by Gert Knutsson

Hydrogeology in the Nordic Countries

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Hydrogeology in the Nordic Countries is characterized by many types of aquifers and great differences in groundwater recharge. Fracture aquifers in crystalline, hard rocks are the most common type of aquifer with, in general, low fracture porosity and low well yields. The most productive crystalline rocks are the basalts in Iceland and the rapakivi granite in Finland. The fracture and fault zones have mostly high conductivity. Porous aquifers are found in various types of geology. The most porous ones are the lava-fields and the pyroclastic rocks in the active volcanic zone of Iceland, but glaciofluvial deposits such as eskers and deltas in Finland, Norway and Sweden, outwash plains in SW Denmark and sandurs in Iceland are also very porous and good aquifers, as are some sedimentary rocks in Denmark. The glacial till has, in general, low conductivity. Fractured porous aquifers in consolidated limestones and sandstones have high well yields in relatively young formations in Denmark and Scania in southern Sweden, but medium or low yields in older strata. Karst aquifers have limited extension, but there are some well developed ones in the Caledonian mountain range in Norway and Sweden. Geothermal water with a lot of springs and even geysers are common in Iceland and of great economic importance. The groundwater chemistry of the crystalline, hard rocks is notable for bacteria, brines and mixed water at great depths (more than 500 m) as well as high contents of arsenic, fluoride and radon in drilled wells in certain regions.

Introduction

Hydrogeology in the Nordic Countries is very varied due to many types of bedrock and superficial deposits as well as great differences in groundwater recharge. Initially, hydrogeological investigations were focused on aquifers for water supply (especially in Denmark, where 98% of the supply is groundwater). Later, they involved acquisition of general data by mapping and monitoring, and nowadays, they mainly concern the requirements of the European Union Water Framework Directive and special environmental goals. Knowledge has improved greatly also for other reasons over the last decades: for example, acidification research in the 1970s–1980s in Finland, Norway and Sweden; the Danish Environmental Research Programme 1992–2004; the Environment of the Subsurface and the Groundwater Programme in Norway in the 1990s; and ongoing research for geothermal and fresh water in Iceland. A lot of data and experiences have also been obtained during construction works such as mining and tunnelling. As regards Finland and Sweden, intensive

research on groundwater in crystalline rocks for the storage of nuclear waste has been carried out for the last 30 years (deep drillings, experiments such as tracer tests in underground laboratories, investigation of sites and modelling). New methods and advanced models have been developed in all these fields over the years. A challenge in the near future will be to manage the consequences of climate change on the hydrogeology (e.g. changes in recharge, flow, quality and sea-level).

Geology

The bedrock geology of the Nordic Countries (see other papers in this volume) is dominated by a large area of Precambrian, crystalline rocks—the Baltic Shield—in Finland, most of Sweden, S and SW Norway and the Danish island of Bornholm (as well as Karelia and the Kola peninsula in Russia). The Shield is flanked by the Caledonian mountain range in southwestern, central and northern Norway and the bordering areas of Sweden, and by sedimentary rocks in the east and south (above all in Denmark). Volcanic rocks occur in the Oslo Rift and further north-westwards on Iceland and the Faeroe Islands. On Spitsbergen (Svalbard), Caledonian rocks and most of the younger Phanerozoic formations are represented. Greenland is excluded in this short article.

Unconsolidated deposits of Quaternary age cover most of the glacially eroded bedrock, but there are widespread areas of bare rocks in the mountains and along the coasts, especially in Norway. The most common deposit is hard-packed sandy and silty till (moraine). The till cover is mostly only a few metres thick, but may be 50 m or more in some areas, especially in Denmark and parts of Scania in S Sweden, where the till is clayey. The most striking features from the Quaternary period are the elongated ridges of glaciofluvial deposits—the eskers, particularly in Finland, Sweden and SE Norway—as well as some vast deltas, the outwash plains in SW Denmark, the large sandurs in Iceland and the ice-marginal deposits, e.g. the Salpausselkä in S Finland and the Raerne in S Norway.

Sand and gravel deposits in river valleys all over the region and in the buried valleys in Denmark and Scania, S Sweden are also notable.

Climate and groundwater recharge

The Nordic Countries are situated in a border zone between different types of climate. Denmark, SW Norway and SW Iceland and the Faroes have a cold-temperate, maritime climate; S Sweden and Finland a cold-temperate continental climate and, further north, a boreal (or sub-arctic) climate. A great part of Iceland, Spitsbergen and some small areas of the high mountains in Norway and Sweden have a polar climate. All these climate types are characterized by higher annual precipitation than evapotranspiration, which means that the overall climate is humid. Precipitation is moderate (500–1000 mm/year) in most of the region, but high in a great part of Iceland and W and S Norway (1000–2000 mm/year) and very high in the western parts of the high mountains in Norway (2000–4000 mm/year) as well as in the southeastern parts of the glaciated,

