Radon content in groundwater from drilled wells in the Stockholm region of Sweden

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Radon is the most important contribution to the radioactivity in groundwater and has been studied for different reasons during the last hundred years in Sweden, in later time focused on radon as a health problem. Based on data from a national survey on radon concentration in drinking water in the 1980s, airborne radiometric measurements, geological maps and uranium prospecting, a groundwater radon risk map of Sweden was compiled in the 1990s. The map showed that there is more pronounced risk for radon in groundwater in several, fairly large areas in central and northern Sweden. The bedrock in these areas usually has a granitic composition. Many detailed investigations of wells on regional and local scales were made during the 1980s and 1990s, altogether 31,000 radon analyses of groundwater from 229 municipalities in Sweden. 12.2% of all wells had a radon value >1000 Bq/L, but some counties had much higher percentage, up to 23%. The highest value in a single well was 57,000 Bq/L. Data from the county of Stockholm showed very large local differences. The conclusions are that there are some pronounced risk areas and a positive correlation between high radon concentrations in drilled wells and granites, pegmatites, acidic volcanites and some acidic gneisses. However, wells with high radon concentrations may be found locally outside areas with such rock types. Statistical analyses of data from Österåker and Uppsala municipalities show that the installations for groundwater withdrawal and the use of the well clearly affect the radon content, whereas no clear correlation between well depth and soil depth versus radon content is seen.

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Radon - occurrence and migration

Radon is the most important contribution to the radioactivity of groundwater. There are three different isotopes of radon, but only ^{222}Rn, with a halflife of 3.8 days, formed within the uranium chain by decay of ^{226}Ra, is of interest as the other isotopes are very short-lived. The migration of radon in the ground takes place in several steps including emanation and diffusion from uranium- and radium-bearing mineral grains, diffusion of radon through permeable rocks and soils, and transport of radon by groundwater flow. Groundwater in uranium-rich crystalline rocks often has an elevated radon concentration in relation to the radon concentration of the surrounding rock. It is most likely explained by the fact that uranium is leached out of the rock and precipitated together with its decay products, for example radium, on the surfaces of the fractures in the rock. Radon is then emanating from the radium-enriched coatings directly to the groundwater in the fractures (Åkerblom & Lindgren 1997) (Fig. 1).

The consequences of these processes are not only that the radon concentration in groundwater is highly elevated, but also that, in a first step, leached uranium and radium can be transported by groundwater fairly long distances and is precipitated along the flow paths in the fractures. Then, in a second step, radon emanates to groundwater and is transported farther away by groundwater flow. This means that groundwater with a high concentration of radon may be found in bedrock with low uranium concentrations, for

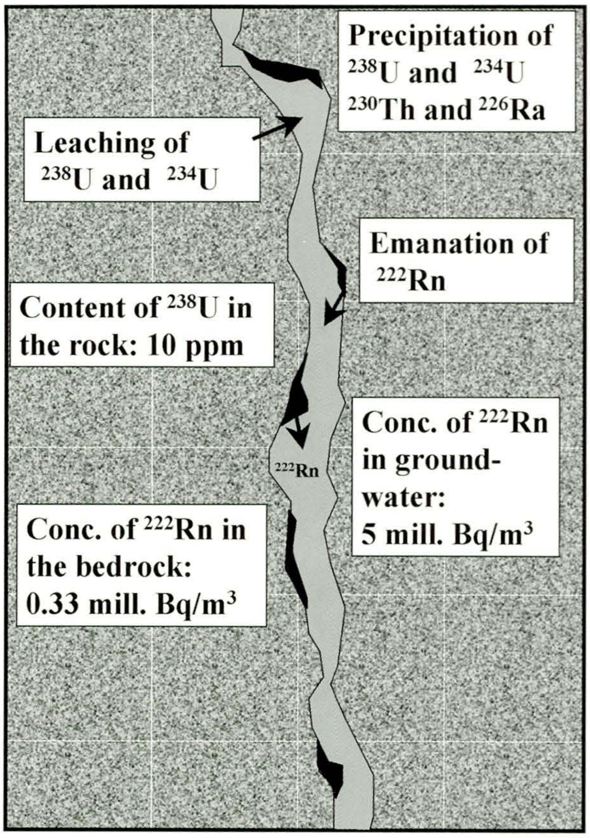

Fig. 1. Formation of radon gas in a water-filled fracture (after Åkerblom & Lindgren 1997).

example, an artesian spring in sedimentary rocks may have acquired its high radon in contact with precipitated radium, which originates from underlying uranium-rich granite.

