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An introduction to Groundwater in Crystalline Bedrock

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Published by
Norges geologiske undersøkelse
(Geological Survey of Norway)
N-7491 Trondheim
Norway

ISBN 82 7386 100 1

Editor: Rolv Dahl

Design and print: Grytting AS

Recommended bibliographical reference for this volume:
Banks, D. and Robins, N. (2002): An introduction to Groundwater in Crystalline bedrock
Norges geologiske undersøkelse, 64pp
ISBN 82 7386 100 1

An introduction to Groundwater in Crystalline Bedrock

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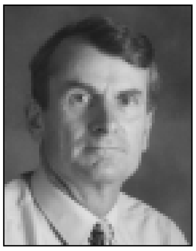
Holymoor

Nick Robins



Dr Nick Robins works with the British Geological Survey at Wallingford in Oxfordshire. He has extensive experience overseas on hard rock hydrogeology and has also been responsible for promoting interest in groundwater throughout Scotland and Northern Ireland. Other interests include groundwater in Chalk, in Quaternary deposits, mine water arisings and island hydrogeology, as well as groundwater management.

BGS
1835

Prologue

"Therefore a miner, since we think he ought to be a good and serious man, should not make use of an enchanted twig, because if he is prudent and skilled in the natural signs, he understands that a forked twig is of no use to him.....So if *Nature* or *Chance* should indicate a locality suitable for mining, the miner should dig his trenches there; if no vein appears, he must dig numerous trenches until he discovers an outcrop of a vein."

Agricola (1556). De Re Metallica.

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Cover photos:

1. *Shedding light on rock and water. Corbiere Lighthouse, Jersey, Channel Islands.* Photo by Joe Bates.
2. *Geologist Helge Skarphagen examines springs from gneisses exposed in a road cutting near Herefoss, southern Norway. Note that groundwater tends to emerge along the boundaries of pegmatites (light rocks).* Photo by David Banks. See Figures 25a,b for locations of sites mentioned in the text.
3. *Winter drilling, near Glasgow, Scotland.* Photo by Nick Robins.

Introduction

This small book has a big ambition. It aims to present practical information and a little philosophy to those involved in locating groundwater resources in areas underlain by crystalline bedrock, that is to say:

- Private groundwater users, potential well owners and water bottlers
- Local authorities
- Water companies and local water supply undertakings
- Drillers
- and Consultants

Each of these users will inevitably have different requirements and this volume may be considered to be a "maximum version", hoping to provide something for everyone. We have consciously mixed practical advice with some hydrogeological theory. Pick and choose the parts that you find useful. We have also provided a comprehensive reference list for those of you who wish to delve further into the subject. We aim to try to communicate Scandinavian findings (often largely published in Nordic languages) to an international audience. A Norwegian version of this book will be published later.

Almost all of Norway (Figure 25b) is underlain by some type of crystalline bedrock, and groundwater from such rocks is an important drinking water resource in rural areas, with over 100,000 bedrock wells thought to exist in a country with a population of somewhat over 4 million! In the United Kingdom, crystalline bedrock groundwater is probably an underused resource. Such rocks underlie much of the U.K.'s "Celtic Fringe" - Cornwall, Wales, Scotland and parts of Northern Ireland (see Figure 25a: Robins 1990, 1996a,b, Robins and Misstear 2000), as well as the Channel Islands (Robins & Smedley 1994, Blackie et al. 1998). A number of small British communities are almost entirely dependent on bedrock groundwater, such as several of the islands of Scilly (Banks et al. 1998e), and such groundwater provides an attractive alternative resource for other communities with a currently unsatisfactory water supply (Ellingsen & Banks 1993).

Bedrock aquifers are also exploited widely in tropical climes; in much of Africa and India, for example. There, however, the hydrogeological conditions are very different. The rocks are deeply weathered and rainfall recharge may be scarce. We will thus largely, though not exclusively, restrict ourselves to consideration of bedrock aquifers in the glaciated terrain of Norway and the northern U.K., where rock outcrops are relatively fresh and where the quantity of precipitation is depressingly abundant.