high mountains in Iceland (up to 8000 mm/year, Rögnvaldsson et al., 2007). The eastern parts of the mountains in Norway and Sweden, as well as the highland north of Vatnajökull in Iceland, lie in rain-shadow with an annual precipitation of only 300–400 mm/year. Characteristic climate conditions during winter time mean that the lakes are ice-covered and that most of the precipitation accumulates as snow, which gives a period of intensive groundwater recharge during and after the snowmelt. The duration of the snow cover is one to two months in the southern parts of Norden, four to six months in the central parts, up to seven to eight months in the northern parts and still more in the high mountains, with the formation of glaciers, above all in Iceland, which has the largest glacier in Europe, Vatnajökull. Another significant feature of the winter climate is the frozen ground and even permafrost in small areas in the high mountains and in the extreme north. Permafrost increases the surface runoff and diminishes the infiltration capacity and the groundwater recharge. On Spitsbergen, permafrost with a depth of 100–400 m gives rise to confined aquifers and artesian conditions (Haldorsen et al., 1996).

A very important parameter for long-term groundwater recharge is the hydraulic conductivity of the soils, the unconsolidated deposits and the bedrock. The most permeable ground is the young lavas in Iceland, mostly covered only by moss. In contrast, almost impermeable areas with clayey soil and thick layers of clay on top of gneiss or schist can be found, for example, in central Sweden. Groundwater recharge in the Nordic countries has been studied in different types of climate, geology and topography, using various types of methods (Johansson, 1987; Englund et al., 1988; Olofsson and Knutsson, 2004). The methods used can be classified in three groups: recharge methods (e.g., tracers, modelling), response methods (e.g., groundwater level analysis, chloride balance, groundwater flow modelling) and discharge methods (e.g., isotope analysis and runoff measurements). Ideally, several independent methods have been tested in the same case. The highest figures of recharge are to be found in areas with high precipitation and very permeable ground, e.g., lava-fields in Iceland and gravel deposits in Norway (647 mm/year with $P = 1703$ mm/year in a glaciofluvial delta in N Norway; Storö, 1990). Fairly high figures (390 mm/year) are reported from areas with moderate precipitation (700–800 mm/year) in sandy-gravelly deposits in S Finland (Lemmälä, 1990) and SE Norway (Jørgensen and Østmo, 1990). Some figures of groundwater recharge in Sweden can be mentioned: in E Sweden, 280 mm/year in sandy soil but only 20 mm/year in “mixed” crystalline rocks with 10 m thick overburden of compact sandy till and 1.6 mm to 5.7 mm/year at a depth of 500 m in crystalline rock in the same area; in SE Sweden, 170–200 mm/year in an area of shallow sandy till, 160 mm/year in a thick esker surrounded by fine-grained sediments, 150 mm/year in the upper part of a moderate fractured granite and 5 mm/year at a depth of 450 m in the same granite; in SW Sweden, 100–120 mm/year in a heavily fractured gneiss with a thin, coarse overburden—the figures at depth are calculated by modelling (Olofsson and Knutsson, 2004). The recharge figures in Denmark vary between 170–193 mm/year in W Jutland to only 15–60 mm/year in E Denmark (Jacobsen, 1995).

Principal types of aquifers

Hydrogeology can be described in different ways. This short presentation focuses on the main types of aquifers.

Fracture aquifers

The hard crystalline rocks of the Precambrian, most of the rocks in the Caledonian mountain range and the basalts in Iceland and the Faeroes are typical fracture aquifers, where the storage and movement of water is restricted to fractures. Some types of compact limestone and quartzitic sandstones also belong to this type of aquifer. The total vol-

ume of these types of voids forms the fracture (secondary) porosity. This is dependent on the frequency, orientation and width of fractures and their mineral fillings, which in some areas stop up 70–80% of the conductive fractures (Hellä et al., 2005). Therefore, it varies strongly due to the composition, texture and structure of the rock and the geological history of the bedrock. The total fracture porosity is generally not more than 1%, but the effective (kinematic) porosity is still lower (0.1–0.0001%), as some fractures are disconnected or contain dead-end pits and therefore do not contribute to the groundwater circulation. Microscopic fluid flow inclusions (sometimes salt-rich) also exist and make up a closed system (Olofsson et al., 2001). In Iceland, the effective porosity of young, volcanic fractured rocks is generally very high, up to 5–10% (Einarsson, 2007).

There are hydrogeological differences between various types of crystalline rocks (Figure 1B). Granitic rocks with a high quartz content (acid) are often brittle and easily broken when stress conditions change, which results in well-developed, open fractures and a hydraulic conductivity (K) in the range of 10^{-7} to 10^{-5} m/s. The transport pathways in fracture networks have been studied in detail by tests with different types of tracers extending over 100 m at Äspö, SE Sweden (Winberg, 2007). Hydraulic connections have been established in fracture zones by interference tests stretching up to 1,600 m (by on-going tests almost 3,000 m) in the site investigations for the storage of nuclear waste at Forsmark, E Sweden (Gokall-Norman and Ludvigsson, 2007). A very good example of an abundantly fractured rock is the rapakivi granite in SE and SW Finland, which locally disintegrates to gravel (Lahermo, 1971). The highest well output in this granite is reported to be 13.8 l/s (UNESCO, 1982). The normal yield of wells in granitic rocks is much lower, for example, 600–2000 l/h in large parts of Sweden (SGU, 1995), which is sufficient for the supply of farms and country houses. High-grade metamorphic rocks such as strongly folded gneisses are generally very compact with few fractures and low values of K (10^{-9} to 10^{-7} m/s, Olofsson et al., 2001). The same low values are common for basic rocks such as gabbro and diorite, which normally are tough and can withstand fracturing. The yield of wells is very low in metamorphic rocks such as amphibolite, phyllite and schist, e.g., 100–500 l/h in Norway (Henriksen and Nielsen, 2001), which is in contrast to that in interglacial basalts on Iceland, which have primarily very well developed fracture systems and thereby much higher K -values (10^{-4} to 10^{-2} m/s, Sigurdsson 1986). All values of K and T are, however, highly scale-dependent.

