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Sara Grolander
Svensk Kärnbränslehantering AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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Abstract

Radon concentrations were measured in different water types in Forsmark and Laxemar during the site investigation and within this study. This gives an extensive database over radon concentrations in different water types. From these measurements it can be concluded that large differences between surface water, near surface groundwater and deep groundwater can be found in both Laxemar and Forsmark. The differences in radon concentrations between different water types are used in this study to detect interactions between surface water, near surface water and deep groundwater. From the radon measurements it can also be concluded that radon concentration in deep groundwater varies largely with depth. These variations with depth are probably caused by groundwater flow in conductive fracture zones in the bedrock.

The focus of this study has been the radon concentration of near surface groundwater and the interaction between near surface groundwater and deep groundwater. Radon measurements have been done using the RAD-7 radon detector within this study. The results were evaluated and proven to be reliable and of good quality. It could be concluded that RAD-7 is a good technique for radon measurements and also easy to use in field.

The radon concentrations measured in near surface groundwater in Laxemar within this study were low and homogenous. The variation in radon concentration has been analyses and compared to other parameters. Since the hypothesis of this study has been that there are differences in radon concentrations between recharging and discharging groundwater, the most important parameter to consider is the recharge/discharge field classification of the wells. No correlation between the recharge/discharge classifications of wells and the radon concentrations were found. The lack of correlation between groundwater flow patterns and radon concentration means that it is not possible to detect flow patterns in near surface groundwater using radon as a tracer in the Laxemar area. The lack of correlation can be caused by the fact that there are just a few wells located in areas classified as recharge area. It can also be caused by the homogenous radon concentrations measured in the Laxemar area.

The radon concentrations in near surface water measured in Forsmark showed large variability with both low and high radon concentrations. This large variability in radon concentration could not be explained by the flow pattern of the groundwater since no clear correlation between radon concentration and recharge/discharge classification was found.

The radon concentration was also measured at different depths in the soil profile at three locations in the Forsmark area. The results showed large differences with increasing radon concentration with increasing depth. This gradient of radon concentration can be explained largely by the radon emanation potential of the local soil type at different depths. Soils with high organic content as peat and gyttja can be expected to have lower radon emanation potential due to lower radium content; wells in these types of soils also had low radon concentrations. High radon concentrations were found in wells with higher radon emanation potential like till and bedrock. These observations showed the importance of the radon emanation potential of the local soil for the radon concentration in groundwater.

The main purpose of this study has been to evaluate the use of radon as a tracer for groundwater flow patterns. The method is based on the ingrowth of radon from its progenitor radium according to the law of radioactive decay. According to this law the radon concentration in groundwater will reach equilibrium conditions after approximately 30 days in contact with the surrounding soil. The equilibrium radon concentration (or steady state concentration) of the near surface groundwater was measured at several location in the Forsmark area and a range of the steady state radon concentration was calculated. The measured steady state radon concentration was then used to evaluate the radon concentrations measured in near surface groundwater in the area. A recharge/discharge classification of the wells was done based on the range of steady state radon concentration and the measured radon concentrations in groundwater. All wells with radon concentration below the steady state radon

concentration were classified as recharge wells and all wells with radon concentrations above the steady state radon concentration were classified as discharge wells. The wells with radon concentrations within the range of steady state concentrations were classified as wells with groundwater that had been stagnant for at least 30 days.

Most of the classified wells were classified as stagnant wells with concentrations within the range of steady state radon concentration. The groundwater in these wells is likely not influenced by recharging or discharging water in a significant way. Only one well had low radon concentration and was classified as recharging well. This means that radon probably is a poor tracer for recharging groundwater in the Forsmark area since recharge is only identified at one site.

Four wells hade radon concentration significantly higher than the steady state radon concentration. This indicates discharge of deep groundwater with high radon concnetration from conductive fracture zones in the bedrock at these sites. Three of these four wells, SFM0013, SFM0095 and SFM0103, are found in the catchment of Gällsboträsket where signs of discharging deep groundwater have been found in previous investigations. This shows that the results from this study can be used to support the conclusions from previos studies.

In general this study showed that there were no systematic differences in radon concentrations of groundwater between recharge areas and discharge areas. Even if discharging groundwater was detected in the catchment of Gällsboträsket in Forsmark the usefulness of radon as a tracer was proven to be limited in this study since no general conclusions of the groundwater flow in Laxemar or Forsmark could be drawn from the radon measurements. This may be due to the short half-life of radon that makes the signals of recharge and discharge waters decay away before the water reaches the sampling wells. It can also be caused by the fact that signals from deep groundwater with high radon concentrations are diluted by the much larger volume of near surface groundwater. This makes the signal of high radon concentration weak and hard to detect.

Sammanfattning

Radonkoncentration har mätts i olika vattentyper i Forsmark och Laxemar under platsundersökningarna och inom denna studie. Detta har gett en omfattande databas över radonkoncentrationer i olika vattentyper. Från dessa mätningar kan man dra slutsatsen att stora skillnader i radonkoncentration existerar mellan ytvatten, ytnära grundvatten och djupt grundvatten i både Laxemar och Forsmark. Skillnader i radonkoncentration mellan olika vattentyper används i denna studie för att påvisa interaktioner mellan ytvatten, ytnära grundvatten och djupt grundvatten. Från radonmätningarna i djupt grundvatten kan man dra slutsatsen att radonkoncentrationen varierar stort med djupet i berggrunden. Dessa variationer är sannolikt orsakade av grundvattenflöde i konduktiva sprickzoner i berggrunden.

Fokus i den här studien har varit radonkoncentration i det ytnära grundvatten och interaktioner mellan ytnära grundvatten och djupt grundvatten. Radonmätningar har gjorts med hjälp av radondetektorn RAD-7 inom denna studie. Resultatet av radonmätningarna har utvärderats och visats vara pålitligt och av god kvalité. Slutsatsen kunde dras att RAD-7 är en bra teknik för radonmätningar som dessutom är lätt att använda i fält.

Radonkoncentrationerna uppmätta i ytnära grundvatten i Laxemar inom denna studie var låga och homogena. Variationerna i radonkoncentration har analyserats och jämförts med andra parametrar. Eftersom hypotesen i den här studien har varit att det finns skillnader i radonkoncentration mellan in- och utströmmande grundvatten, är den viktigaste parametern att beakta in- och utströmningsklassificeringen av de provtagna brunnarna. Ingen korrelation mellan in- och utströmningsklassificeringen av brunnarna och radonkoncentration hittades. Bristen på korrelation mellan grundvattenflödesmönster och radonkoncentration betyder att det inte är möjligt att använda radon som spårämne för att påvisa flödesmönster i ytnära grundvatten i Laxemar området. Bristen på korrelation kan även bero på att bara ett fåtal brunnar var placerade i områden klassificerade som inströmningsområde.

Uppmätta radonkoncentrationer i ytnära grundvatten i Forsmark visade stora variationer med både låga och höga radonkoncentrationer. Dessa stora variationer i radonkoncentration kunde inte förklaras av grundvattnets flödesmönster eftersom ingen tydlig korrelation mellan radonkoncentration och in- och utströmningsklassificering hittades. Detta betyder att radonkoncentrationen i ytligt grundvatten inte kunde användas som spårämne för grundvattenflöde i Forsmarksområdet.

Radonkoncentrationen mättes också på olika djup i jordprofilen vid tre olika lokaler i Forsmarksområdet. Resultatet visade stora variationer med ökande radonkoncentration med ökande djup. Denna gradient av radonkoncentration kan förklaras till stor del av radonutsöndringspotentialen för den lokala jordarten på de olika djupen. Jordarter med högt organiskt innehåll så som torv och gyttja kan förväntas ha en lägre radonutsöndringspotential på grund av lägre radiuminnehåll; brunnar i dessa typer av jordarter hade också lägre radonkoncentration i grundvattnet. Hög radonkoncentration hittades i brunnar placerade i jordlager med högre radonutsöndringspotential som morän och berggrund. Dessa observationer visade på vikten av radonutsöndringspotentialen hos den lokala jordarten för radonkoncentrationen i grundvattnet.

Huvudsyftet med den här studien var att utvärdera användningen av radon som ett spårämne för grundvattenflödesmönster. Metoden baseras på inväxning av radon från radium enligt lagen om radioaktivtsönderfall. Enligt denna lag så når radonkoncentrationen i grundvatten jämviktsläge efter cirka 30 dagar i kontakt med den omgivande jorden. Jämviktskoncentrationen av radon i det ytnära grundvattnet mättes på flera ställen i Forsmark och ett intervall för jämviktskoncentrationen räknades fram. Detta intervall användes sedan för att utvärdera de uppmätta radonkoncentrationerna i ytnära grundvatten i området. En in- och utströmningsklassificering av brunnarna gjordes baserad på det framräknade intervallet för jämviktskoncentrationen och de uppmätta radonkoncentrationerna i ytnära grundvatten. Alla brunnar med radonkoncentration under jämviktskoncentrationen klassificerades som inströmningsbrunnar och alla brunnar med radonkoncentrationer över jämviktskoncentrationen klassificerades som utströmningsbrunnar. Brunnarna med koncentrationer inom intervallet för jämviktskoncentrationen klassificerades som stillastående brunnar där grundvattnet hade varit stilla i minst 30 dagar.

De flesta brunnarna klassificerades som stillastående med radonkoncentrationer inom intervallet för jämviktskoncentrationen. Grundvattnet i dessa brunnar påverkas troligtvis inte signifikant av in- och utströmmande grundvatten. Bara en brunn hade låg radonkoncentration och klassificerades som inströmningsbrunn. Detta betyder att radon troligtvis är ett dåligt spårämne för inströmmande grundvatten i Forsmark eftersom inströmning bara identifieras vid en lokal.

Fyra brunnar hade radonkoncentrationer som var significant högre än intervallet för jämviktskoncentrationen. Detta indikerar ett utflöde av djup grundvatten med hög radonhalt från konduktiva sprickzoner i berggrunden på dessa platser. Tre av dessa brunnar , SFM0013, SFM0095 and SFM00103, finns i Gälssboträskets avrinningsområde där tecken på utströmmande djupt grundvatten har hittats i tidigare studier. Detta betyder att resultatet från denna studie kan användas för att stödja slutsatser från tidigare studier.

Sammanfattningsvis så visade den här studien att det inte finns några systematiska skillnader i radonkoncentration mellan in- och utströmmande grundvatten. Även om utströmmande grundvatten kunde detekteras i Gällsboträskets avrinningsområde i Forsmark så har användningen av radon som spårämne bevisat begränsad i den här studien eftersom inga generella slutsatser om grundvattenflödet i Laxemar eller Forsmark kunde dras utifrån de uppmätta radonhalterna. Detta kan bero på den korta halveringstiden för radon som gör att signaler från in- och utströmmande grundvatten hinner klinga av innan de når provtagningsbrunnarna. Det kan också orsakas av den utspädning av det djupa grundvattnet som sker med den mycket större volymen av ytnära grundvatten. Detta gör att signalerna med förhöjda radonkoncentrationer från djupt grundvatten är svaga och svåra att detektera.

Contents

1 Background

1.1 Introduction

The flow path and flow velocity of groundwater is of great importance for many reasons. For example, the interaction between groundwater and surface water systems is of importance when assessing groundwater quality since the interaction between water systems makes transportation of contaminants between groundwater and surface water possible. Polluted river water can infiltrate groundwater systems and deplete the quality of the groundwater and in the same way polluted groundwater can spread to surface water systems. It is also important to understand the interaction between groundwater and surface water to allow effective utilization of water resources when competing interests exists.

The need to detect and quantify groundwater flow is also big for Swedish Nuclear Fuel and Waste Management Co. (SKB) that is handling the spent nuclear fuel in Sweden. SKB is investigating the possibility to store the highly radioactive waste in the bedrock /SKB 2005/. One important part of the site investigations conducted by SKB is to study groundwater flow and especially the potential upward flow of deep groundwater that passes the intended repository depth and can transport potential leakage from spent nuclear fuel up to the surface systems.

The use of artificial tracers to detect and quantify groundwater flow is not feasible in most cases since large amounts of artificial tracers need to be added to be able to follow the signal in groundwater aquifers. Therefore the use of natural tracers is a better alternative. In this report the possibility to trace groundwater flow patterns using radon as a natural tracer is investigated. Radon is a radioactive noble gas that has been used as a tracer for many different purposes in previous studies. For example radon has been used as a tracer to detect uranium ore and to detect trust and faults in the bedrock /Prasad et al. 2008/. Several authors have used radon to trace groundwater inflow to streams, lakes and oceans /Dewayne Cecil and Gesell 1992, Wu et al. 2003, Clark and Fritz 1997, Kendall and McDonnell 1998, Corbett et al. 1997/. Radon has also been used to estimate resident time for groundwater /Low 1996/ and to detect infiltration of surface water to groundwater aquifers /Hoehn and von Gunten 1989/.

1.2 Purpose

This report is partly based on my master thesis “Radon as a tracer for groundwater discharge” /Grolander 2008/ where the use of radon to identify recharge and discharge of near-surface groundwater was evaluated. The results from this study were not conclusive and therefore complementary radon measurements in groundwater in both the Forsmark and Laxemar investigation areas were done. The purpose with this additional study is to investigate the possibility to use radon to identify areas with recharge and discharge of groundwater by measuring radon concentrations in groundwater. The questions that this study will attempt to answer are;

- Is the in-air radon detector, (RAD-7), reliable for radon measurements in groundwater?
- Are there systematic differences in radon concentration between different water types like surface water, near surface groundwater and deep groundwater at the two investigated sites?
- What processes determine the radon concentrations in natural waters?
- Are there systematic differences in radon concentrations of groundwater in recharge areas and discharge areas? Can radon be used as natural tracer for recharge and discharge of near surface groundwater?
- Can any site specific conclusions regarding groundwater flow patterns be drawn from the radon measurements in Laxemar and Forsmark?

1.3 Theory

1.3.1 Natural decay chain of Uranium-238

There are three naturally occurring radioactive decay chains in the crust of the earth originating from Uranium-238, (^{238}U), Uranium-235, (^{235}U) and Thorium-232, (^{233}Th) respectively. In Figure 1-1 the decay chain of ^{238}U is shown. This chain is of special interest since the radon isotope, Radon-222, (^{222}Rn), is one of the daughter isotopes of this chain.

According to the law of radioactive decay secular equilibrium will develop if radioactive isotopes are left in undisturbed conditions. When secular equilibrium is reached the activities of daughter and parent isotopes is equal. The time it takes for the secular equilibrium to be established depends on the half life of the daughter isotope since it takes seven to ten half-lives before secular equilibrium is reached depending on the initial activity of the daughter isotope. If the initial activity is low it takes longer for the secular equilibrium to be established. The ingrowth of daughter isotope from its parent is described by Equation 1:

$A_t = A_{eq}[1 - exp(-\lambda)]$ /Hoehn and von Gunten 1989, Kendall and McDonnell 1998/ Eq 1

where A_t is the activity of the daughter isotope at time t=0, t is the time that has passed from when the system was closed and the equilibrium started to build up, A_{eq} is the activity of the daughter isotope at secular equilibrium, λ is the decay constant of the daughter isotope (0.18 day^{-1} for radon).

The secular equilibrium for ingrowth of radon from radium is reached after approximately 30 days as shown in Figure 1-2. This function can be used to calculate t, if the A_t and A_{eq} are known. The time t is the same as the resident time in natural systems which make the equation of ingrowth a powerful tool for studies of resident times and age of natural materials. The usage of ingrowth of radon will be discussed further in section 1.3.3.

1.3.2 Radon in the environment

Radon exists as three isotopes, Radon-219 (^{219}Rn, actinon) and Radon-220 (^{220}Rn, thoron) and Radon-222, (^{222}Rn) which are formed by the decay of different isotopes of radium found in the decay chains of ^{235}U, ^{232}Th and U^{238} respectively. Actinon and thoron have very short half lives (4 and 55 seconds respectively) and because of this they are not abundant in natural air and water /Dewayne Cecil and Gesell 1992, Durridge Company 2000/. The isotope ^{222}Rn has a half life of 3.83 days and can therefore accumulate in the atmosphere and natural waters /Kendall and McDonnell 1998, Wu et al. 2003/. This study will therefore focus on ^{222}Rn and ^{222}Rn will be referred to as radon in this text.

