Hydraulic properties of Swedish crystalline rocks

Hydraulic conductivity and its relation to depth

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Carlsson, A. and Olsson, T. 1977 09 15: Hydraulic properties of Swedish crystalline rocks. Hydraulic conductivity and its relation to depth. *Bulletin of the Geological Institutions of the University of Uppsala,* N. S., Vol. 7, pp. 71—84. Uppsala. ISSN 0302-2749.

For various purpose, such as water supply, constructional work, questions of location, it is of fundamental importance to know in detail the hydrogeological properties of the bedrock. In this work we try to determine the variations of and the reasons for the hydraulic conductivity on the basis of water-loss measurements made in a number of geographically and geologically distinct areas and also to illustrate in greater detail the vertical variations which occur. In order to get a comparable material, data from wells drilled in rock were also analysed to a certain extent.

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Introduction

The water-bearing capacity of the crystalline basement is solely dependent on the presence of developed fissure systems and zones of weakness. For various purposes, such as water supply, constructional work, questions of location, etc., it is of fundamental importance to know in detail the hydrogeological properties of the bedrock.

Today, thanks to the geological and geophysical methods which are available, we can fairly easily locate and identify zones of rock-mechanical and hydrogeological importance. The difficulty, however, lies in obtaining from these investigation results relevant and usable values of the hydraulic and hydrogeological parameters of the rock mass. The methods used are the direct measurement of water loss in drill-holes (Zangar 1951, Banks 1972, Carlsson & Olsson 1976, and others) and the analysis of well data, which are often used in investigations of a regional character (Wenner 1951, Meier & Sund 1952, Jetel & Krásný 1968, Carlsson & Carlstedt 1976, and others). Each of these methods fulfils its own function — the analysis of well data on the regional plane for general investigations and the direct measurement of water loss for the detailed investigation. Measurement of water loss is the only method which allows of the direct measurement of the variation of hydraulic conductivity in the vertical direction in a rock mass. The analysis of well data may indicate the variation of the hydraulic conductivity on statistical grounds, by yielding indirect information in the form of well depth and capacity.

This work is aimed at determining the variations of and the reasons for the hydraulic conductivity on the basis of water-loss measurements made in a number of geographically and geologically distinct areas. We also wished to illustrate in greater detail the vertical variation which occurs.

The general hydraulic properties of the rock mass

Our knowledge of the hydrogeological properties of the crystalline basement is very small, compared with our knowledge of the corresponding properties of the porous deposits.

From the point of view of water supply, attention has been completely concentrated on eskers and others porous formations, when it has been necessary to extract large volumes of water. Consequently, the hydrogeological investigations have also been completely concentrated on these aquifers. The result has been that our knowledge of the porous strata has constantly increased, while there has been but a small increase in our knowledge of the rock's hydrogeological properties.

An important contribution to our knowledge of the bedrock has come from more or less extensive geological and geophysical explorations for various constructions in rock. These investigations often aim at finding out the tightness and the mechanical properties of the rock mass. In its capacity as a builder of large underground chambers and tunnels, the Swedish State Power Board fulfils an important function by carrying out these geological and geophysical explorations. An example of the magnitude of these efforts is to be seen at the Forsmark nuclear-power plant, where, to date, about 100 km of seismic profiling and 10 km rock-drilling have been carried out.

The general fissure conditions in the bedrock

As early as 1881, Crosby demonstrated that the frequency of fissures decreases rapidly with increasing depth below the rock surface. This fact has been verified by a very large number of subsequent investigations. Jahns (1943), amongst others, has shown that there is a high concentration of horizontal fissure systems in the superficial part of the bedrock and that the distance between the horizontal fissures increases with increased depth.

The hydraulic conductivity of the bedrock

A number of investigations have been carried out in order to shed light on this property, but only a few publications have presented direct values of the hydraulic conductivity of the bedrock (in Sweden, Carlsson & Carlstedt 1976 and Carlsson & Olsson 1976). However, a large number of works give some idea of the relative tightness of the rock (Wenner 1951, Meier & Sund 1952, Bergman 1975, Eriksson 1975, and others).

The values presented so far indicate that the hydraulic conductivity is normally between 10^{-5} m/s and 10^{-8} m/s, with more or less pronounced differences between different types of rock and rock structures.

Dependence of hydraulic conductivity on depth

The only Swedish investigation so far that refers to these circumstances (Carlsson & Olsson 1976) states that the hydraulic conductivity decreases with increasing depth below the rock surface. At greater depths, the decrease is not as great, but the tendency is still clearly marked. Some Swedish investigations based on well data show the same tendency (Wenner 1951, Meier & Sund 1952, and others).

In several non-Nordic works, there are careful and detailed analyses of the dependence of hydraulic conductivity on depth in aquifers orginating from fissures in crystalline rocks (Davies & Turk 1964, Snow 1968, and others). The results reported in these works are discussed in more detail in a later section.

Data from well-drillings also indicate that deep wells tend to yield less water than shallow.

The porosity of the bedrock

Rasmussen (1963) states 0,076 % as a median value for fissure-conditioned, effective porosity in crystalline bedrock. The figure is based on about 60 measurements. It agrees with the value of 0,01 % produced by Stewart (1962).

These values of the effective porosity in crystalline rocks may be compared with those of 15 %, which is fairly representative of gravel deposits, and 0,1—0,5 %, which has been calculated for Cambrian sandstone (Carlsson & Carlstedt 1977).

The real porosity of sandstone is thought to be about 10 %, but a large part of this taken up by non-extractable water.

Descriptions of the areas

This account is based on the result from altogether 55 drill-holes in which the water loss was measured. These drill-holes are distributed over five different areas — Forsmark (1), Juktan (2), Ringhals (3), Ylen-Stensjön (4) and Glan (5). The geographical situations of these areas are shown in Fig. 1. They represent geological environments that differ both tectonically and petrographically.

In the Forsmark area, the bedrock is dominated by a gneiss granite with a steeply dipping foliation. The foliation is partly intersected by a relatively well-developed, horizontal fissure system (Carlsson & Olsson 1977).

The bedrock in the Juktan area is dominated by solid Revsund Granite with relatively regular, granitic fissuring.

In the Ringhals region, the bedrock consists of a grey, fine-grained gneiss with a low dip. The rock is heavily fissured and seems to have a relatively great tendency to clay alteration.

In the Ylen-Stensjön area, the predominant type of rock is a greyish-red, fissured, gneissic Småland Granite. The fissure systems seem to be well developed at the surface but decrease greatly with depth. This area displays the highest fissure frequency recorded in the five areas investigated.

