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ABSTRACT

The purpose of the present study is to roughly estimate the flux through a radioactive repository in relation to the flux into a local well under various conditions. The well is assumed to be located at a depth of either 60 or 200 metres below the ground surface. Two main settings are considered, in one the well is located above the centre of the repository, and in the other it is located in a vertical fracture zone at a distance of 100 metres from one of the outer edges of the repository. It is assumed in the calculations that the well is the only cause of the groundwater flow. The withdrawal from the well is assumed to be 6 m^3/day.

The flow domain is characterized by a rather low permeability, which is assumed to decrease with depth over the flow domain. The boundary conditions considered are either a continuously saturated upper boundary and impervious lateral boundaries, or a phreatic upper boundary and hydrostatic lateral boundaries. In all examples an impervious bottom is assumed to be located at a depth of 1500 metres below the ground surface, and the repository is assumed to be located at a depth of 500 metres. The areal extent of the repository is 0.8 km^2 in the first setting and 1 km^2 in the second one. The areal extent of the flow domain is 1.1 km^2 in the first setting and 12 or 24 km^2 in the second one.

The ratio of the flux through the repository to the flux into the well was obtained to be in the range from about 10^{-5} to 10^{-3}, depending on the boundary conditions and the depth of the well. The lowest figures were obtained in the examples, in which the upper boundary was assumed to be continually saturated. It is concluded that these examples may be considered representative of the actual flow problem. This conclusion is based upon the fact that in the case of a phreatic boundary the drawdown caused by the well was very small and the flow responses were very slow, implying that rather a small infiltration rate is required to maintain saturated conditions at the upper boundary. The regional gradients caused by the well were rather small in comparison with the typically naturally occurring gradients. The flow to the well will therefore have little influence on the regional flow pattern in most practical cases.

CONTENTS

SUMMARY

Introduction

The purpose of the present study is to estimate the ratio of the flux through a repository for storage of radioactive waste to the flux into a local well under various conditions. The problem is studied for a set of idealized flow situations, which means that no specific site is referred to in the analysis.

The well is assumed to be located at a depth of either 60 or 200 metres below the ground surface. The repository is assumed to be located at a depth of 500 metres below the ground surface in all of the examples. An impervious bottom is imagined to be located at a depth of 1500 metres below the ground surface. The flow domain is characterized by a low permeability, which is assumed to decrease with depth.

Two main settings are considered, in one the well is symmetrically located above the centre of the repository, and in the other the well is located in a vertical fracture zone situated at a distance of 100 metres from one of the outer edges of the repository. The permeability in the fracture zone is assumed to be 100 times higher than that in the surrounding rock formation. The geometrical properties of the flow domain are such that the three dimensional nature of the flow problem must be accounted for. The flow problem is therefore solved in three dimensions in both settings.

Several examples are worked out for each setting to illustrate the influence on the flow problem of the boundary conditions, especially with regard to the upper and lateral boundaries of the flow domain. Two highly idealized situations are considered, in one the upper boundary is phreatic and the lateral boundaries hydrostatic, in the other the upper boundary is coincident with the ground surface and assumed to be continuously saturated. In the latter case the lateral boundaries are treated as impervious (no-flow) boundaries.

Results

In the examples with the well located above the middle of the repository, the ratio of the flux through the repository to that of the well varied between about 10^{-5} and 10^{-3}. The lowest values were obtained in the examples where the upper boundary was assumed to be continually saturated and the lateral boundaries impervious. Consequently, the highest values were obtained in the examples in which the upper boundary was phreatic and the lateral boundary hydrostatic.

In the examples with the well located in an adjacent fracture zone, the ratio of the flux through the repository was again obtained to be in the range from about 10^{-5} to about 10^{-3}. As in the previous set of examples the lowest values were obtained in the examples in which the upper boundary was assumed to be continually saturated and the lateral boundaries impervious. In all of the examples in the second setting, the well was represented by a single point sink located at the bottom of the considered well.

Self-evidently, the highest fluxes through the repository are obtained in the examples with the well is located at 200 metres depth in comparison with the examples with a well at 60 metres, and especially with the flux into the well is represented by a single point sink at the bottom of the well. For instance, in the setting where the well was located at a depth of 200 metres in an adjacent fracture, the flux through the repository was about 80 times higher than that of a well at a depth of 60 metres.

In the setting where the well is located above the centre of the repository with a saturated upper boundary and an impervious lateral boundary, the fluxes through the repository caused by the 200 metres well were about 20 times larger than that of the 60 metres well with distributed influx into the well, and about 100 times larger with concentrated influx into the well.