National overview

Studies of radon in groundwater have been carried out for different reasons during the last hundred years in Sweden. The first investigations were related to mineral and spa water — radioactive water was thought to be healthy at that time. The radon concentration of the spring water at Västersel (announced as 'health water') was more that 5000 Bq/L. Some springs and wells with considerably high radon concentrations were found, the highest in syenite (Sahlbom 1916). Radon concentrations became of interest again in connection with prospecting of uranium ores in the 1950s; the highest value was measured in a spring area at Masungsby, Lapland, with a bedrock of granite with pegmatite (Armands 1967).

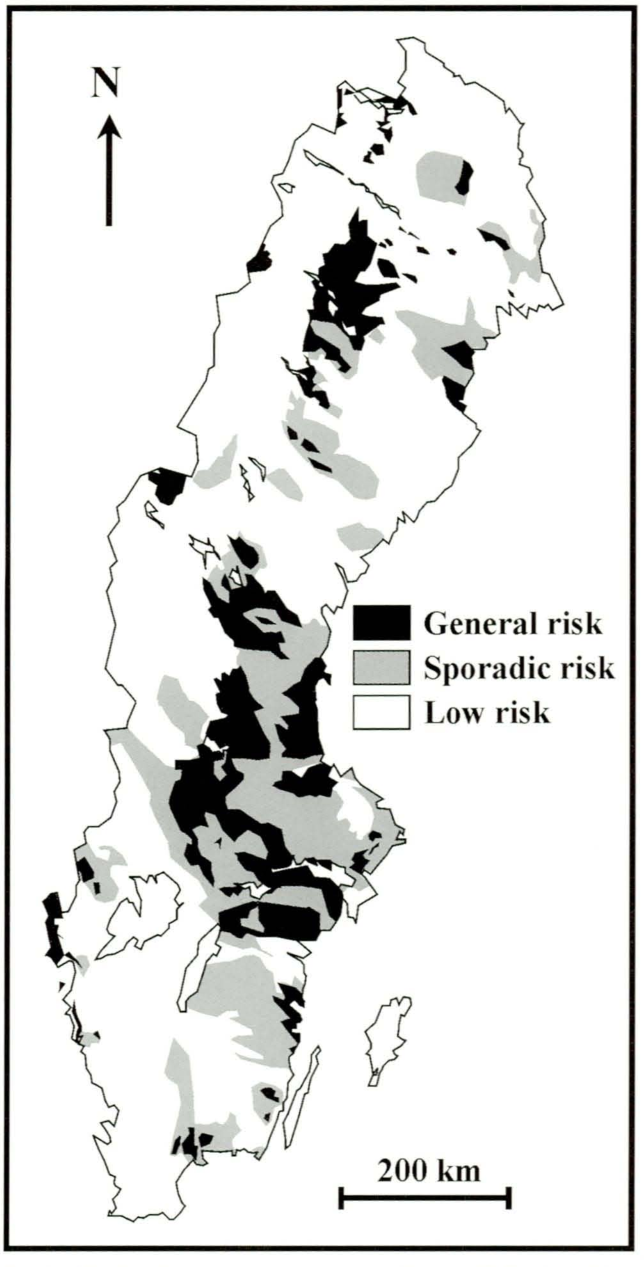

Fig. 2. Preliminary groundwater radon risk map of Sweden (after Åkerblom & Lindgren 1997).

During the 1960s and 1970s, radiation-protection specialists studied radon in drinking water, in milk and minewater (and air). Measurable concentrations of radon were found in milk from 13 dairies of around 300 dairies all over Sweden. Eleven of these dairies were situated in the granitic area of southeastern Sweden, where detailed investigations of groundwater for water supply to the farms in two areas were carried out (Snihs 1973, Knutsson 1977). The highest radon concentrations were found in drilled wells in granites (maximum 2900 Bq/L), above all in a red granite susceptible to both chemical and mechanical weathering. Seasonal fluctuations were obvious but different in various types of groundwater and wells.