The area at Lake Glan consists of a grey, medium-coarse, sedimentary gneiss with few fissures. The main geological and fissure-tectonic features of the five areas are summarized in Table 1.

The rock types represented in the different areas thus give a fairly good cross-section of the Swedish crystalline basement. The gneiss granite in the Forsmark area is strongly foliated, while the Revsund Granite represents the massive granites. The somewhat gneissic Småland Granite occupies an intermediate position between these two granitic types of rock.

Of course, the results reported here for the

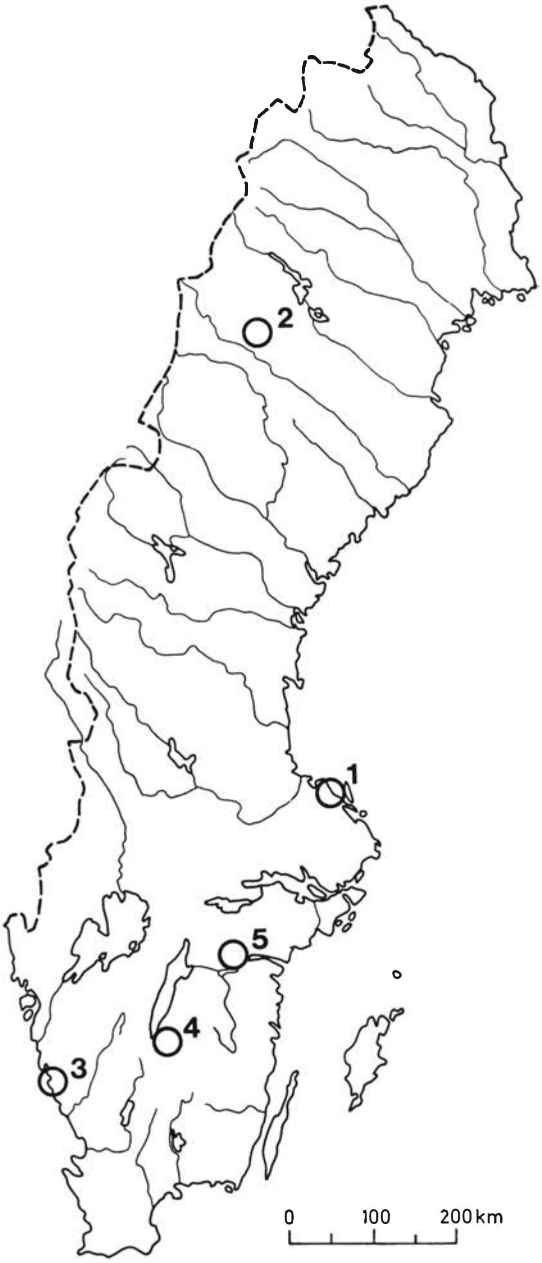

Fig. 1. The geographical positions of the areas. 1, Forsmark. 2, Juktan. 3, Ringhals. 4, Ylen-Stensjön. 5, Glan.

Table 1. The main geological and fissure-tectonic features of the areas.

Area	Main rock type	Structure	Fissure frequency 0—10 m	Fissure frequency 20—30 m	Fissure frequency 40—50 m
1. Forsmark	Gneiss granite	NW—SE; 80° SW	3,2	2,7	—
2. Juktan	Revsund Granite	Solid	—	—	—
3. Ringhals	Grey gneiss	Horizontal	7,8	6,1	2,9
4. Ylen-Stensjön	Småland Granite		13,8	8,6	—
5. Glan	Sedimentary gneiss		—	—	—

different areas cannot be extrapolated to apply to the respective type of rock as a whole. Besides, the material is too small and the bedrock within the same rock-type series is also too heterogeneous. However, the results may serve as a pointer to the differences which may conceivably exist and which are probably due to the rock type, the rock structure and the predominant stress conditions of the bedrock.

Methods

In this work, the results of the water-loss measurements made in the different areas were mainly used. In order to get a comparable material, data from wells drilled in rock were also analysed to a certain extent.

Measurements of water loss

The water losses at 55 drill-holes in the various areas were measured and the results formed the basis of the statistical treatment. On the basis of the measuring results (Moberg 1965, 1972, 1973, and 1975) the hydraulic conductivity of the rock was calculated by a method described by Carlsson & Olsson (1976). This method has long been used by the staff of the State Power Board to obtain a measure of the tightness of a rock mass. In the measurements of the drill-holes, double packers were usually employed, with a distance of 2—3 m between them. In a few measurements, in which the holes were partly blocked or the depth was too great, single packer measurements were made. Some of the holes measured with double packers were also checked with a single packer. The measurements were normally made by forcing the water into the rock under a certain pressure at a level limited by the packers (in single packer measurements at a level limited by the packer and the bottom of the hole), after which the water loss was measured for a certain period of time. The water pressure was increased stepwise up to a maximum of about 800 kPa (8 kp/cm^2), after which the pressure was decreased stepwise. The hydraulic conductivity value may be calculated from the following equation, which is described by Zangar (1953) and Banks (1972), amongst others:

$$k_n = \frac{Q}{LHt} C, \qquad (1)$$

where k_n = hydraulic conductivity at measuring level n,
Q = water loss,
L = length of measuring level,
H = water pressure,
t = measuring time,
C = constant.

Equation (1) applies in conditions of laminar flow but may also allow of a good approximation in conditions of turbulent flow. The constant C has been determined by Moye (1967) as

$$C = \frac{(1 + \ln(L/d))}{2\pi}, \qquad (2)$$

where d = the diameter of the measuring level.

The hydraulic conductivity value was calculated for each measuring level, after which a weighted mean value for each drill-hole was calculated by the following equation:

$$k = \frac{1}{\sum_{n=1}^{m} L_n} \sum_{n=1}^{m} L_n k_n, \qquad (3)$$

where L_n = the length of the measuring level n,
k_n = the hydraulic conductivity at the measuring level n,
k = the hydraulic conductivity of the bedrock at the drill-hole.

In order to obtain the regional picture of each area, mean values were calculated for each of the five areas. The mean values used in this connection are the mean arithmetical value $\bar{k}$, the median value k_M and a mean value weighted against the

Table 2. Hydraulic conductivity values for the different areas.

