The role of some regional factors in the assessment of well yields from hard-rock aquifers of Fennoscandia

Helge Henriksen

Abstract The attributes of about 13,600 hard-rock water wells were arranged in three profiles parallel to gradients of typical regional factors. These factors are thought to be of importance to groundwater yield from wells in the Fennoscandian crust and were subjected to a statistical analysis. The regional factors comprise annual rate of postglacial crustal uplift and annual average precipitation, whereas soil type, soil depth, and bedrock type are considered sub-regional and local factors. There is no clear trend in well yield along the regional gradients. The results of the statistical analysis indicate that for the typical regional variables, the rate of postglacial uplift and average annual precipitation explain not more than 11% of the observed variation in well yields. Some of these factors, and other factors not included in this study, work in opposite directions and may cancel each other out. It is concluded that other, more local factors, such as well depth, proximity to fracture-related lineaments and topography, have a greater influence on well yields in this area.

Résumé Les propriétés d'environ 13,600 puits d'extraction d'eau souterraine dans le socle ont été réparties selon trois profils disposés perpendiculairement aux gradients de facteurs régionaux typiques. Ces facteurs sont considérés comme étant importants pour les rendements des puits dans le bouclier fenno-scandien et ont été soumis à une analyse statistique. Les facteurs régionaux sont le taux de soulèvement postglaciaire et les précipitations moyennes annuelles, alors que le type et l'épaisseur de sol, le type de substratum sont des facteurs sub-régionaux et locaux. Il n'existe pas de tendance dans le rendement des puits selon les gradients régionaux. Les résultats de l'analyse statistique indiquent que pour les variables régionales typiques, le taux de soulèvement postglaciaire et les précipitations moyennes annuelles n'expliquent pas plus de 11,2% de la variation observée du rendement des puits. Certains de ces facteurs, ainsi que d'autres non pris en compte dans cette étude, jouent dans des directions opposées et peuvent s'annuler l'un l'autre. En conclusion, d'autres facteurs, plus locaux, tels que la proximité de linéaments corrélés aux fractures et la topographie peuvent avoir une grande importance pour le rendement des puits dans cette région.

Resumen Se ha recogido los atributos de aguas subterráneas con 13.600 años de antigüedad en tres perfiles perpendiculares a los gradientes de los factores regionales típicos, las cuales son captadas por pozos perforados en rocas duras. Se cree que estos factores tienen importancia en el rendimiento de los pozos realizados en la corteza de Fenoscandia, y han sido analizados estadísticamente. Los factores regionales comprenden la tasa anual de alzamiento postglacial y la precipitación media anual, mientras que el tipo y la profundidad del suelo, y el tipo de roca madre, son tratados como factores sub-regionales y locales. No se aprecia una tendencia clara en el rendimiento de los pozos a lo largo de los gradientes regionales. Los resultados del análisis estadístico indican que, para las variables regionales típicas, la tasa de alzamiento postglacial y la precipitación media anual explican como mucho el 11,2% de las variaciones observadas en el rendimiento de los pozos. Algunos de estos factores, así como otros no incluidos en el estudio, son de signo opuesto y pueden llegar a compensarse. Se concluye que factores diferentes, de escala más local, tales como la proximidad a lineamientos correlacionados con fracturas o la topografía, pueden afectar de forma más importante al rendimiento de los pozos en esta zona.

Keywords Crystalline rocks · Fennoscandia · Groundwater flow · Groundwater statistics · Geographic information systems

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Introduction

Well yields in crystalline hard-rocks possessing only secondary porosity and permeability are difficult to

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predict and display a wide variation. Well yields may differ from one rock type to another and, even for a given rock type, the yields of adjacent wells may differ by many orders of magnitude.

These differences are caused by a combination of both independent and interrelated factors that may influence the hydrological and geological characteristics of the well sites. These factors include topography, rock type, overburden, structural position, joint and fracture characteristics, the amount of recharge from precipitation, runoff, and the recharge from surface-water bodies (Brook 1988; Henriksen 1995; Mabee 1998). Some of these factors are important at the local scale, others at the subregional scale, and still others at the regional scale. Regional-scale factors include neotectonic activity, which can produce gradual changes in rock transmissivity, with the highest values in areas of the most intense neotectonic activity (Krásný 2000).

In Fennoscandia, the isostatic response during the Holocene, caused by the unloading of the Late Weichselian ice sheet, is considered an important regional factor for well yield (Rohr-Torp 1994; Morland 1997). This unloading is thought to contribute to regional differences in the intensity of postglacial crustal stresses and rock fracturing. However, in Fennoscandia, other factors such as recharge by precipitation and the yearly average amount of runoff also display a regional variation that may affect well yield.

In addition, subregional and local factors, such as thickness of Quaternary cover, flatness of topography, distances to lineaments, and rock type always influence the well yield at a particular location. Thus, simple correlation plots between well yield and one independent variable (e.g., annual uplift rate or thickness of overburden), with other factors considered as constants, will not reveal the relative importance of all the factors that actually influence the well yield. Moreover, the one selected variable may be modified by other factors that are not considered. In such situations, analysis of variance (ANOVA) methods that examine the effects of more than one independent factor should be used to explain such complex relations as the well yield of crystalline rocks.

The purpose of this paper is to evaluate the importance of regional and subregional factors on well productivity in Fennoscandian hard-rock aquifers. The variables considered are annual isostatic uplift rate, average annual precipitation, bedrock type, soil type, and soil depth. They were chosen because raw data on these factors are available from governmental institutions, and could be readily imported into a GIS platform for further analysis.

Overview of Hydrogeological Factors

Postglacial Rebound

During the Quaternary, the Fennoscandian land area was covered by ice sheets several times. The latest Weichselian (=Late Vistulian) glaciation had its maximum between 22,000–29,000 B.P. (Sejrup et al. 1994; Bergstrøm 1999). Proposed models for the Scandinavian ice sheet during the Weichselian glacial maximum advocate a domal-shaped ice cap centered in the Gulf of Bothnia (Fig. 1) with a maximum ice thickness of 2,000–3,000 m (Denton and Hughes 1981; Lambeck et al. 1990). The final deglaciation of Scandinavia began about 12,000 B.P., and by 8,500 B.P. most of Scandinavia was ice-free. The Late Weichselian ice load caused a considerable depression of the Fennoscandian lithosphere. The associated glacio-isostatic recovery has caused the Fennoscandian land area to rise, and the highest shoreline (marine limit) is now at approximately 285 m above the present sea level.

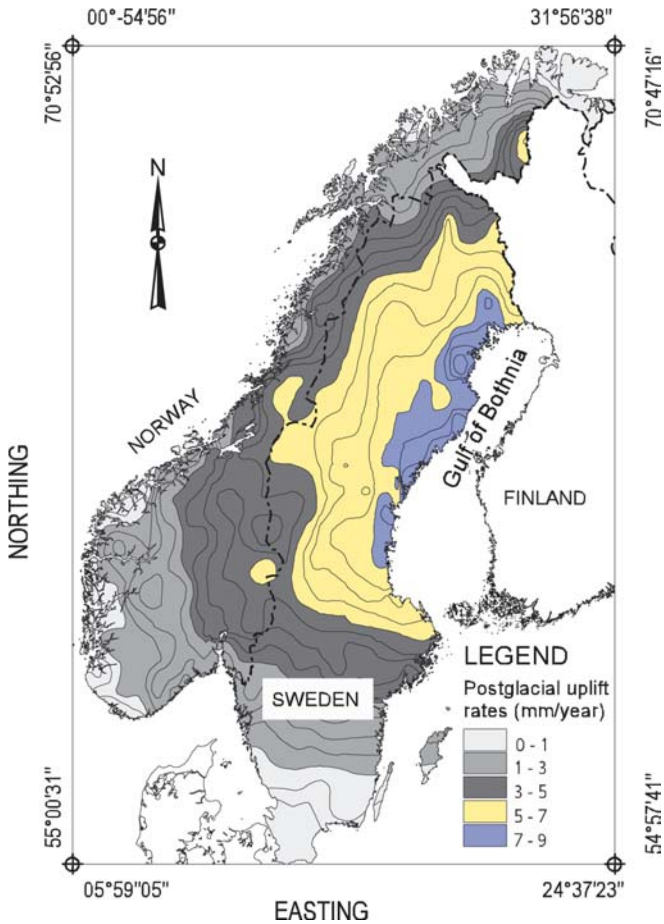

Fig. 1 Isobases for the apparent current rate of postglacial uplift in mm/year for Fennoscandia. Isopleth interval is 0.5 cm/year. After Dehls et al. (2000). *UTM* Universal Transverse Mercator projection

The uplift pattern based on traditional leveling surveys (e.g., Mörner 1980; Bakkelid 1992; Dehls et al. 2000) and time series of geographic positioning system (GPS) crustal velocities (Milne et al. 2001) are in agreement with theoretical models (Gudmundsson 1999; Fjeldskaar et al. 2000) and demonstrate an ongoing regional domal rebound with vertical uplift rates of 0–9 mm/year. The highest uplift rates are found beneath the center of the former ice sheet in the Gulf of Bothnia (Fig. 1).

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GPS observations from the BIFROST-network (Milne et al. 2001) also indicate that the central Fennoscandian land mass is at present subject to horizontal extension; with horizontal crustal GPS velocities increasing radially with distance from the uplift center in the Gulf of Bothnia. It has been proposed that extensional crustal stresses related to the postglacial rebound are capable of fracture initiation and/or reactivation, hence affecting the hydraulic conductivity and well yield of the rocks in the upper crust (Rohr-Torp 1994; Gudmundsson 1999). Based on well data from Norwegian hard-rock boreholes, Rohr-Torp (1994) and Morland (1997) suggested a positive correlation between well yield and uplift rate. Gudmundsson (1999) has modeled a positive correlation between potential tensile and compressive stresses and postglacial uplift.

Precipitation and Runoff

Annual average precipitation show a distinct west to east zonal pattern with values of > 2,000 mm per year in western Norway to about 700 mm in the northeastern parts of Sweden (DNMI 1993; SMHI 1995). However, south-to-north climatic gradients are less distinct, and in southeastern Norway and south-central Sweden the annual average precipitation varies between ~700–1,000 mm.