When the upper boundary was phreatic and the lateral boundary hydrostatic, the fluxes were practically the same in the examples in which the well was represented by several point sinks, and the flux attributed to the 200 metres well was only about 1.2 times the flux attributed to the 60 metres well. The corresponding factor for single point sinks was about 7, i.e. the flux attributed to the 200 metres well was about 7 times the flux attributed to the 60 metres well with each well represented by a single point sink.

The results of the present investigation show that the boundary conditions have great influence upon the flow problem. The remainder of this chapter will therefore be devoted to a discussion about the various assumptions made in the study and their significance to the results.

Discussion

The assumption that the upper boundary is continuously saturated requires in principle a continuous supply of water at this boundary and that the rate of the accretion is sufficient to maintain the water table at the ground surface. This means that only a very small part of the flow to the well will pass through the repository. This fact is particularly emphasized with regard to the assumed relationship between permeability and depth over the flow domain. Thus, the permeability at the level of the repository (500 metres) is roughly about 10000 times lower than the permeability at the ground surface, or rather the uppermost 25 metres as constant permeability is assumed in this region.

The fact that the upper boundary is phreatic implies that the level and shape of this boundary is unknown and part of the problem to be solved. As no accretion to the phreatic boundary is prescribed in the examples, all water to the well must come from the lateral hydrostatic boundaries. An obvious consequence is then that a larger portion of the water flowing to the well will pass through the repository than in the previous case with a fully saturated flow domain. Moreover, the more the water table will be lowered, the larger the fluxes through the repository will become.

To which of the two previous approaches to attach the greatest attention is dependent on the flow parameters. For moderate withdrawal rates and a continuous supply of water at the ground surface, the examples based on full saturation may be appropriate. Conversely, for high withdrawal rates and periods of little infiltration at the ground surface it may be necessary to consider the examples with a phreatic boundary in the upper region of the flow domain.

The approach with hydrostatic boundaries corresponds to a situation where the repository is circumvented by a water filled fracture zone. However, such a situation is very difficult to imagine at the prospective sites for radioactive waste repositories. On the other hand, the approach with constant saturation at the ground surface is unrealistic from the point of view that in practice there will always occur periods when the accretion to the ground surface will be insufficient to maintain the water table at the ground surface. In conclusion, one may say that the two approaches represent two rather extreme flow conditions, with regard to the boundary conditions.

The examples worked out for transient flow conditions indicate that the flow responses, especially at the repository, are very slow under the present circumstances. The regional drawdown caused by the well was very moderate, implying that rather small an infiltration rate will be required to maintain the water table close to the ground surface. This means that it seems appropriate to assume that the examples, in which the flow domain was assumed to be continually saturated may be considered representative of the actual flow problem, and that these examples may be used to estimate the amounts of water that may pass through a repository into a local well.

The main reason for not just simply prescribing the rate of accretion to the upper boundary is related to the uncertainty of this parameter. Consequently, there are no data available regarding the order of magnitude of this parameter at any of the test areas for prospective sites. It should be pointed out the same problem applies also to the hydraulic properties of rock under unsaturated conditions.

A rough comparison between the regional flow gradients caused by the well and the gradients associated with the naturally occurring groundwater flow, indicates that the flow to the well will in general have very little influence on the naturally occurring groundwater flow, which in most cases will dominate the flow pattern. This means that if the repository and the well are located below a regional inflow area, there will be practically no flow at all from the repository to the well.

NOMENCLATURE

Symbol	Explanation		
c^f	fluid compressibility	$M^{-1}LT^2$	Pa^{-1}
c^r	rock compressibility	$M^{-1}LT^2$	Pa^{-1}
g	acceleration of gravity	LT^{-2}	ms^{-2}
k_{ij}	permeability tensor	L^2	m^2
p	pressure	$ML^{-1}T^{-2}$	Pa
p_c	capillary pressure	$ML^{-1}T^{-2}$	Pa
Q	mass source	MT^{-1}	kgs^{-1}
S	water saturation	-	-
S'	derivative of saturation versus pressure $S' = \frac{dS}{dp}$		
t	time	T	s
T^f	temperature of the fluid	K	K
z	elevation (z=0 at ground surface)	L	m
β	coefficient of thermal volume expansion	K^{-1}	K^{-1}
μ	dynamic viscosity	$ML^{-1}T^{-1}$	Pas
ρ^f	fluid density	ML^{-3}	kgm^{-3}
ϕ	porosity	-	-

subscripts

i,j	indices used for Cartesian tensor notation, repeated indices indicate summation over these indices (i=j=1,2,3)

$p_{,t}$ partial time derivative of p

$p_{,j}$ gradient of p

1. THE FLOW PROBLEM

1.1 Introduction

The purpose of the present study is to roughly estimate the fluxes that may occur through a hypothetical radioactive waste repository in relation to the withdrawal from a local well. The well is assumed to be the only cause of the groundwater flow in the numerical examples worked out. For simplicity, it is assumed in the calculations that the well is subject to a continuous withdrawal of water.