Area	Median value m/s	Mean value m/s	Depth-dependent mean value m/s
1. Forsmark	$1{,}0 \cdot 10^{-6}$	$1{,}6 \cdot 10^{-6}$	$1{,}6 \cdot 10^{-6}$
2. Juktan	$1{,}8 \cdot 10^{-6}$	$1{,}8 \cdot 10^{-6}$	$1{,}8 \cdot 10^{-6}$
3. Ringhals	$7{,}9 \cdot 10^{-7}$	$1{,}1 \cdot 10^{-6}$	$9{,}9 \cdot 10^{-7}$
4. Ylen	$3{,}0 \cdot 10^{-7}$	$5{,}0 \cdot 10^{-7}$	$3{,}7 \cdot 10^{-7}$
Stensjön	$5{,}5 \cdot 10^{-7}$	$6{,}0 \cdot 10^{-7}$	$6{,}0 \cdot 10^{-7}$
5. Glan	$1{,}3 \cdot 10^{-8}$	$9{,}5 \cdot 10^{-8}$	$2{,}8 \cdot 10^{-8}$

depth of the individual drilling in accordance with equation (4).

$$\bar{k}_L = \frac{1}{\sum_{m=1}^{P} L_m} \sum_{m=1}^{P} L_m k_m, \quad (4)$$

where $\bar{k}_L$ = the mean value of a number of drillings, weighted against the depth of the respective drilling,
L_m = the drilling depth in hole m,
k_m = the hydraulic conductivity in drill-hole m.

The results of the measurements and calculations made are reported in Table 2, in which the three types of mean value are given.

Treatment of well data

In order to investigate whether a similar tendency could be found in the wells drilled in rock, data from 190 wells situated in gneiss granite, in northern Uppland were collected and related to the depth. In addition, 39 wells in the Forsmark-Östhammar area were analysed on the basis of the regional parameters according to Carlsson & Carlstedt (1976), in order to produce data about the hydraulic conductivity of the bedrock in this way also.

Results of measurements of water loss

The basis of this account is the measurements of water loss at altogether 55 drill-holes, of which 25 are vertical holes and 30 are holes drilled at an angle (normally sloping at 45° to the horizontal). Measurements were made at 563 levels in all. The distribution between areas is shown in Table 3.

Hydraulic conductivity determinations

Hydraulic conductivity values were calculated for each of the 563 measurements with the aid of eqaution (1), in order to determine, on the basis of these individual values, the hydraulic conductivity of the bedrock at the respective drill-hole. Table 2 shows the mean values for the different areas and it will be seen that these values vary considerably.

Dependence of hydraulic conductivity on depth

The hydraulic conductivity values of all the drill-holes will be found in Fig. 2, in which they have been plotted against the vertical component of the drilling depth. Fig. 3 shows the same values, but here they have been plotted against the logarithm of the depth below the rock surface.

In order to work out the amount of the dependence of the hydraulic conductivity on depth, the linear equation which best satisfied the measured results was calculated. This equation is for the linear dependence as follows:

$$k = 10^{-(0{,}02\,D + 5{,}6)}, \quad (5)$$

where D = the depth below the rock surface.

In order to assess the fit of the line to the measured values, the determination coefficient r^2 was ascertained from equation (6). This factor has a value between 0 and 1, where the value 1 indicates that the line fits the series of points completely.

$$r^2 = \frac{\left[\Sigma xy - \frac{\Sigma x \Sigma y}{n}\right]^2}{\left[\Sigma x^2 - \frac{(\Sigma x)^2}{n}\right]\left[\Sigma y^2 - \frac{(\Sigma y)^2}{n}\right]}. \quad (6)$$

The determination coefficient is 0,40 for equation (5), which must be considered to be a comparatively close correlation for the heterogeneous bedrock material. In addition to equation

Table 3. The distribution of drillings, drilling depths and measured levels between the different areas.

Area	No. of drillings Total	Vertical	Angular	Drilling depth m	Measurements of water loss No. of measured levels
1. Forsmark	30	15	15	1300,6	324
2. Juktan	1	1	0	321,0	14
3. Ringhals	12	5	7	432,2	107
4. Ylen-Stensjön	7	1	6	367,9	102
5. Glan	5	3	2	633,3	16
Total	55	25	30	3055,0	563

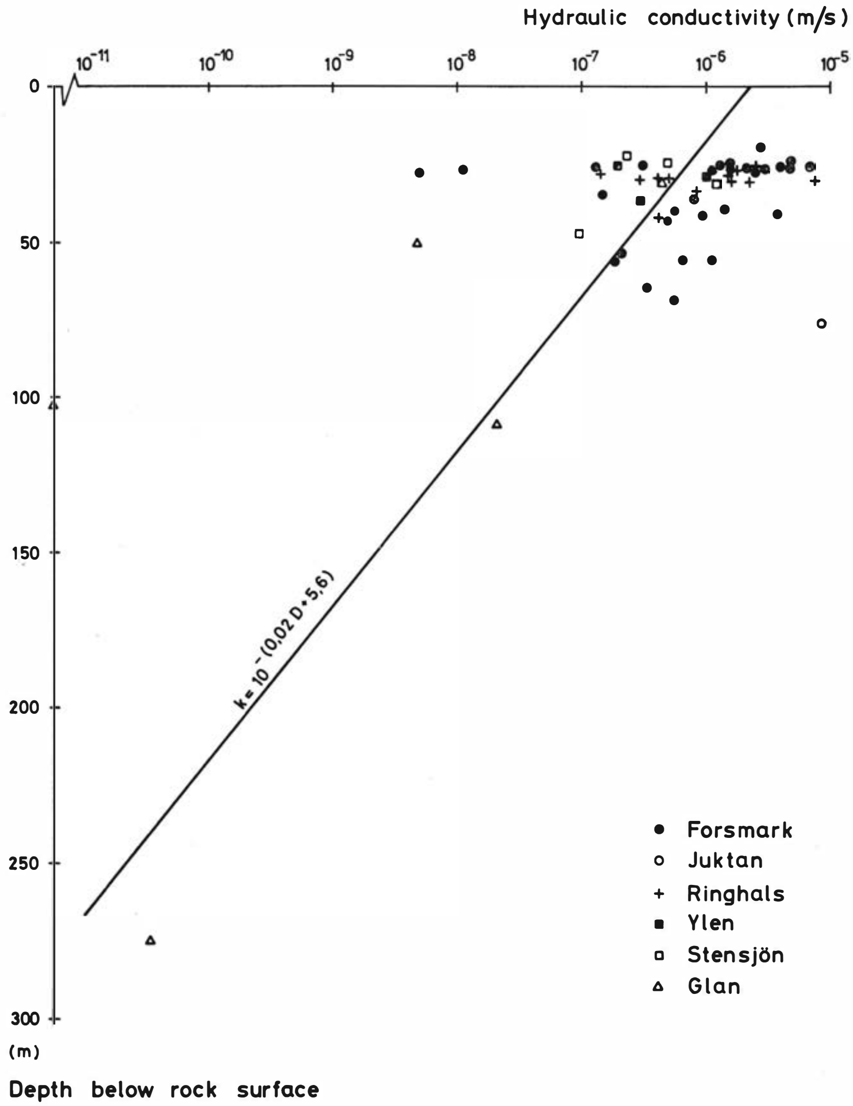

Fig. 2. The mean hydraulic conductivities of the drill-holes in which the water loss was measured, plotted against the vertical depth of respective drill-hole below the rock surface.