Groundwater in bedrock is a difficult resource to understand and pin down. It is very difficult to predict the yield or water quality of a new borehole with any degree of certainty. It is, however, possible to quantify the chances of being successful. We will attempt to guide you through the maze of fractures and uncertainties comprising a bedrock aquifer in such a way as to allow you to make an informed choice about its potential as a water resource.

1. What is Groundwater in Crystalline Bedrock?

There are, of course, two parts to this question:

1.1 What is Groundwater?

Groundwater is simply water that occurs in the ground; in the pore spaces between mineral grains or in cracks and fractures in the rock mass. It is usually formed by rain water or snow melt-water that seeps down through the soil and into the underlying rocks. Unfortunately, we have a very poor understanding of exactly what proportion of rainfall ends up entering a crystalline rock aquifer, although Robins & Smedley (1994), Blackie et al. (1998) and Olofsson (1993) shed some light on the problem. Sometimes, where a pumping well is close to a river or lake, a well may also "suck" river- or lake-water into the river banks and bed, so that it enters the adjacent sediments and rocks and becomes groundwater.

In recent sediments, such as sands or gravels, groundwater flows through the many pore spaces between sand grains. The *permeability* of the sediment is governed by the distribution of grain sizes in the sediment and the yield of a well in such deposits is relatively easy to predict.

1.2 What is crystalline bedrock ?

When we use the term *crystalline bedrock* (or *hard rock* or *bedrock*) in this book we refer to igneous or metamorphic rocks, such as granites, basalts, metaquartzites or gneisses, where the intergranular pore spaces are negligible and where almost all groundwater flow takes place through cracks and fractures in the rocks.

As fractures are not homogeneously distributed in the rock mass, and because the permeability of the fracture system is very sensitive to the fracture aperture and degree of fracture connectivity, it is very difficult to predict the yield of a well or borehole in crystalline bedrock. To be successful, we need to understand, as Agricola recommended in 1556 (see Prologue) both Nature (in the guise of geology) and the element of Chance.

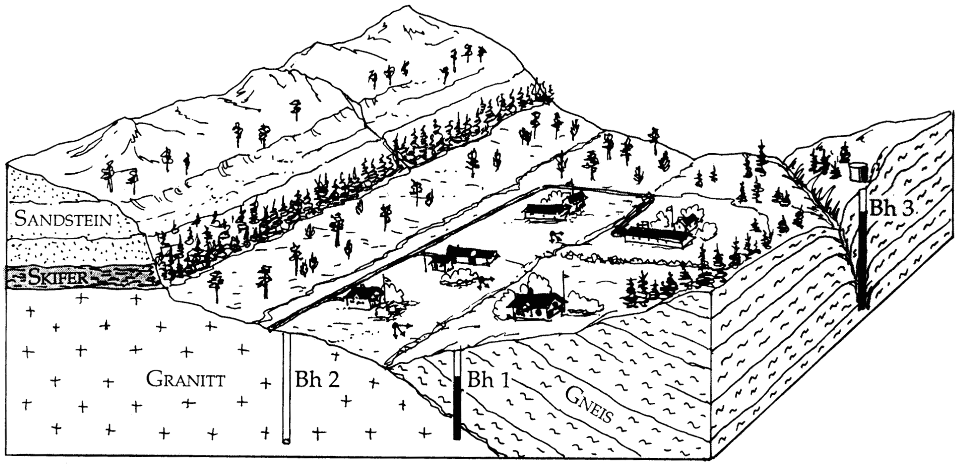
Further reading on groundwater:

Banks & Banks (1993a), Domenico & Schwartz (1990), Downing (1998), Ellingsen (1992a), Ellingsen & Banks (1993), Fetter (1994), Grundfos (1988), ISIS (1990), Knutsson (2000), Lloyd (1999), Olsson (1979), Price (1996), Robins (1990, 1996a,b), Todd (1990).