A national survey of radon concentration in household water was carried out by the Swedish Radiation Protection Institute (SSI) in the 1980s, and radon analyses of randomly selected wells were made during hydrogeological surveys by the Geological Survey of Sweden (SGU). During the 1990s, a groundwater radon risk map of Sweden was compiled by SGU and SSI (Åkerblom & Lindgren 1997) (Fig. 2). It was based on different types of data: a data set of radon in drilled wells, airborne radiometric measurements, geological maps and old data from the areas of uranium prospecting. The risk map shows areas with an elevated risk for radon in three classes: more general risk, more sporadic risk and relatively low risk. More widespread general risk areas were identified in the Bergslagen province of central Sweden. In northern Sweden, Norrland, two large areas with general risk are marked, one area in the south of Norrland and one in the north, the central part of Lapland (Fig. 2). The areas are characterised by bedrock with common occurrences of uranium-rich granites, pegmatites and aplites.

Regional outline

Regional authorities (county boards) as well as many local authorities (the municipalities) have carried out a lot of investigations of radon in groundwater during the 1980s and 1990s. A regional study in Bohuslän (1982), on the west coast, of selected wells in areas with high radiation concentrations showed that 31 % of the wells had a radon concentration above 1000 Bq/L (the compulsory limit for private wells in Sweden) with a maximum at 11,166 Bq/L (Nylund 1987). All wells with the highest concentrations (4% > 4000 Bq/L) were drilled in the uranium-rich Bohus granite, a comparatively 'young' Precambrian granite. Even higher values were measured in a nearby 'young', Precambrian, uranium-rich granite, the Blomskog granite in the municipality of Årjäng, Värmland county. An inventory from this area showed that 54% of the wells had a radon concentration above 1000 Bq/L and 15% above 4000 Bq/L with a maximum at 27,890 Bq/L (Nylund 1987). Later on, the highest

