Strategies for groundwater prospecting in hard rocks: a probabilistic approach

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Private wells in fractured, Precambrian, crystalline rocks are important for rural areas and small communities in Sweden. Since well yields normally are small, systematic approaches to groundwater prospecting are required in order to predict how to site the wells and what costs to expect. The proposed approach is to minimise the sum of investigation and exploitation costs under the assumption of a lognormal distribution of well yields. The strategy involves the drilling of a fair number of exploratory wells, of which the best are connected to the supply system. Statistical data on well yields, in this case from the Swedish Well Archive, are required to support the decisions of pre-investigations and exploratory well drilling programmes that are suggested for small groundwater users and larger supply schemes using this probabilistic approach.

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Introduction

Some 10 % of the Swedish population use their own private wells for domestic water supply. Most of these wells are drilled in Precambrian hardrocks that make up about 90 % of the country's bedrock. Annually, more than 10,000 new wells are drilled. Data on these wells are gathered in the National Well Archive, run by the Swedish Geological Survey (www.sgu.se/databaser/brunnsark_meny.htm), where today more than 200,000 hardrock wells are registered. Data from the Well Archive are frequently used in regional studies and also in ad hoc approaches when siting bedrock wells.

The extensive use of wells in the crystalline basement (Gustafson & Krásny 1994) shows that the Swedish hardrock is an aquifer of significant value, albeit most important for small users in rural areas. However, hardrocks also play a role for water supply systems; and in that case what strategies should be used for groundwater prospecting?

Data in the Well Archive

Reporting of data to the Well Archive by well drillers has been compulsory in Sweden since 1974. Data comprise drilling date, yield, depth, soil depth and co-ordinates in the Swedish survey system. The yield of the wells is normally determined with a simple air-lift test with a duration of one to a few hours. It can also be noted that the drilling depth is commonly determined by the desired yield, in that wells are drilled until a yield of at least 250 l/h is reached or they are abandoned after about 100 m depth.

The siting of the wells is normally governed by a desire to have the well close to the building and in an upstream direction from contaminant sources. In most cases no professional geological or geophysical work is made for the siting. The bulk of the wells can thus be considered randomly sited, since their position is determined by the building they serve rather than by hydrogeological considerations. It must also be kept in mind that data accuracy is low because of the approximate testing and sampling methods, but there is no reason to suspect that there is any systematic bias in the data, and thus the bulk of the wells will give a reasonably good picture of the hydrogeological properties of the rock.

Yield statistics

Tested yields of the wells tend to be approximately lognormally distributed. A typical example of a lognormal probability plot of well yields, in this case a sample from the Uppsala area, Sweden, is shown in Fig. 1. As shown, it is also typical that very low and very high yields deviate from the straight distribution line mainly because of the imperfect testing methodology. This is most evident for low yields, since little effort will be paid to a well that is considered dry.

It may be debated whether the yield, Q, or the specific capacity, Q/s_w, is the right parameter to analyse in this particular case. In most aquifer types, the specific capacity is preferred since it is roughly proportional to the transmissivity, T. However, in the Swedish crystalline rocks there is a strong decline of the hydraulic conductivity with depth (see e.g. Ahlbom & Carlsson 1988) which makes the specific capacity approach dubious for the applied air-lift testing where the well is emptied more or less to its full depth. This means that the proportionality between the apparent specific capacity and transmissivity is lost. For that reason the estimated yield, Q, is analysed in this paper.

Figure 2 shows the Cumulative Distribution Function (CDF) of the approximated lognormal distribution of the