A similar zonal pattern is found for the annual runoff (Nordseth 1987; NVE 1987; SMHI 1995), which exhibits the largest values along the coast of western Norway (>150 l/s per km^2) and the smallest values along the coast of eastern Sweden (1–4 l/s per km^2).

Net precipitation is the most significant regional hydrological factor for groundwater recharge. As for precipitation, it shows a distinct west-to-east zonal pattern with values of about 1,600 mm in western Norway to about 600 mm in northern Sweden. The south–north gradients are less clear, but net precipitation varies from about 200 mm in southern Sweden to about 400 mm in northern Sweden (SMHI 1995).

Values for groundwater recharge and groundwater runoff from hard-rock environments in Scandinavia are few, and restricted to local small catchments. Values are in the range of 0.15–3 l/s per km^2 (Anderberg 2000; Knutsson G., Royal Institute of Technology, Sweden. Personal communication 06.11.2002). Groundwater recharge in granitic terranes in Canada has been estimated to be 5 mm, or about 1% of the annual precipitation (Thorne and Gascoyne 1993). In hard-rock terranes in the Bohemian massif in the Chech Republic, a variation in groundwater runoff from 1–15 l/s per km^2 is ascribed to differences in climate/altitude and geomorphic settings. (Krásný 2002).

Bedrock Geology

The geographic region of Fennoscandia consists of Norway, Sweden, Finland, the Kola Peninsula, and

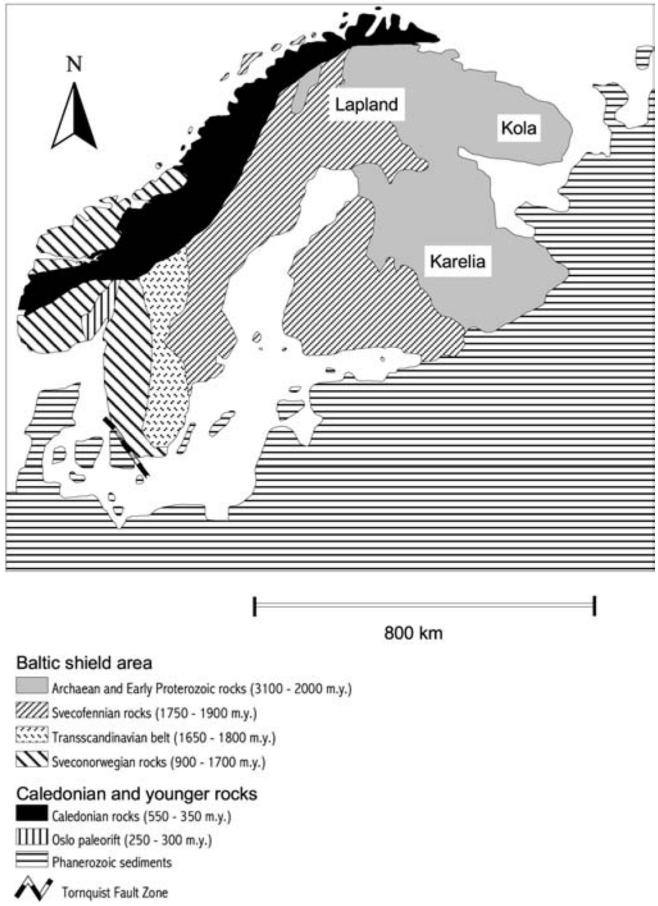

Fig. 2 Simplified geological map of Fennoscandia. Source: SNA (1994)

Karelia (Fig. 2). The main part of Fennoscandia is dominated by Precambrian basement rocks forming the Baltic or Fennoscandian shield area (Fig. 2). The shield is zoned with an old core of Archaean and Early Proterozoic gneisses, granulites, and greenstone belts that are exposed in Karelia, northwest Finland, the Kola peninsula, and in Lapland. Most of the bedrock in northern and central Sweden consists of meta-supracrustals and granites, which were deformed and metamorphosed in the Svecofennian orogenic event (1,900–1,700 million years). The Svecofennian province also contains post-orogenic granites and some Precambrian sandstones. Still younger (1,800–1,650 million years) rocks are found farther to the southwest in the Transscandinavian belt of predominantly undeformed granites and acid volcanics, and in the Sveconorwegian province, which contains rocks that were deformed and metamorphosed about 1,250–900 million years ago.

In the shield area, isolated remnants of Cambro-Silurian platform deposits are found in the Oslo area in southeastern Norway; and in Skåne, Gotland and Jämtland (southeastern Sweden), and in central Sweden. The Tornquist Fault Zone, which extends NW–SE through the Skåne district in south Sweden, marks the border between

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the Baltic shield area and the sedimentary basin of continental Europe. South of this fault zone, there are sedimentary rocks of Cambrian to Tertiary age. In this fault zone, which is about 50 km wide, these younger sediments are also preserved between horst blocks of basement gneisses. Permian diabases and basalts of Jurassic and Cretaceous age are also found in this area.

The closing of the Iapetus Ocean 650–400 million years ago, which had separated Laurentia from Baltica, resulted in the Caledonian orogeny, which reworked the westernmost part of the Baltic shield in Norway. A series of nappes containing oceanic fragments and basement rocks derived from the westernmost margin of Baltica were added onto the Baltic shield along a belt about 2,000 km long and 100–200 km wide, which extends from Stavanger in southwestern Norway to North Cape on the northern coast. The front of the Caledonian nappes extends into the western parts of central and northern Sweden. The Caledonian rocks thus consist of autochthonous reworked basement rocks of the Baltic shield in western Norway and allochthonous metasedimentary and volcanic rocks, as well as nappes of older basement and meta-igneous rocks. Smaller fault-bounded sedimentary basins with post-orogenic Devonian breccias, conglomerates, and sandstones are mainly found along the coast of western Norway.

In southeastern Norway, the Oslo graben opened as an intracratonic rift 305–245 million years ago with the formation of Carboniferous and Permian basalts and intermediate to granitic intrusives. Since the end of the Permian period, the Fennoscandian land area has been uplifted and continuously exposed to erosion. In the Tertiary, the western parts of Fennoscandia were subjected to a tectonic uplift of 1,000–2,000 m in connection with the opening of the North Atlantic rift (Riis and Jensen 1992).

Both Henriksen (1995) and Morland (1997) found that well yields were dependent on lithology of the crystalline rocks in Norway. However, Henriksen (1995) also found from a data analysis of wells in Sogn og Fjordane in western Norway that the lithologic effect on well yield was of less importance than other features such as topography. In a study in southwestern Sweden, Wladis (1995) found no clear conclusions about the influence of lithology on well yield. Also, the relatively poor resolution of the digitized bedrock maps used in the present regional study, precludes any detailed conclusions about the relations between different rock types and well yields.

Soil Types and Thickness

Soil type, soil depth, and the condition of the soil–bedrock interface may provide important impacts on well yield from crystalline rocks (Olsson 1979; 1980; Olofsson 1993). Most of the unconsolidated deposits in Fennoscandia were formed during and after the last glaciation, which had its maximum about 22,000–29,000 years ago. Tills form the major unconsolidated deposits. Central and northern Fennoscandia has the most extensive and

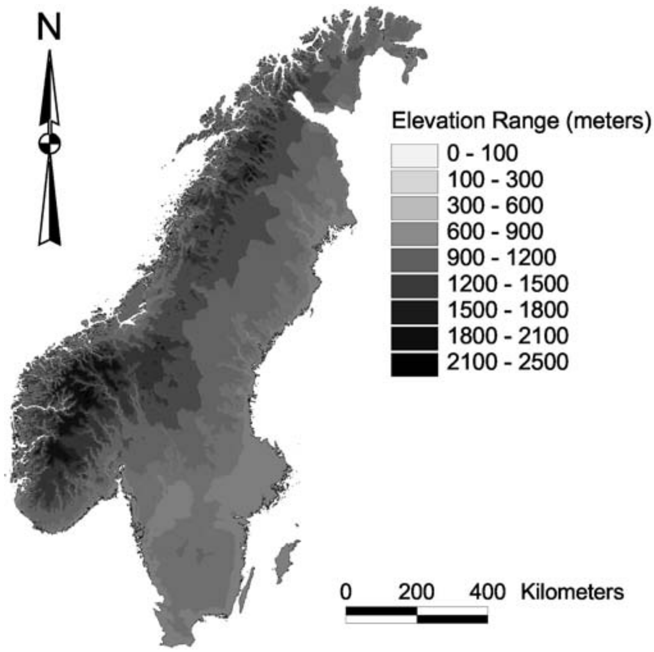

Fig. 3 Digital elevation map of Norway and Sweden illustrating the contrasts in physiography from the coastal zone and landwards. Extracted data from Digital Topographic Database of Norden (Norway, Sweden, Denmark, Finland and Iceland), Norwegian mapping authority (2002)

thickest till cover, with an average thickness of 8–9 m. In western Norway, the thickness is much less and in many places the deposits are practically absent. Glaciofluvial deposits (about 11,000–9,000 million years) are mostly found as eskers, terraces, and deltas in major valleys, whereas marine clays and fine-grained shore deposits may cover some areas beneath the marine limit. Younger fluvial deposits may be found as infillings in valley bottoms.

Topography

Fennoscandia consist of regions with strongly contrasting physiography (Fig. 3).

The region of the 400-million-year-old Caledonian mountain belt forms a mountainous and alpine area with relative relief > 400 m, where large areas have relative relief > 1,000 m. In contrast, much of the shield areas in eastern Norway and Sweden form low lying plains (relative relief < 20 m) and undulating hills where the relative relief is < 400 m (Rudberg 1987).