Figure 1 Hydraulic conductivity from drillhole measurements (injection tests) in granodiorite (A), and calculated hydraulic conductivity for different types of crystalline rocks (B); curves of granites on the right, and of gneisses and basic rocks on the left (from Olofsson et al., 2001).

A special phenomenon in these glaciated regions is that glacial pressure and frost activity have enlarged existing fractures to a depth of 15–20 m. Furthermore, new fractures and even faults developed or were reactivated during fast melting periods of the land ice with rapid changes in the vertical load, especially in northern Fennoscandia (Lagerbäck 1979). The on-going postglacial isostatic uplift has most probably reactivated old fracture systems and maybe also created new ones. There seems to be a relationship between the degree of uplift and the yield of drilled wells (Rohr-Torp, 1998). In general the fracture frequency decreases rapidly with depth. And the apertures become narrower due to increasing lithostatic stress. These factors result in lower values of K , which also differ between various rock types (Figure 1). The variability is, however, significant and highly permeable fractures and fracture zones can be found even at great depths (Figure 1 A). Fracture zones in hard rock areas may have K -values in a range from 10^{-6} – 10^{-5} m/s up to 10^{-1} – 10^{-0} m/s in Iceland (Knutsson, 1997; Sigurdsson, 1986). Such zones are, of course, of great importance for the regional groundwater flow and for the location of drilled wells with high yield. If the zones are continuous over longer distances, yields of 5–15 l/s are obtained and the wells are used for the water supply of villages in the countryside.

The capacity of wells and the volume of groundwater flow in rocks, for example, leakage in connection with construction work, are also due to the hydraulic contact between fracture zones and groundwater reservoirs in the overburden (Olofsson et al., 2001) or even surface water. The most extreme conditions as regards leakage were met during the construction of railway tunnels, one in SE Norway (Romeriksporten) which drained a small lake, and another through the Hallandsås horst in SW Sweden. The latter heavily tectonized horst is known to have the most productive wells in hard rock in Sweden (SGU 1995). The north entrance of the tunnel caused drainage of 35 l/s and a lowering of the groundwater level by 100 m, which influenced springs, brooks and hundreds of wells (Anderberg, 1998).

Porous aquifers

Porous aquifers are characterized by storage and circulation of water in pores. The most porous ones are the postglacial lavas, with bands of scoria (volcanic slag) and pyroclastics rocks of the active volcanic zones in SW Iceland having K -values of 10^{-2} m/s to 10^{-0} m/s (Sigurdsson, 1986). Almost all net precipitation infiltrates and there is no surface runoff. There are around 25 very big springs (>5 m³/s) in Iceland (Figure 2). The largest spring area with a flow of 80–90 m³/s is located on the north shore of lake Thingvallavatn. Spring-fed rivers have a very even, high discharge and almost constant temperature with a mean discharge of 100 m³/s in Sog (Adalsteinsson et al., 1994).

Porous aquifers in more or less consolidated rocks are of considerable importance in Denmark and S Sweden (Scania). Tertiary sand deposits are the dominating aquifer in W Jutland. A loose, glauconitic sandstone (greensand) with overlying limestone, both of Cretaceous age, in Scania with high K -values and a transmissivity (T)-value about 5×10^{-3} m²/s (UNESCO, 1979) forms the most extensive and productive aquifer in Sweden (well yields 17–55 l/s, Gustafsson et al., 2005). This resource is used for the water supply of a medium-sized town and several villages and for intense irrigation.

Figure 2 Spring discharge from a porous lava on a tight basalt at Hraunfossar, Iceland (photo by Knutsson, G., 2005).

Very important porous aquifers are found in coarse-grained, unconsolidated deposits of Quaternary age, such as sand and gravel deposits of glaciofluvial and fluvial origin. The glaciofluvial deposits are of different genetic types. The best aquifers are found in the sub-aquatic type, which were deposited in rather deep water (below the highest shoreline) at the margin of the land-ice, where an esker or a delta was formed (Figure 3). These deposits consist of well-sorted boulders, gravel and sand with K -values of 10^{-4} to 10^{-2} m/s. The eskers have a thickness of 10–100 m, a width of 500–1000 m and are continuous over long distances, 100 km or more, i.e. aquifers of regional size. Some rather large springs occur (Källakadem, 2006) along these eskers (50–330 l/s) in Sweden and in the distal parts of vast deltas, for example, the Romerike delta in SE Norway with a total discharge of 850 l/s (Jørgensen and Östmo, 1990), the Kaldvellfaltet delta in N Norway with a total discharge of 355 l/s (Storö 1990) and the Brattforsheden delta in SW Sweden with a spring discharge of 200 l/s and a total discharge to a lake of 800 l/s (Källakadem 2006). Some large supraaquatic deposits such as the outwash plains in SW Denmark, the sandurs in Iceland and the ice-marginal deposits in Finland, Norway and Sweden are also very good aquifers (for example, Salpausselkä in Finland 450 l/s; UNESCO, 1982). The sand and gravel deposits along rivers with induced infiltration, especially in Norway, and in buried valleys in Denmark and