Two main settings are considered, in one the well is located above the centre of the repository (see Figure 1), and in the other it is located in a vertical fracture zone at the side of the repository (see Figure 2). The present study has mainly been carried out for demonstrative purposes and do not refer to any specific site, but the relationship between rock permeability, the key parameter in the study, and depth has been taken from the Fjällveden study site.

1.2 Geometrical characteristics of the flow domain

The repository is assumed to be located at a depth of 500 metres below the ground surface, and the well is assumed to be located at a depth of 60 metres, or, alternatively, at a depth of 200 metres below the ground surface. An impervious bottom of the flow domain is imagined to be located at a depth of 1500 metres below the ground surface.

In the examples where the well is located above the centre of the repository, it is assumed that the flow is axi-symmetric around the well. In these examples, the repository is represented by a disc, whose radius is 500 metres. The lateral extent of the flow domain is 600 metres. The areal extent of the repository and the flow domain are then about 0.8 km^2 and 1.1 km^2, respectively. The lateral boundary is assumed to be either hydrostatic or impervious.

A hydrostatic lateral boundary is imagined to represent a water-filled fracture zone. However, in the case of saturated conditions prescribed at the upper boundary, the lateral boundary was considered impervious. This means that the two different flow conditions considered represent two rather extreme situations, one in which all water to the well comes from the lateral boundaries, and another in which all water comes from the upper boundary.

In the examples with a vertical fracture zone alongside of one of the outer edges of the repository, the impervious bottom is located at the same depth as in the previous examples, i.e. at a depth of 1500 metres below the surface. The repository is located at a depth of 500 metres below the surface, and it has a total extent of 1 km^2. These examples are constructed such that a symmetry plane may be considered along the middle of the fracture zone. The numerical calculations may therefore be limited to 1/4 of the total flow domain. Two cases are considered, in one the horizontal extent of the flow domain considered is 12 km^2, and in the other it is 24 km^2.

1.3 The well

The withdrawal at the well is assumed to be 6 m^3/day. This figure is chosen with regard to the low permeability and strong decrease in the permeability with depth over the flow domain. The flow domain may therefore be considered unsuitable for water supply, and it is in principle only possible to imagine a well with a comparatively low capacity and located in the shallow region of the flow domain.

In practice, the distribution of fluxes along a well is unknown and part of the problem to be solved. It may be continuous as well as discontinuous depending on the characteristics of the rock formation considered. In a rock formation, such as granite, it is, however, likely that the flow into the well will take place in a limited number of fractures intersecting the borehole.

This means that the modelling of the flow to a borehole in a fractured rock formation requires that every fracture, as well as its physical properties, of significance to the flow be identified and included in the analysis. Such a detailed investigation of the flow to the borehole is beyond the scope of the present investigation, which primarily is directed towards calculation of the flow through a hypothetical radioactive waste repository. This means that the detailed flow conditions at the well are of little interest. It is in the first place the regional effect of the withdrawal from the well that is to be studied in the present flow problem.

Therefore, to simplify the calculations, the flux into the well is concentrated to a single point at the bottom of the borehole, or to a few points along the borehole. In the proximity to the well, this approach may result in flow patterns that may differ from the actual ones, but far from the well the fluxes will be practically indifferent to the representation of the well.

However, in the examples with single point sinks the withdrawal from the well is probably localized to greater depths than can be physically justified with regard to the very low permeability in the lower region in relation to the permeability in the upper region of the flow domain. This means that the computed fluxes through the repository will be overestimated in these examples.