Hydrogeological Maps of Groundwater in Crystalline Rock

In Norway:
Ellingsen (1978), Rohr-Torp (1987).
In Sweden: Maps for each county, of which Karlqvist (1985) is an example.
In the UK: BGS (1990)

Figure 1. Schematic diagram of boreholes in a crystalline bedrock aquifer (from Eckholdt & Snilsberg 1992). Borehole 1 intersects a thrust fault between granite and gneiss and may thus have a good yield. Nevertheless, a stream receiving agricultural run-off runs along the fault outcrop, rendering the well vulnerable to pollution. Borehole 2 is less vulnerable but does not intersect a fracture zone and may thus have a lower yield. Borehole 3 is located up-gradient of polluting activities and intersects a fracture zone (expressed in the topography as a linear valley).



2. How to Get Groundwater out of the Ground

2.1 Springs

Under natural conditions, groundwater flows from regions of high groundwater *head* to low groundwater head. In practice, this usually means, from areas of high topography to the coast or to river valleys. Because rainfall is entering the bedrock aquifer, groundwater has to come out somewhere. Very often it emerges as springs in low-lying areas, which springs typically drain into streams or to the sea. Alternatively, groundwater may discharge directly into the bed of a stream. In either case, this groundwater baseflow maintains some degree of flow in the streams during prolonged dry weather.

Groundwater flow generally follows the gradient of the *water table*. This is essentially the surface separating water-saturated from unsaturated rocks. In other words, it is the level of water in the huge natural storage tank that an aquifer represents. In crystalline bedrock of low permeability, the water table reflects a subdued version of the natural topography. A spring discharge area can be thought of as a location where the water table intersects ground level.

Springs have historically been important water supplies. Very often they have been excavated, lined with timber, brick or stone and maybe covered by a roof or small house to form a well that is protected from contamination by surface run-off and animals. Today, they can still be ideal water supplies, provided that the land-use in the surrounding area is such that it does not contaminate the spring.

2.2 Wells and boreholes

Unfortunately, springs only occur at the whim of nature and topography. While, in historic times, "Mohammed has come to the mountain" and people have settled around springs, more recent

Figure 2. (a) A spring from Precambrian Hecla Hoek marbles, Bockfjord, Svalbard (photo: David Banks).

settlements have grown up in areas devoid of springs and it has been necessary to use technology to access the water table.

In many rocks (e.g. the Chalk of southern England), wells may be dug to considerable depths to reach the water table, but this is not possible in the hard crystalline rocks we are considering. In hard rock terrain, dug wells are at best dug down through superficial soils and sediments to reach a bedrock spring, or are excavated to a few metres depth by the judicious use of explosives.

In crystalline bedrock it is normal to drill a narrow (e.g. 150 mm diameter) borehole to several tens of metres depth below the water table. A pump may then be installed in the borehole. As it pumps out water, the water level in the borehole is depressed, lowering the groundwater head in the adjacent

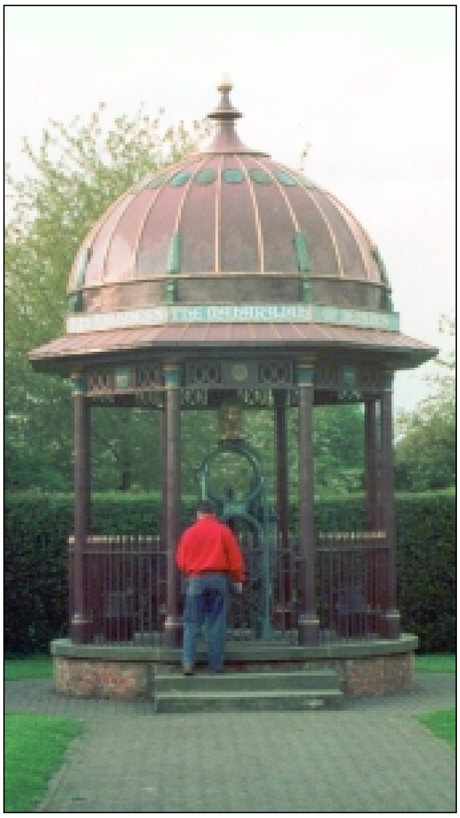


Figure 2. (b) The Maharajah's Well, Stoke Row U.K. A deep dug well in the Chalk, donated to the drought-stricken villagers of the Chilterns by the Maharajah of Benares (photo: David Banks).

