repository area. Red colour indicates fully saturated conditions and blue fully unsaturated.

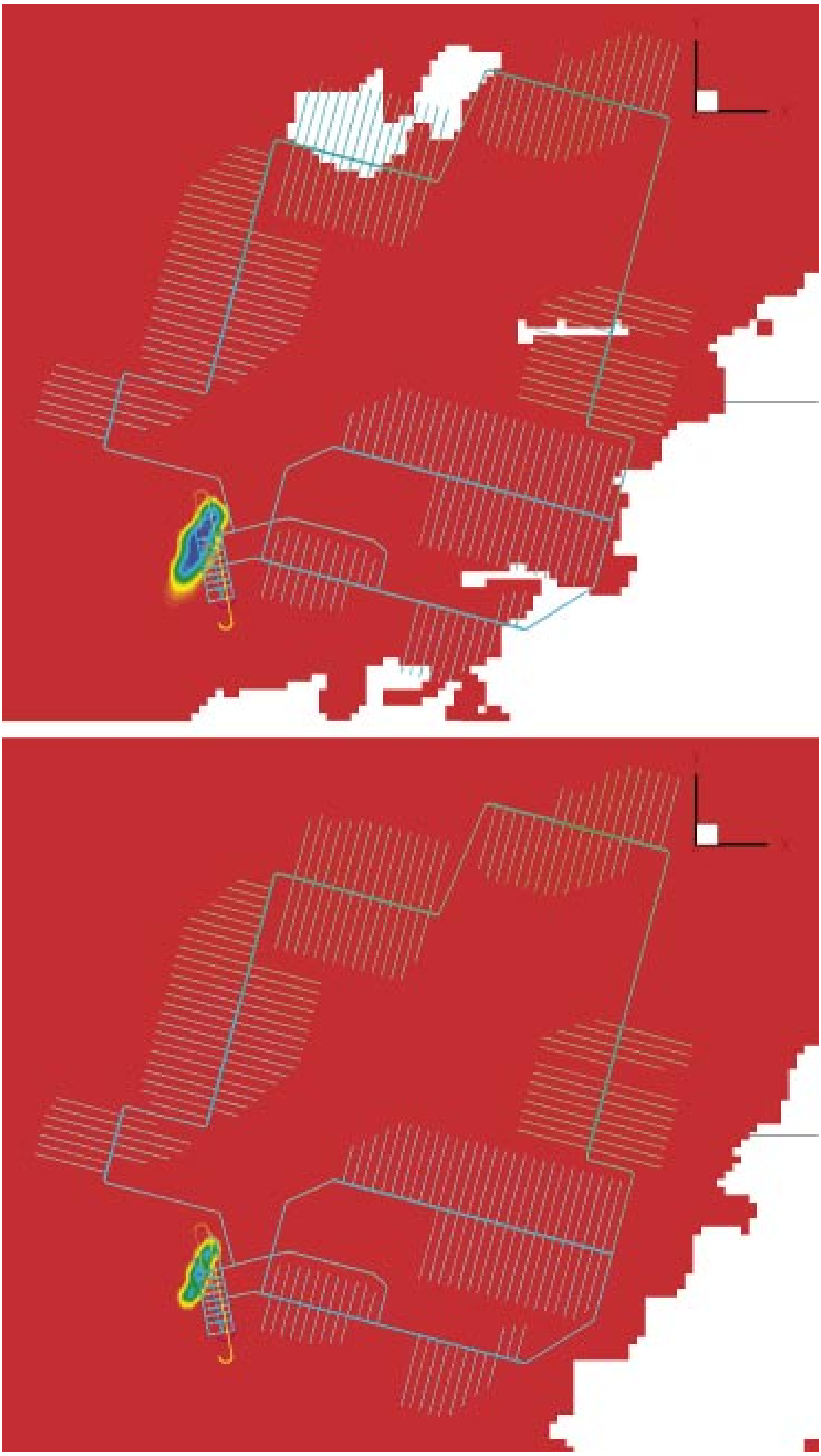

Figure 4-13. *Groundwater table for a skin factor of 0.01. Saturation levels at a depth of 1 metre (top) and 10 metres (m.b.s.l.). Red colour indicates fully saturated conditions and blue fully unsaturated.*

Finally, the pressure and flow distribution in the repository area will be illustrated. In Figure 4-14 the flow at a depth of 515 metres is shown. Ideally this figure should be in a plane that has the same slope as the repository; now it goes through the deposition holes in the northern part of the repository, while it is above the tunnels in the southern part. This is the explanation to the larger flow vectors in the northern part. Anyway, the flow pattern indicated can be compared with the "contact points", shown in Figure 4-5. The pressure distribution at the same depth is illustrated in Figure 4-15. The blue dots indicate deposition holes with atmospheric pressure, which demonstrates that these are resolved individually. One should also note the effect the skin factor has on the recovery of the pressure outside the deposition holes.