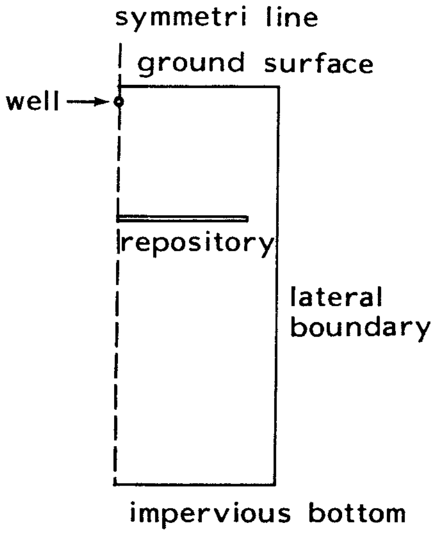
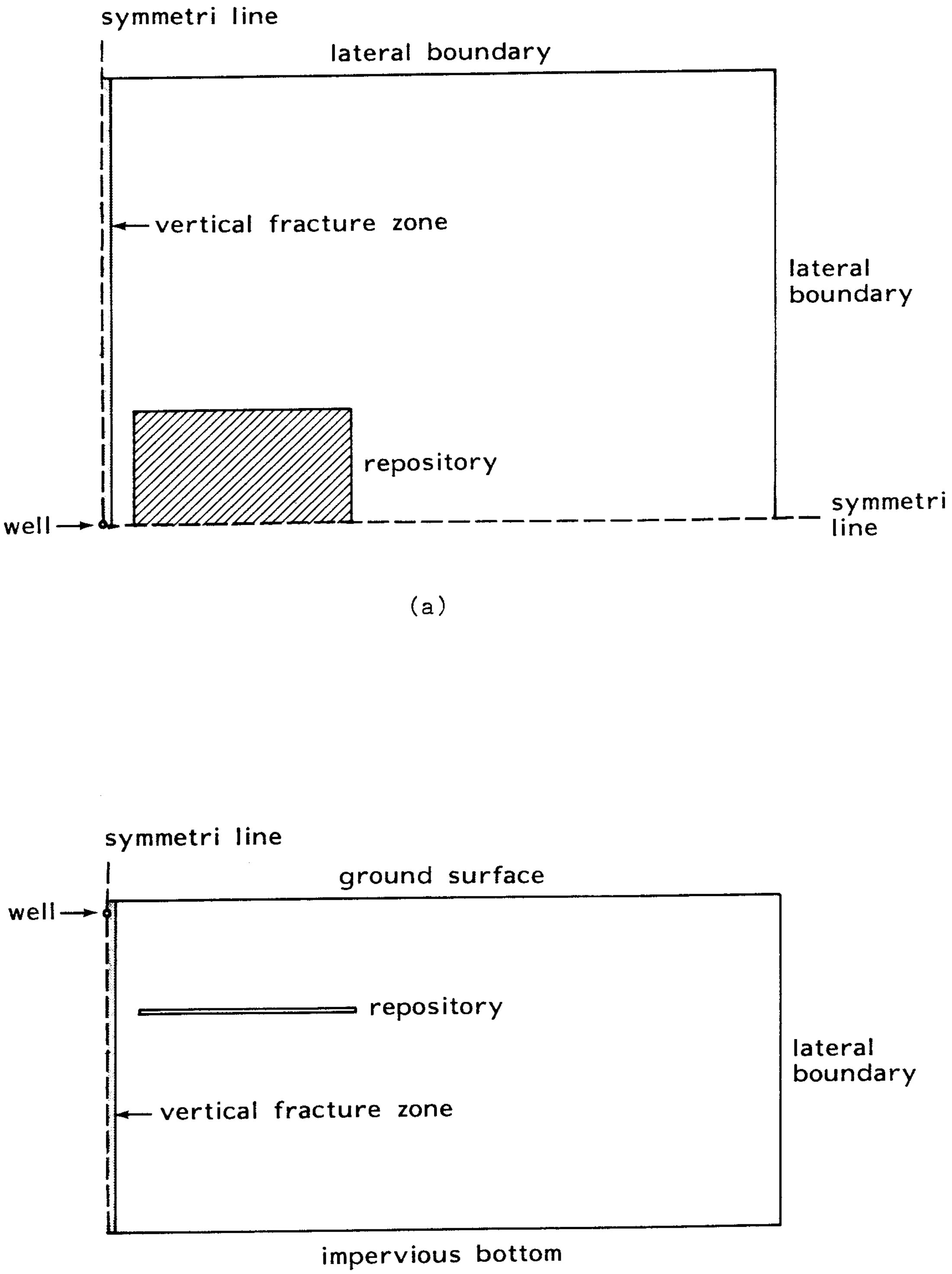


Figure 1. Schematic representation of the geometrical characteristics of the flow domain with a well located above the centre of the repository.



(a)

(b)

Figure 2. Schematic representation of the geometric characteristics of the flow problem with a well located in a vertical fracture zone, showing (a) a horizontal cross-section and (b) a vertical cross-section of 1/4 of the total flow domain.

