

Uranium and radon in groundwater

An overview of the problem

K. Skeppström and B. Olofsson

*Department of Land and Water Resources Engineering,
Royal Institute of Technology (KTH), Stockholm, Sweden
kirlna@kth.se*

Abstract: Radioactive elements occur naturally in the environment. A long-term exposure to the radioactive gas radon (^{222}Rn) can lead to lung cancer. In Sweden, 450 cases of lung cancer, mostly among smokers, are registered every year, due to inhalation of radon gas. The ultimate parent element of ^{222}Rn is uranium (^{238}U), which is found in soil and bedrock in varying concentrations. ^{238}U is also radioactive but causes more harm due to its toxicity; kidney problems arise when uranium is ingested. In some areas of Sweden where municipal water is not available, wells are drilled in bedrock to extract water for drinking purposes and other uses. Groundwater from wells drilled in rock types rich in uranium (e.g. granite) has shown tendency to have both high radon and uranium concentrations. However, high concentrations of radon exceeding the Swedish regulatory limit of 1000 Bq/l have also been observed in bedrock containing low concentrations of uranium (<2 ppm). This observation might indicate that the water came from another bedrock (e.g. pegmatite) at several meters depth, which often goes undetected on geological maps. The uranium concentration in water is usually not routinely measured as an indicator of water quality despite its toxicity. A uranium concentration as high as 445 $\mu\text{g/l}$ (WHO limit is 15 $\mu\text{g/l}$) was observed in one private well in Stockholm County. The heterogeneous conditions in the subsurface, with respect to geochemistry, groundwater flow, geology and fracture pattern, make the development of a risk prediction model that can be applied at a general scale complex. This paper presents an overview of the problem of natural radioactivity in drinking water from drilled wells in Sweden.

Keywords: Radon, Uranium, Groundwater, Risk prediction.

INTRODUCTION

Groundwater is favoured as a source of drinking water in many countries. Water coming from the subsurface is often thought to be cleaner and easier to treat as compared to surface water and as a result of which, many wells have been either dug or drilled. However, besides the risk of being contaminated by anthropogenic pollution, groundwater naturally contains several chemical components, which can lead to different kinds of health problems. According to Reimann and Banks (2004) a groundwater source can potentially contain several naturally occurring chemical elements, many of which are not tested routinely as indices of water quality despite their known toxicity. Uranium and its daughter product radon are two naturally occurring elements that can lead to health problems if present in high concentrations in groundwater. Countries that have problems with natural radioactivity in their water include Sweden, Finland, Norway, USA, Canada, India, Iran and Brazil among others.

Uranium exists as three isotopes: ^{238}U , ^{235}U and ^{234}U . The first two isotopes have their own decay series while the third one is an intermediate product of ^{238}U decay series. Due to its high abundance in total natural uranium 99.28% by weight (Wilkening, 1990), ^{238}U is the isotope of interest and in addition it is the parent element of the most frequently studied isotope of radon, ^{222}Rn . Uranium is radioactive and undergoes a series of decay steps until it reaches a stable state, whereby lead (^{206}Pb) is the final product. In the decay series (Figure 1), radiation is emitted in the form of alpha particles (α), beta particles (β) as well as gamma rays (γ) and intermediate daughter products are also formed.

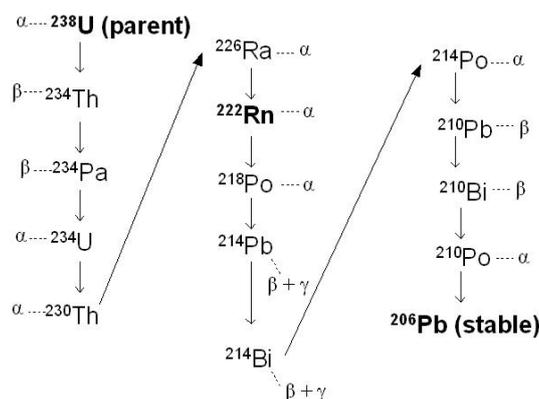


Figure 1. The uranium decay series

^{222}Rn , which exists as a gas, is a health hazard since exposure to the gas over a long period of time increases the risk of developing lung cancer (SSI, 1998; NRC, 1999; Darby et al., 2005). Radon in water is a problem in that the gas easily degasses from the liquid and contributes to the total concentration in an indoor environment, implying that the main risk of contamination is via inhalation (Paulsen, 1991; WHO, 2004). Uranium on the other hand is more harmful due to its toxic nature rather than its radioactivity. Uranium has been identified as a nephrotoxin by the World Health Organisation (WHO), implying it is a naturally produced chemical, which may cause kidney damage. Studies of human and laboratory animals have showed that uranium exposure leads to kidney problems (Zamora et al., 1998; Kurttio et al., 2002).