Figure 3 Conceptual figure of the geology and hydrogeology in a valley below the highest shoreline with a wave-washed, large esker (green) to the left, littoral sediments (orange) and glacial clay (yellow) in the valley and glacial till (light blue) on the slope of hard rock (red) to the right. Groundwater levels (lines), springs (glasses) and wells (shafts) are marked in different aquifers (Damberg, A., 2007; after SGU, 1975).

Scania are of great importance for the water supply of many small and medium-sized towns, e.g. flowing artesian wells in Jutland with a specific capacity of 20–30 l/s/m drawdown (UNESCO, 1979). Wells with high yield (several hundreds l/s) can be constructed in the coarse glaciofluvial deposits, but the natural recharge and/or the groundwater reservoirs are sometimes too small. Therefore artificial recharge is often arranged in Finland and Sweden. The steep and narrow eskers, formed supraaquatically above the highest shoreline, are not such good aquifers but, the resources are sufficient for the water supply of small villages.

The most frequent type of porous aquifer among the Quaternary deposits is various types of till. They are all more or less heterogeneous with a macrostructure of lenses or layers of sorted sand and gravel as well as bedding and fissility. Even clayey till in Denmark has deep fractures (6–8 m or more), which facilitate percolation down to the underlying aquifers, but thereby also the transport of nitrate and pesticides; this is creating a great pollution problem in Denmark (Björn, 2005). The bulk K-values of this fractured clayey till (Fredericia, 1990) are about the same as for the matrix of unsorted sandy or silty till (10^{-8} to 10^{-6} m/s). But the macrostructure and even the microstructure give a higher K in some parts of such till deposits or in special types of moraine terrain, especially in drumlins with spring discharge of 1–10 l/s. The highest discharges of springs in moraine terrain in Sweden have been found at the foot of large and high moraines, probably with sub-moraine layers of sand and gravel (e.g., in N Sweden 10–75 l/s; Källakadem, 2006). Such resources are, of course, of great interest for water supply and for mineral-water production, but normally the capacity of springs and dug wells in till is sufficient only for the water supply of farms and country houses.

Fractured porous aquifers

Consolidated limestones and sandstones, which have been slightly tectonized, develop a combination of fractures and pores, so-called “dual porosity”. The most productive aquifers of this type are the Tertiary (Danian) and Cretaceous limestones in Denmark and Scania. The Danian limestone is partly a calcarenite and partly a Bryozoan limestone, both containing chert. The K-values are low to medium, the highest values in the form of secondary porosity being due to fracturing (in the upper part) caused by glaciations (UNESCO, 1979). The median capacity of the wells is more than 17 l/s (up to 55 l/s) in some areas of Scania (Gustafsson et al., 2005). The aquifer is of utmost importance for the water supply of the capital region of Copenhagen, several towns and villages, and for irrigation. The Cretaceous White Chalk in N Jutland and some parts of Scania has very small interstitial pores, but has a high secondary porosity due to fracturing and karstification. So the K-values are high to medium and the T-values in the order of 10^{-2} m²/s around the city of Ålborg, which means that the White Chalk is an important aquifer in the region (UNESCO, 1979). The Permian basalt and romb-porphry (both with pores) in S Norway are good aquifers with well yields of normally 2–3 l/s, but up to 20 l/s. The Permian Brumunddal sandstone in the same region is a productive aquifer (20 l/s in one single well) as it has an effective porosity of 5% and is strongly fractured. It supplies the town of Brumunddal with water (Gaut and Ellingsen, 1992). Cambrian sandstones in S Sweden have K-values of around 10^{-6} – 10^{-5} m/s and well yields of up to 15 l/s, and these aquifers are used for water supply of villages (SGU, 1995).