(5), the equation for the logarithmic dependence was determined as

$$k = 10^{-(2,5\,\log D + 2,5)} \qquad (7)$$

with a determination coefficient of 0,57. Equations (5) and (7) represent all the areas and all the measurements lumped together. The corresponding equations for each of the different areas are shown in Figs. 4 and 5.

The decrease of hydraulic conductivity with depth was determined on the basis of data given by Snow (1968) as

$$k = 10^{-(1,6\,\log D + 4)}. \qquad (8)$$

Because of the incomplete base data no determination coefficient can be given. This equation has been inserted in Fig. 3 as a comparison.

A more accurate method of calculating the dependence of the hydraulic conductivity on depth is to consider the different measurements and to

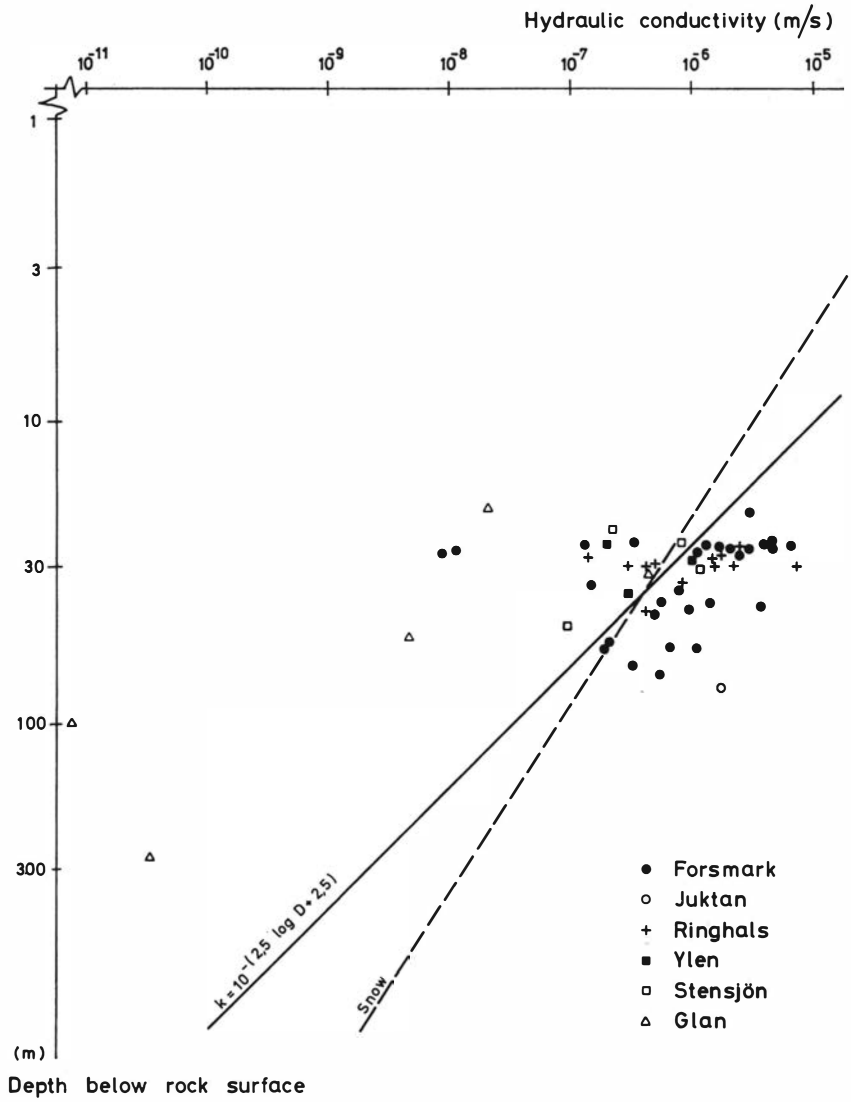

Fig. 3. The mean hydraulic conductivities of the drill-holes in which the water loss was measured, plotted against the logarithm of the vertical depth of the respective drill-hole below the rock surface. The linear equations are based on the measurements reported and are thereby hypothetical below the depths of the drill-holes.

distribute the results on different levels. In order to produce this value, the median value for each 5-m interval was calculated. The result of this calculation will be found in Fig. 6, in which each dot represents the median value for a 5-m level. The graphic representation indicates that there is a drastic decrease within the first 100 m and that below this level the hydraulic conductivity is constant. However, this picture is not representative, since the measurements below 100 m are single packer measurements in one drill-hole. The equation for the dependence of the hydraulic conductivity on depth down to about 75 m is as follows:

$$k = 10^{-(0{,}04\,D + 5{,}6)}, \qquad (9)$$

and its determination coefficient is 0,62. Thus, there is a very marked similarity to equation (5).

Fig. 7 shows the hydraulic conductivity values for the different levels in a logarithmic representation in relation to depth. If the result from the