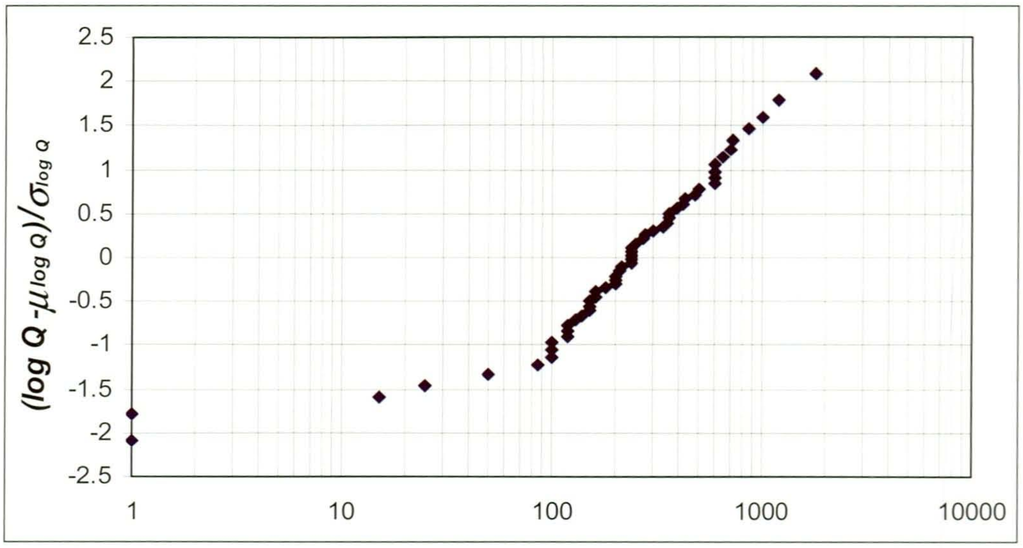

Fig. 1. Normalised CDF-plot of an approximately lognormal sample of 54 well yields in an area in Uppland, Sweden. Log_{10} mean, $\mu_{log\,Q}$ = 2.30. Log_{10} standard deviation, $\sigma_{log\,Q}$ = 0,6. Data from Pettersson (1987).

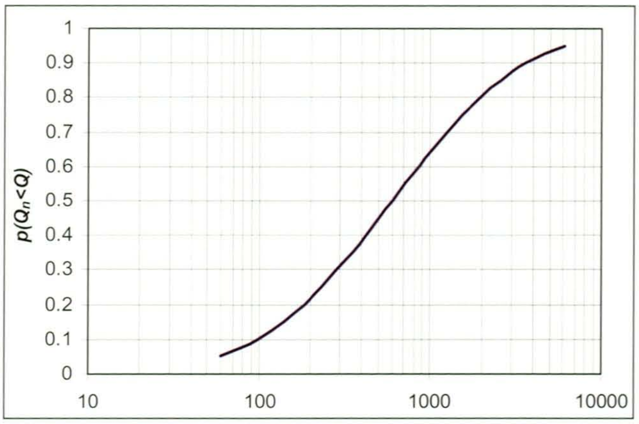

Fig. 2. CDF of the approximate yield distribution for all Swedish hardrock wells based on data from Fagerlind (1988).

yields for all Swedish hardrock wells based on data from 59,000 wells in the Swedish Well Archive (Fagerlind 1988). Median for the population is Q_m = 600 l/h and the average yield is Q_a = 1643 l/h. The large difference between the median and the average is the result of the skewed lognormal distribution. The distribution can be compared to what is generally considered to be a successful well for a single home, Q = 250 l/h. This is fulfilled for about 80 % of the boreholes and, thus, there is, for pure statistical reasons, ample opportunity for water-diviners to take credit for a successful well siting.

Relation between yield and lithology

There have been several efforts to correlate well yields and rock type (see e.g. Carlsson & Carlstedt 1977, Liedholm 1988 and Ahlbom & Carlsson 1988). The general results of these studies are that brittle acid rocks have a higher median yield than basic, ductile and more easily weathered rocks. Median yields fall within an order of magnitude, about 400-1200 l/h, and the spread within each rock group is much larger than the difference between the groups. There is also a tendency for the spread to be greater for the less pervious rocks.

The importance of hydrogeological fieldwork and geophysics

Several low-cost approaches, i.e. lineament interpretation (Ericsson 1988, Wladis & Gustafson 1999), VLF measurements (Pettersson 1987) and slingram electromagnetics (Müllern 1988), have been taken to increase the success rate for well drilling in Swedish hardrocks. In the study by Pettersson (1987), a systematic comparison was made between yields of wells sited on the basis of a simple tectonic analysis and Very Low Frequency (VLF) electromagnetic geophysical measurements of all wells drilled in an area outside Uppsala. The area is dominated by intermediate granites (Uppsala granite) and has a total surface area of 3750 km^2. Here, the rural water supply is based mainly on bedrock wells. The rather low encountered yields have meant that VLF-measurements have been extensively used as a basis for siting. Figure 3 shows CDFs of the yields of the VLF-sited wells and

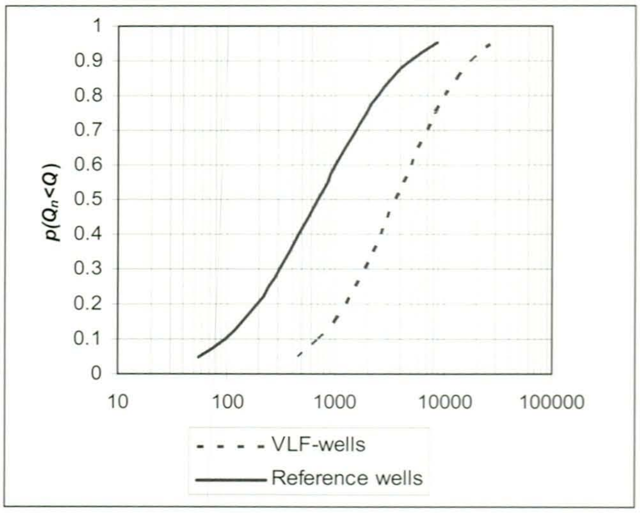

Fig. 3. Comparison of CDFs of yields of wells sited with a VLF-survey and a reference sample from the Uppsala area. Data from Pettersson (1987).

the reference population. VLF-siting gave an increased median yield from 690 to 3600 l/h. The difference between the populations was found to be statistically significant by a two-sample test (Råde & Westergren 1990). As can be seen, the spread of the distributions is large, indicating that there are several wells in the reference population that are good enough but also that some of the VLF-wells could be considered as dry.