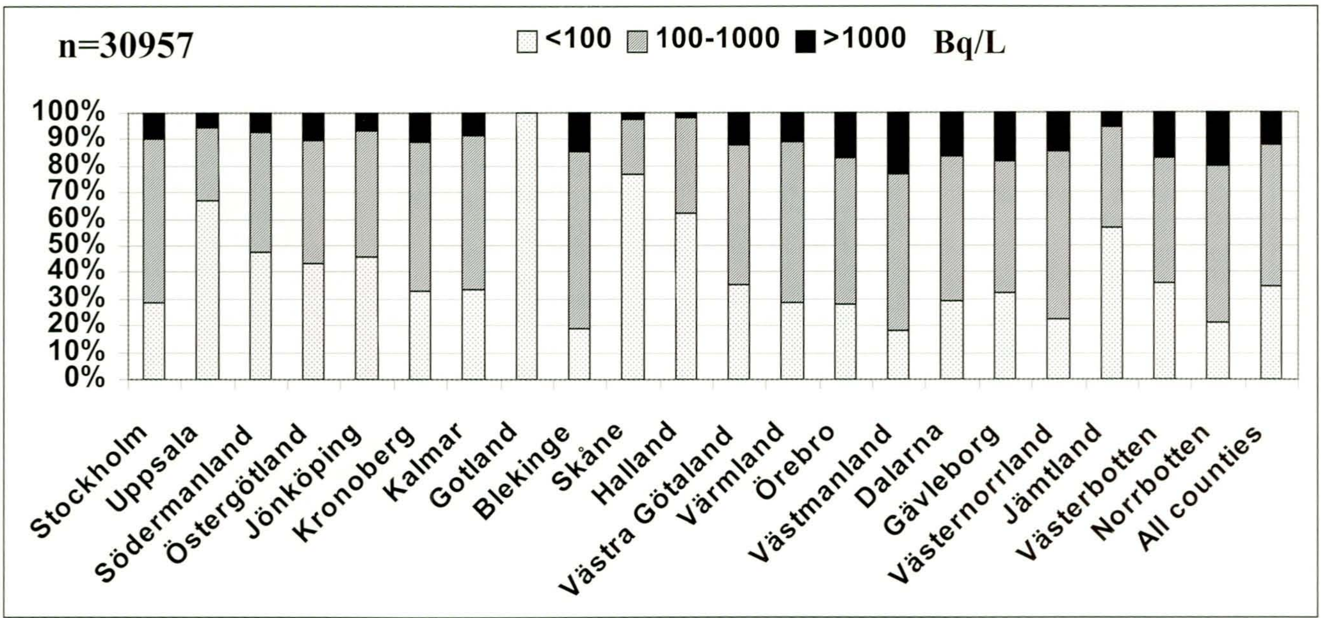

Fig. 3. Radon content in well water in Swedish counties (Based on data from SOU 2001).

value ever found in Sweden, 57,000 Bq/L was measured in a well drilled in the Blomskog granite (Åkerblom & Lindgren 1997). The highest value in Norway, 31,900 Bq/L was found in a similar type of granite, the Iddefjord granite, on the other side of the border between Sweden and Norway (Banks et al. 1998).

Quite different results were obtained in an investigation of wells in the county of Jämtland in central Sweden. 94% of the wells had radon concentrations below 200 Bq/L; even in areas of alum shale. Most of the central and western parts of the county consist of Caledonian metasedimentary rocks, but crystalline granitic and gneissic rocks dominate in the eastern part and the highest radon concentration, 2,368 Bq/L, was found in a drilled well in a Precambrian granite in the southeastern corner of the county.

A comprehensive compilation of all available data in the year 2000 on radon concentrations in drinking water in the municipalities of Sweden has been published in an official report on radon (SOU 2001). Altogether 31,000 analyses from 229 municipalities are presented in tabular form. Based on the compilation, an overview is given for each county in Fig. 3.

The Stockholm region

The Stockholm County Board (2000) has published a progress report on radon concentrations in public and private wells in the county of Stockholm. It is based on an inquiry to all municipalities in the county in 1999. Altogether 5666 analyses were collected from the archives in the municipalities. The procedure to obtain the analyses at the local level has, in general, been that the representatives of the municipalities have given advice, information and a bottle to the well-owner, who has taken the water sample himself and sent it to an approved laboratory, recommended by the municipality. The result of this study is summarised in Fig. 4 and shows that the average conditions are fairly close to the mean values for the whole country. 11% of the wells have a radon content exceeding 1000 Bq/L.

The regional differences, however, are very large (Fig. 5). There is a broad zone in the interior of the northern and central parts of the county with numerous wells with a radon content of 500-1000 Bq/L and >1000 Bq/L, as well as some few clusters of these high radon levels on certain islands. The bedrock in the central part is dominated by a young Precambrian granite (the Stockholm granite) with numerous pegmatites, whereas the northern part and most of the coastal area consist of older granitoids and some smaller stretches of metavolcanites (leptite, leptite-gneiss) and a local massif of basic rocks (gabbro, diorite) along the coast. The radon content is, in general, low in the coastal area (<500 Bq/L or <100 Bq/L) (except on certain islands) as well

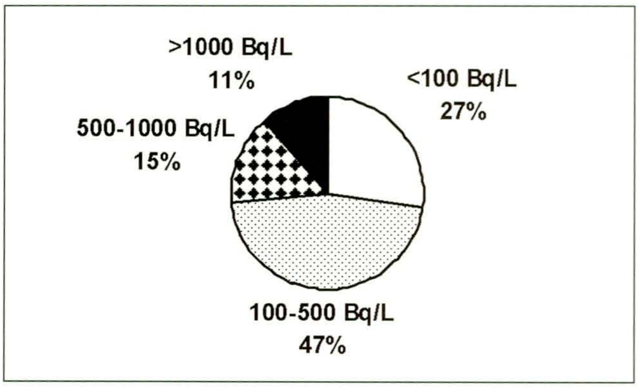

Fig. 4. Radon content in groundwater in the county of Stockholm, n=5666. (Based on data from Stockholm County Board 2000).