Both Henriksen (1995) and Midtbø (1996) consider that topography has an important influence on well yields from the rocks of western Norway. Topography is a complex variable and it is beyond the scope of this paper to analyze the effects of this factor at the regional scale. It could either represent a purely external feature, or it could reflect internal structures in the bedrock such as faults or fracture zones. This has been discussed by LeGrand (1954), Krásný (1974), and Henriksen (1995). It is also

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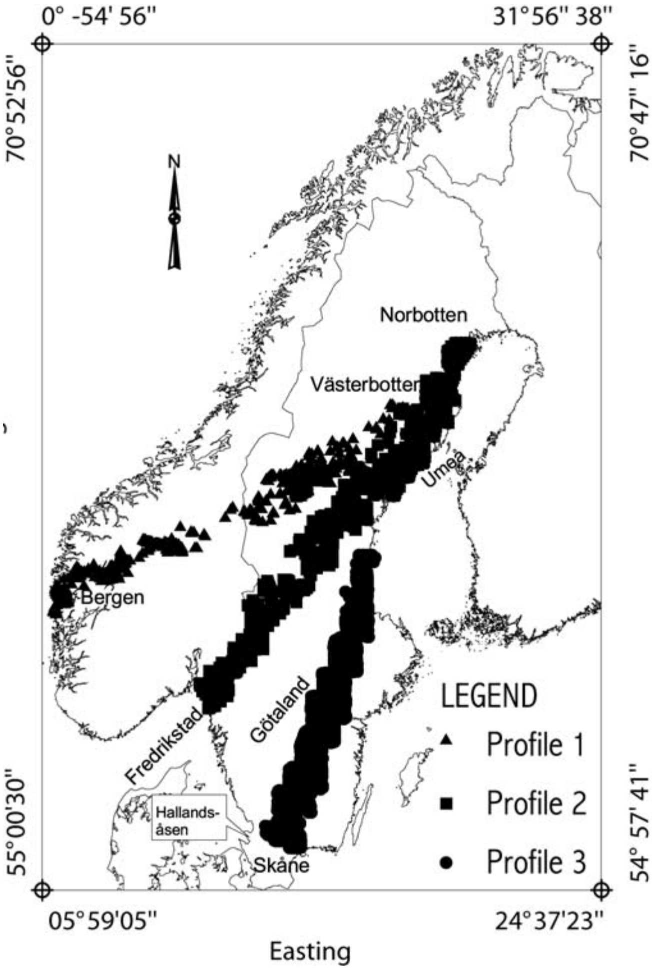

Fig. 4 Location of profiles 1–3. *UTM* Universal Transverse Mercator projection

known from areas of strongly contrasting physiography that topography may cause local stress concentrations and reorientate regional stresses, hence affecting fracture aperture and hydraulic conductivity (Midtbø 1996; NBG 2000).

Database Development and Data Quality

In order to examine these relationships further, borehole data from three profiles across the Fennoscandian crust (Fig. 4) were obtained from the databases of the Norwegian and Swedish Geological Surveys. The data are based on information filed by the well drillers and returned to the well archives of the respective geological surveys, and contain information on well location, well depth, well construction, overburden thickness, yield, and static water level. The individual borehole records vary with respect to the completeness of data entries for these items.

The databases contain incomplete geological and no hydrologic information. This type of information was obtained by combining the well database with digital maps of bedrock, unconsolidated deposits, neotectonics, and precipitation using GIS data. This made it possible to categorize each borehole with respect to bedrock type, type of Quaternary cover, annual precipitation, and amount of isostatic uplift. In this compilation, the following digital databases were *used: National bedrock database of Sweden 1:1,000,000 (SGU* 1999*), National database of surficial deposits of Sweden 1:1,000,000 (SGU* 2001*), Digital bedrock database of Norway 1:3,000,000* 1999a*, Digital database of surficial deposits of Norway 1:1,000,000 (NGU* 1999b*), digital maps of the average yearly precipitation (1961–1990)* from the Swedish Meterological and Hydrological Institute (SMHI 1995) and the Norwegian Meterological Institute (DNMI 1993). Isobases of the apparent annual postglacial isostatic uplift were digitized from the 1:3,000,000 neotectonic map of Norway and adjacent areas, published by the Norwegian Geological Survey (Dehls et al. 2000). This map contains isobases of annual uplift rates for Norway, Sweden, Denmark, and northern Finland.

All digital data were transformed to geographic coordinates based on the World Geodetic System 84 Datum. Once this was done, all data could be plotted and analyzed in any type of projection, e.g., geographic, Universal Transversal Mercator, etc. The complete database consists of the following items: well identity number, geographic coordinates, accuracy of geographic coordinates (Swedish wells only), well yield, well depth, well yield/well depth ratio, well diameter, depth to static water table, overburden thickness, type of overburden, rock type, annual postglacial isostatic uplift, and average annual precipitation.

The rock types (originally 180 different units) were classified in the following five groups: (1) quartzo-feldspathic rocks comprising quartzites, quartz-schists, gneisses, and granites, (2) basic igneous and metamorphic rocks comprising basalts, greenstones, amphibolites, and gabbro, (3) limestones and dolomites, (4) sandstones and conglomerates, and (5) shale, slates, phyllites, and micas schists.

The surficial deposits were classified in six groups: (1) peat and bog, (2) bedrock and bedrock with a thin or discontinuous cover of surficial deposits, (3) fine-grained clayey deposits including clayey tills, (4) fluvial and glaciofluvial sands and gravels, (5) till, and (6) rapid-mass-movement deposits. These deposits include rock-slide, landslide, and snow-avalanche deposits, but not deposits from clay slides.

Overburden thickness was divided into three categories: 0–1; 1–5; and > 5 m.

Annual postglacial uplift rates were categorized into groups with uplift rates of < 1; 1–3; 3–5; 5–7; and > 7 mm/year.

Average annual precipitation was classified as < 700; 700–1,100; 1,100–1,500; 1,500–2,000; and > 2,000 mm/year.

Net precipitation was considered to be a more relevant statistical factor than total precipitation. However, the data acquisition and preprocessing of the data to make a

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seamless GIS theme of net precipitation, which could be used to categorize the wells with respect to net precipitation at the well site, was hindered by differences in data structure and format across the international borders.

In order to ensure the best possible data quality, while still retaining a large volume of well data, a well had to satisfy some minimum requirements. The locations of the Norwegian wells have either been checked by field-site visits in connection with earlier projects (Henriksen 1988), or controlled against 1:50,000-scale topographic maps. Wells in the Swedish database are classified into three groups according to positional accuracy. Only wells with positional accuracy < 100 m were kept in the dataset.

Pumping tests to obtain specific capacities are rarely made in connection with hard-rock boreholes in Scandinavia. The well yields are rather obtained by air-lift tests carried out by the driller at the termination of the drilling, and reported as liters/hour. This is an indicator test which only gives a rough measure of the actual well yield (Banks 1991; DNRE 1997), but has proved to be of great importance in characterizing groundwater potential and hydraulic properties of hard rocks in different regions of Scandinavia (Rohr-Torp 1994; Henriksen 1995; Morland 1997; Wladis and Gustafson 1999). The normalized well yield *Q*/*d*, where *d* is the total drilled depth, is the most commonly used parameter for well yield in the Scandinavian countries (Rohr-Torp 1994; Henriksen 1995; Wladis 1995; Wallroth and Rosenbaum 1996; Morland 1997; Wladis and Gustafson 1999).

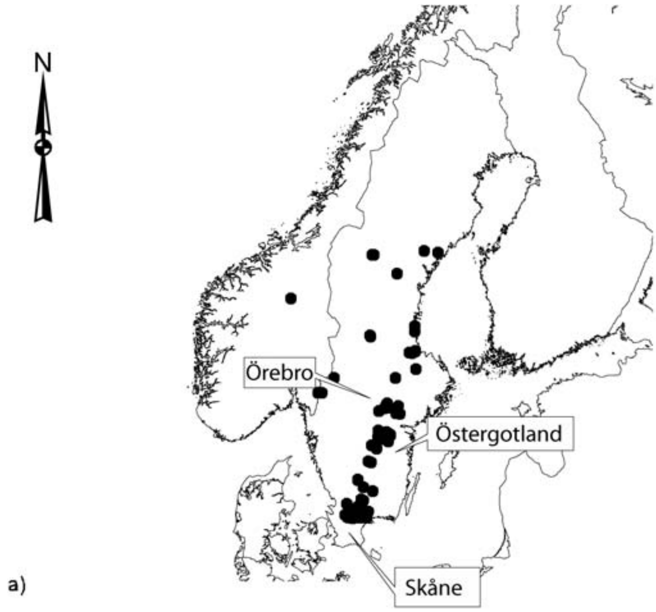
In statistical analysis, the data must often meet requirements that, in the case of hydrogeology and other sciences that explore distributions in nature, come into conflict with an ideal situation that makes use of all data. Statistical inference tests based on the normal distribution, such as ANOVA, are sensitive to extreme values and outliers. Their presence may reduce the power of the test and also affect regional trends. Hence, in order to make a reliable statistical analysis, both the removal of outliers and logarithmic transformation may be necessary. During such processes important information may be lost, and outlier data should, therefore, be dealt with explicitly. In employing data from regional well archives, rejection criteria should also be established to avoid the presence of erroneous data caused by human errors in the registration process (Morland 1997).

In order to ensure as good data quality as possible, the following rejection criteria were applied:

1. Positional inaccuracy $\geq$ 100 m.
2. Total well depth < 20 m.
3. Proportion of well within overburden $\geq 50\%$.
4. Well yield < 100 l/h.
5. Well yield > 20,000 l/h.

Boreholes satisfying these criteria were either deleted, or treated separately.

Rejection criterion 2 was used to identify boreholes in overburden and spring sites or shallow wells in hard rock erroneously registered as hard-rock boreholes.



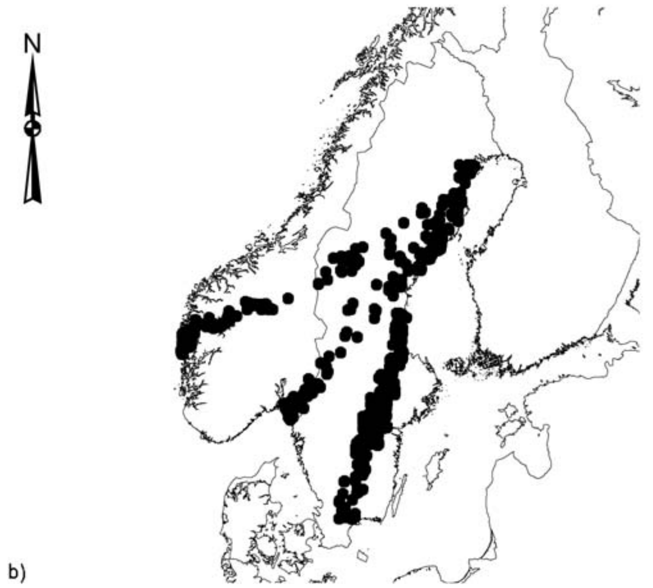


Fig. 5 Maps showing the geographical distribution of boreholes with **a** well yields >20,000 l/h and **b** well yields <100 l/h

The bulk of boreholes that meet rejection criterion 3 have extreme *Q*/*d* values. It is suspected that these wells could either represent erroneous recordings during registration, or that their yields are strongly influenced by the overlying Quaternary soils.

