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Hydraulic evaluation of the groundwater conditions at Finnsjön. The effects on dilution in a domestic well

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HYDRAULIC EVALUATION OF THE GROUNDWATER CONDITIONS AT FINNSJÖN. THE EFFECTS ON DILUTION IN A DOMESTIC WELL

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HYDRAULIC EVALUATION OF THE GROUNDWATER CONDITIONS AT FINNSJÖN

THE EFFECTS ON DILUTION IN A DOMESTIC WELL

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SUMMARY

The Swedish Nuclear Fuel and Waste Management Company (SKB) is presently performing a safety analysis study, SKB 91, for a final repository for spent nuclear fuel. The study is carried out for a generic repository located to the Finnsjön area, which is one of SKB:s oldest study-areas.

An important part of the safety analysis is the dose calculations. Radionuclides can be transported to the biosphere via the sea, a lake, and via extraction of groundwater from drilled or dug wells. Thus, an important scenario to study is the dilution of radionuclides in a domestic well drilled in the future close to the repository.

The present study is discussing;

- Localization, drilling and construction of wells.
- Specific capacities and chloride content of the rock mass and wells found in the Finnsjön area.
- Risk areas for future drilled wells.
- Dilution in future wells drilled in fracture zones or in the hard rock in the vicinity of the repository.

Saline groundwater with chloride concentrations of about 5000 mg/l is found in the Finnsjön area below a depth of a few hundreds of metre. However, six domestic wells drilled to depths of about 60 m have been found some kilometre northeast of the Finnsjön Rock Block, close to discharge areas, having a maximum chloride concentration of 57 mg/l. Thus, it is likely that a future well for domestic water supply purposes in the vicinity of the repository will be drilled in a water-bearing fracture zone or to shallow depths in the hard rock. The fresh water requirements for a permanent household of four persons is today about 1 m^3/day, while the requirements for a summer residence only is about half of that. A middle sized farm with about 25 - 30 milkcows needs about 6 m^3/day.

The median value of specific capacities found in wells drilled in the rock mass in the Finnsjön area is about 0.3 m^3/day and metre drawdown in the well, and the median depth is 60 m. This is comparable to the lower values calculated for the investigation boreholes drilled in the southern part of the Finnsjön Rock Block. The boreholes drilled in the northern part show specific capacities of 4 - 8 m^3/day and metre drawdown for the upper 60 m of the rock mass. Thus, the specific capacities of the rock mass found in the Finnsjön area indicate that the necessary drawdown is 1 - 20 m for a well with a continuous discharge of 6 m^3/day.

Risk areas for future drilled wells, possibly collecting groundwater that has passed the generic repository, are fracture zone 1 downgradient from the intersection of Zone 4. The regional fracture zone Imundbo as well as the discharge areas, swamps and streams, some kilometre northeast of the Finnsjön Rock Block may also be risk areas for future drilled wells.

Simulations of porous media flow in a two-dimensional vertical section of fracture zone 1 show that a well pumping 6 m^3/day at a depth of 60 m may be as close as 100 m from the discharge area and still pump groundwater not affected by the repository. In order to pump groundwater that has passed the repository, the well has to be located in the discharge area for groundwater from the repository or pump more than 30 m^3/day. In the calculations, no consideration is taken to the channeling character of flow in fractured rock or sorption and matrix diffusion. Thus, the calculations should only be seen as illustrations of hydraulic factors influencing the dilution in a well.

The radius of influence for a well located in the rock mass and pumping 6 m^3/day is about 150 m for a groundwater recharge of 50 mm/year. Three-dimensional analytic calculations show that a well drilled in the rock mass to a depth of up to 100 m gets all of its water from groundwater recharge, if the recharge is greater than about 40 mm/year.

Thus, the evaluations show that a well pumping 6 m^3/day, located in a fracture zone or in the rock mass, has no influence on the local groundwater flow system except for the very vicinity of the well. Consequently, a well may be drilled in the hard rock without any risk of pumping groundwater that has passed the repository. Wells may also be located anywhere in fracture zones, except for in the very discharge area, without any risk of getting groundwater affected by the repository. Modelling indicate that a well drilled in the discharge area for contaminated groundwater, may collect all groundwater from the repository. However, this is based on assumptions of homogeneous continuous fracture zones with a high hydraulic conductivity compared to the rock mass, which will give rise to a concentrated discharge area.

Inhomogenieties in the rock mass and fracture zones together with the areal extent of the repository might give rise to a spreading of pathlines from the repository over the discharge area, swamps and streams, northeast of the Finnsjön Rock Block. This implies that all groundwater that passes the repository will not converge to a single well pumping less than 6 m^3/day, even if it is located in the discharge area. However, with the present knowledge of groundwater flow in fractured rock, it can not be excluded that a well drilled in the future in a discharge area could get all of its water from groundwater that has passed the repository. The dilution in such a well is just a function of the pumping rate of the well. Thus, a high capacity well will result in a larger dilution giving a smaller dose to more people, while a low capacity well will be less diluted and give a higher dose to fewer persons.

Assuming that the groundwater flow interacting with each canister is about 1 l/year, gives a total groundwater flow interacting with the canisters of 5 m^3/year. If all canisters are destroyed and leaking and this flow is collected by a well pumping 6 m^3/day, it will be diluted at least 400 times. However, considering the unrealistic scenario with all canisters leaking, the dilution of activity-contaminated groundwater will be much higher.

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1 INTRODUCTION

Studies of the safety around a final repository for spent nuclear fuel is carried out by SKB within the SKB 91 project. The safety analysis will constitute a basis for the localization of the final repository. The primary goal of the investigation is to study how different geological parametres affect the safety of a planned repository. The safety assessment study is carried out for a generic repository in the Finnsjön area, which is one of SKB:s oldest study-areas where geo-scientifical investigations commenced already in 1977 (Figure 1.1).

Dose calculations to the biosphere constitute an important part of the safety analysis. Radionuclides can be transported to the biosphere via the sea, a lake and via extraction from groundwater wells. The safety of the repository is evaluated from doses of radionuclides to individuals. The doses are calculated assuming that the groundwater recipient is a well or lake near a self-supporting small farm. An alternative with discharge into a recipient with brackish water is also evaluated. In both cases the biosphere is represented with typical nuclide specific transfer factors for the chosen recipient.

Thus, an important case to study is the dilution of radionuclides that can be expected in a well drilled in the future, where the groundwater primarily is used for domestic and irrigation purposes of one or a few households.

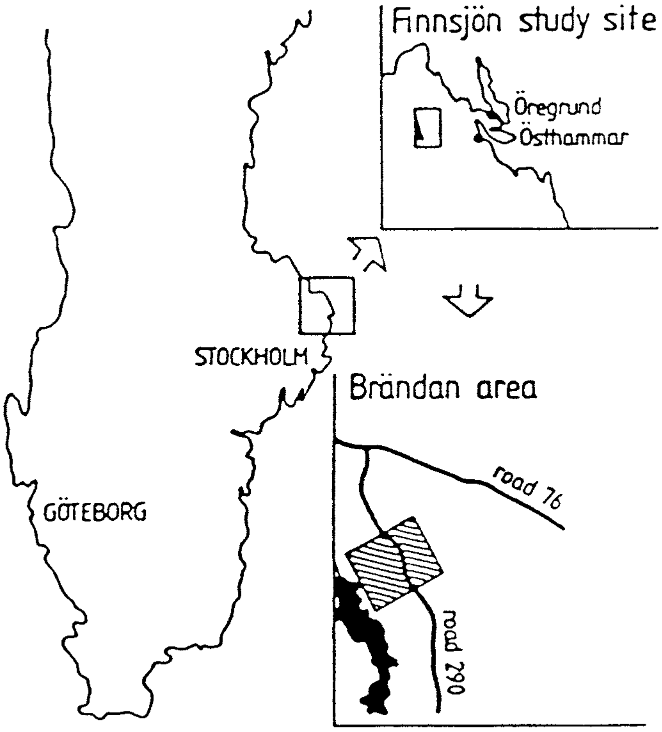


Figure 1.1 Location of the Finnsjön area.

2 BACKGROUND

2.1 Hydrogeological considerations

The landscape can be divided into recharge and discharge areas, depending on whether the water flows into or out from the groundwater system. Important to notice is that the groundwater level does not have to be at the ground surface in a discharge area, but it is sufficient by definition that the gradient in the groundwater system is directed towards the surface.

Topographically high regions are mainly acting as recharge areas, while low-lying areas are discharge areas. Usually recharge areas form a larger part of the landscape, while discharge takes place close to lakes, streams, swamps or as point-discharge in springs. Thus, part of the rain falling over recharge areas form groundwater, while rain falling over discharge areas contribute directly to runoff in streams. This is a dynamic system with varying discharge areas over the year depending on the distribution of rainfall.

The part of the rainfall that is not intercepted and/or evaporated by vegetation forms the so called potential groundwater recharge, i.e. the maximum available water that later may form groundwater. This amount forms groundwater in recharge areas, while it contributes to direct runoff in discharge areas. Research shows that about 85% of the runoff in streams is due to groundwater discharge, except for the snowmelting period, when most of the groundwater recharge takes place (Grip and Rodhe, 1985). The groundwater levels are high during this period, which makes the discharge areas larger, leading to a higher contribution from direct runoff to the formation of streamflow. Accordingly, about 60% of the runoff in streams during snowmelting periods is due to groundwater discharge. In conclusion, the potential groundwater recharge over an area is equal to the specific discharge of the area forming streamflow runoff. Groundwater pumping from a well reduces groundwater recharge to the system and accordingly reduces the specific discharge of the area and streamflow runoff (Carlsson and Gustafsson, 1984)

The driving forces in an aquifer system are the groundwater heads, which are formed by groundwater recharge and bounded by the ground surface. The sinks in the system consist of discharge areas of various types. The groundwater circulation is determined by the strength of the driving forces and the sinks together with the hydraulic conductivity, that may be different in various parts of the system (inhomogeneous) and/or have directional variations (anisotropic). Theoretical considerations show that it is clear that accurate evaluation of groundwater flows is contingent on a detailed knowledge of hydrogeological conditions. Even a "simple" case with a homogeneous and isotropic aquifer with a sinusoidal water table having an amplitude of 15 m and a mean slope of 2% gives a quite complicated picture with varying recharge/discharge areas and regional/local flow systems (Figure 2.1). Considering the variation in hydraulic properties in till/rock aquifers containing fracture systems gives an even more complicated picture of recharge/discharge areas and regional/local flow systems.

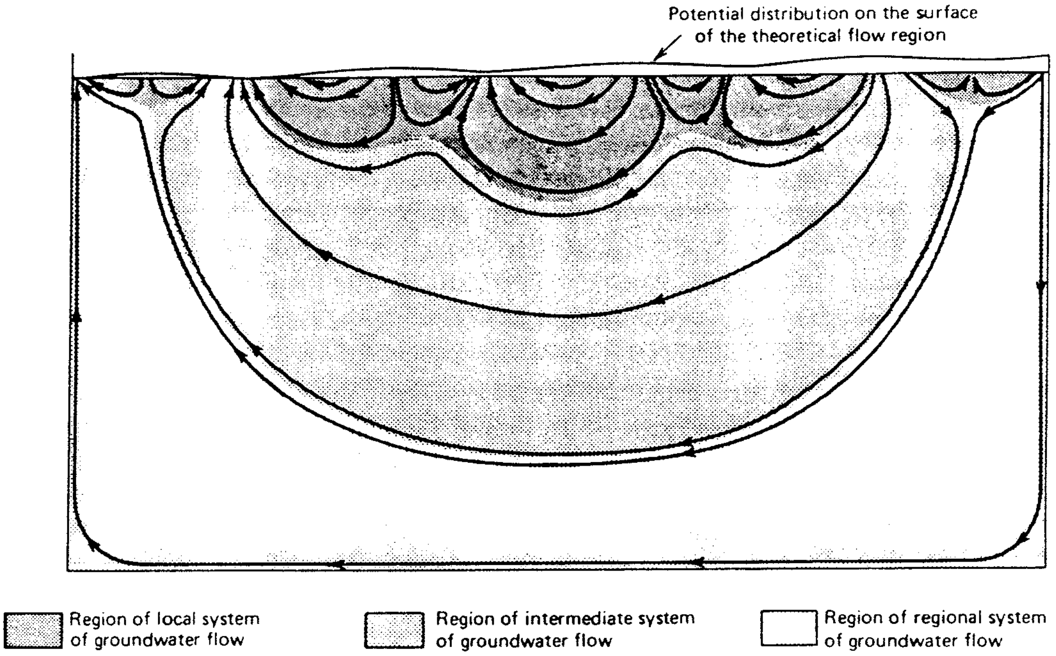


Figure 2.1 Regional and local groundwater flow (Todd, 1980).

When considering wells drilled in the hard rock, an unknown and important factor concerning where a well gets its water from is the location of the recharge area of the fractured rock aquifer. If the recharge area is the soil cover immediately on top of vertical fractures, a majority of the water entering the well originates from the surface. On the other hand, if the soil cover is a low permeable clay, water to the well has to originate from a more horizontal flow pattern or from deeper formations (Figure 2.2). Thus, surface geology is of great importance when setting up risk areas close to the repository.

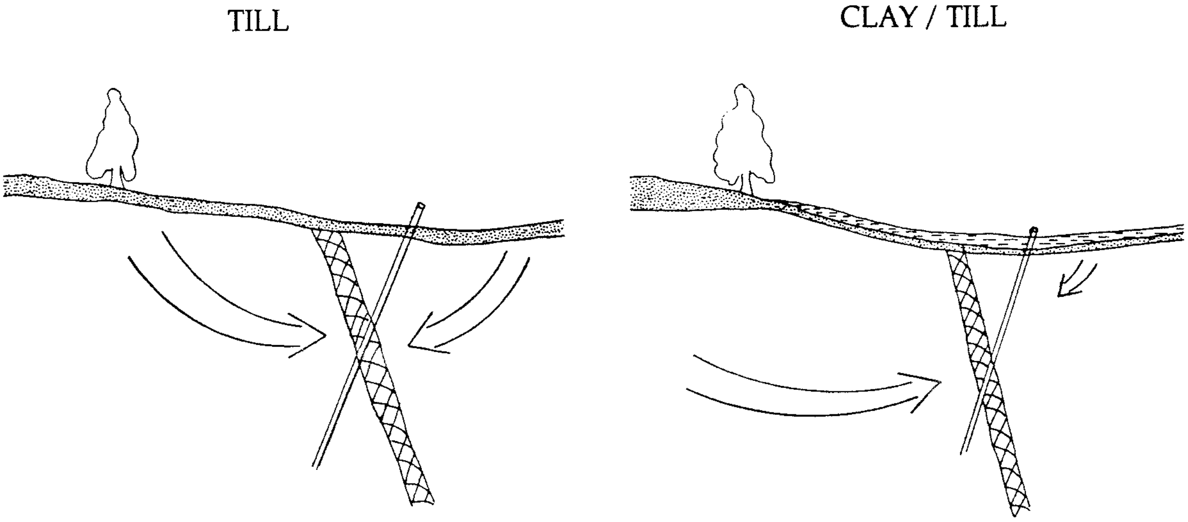


Figure 2.2 The importance of surface geology.

2.2 Other investigations

Dilution in a well has been investigated in two earlier studies within the safety analysis study for the KBS-3 concept (Carlsson et al., 1983 and Thunvik, 1983). Both studies are considering a well pumping 6 m^3/day. The study by Carlsson et al. (1983) is based on analytical calculations for estimating the dilution in a 200 m deep well located in a vertical fracture zone with a hydraulic conductivity of $2*10^{-8}$ m/s to $5*10^{-7}$ m/s. It is stated that the area of influence due to pumping is very limited, up to 5 m from the well, implying that there will be no influence on the natural groundwater conditions at repository depth. The dilution is calculated to be 0.1 to 8 million times. It is also stated that a convergence of streamlines from the repository to the area influenced by the well will give a smaller dilution.

The study by Thunvik (1983) was performed using a groundwater model based on porous media flow and finite element technique assuming radially symmetric flow. A well with a depth of 60 m or 200 m was located in the rock mass above the repository, alternatively in a fracture zone 100 m from the repository. Two types of boundary conditions were used; one with a fixed groundwater table and no-flow boundaries and the other with a varying groundwater table and hydrostatic boundaries. Thus the only active sink in the system was formed by the well, inducing a groundwater flow through the repository. It was stated that the flow through the repository was 10^{-5} to 10^{-3} times that of the well discharge. The conclusion was also given that the drawdown in the well due to pumping was very small, and the induced gradients were small compared to natural gradients. Thus, the flow to the well will have a small influence on the regional groundwater flow system.

A generic study of dilution of released radionuclides that could be expected in future drilled wells adjacent to the repository for storage of low- and medium-level reactor waste, SFR-1, at Forsmark was performed by Axelsson et al. (1990). The work was conducted with a finite element groundwater flow and transport model based on the porous media concept. The repository was modelled as a continuous source with a fixed concentration, and the only transport mechanisms accounted for were advection and dispersion. The pumping rate of the well was assumed to be 1 m^3/day and the hydraulic conductivity of the rock mass was set to $1*10^{-7}$ m/s. It was concluded that the well had a small impact on the groundwater flow system and thus the location of the well compared to the regional groundwater flow was of utmost importance for the dilution. The location of a well at some angle from the gradient resulted in no contaminant entering the well. Dilutions were calculated to be greater than 60% and increase when groundwater recharge is included. It was also stated that discharge areas act as barriers for plume migration.

A three-dimensional finite element groundwater modelling study of the impact of a domestic well on discharge areas, travel paths and travel time distribution from a hypothetical repository at 500 m depth was made for the Canadian Nuclear Fuel Waste Management Program (Reid and Chan, 1988). The well was located in a gently dipping fracture zone intersecting the hypothetical nuclear waste vault. The fracture zone was considered to be porous media of uniform thickness having longitudinal permeabilities of 10^{-13} m^2 and transverse permeabilities of $0.5*10^{-13}$ m^2

across the zone. Conceptually, the well was assumed to be sealed off from the surface down to the fracture zone, with a screened section fully penetrating the thickness of the fracture zone approximately 200 m below the surface. Results are presented for well demands of 120 m^3/year representing the minimum requirement for a single individual, 1500 m^3/year fulfilling the requirements of a family of six persons, without irrigation and 30000 m^3/year including irrigation. It was concluded that the two low-capacity wells (less than about 4 m^3/d) did not dramatically change the discharge area and the well was more or less passive in the system. However, in the high capacity case (80 m^3/d) the well becomes the strongest sink in the system and accordingly particles initiating from more than 70% of the plan area of the vault (2 km by 2 km) will discharge to the well. Risk assessment indicate that human intrusion in the form of a domestic well can have a strong effect on the calculated dose to man (Reid et al., 1989).

3 TECHNICAL APPROACH

3.1 Scope of work

The hypothetical repository in the Finnsjön site is located at a depth of 500 m and has an extension of about 1 km by 1 km. The repository area is surrounded by larger fracture zones, and the rock mass above the repository also contain some minor fracture zones. This indicates that a future domestic well may be drilled in the rock mass or a minor fracture zone above the repository or in a nearby larger fracture zone.

The risk that is associated with the transport of radionuclides released from the repository and the dilution in a domestic well is dependant on factors like:

- **The well itself**; Location, Pumping rate, Depth and Screening.

- **The hydrogeological conditions**; Regional- and local flow pattern (source areas and sinks), Hydraulic inhomogenieties (rock mass/fracture zones and depth dependence) and Groundwater recharge.

Depending on the above mentioned factors, the well act as a more or less active sink in the studied hydrogeological environment, influencing the flow pattern on a larger scale or just in the vicinity of the well. It is therefore necessary to define a number of scenarios that illustrate the effect of different factors on the dilution in a well.

Some qeustions that are important for the assessment of dilution of radionuclides in a future drilled well are:

- The importance of saline groundwater on the location of wells.
- The life of a well.
- The characteristics (capacity/drawdown) of wells located in different hydrogeological environments.
- The importance of well discharge on the travel paths from the repository to the biosphere.

- The importance of well depth and screening on the dilution in a well.
- The importance of groundwater recharge on the dilution in a well.
- The importance of a subhorizontal zone above the repository.

The work performed to answer these questions are as follows:

- Description of location, drilling technique and design of domestic wells.
- Description of well demands and life of a well.
- Hydrogeological description of the rock mass and fracture zones at the Finnsjön site.
- Description of capacity and depth of wells drilled in the vicinity of the Finnsjön site.
- Calculation of catchment area and drawdown in a well as a function of capacity, hydraulic conductivity and groundwater recharge.
- Identifying "risk areas" for drilling of wells based on hydrogeological conditions at the Finnsjön site.
- Selection of well scenarios based on the identified "risk areas".
- Calculation of dilution to wells localized according to selected well scenarios.

It should be noted that this work is based on technology known today and is not accounting for any technical or other development concerning the localization drilling, design and utilization of future drilled domestic wells.

3.2 Methodology

The work was conducted in five different tasks:

- **Litterature study**: This part concentrates on the location of domestic wells, well demands, drilling technique and modern well construction and achievement in order to give a picture of how a well is "working in reality". The life of a well is also discussed.

- **Inventory and analysis of hydrogeological data**: The aim is to relate specific capacities calculated from hydraulic tests at the Finnsjön site with those calculated from drilled wells in the vicinity. A comparison is also made between the hydraulic conductivity measured at Finnsjön and that calculated for the investigated wells. Specifics like depth, capacity and salinity of drilled wells in the area are also discussed.

- **Analytical overwiew calculations and assessment of "risk areas"**: The analytical overwiew calculations give a rough estimate of catchment areas and drawdown in a well as a function of capacity, hydraulic conductivity and groundwater recharge. Based on this and information on the hydrogeological conditions at Finnsjön, "risk areas" for nuclide contamination in domestic wells are discussed. This is then the basis for selection of well scenarios for calculation of dilution.

- **Two-dimensional sectional modelling**: The dilution in a well located in a vertical fracture zone is modelled for different well scenarios concerning location, pumping rate and depth. This modelling is performed with a 2-dimensional finite element groundwater model simulating flow in a vertical plane.

- **Three-dimensional analytical modelling**: These simulations are illustrating where a well drilled in the rock mass above the repository gets its water from. This modelling is performed with an Analytical Element Method simulating 3-dimensional groundwater flow to a partially penetrating well in a heterogeneous aquifer bounded by horizontal and vertical equipotential fracture zones.

4 DOMESTIC WELLS

4.1 Introduction

Wells can be divided into three major groups depending on how they are achieved, viz. drilled, dug and piped wells. The latter two groups are pure soil wells and are only briefly presented, since the use of these types of wells is getting rare and no high capacity well is known in the Finnsjön area. The use of soil wells is decreasing in Sweden, since the quality of surface-near groundwater is getting more and more questioned, as an effect of human exploitation and other environmental impacts such as acidification. Statistics from the Water Well Record Section at the Swedish Geological Survey (Sandström, 1991), indicate that a majority of the new wells are hammer drilled in hard rock (Table 4.1). However, these statistics does not give the true picture of different types of wells, because all new soil wells are not reported. Only the drilled soil wells are reported to the Water Well Record Section. Soil wells like piped or cased wells are commonly used in glacifluvial deposits, e.g. eskers. There is still a significantly large number of municipalities that use esker reservoirs for their water supply. No such glacifluvial deposit is however present in the Finnsjön area.

Rockdrilled wells used for water supply purposes are very seldom drilled to a depth larger than 120 m. The median depth for wells drilled in Sweden in 1989 is 72 m, where 50% of the wells are drilled to depths between 50 and 100 m (Table 4.1).

Taking the median values of depth and capacity of wells drilled in 1989 gives a median specific capacity of 0.23 m^3/day and metre drawdown. This is close to the median value of 0.26 m^3/day and metre drawdown calculated from 59.000 rock-drilled wells all over Sweden (Fagerlind, 1988).

A more detailed description of the location and design of domestic wells is given in Appendix A.

Table 4.1 Well statistics sent to the Water Well Record Section in 1989.

		Welltype		
		Rock wells	Soil wells	Total
No. of wells		8337	186	8523
(%)		97.8	2.2	100
Diameter [mm]		115-165	115-400	
Total depth (m):	Median	72.0	22.0	
	25%	51.0	15.0	
	75%	100.0	31.0	
Casing depth [m]:	Median	6.0	-	
	25%	3.0	-	
	75%	12.0	-	
Capacity [litre/hour]	Median	700	5.000	
	25%	300	2.425	
	75%	1.800	10.000	

No of wells for different users

Households	Farms	Irrigation	Municipality	Industry	Energy	Others	Total
4750	81	57	37	46	395	87	5453*

* Missing information from 3070 wells

4.2 Water demand

The fresh water requirements for different type of consumers are presented in Table 4.2. A household of four persons consumes about 1 m^3/day, while a "standard" farm with 25 - 30 milkcows requires about 6 m^3/day. People living in the country side tends to consume 30% less water than people living in cities. It should be noted that the hydraulic capacity of wells is often larger than the water demand for consumption, which is a necessity for a reliable water supply system.

4.3 Location of wells

In order to optimize the location of rockdrilled wells, a geophysical instrument based on the VLF-technique (Very Low Frequency) has been used to prospect waterbearing fracture zones since the 1970's. The instrument can only measure more or less vertical and linear structures with a certain geometry, e.g. fractures and larger ores. This means that horizontal layers and formations with less dip than 45 degrees are not indicated by this method. Another limitation is the penetration depth of the electromagnetic waves. On blotted crystalline rock the penetration depth is at least 300 m, though accuracy is lost at greater depths.

Table 4.2 Water requirements for different consumers (Geotec, 1991).

Consumer	litres/day	Comments
Household	1.000	Average complete household, 4 persons
	600	Summer residence only
	1.800	Well drillers "Minimum water guarantee" (Geotech 1990, 45 litres/hour, household well)
	150 - 200	Per person/day, except garden irrigation
	15	Per person/day, drinking water only (including cooking)
Farming	ca 6.000	Standard farm Uppland, 50-80 hektar, 25-30 milkcows
	ca 12.000	Large farm Uppland, 500-800 hektar, ~100 milkcows
	45	Per cattle or horse/day
	75	Per milkcow

Clay cover strongly reduces the penetration depth to less than 50 m. The method is developed for crystalline rock, but has also successively been used in sedimentary rock in Sweden and Greece (Arnbom and Sokoutis, 1986). Research has shown that wells located with VLF-technique generally give more water than other wells (Pettersson, 1987). If correctly used, this method gives information, not only of the location of the potential waterbearing conduit, but also the approximate inclination and potential salt water content.

Regarding the estimation that up to 20% of all the well drilling companies already use this instrument before drilling, it is reasonable to assume that the majority of future rock drilled wells will be preferably located to a *vertical* waterbearing fracture zone.

4.4 Well construction

The rock drilled well consists of two different parts; the casing through the soil and the actual borehole in the rock mass.

Casing is carried out through the soil and some metres into the rock, normally with a steel pipe having a material thickness of about 6 mm. Before rock drilling continues, the casing end is grouted. This is done with concrete mixed with an expansion fluid attached at the bottom and/or flushed with high pressure a little further out into the formation. The rock drilling start by drilling through this plug. Well performed, the casing and grouting procedure completely seals off all the soil- and surface-near groundwater.

Rock well drilling is performed preferably with a Down-The-Hole hammer that is flushed with compressed air or/and water if available. The standard diameters for domestic well are 115, 140 and 165 mm. The normal working pressure at the crone varies between 15 and 22 bar, which enables a drilling speed of up to 120 m/day. Thus, the majority of standard domestic wells is done within one or two days.