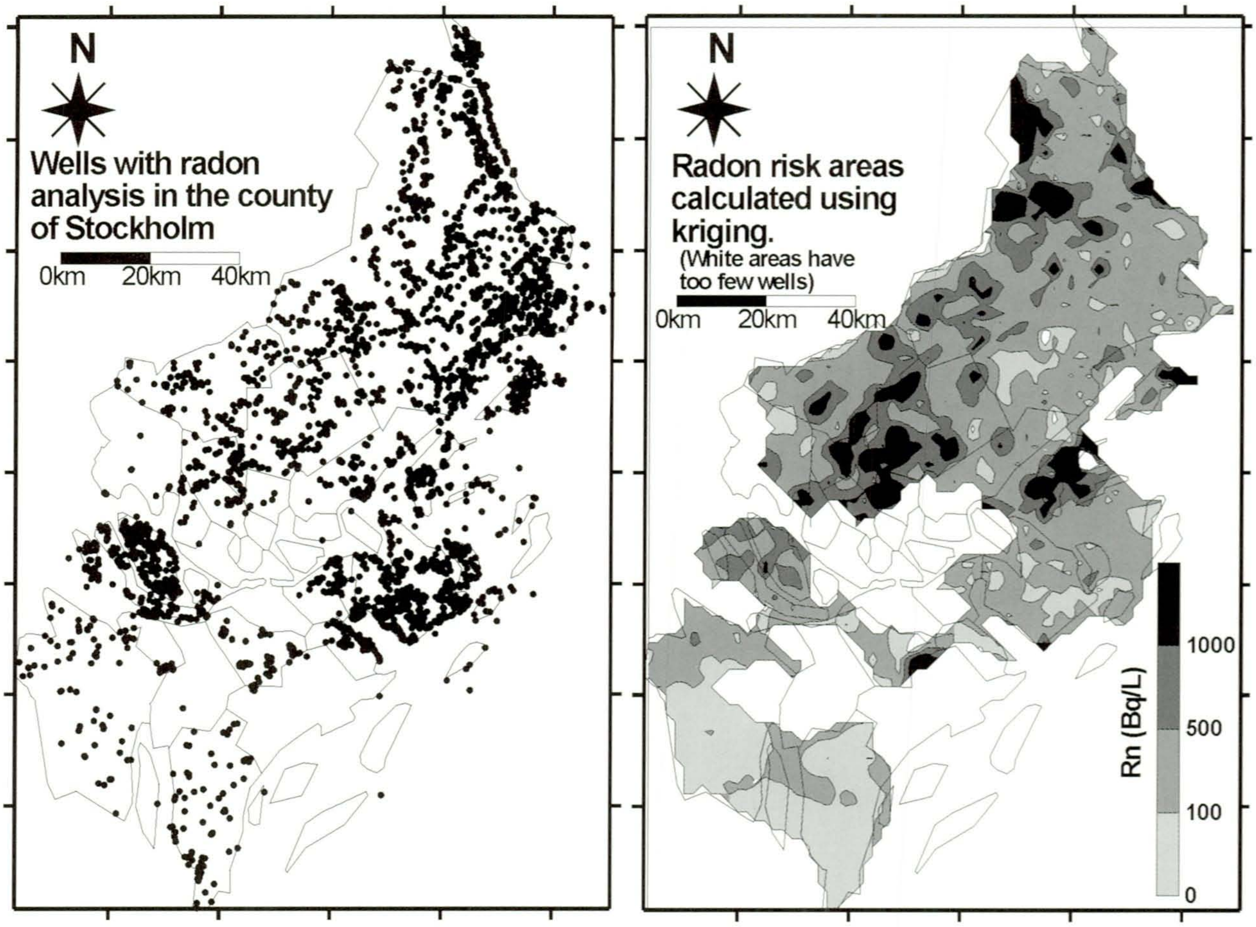

Fig. 5. Radon measurements in drinking water from private drilled wells in the county of Stockholm, and a preliminary risk map calculated from existing wells. (Based on data from Stockholm County Board 2000).

as in the whole southern part of the county, which is dominated by Precambrian metasedimentary rocks (gneiss, mica schist, metagreywacke). Consequently, there is a fairly good correlation between the level of radon in groundwater and the type of bedrock, indicating a high content in 'young' granites and a low content in metasedimentary rocks. However, it is difficult to detect any correlation in some local areas.