Groundwater can either be extracted from bedrock (drilled wells) or from a soil aquifer (dug well). Private wells are often drilled or dug to supply water to individual households that cannot be connected to a public water supply. Groundwater from wells dug in soil aquifers usually contains 5-50 Bq/l in soils with low uranium concentrations and 10-100 Bq/l in soils with normal concentrations (Åkerblom and Lindgren, 1997). Radon is principally a problem in wells drilled in bedrocks that contain average or high concentrations of uranium. Uranium on the other hand can be a significant problem in both dug and drilled wells. This paper focuses on drilled wells. Table 1 shows typical radon concentrations in Swedish groundwater, extracted from different aquifer types.

Table 1. Typical radon concentration ranges in Swedish groundwater

	Radon (Bq/l)
Wells dug in soil	
Normal concentration in Sweden	10 - 300
In granite areas	40 - 400
Maximum concentration registered	3500
Wells bored in sedimentary rocks	10 - 50
Wells bored in crystalline bedrock	
Typical Swedish bedrock	70 - 500
Uranium-rich granites	300 - 4000 (max 89000)
Uranium-rich pegmatites	Max 15000-30000

Source: Åkerblom et al., 2005

Regulatory limits or other maximum admissible concentrations for ^{238}U and ^{222}Rn vary in different countries. The standards and guidelines that are commonly adopted are shown in Table 2. In Sweden, water with a radon concentration of 1000 Bq/l or more, is unsuitable for consumption while water with a concentration of 100 Bq/l or more gets a notice but no remedial action is required, unless the water is a public supply. The European Union does not have any regulatory limit for radon but instead provide recommendations for both public and private water supplies. These recommendations are similar to the limits used in Sweden (European Commission, 2001).

WHO recommends the limit of uranium concentration in drinking water below 15 µg/l. The initial limit suggested by WHO was 2 µg/l and later changed to 9 µg/l. The actual limit (15 µg/l) is suggested as a provisional guideline value until additional information on health effects is obtained. Total Indicative Dose (TID) is also used as an additional guidance level for radionuclides in drinking water in many EU countries. TID includes doses from all natural and artificial radionuclides but excludes radon, daughter products of radon, tritium as well as potassium-40 (Östergren et al., 2005). A TID of 0.1 mSv/year should not be exceeded. It is worth mentioning that a person, consuming water with a uranium content of 100 µg/l on a daily basis, will receive a dose of 0.1 mSv/year. As far as ²²⁶Ra is concerned, one usually refers to an activity concentration in Bq/l as a reference guideline. A daily consumption of water with an activity concentration of 0.5 Bq/l of ²²⁶Ra also leads to a dose of 0.1 mSv/year. While the reference of 0.5 Bq/l is used as regulatory limit for ²²⁶Ra in Europe, an even lower value of 0.185 Bq/l (5 pCi/l) is adopted for total radium (²²⁶Ra and ²²⁸Ra) in the US.

Standards and guidelines must be enforced for public water but there is no requirement for enforcement for private well owners. In Sweden, there are more than 500 000 private owners of drilled wells, half of which use water from the wells on a permanent basis (SOU, 1994). Routine chemical analyses from most of these wells are not carried out.

The objective of this paper is to give an overview of the subsurface conditions that guide the production and migration of radioactive elements (²³⁸U and ²²²Rn) in groundwater. The complexity of predicting risk areas at general scale is also outlined in this study.

Table 2. Standards and guidelines for radon and uranium

	Radon (Bq/l)	Uranium (µg/l)
WHO	-	15
USEPA	~ 150 Bq/l	30
SWEDEN	100 Bq/l [#] 1000 Bq/l ^{##}	15

[#] More than 100 Bq/l is a compulsory action level for public water plants

^{##} More than 1000 Bq/l is a compulsory action level for all kinds of water

Source: WHO (2004), Östergren et al. (2005) and, USEPA (2005)