Figure 2. (c) an artesian (overflowing) borehole in Carboniferous rocks at Catcraig, near Dunbar, Scotland. The photo features the geologist C.T. Clough and derives from c. 1908 (after Robins 1990). Printed with permission from British Geological Survey.

Figure 2. (d) A modern, angled borehole in granite, Hvaler Islands, Norway (photo: David Banks).

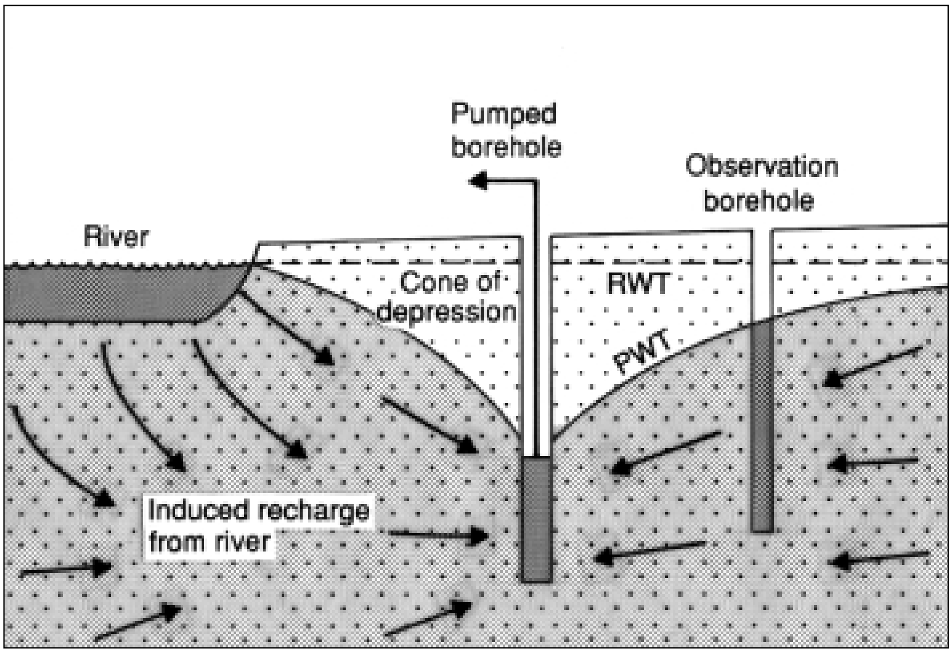


Figure 3. Groundwater flow in the vicinity of a pumped borehole, RWT = rest water table before pumping, PWT = water table during pumping (after Banks 1992d, printed with permission from Blackwell Science Ltd.).

aquifer. This causes groundwater flow to be induced towards the borehole and alters the natural groundwater flow and water balance in the aquifer. Provided we do not try to take too much water, the aquifer will settle down to a new dynamic equilibrium situation. This equilibrium will govern the long-term yield of the borehole. Usually, the long term yield is somewhat lower that the yield initially estimated by drillers on the basis of short-term testing, because in the latter case, the aquifer has not had time to reach its new equilibrium.

Further reading on spring protection, groundwater abstraction and borehole drilling

Clark (1988), Commonwealth Science Council (1987), Lloyd (1999), Skjeseth (1955), Waterlines, UNESCO (1984).