Karst aquifers

Karst is developed by chemical solution and erosion of carbonate rocks along bedding planes, fissures and fractures. The solution process is not favoured by the cold-temperate and boreal climate in the Nordic Countries. Therefore, most of the karst is of moderate size, but even slightly developed karst is of importance for the percolation of water, for example, in the flat, bare limestone areas (so-called Alvar) of the islands of Gotland and Öland in SE Sweden as

well as for the secondary porosity and the K-values of carbonate rocks (see above). Typical features in karst are dolines and sink-holes on the ground, caves and tunnels underground and big springs at the out-let. These features form a very special hydrogeological system with fast drainage of great volumes of water during flood, but low flow of underground water during dry seasons. So the seasonal fluctuations in the discharge of springs are enormous (e.g., 1000 times higher after heavy snowmelt than during dry summertime in the Lummelunda karst system on the island of Gotland, Knutsson 1974). Small and moderate karst systems are found in very slightly tectonized limestone areas of Denmark, S Norway and S Sweden. In certain places, these aquifers are of importance for the local water supply and the karst springs for vegetation, especially fens with orchids. There are, however, some karst systems of larger size and of another type in the Caledonian mountain range. The host rock consists of regionally metamorphosed calcite and dolomite marbles in smaller and greater, steeply dipping bands, which are fractured. The karst is formed along the fractures in these bands. The largest karst region is found in Nordland county in N Norway, where the longest cave is more than 11 km and the deepest system 580 m. Most of the systems are active with flowing water, but there are also some fossil caves from the glacial time (Lauritzen, 1991). Rather large karst systems are found in the Swedish part of the mountain range. The river Bjurälven has a subterranean flow over a distance of more than 1 km just east of the border to Norway and an outflow in a spring with a discharge of several m³/s. Some well-developed, active karst systems with caves and spectacular springs are found around Lake Torneträsk in N Sweden (Figure 4). An exceptional type of karst in carbonate rocks has been discovered on Spitsbergen, the so-called thermoglacial karst. The main recharge area for such a karst aquifer is melt-water from a superimposed glacier, but the water chemistry and the stable isotopes—as well as the water temperature—indicate, that some part of the water in the springs originates from a deep, thermal brine. Sulphate-reducing bacteria are also present in the water of these springs (Lauritzen and Bottrell, 1994).

Figure 4 Karst springs at different levels on a slope in the Caledonian mountain range, Vadvetjåkka National Park, NW Lake Torneträsk, Lapland, Sweden, close to the border to Norway (photo by Damberg, A., 1992).

Geothermal water

Water, which percolates to considerable depths, is heated in relation to the geothermal gradient of the region. This means that in a volcanic region such as Iceland the water will reach a temperature of +100°C or more (dependent on pressure), already at a few hundreds meters depth, and that it will have a high content of solids and gases. The high temperature areas with steam in fumaroles and solfataras are located only in the active volcanic zones. Hot springs (+70–100°C) and geysers (see figures in other papers of this journal) are found in low temperature areas, which are spread over Iceland. The recharge for the hot springs is either based on convection in fairly permeable regions or on long-distance flow along fracture zones, even from the high mountains. Isotope studies have shown, that the recharge area is sometimes a glacier (Arnason and Sigurgeirsson, 1967), as for the thermoglacial karst on Spitsbergen. There are 600–700 large- or medium-sized hot springs in Iceland, including the probably largest hot spring in the world (150 l/s, +100°C). This spring water is used for domestic heating of two small towns (Einarsson, 2005). Geothermal heat is of great economic importance in Iceland. Several hot springs can be used directly for heating, but most hot water and steam come from deep drill-holes. The entire capital city of Reykjavik is heated in this way and, in total, 85% of the households in the country. The heat is also used for greenhouse warming and the production of electricity. Hot springs are also very popular for bathing and washing throughout the country; some have a natural content of carbon dioxide.

Geothermal water with a lower temperature than on Iceland occurs in deep-seated sedimentary strata in Denmark and S Sweden and is utilized for heating by means of heat pumps. The most successful example is the district heating of 35% of the households in the medium-sized town of Lund in S Sweden. This is achieved by pumping of water (+16–21°C) in four 700–750 m deep wells in Cretaceous sandstone and reinfiltration of the used water in five other wells. The system has been in function for 22 years. Another system with two very deep (2300 m) wells in Triassic sandstone and fairly hot water (+82–83°C) has recently been established for heating in the capital city of Copenhagen (Bjelm, 2007).

Groundwater chemistry in the Nordic Countries: notable characteristics

Good knowledge of both the chemistry of groundwater and pollution problems exists in the Nordic countries. There are well documented examples of saline groundwater in coastal areas, chloride pollution by de-icing salt from roads, other types of pollution from roads, air-fields and industries as wells as nitrate and pesticide pollution in agricultural areas. However, only some particularly noteworthy characteristics are mentioned here.

Bacteria, brines and mixed water at great depths

Intense investigations in connection with the underground storage of nuclear waste have mostly reached a depth of 500–700 m (maximum 1700 m). A few very deep holes have also been drilled for energy and scientific purposes to a maximum depth of 7,000 m in Sweden. And many drillings have been made for gas and oil in Denmark and Norway and for geothermal energy in Iceland.