BACKGROUND

The natural radioactivity of the earth can be of two types: primordial radionuclides that have survived since their creation (several billion years ago) and secondary radionuclides that are formed from the decay of primordial nuclides (Eisenbud and Gesell, 1997). Uranium is a primordial radionuclide with a half-life of 4.5×10^9 years. In the earth's crust, the average concentration of uranium is of the order of 2.7 ppm (Siegel and Bryan, 2004). Uranium originates from magma and in some rocks, the uranium concentration is naturally higher than average amount due to the way they were formed and the types of minerals they contain (Keller, 1992). Rocks are made up of one or more minerals. The major primary ores of uranium are uraninite (UO₂) and pitchblende (U₂O₅.UO₃) whereas secondary uranium minerals, which were formed as a result of alteration and redistribution by groundwater, are mainly a mixture of uranium oxides, other elements (Pb, Th, Cu, Ca, P) and a certain content of water (Burns and Finch, 1999). Acid igneous rocks such as granite often have higher than average concentrations of uranium of the order of 5 ppm (Åkerblom and Lindgren, 1997). Other rock types that often have enhanced uranium concentrations include syenites, pegmatites, acid volcanic rocks and acid gneisses (Knutsson and Olofsson, 2002).

Despite a high content of uranium, some rock types are usually not considered problematic since water is not extracted from them because either they give no sustainable yields or the water cannot be used for drinking purposes due to contamination by other heavy metals, even more toxic than uranium. Carbonaceous black shale is one example. A typical situation that is sometimes encountered is that wells are thought to have been drilled in low-uranium containing rocktypes,

which in reality are supplied with water from an intrusion of another rock type deep below the surface that causes the radon problem. Flow of groundwater to a drilled well in crystalline rock often follows fractures and fracture zones and other rock structures such as rock contacts (Olofsson et al., 2001). It is very difficult, often impossible to clarify the flow pattern to a well in detail.

^{222}Rn is formed during the decay of radium atoms (^{226}Ra). During that process, the radon formed is propelled away from the site of decay (Figure 2) and an alpha particle is recoiled in the opposite direction. Depending on its position and orientation in a mineral grain, ^{222}Rn may either end up in the fracture carrying water or gets buried deeper in the rock matrix (Fleischer, 1980). The fraction of radon atoms released into a pore as compared to the total radon produced from a radium-bearing grain is called the 'radon-emanating coefficient' (Edsfeldt, 1998). After emanation, other processes like diffusion and dispersion are responsible for the transport of the radon formed.

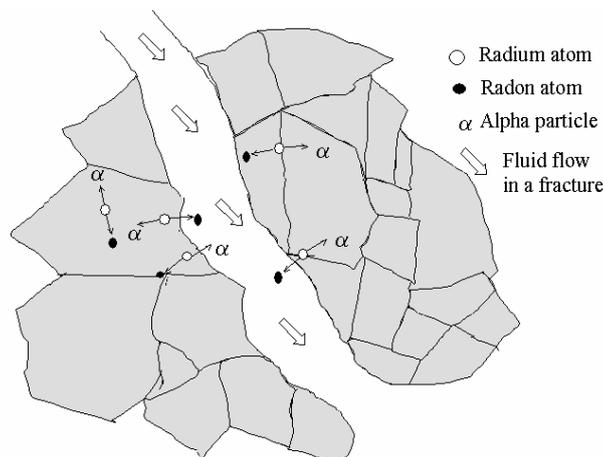


Figure 2. Radon emanation from mineral grains in a rock mass

Prerequisites for uranium, radon and radium to be transported in groundwater depend on the presence of fractures and the degree to which these fractures are connected in the bedrock. The flow of groundwater depends on potentials, which are often formed from groundwater recharge and topography. Groundwater flow is usually slow in fractures except in the vicinity where pumps are in operation (Olofsson et al., 2001). Not all fractures are hydraulic conductors. Hydraulically significant fractures facilitate fluid flow and are connected to other hydraulically conductive fractures to form a network of fractures (NRC, 1996).

Uranium, radium and radon are transported by different mechanisms in the groundwater. Uranium and radium are solutes while radon is a gas. In rock minerals, uranium occurs in the +4 oxidation state and is immobile in that state, at low temperatures and pressures. In an oxidizing environment (in which the groundwater in fracture contains an appreciable amount of dissolved oxygen), U is oxidised to the more mobile +6 state (UO_2^{2+}). Leached uranium gets into solution and is transported together with the groundwater. In the water, uranium(VI), as UO_2^{2+} ions, can also form complexes with commonly existing ions in groundwater such as OH^- , CO_3^{2-} , F^- , PO_4^{3-} and SO_4^{2-} (Chen and Yiacomini, 2002), and may also be strongly complexed by dissolved humic substances (Glaus et al., 2000; Saito et al., 2004). Uranium (VI) is also strongly bound by Fe oxides, at $\text{pH} > 5$ (Waite et al., 1994). Under reducing conditions when U(IV) predominates, sorption or co-precipitation of uranium with metal oxides in grain coatings becomes an important process (Schumann and Gundersen, 1996).