3. Well Drilling in Bedrock. Bingo, Poker or Chess?

It is tempting to regard well-drilling in bedrock as a game where the prize is a high quality, cheap water supply. But is it a game like chess, where a geologist's skill and knowledge can find the right borehole location and drilling strategy, or is it like bingo, where the outcome is solely determined by a random selection of unpredictable numbers? Most hydrogeologists would probably make a comparison with poker, which is mostly determined by a blind selection of random cards, but where a sensible playing strategy can increase our chances of success. And like hardened card-sharps, many professional hydrogeologists and water-witches have expended considerable effort in building up a reputation and bluffing that their "infallible systems" can overcome the random element. You, as customers and well-drillers, should treat such claims with great caution. Well drilling in bedrock always bears a greater or lesser risk: what we hydrogeologists can do is estimate that risk and quantify your chances of success.

3.1 Yield distribution curves

If we examine a particular rock type, such as the Iddefjord Granite of southern Norway, we can take the yields of all the boreholes in the granite and plot them on a cumulative probability diagram, such as that in Figure 4. From such a diagram, we can see that the median yield is 600 l/hr (follow the red line horizontally from the 50% mark to the curve for the Iddefjord Granite, and

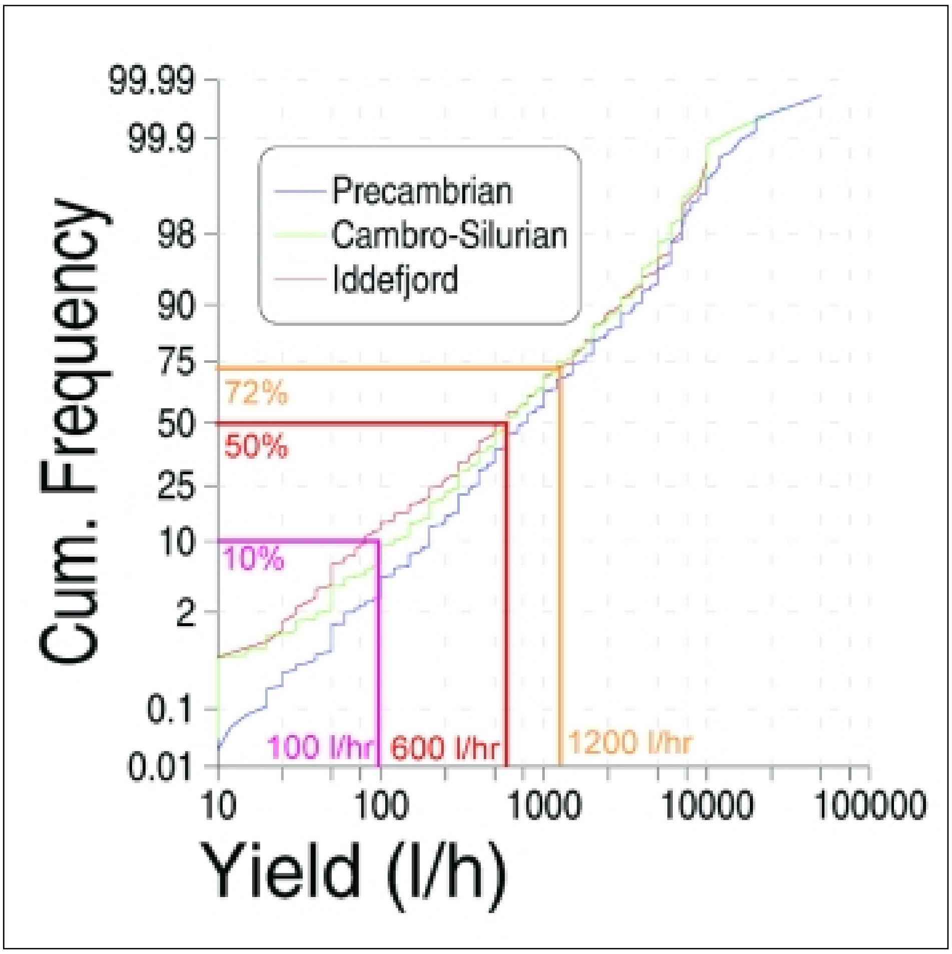


Figure 4. Cumulative frequency diagram showing yield distribution curves for Norwegian wells in the Iddefjord Granite ("Iddefjord"), Cambro-Silurian metasediments of the Norwegian Caledonian terrain ("Cambro-Silurian") and Precambrian gneisses ("Precambrian"). The added purple guide-line shows the approximate 10% yield for most lithologies (i.e. 90% of wells yield better than this figure). The red and orange guide-lines show the median yield (50%, red) and the 72% yield (orange) for the Iddefjord Granite. (Figure prepared by Geir Morland, using data from his thesis of 1997).