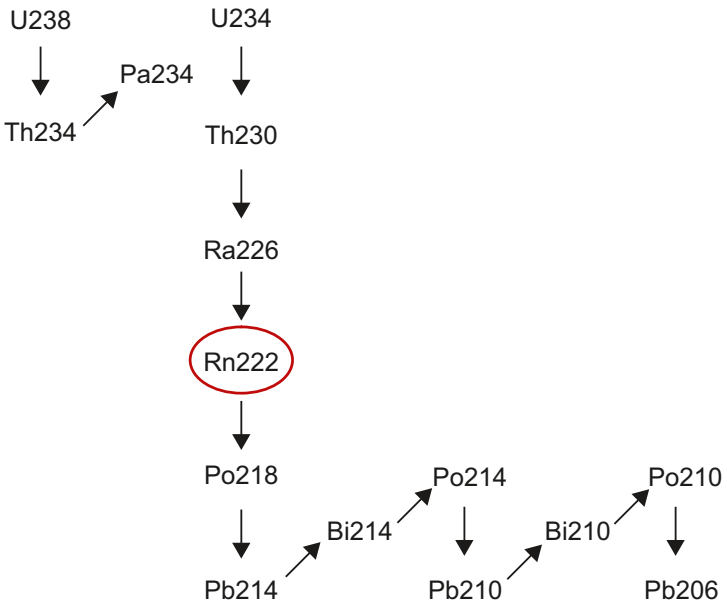

Figure 1-1. *Decay chains of ^{238}U. Vertical steps represent alpha decay; steps to the side represent beta decay /after Kendall and McDonnell 1998/.*

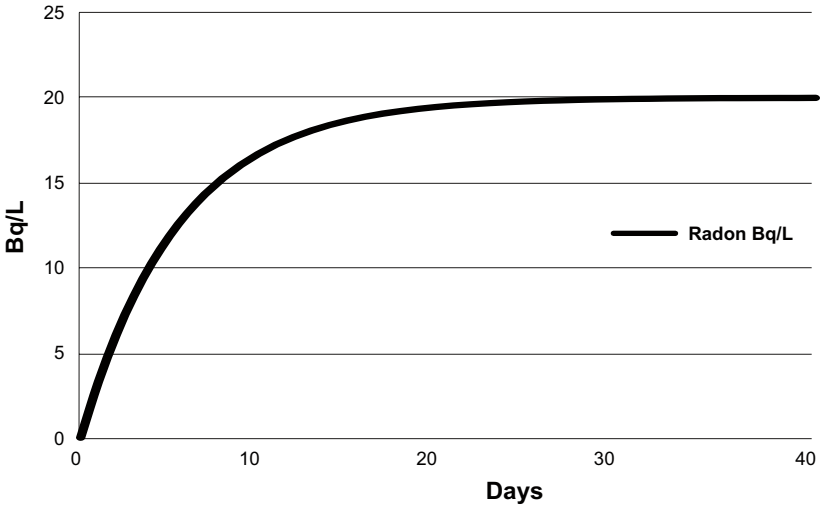

Figure 1-2. *Ingrowth of radon according to Equation 1. The equlibrium concentration is reached after approximatley 30 days.*

Radon comes into the natural water and atmosphere due to ingrowth from ^{226}Ra that exists in geological materials and waters. The process by which radon escapes from the solid material is called *emanation*. The emanation process consists of both a chemical and a physical process. The chemical process is diffusion of radon through the crystalline lattice into the surrounding environment. Diffusion of radon depends on the surface area to volume ration of the solid material since a large surface area exposed to the surroundings enables more radon to diffuse /Andrews and Wood 1972/.

The physical process is alpha particle recoil. Alpha particle recoil is when radium decays and an alpha particle and a radon atom are formed and ejected in opposite directions. For the radon to escape from the crystalline lattice by alpha particle recoil the decay of ^{226}Ra must take place in the uttermost layer of the solid material since the recoil range of radon is short. The recoil range depends on the density of the material and ranges between 0.02–0.07 mm for minerals /Skeppström 2005/. The radon atom also has to be ejected in the right direction towards the surface of the solid material in order to escape into the surrounding environment. The probability for a radon atom that is formed within the distance of the recoil range to escape to the surrounding environment is 23.5%; the rest of the radon that is formed is ejected deeper into the rock matrix /Andrews and Wood 1972/. This means that this process also depends on the surface area to volume ratio of the solid material.

Since these processes govern the emanation of radon the emanation potential of solid material depends on two factors; the first factor is the surface-area to volume ration which means that small grained soils and fractured rocks are emitting more radon than coarse grained soils and less fractured rocks /Kendall and McDonnell 1998, Cook et al. 1999/. The second factor is the radium content of the solid material. The radium content of the material depends on the concentration of ^{238}U which is normally high in granite and pegmatite bedrock since acid igneous rocks often have high uranium content /Skeppström 2005/. The radium content of the solid material is also affected by secondary mineral enrichment when ^{226}Ra is transported away from the source and then re-deposited on the walls of fractures or soil particles /Skeppström 2005/. The secondary mineral enrichment is governed by complex hydro geochemical processes which can dissolve and transport radium in groundwater and then redeposit radium on walls of fractures or soil particles. The redeposited radium atoms will decay and contribute to the radon emanation of the material.

The radon concentration in groundwater depends on the emanation potential of the solid material but also on several other factors that affect the radon concentration in groundwater. These factors are the outgassing of radon to the atmosphere, transport processes like diffusion and dispersion in the groundwater and the volume of water in the soil and bedrock that dilutes the emanated radon.

The relationship between radium content, radon emanation potential and radon concentration was studied by /Mullinger et al. 2009/. The radon concentration of groundwater, radium content of the

borehole core material and the radon emanation coefficient at different depths of the wells were measured and the patterns found were evaluated. The radon concentration, radium content and radon emanation decreased with increasing depth in this area which suggested that the radon concentration is controlled by the radium content and radon emanation of the local soil or bedrock. Temporal variation in radon concentration was also observed in connection with hydrological events and variations in water table elevations. The conclusions from this study show that radon concentration is govern by the radon emanation of the local environment but also by hydrology like precipitation event.

Table 1-1 below shows radon concentration of groundwater typical for Swedish conditions. Since radon is harmful for humans a limit for radon concentration in drinking water has been set to 100 Bq/L in public water and 1,000 Bq/L for private wells /SSI 2008/. This means that harmful radon concentration can be found in wells dug in soil in granite areas and in wells in crystalline bedrock.

The radon concentration is in general lower in soil than in bedrock as seen in Table 1-1. In the study conducted by /Skeppström 2005/ it is shown that areas with high uranium content recorded with airborne measurements do not always have high radon concentrations in groundwater. This can be caused by the fact that the airborne measurements only give information on the uranium intensities of the surface layers in soil and bedrock and the uranium content can be different a few meters down in the soil or bedrock /Isaksson et al. 2004/. The difference between the airborne uranium measurements and the radon concentrations in groundwater can also be caused by secondary mineral enrichment when ^{226}Ra is transported away from the source and then re-deposit on the walls of fractures /Skeppström 2005/. This can alter the radon concentration in groundwater and it is said that the radon concentrations in those areas are unsupported since the source of the radon is not present at the same location.

The relationship between fractures and radon concentration was investigated by /Skeppström 2005/ who found that high radon concentrations are present near fractures in the bedrock. The higher radon concentration in vicinity of fractures is explained by the increased emanation of radon from fractured rock but also by the increased mobility of radon within fracture rock. The increased mobility of radon means that the radon rich water can move upwards and into the sampled wells. Radon concentration is also higher in hydraulic active fracture within the rock since the radon in these fractures is replaced faster than it decays which allows the high radon concentrations to be maintained. In fractures with stagnant water the radon will decay and no new radon will be added which gives low radon concentration.

1.3.3 Radon as a tracer

Radon is a noble gas which means that it is chemically stable and does not react with the surrounding environment. Instead it forms a clathrate-hydrate, $Rn{\cdot}6H_2O$, in contact with water. This means that radon is trapped inside a lattice of water molecules. The fact that radon is inert and not affected by complex geochemical processes makes it a good tracer for many different purposes. The most extensive use of radon as a tracer in previous studies has been for interactions between groundwater and surface water. In these studies the differences in concentration between groundwater and surface waters has been used to trace and quantify inflow of groundwater in streams, lakes and oceans /Dewayne Cecil and Gesell 1992, Wu et al. 2003, Clark and Fritz 1997, Kendall and McDonnell 1998, Corbett et al. 1997/.

Table 1-1. Typical radon concentration in Swedish groundwater /Skeppström 2005/.

	Radon concentration Bq/L
Wells dug in soil	10–30
Wells dug in soil in granite areas	40–400
Wells drilled in crystalline bedrock	70–500
Wells drilled in uranium rich granite	300–4,000
Wells drilled in uranium rich pegmatite	15,000–30,000

The large difference in radon concentration between surface water and groundwater is caused by the fact that surface water is not in contact with solid material to the same extent as groundwater and the input of radon is therefore low. The radon found in surface water comes mostly from inflow of radon rich groundwater but this radon is quickly lost through outgassing of radon from the water surface to the atmosphere. This means that elevated radon concentration in surface water can be found in connection with groundwater inflow. This fact is used to detect and quantify groundwater inflow to streams by measuring radon concentrations in surface water and groundwater at different sites along the investigated stream. The concentration gradient is used together with flow measurements in the stream to create a combination of the mass balance of water and the mass balance of radon. The combined mass balance is then used to quantify the groundwater inflow to the stream /Dewayne Cecil and Gesell 1992, Wu et al. 2003, Clark and Fritz 1997, Kendall and McDonnell 1998, Corbett et al. 1997/.

This is not the only way of using radon as a tracer; it is also possible to use radon to locate hydraulically active fractures in bore holes /Cook et al. 1999/. /Cook et al. 1999/ used the concentration profile before and after purging the well to be able to assess the flow rate of the groundwater in the fractures. The concentration of the purged well is representing the radon concentration of the surrounding aquifer and difference between this concentration and the radon concentration in the unpurged well can be used to estimate the flow rate of the groundwater in the different sections /Cook et al. 1999/. Radon has also been used to trace trust and faults in the bedrock since radon concentration is normally higher in areas where trust and faults are present /Choubey and Ramola 1997/.

Radon has also been used to study flows and resident time of groundwater by using the ingrowth of radon described in Equation 1 and Figure 1-2 /Clark and Fritz 1997, Low 1996, Hoehn and von Gunten 1989, Hoehn et al. 1992/. As described earlier radon comes into groundwater by decay of radium in soils and bedrock. This means that equilibrium or steady state radon concentration in groundwater is reached after approximately 30 days in contact with the soil or bedrock /Wu et al. 2003, Hoehn and von Gunten 1989/. When radon free recharge water enters the groundwater system the radon concentration starts to build up until steady state radon concentration is reached. If the steady state radon concentration is known the resident time of the infiltrating water can be calculated with the help of Equation 1.

In a study conducted by /Low 1996/ this method was evaluated. A conceptual model was developed where radon free recharge water diluted the groundwater in the underlying aquifer with a specific equilibrium radon concentration in /Low 1996/. The signal from the recharging water could according to /Low 1996/ be traced until secular equilibrium was reached after 30 days. When the water from the aquifer then entered the second aquifer with a higher emanation potential this signal could also be traced for 30 days. /Low 1996/ recorded changes in radon concentration over time with lower concentrations during periods with precipitation which supported the conceptual model. Even if the study did not quantify the groundwater flow it could be concluded that with more studies radon had a potential to be used as tracer for groundwater flow.

In two studies /Hoehn and von Gunten 1989/ and /Hoehn et al. 1992/ investigated the use of radon as a tracer to detect groundwater flow and resident times. These studies were also based on the ingrowth of radon from radium explained in Equation 1. If the initial radon concentration, A_t, and the radon concentration at equilibrium, A_{eq}, are known the measured radon concentration in-between these two values allows you to make an estimation of the resident time, t, of the groundwater.

In the first study that was a field study conducted in Switzerland the radon concentration in groundwater was measured at different distances from three rivers /Hoehn and von Gunten 1989/. The concentration was also measured at different depths in the sampled wells. The results showed that the radon concentration increased with the distance from the river. This was explained by river water with very low radon concentration infiltrating the aquifer and diluted the radon concentration of the groundwater. The radon concentration increased over distance due to the ingrowth of radon from the radium in the aquifer according to Equation 1. The equilibrium concentration (A_{eq} in Equation 1) was not measure. Instead the equilibrium concentration was assumed to have been reached on a distance of 100 m from the river.

In the same study it was also shown that the radon concentration varied with depth within the sampled wells, with higher radon concentration in the deeper groundwater. This gradient was explained by the infiltrated surface water that diluted the shallow groundwater to a higher extent than the deeper groundwater. This gradient was more pronounced in the wells close to the river where surface water infiltrated and diluted the shallow groundwater but became less pronounced with distance from the rivers because of the ingrowth of radon. The ingrowth of radon was used to calculate resident time up to 15 days using Equation 1. By knowing the resident time also the flow velocities could be calculated. The results from these calculations were then compared to the results from previous studies and the results were shown to be consistent /Hoehn and von Gunten 1989/.

The second study evaluating the use of radon to tracer groundwater flow was a laboratory study conducted by /Hoehn et al. 1992/. Water was led through a 4.8 meter long sand box and the radon concentrations were measured at different distances from the inlet. This gave radon concentrations in relation to distance and resident time at constant flow conditions. The equilibrium radon concentration was also measured after the water had been left stagnant in the box for one month. The resident time and flow velocities were calculated using the Equation 1. To be able to evaluate the method a tracer test with NaCl was conducted to estimate flow velocities and resident time. The comparison between the two methods showed cohesive results in general even if some of the results deviated. This was thought to be caused by uneven distribution of radon emanation potential within the soil.

1.4 Hypothesis

The hypothesis of this study is that groundwater can be classified as recharging or discharging groundwater by using radon as natural tracer. The method is based on systematic differences in radon concentrations between different water types like surface water, near-surface groundwater and deep groundwater. High radon concentration is found in deep groundwater and low radon concentration is found in surface water. The interactions between the different water types will affect the radon concentration and therefore the origin of the groundwater can be assessed. For near surface groundwater, which is the focus in this study, the radon concentration is thought to be influenced by infiltrating low radon surface water or by discharging deep groundwater with high radon concentration. The differences in radon concentration in near-surface water can therefore be used to trace the origin of the groundwater.

To be able to use these concentration differences to trace groundwater the steady state concentration of the near surface groundwater has to be considered. The steady state radon concentration (or equilibrium concentration) is the radon concentration that will prevail when secular equilibrium is reached between the radium in the local soil and the radon in the surrounding water. The steady state radon concentration will be measured in Forsmark by soil sampling. This steady state radon concentration will be compared to measured radon concentration in near surface groundwater.

If the radon concentration in the near surface groundwater is higher than the steady state radon concentration it can be concluded that radon has been added from some other source than the decay of radium in the local soil. The elevated radon concentration indicates inflow of high radon groundwater from the deep groundwater and the well will therefore be classified as a discharging well.

If the groundwater radon concentration is lower than the steady state concentration it indicates groundwater that has not reached steady state radon concentration. This can be caused by infiltration of radon free recharge water that dilutes the radon concentration in the groundwater. These wells with low radon concentrations are classified as recharging wells.

2 Site descriptions and methods

2.1 Site description of Forsmark

SKB's investigations in the Laxemar and Forsmark areas began with feasibility studies and were followed by site investigations between 2002 and 2007. The objective of the site investigations have been the siting of a geological repository for spent nuclear fuel. The investigated area in Forsmark is located on the east coast of Sweden in the municipality of Östhammar as shown in Figure 2-1**.** The Forsmark nuclear power plant and the final repository for low radioactive waste (SFR) are already located in the area. Forsmark has been selected for the siting of the repository for spent nuclear fuel after a decision by SKB in June 2009.

The Forsmark area has a low relief and almost the whole area is located below 20 meters above sea level, this gives the area a small-scale undulating topography. The area is covered to 75% with a thin layer of till mostly thinner than 5 metres. The till is mostly sandy but in the south east part of the candidate area the till is clayey. The bedrock is exposed at many sites but covers only 5% of the total area. Wetlands are frequent in the area and cover up to 25% of the area of some sub-catchments. There are four major lakes in the area; Lake Fiskarfjärden, Lake Bolundsfjärden, Lake Eckarfjärden and Lake Gällsboträsket. All of these lakes are small and shallow. There are no major water courses that carry water all year round in the area but some small brooks draining the area exist.

The recharge in the area is dominated by precipitation surplus and the groundwater levels show strong correlation with the precipitation and the evapotranspiration cycle. There are indications that direct recharge of lake water to groundwater can occur in dry summer months due to lowered groundwater levels caused water uptake by vegetation. The groundwater level in the Quaternary deposits is low mostly within one meter below the ground surface. The near surface groundwater flow is dominated by

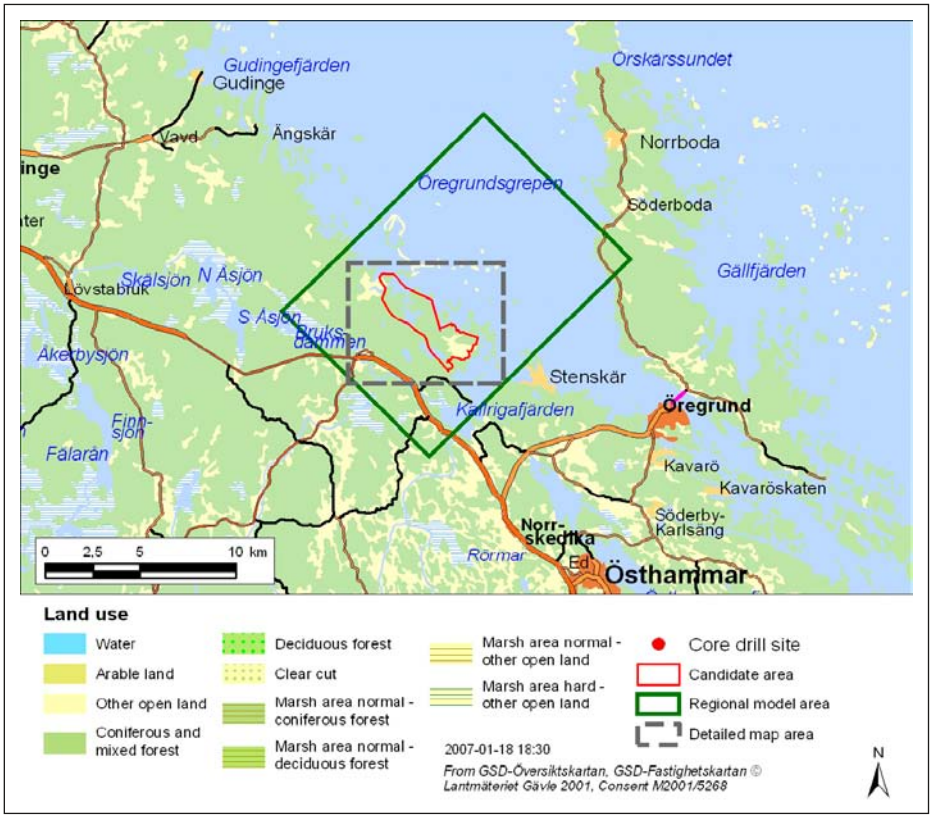

Figure 2-1. *The location of the Forsmark investigation area in the municipality of Östhammar. The green square shows the regional model area and the red line shows the candidate area. /after Tröjbom et al. 2007/.*

small-scale shallow flow systems cause by the small scale undulating topography. There is anisotropy in the till with higher hydraulic conductivity in the horizontal direction than in the vertical direction. This causes most of the groundwater to flow in very shallow flow paths.