Groundwater in the Precambrian crystalline rocks at depths below 1,000 m is saline (30,000–100,000 mg Cl/l) with a turnover-time of thousands to millions of years (Laaksoharju and Wallin, 1997). A very interesting discovery is that a special type of bacteria exists at these great depths. This type has carbon dioxide as a source of carbon and uses energy from hydrogen gas, which diffuses from very great depths (Pedersen, 2000). The microbes act as a catalyst for many of the inorganic reactions in groundwater, which would other-

wise not take place. The groundwater down to a depth of 1,000 m and close to the Baltic Sea is a mixture of the old saline groundwater and water of other origins. The complex groundwater evolution at depth is a result of many factors such as: a) the present-day topography, water-table and proximity to the Baltic Sea; b) past changes in hydrogeology related to glaciation and deglaciation, land uplift and repeated marine and fresh water regressions and transgressions; and c) organic or inorganic alteration of the groundwater composition caused by microbial processes or water/rock interactions. The major discovery is that changes resulting from glacial rebound and land uplift (hence hydrogeology) seems to have a major influence on the groundwater chemistry at depth (Blomqvist, 1999; Laaksoharju 1999; Pitkänen et al., 2004).

Certain quality problems

Radon in groundwater has been observed in springs for more than 100 years, when radioactive water was supposed to be beneficial. Some information on radon in groundwater was gathered during the time of uranium prospecting in Sweden in the 1950s. However, most data has been collected during the last few decades for radiation-protection purposes. Today there is also an interest in the radium and uranium content in groundwater. The highest concentrations of radon have been found in water from drilled wells in Precambrian young granites and pegmatites (Knutsson and Olofsson, 2002), and in Norway also in a Permian granite around Oslofjord (Banks et al., 1998). The maximum values hitherto observed are 77,500 Bq/l in S Finland (Leveinen et al., 1998), 57,000 Bq/l in SW Sweden (Åkerblom and Lindgren, 1997) and 31,900 Bq/l in SE Norway (Banks et al., 1998). A regional study in the county of Bohuslän (SW Sweden) showed that 31% of the drilled wells had a radon concentration above 1,000 Bq/l (the mandatory limit for private wells in Sweden), while another study in the county of Stockholm showed that 11% of the wells had values above 1,000 Bq/l. However, great local differences were found, mostly related to the type of bedrock (Knutsson and Olofsson, 2002). The analysis of radium and uranium in groundwater in Sweden identified relatively high concentrations of uranium, but mostly low concentrations of radium. The highest values of uranium (100–300 µg/l) were found in drilled wells in the same type of bedrock as for high radon; 23% had values above the mandatory value 15 µg/l (Ek, 2005). The maximum value in Norway was recorded at 750 µg/l and 18% were above 20 µg/l (Frengstad et al., 2000), but the most extreme value of uranium in Nordic groundwaters was found in S Finland: 12,400 µg/l (Leveinen et al., 1998). The health risk for uranium is, however, not so much the radiation problem as the serious effect of uranium as a heavy metal on the kidney function.

Acidification is a natural process, which has gone on for a long time in poor, podsollic soil on acid overburden and bedrock, whereby shallow groundwater with low alkalinity also has developed low pH. However, the Nordic Countries (except in Iceland) have also experienced a period of increased acidification due to acid rain. Time-series indicate that some types of groundwater have changed their composition, as has been shown in the research catchment of Birkenes in Norway. Alkalinity and pH decreased significantly in drilled wells in sandy aquifers in SW Denmark during 1950–1986, as it did in some Finnish and Swedish shallow wells and springs in regions with acid deposits and rocks in the 1970s and 1980s; these changes were accompanied by increased concentrations of Al, Ca, Mg and SO₄ (Knutsson 1994). The reduction of acid precipitation has now stopped the acidification, and some groundwaters have even recovered.

Fluoride is a common component in groundwater from crystalline rocks and in volcanic areas, for example, in hot springs on Iceland. There are some similarities in the geologic distribution of fluoride and radon in crystalline rocks, especially to young granites. Lahermo et al. (1990) found the strongest correlation between fluoride and rapakivi granite in SE Finland, with the highest value of 5.8 mg/l, but in general 15–17% were above the drinking water limit of 1.5 mg/l (Leveinen et al., 1998). The highest value in Norway

(8.26 mg/l) is, however, reported from mafic rocks in W Norway. 16% of the drilled wells in Norway had values above the drinking water limit (Banks et al., 1998) compared with 25% of the drilled wells in Sweden (Aastrup et al., 1995).

Heavy metals such as As, Cd and Pb are observed in groundwater in crystalline rocks, especially those with pyrite and sulphide mineralizations. But heavy metals are also found in groundwater in volcanic and some sedimentary rocks, for example, alum shale. In SW Finland, 15% of the investigated drilled wells had a concentration of As above the drinking water limit of 10 µg/l, with values up to 1–2 mg/l (Leveinen et al., 1998). In Norway, 1.5 % of the drilled wells had values above the limit (Frengstad et al., 2000), and in Sweden 5%, but 2% had values above 100 µg/l and still higher values were recorded in a sulphide mine district in N Sweden (Socialstyrelsen, 2006). Surprisingly, arsenic has also been found in several production wells in sedimentary rocks and Quaternary deposits in Denmark. Heavy metals may also derive from pollution and it is possible to distinguish the real origin of some of these metals by means of analysis of the isotope ratios, for example, $^{206}\text{Pb}/^{207}\text{Pb}$.