then vertically down to where it meets the x-axis at 600 l/hr). For a well drilled randomly in the granite, there is thus a 50% chance that a yield of 600 l/hr will be achieved. Similarly, we can assess the 25 % or 75 % yields. Or if, we wish to obtain 1200 l/hr we can see (by following the orange line vertically up from the 1200 l/hr mark to the Iddefjord Granite curve, and then horizontally across) that we have a 72 % chance of *not* achieving this amount (28 % chance of achieving it).

However, different rock types have different yield distribution curves. For example, Caledonian slates and schists of Norway have a lower yield distribution. This is because permeability is determined by fracture aperture, which is, in turn, governed by the rock's geomechanical properties. In fact, theory can show that a single fracture of 1 mm aperture can transmit more water than 900 planar, parallel fractures of 0.1 mm aperture (the transmissivity of such fractures is proportional to the *cube* of the aperture). Brittle, hard rocks, such as granite, are better able to sustain fractures with wide apertures than soft, deformable rocks, such as shales and slates.

A word of caution, however. The construction of such yield distribution curves pre-supposes the existence of an adequately comprehensive well database (data for the UK, for example, are not good enough to be used for this purpose). The yields submitted by drillers to such databases are often short-term yields. The sustainable, long-term yields may be considerably less. Additionally, dry boreholes may not have been reported at all, so inducing a positive spin to the statistics. It is also important also to know whether such databases include wells whose yield has artificially been stimulated by explosives or hydraulic fracturing (see Chapter 12).

3.2 Dowsers and Water-Witches

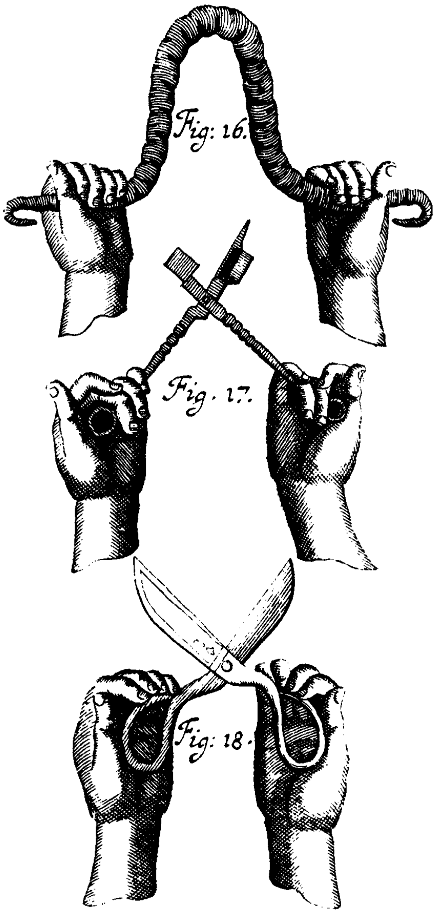
In hard-rock terrain, whether it be in Nigeria, Norway or Cornwall, dowsers are very often used to locate underground water and often seem to achieve similar results to hydrogeo-logists (see Text Boxes 1 and 2). The authors would venture to argue that this is not because of special prowess on behalf of the dowser, but often because of lacking insight on the part of the hydrogeologist. Dowsers will often try to locate water using forked twigs, bent clothes hangers, German sausages or pendula (Figure 5). Some may even ply their skills in the office over a map, without venturing into the terrain. The most honest dowsers will admit that it is difficult to conceive of a physical explanation for dowsing and that their skill is purely "spiritual". Agricola (1556) tells us that, "..wizards, who also make use of rings, mirrors and crystals, seek for veins with a divining rod shaped like a fork; but its shape makes no difference... for it is not the form of the twig that matters, but the wizard's incantations which it would not become me to repeat". It is likely that customers use dowsers for three reasons:

(i) They are cheaper than hydrogeologists
(ii) The subject of groundwater is difficult to understand and has always been associated with magic and mysticism – see Kubla Khan by Samuel Taylor Coleridge
(iii) In a field where the uncertainty of the result is so great, people feel drawn to mystical, rather than scientific, methods.