As a secondary effect of the high pressure used when drilling, up to 22 bar, a certain grouting effect will occur in the shallow fractures of the borehole. The pressure flushes the drilling mud into the conduits, where it mixes with water and decreases the permeability of the conduits significantly (Figure 4.1). This effect is rapidly decreasing towards depth after the first 30 m of the borehole. When the well have been used for some time, this grouting effect will be reduced due to outwash of the conduits by the flowing water.

A commonly used method to increase the well capacity is hydraulic fracturing. A section of the borehole is sealed off with a packer and water is pumped into the section at a high pressure (150 - 200 bar). The desired effect is to rinse the smeared fractures and open up the formation to other conduits/aquifers. About 20% of all rock drilled wells are fractured hydraulically with the described method (Fagerlind, 1989). An older method of fracturing a borehole is blasting, which is still used but only for about 1% of the drilled wells. This is not expected to have the same positive effect and brings a risk of the borehole collapsing.

The pump is installed about 5 m above the bottom of the well in order to use the borehole storage at maximum, but still avoid particles causing pump failure. The last 5 m then works as a collector/sedimentation sump for the material that is released into the well.

4.5 The life of a well

The question how long a well construction can last is difficult to answer. The opinions differ, but all agree to the fact that the weak point is the steel casing. There is an increasing risk of corrosion due to acid groundwater, saltwater intrusions, variation in redox-potential due to undulating groundwater levels, etcetera. There is seldom any protection made to enhance the long lasting capacity of the casing. Assuming that the corrosion is similar to the standard values used on steel piles, which is less than 2 mm/10 year, the life of a modern well is approximately 40 to 60 years unless something is done to replace the casing.

However, even if the casing is corroded, the well still gets the necessary quantity of water but the quality may be affected by infiltrating surface water.

There are other aspects in special chemical environments, such as secondary tightening of fractures caused by swelling minerals or dissolved salt. Though, this type of problem seems to be more common in greenstones, such as gabbro.

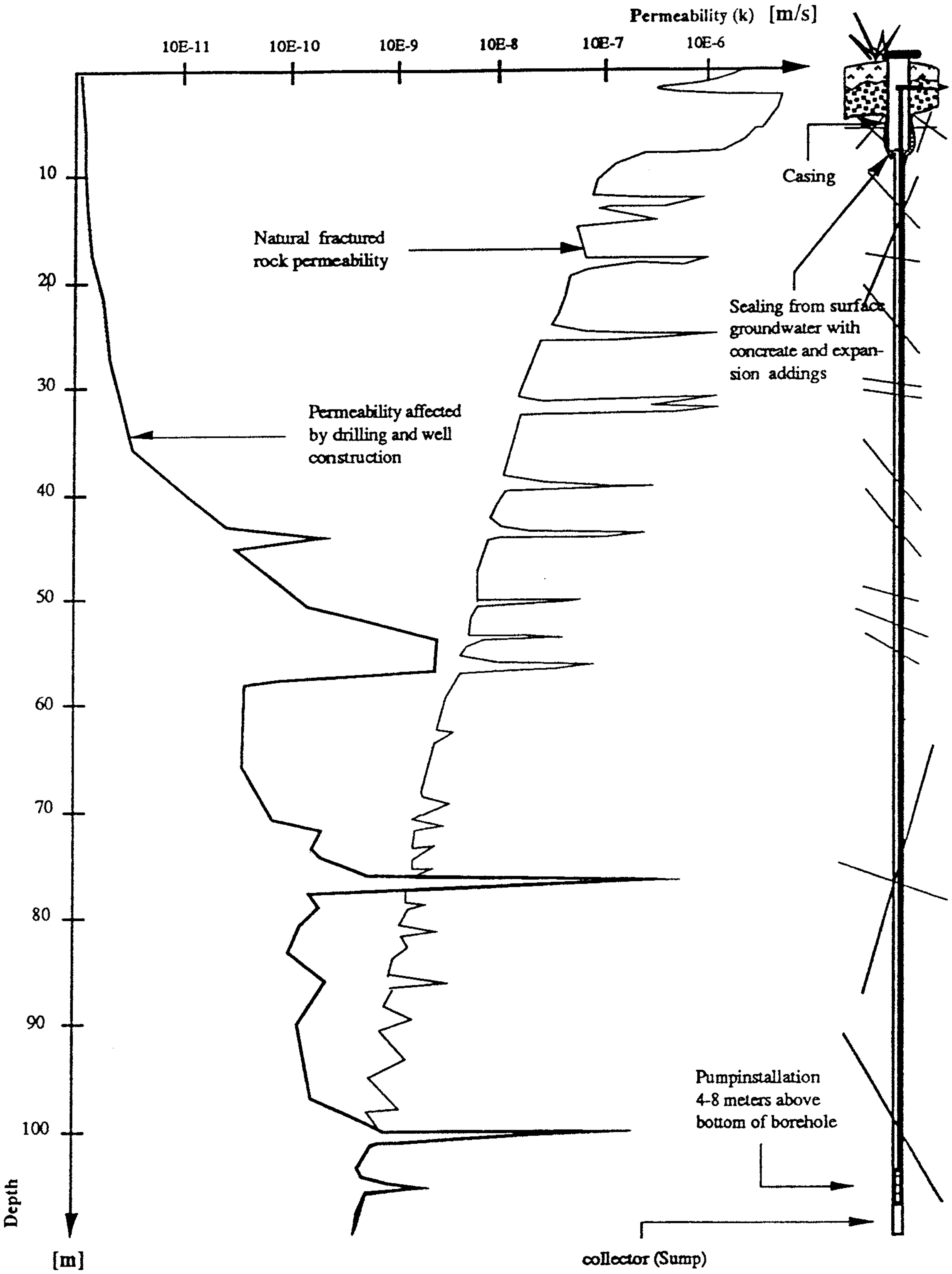


Figure 4.1 Tentative sketch of well drilling and construction effects on formation permeability (No concern is taken to hydraulic fracturing).

4.6 Salt water considerations

Saltwater intrusion is a serious problem in coastal regions and in the major part of the valley of lake Mälaren as well. The inland problems are an effect of relict salt water, where the interface occurs at various depths, approximately between 60 - 150 m below the groundwater table. The taste limit of drinking water is 300 mg/litre, expressed in chloride content. Thus, a well which exhibits a chloride content in excess of that is today abandoned or measures are taken to lower the chloride content.

It is well known that it is possible to lower the saltwater content simply by raising the pump from the bottom position some 20 - 30 m or/and seal off the bottom section of the borehole.

To face the problem in saltwater risk areas, well drillers try to get the water from shallower depths through inclined drilling, up to 30°. A limitation of the vertical depth is then recommended to be about 60 m. Thus, the strategy is to drill shallow wells and, if necessary, increase the capacity by hydraulic fracturing.

Saltwater intrusion is considered to be a continuously increasing problem. This might be an effect of an increased use of groundwater, emptying the fresh water aquifers, but it can also be viewed as an evidence of modern well drilling and design effects on natural permeability, since the saltwater is located at the bottom of the formation due to density.

4.7 Discussion

It must be stressed that there is little experience of transport of water into a rock drilled well. As the rock is a heterogenious material, the understanding of the hydraulics is even more complicated when trying to adopt transport models to the reality of casing-sealing, smeared fractures from drilling, transient pumping and level of pump, etcetera.

The modern well drilling technique is effectively changing the natural distribution of permeability in a borehole. Primarily, the technique is developed to avoid near surface groundwater. The effect of casing and grouting of the casing bottom is obvious, smearing of fractures is known, but considered to be a small problem. Hydraulic fracturing will rinse the smeared fractures and open up the formation to other conduits/aquifers, thus increasing the capacity of the well.

It seems reasonable to believe that the active section of the well, in terms of transport, is short (about 10 to 20 m) and distributed around the pump at the bottom of the well. This is based on the fact that the pump (or ejector inlet) is installed at the bottom of the well and that pumping runs a few powerful cykles per day. Another prerequisite is a number of intersecting fractures distributed along the complete borehole. If there is only one waterbearing fracture in the borehole, naturally the water will enter the well at this level independent of where the pump is located.

5 HYDROGEOLOGICAL CONDITIONS

5.1 Geology

The bedrock within the Finnsjön site is of Svecocarelian age and consists mainly of four different rock types (Almén et al., 1978). The central part of the Finnsjön area is dominated by a grey granodiorite. This area is in the north bounded by basic to ultra basic rocktypes, to the east of granites and to the west of leptites. The west part of the Finnsjön area could be described as a rock-till-peat area with a high proportion of bare rock at the surface and thin layers of soil. The soil cover is thicker in the eastern part of the area. Swamps cover big parts and clay and surge gravel are common.

5.2 Hydraulic features

Hydraulically the area can be divided into two different categories; the rock mass and fracture zones of different orders. Most frequent in the Finnsjön area are fracture zones oriented in the N5E-N20W. Another abundant set of fracture zones are N50-55W. Easterly fracture zones only occur as N30-35E zones, and these zones are frequent. A generalized map of the fracture zones in the Finnsjön area is shown in Figure 5.1. The regional fracture zones 3, 4, 12, 13 and 14 delineates a rock formation called the Finnsjön Rock Block. This block is divided in a northern and a southern part by the fracture zone 1. A dominating sub-horizontal structure, called fracture zone 2, also occurs in the area (Figure 5.2). This zone is only found in boreholes in the north block and is interpreted to have an extension within the fracture zones 1, 4, 12 and 7. The total thickness of this zone is estimated to be about 50 - 100 m. The dip is 16 degrees towards SW and the depth of the upper surface is about 25 m at the fracture cross 4/1 and about 325 m at the fracture cross 12/7.

5.3 Hydraulic conductivity

The hydraulic conductivity of the fracture zones and rock mass have been estimated from hydraulic tests by Andersson et al. (1991). Hydraulically, the rock mass can be divided into a north block and a south block separated by fracture zone 1. The hydraulic conductivity of the rock mass in the north block, where the subhorizontal Zone 2 is present, is about 5 - 10 times higher than that of the south block. The upper 100 m of the rock mass has a conductivity of about 10^{-8} - 10^{-7} m/s, which decreases to about 10^{-9} - $5*10^{-9}$ m/s at a depth of 500 - 600 m (Table 5.1).

The dominating fracture zone is the subhorizontal Zone 2 with a conductivity that is more than 1000 times that of the rock mass. The conductivity of the fracture zones 1, 5 and 11 is about 100 - 1000 times that of the rock mass. Some of the fracture zones (Zone 6, 9 and 10) have conductivities that are close to that of the rock mass or even tighter than the rock mass.

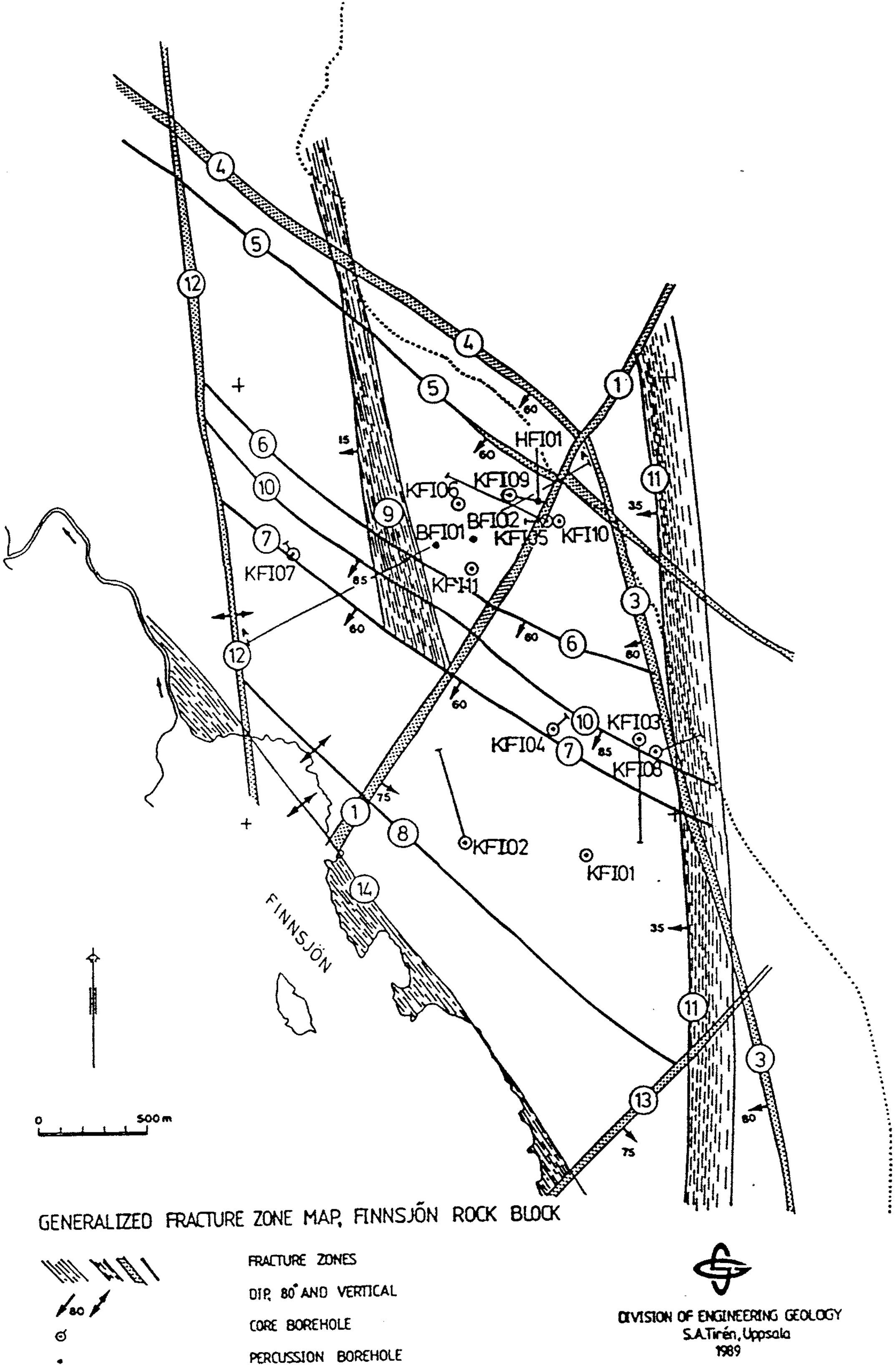


Figure 5.1 Generalized map of fracture zones in the Finnsjön Rock Block (Ahlbom and Tirén, 1991).

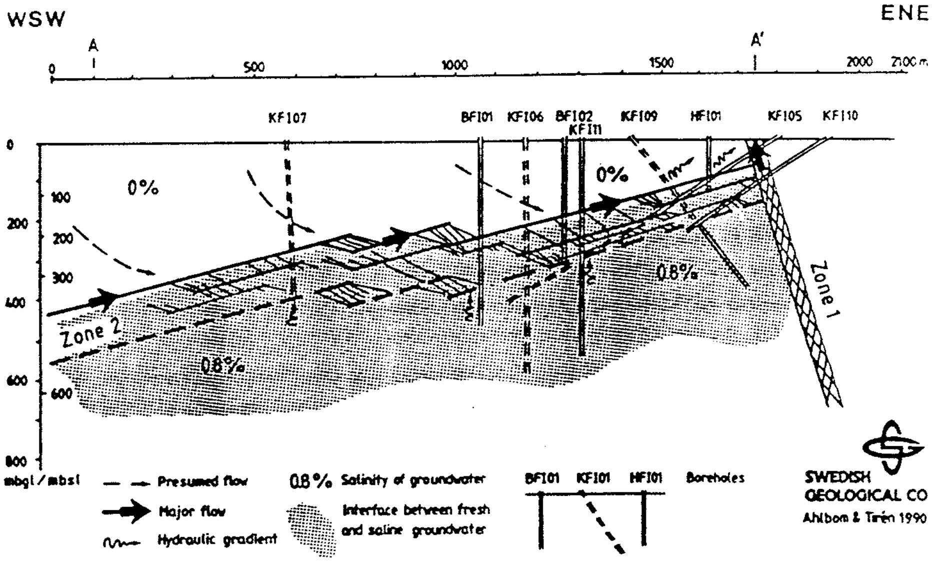


Figure 5.2 Vertical section showing the sub-horizontal fracture zone 2 in the northern part of the Finnsjön Rock Block (Ahlbom and Tirén, 1991).

Table 5.1 Hydraulic conductivities in fracture zones and the rock mass estimated from hydraulic tests (from Andersson et al., 1991).

Rock mass/ Zone	Depth (m)	Width (m)	Inclination (degrees)	K (m/s)
North block	0-100 500-600			$1.2*10^{-7}$ $4.4*10^{-9}$
South block	0-100 500-600			$1.7*10^{-8}$ $8.6*10^{-10}$
Zone 1	55-75	20	75 SE	$5\text{-}25*10^{-6}$
Zone 2	100-300	100	16 SW	$2\text{-}4*10^{-5}$
Zone 3	30-120	50	80SW	$1\text{-}10*10^{-6}$
Zone 5	170-180 320-350 550-560	5	60 SW	$5\text{-}50*10^{-6}$ $1\text{-}5*10^{-6}$ $1\text{-}5*10^{-7}$
Zone 6	515-520	5	60 SW	$1\text{-}10*10^{-9}$
Zone 9	105-160	50	15 SW	$1\text{-}10*10^{-8}$
Zone 10	45-48	5	85 SW	$1\text{-}10*10^{-9}$
Zone 11	16-120 82-174 364-394 364-436	100	35 SW	$1\text{-}5*10^{-6}$ $5\text{-}10*10^{-6}$ $1\text{-}5*10^{-6}$ $5\text{-}10*10^{-9}$

5.4 Groundwater conditions

5.4.1 Groundwater heads

The groundwater levels and local flow pattern near the surface of the bedrock within the Finnsjön Rock Block are shown in Figure 5.3. The general flow pattern from the generic repository site between fracture zones 1, 4, 12 and 7 is towards the northeastern part of fracture zone 4 close to Zone 1. This is due to higher elevations in SW, where a water-divide is present SW of Zone 7.

The gradient of the groundwater level within the Finnsjön Rock Block is about 0.3% directed towards northeast. The regional gradient of the area covering some 10th of kilometres northeast of Finnsjön is in the order of 0.2%.

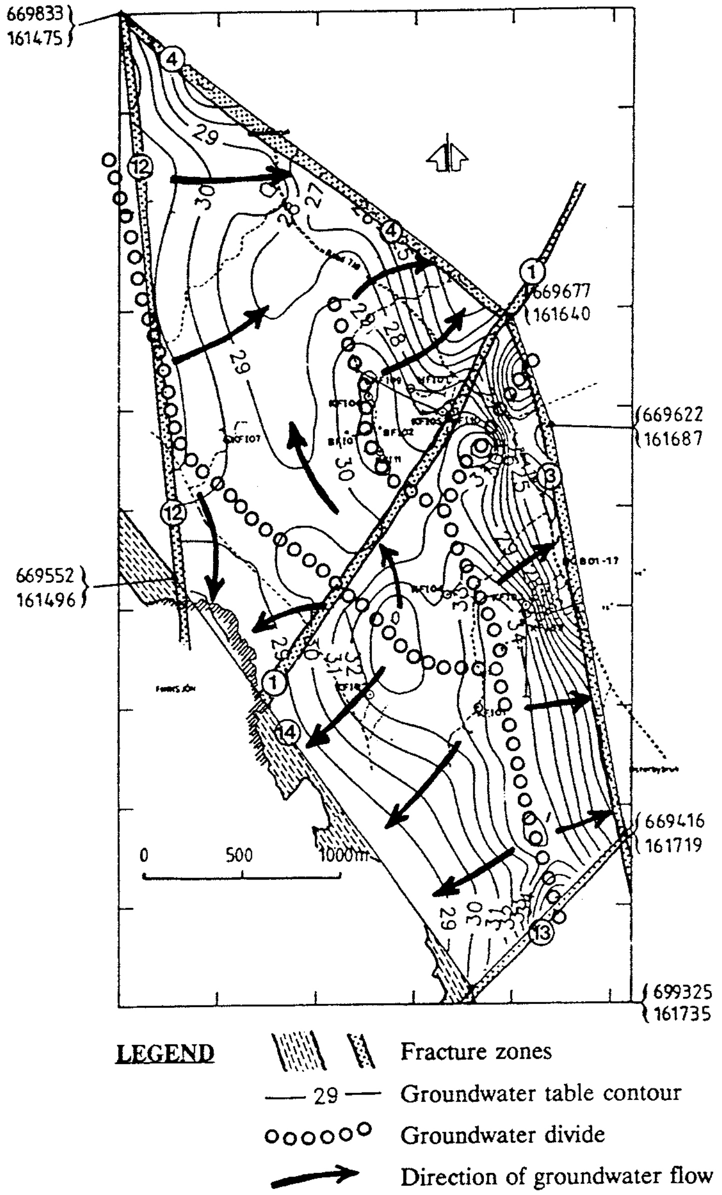


Figure 5.3 Groundwater levels and flow pattern in the Finnsjön Rock Block.

The fracture zones 1 and 2 are considered to have a large influence on the groundwater flow in the area.

Hydraulic interference tests and tracer tests have indicated that the upper part of Zone 2 may be treated as a separate high transmissivity aquifer unit with uniform hydraulic properties, and the rest of the zone as another aquifer unit with hydraulic anisotropy in the vertical direction. The natural groundwater flow in Zone 2 is determined by point dilution and gradient methods to be about 150 000 to 300 000 m^3/year (Andersson et al., 1991). Piezometric measurements have indicated that fracture zone 2 is recharged relatively deep. It has been estimated that about 60 - 80% of the groundwater flow is recharged regionally (Gustafsson and Andersson, 1989). This indicates that Zone 2 will act as a vertical barrier for the local groundwater flow, and that flow under the zone is dominated by regional flow.

5.4.2 Groundwater discharge at ground surface

Groundwater flowing in the rock mass within the Finnsjön Rock Block, will eventually reach the ground surface. Here it will be discharged in seepage areas such as swamps, rivers and lakes or into springs if the discharge is concentrated. The groundwater discharging into a spring consists of both local groundwater infiltrating relatively close and regional groundwater that might have inflitrated far away. Generally the local groundwater dominates the flow in springs. However, for perennial springs, discharging throughout the year, the regional groundwater flow will constitute a substantial part of the total flow during dry seasons.

In the Finnsjön area, two springs have been identified, the so called Björnkällan and Norrvretskällan (Jacobsson, 1980). Björnkällan dried up during the summer of 1979 (Jacobsson and Larsson, 1980). This indicates that this spring is not fed by regional groundwater, but is dependent on water infiltrated locally.

There are also two larger swamp areas and streams northeast of the Finnsjön Rock Block, that act as discharge areas (Figure 5.4). One is situated some hundreds of metres north of the southern block with an area of 1.0 km^2, and the other is about 1 km to the north of the northern block with an area of about 0.3 km^2.

The baseflow of the stream draining the southern part of the Finnsjön area (drainage area of 16.7 km^2) have been measured to about 700 m^3 per hour, with a minimum in july of 250 m^3 per hour (Carlsson and Gidlund, 1983).

5.4.3 Saline groundwater

Water chemistry investigations have revealed saline groundwater in all boreholes in the northern block at depths between 90 and 300 m. For all boreholes, the depth to the saline groundwater coincide with the upper hydraulically active boundary of fracture zone 2 (Figure 5.5). The groundwater contains 5000 - 6000 mg/l of chloride with a salinity of about 0.8% (Smellie and Wikberg, 1989).

In the southern rock block, south of Zone 1, four boreholes have been drilled to

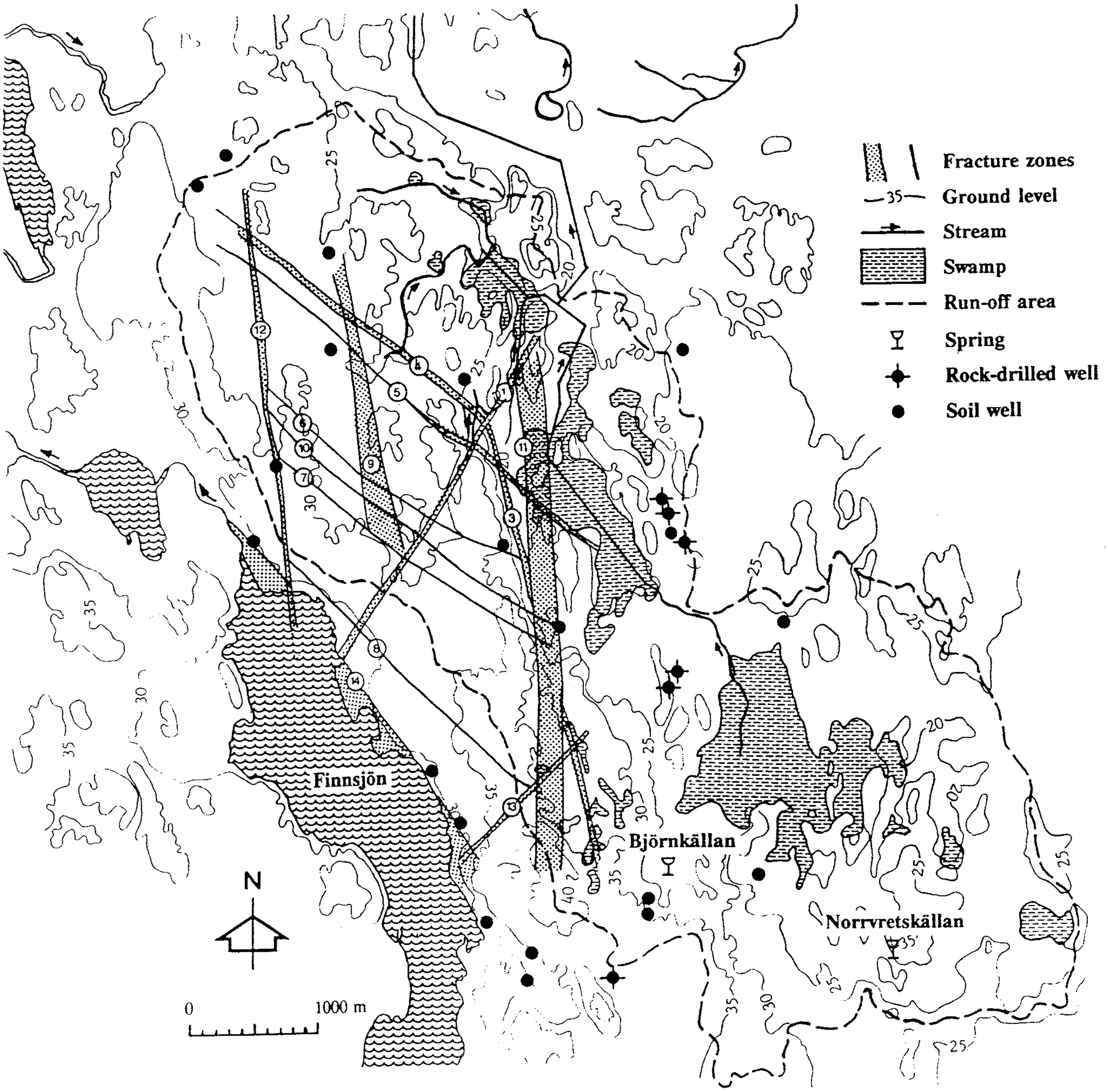


Figure 5.4 The Finnsjön run-off area with wells and discharge areas for groundwater.

depths of 500 - 600 m. Saline groundwater has not been found in any of these boreholes.

The difference in salinity between the north and south block in the deeper part of the rock mass have been investigated by Ahlbom and Svensson (1990). The absence of saline groundwater in deeper parts of the south block may be explained by locally high groundwater levels, which forces the saltwater interface downwards. This effect is neutralized in the northern block by the highly conductive fracture zone 2, which redistributes and deminishes the pressures at depth.

Depending on the pressure distribution in the saline groundwater below Zone 2, deeper saline groundwater may flow upwards toward Zone 2, where it is flushed away in the uppermost, highly conductive part by the natural groundwater flow in the zone.