1.4 The flow model

The calculations have been carried out by means of a modified version of the numerical model for the flow of groundwater and heat developed by Thunvik and Braester (1980). In the modified version of the model the groundwater flow is described by the following non-linear partial differential equation

$$\phi\rho^f(S(c^f + c^r) + S')\, p_{,t} - \phi S\rho^f\beta\, T^f_{,t} +$$

$$+ (\rho^f \frac{k}{\mu}_{ij}\, (p_{,j} - \rho^f g_j)_{,i} + Q = 0$$

where fluid compressibility is defined as

$$c^f = \frac{1}{\rho^f} \frac{\partial \rho^f}{\partial p}$$

rock compressibility is defined as

$$c^r = \frac{1}{\phi} \frac{d\phi}{dp}$$

and the coefficient of thermal volume expansion is defined as

$$\beta = - \frac{1}{\rho^f} \frac{\partial \rho^f}{\partial T^f}$$

For explanation of the rest of the symbols see the nomenclature. The flow equation is solved numerically by the Galerkin finite element method. The numerical formulation of the flow equation leads to an algebraic system of equations, which is solved by Gauss elimination, using the frontal method. The non-linearitites, arising from the fact that permeability and capillary pressure are functions of saturation, are treated iteratively either by a direct iteration technique, using weighted averages on the most recent iterations, or by a Newton-Raphson iteration technique. A more detailed description of the model formulation is given in the above-mentioned report by Thunvik and Braester (1980) and will therefore not be given here.

1.5 Input parameters

The key parameter in the present study is permeability. The following relationship between permeability and depth is assumed

$$k = k_o * (-z)^{-2.78}, \qquad z < -25$$

where k is permeability, k_o is a reference value of the permeability and z is the elevation with reference to the ground surface. Constant permeability is assumed until a depth of 25 metres. The parameter values used in the numerical examples are summarized in Table 1 below.

The hydraulic characteristics of the unsaturated flow conditions were initially assumed to be homogeneous over the flow domain, despite the rather strong decrease in permeability with depth. The decreasing permeability with depth implies also that porosity is decreasing with depth. This means that the relationship between capillary pressure and saturation also will change with depth over the flow domain. However, in the preliminary numerical examples worked out, the water table never went below the zone of constant permeability. This region is therefore tacitly assumed to consist of a homogeneous soil, which means that what is assumed to be rock never will be subject to unsaturated flow conditions.

Table 1. Material properties

Reference value of permeability (k_o)	$1.5*10^{-10}$	m^2
Porosity	0.001	-
Dynamic viscosity	0.001	Pas
Acceleration of gravity	9.81	m/s^2
Fluid density	998	kg/m^3
Rate of withdrawal from the well	6.0	m^3/day
Fluid compressibility	10^{-10}	Pa^{-1}
Rock compressibility	10^{-10}	Pa^{-1}
Coefficient of thermal volume expansion	0.0	

As already pointed out, permeability is a function of saturation. In the flow model permeability is expressed as

$$k_{ij} = k^{s}_{ij}\, k^{rel}(S) \;, \quad 0 < k^{rel} < 1$$

where k^{s}_{ij} is the permeability at full saturation (S=1) and k^{rel} is the relative permeability being a function of the water saturation (S). The relationships between the relative permeability and saturation, and the capillary pressure and saturation are shown in Figure 3.

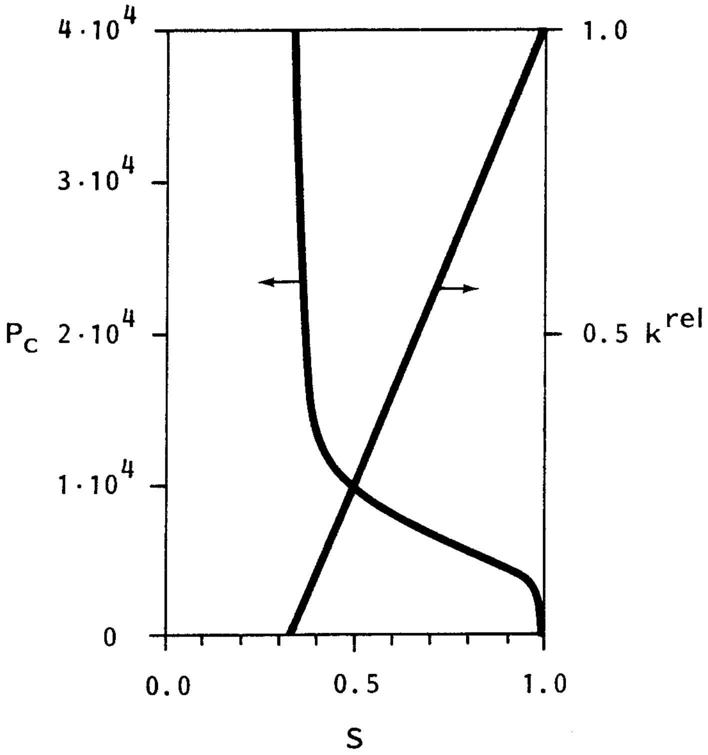


Figure 3. Relationships between relative permeability (k^{rel}) and saturation (S), and between capillary pressure (p_c) and saturation (S).