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References

- Aastrup, M., Thunholm, B., Johnsson, J., Bertills, U., and Berntell, A., 1995, Groundwater chemistry in Sweden: Swedish Environmental Protection Agency Report, 4416, pp.52.
- Adalsteinsson, H., Jónasson, P.M., and Rist, S., 1992, Physical characteristics of Thingvallavatn, Iceland: Oikos 64, pp. 121–135.
- Anderberg, J., 1998, The Hallandsås railwaytunnel – geology and groundwater, in Knutsson, G., ed., Hardrock hydrogeology of the Fennoscandian Shield: NHP Report, No. 45, pp. 5–12.
- Árnarson, B. and Sigurgeirsson, Th., 1967, Hydrogen isotopes in hydrological studies in Iceland: Isotopes in Hydrology, IAEA, pp. 365–382.
- Banks, D., Frengstad, B., Midtgård, Aa. K., Krog, J. R., and Strand, T., 1998, The chemistry of Norwegian groundwaters I: The Science of the Total Environment, 222 (1998), pp.71–91.
- Bjelm, L., 2007, Personal communication.
- Björn, C., 2005, Grundvand – Pesticider og Grundvand (Pesticides and groundwater). Det strategiske miljøforskningsprogram 1992–2004: Aarhus Universitetsforlag, pp. 89–98.
- Blomqvist, R., 1999, Hydrochemistry of deep groundwater in the central part of the Fennoscandian Shield: Geological Survey of Finland, Report YST-101, pp 41.
- Einarsson, Kr., 2007, Personal communication.
- Einarsson, Th., 1994, Geology of Iceland, Rocks and Landscape: Mal og menning, Reykjavik, pp. 309
- Ek, B.-M., 2005, Uran i dricksvatten – nya rekommendationer (Uranium in drinking water – new recommendations): Sveriges geologiska undersökning, Grundvatten, 1-2/05, pp. 10–12.
- Englund, J.-O., Knutsson, G., and Soveri, J., eds, 1988, Studies on groundwater recharge in Finland, Norway and Sweden: NHP Report, No 23, Helsinki, pp 117.
- Fredericia, J., 1990, Saturated hydraulic conductivity of clayey tills and the role of fractures, in Haldorsen, S. ed., Hydrogeological properties of Nordic Tills: NHP Report, No 25, pp.67–74.
- Frengstad, B., Midtgård Skrede, Aa. K., Banks, D., Krog, J. R., and Siewers, U., 2000, The chemistry of Norwegian groundwaters III: The Science of the Total Environment, 226 (2000), pp. 21–40.
- Gaut, A. and Ellingsen, K., 1992, Grunnvannsmuligheter i Norge (Prospects of groundwater in Norway): Norges Geologiske Undersøkelse, Skrifter 106, GIN-VEILEDER nr 8.
- Gokall-Norman, Kr. and Ludvigson, J.-E., 2007, Forsmark site investigation. Hydraulic interference test in borehole HFM14: SKB P-06-196, pp. 172.
- Gustafsson, O., Thunholm, B., Gustafsson, M., and Rurling, S., 2005, Description to the Hydrogeological map of Skåne county: SGU Serie Ah nr 15, pp. 52.
- Haldorsen, S., Heim, M., and Lauritzen, S.-E., 1996, Subpermafrost groundwater, Western Svalbard: Nordic Hydrology, 27 (1996), pp. 57–68.
- Hellä, P., Tammisto, E., and Ahokas, H., 2005, Hydraulic conductive fractures and their properties in boreholes KR4 and KR7 - KR10 at Olkiluoto site, Eurajoki, in Rönkä, E., Niini, H. and Suokko, T., eds, Proceedings of the Fennoscandian 3rd Regional Workshop on Hardrock Hydrogeology: The Finnish Environment. 790, pp. 79–85.
- Henriksen, H. and Nielsen, J.T., 2001, Innføring i hydrogeologi (Introduction to hydrogeology), Undervisningskompendium ANF 16/2001: Høgskulen i Sogn og Fjordane, pp. 252.
- Jacobsen, O.S., ed., 1995, Grundvandsovervågning (Monitoring of groundwater) 1995: Danmarks og Grönlands Geologiske Undersøgelse, København, pp. 56–58.
- Johansson, P.-O., 1987, Methods for estimation of direct natural groundwater recharge in humid climates (dissertation): Royal Institute of Technology, Dept of Land Improvement and Drainage, Meddelande Trita-Kut 1045, pp. 107.
- Jørgensen, P. and Östmo, S.R., 1990, Hydrogeology in the Romerike area, Southern Norway: Nor. geol. unders. Bull. 418, pp. 19–26.
- Knutsson, G., 1974, Tracing water flow in organic soils and in some karst areas of Sweden, in Nordisk Hydrologisk Konferens, 1974, Aalborg 23–26 juli, Bind II, pp. 488–507.
- Knutsson, G., 1994, Trends in the acidification of groundwater, in Kovar, K. and Soveri, J., eds, Groundwater Quality Management: IAHS Publ. no. 220 (1994), pp. 12.
- Knutsson, G., 1997, New findings on the hydrogeology of hard rocks in Sweden, in Bochenska, T. and Stasko, S., eds, The second workshop on Hardrock Hydrogeology of the Bohemian Massif: Acta Universitatis Wratislaviensis, No 2052, pp. 21–31.
- Knutsson, G. and Olofsson, B., 2002, Radon content in groundwater from drilled wells in the Stockholm region of Sweden, NGU-BULL 439, (2002), pp. 79–85.
- Källakademien, 2006, Källor i Sverige (Springs in Sweden): AB Svensk Byggtjänst, Stockholm, pp. 256.
- Laaksoharju, M., 1999, Groundwater characterisation and modelling: problems, facts and possibilities (dissertation): Royal Institute of Technology, Division of Land and Water Resources, TRITA-AMI-PHD 1031, pp. 130.
- Laaksoharju, M. and Wallin, B., eds, 1997: Evolution of the groundwater chemistry at the Äspö Hard Rock Laboratory: Proceedings of the second Äspö International Geochemistry Workshop, Äspö, Sweden, June 6–7, 1995. SKB, Stockholm, Sweden.
- Lagerbäck, R., 1979, Neotectonic structures in northern Sweden: Geologiska Föreningens Förhandlingar (GFF), Volume 100, pp. 263–269.
- Lahermo, P., 1971, On the hydrogeology of the coastal region of southeastern Finland: Geological Survey of Finland Bullentin, 252, pp. 44.
- Lahermo, P. Ilmasti, M. Juntunen, R., and Taka, M., 1990, The hydrochemical mapping of Finnish groundwater: Geological Survey of Finland, pp. 66.
- Lauritzen, S.-E., 1991, Karst resources and their conservation in Norway: Norsk geogr. Tidsskr. Vol. 45, pp. 119–142.
- Lauritzen, S.-E. and Bottrell, S., 1994, Microbiological activity in thermoglacial karst springs, South Spitsbergen: Geomicrobiology Journal, Volume 12, pp. 161–173.
- Lemmela, R., 1990, Water balance of a sandy aquifer at Hyrylä in Southern Finland: Annales Universitatis Turkuensis Ser. A 73, pp. 105.
- Leveinen, J., Rönkä, E., and Karro, E., 1998, Groundwater quality – a constraint of groundwater exploration in hard rock areas, in Knutsson, G., ed, Hardrock hydrogeology of the Fennoscandian Shield: NHP Report, No. 45, pp. 79–89.
- Olofsson, B. and Knutsson, G., 2004, Some hydrogeological methods for determining groundwater recharge and groundwater flow, in Nuclear waste state-of-the-art reports 2004: Swedish Government Official Reports SOU 2004:67, pp. 225–272.
- Olofsson, B., Jacks, G., Knutsson, G., and Thunvik, R., 2001, Groundwater in hard rock – a literature review, in Nuclear waste state-of-the-art reports 2001: Swedish Government Official Reports SOU 2001:35, pp 77.
- Pedersen, K., 2000, Subterranean microorganisms and their influence on the hydrochemical conditions in hardrock aquifers, in Knutsson, G., ed, Hardrock hydrogeology of the Fennoscandian Shield: NHP Report, No. 45, pp. 79–89.