An attempt was also made to calculate the effects of the repository on the flow rate of Laxemarån and the water level in lake Frisksjön. The effect on the water level in Frisksjön was found to be below resolution, while it was found that the flow rate in Laxemarån should increase somewhat with the repository present. This may be correct, but certainly needs further analysis.

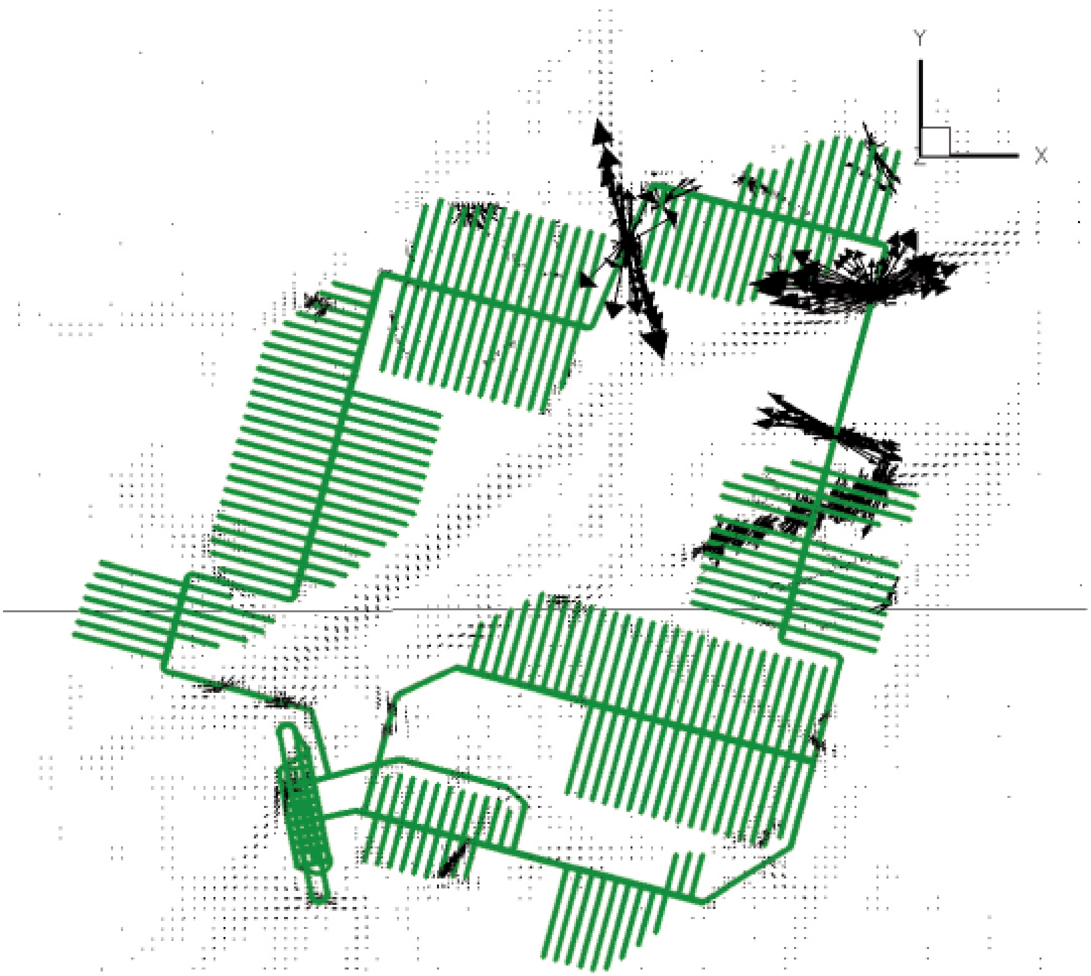

Figure 4-14. *Flow vectors at a depth of 515 metres (m.b.s.l.).*

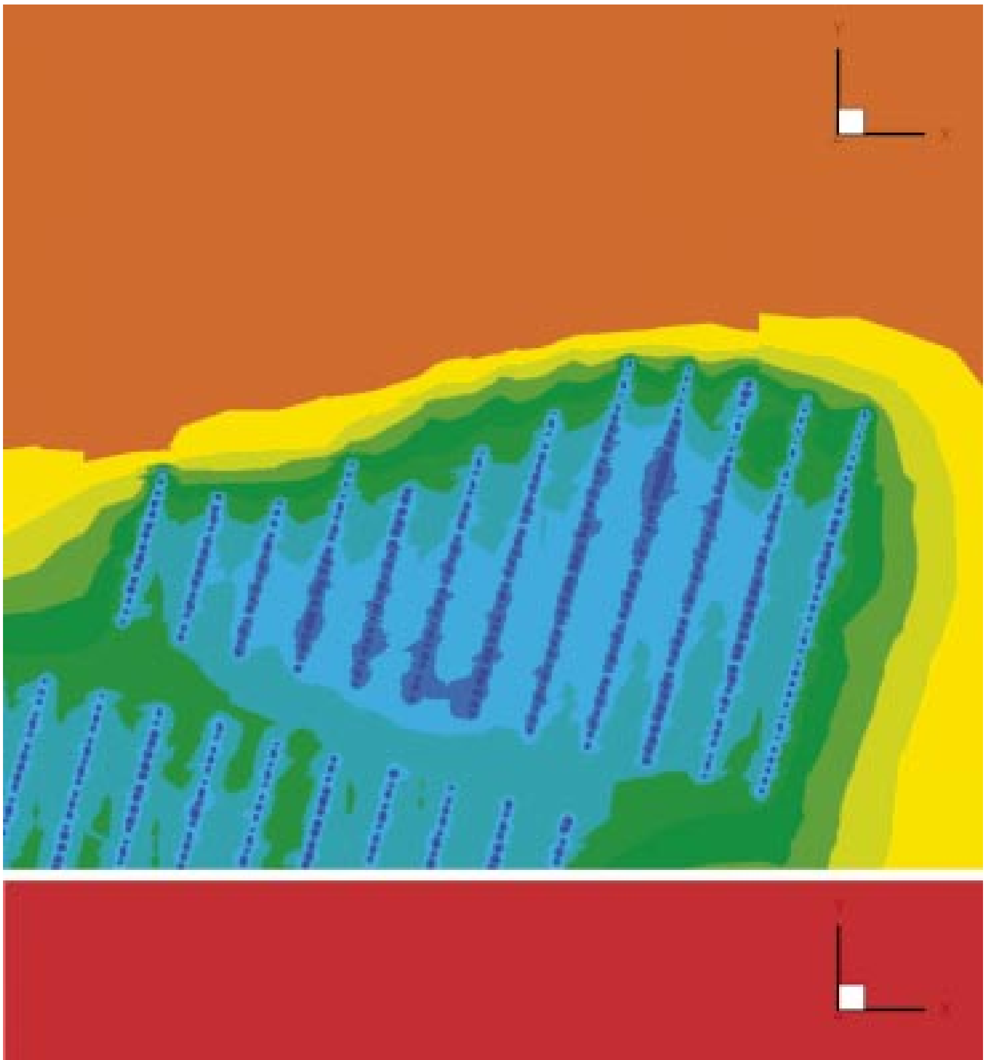

Figure 4-15. *Pressure distribution in the northern part of the repository, at a depth of 515 metres (m.b.s.l.). Skin factor 0.1 (top) and 0.001. The pressure contours indicate a pressure head range from zero (blue), or atmospheric pressure, to a pressure head of about 500 metres (red).*

5 Preliminary sensitivity tests

5.1 Introduction

A proper sensitivity test should evaluate a range of values for the variables believed to be most influential or uncertain. This will not be carried out here. Instead we will note that the results presented show a sensitivity to the total inflow to the tunnel system and then ask "What are the main factors influencing the total inflow?" The following issues will be addressed:

- How will the total inflow change if no deposition holes are present?
- The smallest fracture in the network is 100 metres. What is the effect of adding a local network with l_{min} = 10 metres?
- No grouting. What is the total inflow for a skin factor of 1.0, i.e. no grouting?

For the first two issues a skin factor of 0.1 will be used.

5.2 Results

Neglecting the 6,600 deposition holes will reduce the inflow from 180 l/s to 160 l/s. The reduction is thus fairly small, but seems to have a large effect on the drawdown, see Figure 5-1. The figure should be compared with Figure 4-11, which gives the drawdown with the deposition holes included. The reason for investigating this case is that only a limited number of deposition holes will be open at a certain time interval; holes with a canister are sealed and some holes are still to be drilled.