Local conditions

Some municipalities have been very active in providing information and sponsorship, and therefore a lot of samples have been taken and analysed, especially in the northern part of the county, where the radon risk is greatest. In Norrtälje municipality, there are almost 2000 analyses, in Värmdö and Österåker around 1000 each. Haninge municipality in the south has carried out local investigations on three islands in wells at permanent settlements (most of the wells on islands in the archipelago belong to summer-houses). All samples collected at Haninge archipelago had radon contents < 1000 Bq/L.

The database at Österåker municipality has been used for further statistical analyses. About 20% of the wells have a radon content exceeding 1000 Bq/L, whereas 16% fall in the range 500-1000 Bq/L (Fig. 6).

In order to analyse the diverse variables and their influence on the radon content, well type, well depth, age of the well and well use were studied versus the radon content in the groundwater (Fig. 7). It was found that the specific use of the well was significantly affecting the radon content and a sporadic use, common at summer houses, led to generally higher values. Some of the wells were dug in soil and such

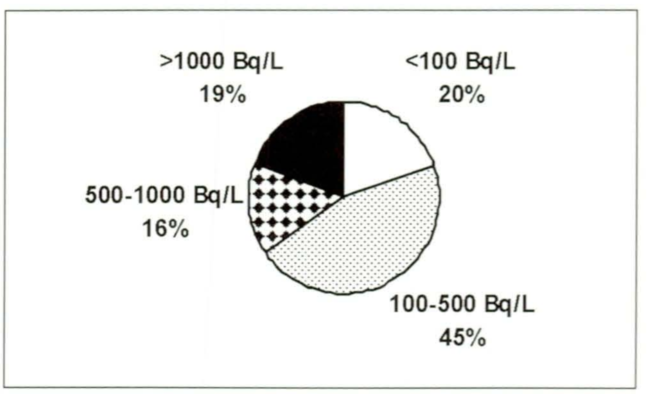

Fig. 6. Radon content in groundwater within Österåker municipality, n=999. (Based on data from Österåker municipality).