The chloride content in wells in the Finnsjön area is found to be well below the taste limit for drinking water. An inventory of wells in the area found 21 wells in soil with a maximum depth of 5.9 m and 6 wells drilled in the hard rock to a maximum depth of 58 m (Figure 5.4). Wells in soil were found to have a chloride content between 1 and 97 mg/l, while wells in the rock mass had a chloride content of 2 - 57 mg/l (Jacobsson, 1980). The two springs in the southern part of the Finnsjön area showed a chloride content less than 4 mg/l.

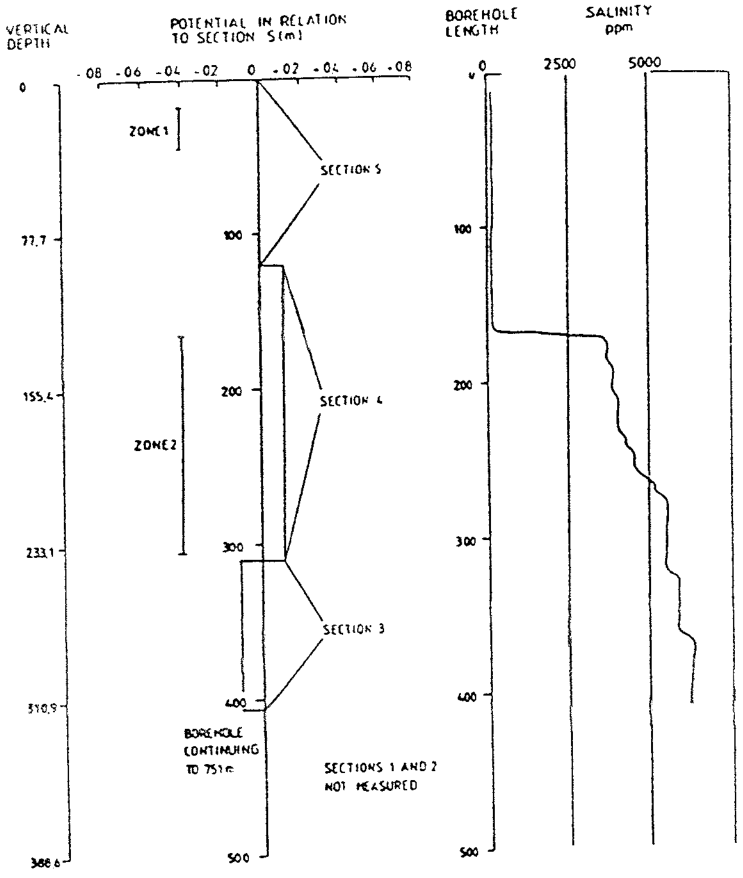


Figure 5.5 Salinity profile in borehole KFI05.

5.5 Hydraulic evaluation of investigation boreholes

The hydraulic conductivity has been measured by packer tests in 14 boreholes within the Finnsjön area (Andersson et al., 1991). In an attempt to assess the characteristics of a future well drilled in this area, the data from the hydraulic tests in 9 of the boreholes have been evaluated (Appendix B). The well depth is assumed to be 60 m, which is the mean depth of rock drilled wells located in older granitoid in Uppland (Söderholm et al., 1983). The depth to the groundwater table is assumed to be 2 - 3 m below ground level. The upper part of the boreholes where no measurements have been carried out is assumed to have the average hydraulic conductivity of the uppermost 5 measured sections. The top section column in Table 5.2 gives the depth below ground level below which conductivity values have been measured. As earlier investigations in this area have revealed a trend of decreasing conductivity with depth, this method will lead to conservative results. For the inclined boreholes, the data is adjusted to get vertical depths below ground level.

The specific capacity of each tested section in a borehole, from the groundwater level down to a depth of 60 m, has been calculated using the Thiem equilibrium equation for a fully penetrating well in a confined aquifer, with no account taken to skin effects.

$$q_s = \frac{2\pi K b}{\ln(r/r_w)} \qquad \left(\frac{\mathrm{m}^3}{\mathrm{day}\cdot\mathrm{m}}\right) \qquad (5\text{-}1)$$

Where q_s = Specific capacity of section
K = Hydraulic conductivity of section
b = Length of section
r = Radius of influence
r_w = Radius of section

Defining:

$$a = \frac{2\pi}{\ln(r/r_w)} \qquad (5\text{-}2)$$

and

$$T = Kb \qquad (5\text{-}3)$$

gives the specific capacity, q_s, of a tested section in a borehole:

$$q_s = aT \qquad \left(\frac{\mathrm{m}^3}{\mathrm{day}\cdot\mathrm{m}}\right) \qquad (5\text{-}4)$$

A well radius r_w = 55 mm and a radius of influence r = 150 m have been used in the calculations. This give a value of a = 0.91, which is a reasonable value for wells drilled in Swedish bedrock according to Carlsson and Carlstedt (1977). The specific capacity of an imaginary well, q, is calculated by summing the specific capacities of each tested section in a borehole from the groundwater table down to a depth of 60 m.

$$q = \sum_{z \leq 60\text{m}} q_s \tag{5-5}$$

By specifying a pumping rate Q of 6 m^3/day, the drawdown h-h_w in each imaginary well may be calculated from:

$$h - h_w = \frac{Q}{q} \tag{5-6}$$

After using this drawdown to determine which sections (and which fractions of the sections) are available, the capacities of the available sections are summed, and the total capacity of each imaginary well is calculated.

Following this method, the specific capacities for the boreholes have been compiled both for a well that gets its water along the whole borehole and a well for which the upper 30 m of the borehole is assumed to be tight (Table 5.2).

Table 5.2 Specific capacities and drawdowns of imaginary wells in the Finnsjön area, based on hydraulic tests in boreholes.

Borehole	Top section (mbgl)	Drawdown (m)		Specific capacity (m^3/day∘m)		Comments
		0-60	30-60	0-60	30-60	
HFI 01	4	0.6	0.6	10.8	9.4	North block
KFI 01	14	11.6	31.1	0.5	0.2	South block
KFI 02	12	0.8	1.4	7.9	4.2	South block
KFI 03	6	17.3	30.6	0.4	0.2	South block
KFI 04	49	1.2	2.2	5.0	2.7	South block
KFI 05	38	0.7	1.5	8.6	4.0	Fr. zone 1
KFI 07	18	0.9	1.4	6.4	4.3	North block
KFI 08	35	1.0	1.7	5.8	3.5	Fr. zo. 3, 11
KFI 10	46	0.6	1.2	9.7	5.2	Fr. zone 1

It is shown that scale effects are important when determining the effective hydraulic conductivity in a rock mass (Gustafson et al., 1989). The method used by summation of specific capacities of each tested section gives probably a too high value of the specific capacity for the entire borehole.

The median value of the specific capacity of the upper 60 m of the rock is calculated to 6.4 m^3/day*m. The specific capacity will be reduced by about 50% if the uppermost 30 m of the borehole is excluded. Still, it will probably not be necessary to drill a well deeper than 60 m in this area to reach a capacity of 6 m^3/day. The resulting drawdown in the well will be in the order of 1-2 m. The specific capacities of fracture zones deeper than 60 m can therefore be disregarded in this study.

The calculations also show that there is no significant difference between the rock mass and fracture zones in the uppermost 60 m. The borehole (HFI01) that gives the highest specific capacity (10 m^3/day*m) is drilled in the northern block close to fracture zone 1.

An explanation for the high specific capacities of the boreholes in the Finnsjön Rock Block may be that all are drilled close to (100-200 m) interpreted fracture zones. Studies have shown that wells drilled close to tension zones have about 3 times higher specific capacity than wells drilled close to shear zones or in the hard rock (Ericsson, 1988).

5.6 Hydraulic description of drilled wells

In order to test the representativity of specific capacities calculated from boreholes, a comparison is made with data from existing wells in the same kind of rock formation and geographical location. Information from well drillers, regarding the capacity and depth of wells, collected at the Water Well Record Section at the Swedish Geological Survey is used for this purpose.

After the completion of a well, the capacity is often tested by blowing high pressure air into the borehole, which gives an estimate of the well capacity at maximum drawdown. This render a possibility to calcualte the specific capacity of a well.

Assuming a depth to the groundwater table of 2 m, the specific capacity of a well can be calculated as:

$$q = \frac{Q}{d-2} \qquad \left(\frac{\mathrm{m}^3}{\mathrm{day \cdot m}}\right) \qquad (5\text{-}7)$$

where q = Specific capacity
Q = Discharge of the well
d = Depth of well

Fifteen wells have been drilled (in Basic volcanic rock and rock of Svionic age) in the surroundings of the Finnsjön Rock Block (Figure 5.6). The calculated specific capacities of the investigated wells are shown in Table 5.3.

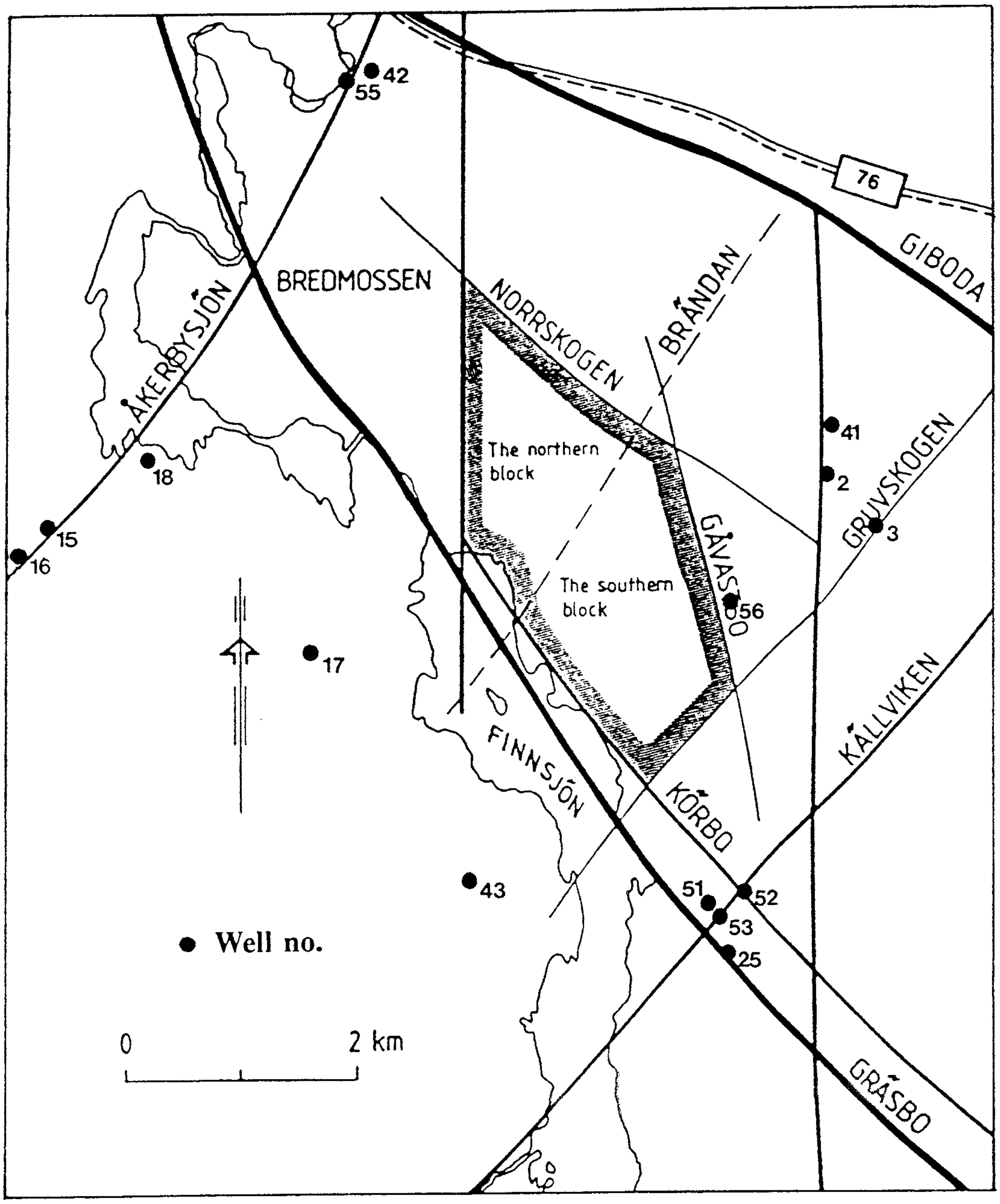


Figure 5.6 Location of wells used for calculation of specific capacity.

Table 5.3 Specific capacities for wells drilled in bedrock in the Finnsjön area.

Well no.	Discharge (m^3/day)	Depth of well (m)	Specific capacity (m^3/day$\circ$m)
2	9.6	23	0.5
3	28.8	17	1.9
15	144.0	33	4.6
16	7.2	58	0.1
17	8.6	49	0.2
18	21.6	85	0.3
25	14.4	120	0.1
41	16.8	61	0.3
42	16.8	56	0.3
43	3.6	100	0.04
51	9.6	93	0.1
52	10.8	82	0.1
53	21.6	49	0.5
55	72.0	59	1.3
56	21.6	30	0.8

The specific capacities of wells can be assumed to be lognormally distributed. This implies that the relative frequencies are higher in low ranges of specific capacities than in the high ranges. Thus, when comparing specific capacities, median values are the most proper to use.

Wells located in older granitoid in Uppland have a median depth of 60 m and a median capacity of 940 l/h (Söderholm et al., 1983). This gives a median capacity of 22.6 m^3/day, which should be compared with the median capacity of the investigated wells of 16.8 m^3/day. The depth of that particular well happens to be 61 m. Thus, the investigated wells may be viewed as a representative sample of future drilled wells in the area.

The median value of the specific capacity of investigated wells is 0.3 m^3/day*m. This gives a drawdown in the well of 20 m for a continuous discharge of 6 m^3/day.

This may be compared to the median specific capacity of 4-6 m^3/day*m for the boreholes within the Finnsjön Rock Block. However, in the southern part of the

Finnsjön Rock Block, two of the four boreholes have specific capacities of 0.2-0.5 m^3/day*m, which is comparable with the median value of the investigated wells.

For regional studies Jetel and Krasny (1968) have introduced the parameter Z.

$$Z = \log\left(\frac{q \times 10^9}{h}\right) \tag{5-8}$$

where q = Specific capacity of a well
h = Length of the open section

The transformation of the regional parameter Z to the regional hydraulic conductivity, K_r, for non-steady state conditions is given by Carlsson and Carlstedt (1977).

$$K_r = \frac{10^{Z-9}}{\alpha}\ , \qquad 0.9 < \alpha < 1.1 \tag{5-9}$$

For the investigated wells located in the vicinity of the Finnsjön Rock Block, the median value of the regional hydraulic conductivity is calculated to $5.5*10^{-8}$ m/s. This is in accordance with the geometric mean value of the hydraulic conductivity of the uppermost 100 m of the southern block, which is $1.7*10^{-8}$ m/s. This indicate that the hydraulic conductivity of the southern block is more close to the rock mass encountered in the wells in the surroundings of the Finnsjön Rock Block.

6 FUTURE RISK ZONES FOR DRILLED WELLS

6.1 Natural conditions

Groundwater that flow through a generic repository at 500 m depth, situated between the fracture zones 1, 4, 12 and 7, will probably flow out in the corner between the fracture zones 1 and 4 and in the discharge areas north and east of Zone 3. This is supported by earlier three-dimensional simulations of the groundwater flow in the Finnsjön area (Lindbom et al., 1991). This local flow pattern is also supported by pressure measurements in the subhorizontal fracture zone 2, that discharges along fracture zone 1 and 4 about 50 to 100 metre below the ground surface (Andersson et al., 1991).

The groundwater that flows out in fracture zone 1 will probably continue in this zone to discharge areas, swamps and streams, between the Finnsjön Rock Block and the lake Skålsjön (Figure 6.1). The groundwater that flows out in fracture zone 4 will discharge at the ground surface or flow out in Zone 1. A minor portion might flow through the rock mass towards the lake Skålsjön. This means that all of fracture zone 1, except about 2 km down south towards the lake Finnsjön, will recieve groundwater that has passed through the repository. The part of fracture zone 4 that is close to fracture zone 1 will also act as a collector for groundwater flowing through the repository. Other parts of Zone 4 and other fracture zones in the Finnsjön Rock Block will probably not be influenced under natural conditions.

The regional fracture zone Imundbo, which is located at the discharge area about 2 km east of the Finnsjön Rock Block, will probably also recieve groundwater that has passed the generic repository. This is eventually discharged in the lake Skålsjön. Depending on the conductivity contrast between fracture zones and rock mass, some of the groundwater that has passed the repository might flow through the rock mass towards the lakes 7 km NE of the Finnsjön Rock Block.

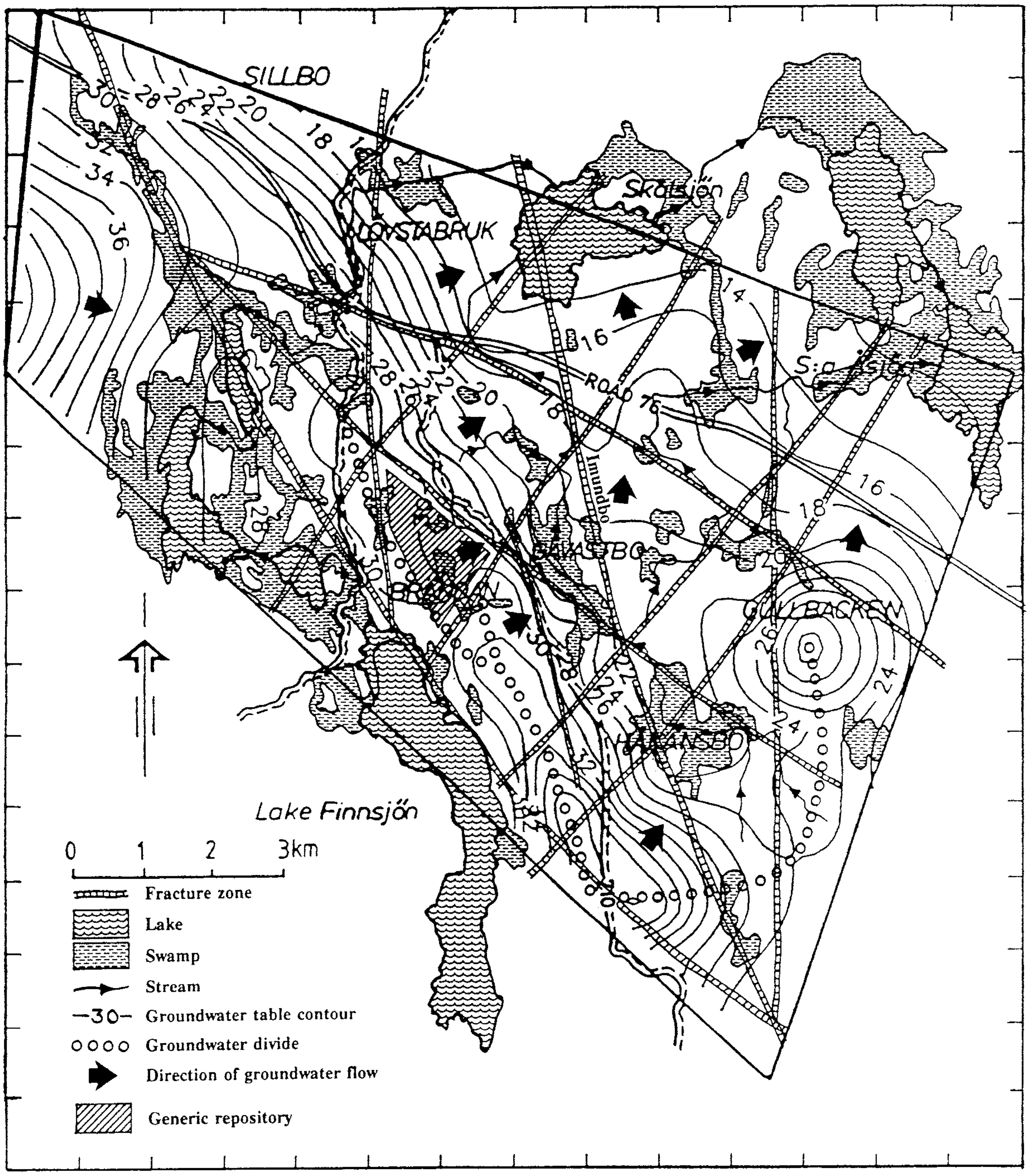


Figure 6.1 Regional groundwater levels and flow pattern.

6.2 Effects of pumping from a well

The drawdown associated with the discharge from a well, may or may not disturb the natural groundwater flow pattern depending on:

- Pumping rate of the well
- Pumping depth and screening
- Groundwater recharge
- Hydraulic conductivity of the rock mass
- Natural groundwater flow

Simple analytical calculations and model simulations were performed to illustrate the importance of some of the factors.

Assuming that the well gets all of the pumped water from recharge gives an increasing radius of influence with decreasing recharge and increasing pumping rate (Figure 6.2). A reasonable value on the groundwater recharge in till/rock terrain in coastal areas is about 50 mm/year (Ericsson, 1981a). The radius of influence at a recharge of 50 mm/year is approximately 120 m when pumping 6 m^3/day. Notice that the radius of influence in this sence is not eqaul to the distance at which the well ceases to have an effect on the groundwater heads. It should be viewed more as the distance from which the well may get its discharge at various recharge rates. However, the calculations are in agreement with experiences from testpumping in coastal areas that show influence radius in the order of 150 - 300 m (Ericsson, 1981b).

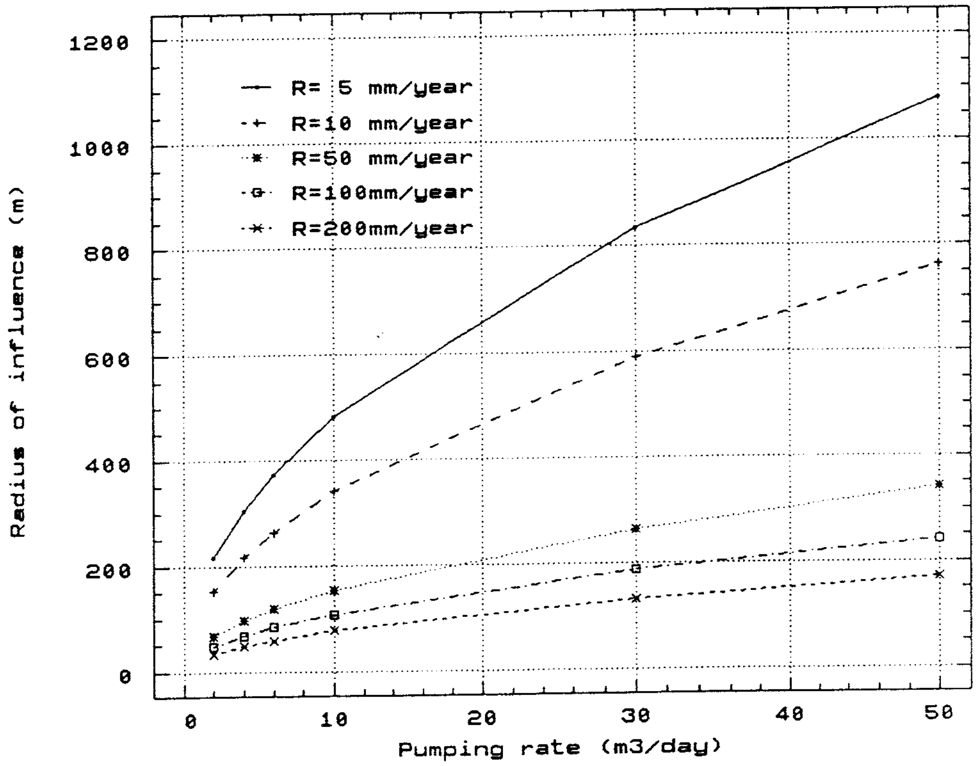


Figure 6.2 Radius of influence versus pumping rate and groundwater recharge.

Taking also the hydraulic conductivty of the rock mass into account gives the possibility to calculate the necessary drawdown in the well for various pumping rates and groundwater recharge rates. Figure 6.3 shows the drawdown for a pumping rate of 6 m^3/day at various recharge rates and hydraulic conductivities without any consideration taken to skin effects. If there is a recharge of 50 mm/year during the pumping of a well in a rock mass having a hydraulic conductivity of $1*10^{-8}$ m/s, the drawdown will be about 4 m. However, the drawdown will be greater than 20 m if there is no recharge.

In the rock mass at Finnsjön, with a hydraulic conductivity in the order of $1*10^{-8}$ to $1*10^{-7}$ m/s in the uppermost 100 m, the drawdown of a well pumping 6 m^3/day will be limited to some metres during recharge periods, while the drawdown during dry periods will be larger. Though, the impact from a well on the regional groundwater flow will be minor.

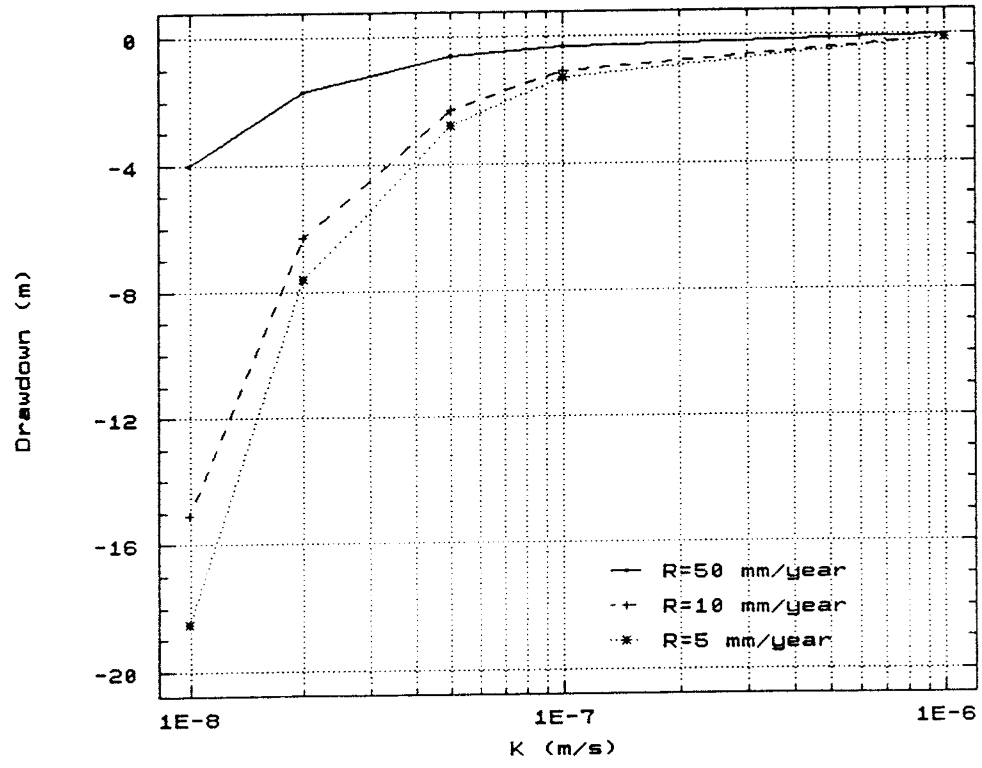


Figure 6.3 Drawdown in a well pumping 6 m^3/day versus hydraulic conductivity (K) and groundwater recharge (R).

7 MODELLING OF DILUTION IN A WELL

7.1 General considerations

Calculation of the dilution of radionuclides in a well, released from a repository located in a rock mass, is complicated and involves flow and transport in fractured rock.