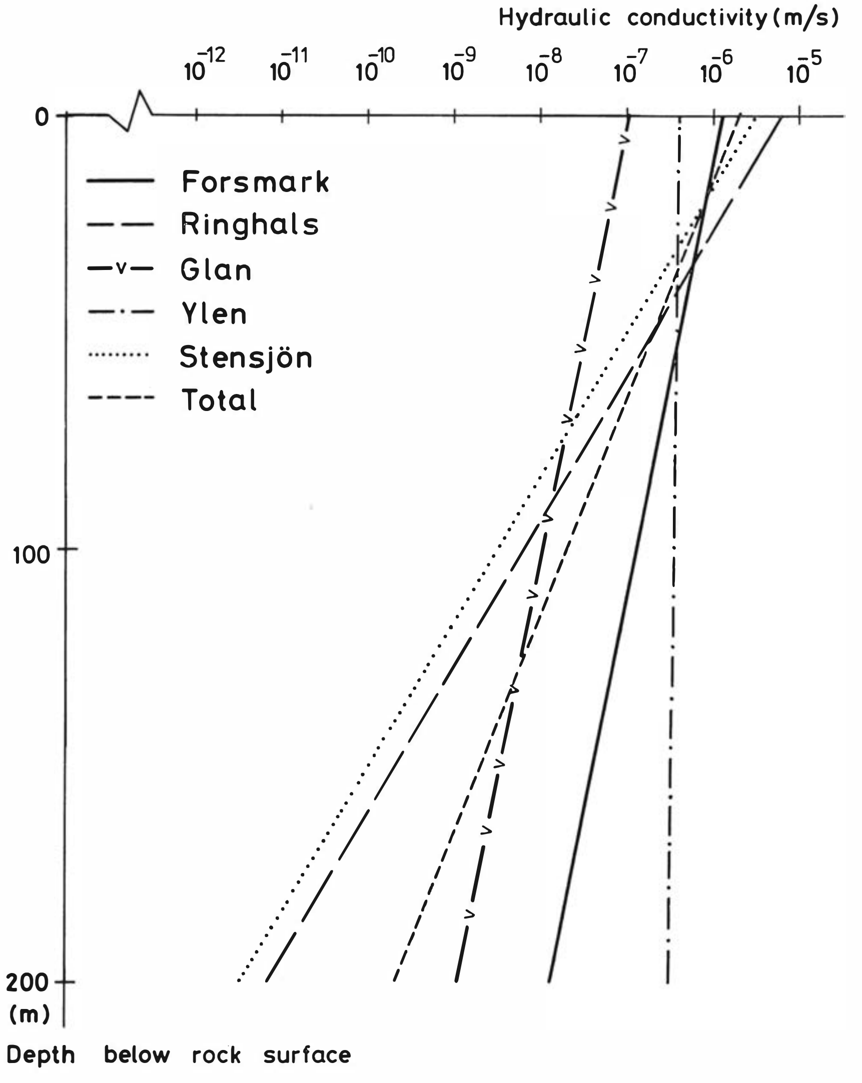

Fig. 4. The functional relations between the hydraulic conductivity of the bedrock and the depth below the rock surface for the different areas. The linear equations are based on the measurements reported and are thereby hypothetical below the depths of the drill-holes.

drill-hole in the Glan area (depth 274,9 m) be excluded, the remaining measured values fall on a line described by the equation

$$k = 10^{-(1{,}65\ \log D + 4{,}5)}. \qquad (10)$$

In this case, the determination coefficient is 0,65.

Yet another way of determining the variation of the hydraulic conductivity with the depth was used in this investigation. By examining how the percentage distribution of impermeable rock appears as a function of the depth, we obtain a measure of the variation with depth of the hydraulic conductivity. Here impermeable rock means measured levels with hydraulic conductivities of less than 10^{-10} m/s. The distribution which emerged in this connection is Fig. 8. It can be seen fairly clearly that there is an increase of the frequency of tight measuring levels with increased

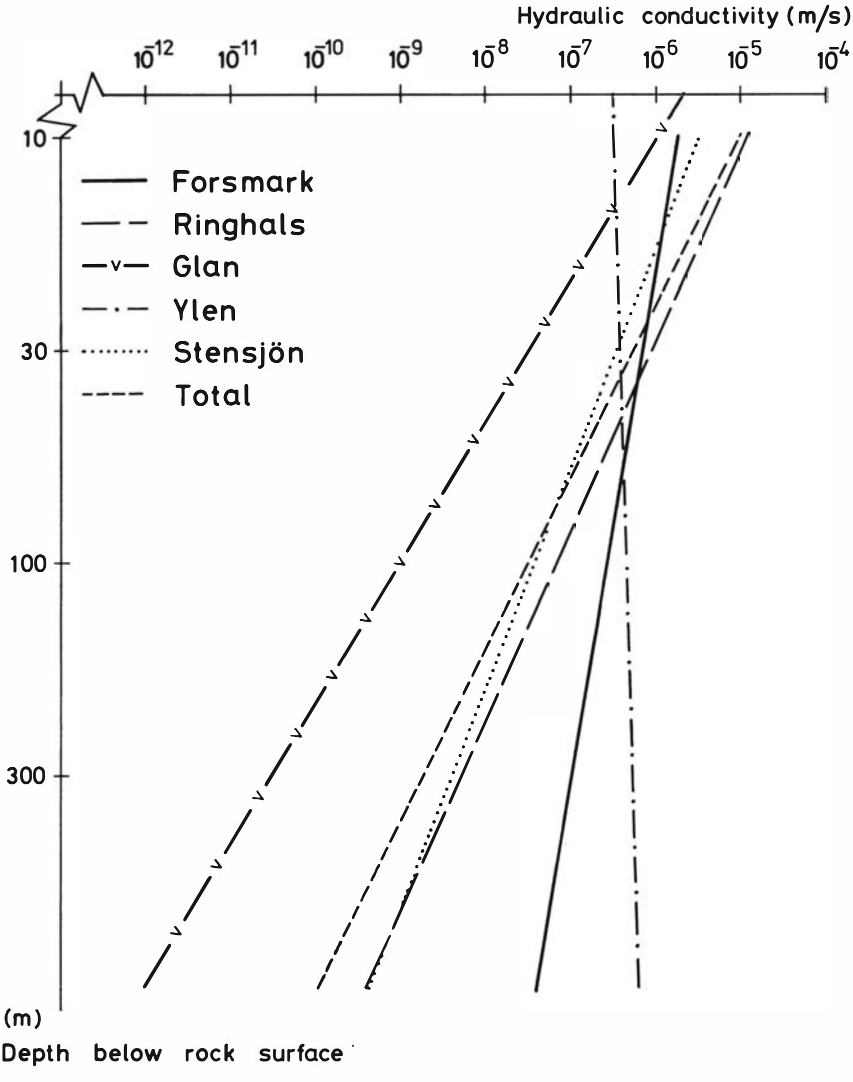

Fig. 5. The functional relations between the hydraulic conductivity of the bedrock and the depth below the rock surface for the different areas. Logarithmic representation. The linear equations are based on the measurements reported and thereby hypothetical below the depths of the drill-holes.

depth. The equation which best expresses this state of affairs is the following:

$$\log D = 1{,}06\,P + 1{,}2, \qquad (11)$$

where P = the percentage of measurements in which tight rock was recorded.

The determination coefficient for this function is 0,77. The distribution is probably not linear, but there would seem to be an asymptotic connection with the 0 % axis and the 100 % axis. This tendency is also indicated in Fig. 8.

The linear function according to equation (11) indicates that, below 54 m, more than 50 % of the measurements were recorded as impermeable rock, defined as above.