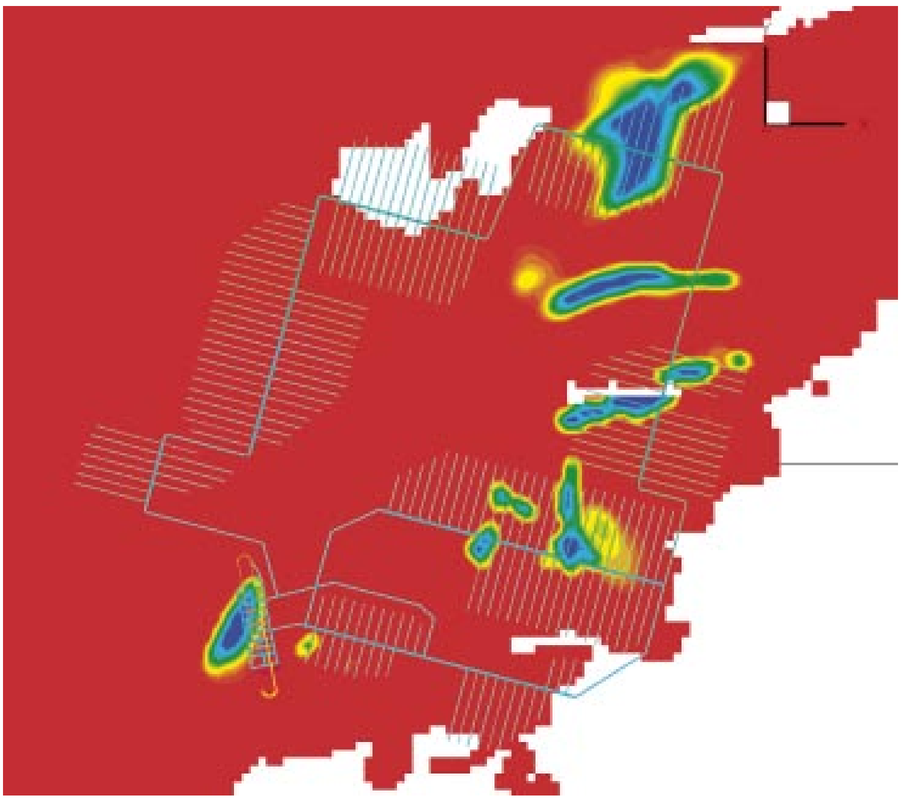

Figure 5-1. *Groundwater table for a tunnel system that excludes deposition holes. Skin factor put to 0.1. Saturation at a depth (m.b.s.l.) of 1 metre. Red colour indicates fully saturated conditions and blue fully unsaturated.*

Next we study the effect of adding a local fracture network with fracture lengths from 10 to 100 metres. The properties of the network are in accordance with the ones used in the Site-descriptive model, in particular one should note that the transmissivity (T) – length (l) relation is given by:

$$T = 5\times10^{-8}\ (l/100)^2 \qquad (5\text{-}1)$$

For a l of 10 metres we thus have a T equal to 5×10^{-10} m^2/s. The network was added to a volume of 3,000×3,000×300 m^3, centred on the repository. The number of contact points between the fracture network and the tunnel, discussed earlier, will now increase from 7% to 17%. An illustration is given in Figure 5-2, which can be compared with Figure 4-5. The local fracture network consists of 160,490 connected fractures. However, the total inflow to the tunnel system was not affected by the addition of the local network (still 180 l/s). It is not obvious why this is the case, but maybe the transmissivities of the added fractures are too low to influence the inflow.

Finally a simulation with the skin factor put to 1.0, i.e. no grouting, will be discussed. This is not a realistic scenario, but it is of interest as a reference. The total inflow for this case was predicted to 330 l/s. The maximum drawdown was about 400 metres and was hence approaching repository depth.

5.3 Conclusion

The simulations in this section indicate how sensitive the total inflow is to some of the assumptions that are a part of the model. The most surprising result is probably that the total inflow was not affected by the addition of a local fracture network. However, guided by the analytical solution for tunnel inflow in a porous media, one can expect that the transmissivities assigned to the fractures is the crucial step. Equation 5-1 gives, in the author's view, rather low transmissivity values.