Groundwater flow in fractured crystalline rock is concentrated to paths (channels) in fracture planes. This is shown by laboratory experiments on small scale fractures by Hakami (1989) and by in-situ channeling experiments in the Stripa mine by Abelin et al. (1990). Individual channels in a fracture plane may be isolated or may connect to other channels in intersecting fractures to form a continuous network of more or less conductive pathways in the rock mass. Observations of water leakage in tunnels by Palmqvist (1990) indicate that the major part of the groundwater flow may be found in a few pathways. Little is known today about the mixing between individual channels. Mixing may be small, implying distinct channeling from the transport point of view (Neretnieks, 1990).

The radionuclides will interact with the surrounding rock, by sorption on the mineral surfaces and diffusion into the rock matrix. These effects are strongly dependent on how much rock surface that is in contact with the flowing groundwater in the channels.

Consequently, the mixing between channels, sorption on channel surfaces and diffusion into the rock matrix will be important factors for decreasing the concentration of radionuclides before reaching a well.

It can be argued that a flow channel from the repository can reach a well without any dilution (except for sorption and diffusion). The only dilution that will occur in the well is dependent on the ratio between the pumping rate and the flow in the channel (Skagius and Svemar, 1989).

Research is presently carried out within the SKB 91 safety analysis project, to use several models describing different aspects of flow and solute transport in fractured rock. These models involves;

- Flow in a connected network of discrete fractures, with channeling in the individual fracture planes (Geier and Axelsson, 1991).
- Generation of flowfields by stochastic continuum technique (Norman, 1991).
- Flow and solute transport in a network of channels (Moreno and Neretnieks, 1991).
- Solute transport in streamtubes (Norman and Kjellbert, 1990)

7.2 Modelling technique

As have been stated earlier, the groundwater flowing through the repository will probably be discharged in fracture zone 1. The modelling exercise is therefore concentrated on illustrating the dilution in wells located in this fracture zone. The basic case is assumed to be a well pumping 6 m^3/day at a depth of 60 m below ground surface. The well is assumed to be located at various places between the generic repository site and the discharge area. Some scenarios are also illustrating a well pumping at larger depths and with other capacities.

To study the dilution in a well located in fracture zone 1, a vertical two-dimensional groundwater model is used. Modelling of the groundwater flow is performed using the Golder Groundwater Computer Package (GGWP), a series of finite element models developed by Golder Associates (Golder Associates, 1983).

Groundwater modelling is also performed for the scenario with a well located in the rock mass above the generic repository. This type of well gets its water from groundwater recharge or from the subhorizontal fracture zone 2 or other near-vertical fracture zones like Zone 1. The aim with this modelling exercise is to illustrate the importance of factors like; well discharge, well depth, screening of the well, groundwater recharge and hydraulic conductivity, for the way that the well gets its water.

This modelling is performed using an analytical technique developed by Strack (1989) and Haitjema (1985, 1987). The technique allows to have a partially penetrating well pumping water at different depths in a three-dimensional aquifer with equipotential boundaries (Appendix C).

7.3 Wells located in a fracture zone

7.3.1 Model design and assumptions

The modelled section of fracture zone 1 in the Finnsjön Rock Block is 7400 m long and extends from a topographic water divide west of lake Finnsjön to a more diffuse water divide north-east of road 76 (Figure 7.1). The vertical section has a depth of 1000 m and is 20 m wide. The finite-element mesh consists of 6600 elements, which are more refined from the centre of the Finnsjön Rock Block towards north-east in the direction of the topographic gradient (Figure 7.2). The vertical and bottom boundaries are assumed to be no-flow boundaries, while the upper surface exhibits two different boundary conditions. Lake Finnsjön is defined as a specified head boundary, with the head equal to the lake elevation. The rest of the upper boundary is defined as an unconfined aquifer with a phreatic water table with groundwater recharge. To correctly model the unconfined fracture zone, the ground elevation is specified at the top boundary as an upper bound for the phreatic surface. Groundwater recharge will only occur at unsaturated parts of the fracture zone, while groundwater discharge occurs at places where the groundwater table reaches the ground surface.

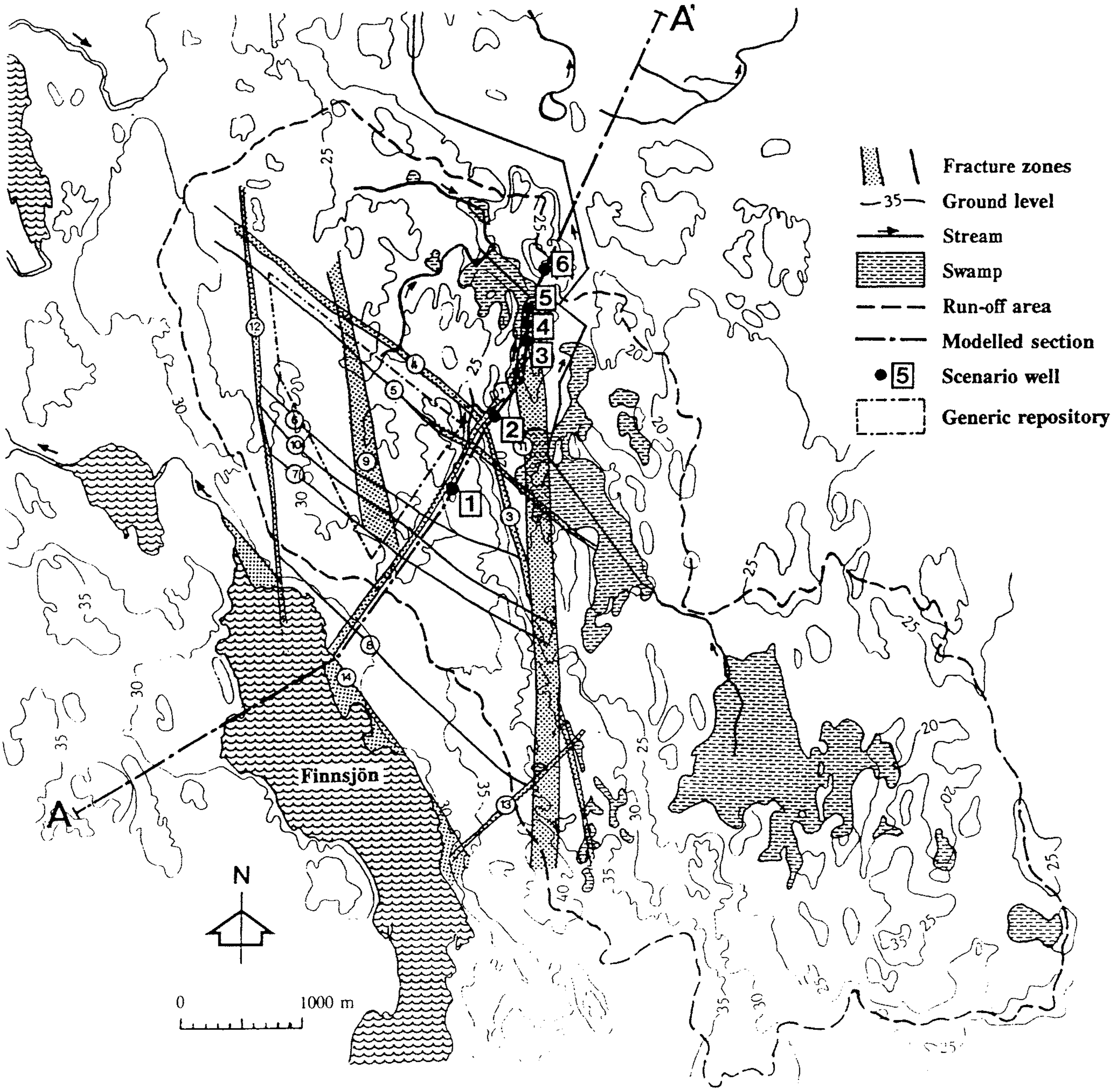


Figure 7.1 Modelled section (A - A′) and scenario wells along fracture zone 1.

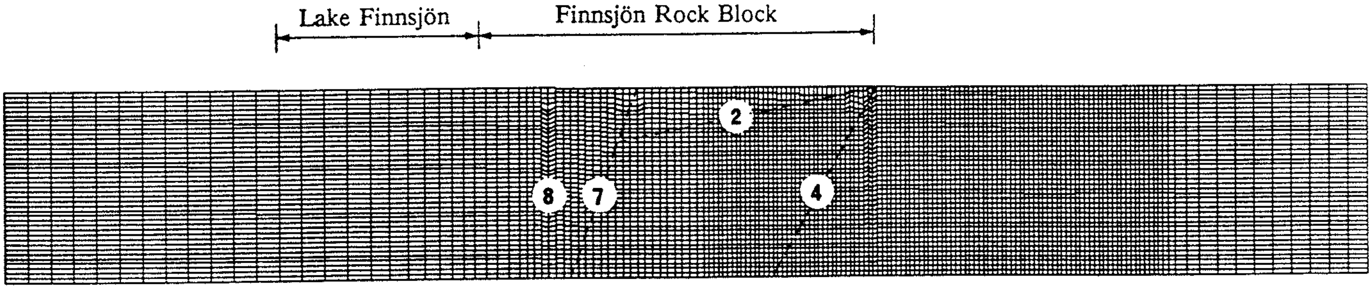


Figure 7.2 Finite element mesh of the modelled section.

The hydraulic conductivity used in the model of fracture zone 1 is assumed to be dependent on depth. The function describing the decrease in conductivity with depth was calculated by Lindbom et al (1991) and based on field investigations and statistical evaluation of the collected data. Fracture zone 1 is divided into 16 zones, each representing a specific elevation. The hydraulic conductivity of each zone is calculated according to the formula:

$$K = 1.21 * 10^{-3} * Z^{-1.10} \qquad (7\text{-}1)$$

where K = hydraulic conductivity (m/s)
Z = depth from ground surface (m).

The potential (maximum available) groundwater recharge assigned to the model of fracture zone 1 is assumed to be 180 mm/year. This is based on water balance calculations for the Finnsjön area made by Carlsson and Gidlund (1983).

7.3.2 Model calibration

The goal of the model "calibration" is to establish a two-dimensional site-specific model of fracture zone 1, based on field data and the results from the initial three-dimensional groundwater modelling of the Finnsjön site (Lindbom et al., 1991). Four fracture zones; Zone 8, 7 and 4 and the sub-horizontal Zone 2, are intersecting fracture zone 1 and incorporated in the model. To account for the three-dimensional flow in the connected fracture system, the intersecting fractures with the two-dimensional model of Zone 1 are specified as inflow to or outflow from the modelled section.

To calculate the flow from the Zones 8, 7 and 4 to Zone 1, simple models were created for each fracture zone. These were modelled as unconfined two-dimensional vertical sections bounded by Zone 12 and Zone 1. At Zone 12 and close to Zone 12 the specified head boundary were used, where the head values were taken from a topographic study of swamped areas in the surroundings of Zone 12. Specified head boundary was also used at the contact with Zone 1, where the head values were obtained from the three-dimensional model of the Finnsjön site. When calculating flow in fracture zone 4, flow from Zone 2 into Zone 4 was assigned values according to the three-dimensional modelling. The flow in the fracture zones 8, 7 and 4 at the connection with Zone 1, was thus calculated from these simple models.

The interchange of flow between the sub-horizontal Zone 2 and Zone 1 is based on the results of the three-dimensional model, which predicts an outflow from Zone 1 to Zone 2 close to the connection with Zone 7, and an inflow to Zone 1 from Zone 2 close to the connection with Zone 4 (Figure 7.3). The flow rates predicted by the three-dimensional model are 49500 m^3/year and 14000 m^3/year respectively. This indicate that Zone 1 recharges Zone 2 with about 35000 m^3/year. The higt flow rates could be a result of the assumed hydraulic conductivities and the used modelling technique, where the groundwater table is defined at the same elevation as the ground surface, by specified head nodes at the upper boundary. In reality the groundwater table do not exactly follow the surface topography. If the surface topography is defined as the groundwater table, the groundwater head gradient and accordingly the groundwater flow will be overestimated.

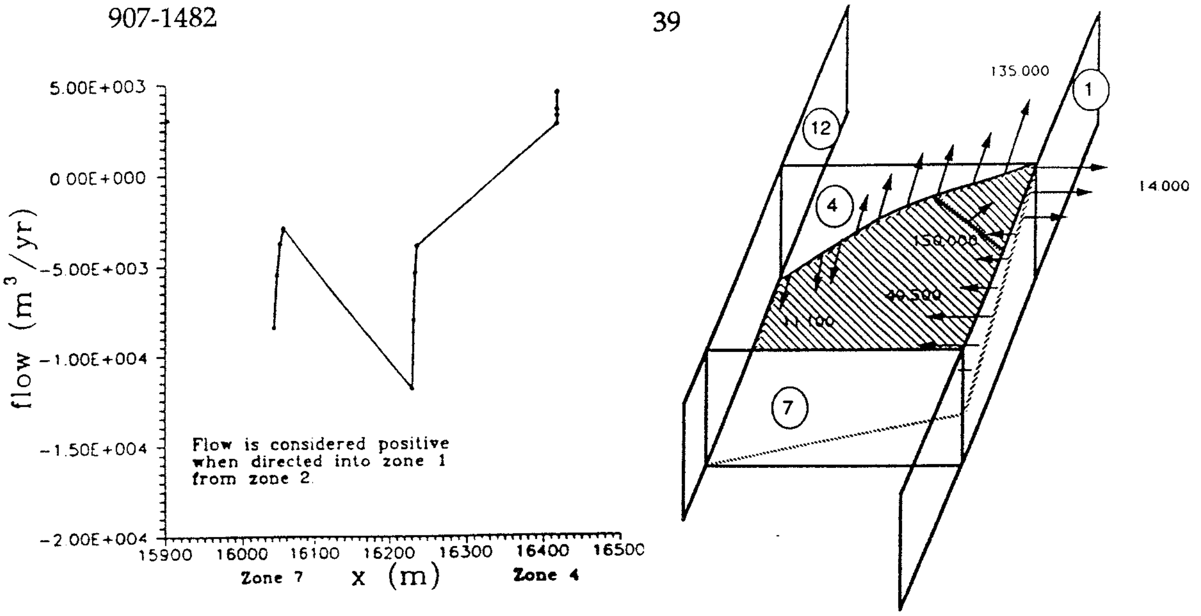


Figure 7.3 Distribution of flow between Zone 2 and Zone 1 (Lindbom et al., 1991).

According to the three-dimensional model, the groundwater flowing through a generic repository at 500 metre depth, situated between the fracture zones 1, 4, 12 and 7, will probably be transported to the intersection between fracture zone 1 and 4 (Figure 7.4). The potentially contaminated groundwater will probably enter Zone 1 at a depth between 300 m and 500 m and at a distance from lake Finnsjön of about 1750 m. To study the flow pattern in Zone 1 of the groundwater eminating from the repository, a concentration equal to 1.0 is assigned to the water entering Zone 1 from Zone 4 at a depth between 340 m and 480 m. The spreading of the plume is calculated by assuming a longitudinal dispersivity of 10 m and a transverse dispersivity of 1 m.

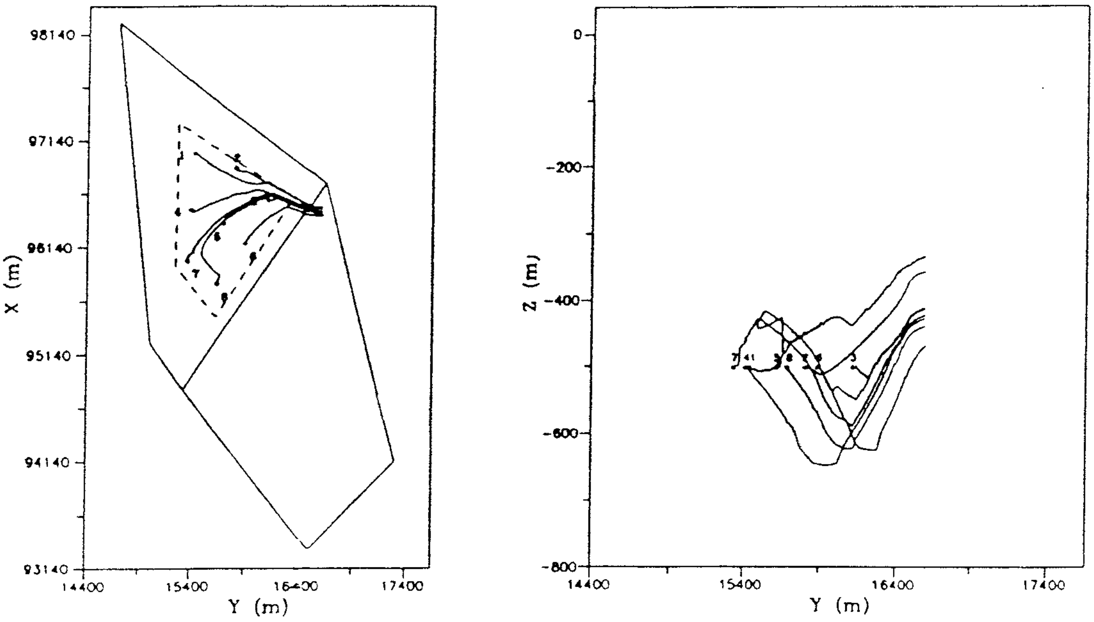


Figure 7.4 Horizontal (left) and vertical (right) projection of pathlines according to the three-dimensional modelling (Lindbom et al., 1991).

The groundwater heads and plume migration in fracture zone 1 with inflow from Zone 2 predicted by the three-dimensional model gave unrealistic results, with fracture zone 2 acting as a strong sink in the system (Figure 7.5). To gain a smooth flow pattern in the sectional model of fracture zone 1, similar to that predicted by the three-dimensional model, the flow rates in fracture zone 2 calculated by the three-dimensional model had to be reduced by 80% (Figure 7.6).

The contribution of flow to fracture zone 1 from fracture zones 8, 7, 4 and 2 in the two-dimensional model are as follows:

- Inflow from Zone 8 to Zone 1 of 1941 m^3/year.
- Inflow from Zone 7 to Zone 1 of 946 m^3/year.
- Inflow from Zone 4 to Zone 1 of 2818 m^3/year.
- Inflow from Zone 2 to Zone 1 of 2800 m^3/year and outflow from Zone 1 to Zone 2 of 9900 m^3/year.

The error in the overall water balance of the final "calibration" is about 0.03%.

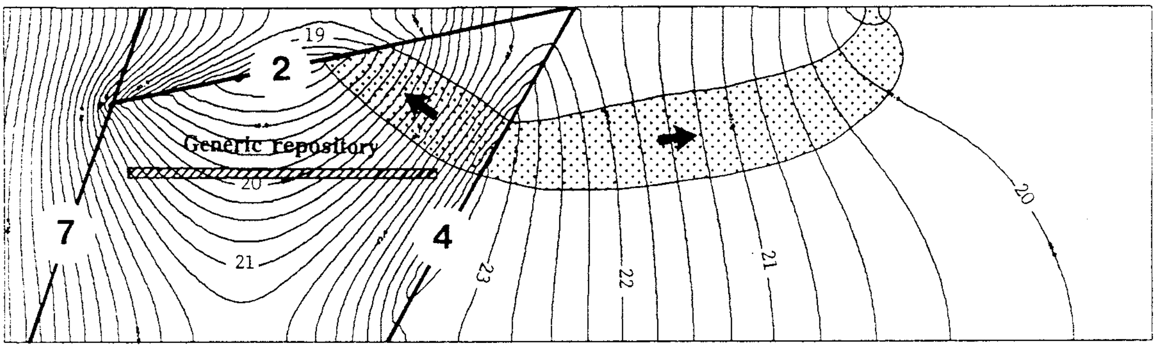


Figure 7.5 Piezometric head distribution and plume migration in fracture zone 1 for flow in Zone 2 predicted by the three-dimensional model.

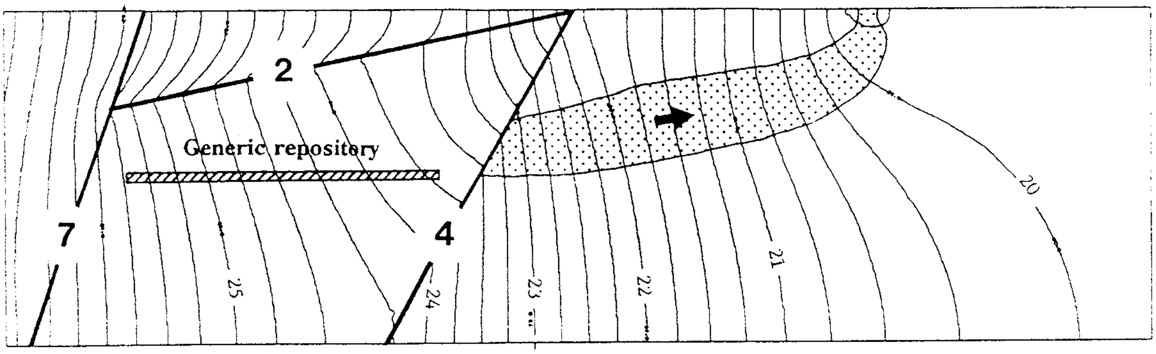


Figure 7.6 Piezometric head distribution and plume migration in fracture zone 1 for "calibrated" natural conditions.

The potentially contaminated plume eminating from the repository is about 140 m wide at the starting-point in fracture zone 1 and the length is 1700 m. The plume reaches the ground surface at a discharge area, a swamp, close to a stream and the plume is at this point limited to about 60 m, which is slightly less than the discharge area of 120 m.

The sensitivity to different dispersion coefficients has also been evaluated. The shape of the plume is stabile, in the sense that the contaminated water will allways flow towards the same discharge area (Figure 7.7).

The computed groundwater table and the defined ground surface are shown in Figure 7.8. The figure also illustrates discharge and recharge areas of Zone 1. The gradient of the groundwater table obtained from the model can be compared to the gradient of the ground surface. Due to the more smooth and flat gradient of the groundwater table, compared to the gradient of the ground surface, the flow rates predicted by this model are less than the flow rates predicted if the upper boundary is set to the ground elevation, which is the case with the three-dimensional flow calculations at the Finnsjön site (Lindbom et al., 1991).

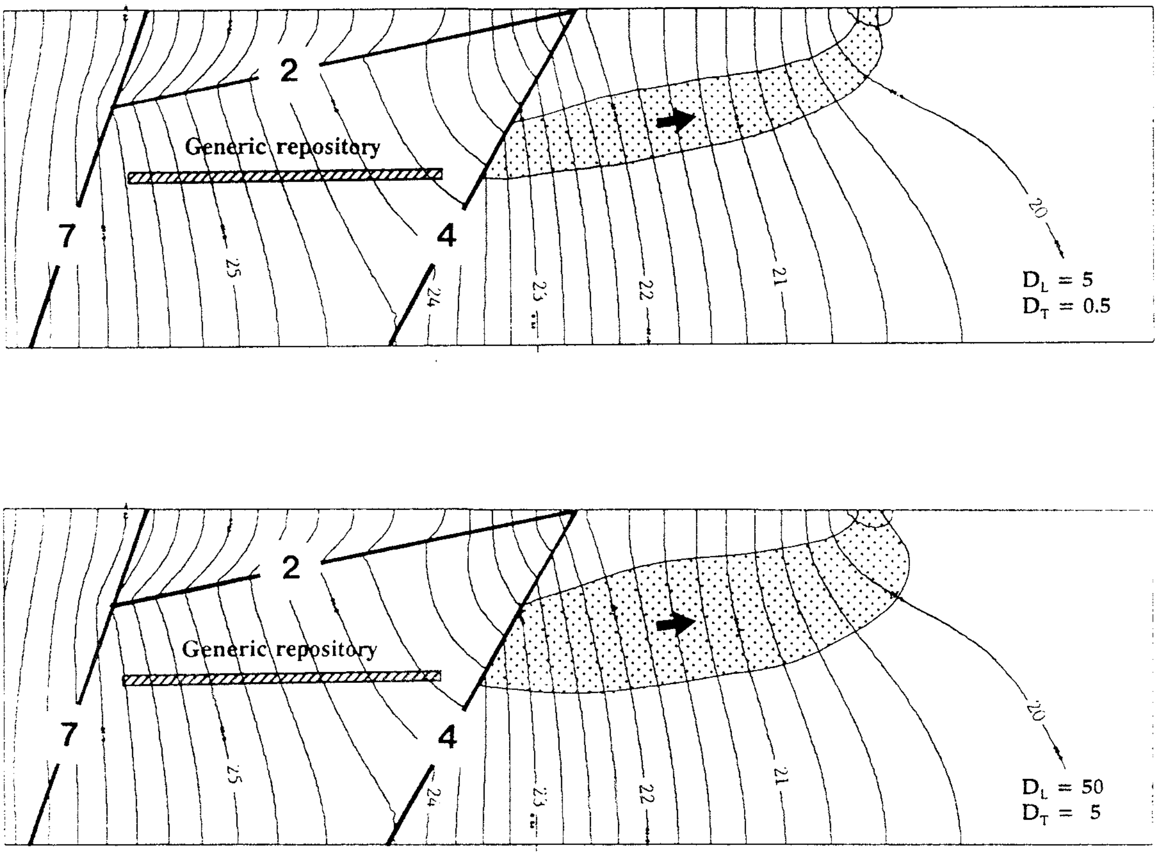


Figure 7.7 The effect of different longitudinal (D_L) and transverse (D_T) dispersion coefficients.

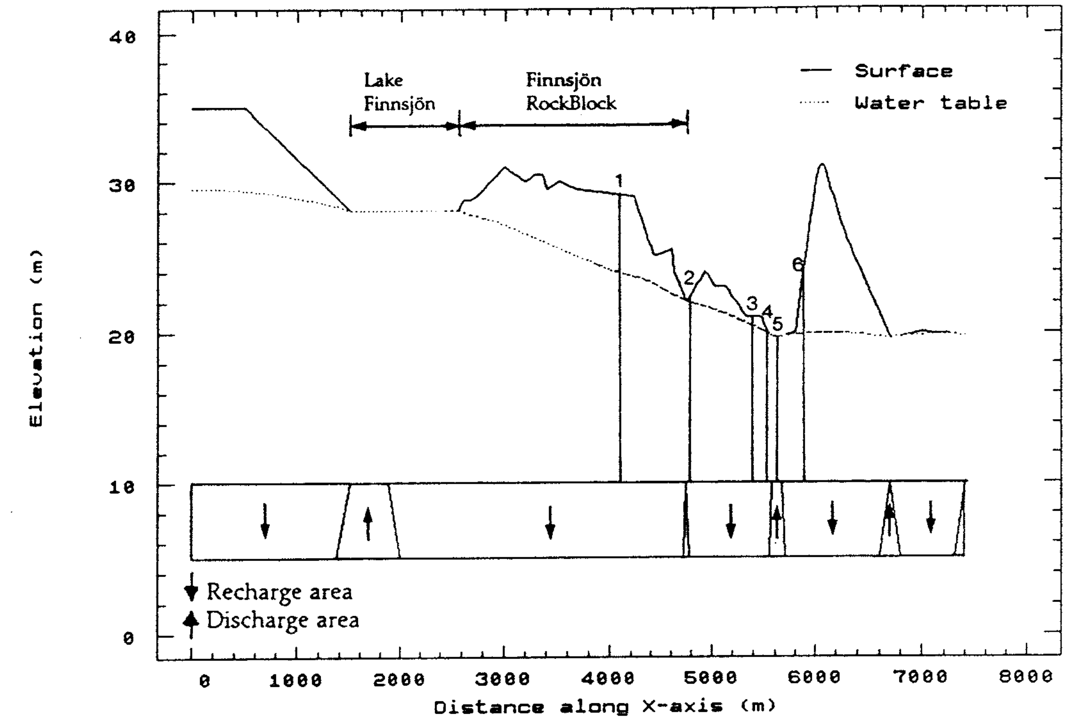


Figure 7.8 Computed groundwater table and ground surface with discharge and recharge areas.
1 - 6 Different well scenarios

7.3.3 Simulation of different well scenarios

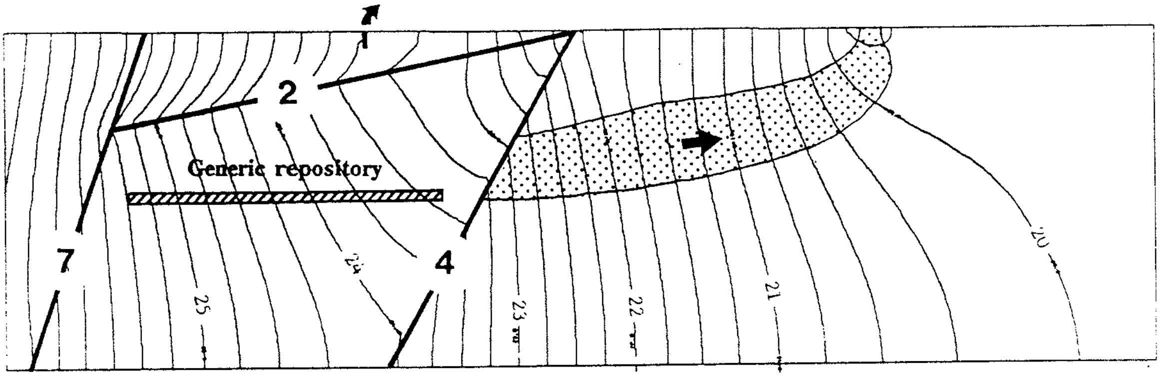
The purpose of the simulations is to study the effect of a pumping well on the flow pattern of groundwater eminating from the repository. The initial conditions for the predictive modelling are defined by the final "calibration" and all simulations are conducted under steady state conditions.