The occurrence and distribution of ^{226}Ra in groundwater is principally controlled by its production from its immediate parent isotope, thorium (^{230}Th) as well as its removal from solution by adsorption or cation exchange processes (Herczeg et al., 1988). According to Langmuir and Riese (1985), in natural waters Ra predominates as the free ion, Ra^{2+} , or as an uncharged complex, RaSO_4^0 . Based on previous studies by Gascogne (1989), Langmuir and Riese (1985) and Langmuir and Melchior (1985), radium is easily removed from solution by adsorption (on e.g. clays and rock

silicates) or by coprecipitation with insoluble sulphates. It was also found that Ra appears to be stabilised in solution where high concentrations of Ca^{2+} , Mg^{2+} and Cl^- prevail. This is because these ions compete for adsorption site.

As a result of the hydrogeochemical processes occurring in the subsurface, uranium and its decay products such as radium may be enriched on the surface of the fractures (Åkerblom and Lindgren, 1997). This geochemical process significantly increases the radon emanation efficiency of the rocks (Schumann and Gundersen, 1996). Consequently, groundwater in uranium-rich crystalline rocks can have an elevated radon concentration in relation to the radon concentration of the surrounding rock types. Radon migration depends on a number of factors including emanation, diffusion and permeability of the rock.

As explained in a previous section, only a certain percentage of radon atoms emanated, gets released into the fracture and mobilized. The recoil distance is dependent on the density and composition of the material. The diffusion length of ^{222}Rn is short and is of the order of 0.02-0.07 mm in mineral grains (Tanner, 1980). It is thus justified to assume that only a few mm layer of the rock near to the fracture surface can potentially contribute to increase the total ^{222}Rn concentration in the groundwater. This migration of radionuclides results in a disequilibrium of the water-rock system, implying that the activity of radionuclides in the groundwater is different from that in the surrounding matrix. The mass transfer from matrix into the groundwater in the fracture is illustrated in Figure 3. The consequences of the geochemical reactions and the transport processes can result in high radon concentration in water and can render uranium and radium mobile and then transported by groundwater flow.

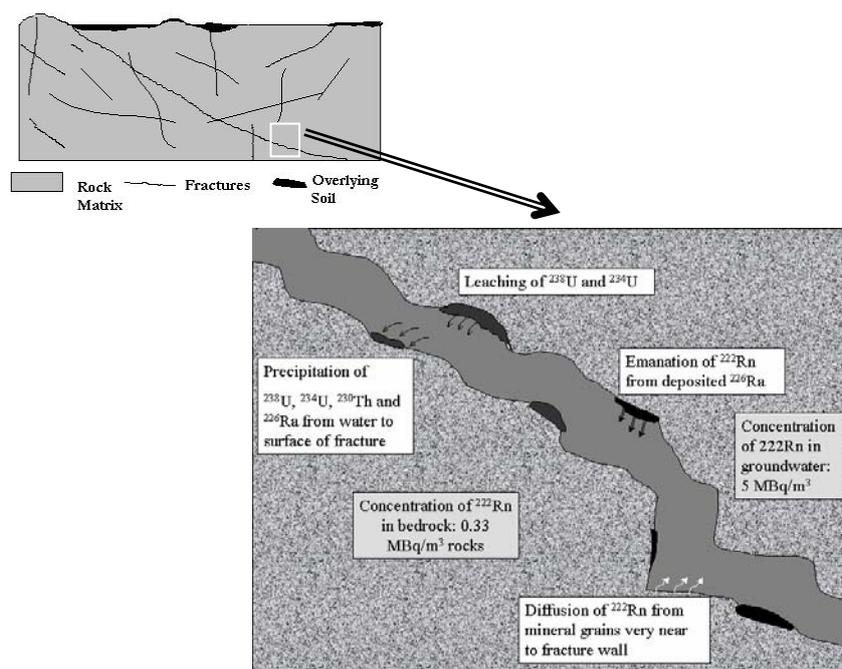


Figure 3. Radon and uranium migration in crystalline rock (modified after Åkerblom and Lindgren, 1997)