Rejection criteria 4 and 5 are mainly set to identify boreholes with outlying and extreme values. Rejection criterion 4 also identifies boreholes with no data entries for well yield. The specific capacities of these low-yield wells are generally also measured by other methods than air-lift tests. Rejection criterion 5 will also exclude boreholes in rocks with primary porosity, which were not

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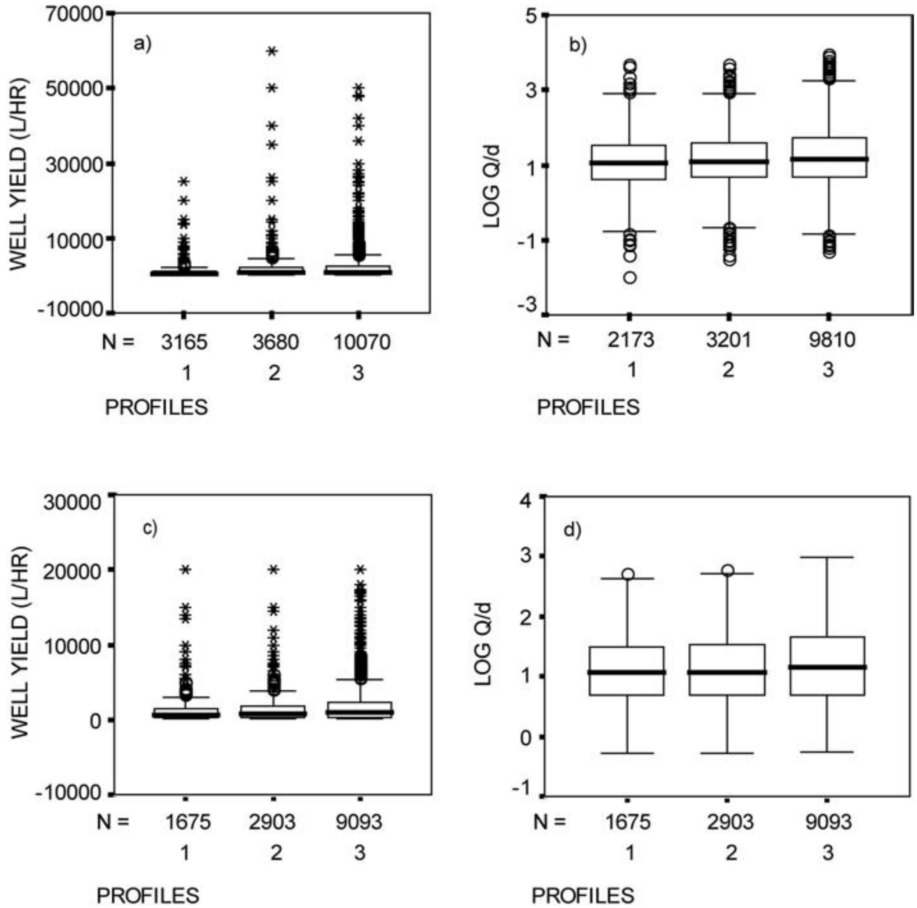

Fig. 6 **a** Box plots of well yield for unfiltered data, **b** log *Q*/*d* for unfiltered data, **c** well yield for filtered data, and **d** log *Q*/*d* for filtered data. The *box* represents the lower and upper quartiles, while the median is represented by the *horizontal line within the box*. Outliers (marked by *circles*) are values more than 1.5 box lengths, while extreme values (marked by *crosses*) are more than three box lengths away from the box. The *vertical lines outside the box* (*whiskers*) connect the smallest and largest values in the dataset that are not outliers or extreme values. Boreholes in the Hallandsåsen area are included in the data sets

considered in this study. However, some high-yield boreholes in crystalline igneous and metamorphic rocks will be excluded from the data analysis when this criterion is used.

Figure 5 shows the geographical distribution of the outlying and extreme values identified by rejection criteria 3 and 4. Boreholes with yields < 100 l/h are mostly evenly distributed along the length of all the three profiles. There is, however, some clustering of low-yield boreholes in the outer coastal areas in western Norway, but this could be explained logically (well sites below the marine limit, well sites close to the coastline were groundwater resources and are limited due to the landward dipping interface between seawater and freshwater, small catchments, high runoff, no soil cover). Boreholes with yields > 20 000 l/h are clustered in three areas in southern and central Sweden (profile 3). The southernmost area is the Hallandsås area in northern Skåne where boreholes have extremely high yields compared with other parts of the country (Anderberg 2000; Knutsson and Morfeldt 2002). The other two clusters are in the Östergotland and Örebro areas where the boreholes are located in Precambrian granites and Phanerozoic sandstones and limestones.

Figure 6 displays how the filtering of data with the rejection criteria 1–5 and logarithmic transformations affect the data distributions. Figure 6a, b shows box plots of the unfiltered data, only with boreholes with positional inaccuracy removed. Figure 6c, d shows the same data, filtered according to the criteria outlined above. In Fig. 6b, d, the data set for profile 3 contains wells from the Hallandsåsen area, but these were excluded in the final statistical analysis.

The use of the *Q*/*d* parameter introduces some bias in the data set. As the well yield of hard rocks is related to the hydraulic conductivity of joints and fractures intersecting the borehole, wells with low yields often tend to be deeper than high-yield wells. Dividing well yield with depth, therefore, may exaggerate the differences between wells with low and high yields. This problem is partly solved by rejection criteria 1, 2, and 3, which excludes wells with yields < 100 and > 20,000 l/h, and wells with total depths < 20 m. The *Q*/*d* parameter may also be distorted by some cultural bias, e.g., a domestic well is usually not drilled to obtain optimized well yield, but is rather terminated when the yield is just adequate for the household's water supply, hence reducing the precision of the *Q*/*d* parameter. The risk of obtaining seawater intrusions in boreholes is another factor that may underestimate the true groundwater potential in coastal regions such as the coastal parts of western Norway.

The validity of using imprecise well-archive data in regional hydrogeological studies was discussed by Henriksen (1995).

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Wallroth and Rosenbaum (1996) and Wladis and Gustafson (1999) used *Q/d* values based on air-lift data from the well archive of the Swedish Geological Survey to make regional estimates of specific capacity and transmissivity of hard-rock areas in southeast Sweden. In these studies, *Q/d* is considered a conservative estimate of specific capacity, which itself is proportional with transmissivity. These local-scale studies (< 300 km^2) indicate that air-lift data from the borehole archive also produce relevant estimates of these hydraulic properties. However, it would be suspected that the influence of regional factors that affect *Q/d* is smaller on the local scale, where factors such as net precipitation and lithology may be considered constants, than on the regional scale.

Description of Profiles

Profile 1

Profile 1 starts in Precambrian gneisses north of Bergen, proceeds in a northeast direction through the central Caledonides of southern Norway and the eastern Caledonian margin in Sweden, and ends in the autochthonous Precambrian (Svecofennian) basement in the Västerbotten area in northern Sweden (Fig. 4). The profile runs perpendicular to the 0–8.5-mm-year isobases for apparent postglacial uplift (Fig. 1; Dehls et al. 2000). Along this profile, regional variables such as annual precipitation and runoff also display distinct east–west gradients. Topographic relief also varies from east to west from 20–100 m in the eastern parts to 100–400 m in the middle parts, and > 400 m in the western parts.

The dominant surficial deposit is till. In the western parts of the profile, bare rock areas and areas with thin (< 1 m) till cover are most common. Eastwards from the middle parts of the profile in east-central Norway, the thickness of the till cover gradually increases reaching an average of 8–9 m in northern Sweden (Rudberg 1987). The original data set consisted of 5,257 wells. After having removed the wells according to the rejection criteria, the data set was reduced to 1,675 wells.

Profile 2

Profile 2 extends northeast from the southeastern coast of the Oslofjord in Norway, by Fredrikstad, to the Västerbotten coastal area in northern Sweden (Fig. 4). In Norway, the profile passes mainly through rocks of the Sveconorwegian province. In Sweden, the profile crosses rocks of the Svecofennian province. The profile extends approximately perpendicular to the 2.5–8.5-mm/year isobases for apparent postglacial uplift (Fig. 1; Dehls et al. 2000).

The profile crosses topographic regions of low-to moderate relief (20–100 and 100–400 m), and it is not characterized by distinct climatic gradients. Along this transect, the only parameter displaying a significant gradient is the annual amount of isostatic uplift (Fig. 1). The original data set consisted of 8,331 wells. After having removed the wells according to the rejection criteria, the data set was reduced to 2,903 wells.

Profile 3

Profile 3 transects the Svecofennian gneisses of Sweden and extends from northern Skåne in a northeast direction through the South Swedish Lowlands in Götaland ending north of Umeå in Norbotten in northern Sweden. In the south, the areas of the Tornquist Fault Zone and Hallandsåsen in northern Skåne, were omitted due to the highly weathered state and intense fracturing of the bedrock caused by the Cretaceous and Tertiary fault movements. The profile is essentially perpendicular to the 0–8.5-mm/year isobases for apparent postglacial uplift (Fig. 1; Dehls et al. 2000), and crosses a topographically low area (0–500 m) with low relief (< 100 m). The annual specific runoff and annual precipitation is fairly constant along the profile, with values of 200–400 and 500–1,000 mm, respectively.

The number of wells contained in the profile was originally 20,822. After omitting wells according to the rejection criteria and excluding wells in the area of the Tornquist Fault Zone, the number of wells was reduced to 8,603.

Data Analysis

Distributions of the calculated *Q/d* values are typically strongly skewed and often with outlying and extreme values. These are important in applied hydrogeology (Krásný 1993), but their presence in large data sets makes them not well suited for statistical analysis by parametric techniques such as ANOVA, which assume homogeneous variances and normality (Johnston 1980). This assumption can be partly achieved by logarithmic transformation of the original data. As an alternative, or complement, non-parametric techniques can be used.

As a first step in the data analysis, a logarithmic transformation was applied to the original data sets in order to make them approximate normality and stabilize the variances. The log *Q/d* values have close to normal distributions (Fig. 7).