Different well scenarios are simulated by pumping 6 m^3/day in a well at various locations within fracture zone 1 (Figure 7.8). The well is simulated by a specified flow node defined at 60 m below ground surface. To illustrate the effect of depth and pumping rate, two additional well scenarios are modelled; one with a well 200 m from the discharge area pumping at a depth of 120 m and the other with a well pumping 30 m^3/day at a depth of 60 m.

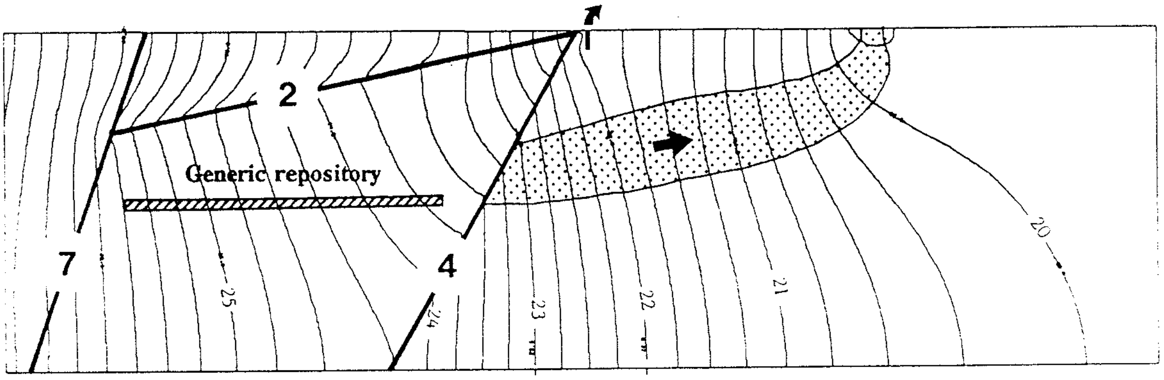
The error in the overall water balance of the different simulations is in the range 0.01-0.03%.

The regional flow pattern is not changed by the well and the plume does not flow into the well even if it is located about 100 m from the discharge area (Figures 7.9 and 7.10). The shape of the plume is stabile and the groundwater eminating from the repository will allways flow towards the same discharge area. Thus, the well has to be drilled closer than 100 m from or in the discharge area if a major part of the potentially contaminated groundwater is to be collected by the well. If the well is placed in a discharge area, it is possible that all of the contaminated groundwater will be collected by the well.

WELL SCENARIO 1



WELL SCENARIO 2



WELL SCENARIO 3

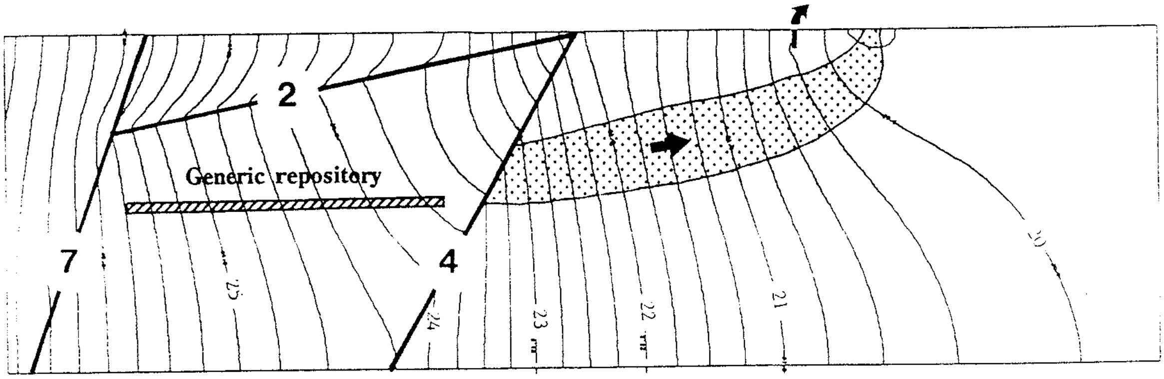
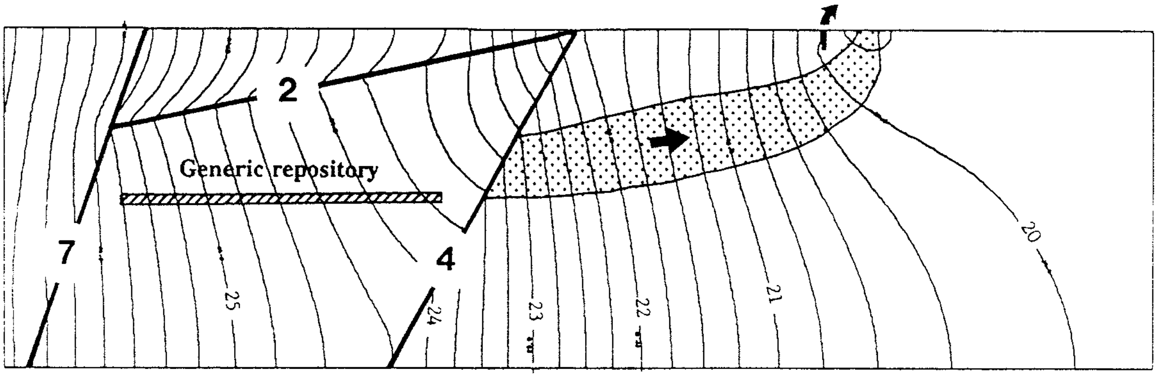
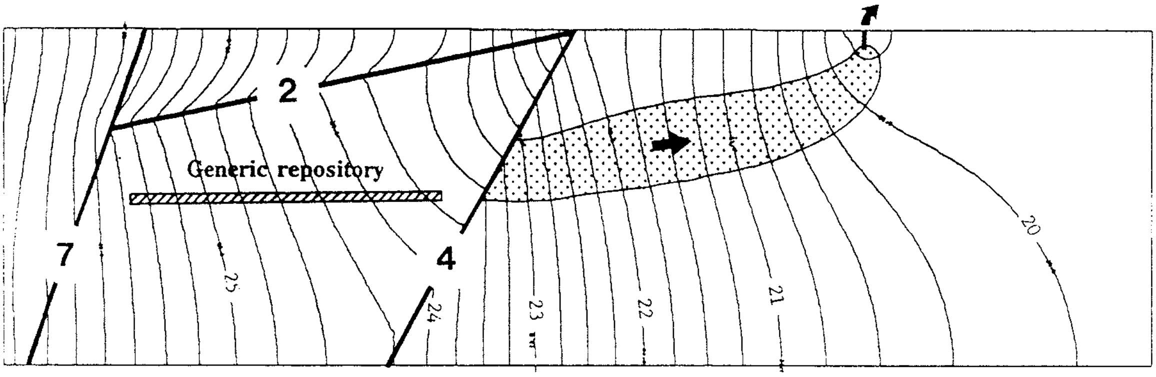


Figure 7.9 Spreading of plume eminating from the repository for a well pumping 6 m^3/day at a depth of 60 m (well scenario 1 - 3).

WELL SCENARIO 4



WELL SCENARIO 5



WELL SCENARIO 6

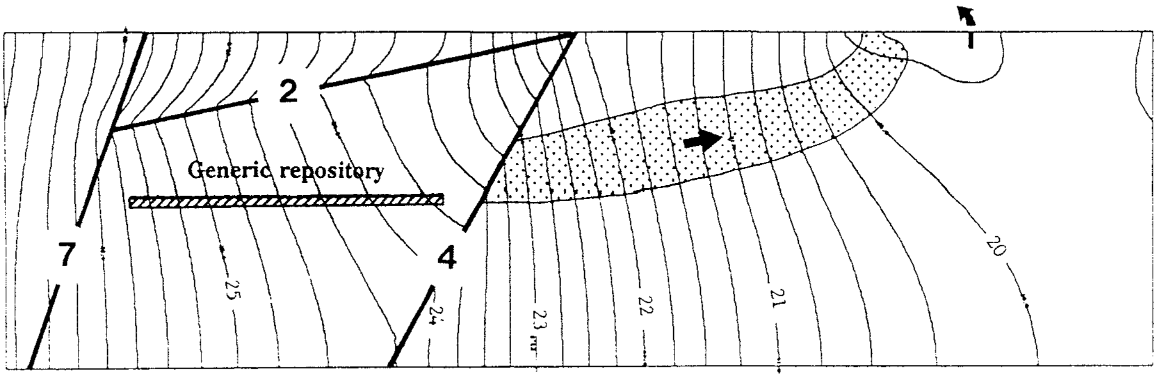


Figure 7.10 Spreading of plume eminating from the repository for a well pumping 6 m^3/day at a depth of 60 m (well scenario 4 - 6).

However, if the pumping depth is increased to 120 m below ground surface for a well located 200 m from the discharge area, then part of the plume will flow into the well (Figure 7.11). This may be interpreted as some of the streamtubes emanating from the repository will enter the well. The explanation being the areal extent of the repository, which will cause individual streamtubes to be spread over some area.

A well with a pumping rate that is increased by 5 times to 30 m^3/day, will affect the flow pattern in the vicinity of the well. The well itself will form the major discharge point and if the well is placed between fracture zone 4 and the local discharge area, it will probably collect all groundwater emanating from the repository. This is illustrated in Figure 7.12, which shows a well located 200 m from the discharge area.

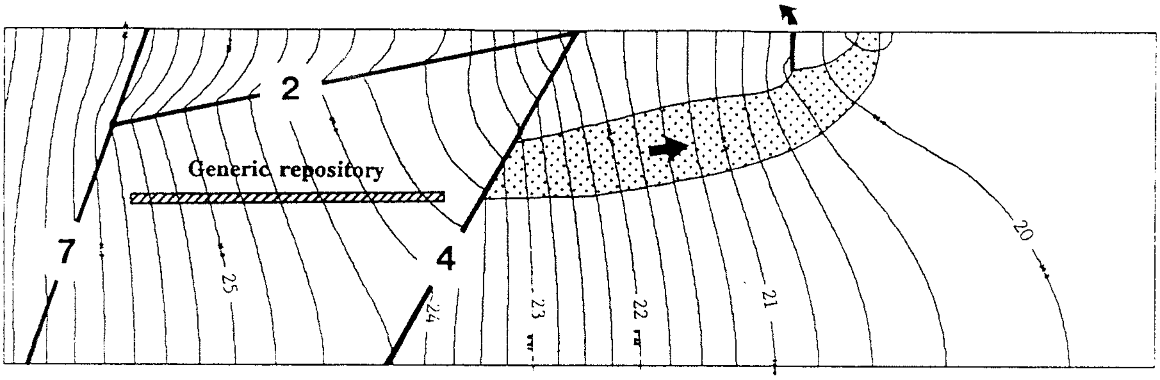


Figure 7.11 Spreading of plume eminating from the repository for a well pumping 6 m^3/day at a depth of 120 m.

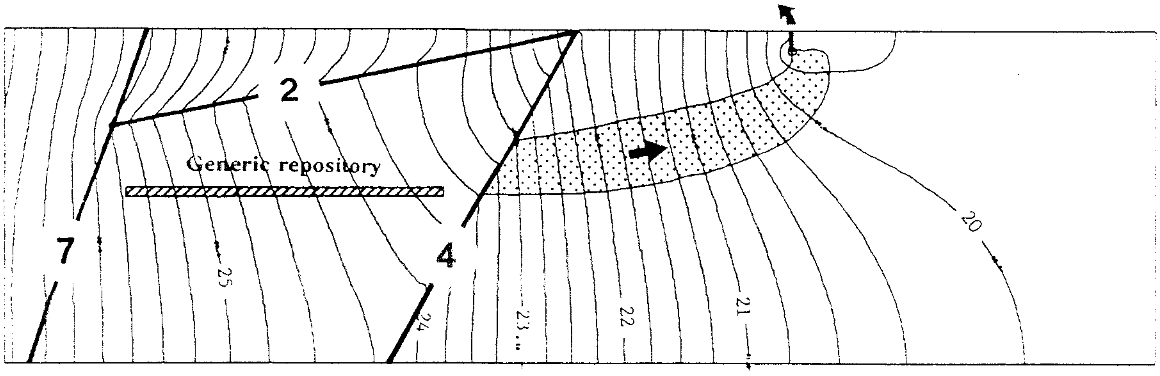


Figure 7.12 Spreading of plume eminating from the repository for a well pumping 30 m^3/day at a depth of 60 m.

7.4 Wells located in the rock mass

7.4.1 Model design and assumptions

Three-dimensional modelling was carried out with an analytical technique to illustrate where a well, located in the rock mass above Zone 2, gets its water from (Figure 7.13). The well may get the water from recharge or draw groundwater from the subhorizontal Zone 2 or from a vertical fracture zone, depending on:

- Pumping rate of the well
- Pumping depth and screening
- Groundwater recharge
- Hydraulic conductivity of the rock mass
- Natural groundwater flow

Simulations were made for a well with a depth of 40, 60 and 120 m, screened in the lowermost 10 m. The pumping rate was assumed to be 1, 3 and 6 m^3/day, and the recharge was set to 2 and 40 mm/year. The fracture zones were simulated as equipotential surfaces. Two different conceptual models of the hydraulic conductivity in the rock mass were used.

- **SINGLE - LAYER SYSTEM**: uniform conductivity of $1.2*10^{-7}$ m/s in the uppermost 200 m.
- **DUAL - LAYER SYSTEM**: uniform conductivity of $1.2*10^{-7}$ m/s in the uppermost 100 m and $1.0*10^{-8}$ m/s between a depth of 100 and 200 m.

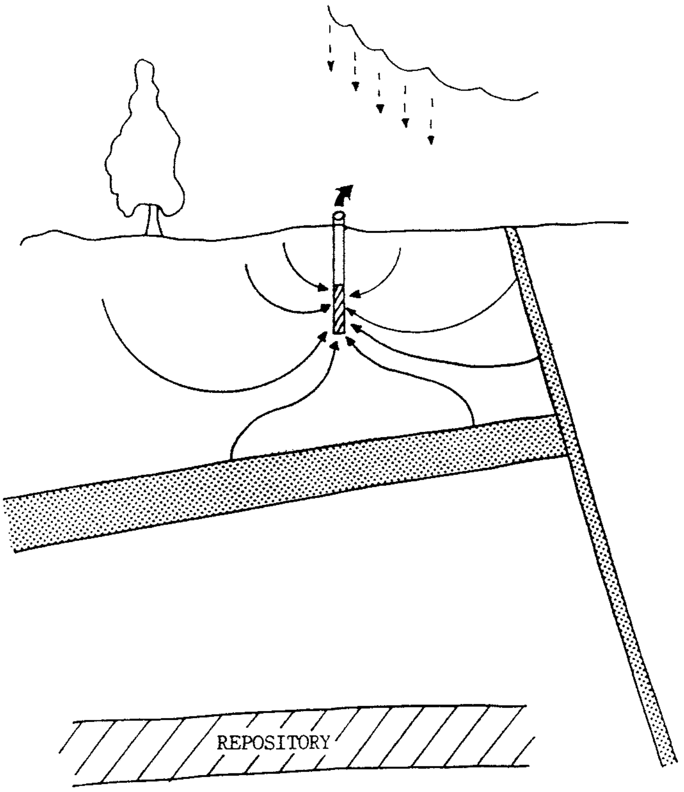


Figure 7.13 Illustration of modelling of a well in the rock mass above Zone 2.

7.4.2 Simulation of different well scenarios

The result is given as the percentage of the total pumping rate that is coming from the subhorizontal Zone 2.

SINGLE - LAYER SYSTEM

The results of the simulations for a well located far from a vertical fracture zone in a single-layer system with a groundwater recharge of 2 mm/year are shown in Figure 7.14. For a well with a pumping rate of 6 m^3/day, about 50% - 65% is coming from fracture zone 2. If the groundwater recharge is 40 mm/year or greater, the well gets all of its water from recharge. However, for a deep well (120 m) with a pumping rate of 6 m^3/day, about 1% is contributed from Zone 2.

Groundwater heads and streamlines in the vicinity of a well pumping 6 m^3/d at different groundwater recharge are shown in Figure 7.15.

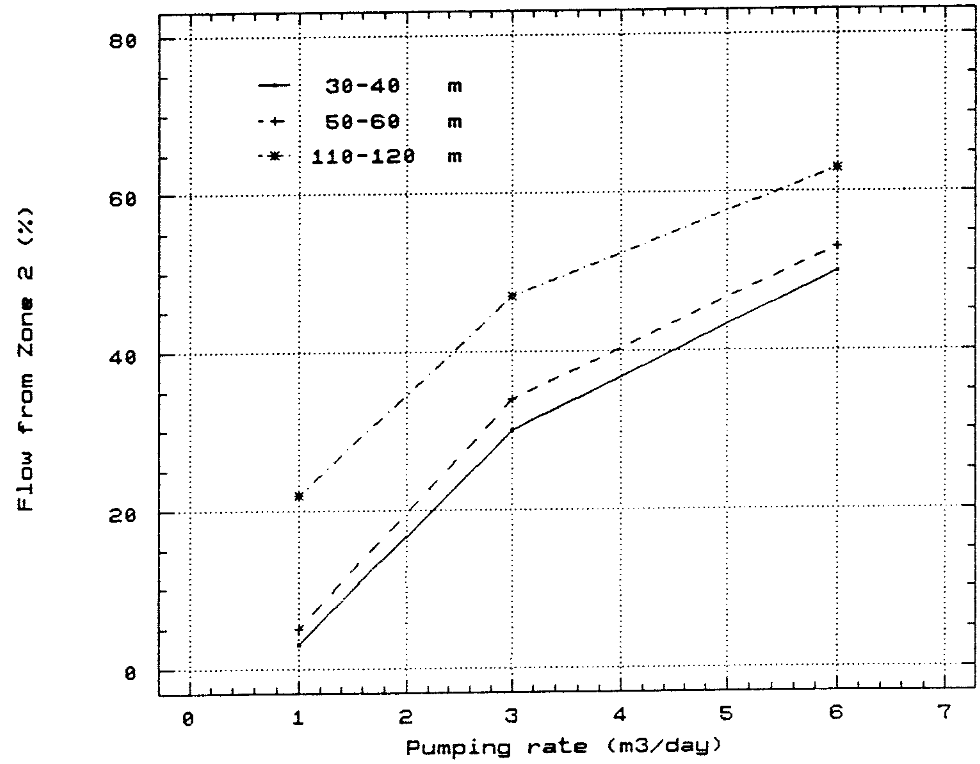
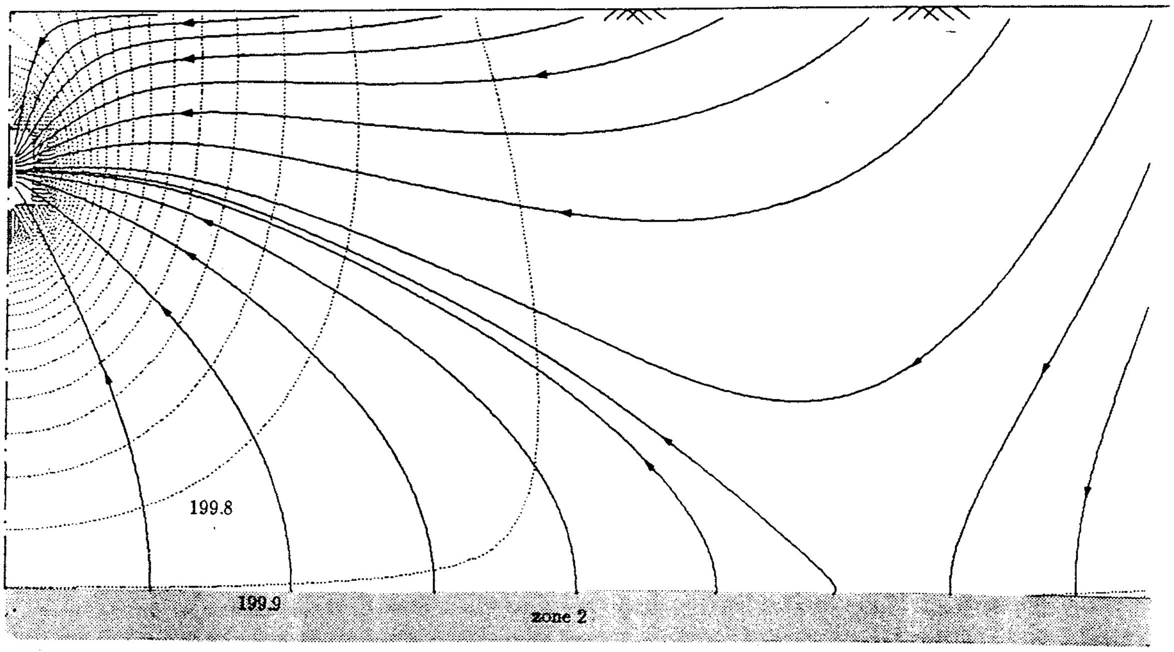


Figure 7.14 Contribution of flow from Zone 2 versus pumping rate and well depth in a single-layer system with a recharge of 2 mm/year.

Groundwater recharge = 2 mm/year



Groundwater recharge = 40 mm/year

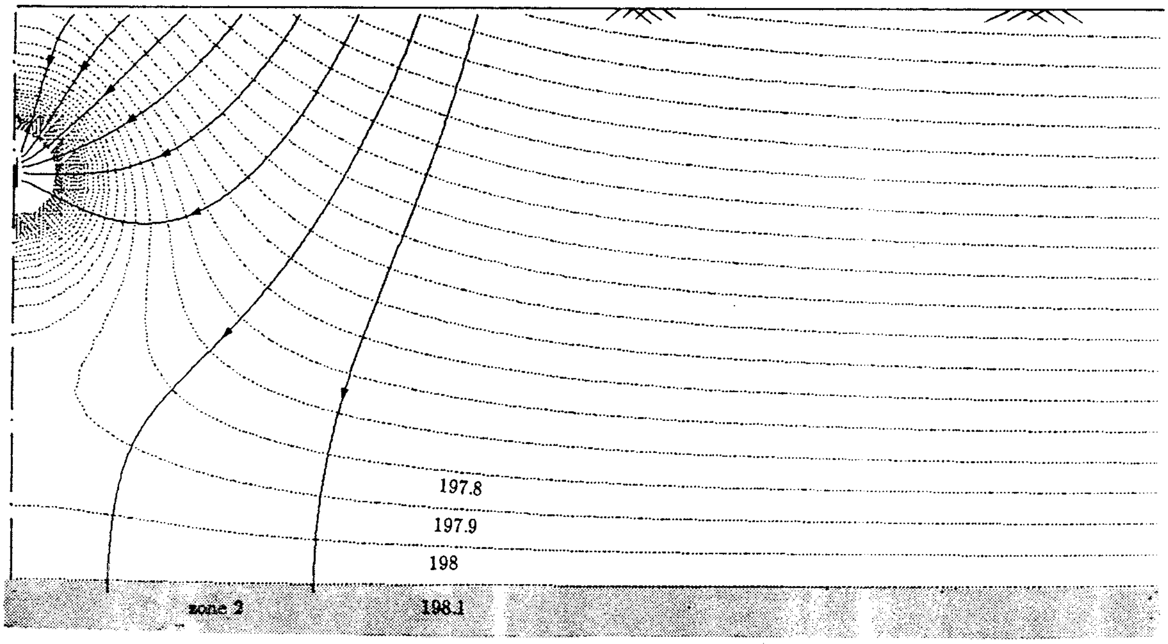


Figure 7.15 Groundwater heads and streamlines in the vicinity of a well pumping 6 m^3/day assuming a single-layer system.
(Heads omitted close to well)

Sensitivity analysis was also performed concerning the hydraulic conductivity of the rock mass. A rock mass with a hydraulic conductivity of $1.2*10^{-8}$ m/s can not supply water to a 120 m deep well pumping 6 m^3/day if the recharge is 2 mm/year unless the well takes water from a 90 m long section (screening 30 m to 120 m). For this case about 53% of the well discharge comes from fracture zone 2, which can be compared with 60% for a well screened between 110 - 120 m in a rock mass with the conductivity $1.2*10^{-7}$ m/s. Conclusively, a well that takes groundwater over a larger section will get more water from recharge, which of cource is quite obvious.

DUAL - LAYER SYSTEM

The results of the simulations for a well located far from a vertical fracture zone in a two-layer system with hydraulic conductivities of $1.2*10^{-7}$ m/s down to a depth of 100 m and $1.0*10^{-8}$ m/s from 100 m to 200 m are shown in Table 7.1.

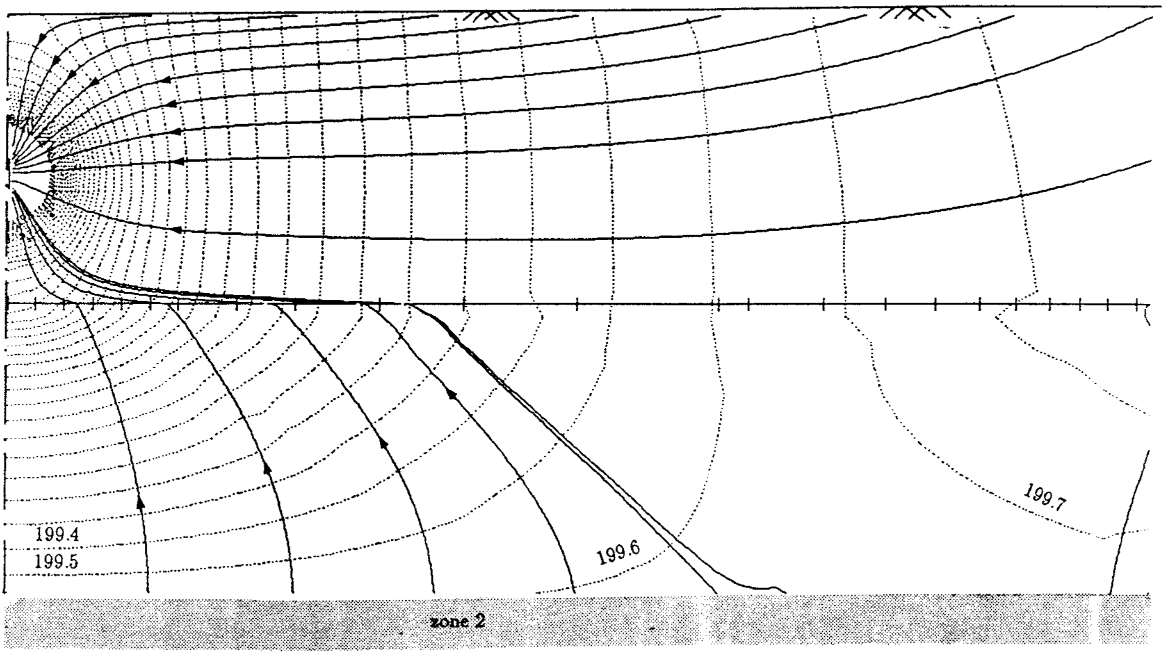
Table 7.1 Results from analytical modelling of a dual-layer system.