2. NUMERICAL EXAMPLES

2.1 Introduction

The numerical calculations were carried out by solving the equation of the groundwater flow for the initial and boundary conditions as have been described in the previous chapter. The study is particularly directed towards studying the fluxes through the repository in relation to the withdrawal from the well.

The total flux through the repository is obtained by integration of the normal fluxes through a horizontal cross-section, representing the repository. The withdrawal from the well is represented either by a single point sink at the bottom of the well or by several points sinks along the well. The mass balance is checked by integration of the normal fluxes along the exterior boundaries.

In some examples the normal fluxes through the repository are directed upwards (positive) in one part of the repository and downwards (negative) in another. To avoid cancelling of positive fluxes by negative ones, the integration was performed for the absolute values of the normal fluxes through the repository. This may in the worst case lead to an overestimation of the total flux through the repository by a maximum of a factor two.

The results of the calculations are presented in four sections. The first two sections (2.2 and 2.3) deal with the setting where the well is assumed to be located above the centre of the repository. Section 2.2 deals with the case where the well is assumed to be located at a depth of 60 metres and section 2.3 deals with the case where the well is assumed to be located at a depth of 200 metres below the ground surface. As for the rest of the geometrical properties in the two cases they are the same. The flow is assumed to be axi-symmetric around the well, allowing the flow domain to be discretized as a two-dimensional mesh of quadri-lateral elements.

The last two sections deal with the setting where the well is assumed to be located in a fracture zone located at a distance of 100 metres from one of the outer edges of the repository. In this case the flow domain is discretized as a three dimensional mesh of hexahedral elements. It is assumed that the flow is symmetric in such a way that a symmetry plane can be imagined in the middle of the fracture zone, and that another symmetry plane can be imagined to intersect the first one at right angles at the well. In this way only 1/4 of the total flow domain needs be considered in the calculations.

The fluxes presented in the tables correspond to one symmetric half of the repository. The examples treated in the last two sections, i.e. section 2.4 and 2.5. The difference between the two examples is attributed to the horizontal extent of the flow domain. Thus, in the first case (section 2.4) the flow domain has an areal extent of 24 km^2, and in the second case (section 2.5) it has an extent of 12 km^2.

2.2 Flow to a well located symmetrically above the centre of the repository at a depth of 60 metres below the ground surface

This case includes four examples. These are denoted W11, W13, W1A and WA1. The first two examples were worked out for transient flow conditions, while the last two ones were worked out for steady saturated flow conditions. An element mesh consisting of 230 elements and 757 nodes was used in the examples. The results of the calculations are presented in table 2.

W11 In this example the upper region of the flow domain is characterized by an unsaturated zone, initially with a thickness of 10 metres, and a hydrostatic lateral boundary. The well is represented by a single point sink located at a depth of 60 metres below the ground surface. This example was run for transient flow conditions and the calculations were carried through until steady state flow conditions were reached and the mass balance was acceptable. Steady state flow conditions occurred after about two years.

The ratio of the flux through the repository to that of the well was found to be about $8.9*10^{-4}$.

W13 In this example the initial and boundary conditions are the same as in the previous example. However, the well is represented by 5 point sinks, whose strength is proportional to the permeability at the depth of respective point sink. The point sinks are located at 20, 30, 40, 50 and 60 metres, and the proportionality factors are 0.475, 0.296, 0.129, 0.069 and 0.042, respectively. The results of the calculations in this example were rather similar to those of the previous one. Steady state flow conditions occurred, as in the previous example, after about two years.

The ratio of the flux through the repository to that of the well was found to be about $8.5*10^{-4}$.

W1A In this example the upper boundary is continuously saturated and the lateral boundary is impervious. The results of the calculations showed that the flux through the repository was considerably less than in the previous two examples.

The ratio of the flux through the repository to that of the well was found to be about $6.8*10^{-5}$.

WA1 This example is similar to the previous example but the well is represented by 5 point sinks, located at 20, 20, 40, 50 and 60 metres depth, and the strength of the sinks are set proportional to the rock permeability at the respective depth as in example W13 above.

The ratio of the flux through the repository to that of the well was found to be about $1.3*10^{-5}$.