Exploratory Data Analysis

Along the selected profiles, gradients of regional variables occur in either east–west or north–south directions. In order to explore any regional trends in the data, scatter plots with log Q/d as the dependent variable were made against easting (profile1) and northing (profiles 2 and 3). The scatter plots (Fig. 8) display no clear relationships between the parameters. To remove any interference from lithology and overburden type, the datasets were first reduced to quartzo-feldspathic rocks only. This reduces the number of wells to 971, 2,506, and 7,412, respectively. In the next step, wells with overburden other than till were also excluded. This further reduces the number of

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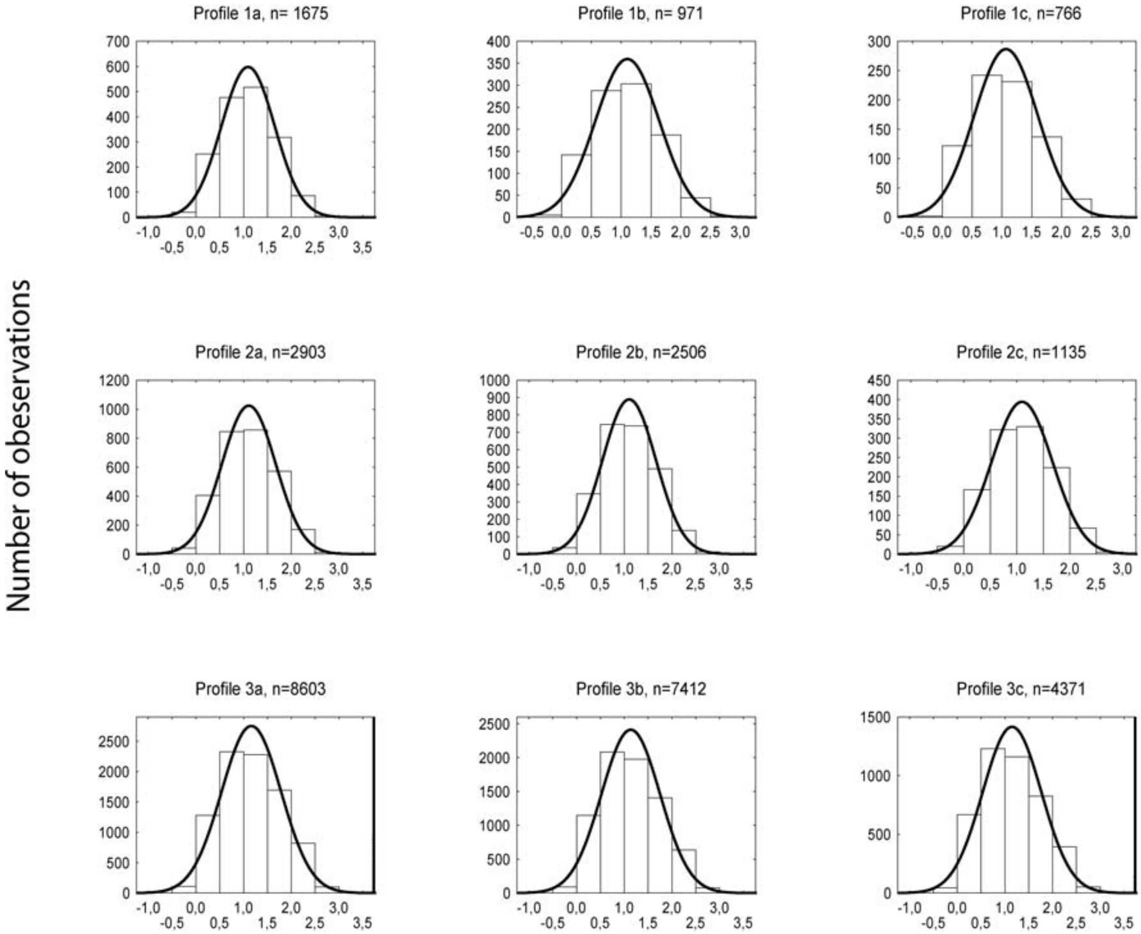

Fig. 7 Histograms of log *Q*/*d* for profiles 1–3 for the complete data sets and various subgroups: **a** profiles with all wells, **b** profiles with wells in quartzo-feldspathic rocks only, and **c** profiles with wells in quartzo-feldspathic rocks and with till or thin or no overburden. The normal curve is superimposed on the observed frequencies

wells to 766, 1,135, and 4,371. The scatter plots still display no clear regional trends for log *Q*/*d*.

For profile 1, there is a weak positive correlation (r = 0.09–0.15) between log *Q*/*d* and easting. Profile 2 displays a weak positive correlation (r = 0.005–0.037) between log *Q*/*d* and northing, while the scatter plots for profile 3 show weak negative correlations (r = –0.1 to –0.11) between northing and log *Q*/*d*. In crystalline rock regions, there is often dependence of well yield on well depth, with decreasing well yield with increasing depth (e.g., Brook 1988). Regression results of the data sets from this work indicate a good negative correlation between log *Q*/*d* and depth (r = –0.46 to –0.54) for the different well groupings shown in Fig. 8.

Well depth represents a significant local factor for well yield and is, for example, correlatable with distance to lineaments (e.g., Brook 1988). The effects of well depth can be removed from the regional analysis if well depth is included in a partial correlation analysis together with the easting and northing variables in Fig. 8. The correlation coefficients, after correcting for depth, are in the ranges 0.14 to 0.18 (profile 1), 0.005 to 0.013 (profile 2), and –0.09 to –0.12 (profile 3).

However, the results of this simple regression exercise might not portray accurately any trend in the data because the raw data, although normally distributed, do not meet all of the requirements for bivariate regression analysis (for example Johnston 1980).

Median-based box plots for groupings of the wells according to the apparent amount of annual postglacial uplift rates (Fig. 9) reveal no clear distinctions between the different groups. For profile 1, there is a weak positive correlation between the median log *Q*/*d* values and uplift rate, but not as strong as depicted by Rohr-Torp (1994). For profile 3, the grouping with annual uplift < 1 mm/year has the highest median value, and median log *Q*/*d* and uplift rate appear to be negatively correlated. A visual examination of the box plots for the groupings of the uplift factor (Fig. 9) indicates that the variances are similar to those shown in Fig. 7. Some outlying values, however, are also present in the transformed data sets.

Statistical Tests

For each profile, univariate analysis of variance (ANOVA) procedures were used to determine if any of the

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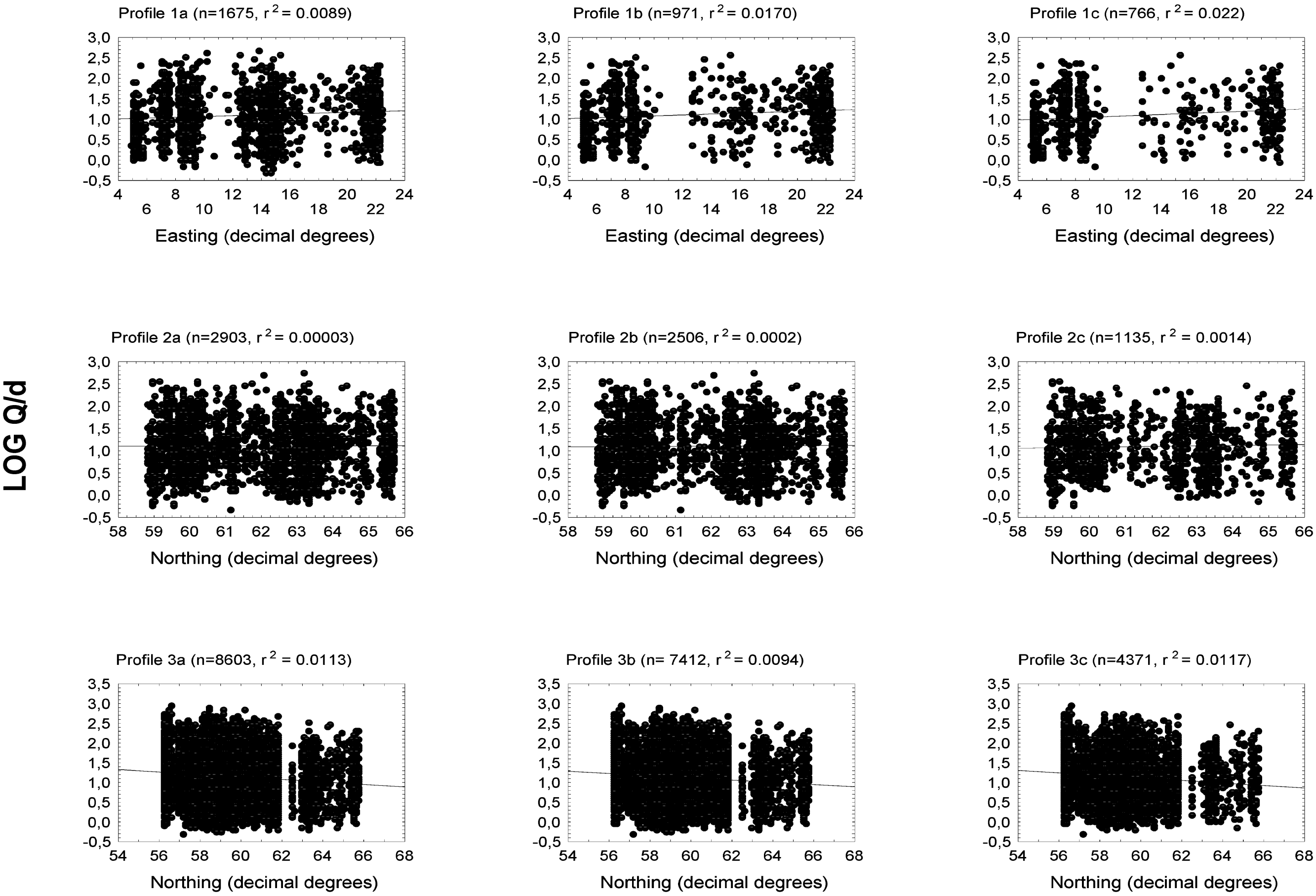

Fig. 8a–c Scatter plots of log *Q*/*d* versus easting (decimal degrees) for profile 1 and versus northing (decimal degrees) for profile 2 and profile 3. **a** Profiles with all wells; **b** profiles with wells in quartzo-feldspathic rocks only; and **c** profiles with wells in quartzo-feldspathic rocks and with till or-no/thin overburden. Simple linear regression lines and r^2 values are indicated

observed differences in mean values were statistically valid, and to determine the degree to which each factor can explain the observed variability in the well yields. ANOVA methods assume that the grouped data are from approximately normal populations with homogeneous variances. Visual inspections of distributions of the various data sets and normality tests, using the Kolmogorov–Smirnov statistic (e.g., Sheskin 2000; p. 133), indicate that the different data sets are approximately normally distributed.