Nevertheless, some dowsers often seem to enjoy considerable success (although others, in the authors' experience, have cost their clients large sums of money). Why should this be so ? We offer two explanations:

(i) Most dowsers work for domestic clients where the water demand is only maybe 100 l/hr (most people use 300-400 l water every day). From Fig. 4, it will be seen that there is usually a c. 90 % chance of achieving this yield wherever one drills (follow the purple line from the 10% mark).

Figure 5.Three subtle and esoteric implements of the Hermetic art of dowsing: (a) the Knackwurst (or German Sausage); (b) the Liechtputze (or candle trimmer); (c) the Schneiderscheer (the tailor's scissors) (from Zeidler 1700, reproduced in Prokop & Wimmer 1985).



The Unacceptable Face of Dowsing

While we would argue that many dowsers are honest and have a good intuitive understanding of groundwater, a few dowsers can cause great distress to their clients. A Norwegian dowser is cited in the newspaper "Agder" (20/4/90) as saying (in English translation):

"The dowsing twig is on the way out, many say. The reason is supposedly that there is no scientific evidence for its many uses. In my opinion, that is utter rubbish....Hundreds of years before we began drilling boreholes, we used the forked twig to find water....No, the dowsing rod is by no means outdated."

Fair enough, one might say, but now things become macabre:

"the dowsing rod can be used .....to find all sorts of radiation. One thing's for sure. Many people have back problems due to "veins of water", which run under their house. The radiation from these can be drawn away by cheap and effective means."

Luckily, the solution to such problems does not involve digging up the foundations of the house to find the offending fracture. A simple "radiation damper" can be placed under the bed ! One may find such psychobabble amusing, but for some it is definitely not a joke. One of the authors was contacted in the UK by a distraught woman several years ago, whose husband was suffering a serious illness. In desparation, she turned to a dowser who told her that the illness was caused by a "groundwater vortex" beneath the property. So, as well as her uncertainty and distress over her husband's health, she now was being asked to consider moving house or some serious engineering geology. Our advice to you is the same at that we gave to her - "Stay away from such practicioners and trust your doctor. Dowsing and medicine do NOT mix".

(ii) Most dowsers operate in a geographically limited area. They get to know their terrain and gain an instinctive (often subconscious) feel for how the hydrogeology of the area functions.

Dowsers can, however, create and perpetuate grave misconceptions. On the Channel Island of Jersey, for instance, rainfall on the Pyrenees is reputed to flow underground and beneath the Bay of Biscay to rise up onto Jersey to discharge as springs 200 m above sea level. This is an improbable situation given the abundance of local rainfall and local recharge and the friction (or head loss) in driving the water underground all the way from the Pyrenees!

Our advice: for small domestic supplies, the best person to site a borehole is often a local well driller. He usually has a reasonable hydrogeological understanding and is able to assess the logistical and well-head protection factors that maybe far more important than the merely geological. For larger supplies, use the services of a hydrogeologist with experience of hard rock terrains.

Further Reading on Dowsing and Well Yield Statistics

Agricola (1556), Banks (1998), Henriksen (1995), Knutsson (2000), Morland (1997), Persson et al. (1985), Prokop & Wimmer(1985), USGS (1993), Wladis & Gustafson (1999).

Water Divining in Kosova

Our colleague Habib Meholli tells us about the following methods for locating groundwater in Kosova.