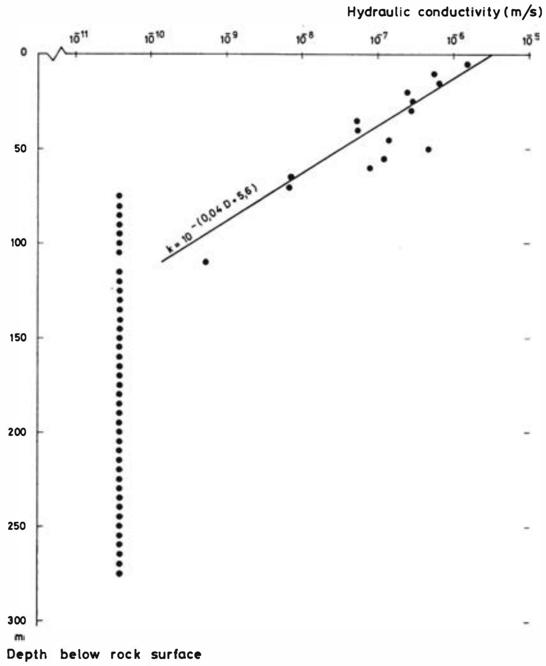

Fig. 6. The median value of the hydraulic conductivity for each 5-m level below the rock surface.

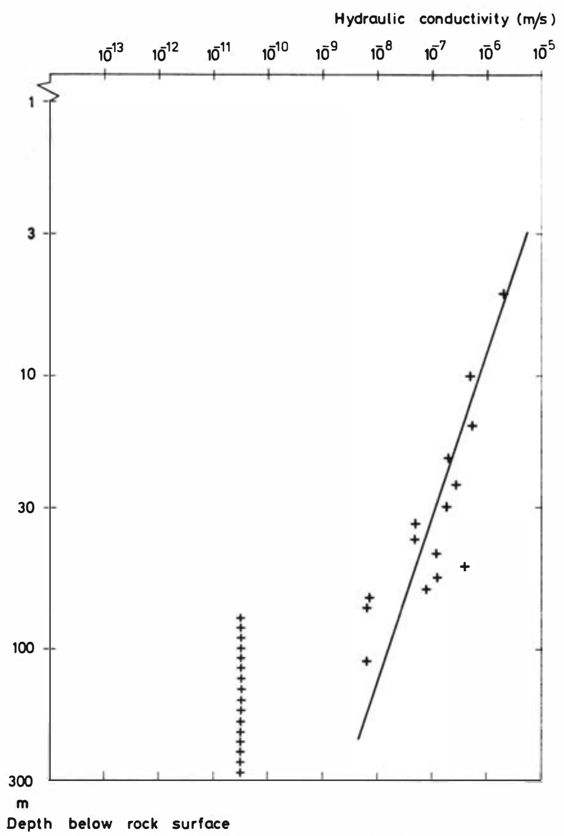

Fig. 7. The median value of the hydraulic conductivity for each 5-m level below the rock surface. Logarithmic representation.

Summary account of the dependence of the hydraulic conductivity on depth

The dependence of hydraulic conductivity on depth is determined on the basis of three different methods:

1. The mean hydraulic conductivity of the drill-holes is related to the vertical depth of the respective drill-hole below the rock surface.
2. The hydraulic conductivity of the bedrock in each 5-m interval is related to the depth of the interval below the rock surface.
3. The distribution of measurements with recorded impermeable rock is related to the depth.

All three methods indicate that there is a decrease of the hydraulic conductivity with increasing depth. However, the decrease is not clear-cut and the variations are large. It has been possible to determine the actual amount of the decrease by the first two methods, while, on the other hand, the third method only gives the tendency.

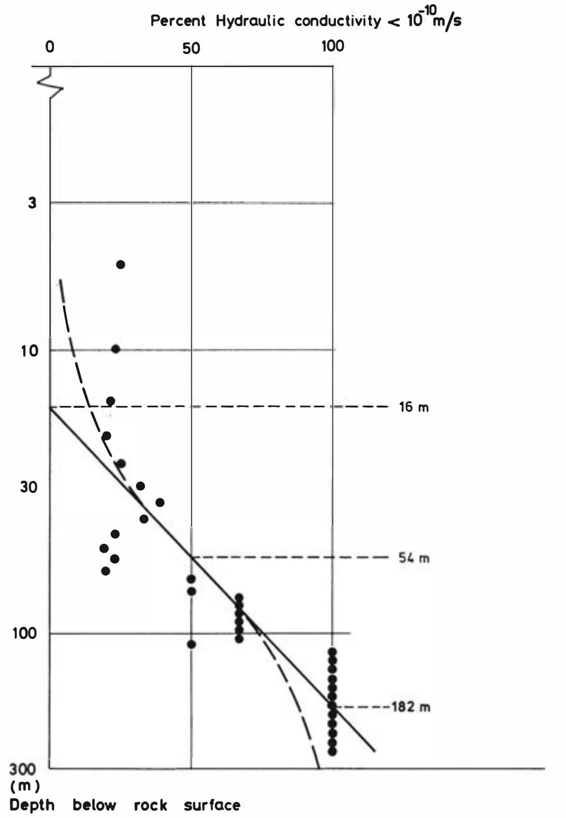

Fig. 8. The percentage distribution of impermeable rock at various levels in the rock. The straight line indicates that, at levels deeper than 54 m, more than 50 % of all measurements are recorded as impermeable rock.