The assumption of homogeneity of variances was investigated by performing explicit statistical tests with the Bartlett chi-square test (Bartlett 1937) and the Levene's test (Levene 1960). As could be expected from the inspection of Fig. 9, the results indicate that this assumption is violated for some of the groupings. Although many sources claim the ANOVA analysis to be robust to violation of its assumptions (Lindman 1974; Sheskin 2000), the results of the tests should be considered with some caution. Consequently, a non-parametric alternative was also used to check the validity of the ANOVA results.

The null hypothesis in ANOVA is that all the group means are equal. If the ANOVA is significant, the null hypothesis is rejected and the alternative hypothesis, that some of the means are not equal, is accepted. The ANOVA tests were significant for all profiles, except profile 2b for wells in quartzo-feldspathic rocks and profile 2c for wells in quartzo-feldspathic rocks with till or thin or no overburden.

In an ANOVA setting, the Tukey's Unequal N HSD procedure (Sheskin 2000) performs all possible pairwise comparisons between groupings with unequal sample sizes. It was used to determine whether differences in log *Q*/*d* values between the categories within each group were statistically significant. The results for the annual uplift-rate groupings are shown in Tables 1, 2, and 3. For profile 1, only wells with annual uplift rates < 1 mm/year have significantly lower log *Q*/*d* values. Wells with annual uplift rates > 7 mm/year have the highest mean log *Q*/*d* values. However, this group of wells does not have significantly higher log *Q*/*d* values than the other groupings, except for wells with annual uplift rates of 5–7 mm/year in the data set consisting of all wells. For profile 2, there are no clear differences between the various groupings, but wells with annual uplift rates of 5–7 mm/year have the highest mean log *Q*/*d* values. In profile 3, wells with annual uplift rate < 1 mm/year

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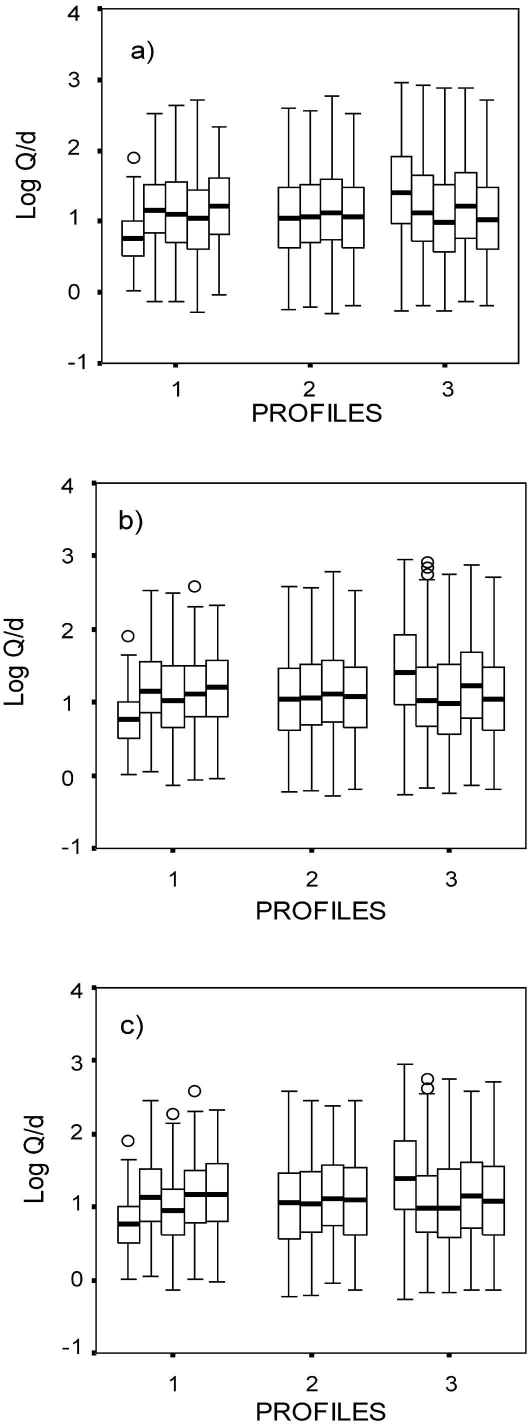

Fig. 9a–c Clustered box plots for log *Q*/*d* summarizing the median, quartiles and outliers for profiles 1–3. The clusters are defined by uplift category (mm/year; <1, 1–3, 3–5, 5–7, 7–9; Fig. 1), which are sequentially arranged from left to right for each cluster. Note that profile 2 has no boreholes in uplift category 1. **a** Summary for all wells; **b** summary for wells in quartzo-feldspathic rocks; **c** summary for wells in quartzo-feldspathic rocks and till or thin or no overburden

always have the highest log *Q*/*d* values. Wells in areas with annual uplift rates > 7 mm/year have the lowest average log *Q*/*d* value, but with no clear differences from the other groupings except the one with annual uplift rates <1 mm/year.

The results of a one-way ANOVA performed on the data sets of all well groupings indicate that each of the factors (annual uplift, annual average precipitation, soil type, bedrock type, and soil thickness) explain only small percentages of the observed variation in log *Q*/*d* values for each of the profiles (Table 4). The most important factor is the annual uplift rate, but this explains only 9% of the observed variation in log *Q*/*d* in profile 1 when wells in quartzo-feldspathic rocks and till, or thin, or no overburden are selected.

For the other profiles, this factor is even of lesser importance. Inclusion of the other factors in the ANOVA model only causes a modest increase in the statistical explanation of variation in log *Q*/*d*. For example, the statistical explanation of variation in log *Q*/*d* is increased from 9–11% by inclusion of the precipitation factor in profile 1 for the data set with wells in quartzo-feldspathic rocks and till, or thin, or no overburden.

The Kruskall–Wallis test (e.g., Sheskin 2000; p. 596) is the non-parametric equivalent to the univariate one-way ANOVA. The null hypothesis is that all the groups have identical distributions. If the test is significant, the null hypothesis is rejected and the alternative hypothesis, that some of the groups differ with respect to the location of their medians, is accepted. The test was run on the data sets from profiles 1–3 to investigate whether the medians of each uplift grouping were significantly different. The tests were significant for all profiles, except profile 2b for wells in quartzo-feldspathic rocks and profile 2c for wells in quartzo-feldspathic rocks with till, or thin, or no overburden.

The Mann–Whitney (e.g., Sheskin 2000; p. 290) test was performed to evaluate which uplift categories were different. The null hypothesis is that the two groups have identical distributions. If the test is significant, the null hypothesis is rejected and the alternative hypothesis, that the groups differ with respect to the location of their medians, is accepted. The results of the non-parametric tests, which do not differ much from the results obtained from the Tukey's Unequal N HSD tests, are shown in Table 5.

To summarize, models based on the typical regional factors have a low explanation power, and a considerable amount of variation is left unexplained. Hence, other predictive factors should be looked for in order to explain the variation in log *Q*/*d*. One of these factors, which has already been discussed, is well depth. If the ANOVA analysis is carried out with annual uplift rate as a categorical predictor variable and well depth is included as a continuous predictor variable (covariate), this model explains 35, 29, and 32% of the variation in log *Q*/*d* for profiles 1C, 2C, and 3C in Table 4.

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Table 1 Results of Tukey's HSD significance tests for unequal N's on the different uplift categories (1, 3, 5, 7, 9) for profile 1. *a* Profiles with all wells, *b* profiles with wells in quartzo-feldspathic rocks only, *c* profiles with wells in quartzo-feldspathic rocks and till or thin or no overburden. *M* Mean value. Italic type indicates statistically significant results (α=0.05)

Profile 1					
a	<1: *n*=160 M=0.76490	1–3 *n*=450 M=1.1670	3–5: *n*=295 M=1.1262	5–7: *n*=488 M=1.0365	>7: *n*=282 M=1.2100
<1	x	*0.000017*	*0.000017*	*0.000097*	*0.000017*
1–3	*0.000017*	x	0.894115	*0.003125*	0.882240
3–5	*0.000017*	0.894115	x	0.268222	0.358946
5–7	*0.000097*	*0.003125*	0.268222	x	*0.001507*
>7	*0.000017*	0.882240	0.358946	*0.001507*	x
b	<1: *n*=160 M=0.76490	1–3: *n*=418 M=1.1753	3–5: *n*=59 M=1.0868	5–7: *n*=101 M=1.1219	>7: *n*=233 M=1.1837
<1	x	*0.000017*	*0.006635*	*0.000026*	*0.000017*
1–3	*0.000017*	x	0.886027	0.948752	0.999790
3–5	*0.006635*	0.886027	x	0.996109	0.847930
5–7	*0.000026*	0.948752	0.996109	x	0.915259
>7	*0.000017*	0.999790	0.847930	0.915259	x
c	<1: *n*=157 M=0.7633	1–3: *n*=366 M=1.1538	3–5: *n*=50 M=0.9806	5–7: *n*=58 M=1.1188	7–9: *n*=135 M=1.1866
<1	x	*0.000017*	0.206833	*0.001631*	*0.000017*
1–3	*0.000017*	x	0.434764	0.996055	0.984355
3–5	0.206833	0.434764	x	0.656003	0.255869
5–7	*0.001631*	0.996055	0.656003	x	0.952883
>7	*0.000017*	0.984355	0.255869	0.952883	x

Table 2 Results of Tukey's HSD significance tests for unequal N's on the different uplift categories (1, 3, 5, 7, 9) for profile 2. *a* Profiles with all wells, *b* profiles with wells in quartzo-feldspathic rocks only, *c* profiles with wells in quartzo-feldspathic rocks and till or thin or no overburden. *M* Mean value. Italic type indicates statistically significant results (α=0.05)