The bedrock that is dominated by granite has highly conductive horizontal fracture zones that has a big influence of the hydrology in the area /Johansson 2008/. A conceptual picture of the hydrology is shown in Figure 2-2. The figure shows the highly conductive horizontal fracture zones that are present in the first 150 metres of the bedrock but under the depth of 200 meters almost no conductive fractures are found /Werner et al. 2007, Johansson 2008/. The fracture zones are interconnected and can transport groundwater over large distances. This creates long and shallow flow paths in the bedrock /Werner et al. 2007, Johansson 2008/. These flow paths also collect discharging deep groundwater and prevent discharge of deep groundwater within the investigated land area. Instead the deep groundwater is discharged below the Baltic Sea.

The interactions between deep groundwater and the near surface groundwater were investigated in /Johanson 2008/. The percussion drilled wells and the wells in Quaternary deposits at Drill Sites 1, Drill Site 2, Drill Site 4, Drill Site 5 and Drill Site 6 were used in the investigation, the location of the Drill Sites are shown in Figure 2-3. All sites except Drill Site 4 are within the candidate area and also within the tectonic lens. The tectonic lens is the area where the candidate area is located. The bedrock in this area is less fractured than the surronding bedrock and the lens is surronded by deformations zones on each side of the lens. Groundwater levels measured in percussion drilled wells in the bedrock and groundwater levels measured in wells in Quaternary deposits were compared to evaluate if any co-variation existed.

The results show that the groundwater level in Quaternary deposits are much higher than the groundwater level in the bedrock. This pattern was observed at all investigated sites located within the tectonic lens in the central part of the investigation area. At these sites the groundwater levels in bedrock and Quaternary deposits show co-variation with the precipitation and evapotranspiration. In some dry summer periods the groundwater levels in Quaternary deposits were lower than the groundwater levels in bedrock.

Even though both groundwater levels in bedrock and Quaternary depostits show correlation to the precipitation and evapotranspiration the hydraulic connection between the groundwater in the bedrock and Quaternary deposits is limited. This is obvious since the groundwater levels in bedrock show a clear response to a pumping test in the bedrock conducted in the summer/autum of 2006. The response is not shown in the Quaternary deposits even though the groundwater level in the bedrock is lowered with several meters. The fact that the respons to the pumping tests is shown in wells as much as 800 metres from the pumping wells also indicate a good hydraulic contact within the bedrock.

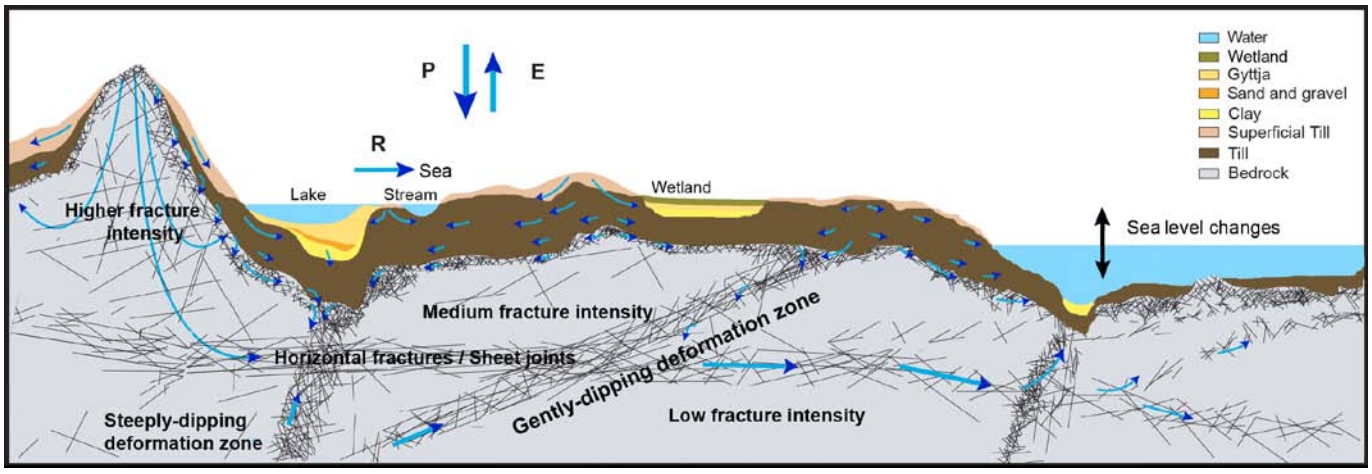

Figure 2-2. *The conceptual hydrogeological model of the Quaternary deposits and the upper bedrock shows the effect of the highly conductive fracture zones in the shallow bedrock /from Johansson 2008/.*

Figure 2-3. *There are seven Drill Sites in the Forsmark area. Five of them are used to evaluate the interactions between groundwater in the Quaternary deposits and groundwater in the bedrock /Tröjbom et al. 2007/.*

The pattern with lower groundwater levels in bedrock than in Quaternary deposits is not present at Drill Site 4 outside the tectonic lens. The groundwater level measured in wells in bedrock and Quaternary deposits at Drill Site 4 close to Lake Gällsboträsket are shown in Figure 2-4. Here the groundwater level is higher in the bedrock than in the Quaternary deposits. The lowest groundwater levels are measured in wells SFM0011 and SFM0013 in Quaternary deposits and the highest levels were measured in the percussion drilled wells HFM09, HFM10 and in the well SFM0057 in the Quaternary deposits. The location of the wells can be seen in Figure 2-5. This patterns indicate a upward gradient of groundwater from the deeper bedrock. There is no respons to the pumping test in groundwater levels in the bedrock or in the Quaternary deposits which indicate that there is no hydraulic contact with the area inside the tectonic well.

During the site investigation an extensive program for chemical characterisation of different water types was conducted. The chemical signals of the near surface groundwater were used to detect discharge of deep groundwater in the near surface groundwater. An ion source model was used to evaluate the origin of the groundwater and a classification was done. Most of the wells in Quaternary deposits in the area are classified as fresh water or altered meteoric groundwater with the ion source model. The wells located within the depression of Lake Gällsboträsket (SFM0011, SFM0012, SFM0013) are classified as influence from relict marine groundwater with high chloride concentrations. Well SFM0057 also located in the depression of Lake Gällsboträsket show indication of influence of deep saline groundwater. The chloride concentration in the brook draining Lake Gällsboträsket is also elevated compared to the expected chloride concentration. A mass balance calculation of chloride in the catchment area shows that chloride has to be added from an additional source like inflow of deep saline groundwater in order to maintain the high chloride concentration in the brook.

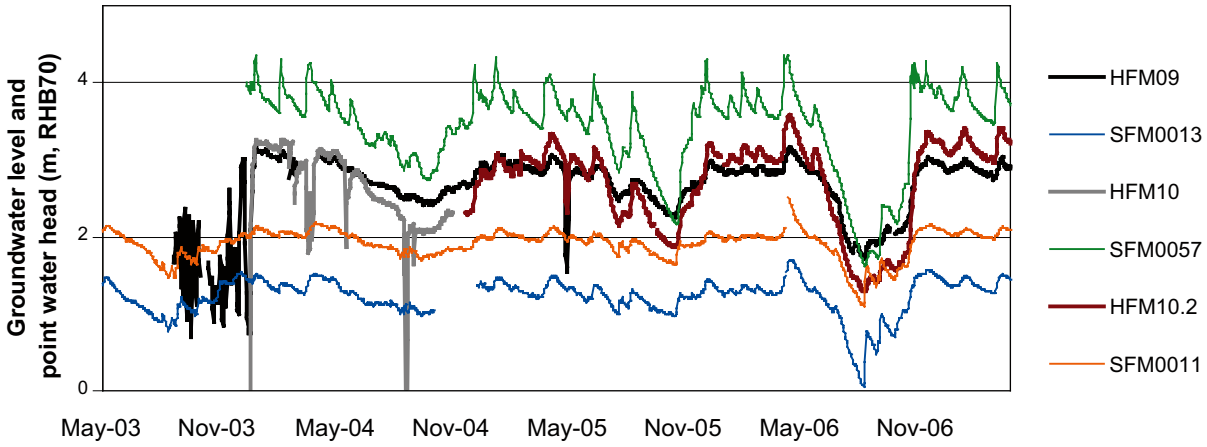

Figure 2-4. *The groundwater levels as m.a.s.l. (metres above sea level) are shown in this figure. It is obvious that the groundwater levels are higher in the bedrock than in the Quaternary deposits /after Johansson 2008/.*

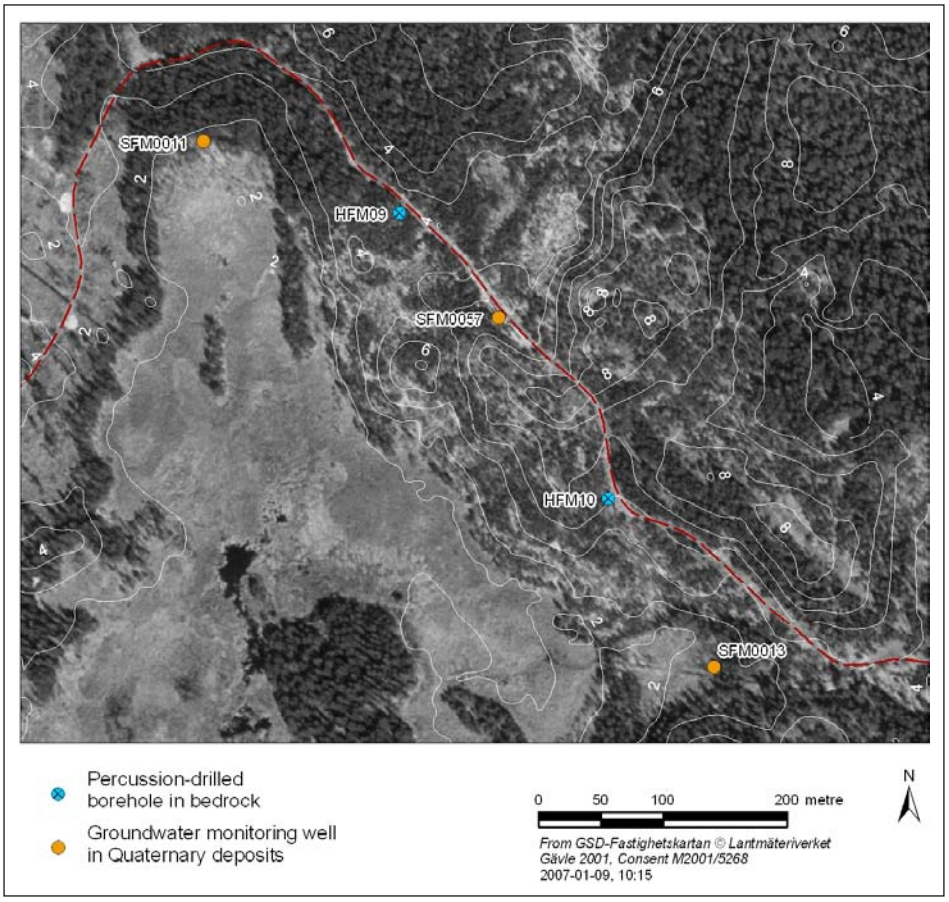

Figure 2-5. *The location of wells in soil SFM0011, SFM0013, SFM0057 and the percussion-drilled boreholes HFM009 and HFM010 at Drill Site 4.*

2.2 Site description of Laxemar

The Laxemar site investigation area is located in the south east part of Sweden in the municipality of Oskarshamn. The regional model area that includes the Laxemar area, the Simpevarp peninsula and the islands of Hålö and Ävrö is shown in Figure 2-6. The site investigations were concentrated in the local model area marked with the smaller square in Figure 2-6. The Äspö Hard Rock Laboratory is located on the island of Äspö north of Ävrö and the Simpevarp Nuclear power plant and the Central interim storage facility (Clab) are located on the Simpevarp peninsula.

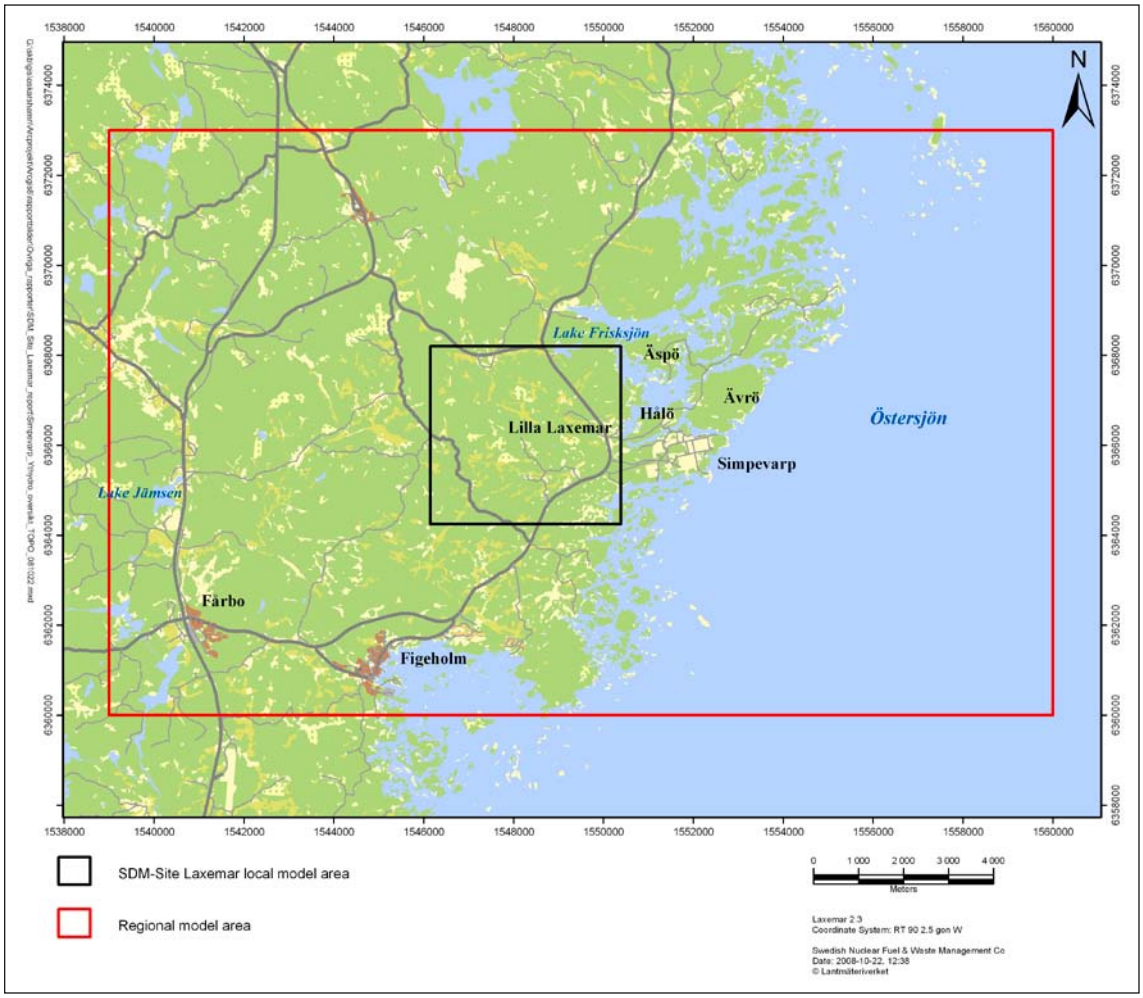

Figure 2-6. *The regional model area is within the red square with the local model area where the site investigations are concentrated within the black square /Werner 2009/.*

The Laxemar area is characterised by small-scale topography with distinct valleys surrounded by higher-altitude areas. In the south-western and central part of the area hummocky moraine prevails and creates a small-scale undulating topography. There are also some eskers in the area. The whole area is located below 50 m.a.s.l. and is under the highest coastline. There are six lakes in the area; Lake Jämsen, Lake Frisksjön, Lake Sörå, Lake Plittorpsgöl, Lake Fjällgöl and Lake Grangöl. The lakes are small and shallow with an average depth of 1–4 m. There are streams in almost all the delineated catchments areas but only two streams; stream Laxemarån and stream Kåreviksån, carry water all year. The other monitored streams carry water parts of the year. All of the streams show large seasonal variability and most of the streams are affected by draining and land improvement operations.