A siting strategy for the small user

The most likely yield of a lognormal population is the median value. This means that there is a 50 % chance of getting 690 l/h or more in a randomly sited well in the investigated area. The chance of getting more is much higher in a VLF-sited well, but how that influences the economy of the project can be analysed with a simple risk analysis. The risk, or risk cost, R, is defined as the probability of failure of a project, p_f, multiplied by the economic consequences (cost) of a failure, C_f. Thus:

$$R = p_f \cdot C_f \qquad (1)$$

If we drill the well in a random position, the cost of a failure is the same as the cost of drilling a dry well, B. In the case of a VLF-sited well, we also have to add the investigation cost, V, if the well is dry. If we assume that the drilling of a well costs B = 20,000 SEK, and we have a need for a yield of 1000 l/h, we find from Fig. 3 that the probability of failure for the randomly sited well is $p_f = p$ (Q<1000 l/h) = 0.6. The risk cost will then be:

$$R_W = 0.6 \cdot 20{,}000 = 12{,}000 \text{ SEK} \qquad (2)$$

For the VLF-sited well the probability of failure is only 0.15 and the risk cost for the well will only be:

$$R_V = 0.15 \cdot 20{,}000 = 3{,}000 \text{ SEK} \qquad (3)$$

The obvious thing to do is to use VLF-siting if it costs less than $R_W - R_V$ = 9,000 SEK. In reality, the complete risk calculation is a bit more complicated since the desired yield can be obtained from more than one well.

The strategy for a small well user would then be to first check the data in the Well Archive and if there is a high probability of success – drill! In an area with less pervious rocks, use a simple tectonic analysis combined with VLF for positioning the well.

A strategy for large users

For larger users it is likely that a well-field, i.e. two or more wells, will have to be used. In order to optimise this system we have to consider that the wells will have to be spread to allow for recharge, and that they have to be connected to the distribution system and installed with pumps, electricity supply, etc.

Assume that:

- B is the cost of drilling a borehole that later can be used as a production well and that b boreholes are drilled during pre-investigation and exploitation.
- I is the cost of connecting a borehole to make it a production well and that i boreholes are connected to the production system.
- There is an average relation between the costs so that $I = c\,B$

Our strategy will be to minimise the cost:

$$C = bB + iI = B(b + ic) \quad \textit{given a demand } Q \qquad (4)$$

Our next task is to estimate the yields of N drilled wells. Given a CDF for a large number of wells such that $p(Q < Q_n) = F[Q]$, the probable yield for well n in an ordered sequence of yields using equal density sampling in the CDF can be estimated to be (Kite 1977):

$$Q_n \approx F^{-1}[n/(N+1)] \qquad (5)$$

Thus, it is possible to construct a cumulative diagram of the sum of expected well yields starting with the largest ones. Since the lognormal distribution is rather skewed one finds that the best wells contribute proportionally much more to the sum and, what is more important, the sum of the i best wells of a large sample b will be considerably greater than the sum of i randomly drilled wells.

$$\Sigma Q(i,b) = \Sigma F^{-1}[(b-n+1)/(b+1)] \quad \text{for } n = 1 \text{ to } i \qquad (6)$$

If the CDF for the VLF-wells, with median 3600 l/h and log standard deviation 0.6, in the example above is used,