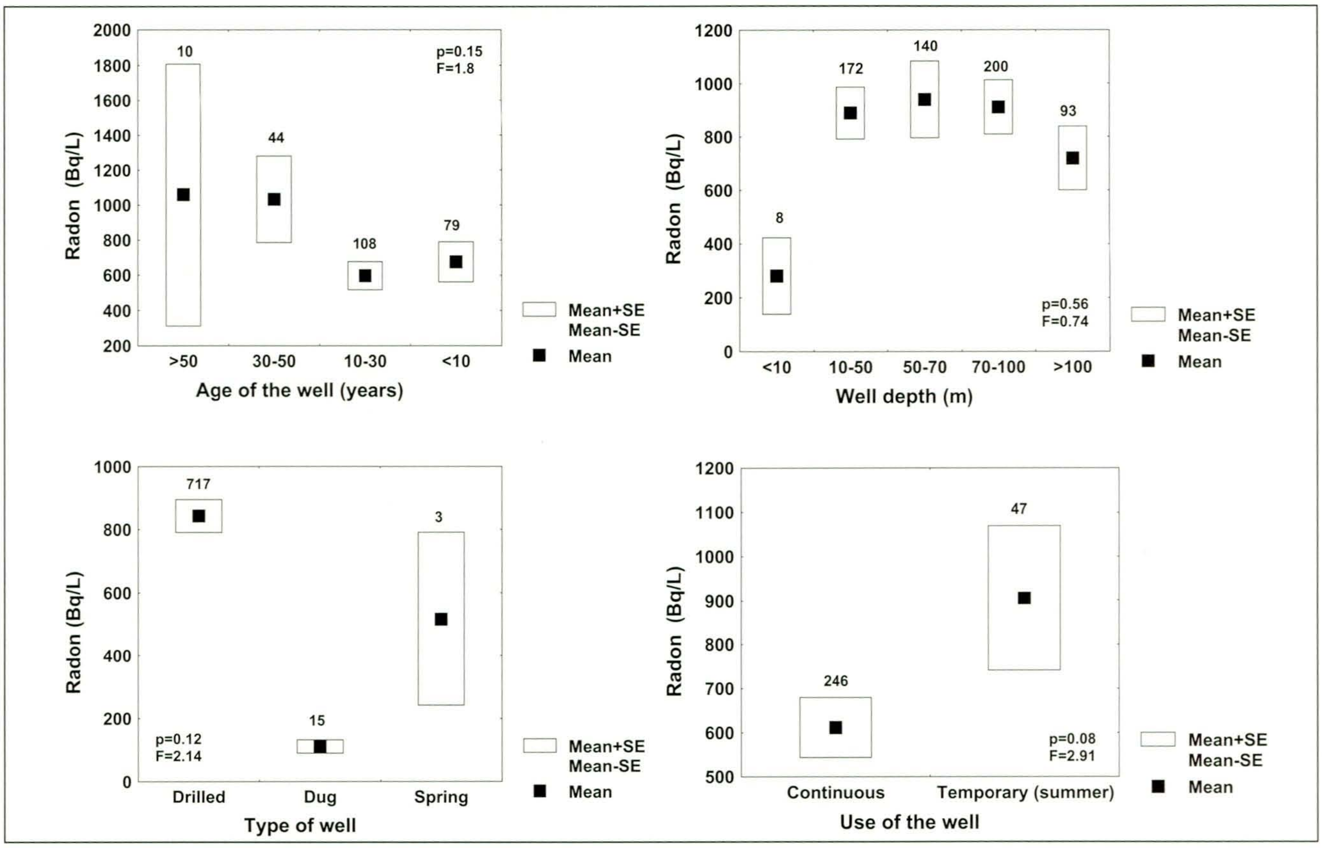

Fig. 7. Analysis of variance (ANOVA) for various classes of variables versus radon content (Bq/L) in groundwater within Österåker municipality. Mean and standard errors (SE) are presented. (n=300-900). (Based on data from Österåker municipality).

wells have significantly lower radon values than drilled wells in crystalline rocks. No clear correlation to well depth is seen, since the smallest class (<10 m) mainly comprises dug wells. Young wells show slightly lower radon values compared to older wells (Fig. 7).

Comparable results were obtained from Uppsala municipality north of Stockholm. The bedrock at Uppsala, mainly gneiss-granite and granite, is rather similar to that in the northern part of Stockholm county but there are no young granites in Uppsala municipality. A fairly detailed and scientifically based investigation has been carried out in Uppsala municipality, comprising 300 wells, which were randomly selected and carefully sampled by personnel from the municipality in co-operation with SGU (Lewin & Simeonidis 1998, Lewin Pihlblad 1998). Fluoride and heavy metals were also analysed. Only 12 wells (4%) had radon contents >1000 Bq/L with 2363 Bg/L as maximum value and a mean of 338 Bq/L. Several statistical analyses were carried out but no relationships were found between radon content and well capacity, well depth or soil thickness (Lewin Pihlblad 1998). There is, however, a distinct difference in radon content between the oldest Precambrian granites (=granitoid in Stockholm county) and acidic and intermediate volcanic rocks (Fig.8). Another important difference in radon content was found in relation to the extraction method. Wells with large water tanks have much lower radon contents than wells with pressurised withdrawal systems (Fig.8). No difference was noticed with regard to the land use around the wells.

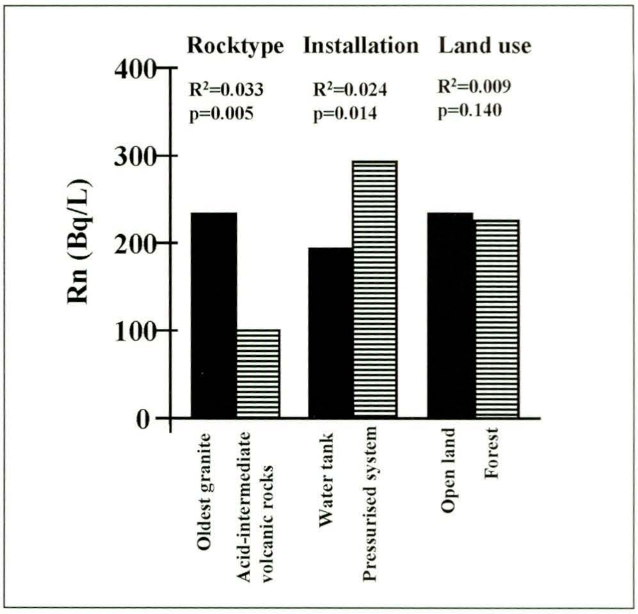

Fig. 8. Radon content versus geology, withdrawal systems and land use, n=300. (After Lewin Pihlblad 1998).