Recharge (mm/year)	Pumping rate (m^3/day)	Flow from Zone 2 (%) Screening 50 m - 60 m	Flow from Zone 2 (%) Screening 110 m - 120 m
2	1	0	5
2	3	1	IMPOSSIBLE
2	6	10	IMPOSSIBLE
40	1	0	0
40	3	0	0
40	6	0	0

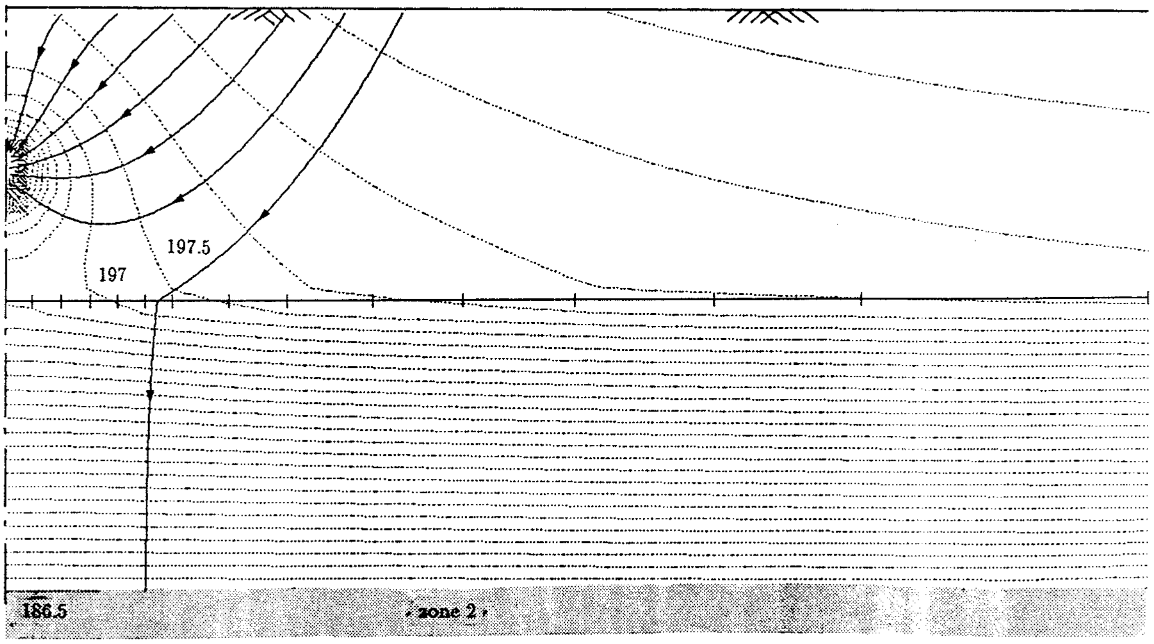
No contribution of groundwater from Zone 2 is necessary for a pumping rate of 6 m^3/day if the groundwater recharge is greater than 40 mm/year. If the groundwater recharge is 2 mm/year, a 60 m deep well pumping 6 m^3/day will get 10% of its water from Zone 2. If the well is 120 m deep and assuming that it takes groundwater from the lowermost 10 m, it is only possible to pump about 1 m^3/day.

The assumption of a dual-layer system reduces significantly the amount of water from Zone 2 contributing to the discharge of the well compared to a single-layer system. For a well pumping 6 m^3/day and a groundwater recharge of 2 mm/year, the amount of groundwater from Zone 2 is reduced from 53% to 10%.

Groundwater heads and streamlines in the vicinity of a well pumping 6 m^3/day at different groundwater recharge are shown in Figure 7.16.



Groundwater recharge = 2 mm/year



Groundwater recharge = 40 mm/year

Figure 7.16 Groundwater heads and streamlines in the vicinity of a well pumping 6 m^3/day assuming a dual-layer system.
(Heads omitted close to well)

SINGLE - LAYER SYSTEM AND VERTICAL FRACTURE

The results of the simulations for a 60 m deep well located in the vicinity of a vertical fracture zone in a single-layer system with a groundwater recharge of 2 mm/year are shown in Figure 7.17. The well draws more groundwater from Zone 2 when it is located further away from a vertical fracture zone. This is explained by the fact that the well gets less water from the vertical fracture zone. If it is located about 100 m from the vertical fracture zone, it gets about 50% less groundwater from Zone 2 than if the vertical fracture zone was not present. It is also demonstrated that the impact of the vertical fracture zone is most prominent within about 200 m from the well.

Groundwater heads and streamlines in the vicinity of a well pumping 6 m^3/day at different groundwater recharge are shown in Figure 7.18.

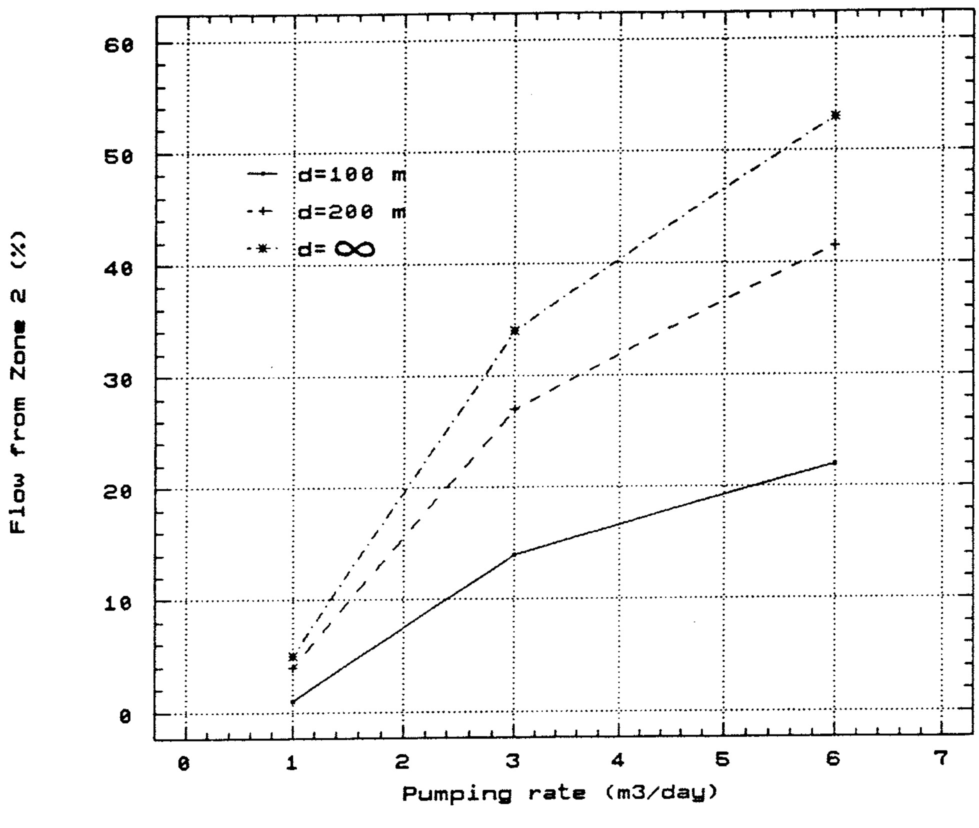
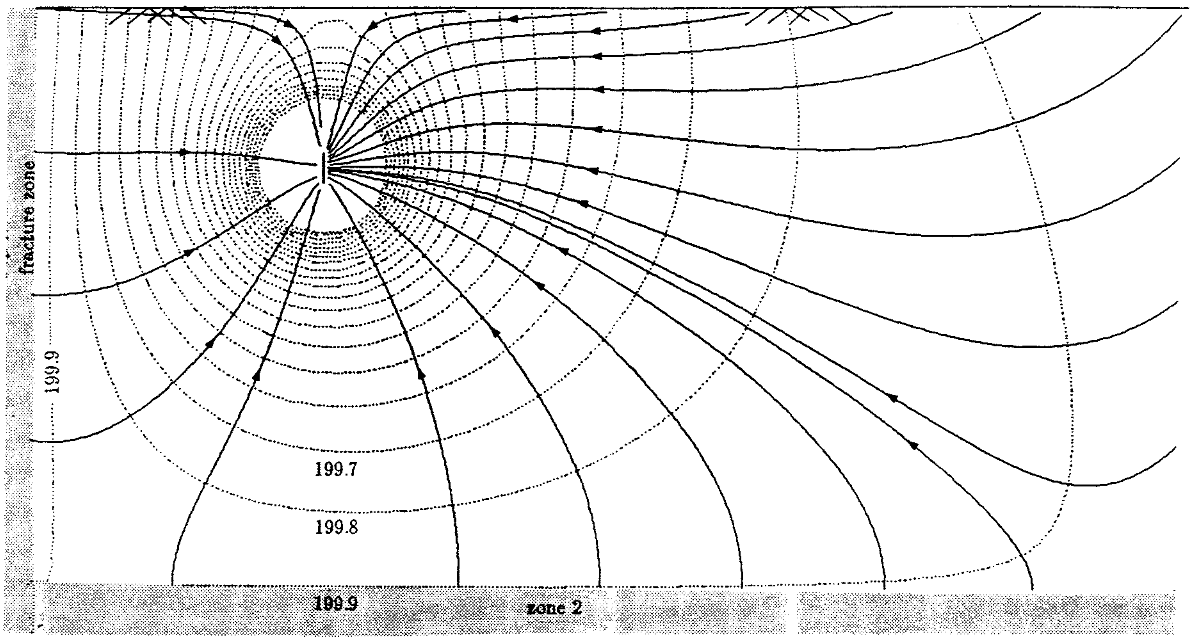


Figure 7.17 Contribution of flow from Zone 2 versus pumping rate and distance from a vertical fracture zone for a well depth of 60 m in a single-layer system with a recharge of 2 mm/year.

Groundwater recharge = 2 mm/year



Groundwater recharge = 40 mm/year

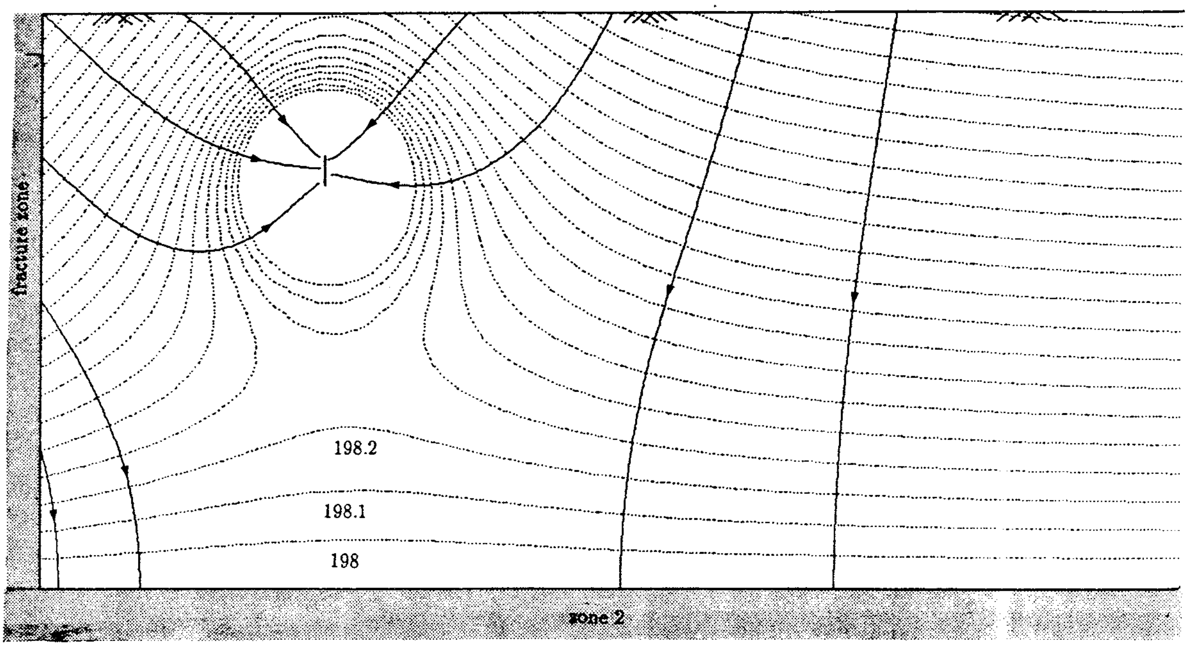


Figure 7.18 Groundwater heads and streamlines in the vicinity of a well pumping 6 m^3/day assuming a single-layer system and a vertical fracture zone. (Heads omitted close to well)

7.5 Discussion

7.5.1 Wells located in a fracture zone

The two-dimensional finite element modelling of fracture zone 1 should be seen as a semi-generic study of what the consequenses may be for a domestic well, if contaminated groundwater reaches fracture zone 1 according to predictions made by an earlier groundwater modelling study (Lindbom et al., 1991). The semi-generic character of the study is caused by the fact that it is impossible to account for three-dimensional effects in a two-dimensional model. This is especially true for the complicated flow pattern with flow into and out from the subhorizontal Zone 2 and other fracture zones intersecting Zone 1. Furthermore, no account is taken to groundwater flow from the rock mass to Zone 1. This may be justified by a high conductivity contrast between Zone 1 and the surrounding rock mass (60 - 400 times). Thus, given the assumptions, the modelling gives an indication of what the impact would be on a domestic well located at various places within Zone 1.

The modelling shows that a well pumping 6 m^3/day at a depth of 60 m may be located as close as 100 m from the discharge area, a swamp, without being contaminated with groundwater from the repository. This is due to the high groundwater flow in the upper parts of Zone 1 compared to the pumping rate of the well. The flow in the upper 60 m of Zone 1 is about 9 m^3/day, which will feed the well without pumping any groundwater from deeper parts of the rock mass. Thus, the well is inactive in the local groundwater flow system, implying that it has to be located in the discharge area to get groundwater that has passed the repository. However, if the well is deeper than 60 m, it may interfere with the groundwater from the repository even if it is located some hundreds of metres from the discharge area. For a well pumping at a rate of 30 m^3/day, all groundwater from the repository will be discharged by the well. This shows that the well becomes an active sink in the local groundwater flow system for larger pumping rates.

All the above mentioned conclusions are based on the fact that Zone 1, 4 and 5 are homogeneous continuous structures for at least some kilometres and with a hydraulic conductivity of about 100 times that of the surrounding rock mass. If this is not true, it is anticipated that pathlines from different parts of the repository area will not be totally collected by these fracture zones, but spread over a larger discharge area than assumed in the two-dimensional modelling. Indications that this might be the case is given by the surface extension of discharge areas, swamps and streams, some kilometre north and east of the Finnsjön Rock Block. However, the water in the swamps and streams are not dependent on the discharge from deep groundwater but consists mostly of discharge from shallow groundwater in the soil and the upper highly fractured part of the rock mass. Though, the swamps and streams constitute discharge areas for all groundwater in the rock mass.

7.5.2 Wells located in the rock mass

The three-dimensional analytic element modelling of the influence of a well located in the rock mass close to horizontal and vertical fracture zones should be seen as illustrations of the effect of a well superimposed on the actual groundwater flow system. Thus, the prevailing flow system at Finnsjön is not modelled but merely the hydrogeological "environment" like hydraulic conductivity of the rock mass and groundwater recharge together with the presence of horizontal and vertical fracture zones.

The modelling exercise, resulting in the contribution of flow from Zone 2 to the total well discharge, may be seen as the degree of contamination of a well given a contamination of the upper part of Zone 2. The flow in the upper part of Zone 2 is calculated to 150000 - 370000 m^3/year through a 1000 m vide section of Zone 2 (Andersson et al., 1991). Assuming that the total flow that interacts with the canisters in the repository (5 m^3/year) will be diluted in the flow in Zone 2, implies an initial dilution in the upper part of Zone 2 of about 30000 - 75000 times. However, this situation might be unrealistic as previous model studies show that Zone 2 may serve as an efficient barrier to groundwater flow (Lindbom et al, 1991). The extension and complexity of the zone with an upper and a lower conductive part, separated by a more tight but fractured slab of rock, indicate that it may be conceptualized as a two-aquifer system separated by a leaky aquitard (Andersson et al., 1991). This may give Zone 2 a specific hydraulic character by effectively separating flow coming from above (as groundwater recharge) from flow coming from below (from the repository). The fracture system and hydraulic gradients within Zone 2 will determine the possibility of contamination of the upper part of the zone.

The dual-layer system, with an order of magnitude higher hydraulic conductivity in the uppermost 100 m of the rock mass, is probably a suitable interpretation of the prevailing conditions in the northern part of the Finnsjön Rock Block, though it is based on information from a few boreholes. Accordingly, the dual-layer system simulates the impact of a well located above the subhorizontal Zone 2 and away from vertical fracture zones that may influence the flow pattern around the well.

The single-layer system with a vertical fracture zone, illustrates the conditions with a well located above Zone 2 and close to a vertical fracture zone, which is not contaminated. This is an outcome of the modelling technique, in which groundwater recharge creates a downward gradient in the vertical fracture zone. Thus, the well is assumed to be located close to any vertical fracture zone above Zone 2, except for the discharge area of Zone 1 close to Zone 4.

The results from the three-dimensional analytic element modelling show that a well, located in the rock mass and pumping 6 m^3/day at a depth of 60 m, gets all of its water from groundwater recharge, if the recharge is greater than about 40 mm/year. This is a reasonable estimate of the recharge according to earlier modelling of the area (Lindbom et al., 1991) and practical experiences (Ericsson, 1981a). However, if the groundwater recharge is 2 mm/year, the well will pump about 10% of the water from Zone 2. This may be the case during dry periods. It is also shown that the presence of vertical fracture zones within about hundred metre from the well will contribute with water during dry periods (recharge = 2 mm/year), thus decreasing the contribution from Zone 2 by about 50%.

8 CONCLUSIONS

Wells for domestic use in Sweden are usually drilled in hard rock. Soil wells are also used, but only for minor water supply purposes, except soil wells in sand and gravel deposits. However, sand and gravel deposits are not present in the Finnsjön area today and will probably not be in the future. Therefore, it is likely that a future well for domestic water supply in the vicinity of a generic repository in the Finnsjön Rock Block is drilled in the hard rock. Most of the rock-drilled wells today are localized by geophysical methods (VLF-technique) to near vertical waterbearing fracture zones. The drilling technique tends to seal off the upper conductive fractures in the rock mass and the well completion seals off the groundwater from the loose deposits. Thus, a rock-drilled well gets its water from the lower part of the borehole or, where the borehole intersects larger conductive zones in the rock. Hydraulic fracturing is often used to increase the capacity of low-yielding wells.

Saline groundwater with chloride concentrations of 5000 mg/l is found below Zone 2 in the northern part of the Finnsjön Rock Block and also at depth northeast of the southern part. Thus, future wells will probably be located in fracture zones with non-saline groundwater or drilled to shallow depths in the hard rock. Today, there are six domestic wells drilled in the rock mass close to the discharge area some kilometre northeast of the Finnsjön Rock Block in the vicinity of the Imundbo zone. The maximum well depth is 58 m and the maximum chloride concentration in the groundwater is found to be 57 mg/l. This is well below the taste limit of 300 mg/l.

The fresh water requirements for a permanent household of four persons is today about 1 m^3/day, while the requirements for summer residents only is about half of that. A middle sized farm with about 25 - 30 milkcows needs about 6 m^3/day. To achieve a reliable water supply system, the hydraulic capacity of a well should be greater than the water demand.

Rock-drilled wells in Uppland located in the same type of rock formation as is present at Finnsjön shows a median depth of 60 m and a median capacity of about 23 m^3/day. This gives a specific capacity of about 0.4 m^3/day and metre drawdown in the well. It should be noted that most of the older wells are located randomly, and not drilled to penetrate water-yielding zones by purpose.

Evaluations of hydraulic test data of the investigation boreholes at the Finnsjön site show that the median value of the specific capacity, down to a depth of 60 m, is in the range 4 - 8 m^3/day and metre drawdown. This indicates that a future well for domestic purposes located in the Finnsjön Rock Block may get the necessary water quantity by drilling about 60 m down in the rock. The resulting drawdown in the well will be about 1 - 2 m. A comparison with fifteen drilled wells found in the vicinity of the Finnsjön site shows a median specific capacity of 0.3 m^3/day and metre drawdown. This is more comparable to the conditions found in the southern part of the Finnsjön Rock Block. Specific capacities in the southern part and in the rock mass outside the Finnsjön Rock Block indicates a necessary drawdown of 15 - 20 m in a well for domestic use.

Risk areas for future drilled wells, possibly collecting groundwater that has passed the generic repository, are estimated to be wells drilled in fracture zone 1 downgradient from the intersection with Zone 4. The regional fracture zone Imundbo as well as discharge areas, swamps and streams, some kilometre northeast of the Finnsjön Rock Block may also be risk areas for future drilled wells.

Two-dimensional groundwater modelling of fracture zone 1 shows that a well may be located as close as 100 m from the discharge area and still pump groundwater not affected by the repository. This is due to local groundwater recharge and relatively high groundwater flow (9 m^3/day) in the upper 60 m of Zone 1, which makes a well pumping less than 6 m^3/day a passive collector in the groundwater flow system. In order to pump groundwater emanating from the repository, the well has to be located in the discharge area. The impact of the well is of course a function of the pumping rate and the natural flow in the rock mass. If the well is pumping about 30 m^3/day, it will influence the local groundwater flow system and capture all groundwater from the repository.

An inventory of wells shows that the hydraulic properties of the rock mass yield capacities that are sufficient for a domestic demand of 6 m^3/day. The radius of influence for a well pumping 6 m^3/day is about 150 m, for a groundwater recharge of 50 mm/year. For the hydraulic conductivity of the rock mass found at Finnsjön, the drawdown in the well will be between 1 and 20 m. Modelling shows that wells drilled in the rock mass to a depth of up to about 100 m and pumping less than 6 m^3/day gets all of its water from groundwater recharge, if the recharge is greater than about 40 mm/year.

These evaluations of the impact of a well show that a well has no influence on the local groundwater flow system except for the very vicinity of the well. Consequently, a well may be drilled in the rock mass and not being subject to pumping groundwater that has passed the repository. Wells may also be located anywhere in fracture zones around the repository area, except for in the very discharge area, without any risk of getting groundwater affected by the repository. Modelling indicate that a well drilled in the discharge area for contaminated groundwater, may collect all groundwater from the repository. However, this is based on assumptions of homogeneous continuous fracture zones with a high hydraulic conductivity compared to the rock mass, which will give rise to a concentrated discharge area.

In the calculations no consideration is taken to the channeling character of flow in fractured rock or sorption and matrix diffusion. Thus, the calculations should only be seen as illustrations of hydraulic factors influencing the dilution in a well.

Inhomogenieties in the rock mass and fracture zones together with the areal extent of the repository might give rise to a spreading of pathlines from the repository over the discharge area, swamps and streams, northeast of the Finnsjön Rock Block. This implies that all groundwater that passes the repository will not converge to a single well pumping less than 6 m^3/day, even if it is located in the discharge area. However, with the present knowledge of groundwater flow in fractured rock, it can not be excluded that a well drilled in the future in a discharge area could get all of its water from groundwater that has passed the repository. The dilution in such a well is just a function of the pumping rate of the well. Thus, a high capacity well will result in a larger dilution giving a smaller dose to more people, while a low capacity well will be less diluted and give a higher dose to fewer persons.

The groundwater flow in the rock mass is dependant on the hydraulic conductivity. Groundwater modelling shows that the flow at repository depth is about 0.1 l/m^{2}*year if the hydraulic conductivity of the rock mass is based on geometric mean values of measured conductivities (Lindbom et al., 1991). However, the arithmetic mean values of the hydraulic conductivity in 100 m intervals down to a depth of 500 m are 5 to 10 times higher than the geometric mean values. Accordingly, the flow in the rock mass will increase by a factor of 5 to 10 if arithmetic mean values of the hydraulic conductivity are used.

The conclusions of the present study will not be changed if arithmetic mean values of the hydraulic conductivity are used. On the contrary, the well will have even less influence on the groundwater flow system if the rock mass is more conductive.

The groundwater at repository depth contains about 5000 mg/l of chloride. Assuming a vertical flow of 0.1 l/m^{2}*year through a repository with an areal extent of 10^6 m^2 gives a total groundwater flow through the repository of about 0.3 m^3/day. If that water enters a well pumping 6 m^3/day, it will be diluted about 20 times. This implies a chloride concentration of the pumped groundwater of about 250 mg/l, if the diluting groundwater is free from salinity. This is below the taste limit of drinking water, implying that the well can be used for domestic purposes concerning the chloride concentration. However, if the flow in the rock mass at repository depth is greater than 0.1 l/m^{2}*year, the well will probably be abandoned due to high chloride concentration.

Assuming that the groundwater flow interacting with each canister is about 1 l/year, gives a total groundwater flow interacting with the canisters of 5 m^3/year. If all canisters are destroyed and leaking and this flow is collected by a well pumping 6 m^3/day, it will be diluted at least 400 times. However, considering the unrealistic scenario that all canisters are leaking, the dilution of activity-contaminated groundwater will be much higher.

Although it is more likely that a future well for domestic use will be drilled in the hard rock, than drilled or dug in soil deposits, it is worth mentioning dilution in soil wells. Wells dug some metres down in the soil will probably only get groundwater from nearby infiltration. The only risk for contamination of a soil well is if it uses groundwater from a possible future spring, where the groundwater originate from the repository.

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APPENDIX A

DOMESTIC WELLS - LOCATION AND DESIGN

TABLE OF CONTENTS

A.1 INTRODUCTION

Wells can be divided into three major groups depending on how they are achieved, viz. drilled, dug and piped wells. The latter two groups are pure soil wells and are only briefly presented, since the use of these types of wells is getting rare and no high capacity well is known in the Forsmark area. The use of soil wells is decreasing in Sweden, since the quality of surface-near groundwater is getting more and more questioned, as an effect of human exploitation and other environmental impacts such as acidification. Statistics from the Water Well Record Section at the Swedish Geological Survey (Sandström, 1991), indicate that a majority of the new wells are hammer drilled in hard rock (Table A.1). However, these statistics does not give the true picture of different types of wells, because all new soil wells are not reported. Only the drilled soil wells are reported to the Water Well Record Section. Soil wells like piped or cased wells are commonly used in glacifluvial deposits, e.g. eskers. There is still a significantly large number of municipalities that use esker reservoirs for their water supply. No such glacifluvial deposit is however present in the Forsmark area.

Table A.1 Well statistics sent to the Water Well Record Section in 1989.