A CASE STUDY IN STOCKHOLM AREA

Background

Every year, 450 people die of lung cancer in Sweden due to inhalation of radon, usually in combination with smoking (Falk and Söderman, 2005). Exposure to radon gas is the second leading cause of lung cancer in Sweden after smoking (SSI, 1998; Mjönes and Åkerblom, 1999). Radon problem in wells is due to the occurrence of Precambrian bedrock consisting predominantly of

granites, acid gneisses, and acid volcanics with a high content of radioactive minerals (Åkerblom and Lindgren, 1997). More than 200000 drilled wells are used on a permanent basis and additionally there are more than 300000 drilled wells used in summerhouses, many of which are converted to permanent houses yearly (SOU, 1994). In the early 1990's, the Swedish Geological Survey (SGU) in collaboration with the Swedish Radiation Protection agency (SSI) produced a groundwater risk map based on airborne radiometry, bedrocks data, ground survey, analyses of water samples as well as experience from the mining industry. The risk regions were principally correlated to the granite types of rock with enhanced uranium concentration (> 4 ppm). Knutsson and Olofsson (2002) have shown that high radon concentrations could however be encountered outside risk regions. In the Stockholm archipelago, there are big differences in the concentrations of radon in groundwater from drilled wells despite that surface geological mapping has revealed similar rock types. The island of Ljusterö has been the focus of this paper. Figure 4 shows an overview of the situation in Stockholm County as well as location of Ljusterö.

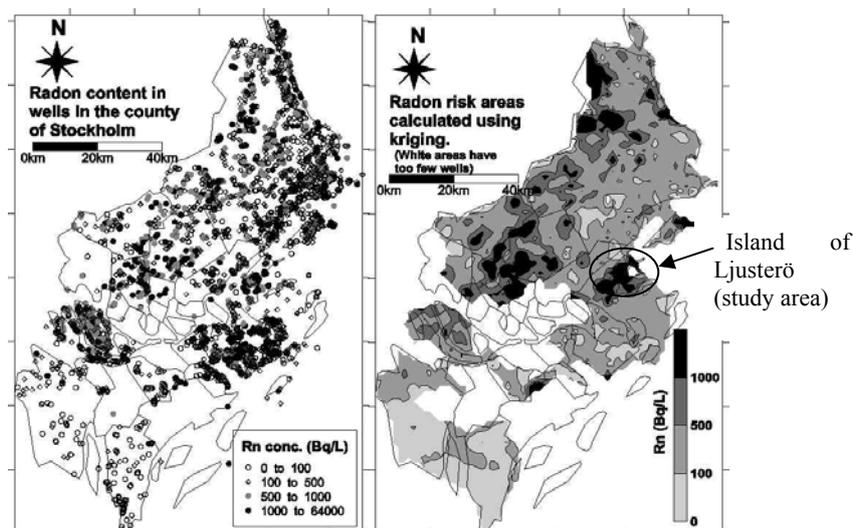


Figure 4. Radon concentrations in drinking water from private wells and interpolation of point data to produce a radon surface map (Knutsson and Olofsson, 2002)

Description of study area

Ljusterö is located in the Stockholm archipelago and stretches 13 km from north to south (Figure 4). Many houses are summerhouses but 1700 people are permanently living on the island. The Precambrian bedrock of Ljusterö originates from the Svecokarelian orogeny 1750 to 1900 Ma. The bedrock consists of more or less gneissic grey or red older granites (Emell and Moen, 2005). The topography varies throughout the island with a maximum altitude slightly above 40 m.

Data and Methods

Radon concentrations on 195 wells were obtained from the municipality and basic statistics were performed. Since the relationship between radon in groundwater and uranium content of the bedrock from which the well is drilled was to be investigated, uranium data from airborne measurements were collected from the Swedish Geological Survey as an ASCII file and were converted into a surface map using the software ArcMap. For each well, the corresponding uranium was extracted using the zonal statistics function. A sampling program related to an ongoing project by the corresponding author was conducted in 2004 on Ljusterö and an additional database comprising 38 wells were available for analysis of radon with respect to uranium in water, radium in water and uranium in bedrock, measured on outcrops. Kruskal-Wallis ANOVA by ranks and

correlations were calculated using the statistical software package STATISTICA release 6 - StatSoft, 2001. It is worth mentioning that a complete analysis of groundwater chemistry was performed and would be modelled and presented in a future work.