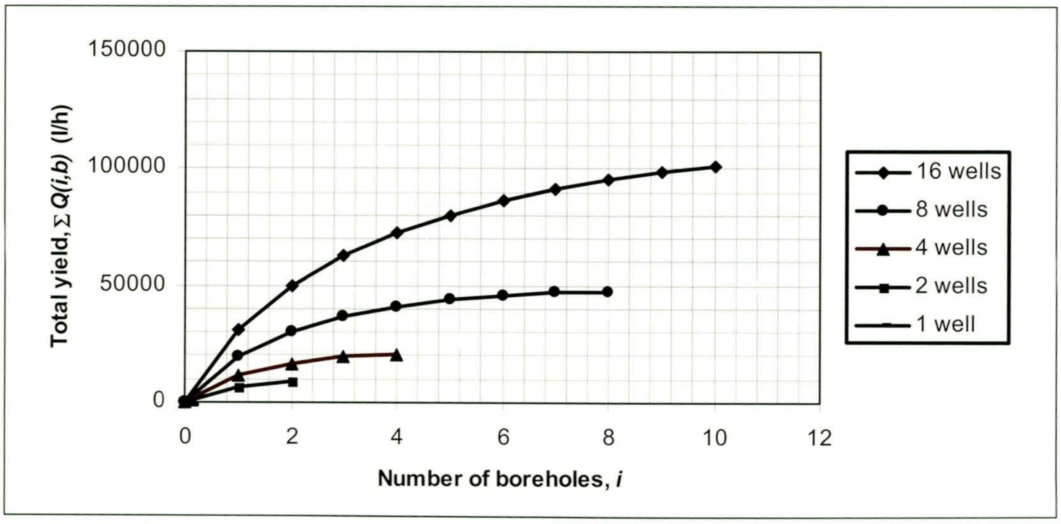

Fig. 4. Cumulative plots of predicted borehole yields from the i best wells out of b drilled.

cumulative plots of the yield for i boreholes out of *b* drilled will be as shown in Fig. 4.

If we assume that the need is Q = 20,000 l/h = 480 m3/d, we find that it is not likely that we can cover it if we drill just one or two wells. If we drill 4 wells we will probably need all 4 of them but without any safety margin. If we drill 8 wells we might cover the need with one but most probably with two and if we drill 16, one well will probably be sufficient.

Going back to Equation 4 we will analyse what that means for the economy. Assuming a water need of 20,000 l/h, the drilling cost per well of B = 20,000 SEK and the cost factors c = 3 and c = 5 we obtain the values of the cost function C given in Table 1.

Table 1. Optimisation of cost for a well system.

Number of drilled boreholes, b	Required number of connected boreholes, i	Cost function, C (SEK) c = 3	Cost function, C (SEK) c = 5
1	Not likely, i > b	-	-
2	Not likely, i > b	-	-
4	4	320,000	480,000
8	2 (1?)	280,000	360,000
16	1	380,000	410,000

The magnitude of the cost factor c can be debated. The results above are not too sensitive for that, as there is, in both cases, a minimum for 8 drilled exploratory wells. The analysis shows, however, that it is better to site and drill a fair number of exploratory wells in a well organised drilling campaign than to drill them one by one. This is further enhanced by the fact that an efficient siting process and better prices for drilling can be obtained for a campaign of several boreholes.

Conclusions

As Fagerlind (1988) pointed out, the crystalline bedrock of Sweden is an underestimated aquifer. The main reasons for this lie both in the conception that the crystalline bedrock is best suited for the rural water supply to single farms and other small uses, and that adequate strategies for groundwater prospecting have been lacking in these hydraulically inhomogeneous rocks. A certain amount of economic caution by those responsible for water supply in small communities has also prevented extensive exploratory drilling campaigns ("please drill the best wells first"). However, the importance of the approach lies in the fact that it is possible to follow a strategy that is based on a simple reasoning that most decision makers can accept.

Examples of the methodology proposed are the water works for the communities of Åmotfors, Värmland county, Sweden, and Rakkestad in SE Norway, where the author was heavily involved in the groundwater exploration. In both cases, groundwater from the fractured crystalline rocks was shown to be the most cost-effective system for the water supply. Finally, a word of caution – the approach does not tell us anything about the recharge conditions and water quality. These also have to be investigated, but since the well yield normally is the limiting factor in the Swedish hard rocks, the approach gives a good basis for strategic decisions.

Explanation of symbols used

Symbol	Unit	
B	(SEK)	The cost of drilling a well
b	(-)	Number of exploratory wells
c	(-)	Cost relation between drilling and connecting a borehole
CDF	(-)	Cumulative distribution function
C_f	(SEK)	Economic consequences of a failure
$F[Q]$	(-)	Distribution function for a sample of well yields
I	(SEK)	Cost of connecting a borehole to the supply system
i	(-)	Number of connected boreholes
N	(-)	Total number of wells in a sample
n	(-)	Sequential number of a well in an ordered sample
p_f	(-)	Probability of failure
Q	(l/h)	Well yield
Q_a	(l/h)	Average well yield of a sample
Q_m	(l/h)	Median well yield of a sample
Q_n	(l/h)	Yield of well n in a sequence
Q/s_w	(m²/s)	Specific capacity
R	(SEK)	Risk cost
R_V	(SEK)	Risk cost for a VLF-sited well
R_W	(SEK)	Risk cost for a dry well
T	(m²/s)	Transmissivity
V	(SEK)	Investigation or siting cost for a well
$\mu_{\log Q}$	(log [l/h])	Mean of logarithms of Q
$\sigma_{\log Q}$	(-)	Standard deviation of logarithms of Q
$\sum Q(i,b)$	(l/h)	Sum of the yield of the i best wells out of b drilled

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