		Welltype		
		Rock wells	Soil wells	Total
No. of wells		8337	186	8523
(%)		97.8	2.2	100
Diameter [mm]		115-165	115-400	
Total depth [m]:	Median	72.0	22.0	
	25%	51.0	15.0	
	75%	100.0	31.0	
Casing depth [m]:	Median	6.0	-	
	25%	3.0	-	
	75%	12.0	-	
Capacity [litre/hour]	Median	700	5.000	
	25%	300	2.425	
	75%	1.800	10.000	

No of wells for different users

Households	Farms	Irrigation	Municipality	Industry	Energy	Others	Total
4750	81	57	37	46	395	87	5453*

* Missing information from 3070 wells

A.2 WATER DEMAND

The fresh water requirements for different type of consumers are presented in Table A.2. A household of four persons consumes about 1 m^3/day, while a "standard" farm with 25-30 milkcows needs about 6 m^3/day. People living in the country side tends to consume 30% less water than people living in cities. It should be noted that the hydraulic capacity of wells is often larger than the water demand for consumption, which is a necessity for a reliable water supply system.

Table A.2 Water requirements for different consumers (Geotec, 1991).

Consumer	litres/day	Comments
Household	1.000	Average complete household, 4 persons
	600	Summer residence only
	1.800	Well drillers "Minimum water guarantee" (Geotech 1990, 45 litres/hour, household well)
	150 - 200	Per person/day, except garden irrigation
	15	Per person/day, drinking water only (including cooking)
Farming	ca 6.000	Standard farm Uppland, 50-80 hektar, 25-30 milkcows
	ca 12.000	Large farm Uppland, 500-800 hektar, ~100 milkcows
	45	Per cattle or horse/day
	75	Per milkcow

A.3 WELLTYPES

Rockdrilled wells

Future wells for domestic water supply purposes drilled in the Forsmark area is assumed to be achieved as rock wells. These are today the overall dominant well type and the majority of them are made with a down-the-hole hammer system. If the well is used only for water supply, this type of well is very seldom drilled to a depth larger than 120 m. The median depth for wells drilled in Sweden in 1989 is 72 m, where 50% of the wells are drilled to depths between 50 and 100 m (Table A.1).

Taking the median values of depth and capacity of wells drilled in 1989 gives a median specific capacity of 0.23 m^3/day and metre drawdown. This is close to the median value of 0.26 m^3/day and metre drawdown calculated from 59.000 rock-drilled wells all over Sweden (Fagerlind, 1988).

The advantage with rock drilled wells in comparison with soil wells is the depth that minimizes the effect of dry periods. The modern casing techniques also offer an effective sealing of the borehole from shallow groundwater.

Rock wells drilled before 1955, are made with a Cable tool equipment. This older technique produced more shallow wells, 30 - 50 meter, and used a different casing method (Sandström, 1991). This method did not seal off the soil/surface groundwater satisfactory.

Screened wells / soil drilled wells

A screened well in Sweden normally refers to a soil well, drilled and screened in a glacifluvial or fluvial deposit, e.g. an esker or a delta deposit. A well of this type, is more or less always made for municipalities and other large consumers but seldom for domestic water supply purposes.

Even though there is a significantly large number of municipalities that use esker reservoirs for water supply, it is of less importance since glacial deposits are not found in the Forsmark area.

Dug wells / shaft well

A dug well normally refers to a well, dug down in the soil to a maximum depth of 10 m, and constructed of concrete rings (modern) or stones (old). This type of well normally gets its water from a till or coarse sediment aquifer, that is from shallow groundwater.

Piped wells

This well type is installed in soil aquifers, e.g. till or sandy sediments, with the help of a Cable tool drill or a Percussion drill (e.g. "Jacket hammer"). The well is simply a standpipe with a diametre of 50 to 125 mm equipped with a filter tip. This technique is still used in some areas in Svealand as the least expensive way of providing groundwater to a minor consumer.

A.4 LOCATION OF WELLS

In order to optimize the location of rockdrilled wells, a geophysical instrument based on the VLF-technique (Very Low Frequency) has been used to prospect waterbearing fracture zones since the 1970's. The use of this instrument increased significantly when an easy-to-use version called VLF-WADI was introduced in 1988.

VLF is a reliable, simple state-of-the-art instrument which measures the difference in electric conductivity of geological formations. The instrument can only measure more or less vertical and linear structures with a certain geometry, e.g. fractures and larger ores. This means that horizontal layers and formations with less dip than 45 degrees are not indicated by this method. Another limitation is the penetration depth of the electromagnetic waves. On blotted crystalline rock the penetration depth is at least 300 m, though accuracy is lost at greater depths. Clay cover strongly reduces the penetration depth to less than 50 m. The method is developed for crystalline rock, but has also successively been used in sedimentary rock in Sweden and Greece (Arnbom, 1986). Research has shown that wells located with VLF-technique generally give more water than other wells (Pettersson, 1987).

If correctly used, this method gives information, not only of the location of the potential waterbearing conduit, but also the approximate inclination and potential salt water content (Figure A.1).

If the potential waterbearing conduit is determined to run vertically, the well-drilling will be performed inclined in order to intersect securely.

Regarding the estimation that up to 20% of all the well drilling companies already use this instrument before drilling, it is reasonable to assume that the majority of future rock drilled wells will be preferably located to a *vertical* waterbearing fracture zone.

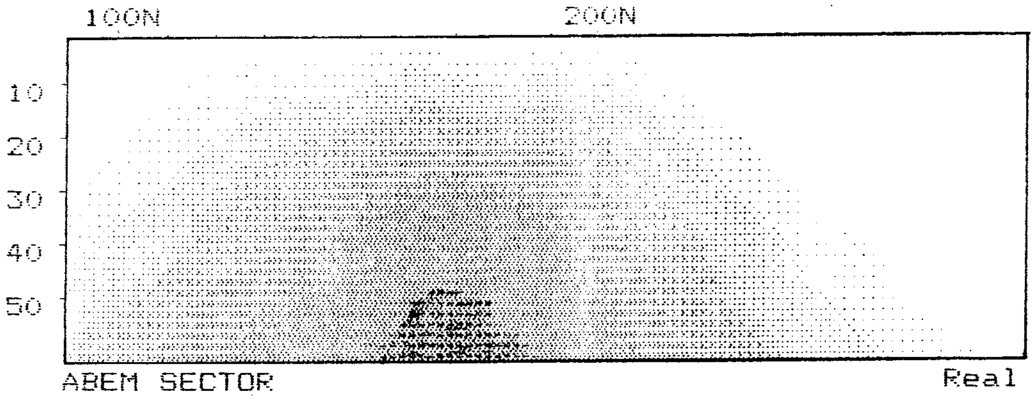

Figure A.1 Example of a vertical cross section plot from a VLF - measured profile. (Darker colour indicates lower electrical resistance, e.g. water compared to surrounding rock).

A.5 DRILLING TECHNIQUES

The rock drilled well consists of two different parts; the casing through the soil and the actual borehole in the rock mass.

A.5.1 Casing and sealing

Casing is carried out through the soil and some metres into the rock. According to branch standards, casing tends to be run at least three to five metres into "good rock" (non-fractured rock). This is done in order to securely seal off the surface near groundwater.

Casing in Sweden is extensively made with the Atlas Copco/Sandvik - technique called ODEX, a combined rotary and hammer drill equipment that allows the driller to install the casing during drilling.

The casing itself is normally a steel pipe (material thickness about 6 mm) to which a casing-shoe is welded at the bottom to fit the special hammer (ODEX). This ODEX-system consists of a hammer with the pilot bit (that drills the pilot hole) and the excentric - reamer bit (that is widening the hole to more than the casing diametre) and of a guide device that hits the casing-shoe so that the casing immediately follows the reamer (Figure A.2).

When the destination depth is reached, back-rotating of the drill pipe rejects the reamer bit so that the complete hammer drilling equipment can be lifted up, leaving the casing in the right position. The ODEX-technique fits both top hammer- and Down-The-Hole hammer equipment. When using ODEX it is strongly recommended to combine the flushing water with foam.

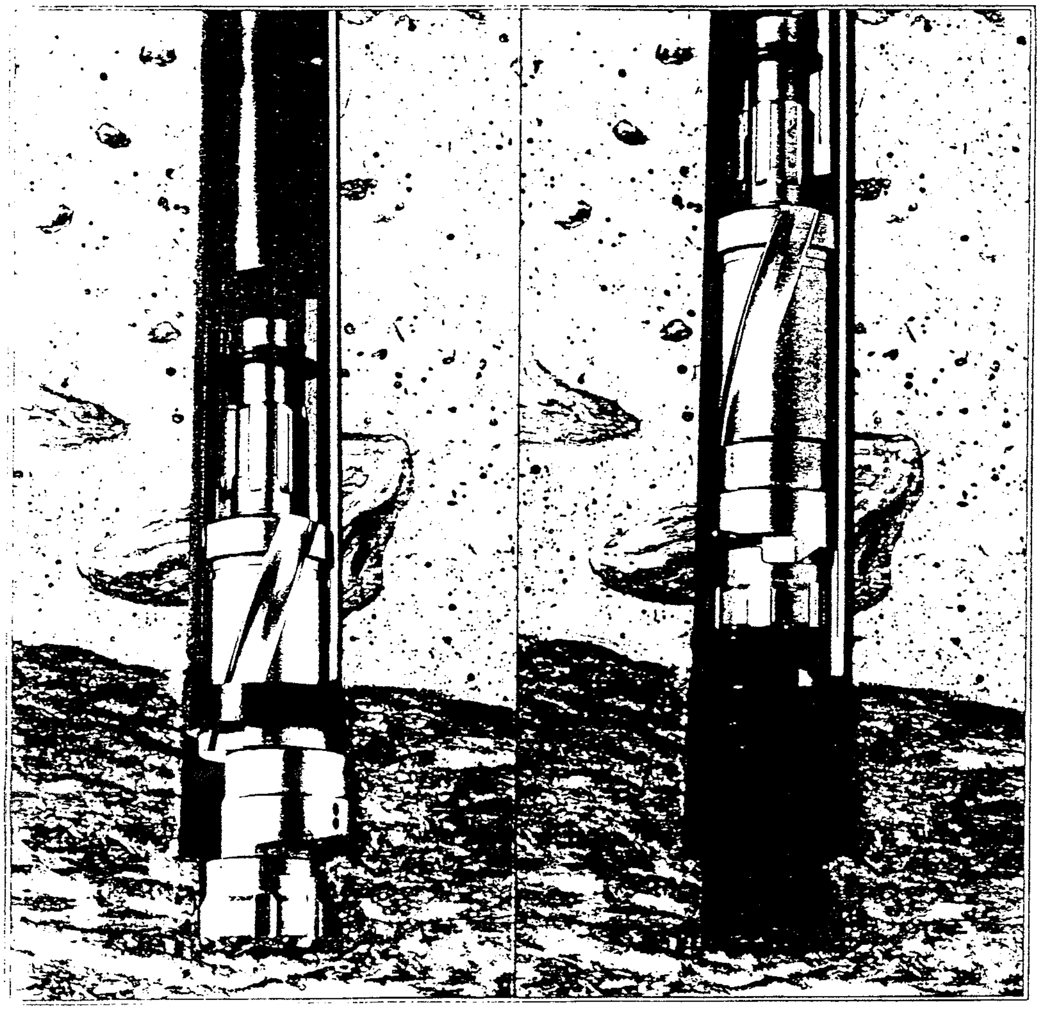

Figure A.2 A Down-The-Hole hammer version of the ODEX system.

The casing normally ends a number of metres down into the rock mass, and before rock drilling continues, the casing end is grouted. This is done with concrete mixed with an expansion fluid attached at the bottom and/or flushed with high pressure a little further out into the formation. The rock drilling start by drilling through this plug.

Well performed, the casing and grouting procedure completely seals off all the soil- and surface-near groundwater.

A.5.2 Rock drilling

Rock well drilling is performed preferably with a Down-The-Hole hammer that is flushed with compressed air or/and water if available. The size and type of drill rig, boom and vehicle that operates the hammer equipment from the surface varies greatly.

The drill bit, with a standard diameter for domestic well use of 115, 140 and 165 mm, cuts the hole with a combination of rotary- and hammer forces. Together with a normal working pressure at the crone between 15 - 22 bar, the technique enables a drilling speed of up to 120 m/day. The drilling speed depends on a number of factors such as rock type, flushing pressure, the shape of the bit, water content of the rock mass, etcetera. Still, the majority of standard domestic wells is done within one or two days.

As a secondary effect of the high pressure on the bit, up to 22 bar, a certain grouting effect will occur in the shallow fractures of the borehole. The pressure flushes the drilling mud into the conduits, where it mixes with water and decreases the permeability of the conduits significantly. This effect is rapidly decreasing towards depth after the first 30 m of the borehole. When the well have been used for some time, this grouting effect will be reduced due to outwash of the conduits by the flowing water.

A.6 HYDRAULIC FRACTURING

The organisation of well drillers offers a water-warranty to guarantee the result of the drilling. This warranty varies between 45 to 200 litres/hour. If the discharge of the well is less than the warranty, a commonly used method of increasing the well discharge is hydraulic fracturing. A section of the borehole is sealed off with a packer and water is pumped into the section at a high pressure (150 - 200 bar). The desired effect is to rinse the smeared fractures and open up the formation to other conduits/aquifers. About 20% of all rock drilled wells are fractured hydraulically with the described method (Fagerlind, 1989). An older method of fracturing a borehole is blasting, which is still used but only for about 1% of the drilled wells. This is not expected to have the same positive effect and brings a risk of the borehole collapsing.

A.7 WATER SUPPLY SYSTEM

After drilling and potentially fracturing, the borehole should be turned into a well and connected to the consumer via a water supply system including pump, tube, and reservoir. The design of the water supply system differ, but some "standards" are described below.

A.7.1 Pump installation

The pump market is dominated by two types, Down-the-hole pumps and Ejector pumps. The most commonly used is the Down-the-hole pump. The Ejector pump is preferably used if there is an obvious risk of losing equipment in the hole (e.g. weak zones in the borehole) since the pump engine is kept at the surface. However, the ejector has a limited capacity (about 3000 litres/hour) and demands more maintenance. The pump is controlled either by a level indicator in an open tank/reservoir or by a pressure transducer attached to a closed tank/reservoir.

The concept of pump installation is as follows:

- The pump is installed about 5 m above the bottom of the well in order to use the borehole storage at maximum, but still avoid particles causing pump failure. The last 5 m then works as a collector/sedimentation sump for the material that is released into the well.

- The pump capacity is preferably chosen to 60 - 70% of the maximum capacity of the well, and to give a working pressure in the system of at least 3.5 bar at the tap. In very low capacity wells, the installed pump capacity often exceeds the hydraulic capacity of the well.

A.7.2 Reservoirs

The reservoir is installed to give a smooth performance of the water supply system. It should limit the number of starts and stops of the pump, reduce pressure pulses and give a certain backup volume when the system is stressed. That is, the volume of the reservoir is always designed to match the pump capacity and the need of the consumer. Standard reservoirs for domestic use is a 60 and 120 litres closed pressure vessle.

A.7.3 Use and maintenance

Still concentrating on the domestic well situation, the use is as follows. When the water supply system is optimized, the pump does not exceed 200 to 300 start-stop cycles per day, normally concentrated to mornings and evenings. Depending on the well efficiency and pump capacity, every start-stop cycle takes some minutes, causing a rapid and large immediate drawdown of the water level in the well (about 5 to 20 m) and a slightly slower recovery after stop. Final or close to final recovery is reached during night time when the well is out of use completely.

Maintenance is rarely necessary on a domestic well system, except for quality problems often occurring when iron or/and manganese ions are dissolved from the water. Pumps and the rest of the system are known to last for more than 20 years.

A.8 THE LIFE OF A WELL

The question how long a well construction can last is difficult to answer. The weak point is the steel casing, which is subjected to corrosion. There is an increasing risk of corrosion due to acid groundwater, saltwater intrusions, variation in redox-potential due to undulating groundwater levels, etcetera. There is seldom any protection made to enhance the long lasting capacity of the casing. Assuming that the corrosion is similar to the standard values used on steel piles, which is less than 2 mm/10 year, the life of a modern well is approximately 40 to 60 years unless something is done to replace the casing.

However, even if the casing is corroded, the well still gets the necessary quantity of water but the quality may be affected by infiltrating surface water.

There are other aspects in special chemical environments, such as secondary tightening of fractures caused by swelling minerals or dissolved salt. Though, this type of problem seems to be more common in greenstones, such as gabbro.

A.9 DISCUSSION

It must be stressed that there is little experience of transport of water into a rock drilled well. As the rock is a heterogenious material, the understanding of the hydraulics is even more complicated when trying to adopt transport models to the reality of casing-sealing, smeared fractures from drilling, transient pumping and level of pump, etcetera. In the light of this, some discussion points are presented together with case experience.

A.9.1 The influence of drilling technique on well efficiency

The modern well drilling technique is effectively changing the natural distribution of permeability in a borehole (Figure A.3). Primarily, the technique is developed to avoid near surface groundwater. The effect of casing and grouting of the casing bottom is obvious, smearing of fractures is known, but considered to be a small problem. Hydraulic fracturing will rinse the smeared fractures and open up the formation to other conduits/aquifers, thus increasing the capacity of the well.

A.9.2 Time variation effects in the water supply system

It seems reasonable to believe that the active section of the well, in terms of transport, is short (about 10 to 20 m) and distributed around the pump at the bottom of the well. This is based on the fact that the pump (or ejector inlet) is installed at the bottom of the well and that pumping runs a few powerful cykles per day. Another prerequisite is a number of intersecting fractures distributed along the complete borehole. If there is only one waterbearing fracture in the borehole, naturally the water will enter the well at this level independent of where the pump is located.

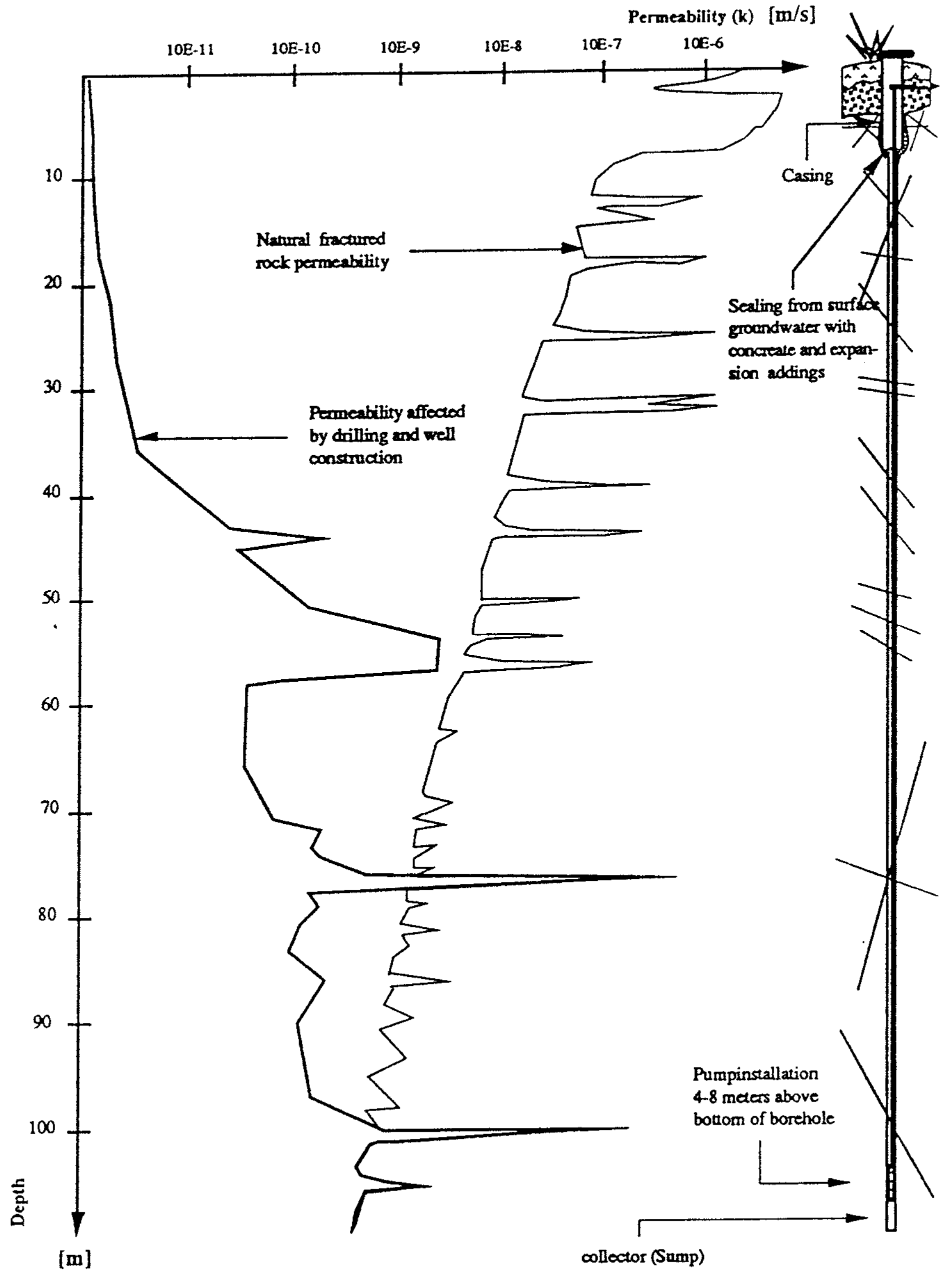

Figure A.3 Tentative sketch of well drilling and construction effects on formation permeability (No concern is taken to hydraulic fracturing).

A.9.3 Salt water considerations

Saltwater intrusion is a serious problem in coastal regions and in the major part of the valley of lake Mälaren as well. The inland problems are an effect of relict salt water, where the interface occurs at various depths, approximately between 60 - 150 m below the groundwater table. The taste limit of drinking water is 300 mg/litre, expressed in chloride content. Thus, a well which exhibits a chloride content in excess of that is today abandoned or measures are taken to lower the chloride content.

It is well known that it is possible to lower the saltwater content simply by raising the pump from the bottom position some 20 - 30 m or/and seal off the bottom section of the borehole.

To face the problem in saltwater risk areas, well drillers try to get the water from shallower depths through inclined drilling, up to 30°. A limitation of the vertical depth is then recommended to be about 60 m. Thus, the strategy is to drill shallow wells and, if necessary, increase the capacity by hydraulic fracturing.

Saltwater intrusion is considered to be a continuously increasing problem. This might be an effect of an increased use of groundwater, emptying the fresh water aquifers, but it can also be viewed as an evidence of modern well drilling and design effects on natural permeability, since the saltwater is located at the bottom of the formation due to density.

A.9.4 Case experiences

At the Krusenberg area, approximately 15 km south of Uppsala, two wells have been studied for water supply purposes (Golder Geosystem AB, 1989). Both wells are located in a leptite formation with small blocks and slices of granite. The distance between the two wells is approximately 300 m. One is 65 m deep, and the soil cover consists of coarse clay with sandy layers. The other well is 110 m deep, with a sandy soil cover.

The 65 m deep well was stressed during 30 days of pumping and the salt water content was measured. After about 14 days of pumping, salt water with a concentration of approximately 200 mg Cl/litre entered the well. The pump was installed at 45 m below the initial groundwater table, and the pumping rate was 3.6 m^3/day.

To evaluate the available fresh water storage, packer tests were achieved.

- The transmissivity of the complete borehole was determined to be $4*10^{-5}$ m^2/s.
- The distribution of fractures (from drill logs) indicated two major, inclined (~45°) zones, 54 and 57 m below the groundwater table and a series of smaller zones about 24 m below the groundwater table.
- The well gives approximately 6 m^3/hour, of which about 30% is contributed from the upper zones and the rest from the lower fracture zones.
- When closing off the lower section of the borehole at the elevation 36 m below the groundwater table, the saltwater content declines to 35 mg Cl/litre with a well capacity of 0.7 m^3/hour.

To test the importance of pumping depth and pump capacity, the pump was installed at a depth of 35 m below the initial groundwater table and the chloride content was analysed for different pumping capacities (Table A.3).

Table A.3 Chloride content as a function of capacity and drawdown at a pump level of 35 m.

Capacity [m^3/hour]	Drawdown [m]	Chloride content [mg/litre]
0.5	0.7	60
0.7*	25*	35*
1	2.9	230
1.7	3.4	121
2.9	6.4	240
6.4	35	255

* Packer installed below pump.

The other well is not documented hydraulically, but the fracture distribution is similar, with larger fractures at 60, 80 and 95 m below the groundwater table and minor in series at deeper levels. This well is drilled for the water supply system of two households. The pump is installed at 90 m below ground surface and the average capacity is 2.5 m^3/day (0.1 m^3/hour). The well was stressed during a simple pumping test in a similar way as the earlier mentioned well, but no increase in salt water content occured. This deeper well has been in use for 6 years, without any chloride problems, while the shallower well was abandoned. The only significant difference in the environment of the two wells is the top soil and depth. A standpipe was installed less than 10 ms away from the shallower well, in the coarse till material, on top of the supposed inclined minor fracture zone. The groundwater level in this standpipe did not respond at all during a short-time pumping test of the shallow well.