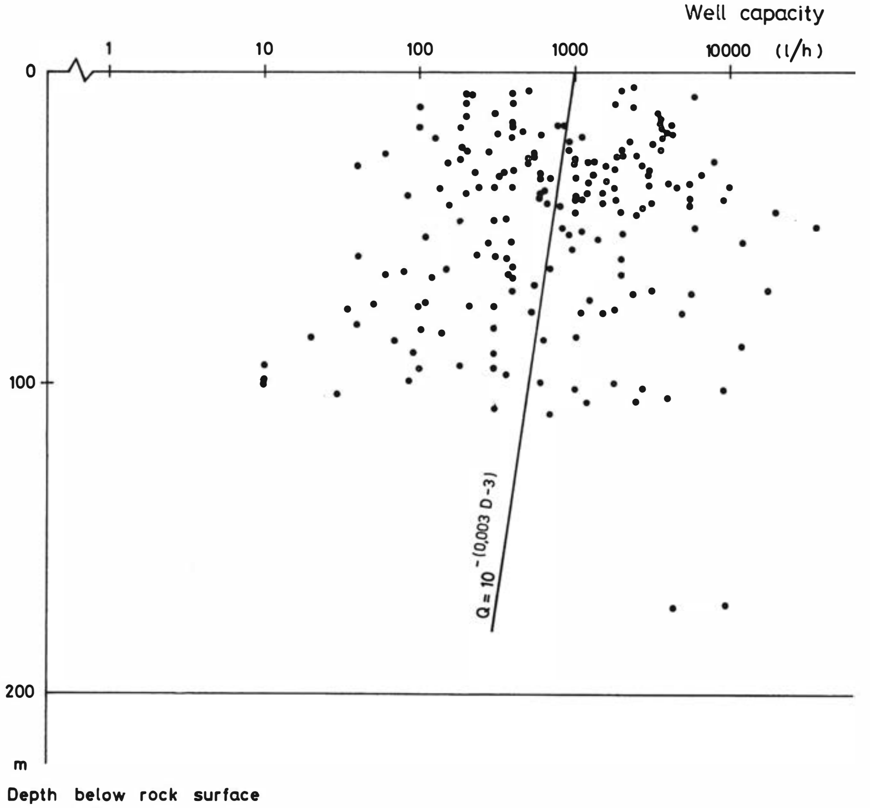

Fig. 9. Capacity values for 190 wells situated in the northern-Uppland, crystalline basement area, plotted against the well depth. The straight line indicates the tendency for the capacity to be dependent on the depth.

In determining the actual decrease, the relation logk—logD has yielded the best result, which indicates that the hydraulic conductivity probably decreases with the logarithm of the depth. Since the first method does not take account of the actual variation of the hydraulic conductivity with depth but only records the mean hydraulic conductivity and the drilling depth, the functional relation for the decrease based on this method would seem to yield a less reliable result than the functional relation produced by the second method. The equations obtained by the second method are as follows:

$$k = 10^{-(2,5\ \log D + 2,5)} \quad (7)$$

$$k = 10^{-(1,65\ \log D + 4,5)} \quad (10)$$

Both these equations have relatively high determination coefficients (0,57 and 0,65 respectively).

Equation (10) shows a very good agreement with the equation determined with Snow's (1968) data:

$$k = 10^{-(1,6\ \log D + 4)} \quad (8)$$

The gradients in equations (8) and (10) (1,6 and 1,65 respectively) agree surprisingly well. The difference lies in the starting-points for the two equations ($3,2 \cdot 10^{-5}$ m/s and $1,0 \cdot 10^{-4}$ m/s respectively, at a depth of 1 m), but this difference is not markedly great either.

Results of the treatment of well data

Data from 190 wells drilled in rock in the northern-Uppland gneiss area were treated and put together to obtain a comparable material. In addition, data from 39 wells in the Forsmark-Östhammar region were treated with the aid of the regional well parameters (Jetel & Krásný 1968, Carlsson & Carl-

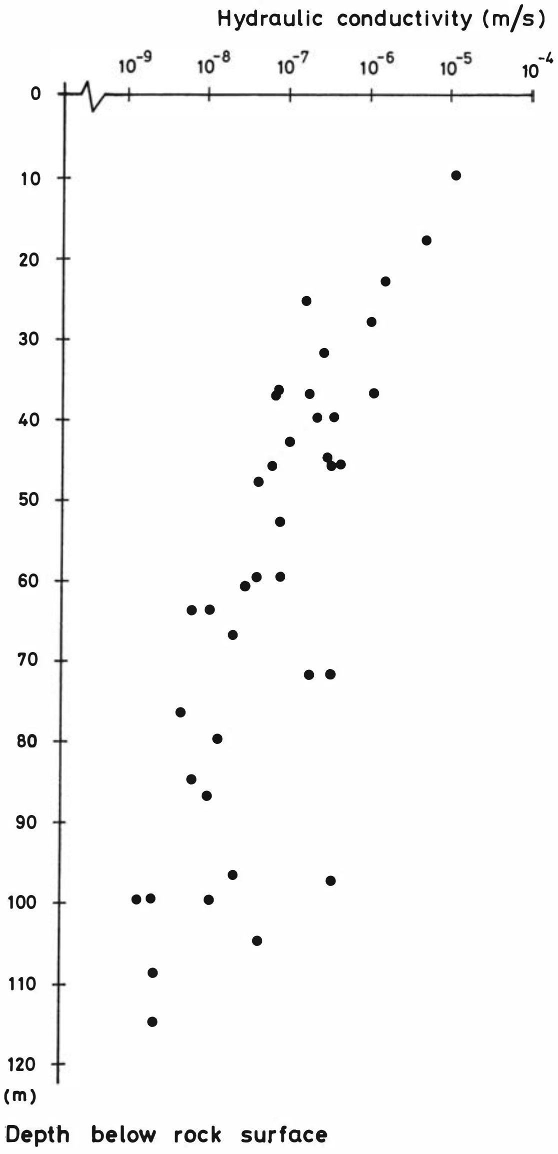

Fig. 10. Hydraulic conductivity values based on well data from 39 wells drilled in rock in the Forsmark-Östhammar area. The hydraulic conductivity is given as a function of the well depth.

stedt 1976), in order to determine the hydraulic conductivity of the bedrock in this way also.

Fig. 9 shows the capacity in relation to the well depth for the 190 wells. As is evident, the scatter is not great, but a slight tendency to reduced capacity with increasing well depth can be observed. The equation which best expresses this tendency is the following:

$$Q = 10^{-(0{,}003\,D - 3)} \qquad (12)$$

However, the determination coefficient is as low as 0,01. The functional equation (12) has been inserted in Fig. 9.

On the basis of the regional parameters, the hydraulic conductivity has been determined for 39 wells drilled in rock. The results of these calculations will be found in Fig. 10.

The tendency here is very marked. The median value of the hydraulic conductivity is $7{,}9 \cdot 10^{-8}$ m/s (Carlsson & Olsson 1976), which should be compared with the hydraulic conductivity of $1{,}0 \cdot 10^{-6}$ m/s determined by waterloss measurements. The equation for these wells is as follows:

$$k = 10^{-(2{,}8 \log D + 2{,}3)}, \qquad (13)$$

with a coefficient of 0,64.

Discussion

It may be relevant to compare the fissure-conditioned hydraulic conductivity of the crystalline basement with the pore hydraulic conductivity of a sedimentary soil. The hydraulic conductivity value of $1{,}0 \cdot 10^{-6}$ m/s for the basement corresponds most closely to that of a silty-sandy sediment. In these circumstances, the hydraulic conductivity of the bedrock is not too low. The normal values for sediments have been inserted in Fig. 11 as a comparison. The great difference between bedrock and sediment is thus not in the hydraulic conductivity value but rather in the porosity value (15 % in a sediment, as against only 0,01 % for the crystalline basement). In other words, 150 litres of water per cubic metre in a sedimentary aquifer, as against 0,1 litres per cubic metre in the bedrock.