Wetlands are scarce in the area and cover only 3% of the delineated catchment areas. The precipitation in the area demonstrates a near-coastal gradient, with less precipitation at the coast compared to areas further inland. The specific recharge is 165 mm/year. The groundwater level is shallow, mostly within a meter below the ground surface. The groundwater level follows the topography which indicates that the topography has a big influence of the recharge and discharge of shallow groundwater. The groundwater recharge is thought to take place in the high areas with exposed bedrock or shallow till layers. The dominating source of groundwater recharge is precipitation and snowmelt, but some evidences of lake water infiltration in near-shore areas during dry periods exist.

The Quaternary deposits are dominated by sandy-gravelly till and are overlying the bedrock in almost the whole area /Werner 2009/. The high-altitude areas that cover 35–40% of the model area are dominated by exposed bedrock or shallow till /Werner 2009/. The Quaternary deposits are

deeper in the valleys mostly between 5–10 m and consist of both glacial deposits and post-glacial deposits as shown in Figure 2-7. The till is overlayed by low permeable glacial clay. This affects the discharge patterns in the valleys since discharging groundwater from the shallow bedrock and till layers are hindered by the clay layer. This creates a horizontal flow of groundwater along the valleys in the till layer and constrains the discharge of groundwater to areas where no glacial or post-glacial deposits exit.

The bedrock is dominated by Ärvö granite. The deformation zones in the bedrock often coincide with valleys in the area and the bedrock is therefore more densely fractured in the valleys compared to other areas. In general the hydraulic conductivity of the bedrock decreases with depth both within the deformation zones and within the rock mass between the deformation zones.

The interactions between groundwater in Quaternary deposits and groundwater in the bedrock have been evaluated within the site investigation and the results are presented in /Werner et al. 2008/. The investigation has been done by comparing groundwater levels measured in percussion drilled wells in the bedrock and groundwater levels measured in wells in Quaternary deposits. The results show that groundwater level in the bedrock is higher than the groundwater level in the Quaternary deposits at eight of the investigated sites which indicates a upward gradient of groundwater from the bedrock, some of these sites are SSM0041 and SSM0037 which are included in this study. In eight other areas there is a downward gradient of the groundwater, some of these areas are the areas around SSM0218 and SSM0009. In some other areas there is little or no diffrences between the groundwater levels in soil and bedrock. It can be concluded that the pattern of groundwater interactions from bedrock to soil is complicated in the area.

In Laxemar chemical signals of dischargin deep groundwater can be found at two locations. The first is the well SSM0241 located below the sea in Bay Granholmsfjärden and the other well, SSM0242, is located below the Lake Frisksjön. No signals of discharging deep groundwater are found in the wells located on land. The classification of wells as recharge and discharge wells according to the major ion classification shows no correlation to the field classification of the wells. This can be caused be the fact that only 3 of the 24 investigated wells were classified as recharge wells.

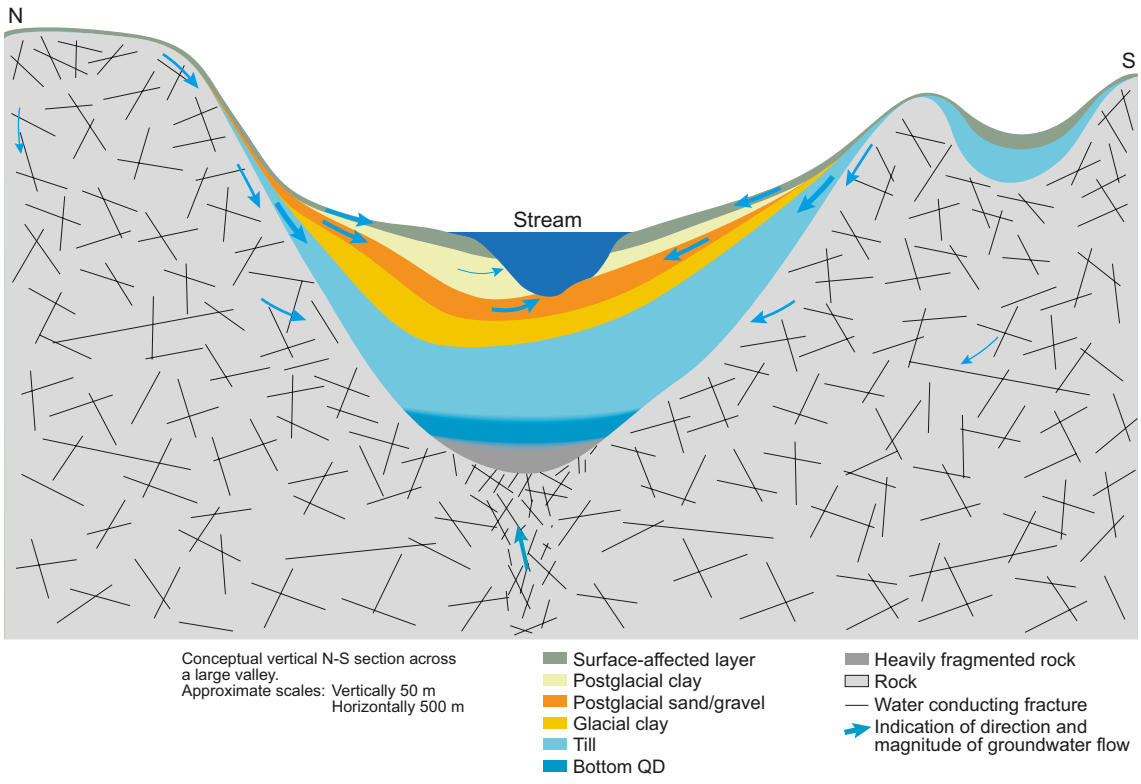

Figure 2-7. *Conceptual picture of the Quaternary deposits in a valley in the Laxemar area /Werner 2009/.*

2.3 Field methods in Forsmark and Laxemar

Groundwater sampling was done in the monitoring wells in soil in the Forsmark area in October 2008 and June 2009 and in Laxemar in May 2009. The sampling location can be seen in Figure 3-1 and Figure 3-2 in sections 3.1.1 and 3.1.2. The wells were purged for one to five well volumes depending on the availability of water and the recovery rate. The RAD-7 H2O method was used with the 250 ml vials. The vials were first rinsed with the sampling water before a water sample was taken. The radon concentration was measured with the RAD-7 as soon as possible after the sampling. The time between sampling and measurement was measured and the loss of radon due to decay was corrected for. For some sampling points double samples were taken both with the 250 ml vial and the 40 ml vial.

In Forsmark three locations with clusters of monitoring wells at different depths were sampled during the radon sampling in June 2009. The locations of these sites are shown in Figure 3-2. Some of these wells were BAT-filter wells. This means that the sampling was done using the BAT-filter equipment. A BAT-filter well has a filter at the screening depth and the water is sampled through the filter via a septum. To get the water through the filter a vacuum pressurised glass vial with a needled is used. The needle is pushed through the septum and the groundwater is sucked up to the sampling vial due to the vacuum pressure. In order to get representative groundwater sample the vial was first filled during a period of 10 to 24 hours depending on the recovery rate of the well and then a second vial was filled from which the sample was taken.

To determine the steady state radon concentration soil samples were taken from approximately 0.3 meters depth in the vicinity of selected sampling wells (SFM0026, SFM0014, SFM0090, SFM0013 and SFM0019). Approximately 0.5 litres of soil was sampled in an airproof bag made of Teflon. To measure the volume of the sample the sides of the hole is covered with waterproof plastic film and water with known volume is added into the hole until it is completely filled. This gave the volume, V, of the soil sample. The bag with the soil sample is sealed and then filled with distilled water and left for approximately 30 days. After 30 days the water is sampled via a septum into a 250 ml glass vial and the radon concentration is measured with RAD-7.

Since distilled water has been added to the Teflon bag the measured radon concentration inside the bag is not equal to the steady state radon concentration that would exist in the natural volume of groundwater in the soil. To be able to calculate the steady state radon concentration the pore water volume of the soil needs to be measured. To do this an additional soil sample was taken from the same sampling hole and the volume is measured in the same way as described above. The dry weight of the soil sample is measured after drying in an oven over night. Since the density of soil is known to be 2.65 g/cm^3, the volume of the soil particles, V_{soil}, can be calculated. From this the pore volume, $V_{porewater}$, and the porosity, n, of the soil is calculated. The pore volume is then used to calculate the steady state radon concentration that would represent the steady state radon concentration in the groundwater.

2.4 Radon measurement technique

In this study the in-air radon monitor RAD-7 was used to measure radon extracted from water. RAD-7 is a commercially used device to determine the radon concentration in air mostly for indoor-air radon measurements. The RAD-7 is an alpha particle detector that uses a solid state detector to detect alpha particles with different energy levels. A solid state alpha detector can convert the energy from an alpha particle to an electrical signal. This makes it possible to identify the specific element that decay since every element emits alpha particles with different energy levels. Inside the RAD-7 is a hemisphere that is coated with an electrical conductor. An ion-implated silicon alpha detector is placed in the centre of the hemisphere se Figure 2-8. A high voltage power circuit creates a high electrostatic field within the measurement chamber. This electrostatic field makes the positively charged radon daughters, polonium-214, ^{214}Po, and polonium-218, ^{218}Po, absorb onto the surface of the detector. This means that when the polonium isotopes decay and emit alpha particles the alpha particles enter the detector and electrical signals with specific energy level will be produced and recorded.

The radon concentration is then calculated from the decay of the radon daughters ^{214}Po and ^{218}Po and not from the decay of radon itself. This technique gives the RAD-7 a quick response time since the half-life of the ^{218}Po, is only 3.05 minutes and the secular equilibrium is reached after only 12 minutes. According to Figure 1-1 the ^{218}Po decays to ^{214}Pb that decays to ^{214}Bi and then ^{214}Bi decays to ^{214}Po. The equilibrium between radon and ^{214}Po takes approximately three hours to reach. Therefore the RAD-7 only measures the decay of ^{218}Po in a short time measurements but if the measurement is going on for more than three hours the RAD-7 starts to count the decay of ^{214}Po as well to improve the statistics /Durridge Company 2000/.

There are two accessories to the RAD-7 that make it possible to measure radon in water. One of them, the H2O accessory is used in this study. The H2O accessory has been used at laboratories for more than a decade and has a detection limit of 0.370 Bq/L /Durridge Company 2000/. A picture of the H2O accessory is shown in Figure 2-8. The water sample is collected in a 40 ml or a 250 ml vial depending on the expected concentration. If the concentration is expected to be higher than 100 Bq/L the 40 ml vial is recommended and if the concentration is expected to be lower than 100 Bq/L the 250 ml vial should be used.

The water sample in the glass vial is aerated when the air pump inside the RAD-7 chamber pumps air into the vial through a plastic tube. The air is then led via a gas purifier into the RAD-7 chamber. This creates a closed loop of air between the vial and the RAD-7 chamber. The RAD-7 chamber is sensitive to moisture and the relative humidity has to be kept below 10% to get good measurements. Therefore the gas purifier (a plastic cylinder filled with $CaSO_4$) seen in Figure 2-8 is used to absorb moisture in the ingoing air. The water sample is aerated for five minutes to get all the radon from the water into the air circulation. After the first five minutes of aeration the RAD-7 waits for five minutes to get the ^{218}Po in equilibrium with the radon. Then the decay of ^{218}Po is counted for four five-minute-periods and the result is printed. The results show four calculated radon concentrations and a statistical uncertainty for each measurement. A mean value for the radon concentration in the four measurement cycles is presented as well as a standard derivation calculated for the four radon measurements.

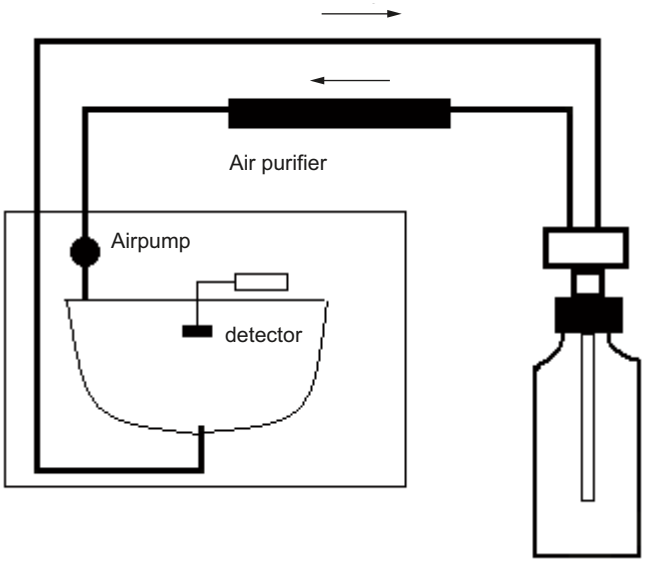

Figure 2-8. *Schematic picture of the RAD-7 H2O accessory /after Durridge Company 2000/.*

3 Results

3.1 Radon concentrations in Forsmark and Laxemar

Radon measurements in groundwater and surface water have been conducted within the site investigation programs in Forsmark and Laxemar. During the first years of the site investigations (2002–2005) the measurements were done at IFE laboratory in Norway. These measurements were later proven to be unreliable and a change of laboratory was done in 2005. After the laboratory change the radon measurements were done with Liquid Scintillation Spectroscopy method at The Scottish Universities Environmental Research Centre (SUERC). After the laboratory change the radon measurements can be considered reliable and the results are presented and discussed in the following sections together with the complementary measurements done with the RAD-7 method within this study.

3.1.1 Laxemar

Most of the radon measurements done within the site investigation program were done in deep groundwater and only a few measurements were done in near surface groundwater and surface water. Surface water measurements were done in one lake, two sea locations and in six streams at different sampling occasions. The results range from > 0.015 to 12.42 Bq/L with a mean of 1.58 Bq/L. The high radon concentration of 12.42 Bq/L in surface water is from a measurement in Stream Kärrviksån. There are 12 radon measurements in near surface groundwater ranging from 1.06 to 27 Bq/L with a mean of 13.4 Bq/L. This mean value is lower than the corresponding mean in Forsmark and also lower than normal radon concentrations for wells in soil in granite areas (see Table 1-1).

There are 87 radon measurements in deep groundwater and they range from 14.13 to 1,179 Bq/L with a mean of 134 Bq/L. This is significantly lower than the measurements in Forsmark and also lower than normal concentrations in wells in granite areas (see Table 1-1). There are five measurements above 400 Bq/L and they are from two sites (KLX04 and KLX05). All the other sites had radon concentrations below 240 Bq/L. The radon measurements were done at different depths in the same bore hole. The distribution of radon concentration at different depths are quite uniform except for well KLX04 where high concentration (1,179 Bq/L) was found at 530 meter depth and low concentration (23 Bq/L) was found at 897 meter depth.

Radon concentrations have also been measured in near surface groundwater with the RAD-7 measurement technique within this study. In Laxemar 31 measurements at 14 different locations were done during a sampling campaign in May 2009. Double and triple samples were taken to be able to evaluate the RAD-7 method. The mean radon concentrations were calculated from the double and triple samples for each sampled site and they range between 35.1 and 175.9 Bq/L and had a mean of 65.0 Bq/L. This can be compared to a mean of 13.4 Bq/L from the measurements done in near surface groundwater within the site investigation program.

The sites and mean radon concentrations measured with the RAD-7 method are shown in Figure 3-1. The radon concentrations are divided into four categories in Figure 3-1. 9 of the 14 sampled wells are found in the second category 41.5–71.9 Bq/L. Only two sites (SSM0031 and SSM0230) had mean concentrations above 71.9 Bq/L and three sites (SSM0037, SSM0041 and SSM0264) hade radon concentrations below 41.5 Bq/L.

3.1.2 Forsmark

Similar to Laxemar most of the radon measurements done during the site investigations are from deep groundwater and only a few measurements for near surface groundwater and surface water are available. The surface water measurements were done at one sea location and three lakes in the Forsmark area. The results range from > 0.015 Bq/L to 0.25 with a mean of 0.075 Bq/L. This is three orders of magnitude lower than the radon concentrations in the near surface groundwater and also lower than the radon concentrations in surface water in Laxemar. This can be explained by the fact that there were no streams among the measured sites in Forsmark. Streams can be expected to have higher radon concentrations than lakes and sea basins due to discharging groundwater with high radon concentration.