- Pitkänen, P., Partameis, S., and Luukonen, A., 2004, Hydrogeochemical interpretation of baseline groundwater conditions at the Olkiluoto site: POSIVA 2003-07, pp.159.
- Rohr-Torp, E., 1988, Postglacial isostatic uplift and ground water potential in Norwegian hard rocks, *in* Knutsson, G., ed, Hardrock hydrogeology of the Fennoscandian Shield: NHP Report, No. 45, pp. 157–164.
- Rögnvaldsson, Ó., Jónsdóttir, J.F., and Ólafsson, H., 2007, Numerical simulations of precipitation in the complex terrain of Iceland – Comparison with glaciological and hydrological data: Meteorologische Zeitschrift, 16.1, pp. 71–85.
- SGU, 1995, Grundvattnet i Sverige (Hydrogeological map of Sweden), skala 1: 1 000 000, serie Ah nr 17.
- Sigurdsson, F., 1986, Hydrogeology and groundwater on the Reykianes peninsula: Jökull, 36, pp. 11–28.
- Sigurdsson, F., 1993, Groundwater chemistry and aquifer classification in Iceland: Memoires of the XXIVth Congress of IAH, Ås, Norway, Part 1, pp. 507–518.
- Socialstyrelsen, 2006, Dricksvattenrening med avseende på arsenik (Treatment of drinkingwater as regards arsenic): Artikel nr 2006-123-10, pp. 47.
- Storrö, G., 1990, Hydrokemi, hydrologi og geologi i Kaldvellfeltet (Hydrochemistry, hydrology and geology of the Kaldvellfeltet): NTH, Trondheim, pp 199.
- UNESCO, 1977, 1979, 1980, 1982, 1985, Explanatory notes Sheet C4 Berlin, C3 Oslo, B2 Island, D3 Stockholm, C2 Trondheim and D2 Haparanda. International hydrogeological map of Europe, UNESCO, Paris.

- Winberg, A., ed, 2007, TRUE Block Scale Continuation Project: SKB Technical Report TR-06-42.
- Åkerblom, G. and Lindgren, J., 1997, Mapping of groundwater radon potential: European Geologist 5, pp. 13–22.

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