Discussion

The investigations carried out in central eastern Sweden indicate that a high content of radon in groundwater (>1000 Bq/L) is a common and widespread problem in areas of Precambrian crystalline bedrock. However, many of the investigations are not scientifically reliable, due to the well selection method and sampling techniques. The number of wells with a high radon content is probably overestimated within the local archives at the municipalities, since the sampling has often been carried out in areas where an increased radon risk is expected. There are very few scientific investigations carried out in Sweden, in which various radon-affecting variables and their influence on the radon content of groundwater have been analysed. Rock type is clearly one of the most important variables, giving a high radon content in acidic granites and pegmatites compared to intermediate and basic rock types. The same lithological dependence has also been found in Norway (Banks et al. 1998) The reason for this is probably the abundance of uranium and thorium in acidic magmatic rocks, in combination with a more pronounced regular fracture pattern which increases the surface area of water-rock contacts. However, local geological conditions, such as the presence of more profuse minor pegmatite veins, which are not shown on the more generalised regional maps, are probably very important. The island of Ljusterö, in Österåker municipality, has, for example, several small villages with very high contents of radon, which cannot simply be explained by the data presented on the generalised geological maps (Table 1).

The actual use of the well is another variable of interest. Continous extraction of groundwater, such as in permanent housing areas, increases the groundwater circulation which decreases the radon content. The technical installations must also be taken into consideration during water sampling since installations with the possibility of aeration (e.g., using water tanks) give lower values than pressurised systems as well as bad well constructions with inflow of surface water (Nilssen 2001).

Conclusions

The conclusions from this overview of the radon content in groundwater from drilled wells in Sweden, mainly from the Stockholm region, can be summarised as follows:

- There are several pronounced risk areas in Sweden, as well as large regional differences in the county of Stockholm, with higher and much higher radon contents than the compulsory limit for private wells >1000 Bq/L.
- Wells with a high radon content are to be found in small areas and scattered sites even outside the main risk regions for radon, which was shown, for example on the island of Ljusterö in the county of Stockholm.
- There is a fairly positive correlation between high radon contents and Precambrian granites (especially comparatively young granites), pegmatites, acidic volcanites and some acidic gneisses.
- Detailed bedrock information from the area surrounding the well and even in the drillhole is needed in order to investigate more fully the precise relationship between radon concentration and rock type.
- The use of the wells and the technical installations clearly affect the radon content.
- Data from well archives in the municipalities have to be handled with great caution due to incomplete information about the wells, different procedures during sampling, different methods for measuring and seasonal changes in radon content.
- Further studies are needed of the relationship between radon content and
  - Hydraulic conductivity of the bedrock
  - Hydraulic connection soil/rock
  - Hydraulic gradients and topography around the well
  - Type and depth of soil cover
  - Chemical composition in the water of the wells

Acknowledgements

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Table 1. Radon content in drilled wells in some small villages on the island of Ljusterö, Österåker municipality.

Village	Total number of wells	Wells with radon content > 1000 Bq/L	Interval (Bq/L)	Geology
Kårnäs	46	11 (24%)	1,200-15,000	Predominant grey gneiss-granite and some clay
Marum	59	42 (71%)	1,200-8,600	Mostly clay with some outcrops of red gneiss-granite
Sundvik	11	10 (91%)	1,800-6,100	Outcrops of red gneiss-granite mixed with till and clay
Åsättra	17	13 (76%)	1,500-8,610	Outcrops of red gneiss-granite mixed with till and clay
Ängsvik	9	3 (33%)	1,300-15,200	Outcrops of red gneiss-granite mixed with till and clay

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