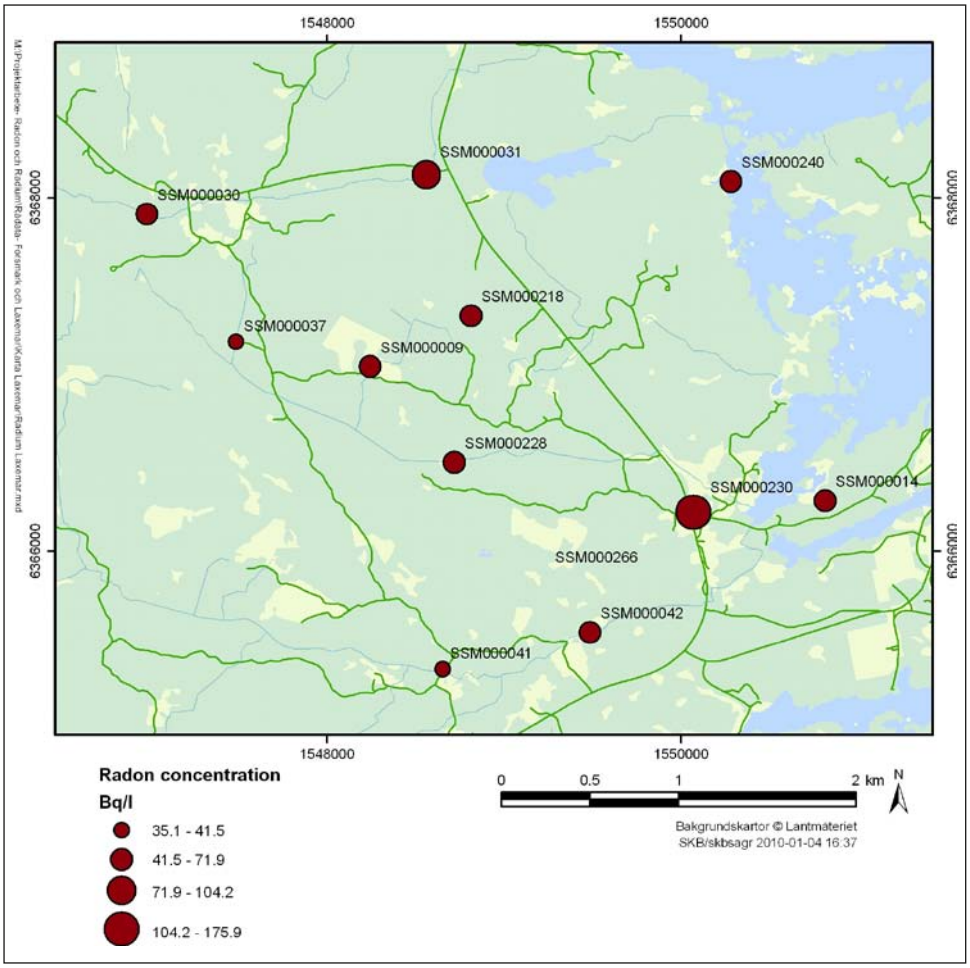

Figure 3-1. *Mean radon concentrations in near surface groundwater measured with the RAD-7 method in the Laxemar area.*

Only 10 radon measurements in near surface groundwater from 6 sites are available from the site investigation program in Forsmark. The results are within the range of normal concentrations for wells in soil in granite areas and ranges from 16.5 to 397 Bq/L with a mean of 70.6 Bq/L. The concentrations are generally lower than in the deep groundwater and higher than the concentrations in surface water.

Radon measurements in deep groundwater range from 15 to 8,310 Bq/L with a mean of 769 Bq/L. Most of the measurements (59 out of 85) are below 500 Bq/L and only 11 of the measurements from 3 sites (KFM02A, KFM02B, KFM03A) are above 2,000 Bq/L. These levels are mostly within the range of normal radon concentration in Sweden even if some of the radon concentrations are higher than the normal radon concentrations in Swedish bedrock (see Table 1-1).

Radon measurements in deep groundwater have been done in percussion drilled bore holes. These measurements are done at the same depth in the well at different sampling occasions. There are no big differences between sampling occasions in the wells except for well HFM013 where the concentrations vary from 348 Bq/L to 1,200 Bq/L between different sampling occasions. Radon measurements in deep groundwater were also done in the core drilled boreholes and these measurements are done at different sampling depths and different sampling occasions in the same well. The biggest differences are found in KFM03A but also well KFM02A and KFM02B show large variations in radon concentrations with depth in the borehole.

In addition to these measurements 35 radon measurements were done in 31 monitoring wells in soil during two sampling campaigns in October 2008 and June 2009 with the RAD-7 measurement technique. The sites and concentrations are shown in Figure 3-2. For the sites were double samples

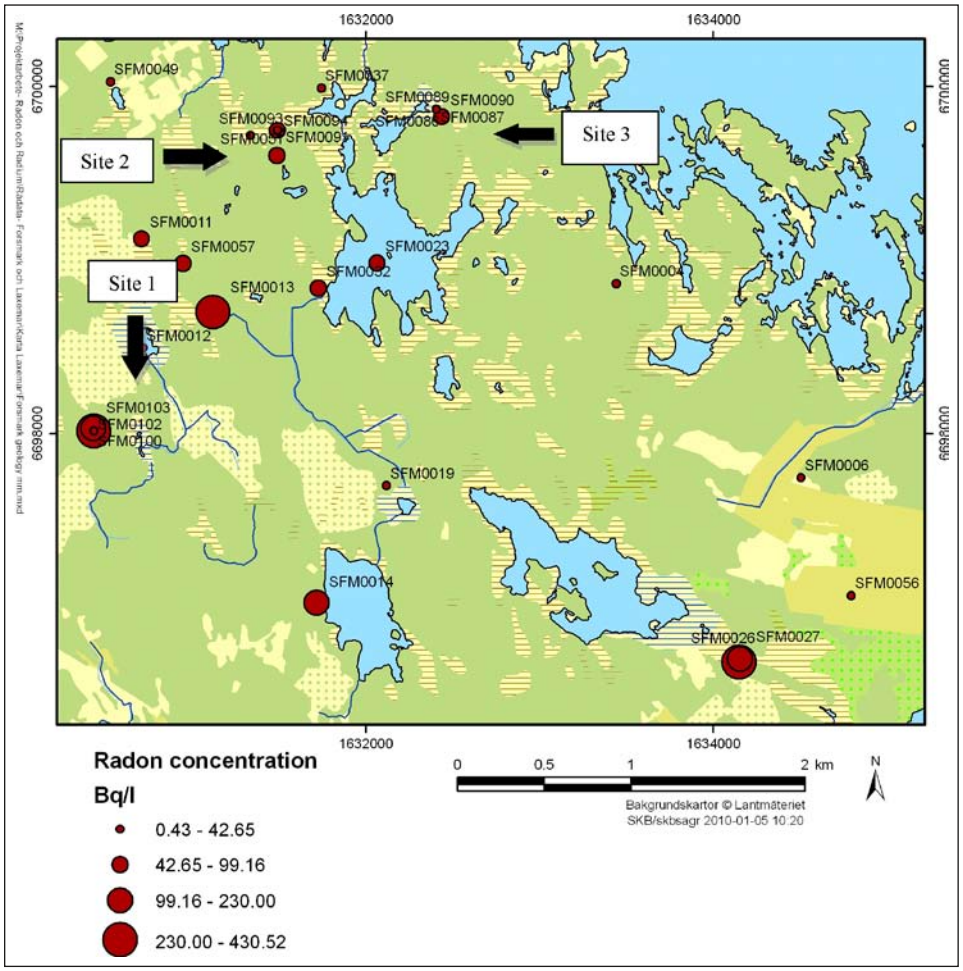

Figure 3-2. *Radon concentrations in groundwater monitoring wells in the Forsmark area.*

were taken the mean concentration are shown. A big range of radon concentrations were found within the area with results ranging from 0.43 to 420 Bq/L with a mean of 93 Bq/L. Most of the radon concentrations (17 of 31) are found in the first category in Figure 3-2 (0.43–42.65 Bq/L) and only 4 radon concentrations are above 230 Bq/L.

There are three locations marked with arrows in Figure 3-2 were several radon measurements are done in wells at the same location. These locations will be referred to as Site 1, Site 2 and Site 3 in this text. At these sites groundwater monitoring wells at different depths have been installed. The installed wells are pumping wells in steal, groundwater monitoring wells (HDPE pipes) and BAT-filter type wells. The radon concentrations were sampled at these locations to enable evaluation of radon concentrations at different depths in the soil profile and the results are presented in Figure 3-3, Figure 3-4 and Figure 3-5 respectively. In some of the BAT-filter wells 40 ml vials were used for sampling since these wells had low capacity and only small amounts of water could be extracted.

At Site 1 the radon concentration increases with increasing depth in the sampled wells as shown in Figure 3-3. The radon concentration is high in the till/bedrock interface and in the till below the peat. The radon concentration is low in the clay and peat layers. The wells SFM0097, SFM0100 and SFM0102 are BAT-filter wells, which makes the sampling difficult and uncertain. These measurements should therefore be considered indications of radon concentration.

At Site 2 three radon measurements were done at different depths as shown in Figure 3-4. The well SFM0093 is a BAT-filter well and the radon measurement is therefore considered an indication rather than an actual measurements. The radon concentration is lower in the bedrock/till interface than in the till layer approximately 1.2 meter above the bedrock. The radon concentration is low in the clay gyttja layer.

At Site 3 five radon measurements were done at different depths as shown in Figure 3-5. The radon concentration increases with depth. There is a clay layer overlaying the till which prohibits interaction between the groundwater in the till and the groundwater in the shallow layers. At this site a soil sample was taken close to well SFM0090 to determine the steady state radon concentration of the soil.

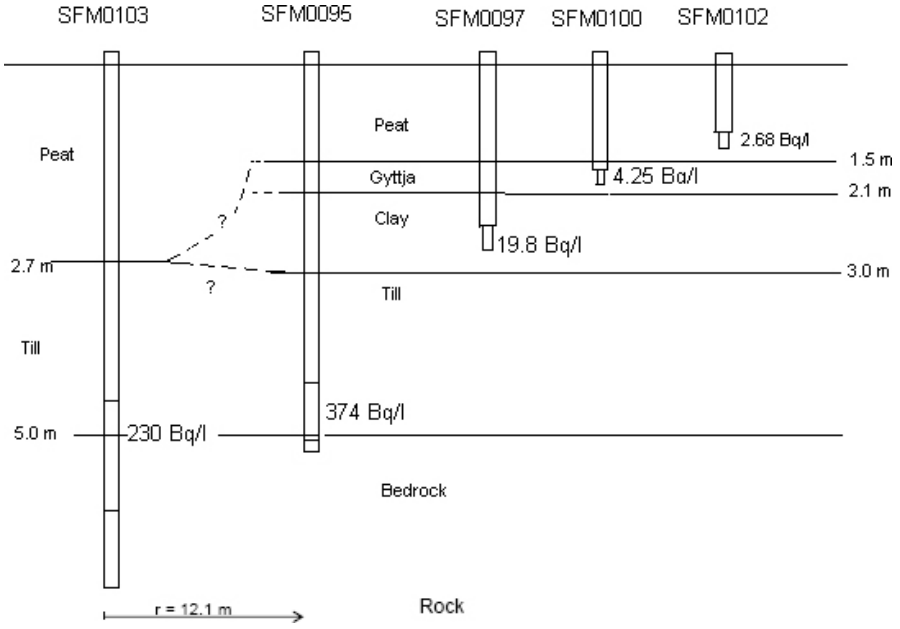

Figure 3-3. *A conceptual picture of sampling Site 1 and the measured radon concentrations. (Note, not in scale.)*

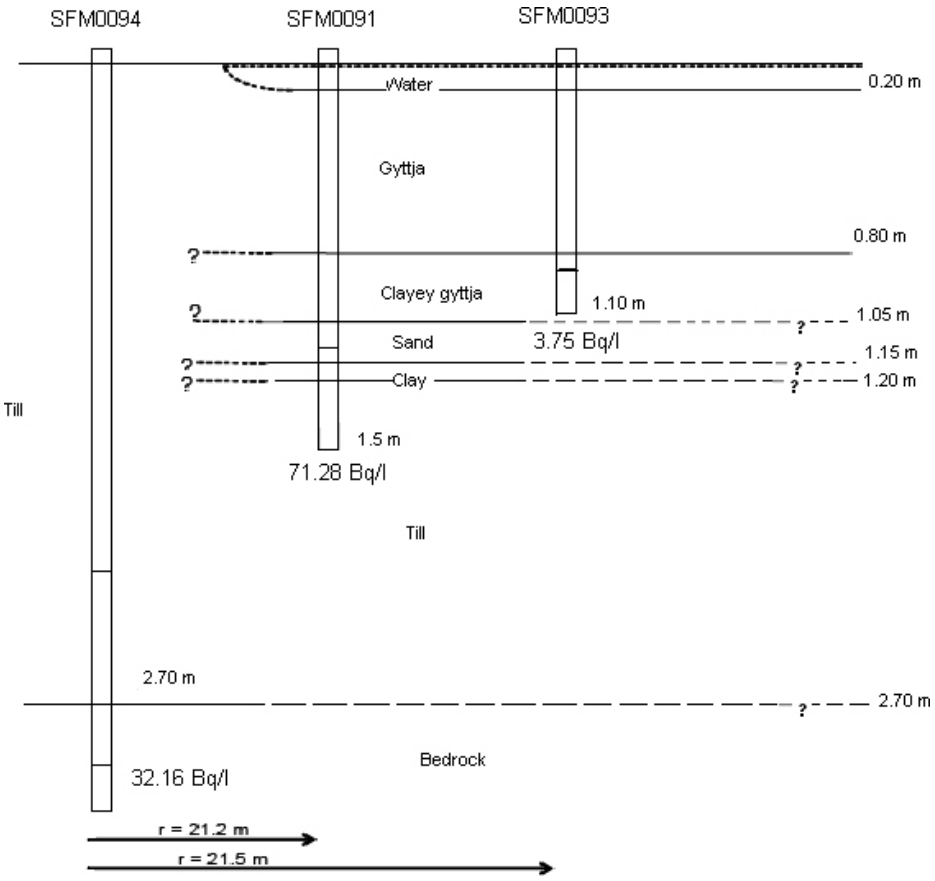

Figure 3-4. *A conceptual picture of sampling Site 2 and the measured radon concentrations. (Note, not in scale.)*

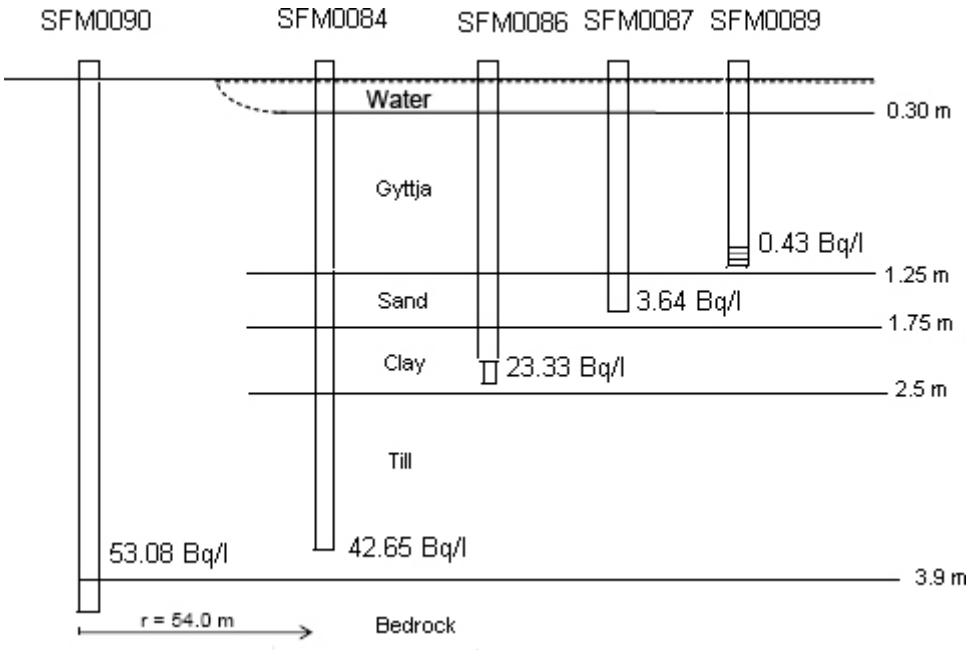

Figure 3-5. *A conceptual picture of sampling Site 3 and measured radon concentrations. (Note, not in scale.)*

3.2 Steady state radon concentration

The steady state radon concentration is the radon concentration in the groundwater that will be reached by ingrowth of radon from radium in the local environment if the groundwater is left in undisturbed conditions in the soil for approximately 30 days. To determine the steady state radon concentration soil samples were taken in the close vicinity of wells SFM0013, SFM0014, SFM0026 and SFM0090 in Forsmark. The samples were taken at approximately 30 cm depth.

The results and the uncertainty interval are presented in Table 3-1. The largest estimated uncertainties are the estimation of the pore volume of the soil and the standard deviation of the radon measurements. The pore volume is as described in 2.3 determined by taking an extra soil sample for measuring the porosity. The largest uncertainty in this estimation is measuring the volume of this sample. This volume can be underestimated since it is hard to get the plastic film directly against the sides of the hole. In the calculations an underestimation of this volume by 10% is taking into account.

The radon concentrations of the water in the airproof bags were relative low and had quite large standard deviations. These uncertainties are included in the calculations and a range of steady state radon concentrations are presented in Table 3-1. The steady state radon concentrations are quite uniform in the area and range from 13 to 33 Bq/L (or 11 to 69 Bq/L if the uncertainties are included).