Table 2. Fluxes[1] to a well located symmetrically above the centre of the repository at a depth of 60 metres

Example	Flux into the well	Flux through the repository	flux through the lateral boundary	flux through the surface boundary
W11	6.000	0.00537	5.847	0.011
W13	6.000	0.00512	5.905	0.000
W1A	6.000	0.00041	0.00009	6.000
WA1	6.000	0.00008	0.00002	6.000

[1] Fluxes are given in m^3/day

2.3 Flow to a well located symmetrically above the centre of the repository at a depth of 200 metres below the ground surface

This case includes four examples. These are denoted W12, W14, W2A and WA2. The first two examples have been worked out for transient conditions and the last two ones for steady flow. An element mesh consisting of 230 elements and 757 nodes was used in the examples. The results of the calculations are presented in table 3.

W12 In this example the upper boundary is characterized by an unsaturated zone, initially with a thickness of 10 metres, and a hydrostatic lateral boundary. This example is analagous to example W11 in the previous case, but the depth of the point source is 200 metres. It should be mentioned that the solution suffered from oscillations, especially in the region around the well. Consequently, a satisfactory mass balance could not be obtained in this example.

The ratio of the flux through the repository to that of the well was found to be about $6.1*10^{-3}$.

W14 In this example the boundary and inital conditions are the same as in the previous example, but the well is represented by 4 point sinks located at 50, 100, 150 and 200 metres depth. The strength of each sink is proportional to the permeability at the depth of the sink, and the proportionality factors are 0.824, 0.120, 0.039 and 0.017. This example was also run for transient flow conditions, but the problem with oscillations in the solutions was considerably less in this example, and steady conditions occurred after about two years.

The ratio of the flux through the repository to that of the well was found to be about $1.1*10^{-3}$.

W2A In this example the well is represented by a single point sink located at a depth of 200 metres. The upper boundary is assumed to be saturated and the lateral boundary is impervious.

The ratio of the flux through the repository to that of the well was computed to be about $6.9*10^{-3}$.

WA2 In this example the boundary conditions are the same as in the the previous example, but the well is represented by 4 point sinks located at 50, 100, 150 and 200 metres below the ground surface.

The ratio of the flux through the repository to that of the well was reduced to about $2.9*10^{-4}$.

Table 3. Fluxes[1] to a well located symmetrically above the centre of the repository at a depth of 200 metres

Example	Flux into the well	Flux through the repository	flux through the lateral boundary	flux through the surface boundary
W12[2]	6.000	0.03666	7.287	0.000
W14	6.000	0.00632	5.927	0.000
W2A	6.000	0.04157	0.00467	6.000
WA2	6.000	0.00173	0.00026	6.000

[1] Fluxes are given in m^3/day

[2] Solution did not converge

2.4 Flow to a well located in a vertical fracture zone situated at a distance of 100 metres from one outer edge of the repository - Case 1

In this case the lateral extent of the flow domain is 3 km in the x-direction and 2 km in the y-direction. The depth of the flow domain (z-direction) is 1.5 km. It should be noted that these figures refer to the 1/4 of the flow domain being subject to the calculations. This means that the fluxes given for the repository refer to one symmetrical half of the imagined repository, and that the total dimensions of the flow domain will be 6 km in the x-direction and 4 km in the y-direction. The results of the calculations are presented in table 4.

The width of the vertical fracture zone was 5 metres (total width 10 metres). The permeability in the fracture zone was assumed to be 100 times higher than in the surrounding rock, with a transition zone of 10 metres, in which permeability was decreasing linearly.

The first three examples presented, W4D, W4X and W4Y, were carried out for a withdrawal of 6 m^3/day from the well. However, this figure was applied to 1/4 of the totally imagined flow domain, implying that the corresponding total withdrawal is four times larger. In examples W4X and W4Y there is a linear relation between the flux through the repository and the prescribed withdrawal from the well. The figures presented in table 4 may therefore be readily adjusted (by dividing them by four) so that the actual withdrawal will correspond to 6 m^3/day.

Two complementary examples have been worked out viz. WX4 and WY4, using a slightly coarser element mesh than was used in examples W4D, W4X and W4Y, where a relatively fine mesh consisting of 1980 elements and 2496 nodes was used. In examples WX4 and WY4 a mesh consisting of 1100 elements and 1452 nodes was used. A comparison between the results showed that the discretization in the coarser mesh was adequate.

W4D In this example the flow domain is initially saturated. The lateral boundaries are hydrostatic. The point sink is located at a depth of 60 metres below the ground surface. As can be seen in the results in table 4, this example was not carried out until steady state flow conditions were reached. This was the result of a simple trade-off between the computer time required to reach steady state and the importance of obtaining these results. The transient behaviour of the flow problem was instead studied for a smaller problem (see example W3D in the next section).

The ratio of the flux through the repository to that of the well was computed to be about $2.1*10^{-4}$ after a period of about 100 days.

W4X In this example the geometry is the same as in the previous example, but the upper boundary is assumed to be continuously saturated and the lateral boundaries impervious.