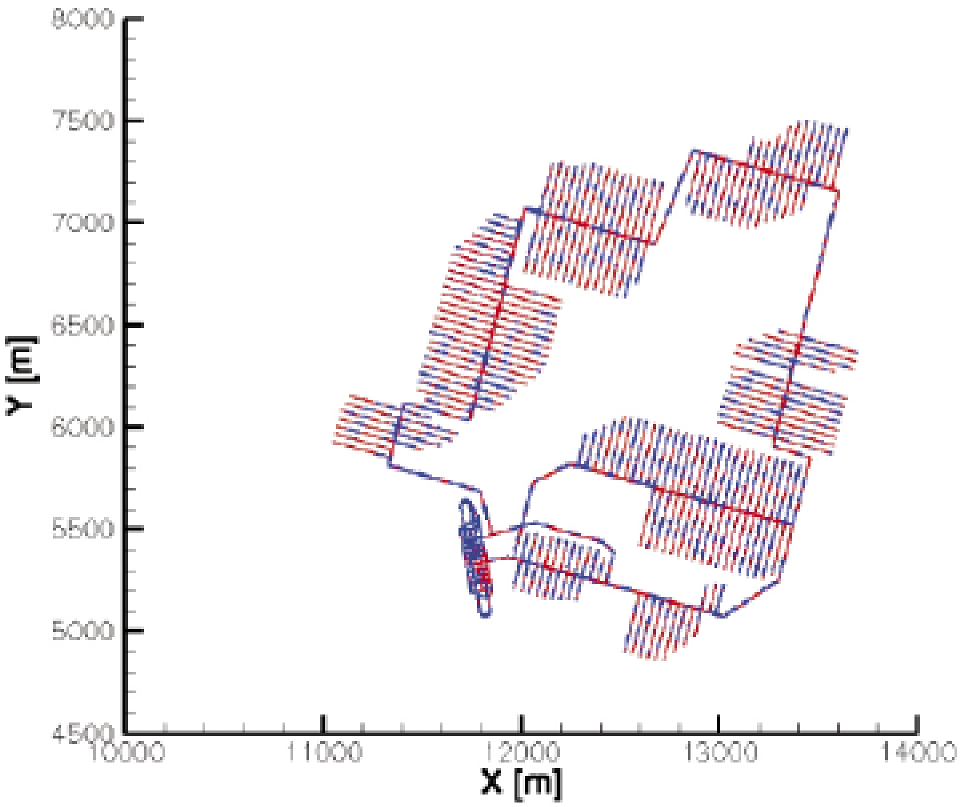

Figure 5-2. *Contact points (blue) between the tunnel system and the fracture network, including a local network.*

6 Discussion

6.1 General

In the author's view the study presented should mainly be considered as a feasibility study, which opens the road for a detailed description of processes related to an open repository. To the author's knowledge it is the first time thousands of deposition holes and long tunnel systems (60 km in the present model) are described individually and also linked to surface hydrological processes. No transport simulations are reported here, but it is clear that the present model can be used to simulate transport from individual canisters that are in contact with the connected fracture network, all the way up to a stream.

6.2 Uncertainties

From the above, one may conclude that it is too early to draw any firm conclusions from the results presented. Before we can have confidence in the simulation results a number of issues need to be revisited and analyzed. A list of such issues includes:

- The fracture network. All aspects of the fracture network need to be improved upon.
- Calibration. A model study without comparisons with field data is incomplete.
- Sensitivity studies. A model study without sensitivity studies is incomplete.
- Discretization in space and time. Ideally all simulation studies should demonstrate how sensitive the results are to the discretization used.

These are some very general aspects of the uncertainties that may influence the predictions.

6.3 Software

DarcyTools Version 3.0 has been used in this study and as this is the first major project that uses Version 3.0 a few remarks about the code may be in place.

- The problem is fully specified by the so called CIF (Compact Input File) and does not require any FORTRAN coding. However, the generation of some input files requires a number of small "service programs".
- A typical run needs about 500 MB of RAM memory. The simulation time for a transient run, with a time step of four months and covering forty years, is about 15 hours. Any standard PC can hence be used for the kind of simulations reported here.
- The visualisation features are still a bit limited.

7 Concluding remarks

With reference to what was stated in the Discussion section, we will refrain from drawing any conclusions about the simulation results; let us instead consider these as illustrations of what can be achieved.

In the author's view the main conclusions of the study concern the methodology. It has been demonstrated that the requested type of simulations can be performed efficiently. In particular, it is the introduction of unstructured grids that are generated directly from geometries specified by CAD files that opens new possibilities. The transport of radionuclides from a canister to ground level was mentioned earlier. With the new methodology, one can store the coordinates of the flow paths and then generate a new grid with a high resolution around one or all flow paths. A high resolution transport model can hence be integrated in a model of the kind presented in this report.

References

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