For well SFM0013 the measured radon concentration in the groundwater is 420 Bq/L which is one order of magnitude higher than the measured steady state radon concentration of 29–38 Bq/L. At this site the soil at the sampling depth is gravel outwash overlaying the till present at the screening dept of the groundwater monitoring well.

Table 3-1. Steady state radon concentrations in the vicinity of selected wells. The estimated uncertainties in the measurement are shown in brackets.

	Steady state radon concentration (Bq/L)	Soil at ground surface	Soil at screen depth	Radon concentration in groundwater (Bq/L)
SFM0013	33 (29–38)	Gravel	Till/ Bedrock interface	420
SFM0014	13 (11–19)	Till (and organic material)	Till	146
SFM0026	26 (16–37)	Gravelly sand	Till/ Bedrock interface	155
SFM0090	44 (27–69)	Till	Till/ Bedrock interface	53

For well SFM0014 there is a difference of almost one order of magnitude between the steady state radon concentration (11 to 19 Bq/L) and the measured radon concentration in the groundwater (146 Bq/L). The soil type is the same at the soil sampling depth and the screen depth. But the soil sample contained organic material which may have lowered the steady state radon concentration.

For well SFM0026 there is a difference of about one order of magnitude between the steady state radon concentration (16 to 37 Bq/L) and the measured radon concentration in the groundwater (155 Bq/L). The soil type at the soil sampling depth is gravelly sand outwash and at the screen depth the soil type is till.

For well SFM090 the soil type is the same at the screen depth and the soil sampling depth. The radon concentration in the groundwater (53 Bq/L) and the steady state radon concentration (27–69 Bq/L) are within the same range.

4 Discussion

4.1 Evaluation of the RAD-7 radon measurements

To evaluate the RAD-7 method double samples were taken with both the 250 ml vial and the 40 ml vial during the sampling campaign in Laxemar in May 2009. The results show excellent repeatability between the 250 ml samples as shown in Figure 4-1. The comparison of the measurements done with the 40 ml vial and the 250 ml vial also show good repeatability but the standard deviation was as expected larger using the 40 ml vial. Therefore, the 40 ml measurements were not used in this study with exception of measurements done in BAT-filter wells where larger samples could not be taken.

The coefficient of variation (CV) is a measurement of the relative uncertainty for a measurement. The CV is calculated by dividing the standard deviation with the mean value for each radon measurements done with the RAD-7 detector in Laxemar and Forsmark. The CV was as expected highest for the measurements with the lowest radon concentrations which means that a low concentration makes the measurement more uncertain. Most of the measurements, 46 of 66, have a CV below 10%. One of the measurements has a measured concentration of 0.4 Bq/L and a CV of as much as 116%. The high CV was probably due to the low radon concentration that was close to the RAD-7 detection limit of 0.37 Bq/L.

In Forsmark two sampling campains were done with the RAD-7 method. A comparison between the radon measurements done in October 2008 and June 2009 at the same sampling locations is shown in Figure 4-2. The comparison shows that the radon concentrations do not vary between the sampling occations. This indicates that the RAD-7 method give good repeatable results and that radon concentrations probably are stable over time.

To further evaluate the RAD-7 measurement technique a comparison was done between the radon measurements done at the SUERC laboratory and measurements done with the RAD-7 method. The results are shown in Figure 4-3 and Figure 4-4 for Forsmark and Laxemar respectively. The measurements show the same trend both in Forsmark and Laxemar. The laboratory analyses in Laxemar are generally lower than the measurement done with the RAD-7 technique. It is not possible to evaluate if the differences are caused by different measurements method or by natural changes in radon concentrations.

In Forsmark SUERC analyses were conducted in both August 2007 and August 2008 and the results show a relatively large difference between the sampling occasions. The differences appear to be large especially in comparison with the small differences shown between the RAD-7 measurement done in October 2008 and June 2009. This can be an indication of better repeatability in the RAD-7 measurements than in the laboratory analyses.

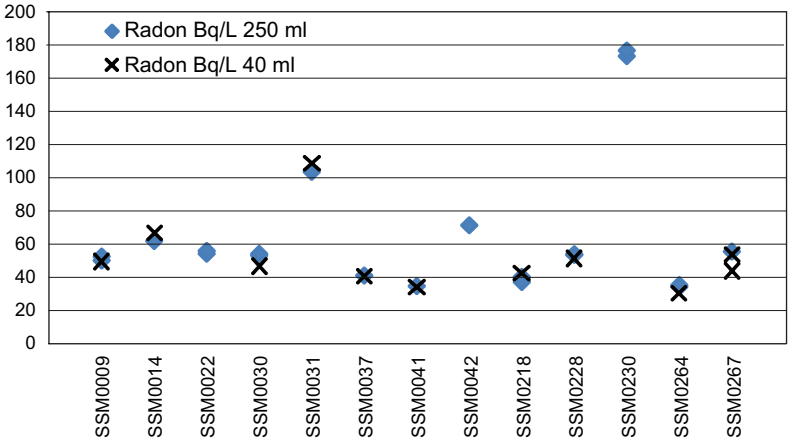

Figure 4-1. *The results from the duplicated of radon measurements done with the 250 ml vial in Laxemar show excellent repeatability.*

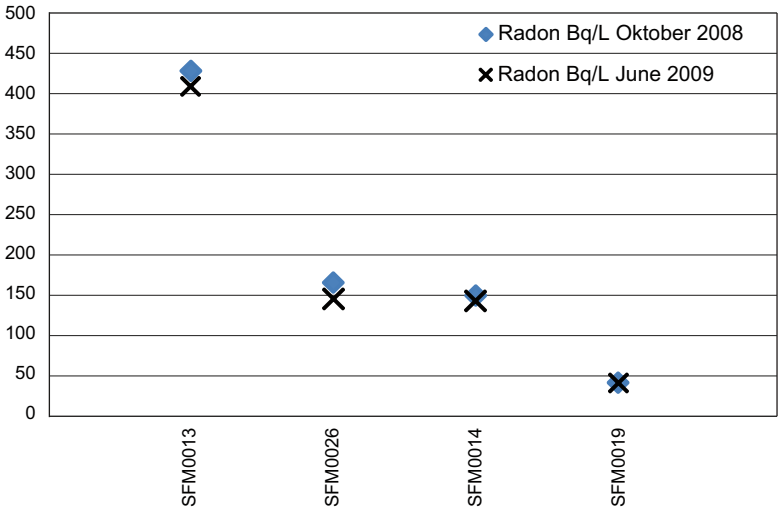

Figure 4-2. *The four wells measured in both October 2008 and June 2009 in Forsmark show almost the same concentration with a variation between 0.6–12%.*

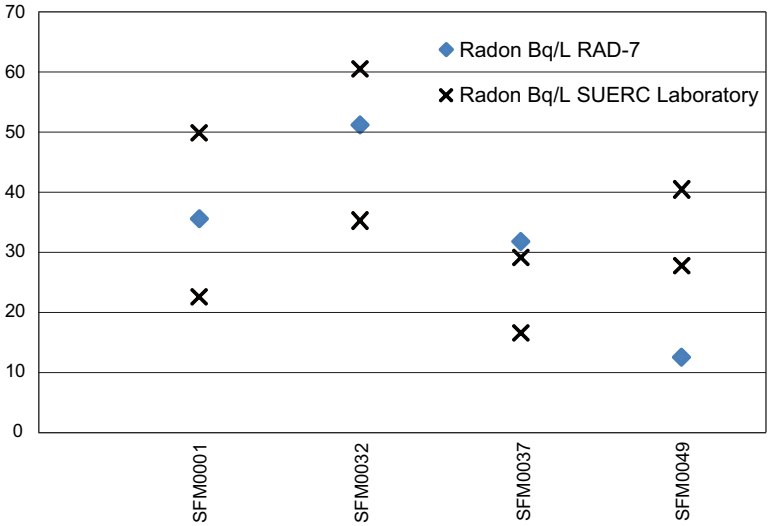

Figure 4-3. *Comparison between radon concentrations in monitoring wells measured with RAD-7 method and previous laboratory analyses in Forsmark.*

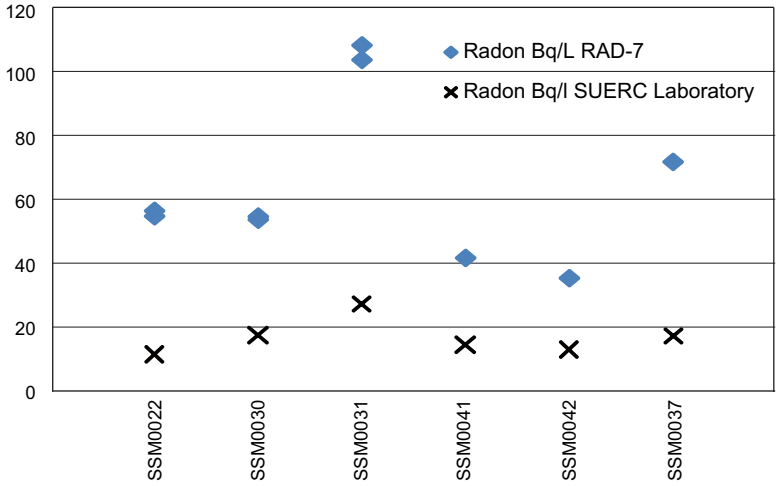

Figure 4-4. *Radon concentrations measured at six sites with both the RAD-7 method and the Liquid Scintillation method in Laxemar. The laboratory analyses are generally lower than the RAD-7 measurements.*

4.1.1 Uncertainties in RAD-7 measurements

The radon measurements done in the wells in the sediments under Lake Bolundsfjärden (SFM0023) and under Lake Gällsboträsket (SFM0012) were done using half of the sampling volume. This was done because gas was produced during aeration of the sample. The gas made the water rise in the plastic tube making it impossible to continue the measurement since the RAD-7 is sensitive to water. Therefore new samples with half the water volume were used to avoid water to rise in the tubes during aeration. The measured concentrations were doubled to get a more accurate estimation of the radon concentration but these measurements should be seen as indications of the radon concentration and not as an actual measurement.

The result from radon measurement in the well SFM0056 is also uncertain since there was very little water in the well and the water may have been aerated during sampling. This sample should also be considered as an indication of the radon concentration rather than an actual measurement of the concentration.

Also the measurements done in BAT-filter type wells should be considered as less reliable since the water is left in contact with air inside the sampling tube for long time periods. These measurements are used as indicators of radon concentration. Some of the measurements done in BAT-filter wells were done using 40 ml vials since the yield of water was too low to get 250 ml samples within a reasonable time period. These measurements are from wells SFM0086, SFM0089, SFM0093 and SFM0100. In BAT-filter well SFM0097 a 250 ml vial was used but the sampled water did not fill the 250 ml, instead approximately 10% of the vial was empty and the measurement was therefore corrected for this by adding 10% of the measured radon concentration.

4.2 Evaluation of physical and chemical factors affecting radon concentrations

As described in section 1.3.2 radon concentration in groundwater depends on several factors like emanation potential of the soil, transport processes in groundwater and outgassing to the atmosphere. In this section the results from the radon measurements in Laxemar and Forsmark are compared to other chemical and physical parameters measured within the site investigation program to investigate if there is any parameter that correlates with the radon concentration and can explain the observed patterns. The parameters used can be divided into three categories: (1) location of the well and groundwater flow patterns, (2) bedrock and soil properties and (3) chemical parameters measured in the groundwater.

1) The parameters used to evaluate if the location and groundwater flow patterns impact the radon concentration in groundwater were, location of the well within the catchment, distance to nearest surface water, distance to nearest fracture zone, depth of the well and the field classification of recharge and discharge wells.

The distance to surface water can affect radon concentration since infiltration of surface water into groundwater can be expected to lower the radon concentration in the groundwater. The distances between the sampled wells and the nearest surface water were measured using ArcGIS and the distances were compared to the radon concentrations.

The mapped fracture zones in the area can be expected to be correlated to elevated radon concentrations as discussed previously. The distances between the known fracture zones and the wells were measured with help of ArcGIS.

The depth of the wells can also be expected to influence the radon concentrations since radon in deep wells are not affected by outgassing in the same extent as shallow wells.

To assess the affect groundwater flow patterns have on radon concentration the radon concentrations were compared to previous studies of groundwater recharge and discharge patterns. The groundwater flow patterns of the area have been investigated using several methods during the site investigations. One of the methods is the field classification method where several field parameters were used to classify the wells as Recharge, Probable Recharge, Varying, Probable Discharge and Discharge wells. The methods and results of this classification are presented in /Werner et al. 2008/

and /Werner et al. 2007/ for Laxemar and Forsmark respectively. The resulting classification of recharge and discharge wells is compared to the measured radon concentrations.

The radon concentration in the near surface groundwater can be elevated due to inflow of groundwater with high radon concentrations from the bedrock. Therefore the interactions between groundwater in the bedrock and the groundwater in soil is of interest when explaining the pattern in radon concentration found in the area. The relationship between groundwater levels in soil and bedrock was investigated during the site investigation and the conclusions from these studies were used here to see if wells that could be expected to be in contact with groundwater in bedrock have higher radon concentrations.

2) Bedrock and soil properties can be expected to have an influence on the radon concentration in groundwater. The soil types at the screening depth of the wells were compared to the radon concentrations. The information about the soil types at the screen depth were determined during the installation of the monitoring wells. The bedrock classification at the well locations was derived from the bedrock map with help of ArcGIS and then compare to the radon concentrations.

During the site investigations airborne geophysical gamma ray spectrometry was done at both Laxemar and Forsmark to assess the relative intensities of uranium, thorium and potassium in the areas. The results were interpreted and classified according to relative intensities of the three different elements. The radon concentrations were compared to the results of these studies since it can be expected to find higher radon concentrations in areas with higher uranium and thorium intensities. This comparison was done with help of ArcGIS.

3) During the site investigations extensive programs for chemical characterisation of different water types were conducted in both Laxemar and Forsmark. Some of the measured parameters were used to evaluate to origin of the groundwater. The groundwater was classified according to the dominating content of major ions. In this classification groundwater dominated by Ca-HCO_3 was classified as young recharging water and groundwater dominating by Na-HCO_3 and Na-Cl was classified as more mature discharging groundwater. This chemical parameters done in both Forsmark and Laxemar showde no clear correlation to the field based classification of the wells.

In this study chemical parameters that are thougth to indicate the age of groundwater are compared to the measured radon concentration to see if any correlation could be found. The first parameter used was the Na/Ca ration. A high Na/Ca ration indicates a mature water were most of the Ca has been replaced by Na in the groundwater due to cation exchange processes that take place in the soil.

The other parameter that is used to assess groundwater age is tritium, (^3H). Tritium was added to the natural systems during the testing of thermo-nuclear bombs during the 1950's and 1960's which means that high tritium concentration are found in groundwater formed during this time period. Low tritium concentrations are found in groundwater that was formed before this time period. Tritium is used in this study to see if tritium is correlated with radon concentrations.

4.2.1 Laxemar

In general the radon concentrations measured in the near surface ground water in Laxemar are uniform with all except two measurements between 35 and 75 Bq/L and only two measurements above 100 Bq/L. The small variability of radon concentration makes the comparison with other parameters hard to evaluate since the observed patterns will be weak.

The distributions of radon measurements in the delineated catchment areas are illustrated in Figure 4-5. There are three catchments in the area with more than one radon measurement but no differences in the radon concentrations can be seen between the different catchment areas. Higher radon concentrations could be seen in the lower parts of the catchments areas than in the higher parts of the catchment area. Since the concentration differences are small it is hard to draw any conclusions from these observations.

The distance to nearest surface water was compared to the radon concentration. 10 out of the 14 sampled wells were located within 12 meters from a stream. These 10 wells were also the wells with the lowest radon concentrations. This can be caused by infiltration of surface water that lowers the radon concentrations in these wells.