Method 1: *First catch your chicken. Remove its head with an axe. Let the headless chicken run around for a few minutes and where it falls motionless, dig your well.*

Method 2: *Provide your horse with salty feed. The horse will soon become thirsty. It will start looking around for water or damp soil. The place where it starts pawing the ground with its hooves may be a good place to dig a well, as groundwater is likely to be close to the surface.*

4. Where Should I Drill My Borehole?

The location of a borehole should take into account at least three factors:

(i) Logistical factors, including access
(ii) Vulnerability factors
(iii) Geological factors

For small domestic supplies, where it is possible to drill a well with satisfactory yield almost anywhere, the first two factors are likely to be paramount. For larger supplies, where the yield of the well is critical, finding a sensible geological location becomes increasingly important.

Logistics and access prevent a number of sources from being developed. In the North-Western Highlands of Scotland, the Precambrian limestones of the Durness and Assynt areas offer karst conditions and the prospects of high-yielding groundwater sources. These are little used simply because few people live in these areas.

4.1 Logistical Factors

It is necessary to consider:

- proximity of the borehole to the point of use, or
- proximity of the borehole to an existing water distribution network
- availability of a power supply for the pump.
- ease of access for a drilling rig.

4.2 Vulnerability Factors

Here, one should consider potential sources of pollution; the borehole should not be located in the immediate vicinity of:

- sewerage pipes, which may leak.
- pit latrines, cesspits, septic tanks, leaking tight tanks
- unbunded oil or paraffin storage tanks
- land subject to intensive use of organic or inorganic fertilisers, pesticides or other chemicals
- surface waters, particularly those known to be bacterially (or otherwise) contaminated
- the sea.

If possible, boreholes should be located at least 50 m (and preferably more, depending on aquifer characteristics and yield) up any topographical gradient from the above, or any other forms of contaminative human activity. In the case of surface waters, the location of a borehole will always be a compromise between the hydraulic advantages that location near a river or lake can offer (a plentiful source of groundwater recharge) and the disadvantages in terms of vulnerability to pollution.

Where an aquifer is covered by a significant thickness of low-permeability materials (e.g. boulder clay), less stringent conditions may apply to locating a borehole near to potential contaminant sources. There should be a presumption against such a location, however, unless it can be clearly demonstrated that the cover offers adequate protection.

It should be noted that the concept of source vulnerability also applies to existing surface water sources (eg. river or stream intakes). It is often these that, due to their vulnerability to pollution, need to be replaced by new groundwater sources. Care needs to be taken to ensure that the new groundwater well does not draw on the surface water, unless a sufficient residence time and "filtration effect" are present to ensure that water quality is safeguarded. Some fluvial sand and gravel deposits act as efficient water purifiers, however, and peat-stained river water may appear as crystal clear "bank infiltration" in a well only 5 m from the bank of the river (a fact now being exploited in the replacement of rural village supplies in Scotland, wherever peat stained surface water supplies existed and which are now outlawed by current EC legislation). Note, however, that appearances may be deceptive, and thorough chemical, bacteriological and hydraulic testing may be necessary before a source can be approved for supply. Fractured bedrock does not necessarily have these same powers of attenuation and purification and riverside boreholes into bedrock exposures should be avoided unless water treatment is available.

4.3 Geological Factors

As previously explained, the hydrogeological factors influencing well yield can be difficult to predict. Ideally one wishes a borehole to intersect one or more fractures of high groundwater *transmissivity*, which also are interconnected with a wider system of fractures or with superficial deposits that provide adequate groundwater *storage*. Most hydrogeologists agree that it is sensible to target:

- zones of intense fracturing. These may be vertical, horizontal or with an intermediate dip and are generally referred to simply as *fracture zones*.
- areas with a moderate (2-5 m thick) cover of superficial deposits (e.g. moraine). These deposits confer a degree of protection to the underlying bedrock groundwater, and may also act as a reservoir for water. The superficial deposits should not be too thick though - they are considerably more costly to drill through than the bedrock itself.

Further Reading on Well Location

Robins & Ball (1998).