Profile 2				
a	1–3: *n*=189 M=1.0472	3–5: *n*=907 M=1.1196	5–7: *n*=770 M=1.1592	>7: *n*=1,037 M=1.0657
1–3	x	0.596238	0.215241	0.988916
3–5	0.596238	x	0.513494	0.174093
5–7	0.215241	0.513494	x	*0.006238*
>7	0.988916	0.174093	*0.006238*	x
b	1–3: *n*=189 M=1.0472	3–5: *n*=819 M=1.1095	5–7: *n*=595 M=1.1420	>7: *n*=903 M=1.0763
1–3	x	0.703428	0.355685	0.958229
3–5	0.703428	x	0.749592	0.630630
5–7	0.355685	0.749592	x	0.181490
>7	0.958229	0.630630	0.181490	x
c	1–3. *n*=147 M=1.0448	3–5: *n*=335 M=1.0905	5–7: *n*=271 M=1.1398	>7: *n*=382 M=1.0864
1–3	x	0.903975	0.488201	0.925351
3–5	0.903975	x	0.750066	0.999722
5–7	0.488201	0.750066	x	0.700887
>7	0.925351	0.999722	0.700887	x

Discussion and Conclusions

The results of this exploratory data analysis do not indicate any clear trends in well yield with regional gradients. These results are at variance with the ideas of Morland (1997) and Rohr-Torp (1994). They found a positive linear correlation between the amount of annual postglacial uplift and well yield, and related their empirical results to a regional radial tensile-stress gradient causing increased hydraulic conductivities towards the area of greatest uplift. However, a geostatistical analysis based on the entire well archive at the Swedish Geological Survey (Berggren 1998) displays no clear regional trend for the estimated hydraulic conductivity values of the bedrock in Sweden.

Numerical-model studies on fracture growth (Gudmundsson 1999; Gudmundsson et al. 2002) also suggest the generation of increasing tensile stresses and associated fracture formation with increasing uplift rate, leading to an increase in the hydraulic conductivity with uplift rate.

While hydraulic conductivity is a genuine physical parameter of the hard-rock environment per se, other parameters such as transmissivity determined by pumping tests, specific capacity, and well yield are more or less affected by external features (Henriksen 1995; Mabee 1998; Krásný 2002).

The results of this study are not directly comparable with the results of Rohr-Torp (1994) and Morland (1997) whose analyses were based on uplift rates from an earlier map by Sørensen et al. (1987) and considered only boreholes in Norway. If the linear-regression lines of Rohr-Torp (1994) and Morland (1997) were extrapolated towards the uplift center in the Gulf of Bothnia, the predicted mean or median well yield would be unrealistically high and far greater than the actual well yields in this area.

On the other hand, the present study comprises hard-rock boreholes from the whole region of postglacial uplift. Moreover, a classification of boreholes according to lithology, surficial cover, and soil depth made it possible to approach a uniform hard-rock environment as close as possible by treating wells in quartzo-feldspathic rocks only, and excluding wells in highly permeable overburden, which might play an important role for groundwater flow from soil to rockfractures.

In Fennoscandia, other factors such as recharge by precipitation and the yearly average amount of runoff also

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Table 3 Results of Tukey's HSD significance tests for unequal N's on the different uplift categories (1, 3, 5, 7, 9) for profile 3. *a* Profiles with all wells, *b* profiles with wells in quartzo-feldspathic rocks only, *c* profiles with wells in quartzo-feldspathic rocks and till or thin or no overburden. *M* Mean value. Italic type indicates statistically significant results (α=0.05)

Profile 3					
a	<1: *n*=1,134 M=1.4264	1–3: *n*=2,277 M=1.1880	3–5: *n*=2,676 M=1.0586	5–7: *n*=1,039 M=1.2195	>7: *n*=1,477 M=1.0483
<1	x	*0.000017*	*0.000017*	*0.000017*	*0.000017*
1–3	*0.000017*	x	*0.000017*	0.765759	*0.000017*
3–5	*0.000017*	*0.000017*	x	*0.000017*	0.991130
5–7	*0.000017*	0.765759	*0.000017*	x	*0.000017*
>7	*0.000017*	*0.000017*	0.991130	*0.000017*	x
b	<1: *n*=1,083 M=1.4250	1–3: *n*=1,614 M=1.0831	3–5: *n*=2,536 M=1.0545	5–7: *n*=839 M=1.2137	>7: *n*=1,340 M=1.0547
<1	x	*0.000017*	*0.000017*	*0.000017*	*0.000017*
1–3	*0.000017*	x	0.655629	*0.000093*	0.737569
3–5	*0.000017*	0.655629	x	*0.000018*	1.000000
5–7	*0.000017*	*0.000093*	*0.000018*	x	*0.000018*
>7	*0.000017*	0.737569	1.000000	*0.000018*	x
c	<1: *n*=867 M=1.4161	1–3: *n*=961 M=1.0566	3–5: *n*=1,573 M=1.0705	5–7: *n*=333 M=1.1689	>7: *n*=637 M=1.0871
<1	x	*0.000017*	*0.000017*	*0.000018*	*0.000017*
1–3	*0.000017*	x	0.986487	0.111573	0.894537
3–5	*0.000017*	0.986487	x	0.213984	0.988143
5–7	*0.000018*	0.111573	0.213984	x	0.398214
>7	*0.000017*	0.894537	0.988143	0.398214	x

Table 4 Summary of one-way ANOVA analyses for profiles 1–3 with wells grouped according to annual-uplift rate, average annual precipitation, bedrock type, soil type, and soil depth .*A* Profiles with all wells, *B* profiles with wells in quartzo-feldspathic rocks only, *C* profiles with wells in quartzo-feldspathic rocks and till or thin or no overburden. The *F*-value is the ratio of the variance between the categories to the variance within the categories, and is the test-statistic of the ANOVA. If categories are equal, *F* will be around 1. The *P*-value is the probability of rejecting the null hypothesis if this is in fact true

	Grouping variable	R^2 and (*F*-value and *P*-value)		
		A	B	C
Profile 1	Annual-uplift rate	0.0486 (21.34, <0.01)	0.0783 (20.52, <0.000001)	0.090 (18.94, <0.000001)
	Annual precipitation	0.0466 (20.42, <0.000001)	0.0875 (23.18, <0.01)	0.095 (20.01, <0.000001)
	Bedrock type	0.00362 (1.52, 0.1945)		
	Soil type	0.020 (6.83, 0.000003)	0.0373 (7.48, 0.000001)	0.024 (19.05, 0.000014)
	Soil depth	0.0212 (18.11, <0.000001)	0.0411 (20.75, <0.000001)	0.043 (17.31, <0.000001)
Profile 2	Annual-uplift rate	0.00506 (4.91, 0.002081)	0.0027 (2.27, 0.077677)	0.0025 0.95, 0.411530)
	Annual precipitation	One level only		
	Bedrock type	0.02089 (15.46, <0.000001)		
	Soil type	0.003122 (2.27, 0.059474)	0.000371 (0.23, 0.920504)	0.000478 (0.54, 0.461916)
	Soil depth	(0.0140 (20.64, <0.00001)	0.008272 (10.44, 0.000031)	0.008719 (4.978, 0.007035)
Profile 3	Annual-uplift rate	0.039 (88.19, <0.01)	0.045 (87.46, <0.01)	0.049654 (57.02, <0.01)
	Annual precipitation	0.010 (43.89, <0.01)	0.0156 (58.87, <0.01)	0.019204 (42.76, <0.01)
	Bedrock type	0.0316 (70.36, <0.01)		
	Soil type	0.008715 (15.11, <0.000001)	0.00866 (12.94, <0.000001)	0.010 (47.05, <0.000001)
	Soil depth	0.0173 (76.86, <0.01)	0.00635 (23.69, <0.000001)	0.007650 (16.83, <0.000001)

display a regional variation that may affect well yield. In addition, subregional and local factors, such as thickness of Quaternary overburden, terrain type, distances to lineaments, structural rock features, and rock type will also influence the well yield at a particular location (Brook 1988; McFarlane et al. 1992; Olofsson 1993; Dine and Adamski 1995; Henriksen 1995; Mabee 1998; Krásný 2002).

The works of Rohr-Torp (1994) and Morland (1997) describe the relationships between annual postglacial uplift (cause) and well yield (effect), from which it is inferred that the crustal stresses associated with the

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Table 5 Results of Kruskal–Wallis test for well groupings according to the uplift factor and Mann–Whitney tests for differences between the different uplift categories for profiles 1, 2, and 3. *a* Profiles with all wells, *b* profiles with wells in quartzo-feldspathic rocks only, *c* profiles with wells in quartzo-feldspathic rocks and with till or thin or no overburden. Log *Q/d* median values for each category are shown in the first column. Italic type indicates statistically significant results (α=0.05)

	1	3	5	7	9	K-W *P*-value
Profile 1a						*<0.0001*
1 (0.7670)	x					
3 (1.1525)	*<0.000001*	x				
5 (1.1060)	*<0.000001*	0.320986	x			
7 (1.0395)	*<0.000001*	*0.000506*	0.053183	x		
9 (1.2100)	*<0.000001*	0.228744	0.068925	*0.000050*	x	
Profile 1b						*<0.0001*
1 (0.7670)	x					
3 (1.1525)	*<0.000001*	x				
5 (1.0270)	*0.000197*	0.193771	x			
7 (1.1080)	*<0.000001*	0.478083	0.523237	x		
9 (1.2000)	*<0.000001*	0.683132	0.172701	0.325458	x	
Profile 1c						*<0.0001*
1 (0.7660)	x					
3 (1.1320)	*<0.000001*	x				
5 (0.9540)	*0.015139*	*0.023454*	x			
7 (1.1615)	*0.000009*	0.701797	0.150239	x		
9 (1.1600)	*<0.000001*	0.529718	*0.021527*	0.459781	x	
Profile 2a						*<0.0056*
1	x					
3 (1.0460)	x	x				
5 (1.0620)	x	0.151480	x			
7 (1.1265)	x	*0.019003*	0.095127	x		
9 (1.0600)	x	0.558899	0.101836	*0.001292*	x	
Profile 2b						*0.1330*
1	x					
3 (1.0460)	x	x				
5 (1.0500)	x	0.237622	x			
7 (1.1140)	x	0.052059	0.187344	x		
9 (1.0790)	x	0.407823	0.487409	0.052765	x	
Profile 2c						*<0.3844*[a]
1	x					
3 (1.0510)	x	x				
5 (1.0430)	x	0.518734	x			
7 (1.1140)	x	0.103626	0.215538	x		
9 (1.0960)	x	0.409281	0.940080	0.252157	x	
Profile 3a						*<0.0001*
1 (1.4055)	x					
3 (1.1250)	*<0.000001*	x				
5 (0.9860)	*<0.01*	*<0.000001*	x			
7 (1.2180)	*<0.000001*	0.074556	*<0.000001*	x		
9 (1.0340)	*<0.01*	*<0.000001*	0.742687	*<0.000001*	x	
Profile 3b						*<0.0001*
1 (1.4050)	x					
3 (1.0135)	*<0.01*	x				
5 (0.9815)	*<0.01*	0.066955	x			
7 (1.2220)	*<0.000001*	*<0.000001*	*<0.000001*	x		
9 (1.0360)	*<0.01*	0.501286	0.428014	*<0.000001*	x	
Profile 3c						*<0.0001*
1 (1.3960)	x					
3 (1.0360)	*<0.01*	x				
5 (0.9860)	*<0.01*	0.957492	x			
7 (1.1585)	*<0.000001*	*0.001092*	*0.001601*	x		
9 (1.0485)	*<0.000001*	0.182810	0.249389	*0.049988*	x	