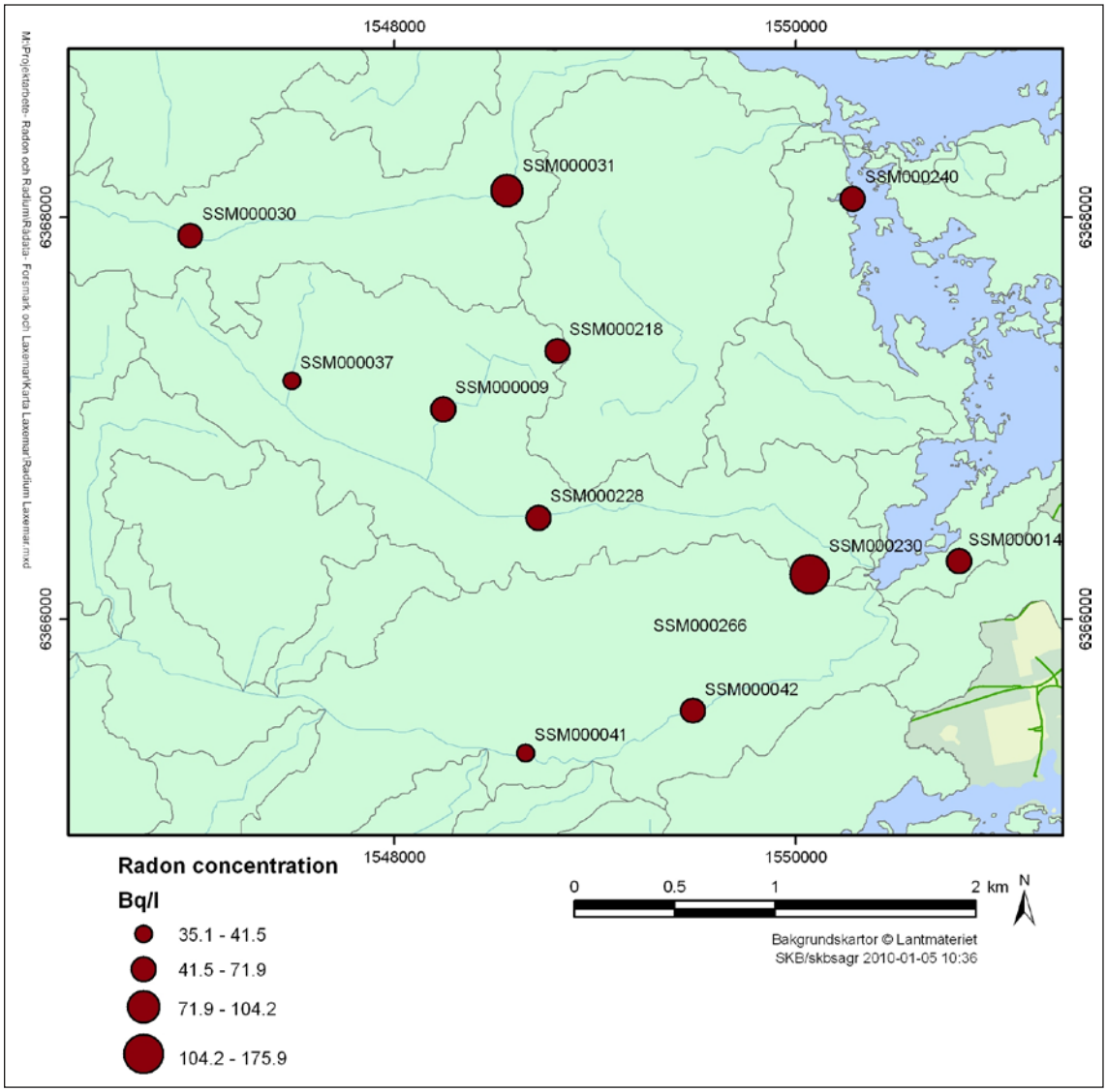

Figure 4-5. *Radon concentration in the delineated catchment areas. The lowest concentration can be found in the upper part of the catchment and higher concentrations are found in the lower part of the catchment.*

The distances to known major fracture zones were compared to the radon concentrations measured in the wells. 6 of the 14 wells were within 17 meters from a major fracture zone; the other wells were located far away from the fracture zones and the effect of any discharging groundwater with elevated radon concentrations from the fracture zone is limited due to the short half-life of radon and slow transport of groundwater. No correlation was found between short distance to fracture zone and radon concentration which indicated that the known major fracture zones do not affect radon in near surface groundwater in the area.

The depths of the wells were also compared to the radon concentrations. The depths of the wells are quite uniform ranging from 3 to 7 meters and no correlation was found between radon concentration and depth of the well.

The comparison between the field classification of recharge and discharge wells and the radon concentrations is shown in Figure 4-6. The comparison shows no correlation between radon concentration and recharge/discharge patterns of the groundwater. In contradiction to the expected pattern, the highest radon concentration was found in a recharging well and low radon concentrations were found in both recharge and discharge wells.

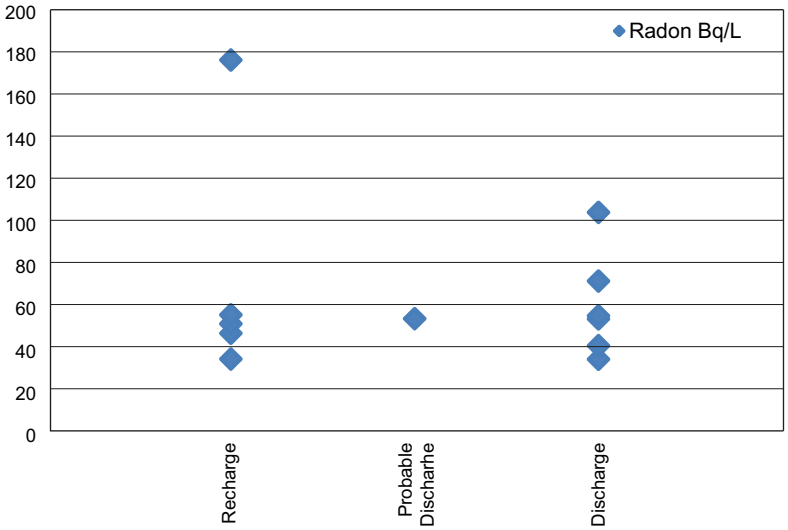

Figure 4-6. *The comparison between the field based recharge/discharge classifcation of the monitoring wells and the measured radon concentrations showed no correlation.*

The results from the investigation of the interactions between deep groundwater and near surface groundwater in Laxemar showed a complicated pattern. In some areas the groundwater level in the bedrock is higher than the groundwater level in the Quaternary deposits and in some areas the groundwater level in bedrock is lower than the groundwater level in Quaternary deposits. At site SSM0041 and SSM0037 which are included in this study the groundwater levels are higher in the bedrock than in the Quaternary deposits which indicates an upward gradinet of groundwater flow. These sites can be expected to have elevated radon concentration due to inflow of deep groundwater but the measured radon concentrations at these sites are among the lowest. At sites SSM0218 and SSM0009 there are downward gradients for groundwater flow and it can therefore be expected to find low radon concentrations at these sites. The measured radon concentrations are also among the lowest radon concentrations measured in this study.

The bedrock and soil have a large impact of the radon concentration as explained previuosly. The bedrock is uniform in the area and all wells are located in granit bedrock. Because of this no correlation between radon concentrations and bedrock was found. The soil types at screen depths are mostly till with sand, silt or boulders. No correlation between soil types and radon concentrations could be found.

The relative intensities of uranium, thorium and potassium measured with airborne gamma ray spectrometry and the radon concentrations are shown in Figure 4-7. The comparison of the uranium, thorium and potassium intensities and radon concentration shown in Figure 4-8 showed the opposite pattern than the expected with the highest radon concentrations in potassium dominated area and low radon concentrations in thorium and uranium dominating areas.

The radon concentrations were compared to the Na/Ca ration and the tritium concentrations. No correlation was found between this parameters and radon concentration. Only one site, SSM0022, had high Na/Ca ration which indicates an old more mature groundwater. The tritium concentrations are moderate within the whole area which indicates a modern groundwater, except for site SSM0022 that shows low tritium concentration. Low tritium concentrations indicate that the groundwater was formed before the nuclear bomb testing in the 1950´s. The site SSM0022 stands out in both of these parameters which indicates that the groundwater at this site is older and more mature, with influence of deeper groundwater. But the groundwater at SSM0022 does not show elevated radon concentration.

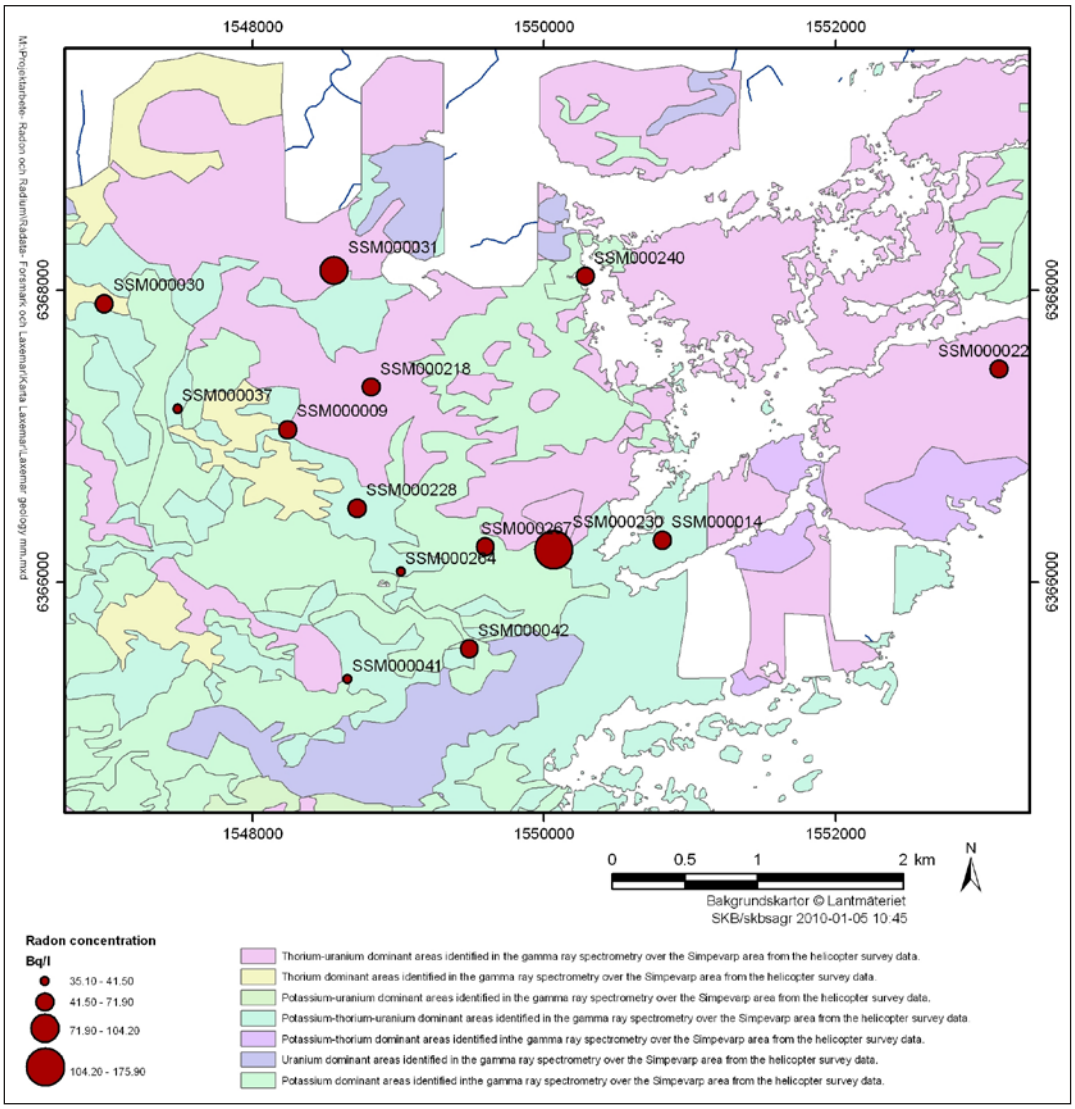

Figure 4-7. *Relative intensities of uranium, thorium and potassium measured with airborne gamma ray spectrometry and measured radon concentrations in near surface groundwater are shown in this figure. The area dominated by uranium is found south of wells SFM0040 and SFM0041.*

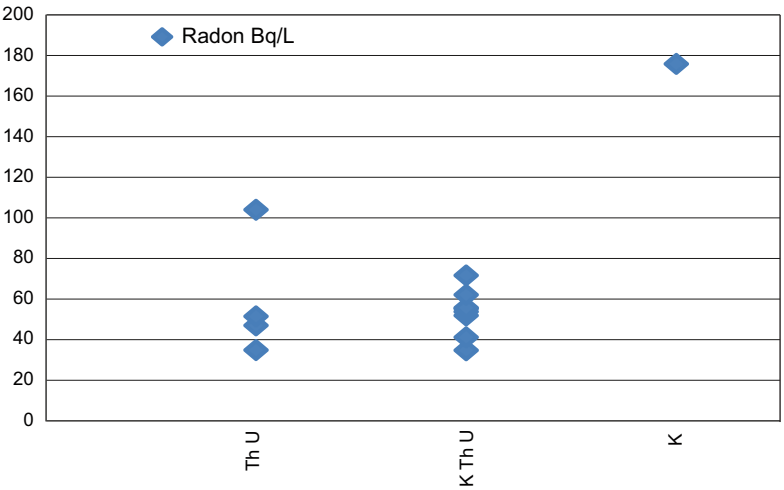

Figure 4-8. *The comparison between the relative intensities of uranium, thorium and potassium and radon concentration showed no correlation. The highest radon concentration was found in a area with dominating potassium intensities in contradiction to the expected pattern.*

4.2.2 Forsmark

The distribution of radon measurements in the delineated catchment areas is shown in Figure 4-9. There are three catchments in the area with more than two radon measurements. The first area is the catchment area of Bolundsfjärden with wells SFM0019, SFM0023 and SFM0032. The second area is Gällsboträsket with wells SFM0011, SFM0012, SFM0013, SFM0057 and Site 1. The third catchment area is the catchment area of Norra bassängen with wells SFM0037, SFM0051, Site 2 and Site 3 (see Figure 3-2 for location of Site 1, Site 2 and Site 3). The highest radon concentrations are found in the catchment area of Gällsboträsket but no general trend in the distribution of the radon concentrations within the catchment areas can be found.

The distance to nearest surface water was compared to the radon concentration but no correlations were found. 12 of the 31 wells were located within 20 meters from surface water. Among these wells both high and low radon concentrations were found. The distances to surface water did not affect the radon concentrations in the sampled wells in this area.

The distances to known major fracture zones were compared to the radon concentrations. There is no correlation between the distance to deformation zones and radon concentrations in near surface groundwater but if wells located more than 60 meters from a deformations zone were excluded a weak correlation could be found with increasing radon concentrations with increasing distance from deformation zones. This is the opposite of the expected pattern with increasing radon concentrations with decreasing distances from deformations zones.

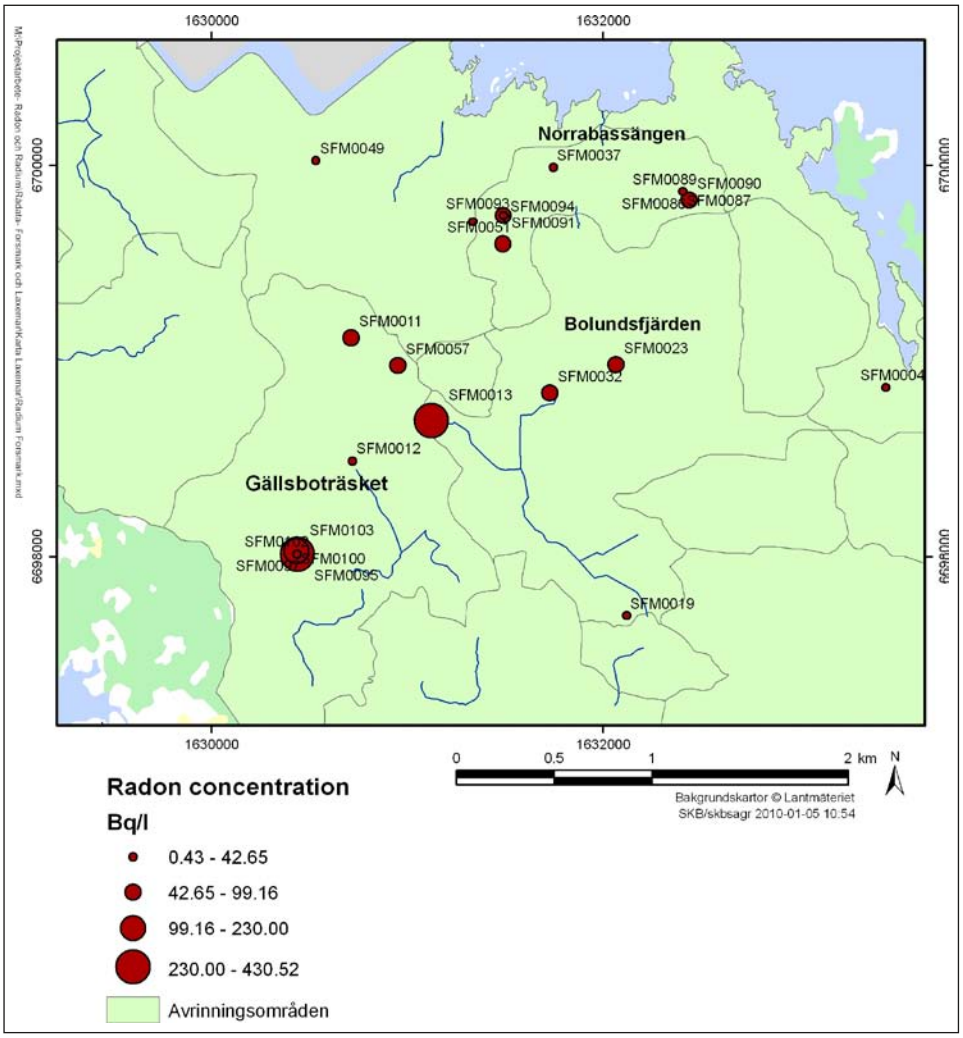

Figure 4-9. *The delineated catchment areas with more than two radon measurements are shown. All of the wells with high radon concentration are located in the catchment area of Gällsboträsket.*

The depths of the sampled wells range from 2 to 16 meters with all except one well within 8 meters of depth. In Figure 4-10 a weak correlation between the depth of the sampled wells and the radon concentration is shown.