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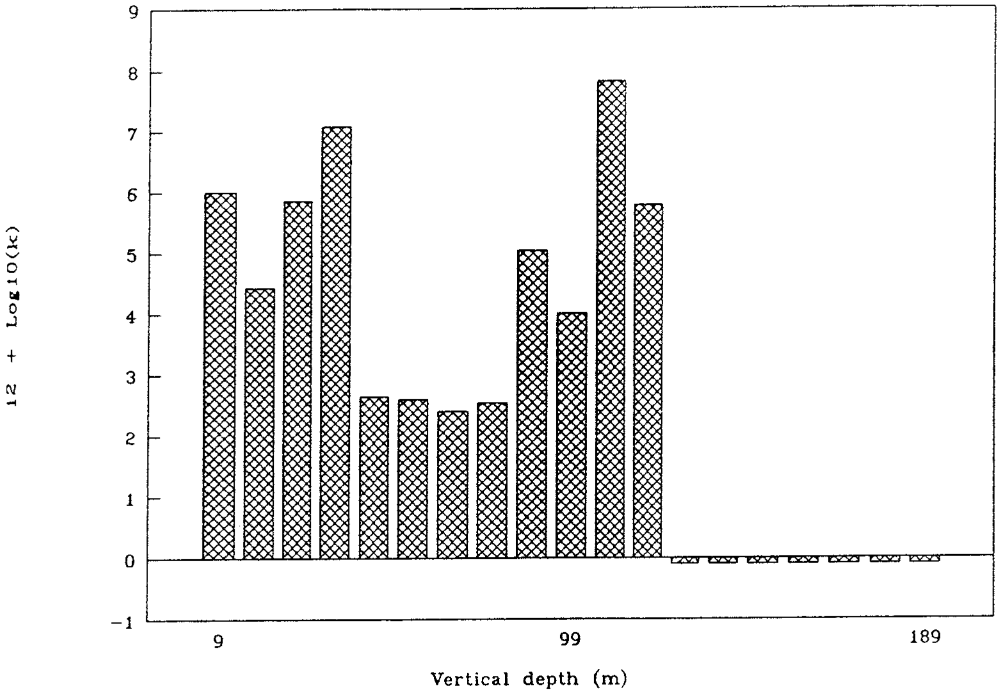
APPENDIX B

HYDRAULIC CONDUCTIVITIES IN BOREHOLES WITHIN THE FINNSJÖN ROCK BLOCK

HFI 01


9
8
7
6
5
4
3
2
1
0
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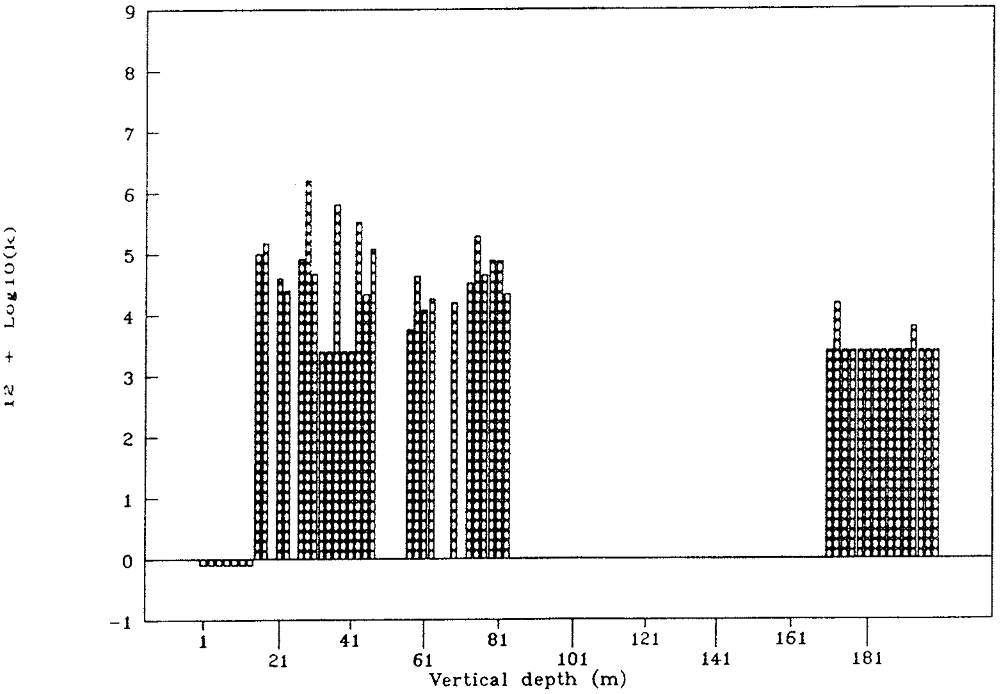
12 + Log10(k)
9
99
189
Vertical depth (m)

KFI 01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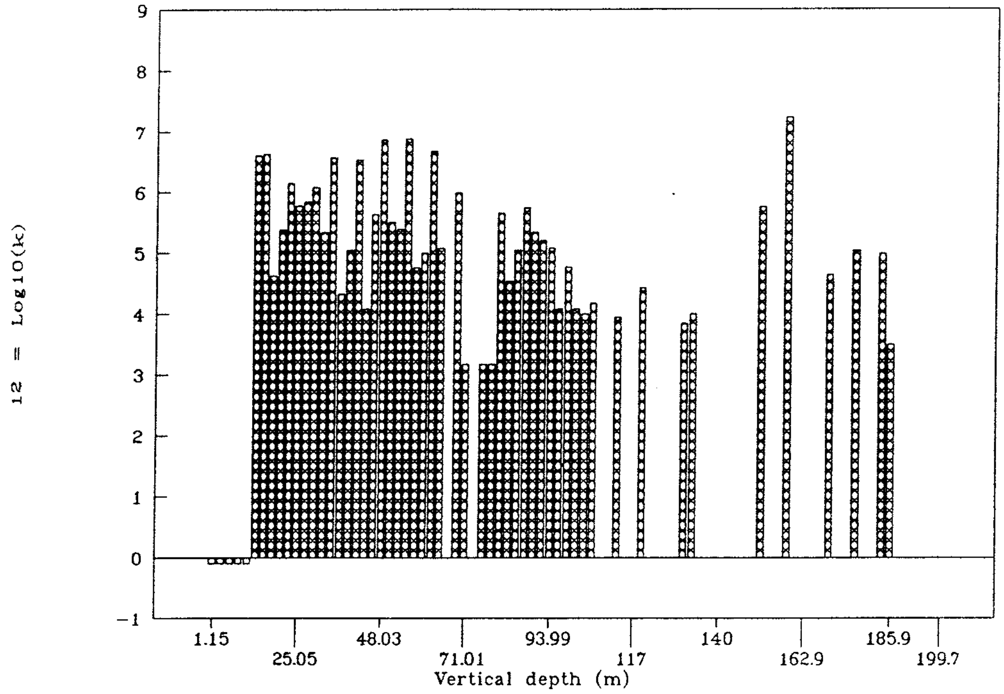
8
7
6
5
4
3
2
1
0
−1
12 + Log10(k)
1
21
41
61
81
101
121
141
161
181
Vertical depth (m)

KFI 02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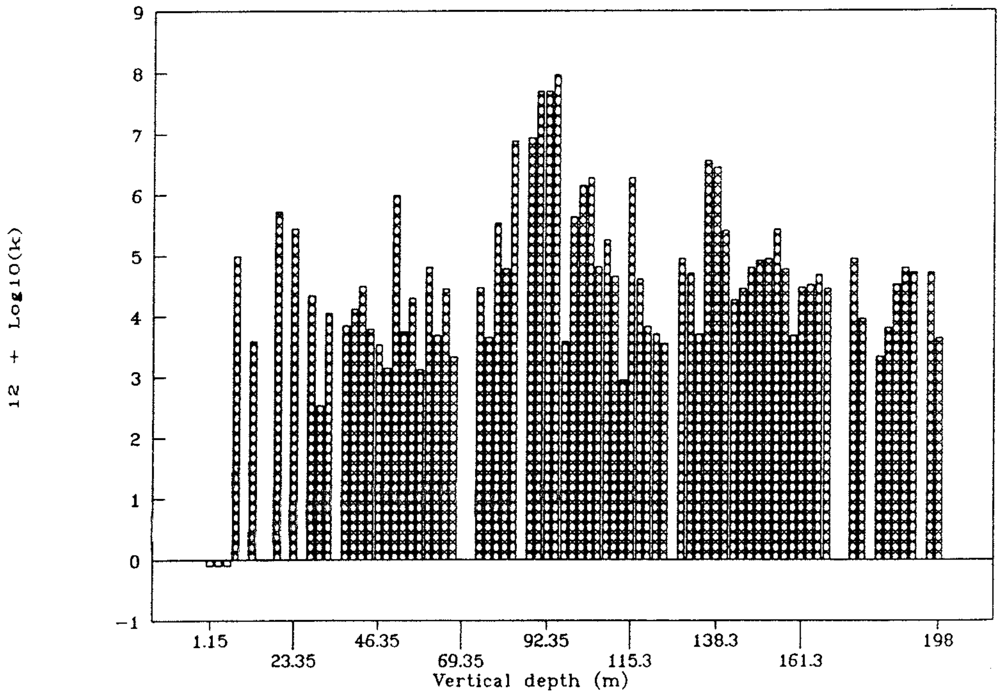
8
7
6
5
4
3
2
1
0
−1
12 = Log10(k)
1.15
25.05
48.03
71.01
93.99
117
140
162.9
185.9
199.7
Vertical depth (m)

KFI 03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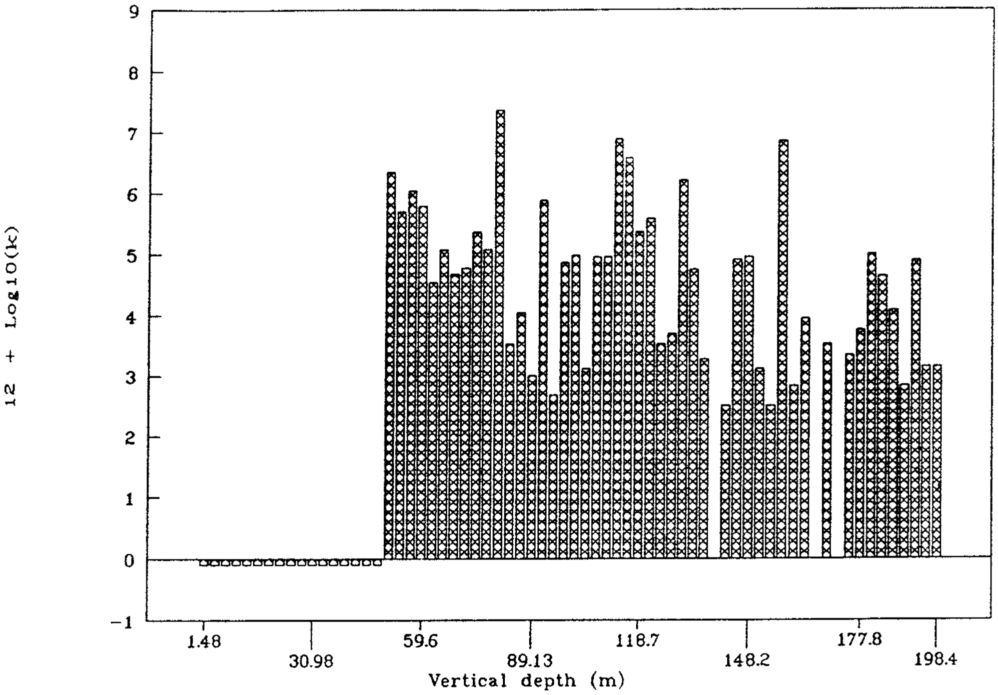
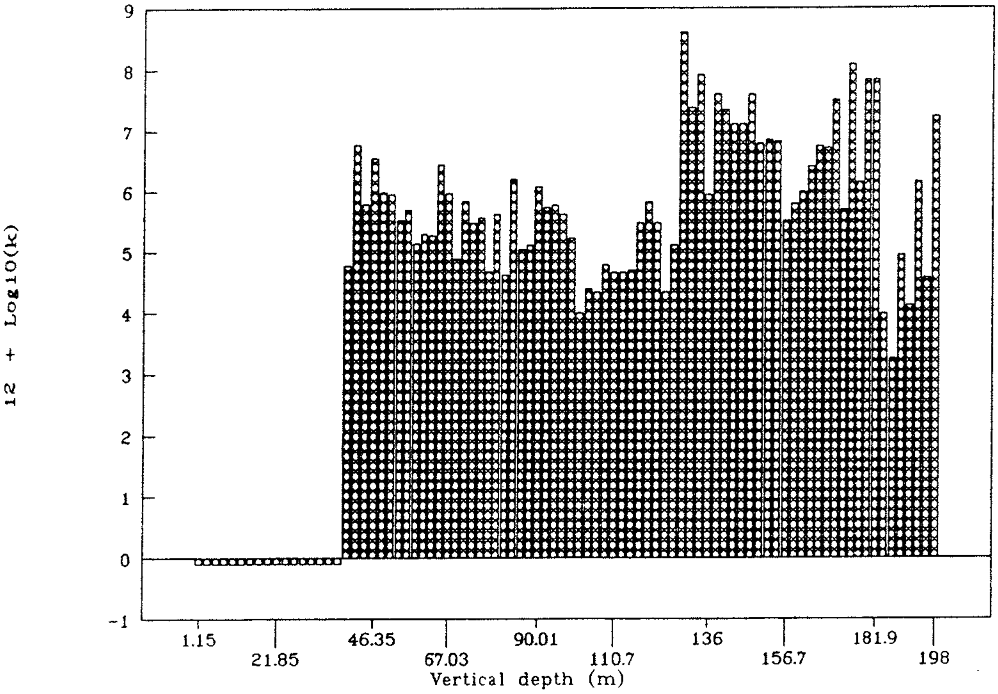
8
7
6
5
4
3
2
1
0
−1
12 + Log10(k)
1.15
23.35
46.35
69.35
92.35
115.3
138.3
161.3
198
Vertical depth (m)

KFI 04


12 + Log10(k)
9
8
7
6
5
4
3
2
1
0
−1
1.48
30.98
59.6
89.13
118.7
148.2
177.8
198.4
Vertical depth (m)

KFI 05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8
7
6
5
4
3
2
1
0
−1
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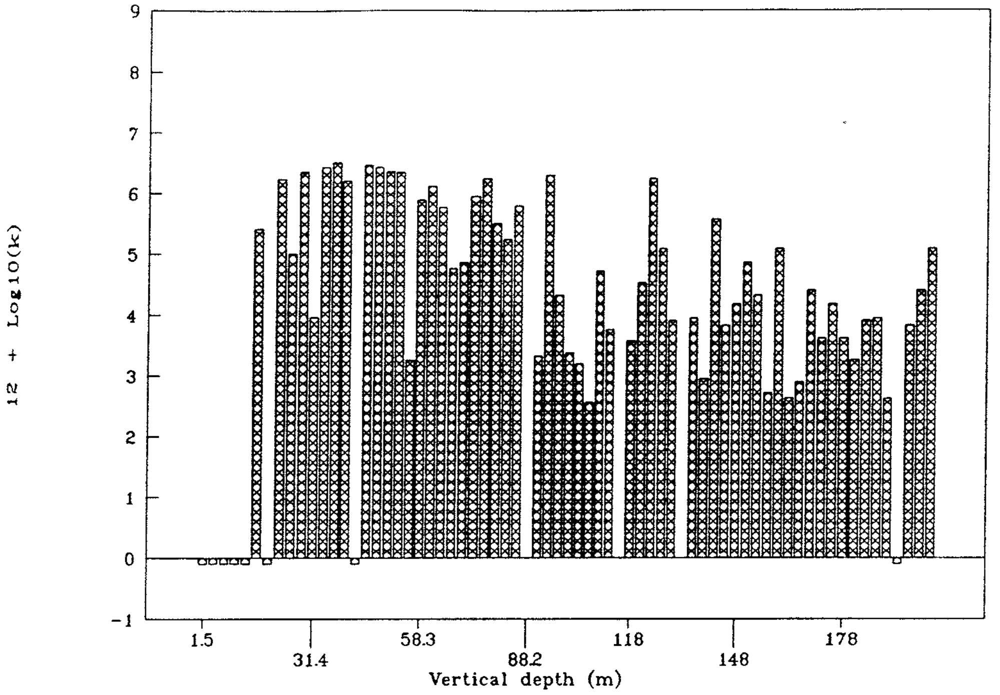
21.85
46.35
67.03
90.01
110.7
136
156.7
181.9
198
Vertical depth (m)

KFI 07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8
7
6
5
4
3
2
1
0
-1
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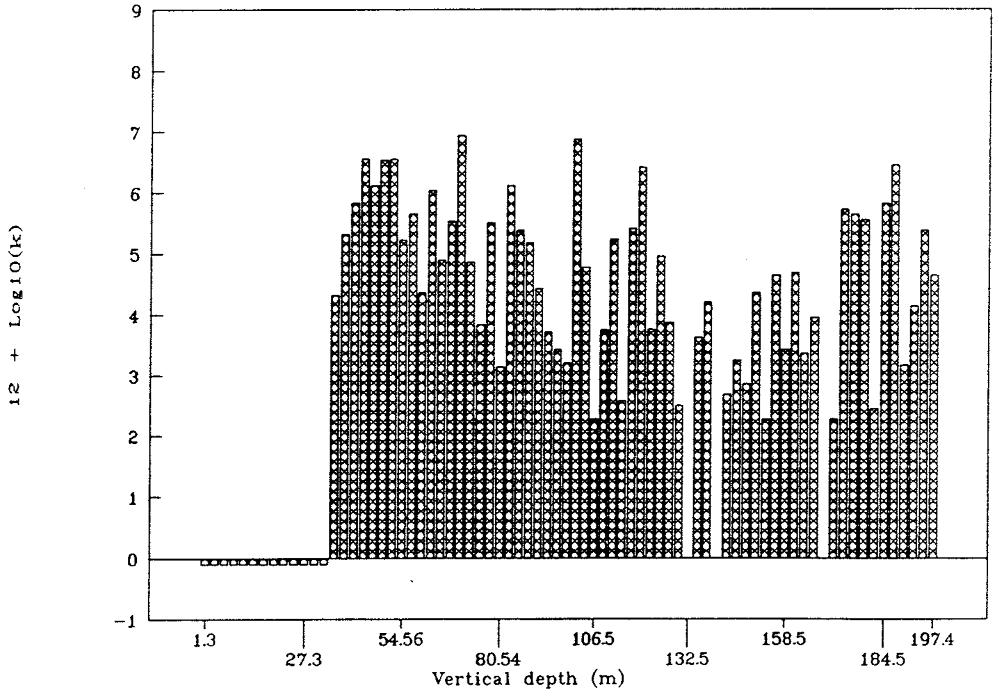
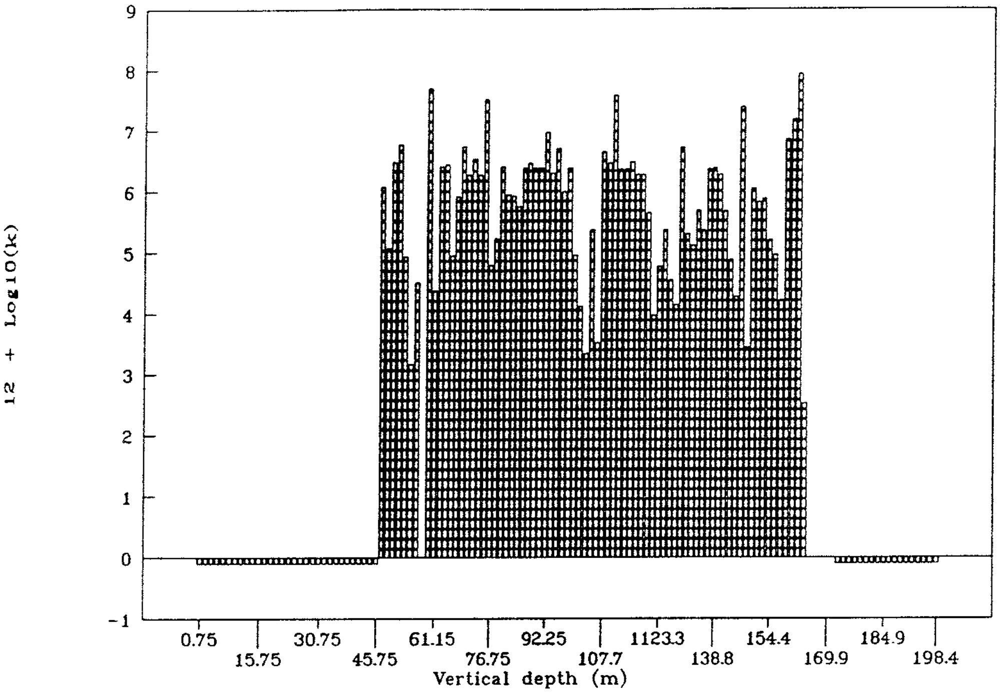
31.4
58.3
88.2
118
148
178
Vertical depth (m)

KFI 08


12 + Log10(k)
9
8
7
6
5
4
3
2
1
0
-1
1.3
27.3
54.56
80.54
106.5
132.5
158.5
184.5
197.4
Vertical depth (m)

KFI 10


9
8
7
6
5
4
3
2
1
0
-1
12 + Log10(k)
0.75
15.75
30.75
45.75
61.15
76.75
92.25
107.7
1123.3
138.8
154.4
169.9
184.9
198.4
Vertical depth (m)

THREE-DIMENSIONAL FLOW TOWARD A PARTIALLY PENETRATING WELL

Potential flow toward a partially penetrating well is modeled by use of a line sink with the following (singular) sink density distribution $s(\lambda)$ $[L^2/T]$, see (*Haitjema and Kraemer*, 1988):

$$s(\lambda) = s^{(1)}\frac{1-\lambda}{2} + s^{(2)}\frac{1+\lambda}{2} + \frac{s^{(0)}}{\sqrt{(1-\lambda)(1+\lambda)}} \tag{1}$$

where $\lambda = z/h$, see figure 1. The first two terms in (1) represent a linearly varying strength distribution, which allows the well to take in more water at the bottom than at the top, or visa versa. The singular strength distribution, last term in (1), accounts for the increased inflow of water near the well ends.

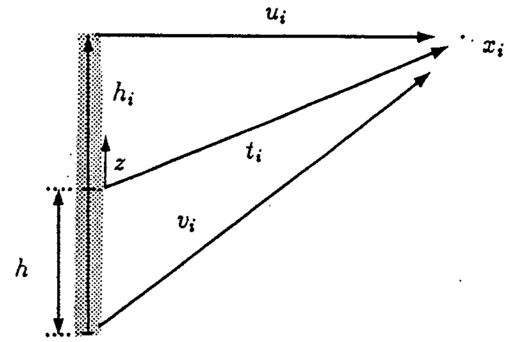


Figure 1: Line sink with singular sink density distribution to model a partially penetrating well.

The specific discharge potential Φ for the well is obtained from the following integral:

$$\Phi(x_i) = \frac{-h}{4\pi}\int_{-1}^{+1} \frac{s(\lambda\, d\lambda}{\sqrt{(t_i - \lambda h_i)(t_i - \lambda h_i)}} \tag{2}$$

where x_i $(i = 1, 2, 3)$ is the point at which Φ is calculated, and where the vectors h_i and t_i are defined in figure 1. The parameter h is the length of the vector h_i. The specific discharge potential is the product of the piezometric head ϕ and the aquifer hydraulic conductivity k:

$$\Phi = k\,\phi \tag{3}$$

The average groundwater velocity v_i is obtained from:

$$v_i = \frac{q_i}{n} = -\frac{1}{n}\frac{\partial \Phi}{\partial x_i} \tag{4}$$

The integral in (2) can be expressed in closed form:

$$\Phi(x_i) = s^{(1)}F(x_i) + s^{(2)}G(x_i) + s^{(0)}\Gamma(x_i) \tag{5}$$

where the functions F, G, and Γ are defined as:

$$F = \frac{1}{8\pi}\left[(1 - \frac{t_i h_i}{h^2})\ln\frac{u+v-2h}{u+v+2h} + \frac{u-v}{h}\right] \tag{6}$$

$$G = \frac{1}{8\pi}\left[(1 + \frac{t_i h_i}{h^2})\ln\frac{u+v-2h}{u+v+2h} - \frac{u-v}{h}\right] \tag{7}$$

$$\Gamma = \frac{-h}{2\pi\sqrt{uv}}K(\kappa) \tag{8}$$

where u and v are the lengths of the vectors u_i and v_i, respectively. The function $K(\kappa)$ is the complete elliptic integral of the first kind, see (*Byrd and M.D. Friedman*, 1971), with modulus κ defined by:

$$\kappa^2 = \frac{h^2}{uv}\left[1 - (\frac{u-v}{2h})^2\right] \tag{9}$$

For more details regarding this analysis refer to (*Haitjema and Kraemer*, 1988).

Incorporating Boundary Conditions

The real boundary conditions for the flow in the rock matrix are formed by the soil surface with a given inflow (recharge) rate and by fracture zones with substantially higher hydraulic conductivities than the rock matrix itself. Consequently, the effect of the well on the piezometric head distribution in the fracture zones may be ignored. In the modeling exercises the horizontal fracture zone 2 has been treated as an equipotential boundary, while the soil surface is treated as a boundary with a specified inflow rate: the recharge rate due to rainfall.

These boundary conditions have been modeled as follows. Images of the partially penetrating well have been used, both with respect to the soil surface and the top of the (horizontal) zone 2. The soil surface has been treated as a known flow boundary for the well, while the top of zone 2 was treated as an equipotential boundary. During the modeling, the theoretical infinite series of images was limited to 13 image wells. The imaging procedure is discussed in more detail in (*Haitjema and Kraemer*, 1988). A vertical downward uniform flow (the recharge rate) was superimposed on the flow problem. Together with the images for the well this uniform flow rate generates an inflow specified boundary at the soil surface (recharge boundary) and maintains the equipotential conditions along zone 2.

For the dual zone cases, a doublet disc (double layer) with radially varying density distribution was used to account for the discontinuity in the specific discharge potential resulting from the discontinuity in the aquifer hydraulic conductivity. In reality, the intrinsic hydraulic conductivity is discontinuous, but in the present modeling the discontinuity in the hydraulic conductivity was generated by creating an appropriate jump in the fluid viscosity. This was done in view of the computer program used for the modeling, which was actually designed to model axi-symmetric interface flow between two or more fluids, (*Haitjema,* 1991). Appropriate image interfaces were introduced to maintain the flow specified upper boundary and the lower equipotential boundary.

For the cases with a vertical fracture zone, the partially penetrating well and its images were once again imaged with respect to the vertical fracture plane. The downward uniform flow creates the same gradient in the vertical fracture zone as in the rock matrix. The well, however, due to its image, does not affect the potential distribution in the vertical fracture zone, as is realistic in view of the much greater hydraulic conductivity in that fracture zone.

Flow From Zone 2 Toward The Well

In all cases any outflow from zone 2 (positive q_z) ends up in the well. The contribution from zone 2 to the well has been calculated in two different ways: (1) integrating q_z over that portion of zone 2 where q_z is positive, and (2) integrating the discharge along the well from the bottom of the well to the bounding streamline from zone 2, see figure 2. The latter integration was carried out analytically by use of (1):

$$Q = h \int_{-1}^{\lambda_b} s(\lambda)\, d\lambda \tag{10}$$

where Q is the fraction of the well discharge obtained from zone 2, and where λ_b defines the point along the well axis where the bounding streamline from zone 2 enters. The integral along zone 2 has been evaluated numerically by use of the trapezoidal rule. In general, average values of the two computations were used for estimating the dilution factors presented in this report. However, for small contributions from zone 2, the integral along the well is inaccurate due to inaccuracies in estimating λ_b. For those cases the integral along the well was used only for confirmation, while the dilution factor was based on the integration of q_z along zone 2.

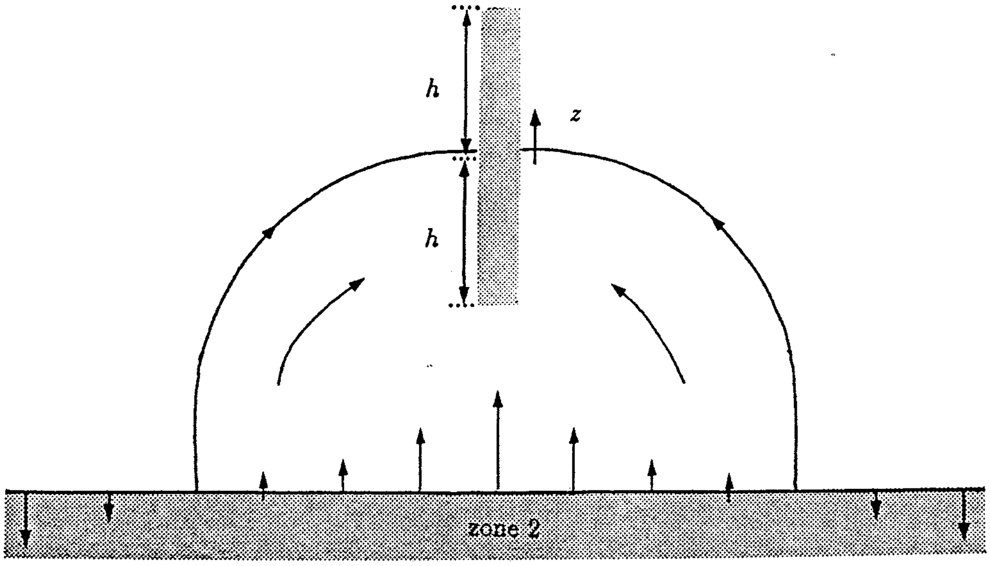


Figure 2: Flow from zone 2 toward the well.

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[2]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
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[1]Vattenfall HydroPower AB
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[2]Chalmers Institute of Technology
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[1]Starprog AB
[2]SKB AB
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[1]KEMAKTA Consultants Co
[2]Chalmers Institute of Technology

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Leonardo Romero
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Kaj Ahlbom[1], Timo Äikäs[2], Lars O. Ericsson[3]
[1]Conterra AB
[2]Teollisuuden Voima Oy (TVO)
[3]Svensk Kärnbränslehantering AB (SKB)
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I Casas[1], A Sandino[2], M S Caceci[1], J Bruno[1],
K Ollila[3]
[1]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
[2]KTH, Dpt. of Inorganic Chemistry, Stockholm, Sweden
[3]VTT, Tech. Res. Center of Finland, Espoo, Finland
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Fjällveden study site. Scope of activities and main results
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