The ratio of the flux through the repository to that of the well was computed to be about $8.3*10^{-6}$.

W4Y In this example the boundary conditions are the same as in the previous example, but the point sink representing the well is located at a depth of 200 metres.

The ratio of the flux through the repository to that of the well was computed to be about $6.6*10^{-4}$.

WX4 In this example the upper boundary is assumed to be continuously saturated. The lateral boundaries are impervious. The well is represented by a point sink located at a depth of 60 metres below the ground surface. The flux into the well is 1.5 m^3/day.

The ratio of the flux through the repository to that of the well was computed to be about $1.0*10^{-5}$.

WY4 In this example the boundary conditions are the same as in the previous example, except for well, which is represented by a point sink at a depth of 200 metres below the ground surface. The flux into the well is 1.5 m^3/day.

The ratio of the flux through the repository to that of the well was computed to be about $7.0*10^{-4}$.

Table 4. Fluxes[1] to a well in a fracture zone located at a distance of 100 metres from the repository - Case 1

Example	Flux into the well	Flux through the repository	Flux through the lateral boundaries	Flux through the surface boundary
W4D-1 100 days	6.000 depth 60 m.	0.00247	0.004 [2] 1.624 [3] (1.077)[4]	3.088
W4X steady	6.000 depth 60 m.	0.00010	0.00000 0.00001 (0.00000)	6.000
W4Y steady	6.000 depth 200 m.	0.00791	0.00001 0.00037 (0.00020)	6.000
WX4 steady	1.500 depth 60 m.	0.00003	0.00000	1.504
WY4 steady	1.500 depth 200 m.	0.00211	0.00010	1.500

[1] Fluxes are given in m^3/day.

[2] Flux through the lateral boundary not intersected by the fracture zone.

[3] Flux through the lateral boundary intersected by the fracture zone.

[4] Same as 3) but only the flux through the fracture zone.

2.5 Flow to a well located in a vertical fracture zone situated at a distance of 100 metres from one outer edge of the repository - Case 2

The lateral extent of the flow domain is 2000 metres in the x-direction and 1500 metres in the y-direction. These dimensions refer to the 1/4 of the flow domain being considered in the calculations. The depth of the flow domain (z-direction) is 1500 metres. Three examples are included in this case and they are denoted W3D, W3E and W3F.

A very coarse mesh, consisting of 480 elements and 693 nodes, was used in these examples. The fracture zone is characterized by a width of 5 metres (total width 10 metres) and a permeability that is 100 times higher than that in the rock, except for in a transition zone, which because of the coarseness in the mesh in this case was as much as 100 metres. Consequently, this case is less representative of the actual flow problem, and is generally leading to exaggerated fluxes through the repository, and the examples were worked out primarily to study the general behaviour of the flow problem.

The results of the calculations are presented in table 5. Note that all figures given in the table refer to 1/4 of the totally imagined flow domain. This means the the flux through the total repository is twice as much as indicated in the table.

W3D In this example the the flow domain is initially saturated, and the lateral boundaries are assumed to be hydrostatic. The point sink is located at a depth of 60 metres below the ground surface.

The ratio of the flux through the repository to that of the well was computed to be about $5.3*10^{-4}$ - $7.6*10^{-4}$.

W3E In this example same geometry as in the previous example, but the upper boundary is assumed to be continuosly saturated and the lateral boundaries impervious.

The ratio of the flux through the repository to that of the well was computed to be about $3.4*10^{-5}$.

W3F In this example the boundary conditions are the same as in the previous example, but the point sink representing the well is located at a depth of 200 metres.

The ratio of the flux through the repository to that of the well was computed to be about $2.8*10^{-3}$.

Table 5. Fluxes1) to a well in a fracture zone located at a distance of 100 metres from the repository - case 2

Example	Flux into the well	Flux through the repository	Flux through the lateral boundaries	Flux through the surface boundary
W3D-1 100 days	6.000 depth 60 m.	0.00632	0.059 2) 2.158 3) (1.954)4)	2.250
W3D-2 364 days	6.000	0.00851	0.112 4.097 (3.722)	1.056
W3D-3 744 days	6.000	0.00914	0.151 4.881 (4.404)	0.718
W3E steady flow	6.000 depth 60 m.	0.00041	0.00000 0.00005 (0.00005)	6.000
W3F steady flow	6.000 depth 200 m.	0.03402	0.00002 0.00074 (0.00069)	6.000

1) Fluxes are given in m^3/day.

2) Flux through the lateral boundary not intersected by the fracture zone.

3) Flux through the lateral boundary intersected by the fracture zone.

4) Same as 3) but only the flux through the fracture zone.

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