Results

Based on data provided by the municipality, it was observed that the radon concentration for the majority of the wells varied between 100 Bq/l and 5000 Bq/l but a maximum concentration of 63 560 Bq/l was also registered on Ljusterö. The piechart in Figure 5 shows the percentage of wells falling into the different radon classes.

The relationship between radon in groundwater and bedrock type was investigated and despite similar surface geology on the island the radon concentration in the wells was varying without a clear distribution pattern. The relationship between radon in water and uranium content in bedrock was analysed and the result was presented in the form of a box-plot (Figure 6). The median radon concentration for all uranium classes (including the class of 0-3 ppm) was significantly high. No increasing trend was observed for increasing uranium concentrations in bedrock.

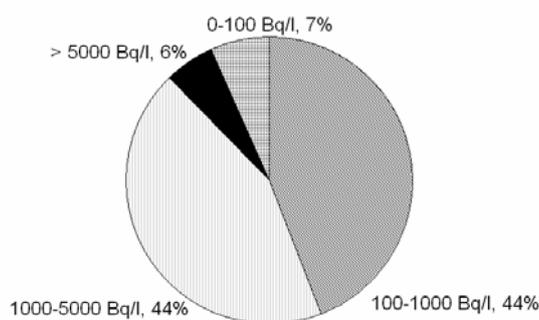


Figure 5. Radon content in drilled wells at Ljusterö, Stockholm archipelago ($n=195$)

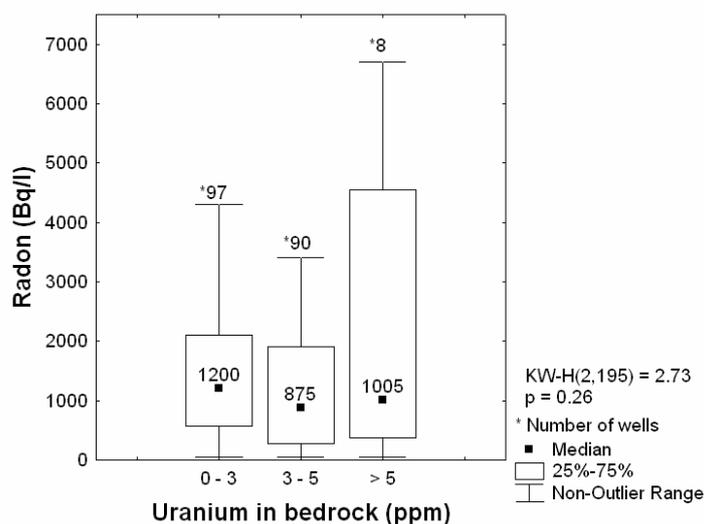


Figure 6. Boxplot showing relationship between ^{222}Rn in water and ^{238}U in bedrock (airborne measurement), $n=195$

Results of sampling by the authors on a total of 38 private drilled wells indicate that the radon concentration in groundwater varied from 3.7 Bq/l to 5800 Bq/l. 65% of the wells were exceeding the Swedish regulatory limit for radon, at 1000 Bq/l. The minimum uranium concentration registered was 0.9 $\mu\text{g/l}$ and the maximum was 30 times higher the limit recommended by the WHO,

at 15 µg/l. ^{226}Ra activity varied between 0.02 Bq/l and 3.77 Bq/l, with 30% of the investigated wells exceeding the recommended guidance level of 0.5 Bq/l.

Results of Kruskal-Wallis ANOVA are presented in the form of boxplots (Figure 7). The median concentration of radon in groundwater was compared to 1) uranium concentrations in water, 2) radium (^{226}Ra) concentrations in water and 3) uranium content in bedrock (measured on outcrops). In all, three cases, high radon concentrations could be observed for low uranium concentrations in water (< 15 µg/l), low radium activity in water (< 0.5 Bq/l) and relatively low content of uranium in bedrock (< 3 ppm). In our dataset, a trend for increasing radon concentration with increasing concentration of uranium and radium ions in groundwater was also observed. No trend was observed for uranium content in bedrock.

The correlations between radon, radium and uranium in solution (Table 3) are positive but very small. The $^{226}\text{Ra}/^{238}\text{U}$ ratio (an indicator of disequilibria in groundwater system) was also found to vary between 0 and 12.