Comparison between different areas

The hydraulic conductivity values for the different areas have been inserted in Fig. 11. Four of the five areas are grouped fairly well around 10^{-6} m/s. One of the areas, Glan, differs markedly from the rest, owing to the fact that the rock has a very low hydraulic conductivity. We know from previous investigations (Wenner 1951, Meier & Sund 1952, Eriksson 1975, and others) that the eastern-Swedish sedimentary gneiss is normally very tight. The greatest hydraulic conductivity was recorded at Juktan, which would seem to be justified, considering the bedrock. The Revsund Granite has also in other connections proved to be a relatively highly productive aquifer (De Geer & Persson

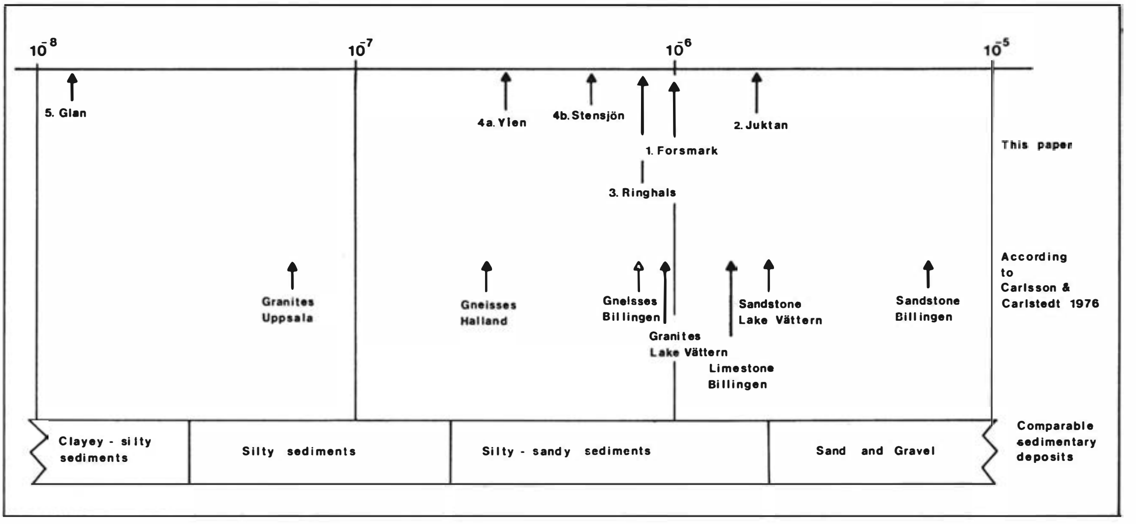

Fig. 11. Hydraulic conductivity values of the areas discussed and hydraulic conductivity values on well data, according to Carlsson & Carlstedt (1976). The hydraulic conductivity values for normal Quaternary sediments have been inserted for comparison.

1977). With regard to the recorded fissure frequencies, the Ylen-Stensjön and Ringhals areas have comparatively low hydraulic conductivities. Both these areas have considerably higher fissure frequencies than the Forsmark area (Table 1) but clearly lower hydraulic conductivities values. This would seem to indicate that the fissures which occur in these two areas are largely watertight, either in the form of clay alterations or on account of the fact that they are under pressure. The fissure frequency decreases rapidly with the depth in these two areas, which would also seem to explain the comparatively low median values.

Comparison with other investigations

Hydraulic conductivity values. — Carlsson & Carlstedt (1976) report a number of hydraulic conductivity values which agree fairly well with those calculated here. Their calculations are based throughout on well data, which may give rise to a certain difference. In Fig. 11, the values which they obtained are shown as a comparison.

Dependence on depth. — The tendency which has been discovered as a result of the measurements of water loss reported here agrees very well with the state of affairs reported by Snow (1968). However, the variation of gradient seems to depend very much on the method of calculation used.

The difference in gradient values between the measurements of water loss and the analysis of well data is, however, great. Broadly speaking, the gradient based on the analysis of well data is almost twice as great as that based on the measurements of water loss.

Comparison between measurements of water loss and analysis of well data in the Forsmark area

The hydraulic conductivity of the rock mass in the Forsmark area was determined, on the one hand, by measurements of water loss ($1{,}0 \cdot 10^{-6}$ m/s) and, on the other, on the basis of well data ($7{,}9 \cdot 10^{-8}$ m/s). These values apply to drillings down to a depth of about 100 m. The difference between the two values is thus very considerable, which may be explained to a certain extent by the following facts:

1. The surface rock at Forsmark is heavily fissured, with horizontal joints filled with easily eroded sediment. In the measurement of water loss, a wash-out may therefore occur, which will result in an increased hydraulic conductivity.
2. If hydraulic pressure is exerted on the surface rock, an extensive widening of the joints may take place through rock-heaving, and consequently a higher hydraulic conductivity value will be obtained.
3. Calculating the hydraulic conductivity on the basis of the regional parameters is a rough method

with large sources of error, which makes it most suitable for regional comparisons. A detailed comparison may therefore produce an erroneous picture.

4. Some of the drill-holes in which water losses were measured have been systematically located in zones of low seismic velocity, while the well drillings have been set out at random. This fact yields, on the average, an increased hydraulic conductivity for values based on measurements of water loss.

If, on account of these facts, we exclude the hydraulic conductivity of the surface rock, the median value of the measurements of water loss will be $2{,}0 \cdot 10^{-7}$ m/s. This value shows good agreement with the regional picture obtained from well data, with a hydraulic conductivity of $7{,}9 \cdot 10^{-8}$ m/s. Since the regional parameters are a rough method of calculation, these results should not be normative in the comparison. Hydraulic conductivity values based on measurements of water loss should yield a more correct result than the analysis of well data, if the measurements are made in such a way as to avoid rock-heaving and wash-out.

Acknowledgements. — We wish to express our gratitude to Dr. J. Martna and Mr. K. A. Scherman, Chief Engineer at the Swedish State Power Board in Stockholm for reading the manuscript critically and for valuable discussions. Our thanks are also due to Drs. L. Carlsson, A. Carlstedt and G. Persson at the Geological Survey of Sweden for valuable criticism. The English was translated by Mr. Neil Tomkinson, B. A., Uppsala.

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Printed by Ekenäs Tryckeri Ab, Ekenäs, Finland September, 1977.