[a] Note different K-W *P*-values

postglacial uplift influences well yield. This assumption could be unsatisfactory because it disregards the general situation in nature that many factors (causes) operate to produce one effect (i.e., well yield). Hence, correlation plots between well yield and only one independent variable (e.g., annual-uplift rate or thickness of overburden), with other factors considered as constants, will not reveal the relative importance of all the factors that actually influence the well yield. Moreover, the one selected variable may be modified by other factors that are not considered. In such situations, methods that examine the effects of more than one independent factor (ANOVA) could produce more relevant information. This approach was taken in this study, which takes into

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account that more than one factor may operate to influence well yield. The relative importance of the factors are examined, and statistical tests of significance were employed to investigate whether places or regions were different with respect to well yield.

Of the factors considered in this study, the annual-uplift rate plays a significant role only in profile 1, but nevertheless accounts for only 9% of the observed variation in well yield. In all profiles, it appears to be masked by other factors, some of which are not accounted for by the regional analysis. Among such unaccounted factors could be local topographic stresses (Midtbø 1996) and structural bedrock features (Braathen et al. 1999).

Regarding the uplift-generated crustal stresses in Fennoscandia, opinions differ with regard to its character, direction, and magnitude. The models of Stein et al. (1989) and Gudmundsson (1999) predict tensile stresses in the central parts and compressional stresses with strike slip or reverse faulting at the margins of the de-glaciated region. Based on recordings of 3-D GPS crustal velocities, Milne et al. (2001) conclude that the Fennoscandian region in Sweden and Finland is subjected to present-day extension with horizontal velocity vectors radiating outward from the center of uplift. All these modeling approaches are compatible with a positive correlation between well yields and postglacial uplift rate.

By contrast, Stephansson (1989) derived compressional stresses associated with the uplift. The model of Wu et al. (1999) predicts compressional horizontal stresses with thrust faulting as the mode of failure both in postglacial times and at present.

Present crustal stresses derived from earthquake focal mechanisms have been compiled by Slunga (1989), Bungum (1989), Arvidsson and Kulhanek (1994), Arvidsson (1996), Lindholm et al. (2000), and Hicks et al. (2000). The regional picture is consistent with ridge-push as the most important stress generator. However, focal mechanisms with extensional stresses in eastern Sweden/Gulf of Bothnia and onshore western Norway also indicate the presence of other stress contributors (Lindholm et al. 2000), but the type of faulting and hence the local stress field may vary within short distances.

Arvidsson and Kulhanek (1994) found a significant extensional component in earthquake focal mechanisms in eastern Sweden and the Gulf of Bothnia (uplift rates >7 mm/year), and attributed this to postglacial rebound stresses. In northern Lapland, at the same distance from the uplift center (uplift rates 5–7 mm/year), both compressional and extensional mechanisms have been determined (Arvidsson and Kulhanek 1994; Arvidsson 1996). Thus, it appears that many fault mechanisms are present in this area (e.g., Wahlström 1989; Arvidsson 1996; Wu et al. 1999; Fjeldskaar et al. 2000) and, hence, a large scatter in the orientation of stresses in the upper parts of the crust is to be expected.

In-situ stress measurements from boreholes, quarries, and underground mines from the whole Fennoscandian region were first summarized by Hast (1966, 1974) who reported high horizontal-compressive stresses (~20 MPa) far exceeding the vertical stress calculated from the weight of the overburden at shallow crustal depths. Open horizontal fissures from the ground level to crustal depths of 1 km were considered to have formed in this horizontal-stress field. Compilation of data from the Fennoscandian Rock Stress Data Base (Stephansson et al. 1987) also show high horizontal NW–SE compressive stresses in Fennoscandia, but with a large scatter of orientation in the uppermost 300 m (Stephansson 1989).

Stress measurements from the Norwegian area were summarized by Fejerskov et al. (2000) who also document the existence of first-order NW–SE-oriented high (10–15 MPa) horizontal compressional tectonic stresses, considered to be generated by ridge-push forces from the North Atlantic spreading ridge.

The hydraulic conductivity of pre-existing fractures may either be increased or reduced, depending on the orientation of the fractures relative to the principal in-situ stress directions (Carlsson and Christiansson 1987; Banks et al. 1996; Singhal and Gupta 1999). The compressional stress magnitudes from the ridge-push forces must decrease inland from the west coast of Norway, so a possible effect of the ridge-push stress on the hydraulic properties of the upper parts of the crust would decrease inland or towards the uplift center.

Detailed modeling of in-situ stress measurements in western Norway from the coastal areas to 100 km inland (uplift categories 1–3; Fig. 1) shows the existence of a regional E–W-oriented stress field with maximum horizontal stresses ~15–20 MPa and minimum horizontal stresses ~8–10 MPa, far exceeding the vertical stresses (Midtbø 1996; SINTEF 1996). These in-situ stresses are considered by Braathen et al. (1998) and Gaut et al. (1999) to affect fracture permeability. In this region, stress direction and magnitude are also strongly influenced by topography. It was found that topography reorientates the maximum horizontal stresses into parallelism with valley sides, and causes stress concentrations in valley bottoms, possibly generating horizontal exfoliation fractures This type of fracturing is likely to enhance the hydraulic conductivities of the rocks present and increase their well yield (Midtbø 1996). These observations are in accordance with the results of Henriksen (1995) who found a correlation between high well yields and well sites in low valley sides and valley bottoms in this region. This correlation can, however, be partly related to a general topographically driven groundwater flow.

The relative importance of different stress-generating mechanisms acting on the Fennoscandian crust in Norway were evaluated by Fejerskov and Lindholm (2000). The mechanisms evaluated include ridge-push, deglaciation, continental-margin effects, sediment flexure, and topography.

They considered ridge-push associated with the ongoing sea floor spreading in the North Atlantic as the most important stress-generating mechanism, while uplift-generated stresses were considered of less importance. In addition to the stress-generating mechanisms men-

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tioned above, lateral contrasts in crustal densities (rock types) will also have an effect on intra-plate stress fields (Zhang et al. 1997).

To summarize, a number of factors, not only deglaciation, will contribute to the total stress field at a particular site. In light of this, the lack of a clear correlation between well yield and transmissivity with distance to the uplift center is not surprising when the Fennoscandian region is considered as a whole.

The geometry and vertical extent of the Late Weichselian ice sheet has been discussed for many years. The traditional central-domed, thick, ice model has been challenged by Nesje and Dahl (1992), who suggest a multidomed and asymmetric, thin ice model with considerable variation in ice thickness. If this is correct, the distribution and magnitude of glacial-rebound stresses could be more complex than previously thought. Moreover, other mechanisms than pure glacio-isostatic rebound are probably contributing to the measured postglacial uplift, and a significant tectonic component has been suggested by Nesje and Dahl (1992) and Fjeldskaar et al. (2000).

A dilemma in this type of exploratory data analysis of the hard-rock environment, based on well archive data, is to ensure a representative collection of data from a hydrogeological point of view, which at the same time does not violate too much the data requirements for the statistical analyses. In such situations, compromises may be necessary by, for example, combining categories to make a qualitative statistical grouping variable. In this work, it could be argued that wells in till or at sites with thin or no overburden should have been tested separately in the statistical analyses because areas with no overburden will react differently from areas with a thick overburden of till as regards surface runoff, direct groundwater recharge, and groundwater storage. On the other hand, this would cause a considerable reduction in the data set and also an unbalance in group sizes, which would strongly reduce the data quality from a statistical viewpoint. As the saturated hydraulic conductivity of Scandinavian lodgement tills is in the range of 10^{-6}–10^{-10} m/s (Haldorsen et al. 1983), which is about the same values as those of crystalline rocks from Sweden (Carlsson and Olsson 1979; SKB 1992; Knutsson 1997) and Norway (Banks et al. 1992), the compromise to combine the categories could be justified.

A salient feature in the evaluation of the results from the analyses of well yields from regional data bases is the precision of the *Q*/*d* parameter as a means of estimating well-yield and hydraulic properties per se (i.e., hydraulic conductivity) of the hard-rock environment. It appears that such studies give meaningful results, provided that sufficient care is taken to ensure as good data quality as possible (Wallroth and Rosenbaum 1996; Wladis and Gustafson 1999).

The results from this study indicate that, although recognized as a significant factor, uplift-generated stresses caused by the removal of the Late Weichselian (=Vistulian) ice sheet in Fennoscandia is only one of several factors that affect the well yields from the hard rocks in this area. Hence, a simple correlation based on the relationships between two variables would not be sufficient to describe the observed regional variations in well yields. The results of the statistical analysis indicate that for the typical regional variables, the grouping of wells based on rate of postglacial uplift and average annual precipitation explains not more than 11% of the observed variation in well yield.

The uplift factor in itself is complex, and other additional factors such as topography, topographic stresses, overburden type, overburden thickness, well depth, and fracture and lineament density, may to various degrees overshadow any effects of the uplift factor.

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