Table 3. Correlation between ^{222}Rn , ^{226}Ra and U

	^{222}Rn	^{226}Ra	U**
^{222}Rn	1		
^{226}Ra	0.18	1	
U	0.16	0.034	1

** U refers to total uranium (234U and 238U) but concentration of 234U is insignificant so that $U \sim 238\text{U}$

Discussion

This preliminary investigation conducted on the island of Ljusterö in the Stockholm archipelago reveals radon, uranium as well as radium problems in groundwater. Most at risk are the inhabitants that are living permanently on the island, who lack access to municipal water and who rely on drilled wells for their water supply.

Based on the data obtained from the municipality, only 7 % of the wells investigated are within the recommended concentration of 100 Bq/l, valid in Sweden. The extreme value of 63 560 Bq/l was the highest recorded in the Stockholm County. Such extremely high concentrations maybe encountered in Sweden in granite rocks enriched with uranium. In fact, Åkerblom et al. (2005) reported a high value of 89 000 Bq/l in a private well in Sweden. The authors of this paper are not in a position to discuss the different uncertainties or errors that may have occurred during sample collection and analysis/measurement steps. The sampling of the 38-drilled wells in 2004 was however conducted by the authors. Although no extreme values were registered, radon concentrations were high and many wells were exceeding the regulatory limit.

Uranium concentrations in drinking water had not been regularly monitored until only recently and this might be due to a lack of awareness of the potential health problems that can arise. A very small correlation between radon in water and the concentrations of its parent elements (uranium/radium) in solution could be found. This observation combined with the results of very high ^{222}Rn concentration associated with low concentrations of uranium and radium (Figure 7a and 7b) support the statement put forward by previous researchers such as Schumann and Gundersen (1996), that radon concentration in water is not solely coming from its parent elements in solution but also from other sources. One most probable source is from deposited radioactive uranium/radium on the surfaces of the fracture. Emanation from the fracture wall then contributes to increase the concentration of radon in the water. Migration of radionuclides in the groundwater in the fractures are reflected in the presence of high radon concentration in water extracted from bedrock that contain either low or average concentration of uranium (0-2 ppm). Alternatively, it can be argued that the water has been extracted from a uranium rich rock (e.g. pegmatite and apatite) at several meters depth in the subsurface. Such details do not appear on a bedrock map. The ratio of

$^{226}\text{Ra}/^{238}\text{U}$ exceeds the value 1 in the majority of the wells analysed, clearly indicating that ^{226}Ra is more mobile than its parent radionuclides.

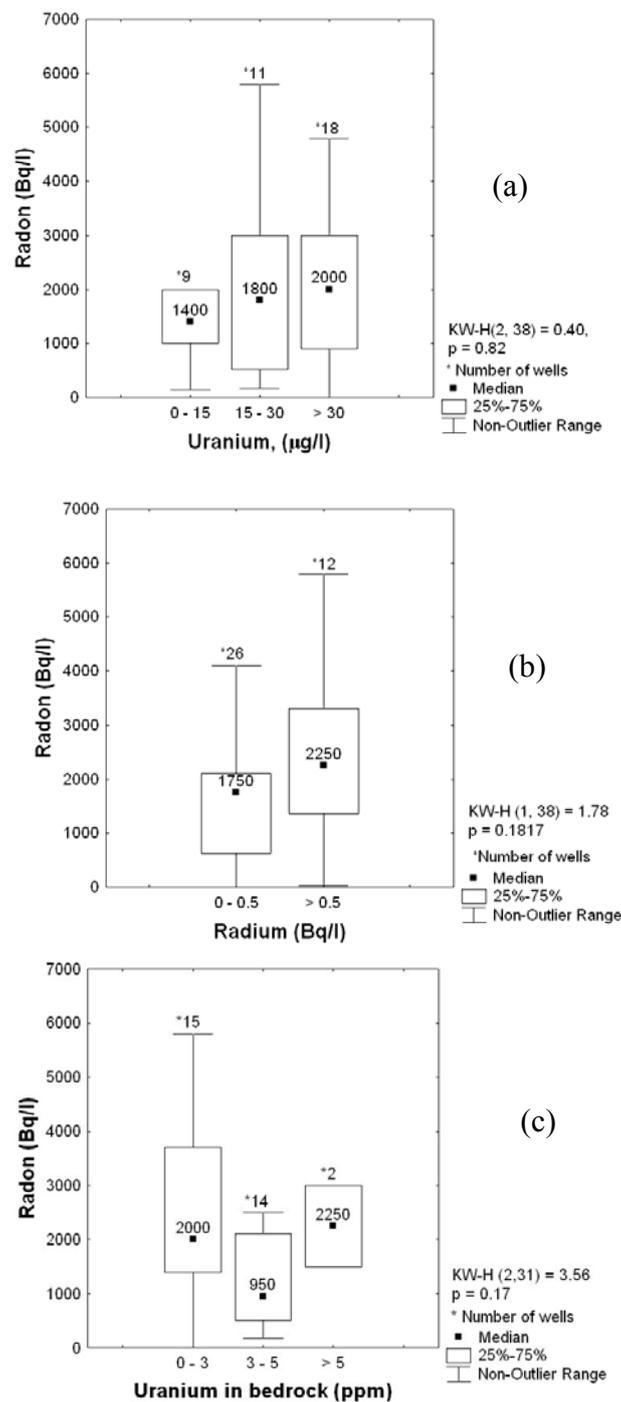


Figure 7. (a) Relationship between ^{222}Rn in water and uranium in water, (b) Relationship between ^{222}Rn in water and radium in water, (c) Relationship between ^{222}Rn in water and uranium in bedrock

PREDICTION OF RISK AREAS – COMPLEXITY OF THE PROBLEM

Several households are using water with high concentrations of radioactive elements on a daily basis, without being aware of the problem of water quality due to radon and uranium. Wells drilled outside uranium rich rock types can contain high concentrations of these radioactive elements. There is thus a need for a tool that can evaluate risk areas as accurately as possible. A prediction

tool (or model) can help decision-makers in two ways: first, in evaluating remediation measures for existing houses and second, in planning the water supply for new buildings.

Most existing risk prediction models for radon problem in water are based on bedrock studies and interpolation of point uranium data, measured in bedrock. The risk map developed in Sweden in the 1990's was based on bedrock, radiometric data, some radon measurements in wells and data that were gathered during a former uranium resource exploration in Sweden (Åkerblom and Lindgren, 1997). Such maps are helpful in giving a general overview of the problem but still need to be complemented with other tools for more accurate prediction of risk areas. A recent on-going study being conducted by the authors is testing the hypothesis that the concentration of natural radioactive elements in drilled wells is governed by a range of factors including; geological, topographical, chemical and technical variables. The aim of that study is to develop a risk prediction methodology (*Risk Variable Method*) based on GIS and multivariate statistical analysis (such as principal component analysis) to evaluate problem areas.

However, the limitations of these approaches used so far, including the *Risk Variable Method*, involve a lack of data and analysis on processes occurring in the subsurface. Water flow to drilled wells often occurs several tens of meters below the surface and the geology, geochemistry and thermodynamics at these depths are likely to be different from conditions at the surface. For a better understanding of the occurrence of natural radioactivity in drinking water, the geochemical processes as well as the flow and transport of radioactive elements in the groundwater need to be studied.

Studies on how radioactive elements are transported in bedrock fractures have often been conducted at nuclear repository sites for the simulation of how these radioactive elements will spread in a restricted environment in the event of a leak (Moreno et al., 1990; Cheng and Cvetkovic, 2003; Neuman, 2005). These studies are detailed and usually carried out at centimetre scale. Transport mechanisms models have been developed and studied at a few sites in the vicinity of a bedrock repository, which constitutes a potential *point source* of radioactive pollution. However these studies cannot be directly transformed for operative decision support in municipal planning due to their exceptional need for detailed data. In our heterogeneous natural environment, radioactive elements occur spatially spread in the bedrock and bedrock fractures and constitute a *diffuse source* of radioactive pollution. The transferability of detailed models to long distance spread to groundwater wells with unclear fracture pathways, unclear distribution of uranium minerals, unclear discharge rates and varying topographical condition, which in turn influences groundwater flow systems, has not been demonstrated. Moreover, research on specifically radon (gas) transport mechanism in groundwater is few as compared to other non-gaseous radioactive elements including uranium, plutonium etc. There is thus a need for additional research in these areas.

CONCLUSION

Wells drilled in uranium-rich bedrock often have enhanced concentrations of the radioactive elements radon, radium and uranium. The factors influencing the concentration of these elements in the subsurface include leaching, precipitation, redox conditions, rock materials properties, fracture system, emanation, and transport mechanisms among others. The consequences of these processes sometimes lead to high radon and uranium concentrations in water extracted from bedrock with a low uranium content. There is a need for further work on prediction models for areas at risk. The natural environment is complex and heterogeneous but risk models should still attempt to include the geology, geochemistry and transport phenomena prevalent in the subsurface.

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