The comparison between radon concentrations and the field classifications of recharge and discharge wells is illustrated in Figure 4-11. There is no clear correlation between the radon concentration and the recharge/discharge classification. Low radon concentrations are found in both recharge and discharge wells. High radon concentrations are only found in discharge wells.

In Figure 4-11 the wells from the three cluster sites are included. These wells are not included in the field classification but they are placed in areas that are typical discharge areas and therefore they are classified as discharge wells in this comparison. Some of these wells are located a few meters away from the actual cluster site and this may make the classification as discharge wells somewhat uncertain since they may be located outside the local discharge area. Another problem with the classification of the cluster wells is that some of the wells at the cluster sites are shallow wells with the screen in shallow soil layers. This means that they are located in soil types like clay, gyttja or peat with lower mineral content and also lower radon emanation potential. This means that the radon concentrations at these wells are not comparable to radon concentration in other wells located in the till/bedrock interface. Therefore the wells from the cluster sites are excluded in the Figure 4-12. In this figure the same pattern can be seen.

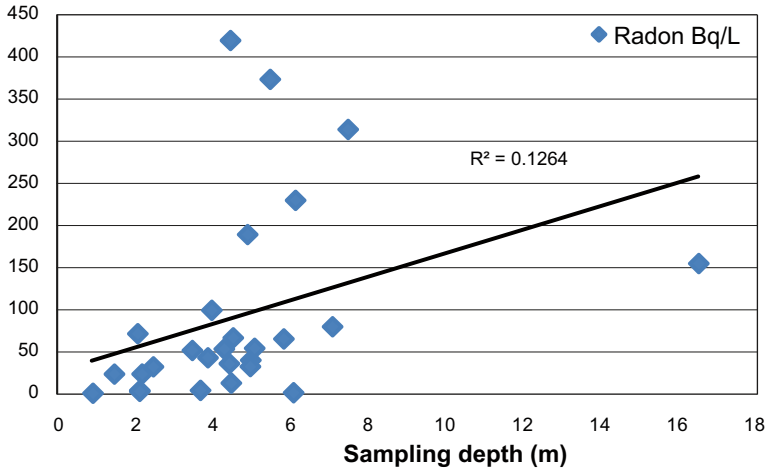

Figure 4-10. *The depths of the wells show a weak correlation with the radon concentration.*

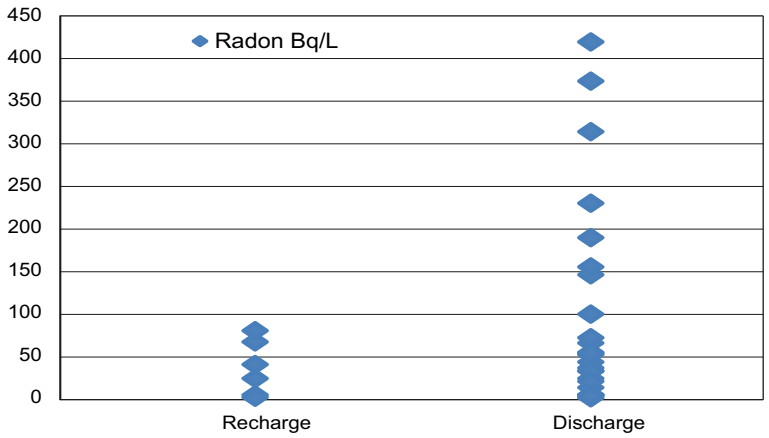

Figure 4-11. *There is no correlation between the recharge and discharge wells and the radon concentration. Low radon concentration can be found in both types of wells.*

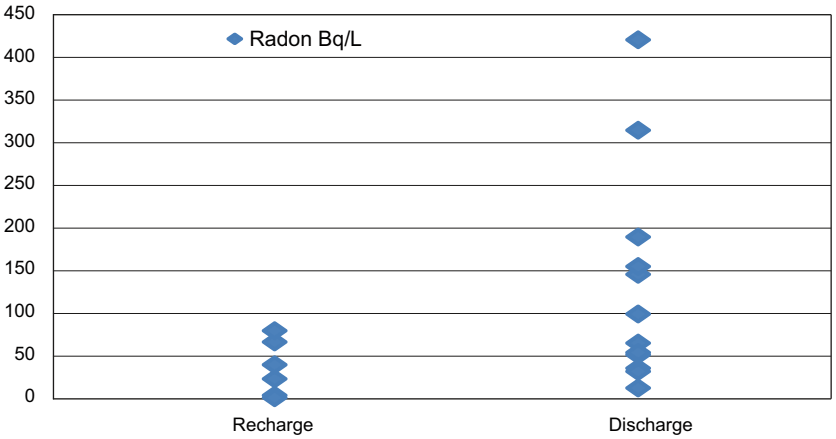

Figure 4-12. *In this figure the wells from the cluster sites are excluded and this gives a somewhat better correlation between the recharge/dischare classification and the radon concentrations. Here high radon concentrations are only found in discharging wells while low radon concentrations can be found in both recharging and discharging wells.*

The interactions between deep groundwater and near surface groundwater have been investigated during the site investigations as descreibed previously. The results show a general picture of lower groundwater levels in the bedrock than in the Quaternary deposits within the tectonic lens. The opposite pattern was observed outside the tectonic lens at Drill Site 4 in the vicinity of Lake Gällsboträsket. Here the groundwater levels in bedrock were higher than the groundwater levels in Quaternary deposits which inidicates an upward groundwater flow. The highest radon concentarations measured in the Quaternary deposits in the area were found in the wells close to Lake Gällsboträsket (SFM0013 and SFM0095) which can be an indication of upward flow of radon rich groundwater from the bedrock at this site.

The bedrock and the soil type at the sampled sites were compared to the radon concentrations. The radon concentrations in wells in till and bedrock/till interface showed a large variation with both high and low radon concentrations. Low radon concentration were found in soil types with high organic content like gyttja and peat. The bedrock showed no correlation to the radon concentration.

The relative intensities of uranium, thorium and potassium measured with airborne gamma ray spectrometry and the radon concentrations are shown in Figure 4-13. In Figure 4-14 the comparison between the relative intensities of uranium, thorium and potassium and the radon concentrations is done and it shows no clear correlation. In fact the highest radon concentrations were found in the areas with background and low intensities of uranium and thorium in contradiction to expected pattern.

The radon concentrations were compared to Na/Ca rations and tritium concentrations. The Na/Ca ratio shows no correlation to the radon concentration. The highest Na/Ca ratio was found in well SFM0056 which is the well with the lowest radon concentrations among the compared wells. The highest radon concentrations were found among the wells with low Na/Ca ration. The tritium concentrations were uniform among the wells around 10 TU which indicate a modern groundwater. The only well with low tritium concentration was well SFM0056 that also showed the highest Na/Ca ratio. This indicates that the water is old and may even come from deep groundwater. The radon concentration in this well is low.

4.3 Classification of groundwater wells based on radon concentration

Since the measured steady state radon concentration showed to be quite uniform in the Forsmark area it may be used as an approximation for the steady state radon concentration in the whole area. The steady state radon concentration was approximated to be in the range of 10–70 Bq/L.

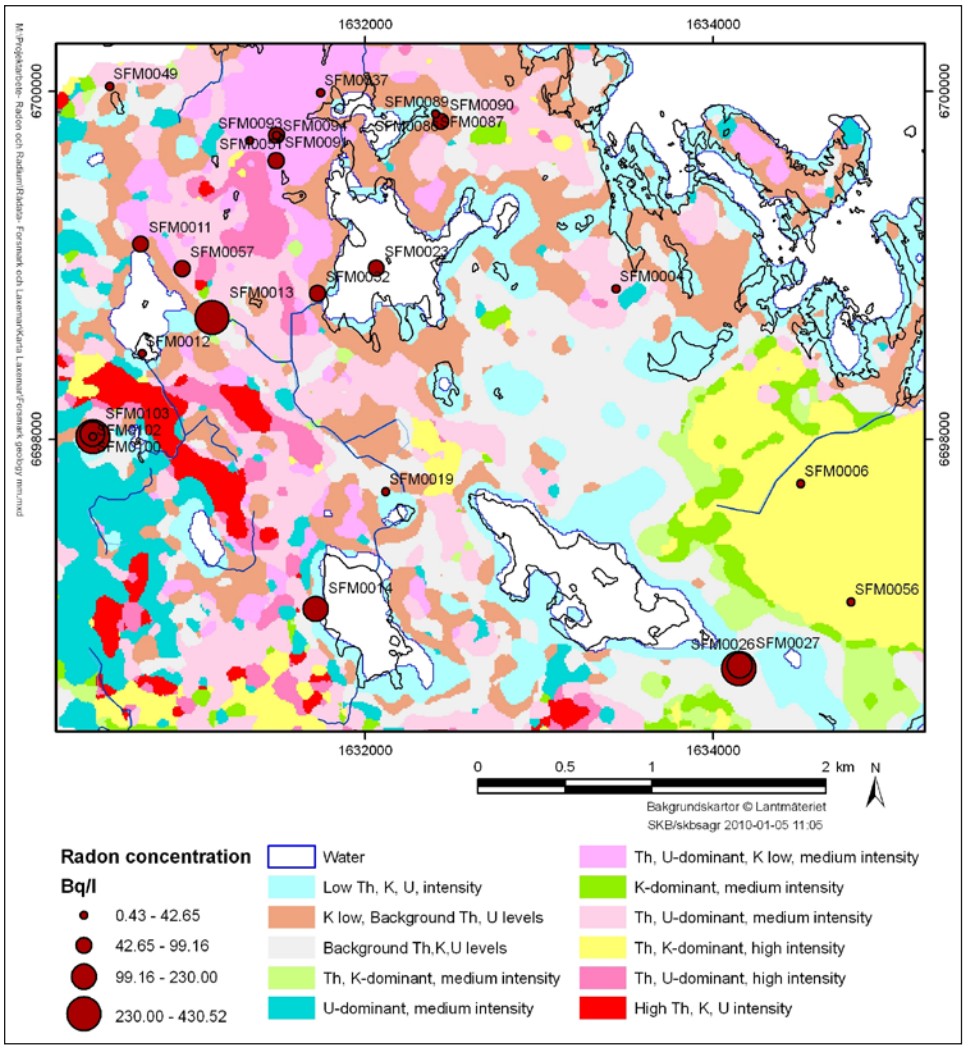

Figure 4-13. *The map shows the relative intensities of uranium, thorium and potassium and the radon concentrations in groundwater in Forsmark area. The red and pink areas that represent high uranium and thorium intensities are dominating in the North West part of the area.*

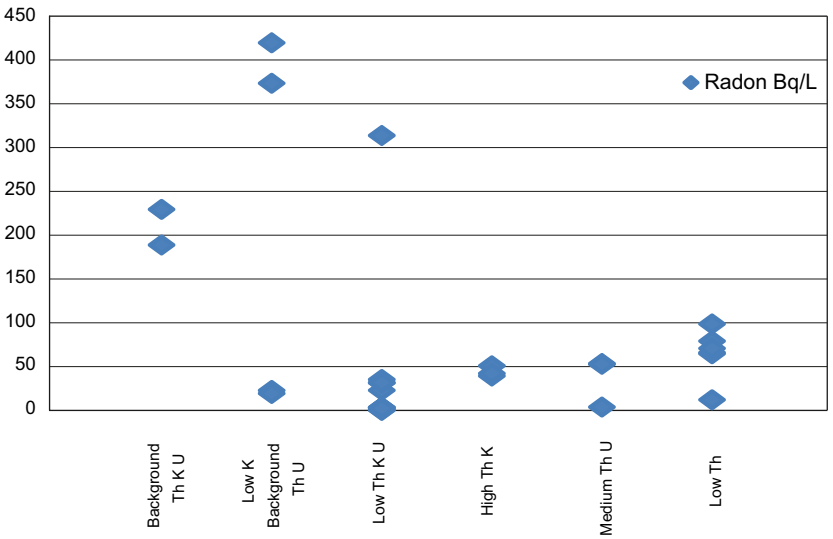

Figure 4-14. *The comparison between raodon concentration and the relative intensities of uranium, thorium and potassium showed no clear correlations. The highest radon concentration are found in areas with lowest uranium and thorium intensities.*

This steady state radon concentration was then used to evaluate the radon concentrations measured in monitoring wells in the whole area.

Groundwater with radon concentration under 10 Bq/L is not in equilibrium with the surrounding soil since the steady state radon concentration has not been reached yet. This can be caused by infiltration of radon free recharge water or the fact that the wells are located in soil with lower radon emanation potential like peat or gyttja.

Groundwater with radon concentrations higher than 70 Bq/L can be thought to be affected by inflow of high radon deep groundwater since the radon concentration is higher than the steady state radon concentration.

Groundwater with radon concentration between 10 and 70 Bq/L can be thought to have reached steady state radon concentration and to be in equilibrium with the radium in the soil. This means that these wells are not affected by recharge water with low radon concentration or by discharging water with high radon concentration. This method of classifying of recharging or discharging groundwater was used to interpret the radon measurements of this study. The classification is presented in Table 4-1.

Table 4-1. The table presents the classification of the wells based on the radon concentrations relative the steady state radon concentration. This classification is compared to the field classification of the wells (R = recharge D = Discharge) and the soil type at the screen depth of the well.

Id code	Radon (Bq/L)	Groundwater type	RD class	Soil type
SFM0089	0.43	Recharging water	D	gyttja
SFM0056	1.06	Recharging water	R	Not known
SFM0102	2.68	Recharging water	D	peat
SFM0087	3.64	Recharging water	D	sand
SFM0093	3.75	Recharging water	D	clayey gyttja
SFM0006	3.86	Recharging water	R	bedrock
SFM0100	4.25	Recharging water	D	gyttja
SFM0049	12.52	Stable water	D	till
SFM0097	19.8	Stable water	D	clay
SFM0004	23.23	Stable water	R	Not known
SFM0086	23.33	Stable water	D	clay
SFM0037	31.87	Stable water	D	till
SFM0094	32.16	Stable water	D	till/bedrock
SFM0001	35.67	Stable water	D	sandy silty till
SFM0019	36.7	Stable water	R	silty till
SFM0084	42.65	Stable water	D	till
SFM0032	51.35	Stable water	D	till
SFM0090	53.08	Stable water	D	Till/bedrock
SFM0051	53.98	Stable water	D	Not known
SFM0012	65.1	Stable water	D	till
SFM0057	66.39	Stable water	R	till
SFM0091	71.28	Discharging groundwater	D	Till
SFM0060	79.6	Discharging groundwater	R	sand
SFM0011	99.16	Discharging groundwater	D	fractured bedrock
SFM0014	145.6	Discharging groundwater	D	till
SFM0026	154.8	Discharging groundwater	D	silty till
SFM0023	189.32	Discharging groundwater	D	till
SFM0103	230	Discharging groundwater	D	till/bedrock
SFM0027	314.37	Discharging groundwater	D	silty till
SFM0095	374	Discharging groundwater	D	Till
SFM0013	420	Discharging groundwater	D	Till/bedrock

Seven of the wells in Table 4-1 were classified as recharge wells with radon concentrations below the steady state radon concentration. The soil types at screen depth of these wells were peat, gyttja, sand or till/bedrock. The wells in gyttja and peat (SFM0089, SFM0093, SFM0100 and SFM0102) can be expected to have a lower steady state radon concentration since the gyttja and peat have high organic content and therefore contain less radium. The low radon concentration in these wells can be at equilibrium with the emanation potential of the gyttja and peat and it is therefore hard to say anything about the groundwater flow at these wells. All of these wells were also located in a typical discharge area.

The well SFM0087 that is classified as a recharging well based on the radon concentration is located in a sand layer at Site 1. The sand layer is overlaying a layer of clay which limits groundwater discharge from deeper layers in the soil profile. On top of the sand layer are layers of gyttja and open water. The low radon concentration in this well is probably due to infiltration of water with low radon concentration from the overlaying gyttja and water layers. This well is also located in a area classified as a discharge area.

The well SFM0006 and SFM0056 also showed low radon concentrations that indicate inflow of radon free recharge water at these sites. The radon measurement at well SFM0056 was uncertain as described earlier and it is therefore hard to draw any conclusions of the groundwater flow at this well.

Most of the wells in Table 4-1have radon concentrations within the range of the steady state concentration. There are both discharging and recharging wells among these wells and the soil type is till or clay. The steady state radon concentration of clay is not measured but since clay has very low hydraulic conductivity the groundwater in clay is almost stagnant and the measured radon concentrations in well SFM0086 and SFM0097 can be assumed to be the steady state radon concentration for clay in the area. For the wells in till no signal from groundwater recharge and discharge can be seen. This suggests that the water has been stable for at least 30 days.

There are 10 wells in Table 4-1 with radon concentrations higher than the steady state radon concentrations. Among these wells only one well SFM0060 was classified as recharge well with the field based method all the other nine wells were classified as discharge wells. The soil types are sand for well SFM0060 and till or fractured bedrock for the rest of the nine wells. The fact that the radon concentrations are elevated at these sites suggests that radon has been added from some other source like groundwater inflow from the bedrock. The wells SFM0013, SFM0027 and SFM0095 show the highest radon concentration and the strongest signal of inflow of radon rich groundwater.

In Figure 4-15 the distribution of the wells classified based on the radon concentration is shown. Well SFM0013 and SFM0095 are located in the catchment area of Gällsboträsket and well SFM0027 are located south of Lake Fiskarfjärden.

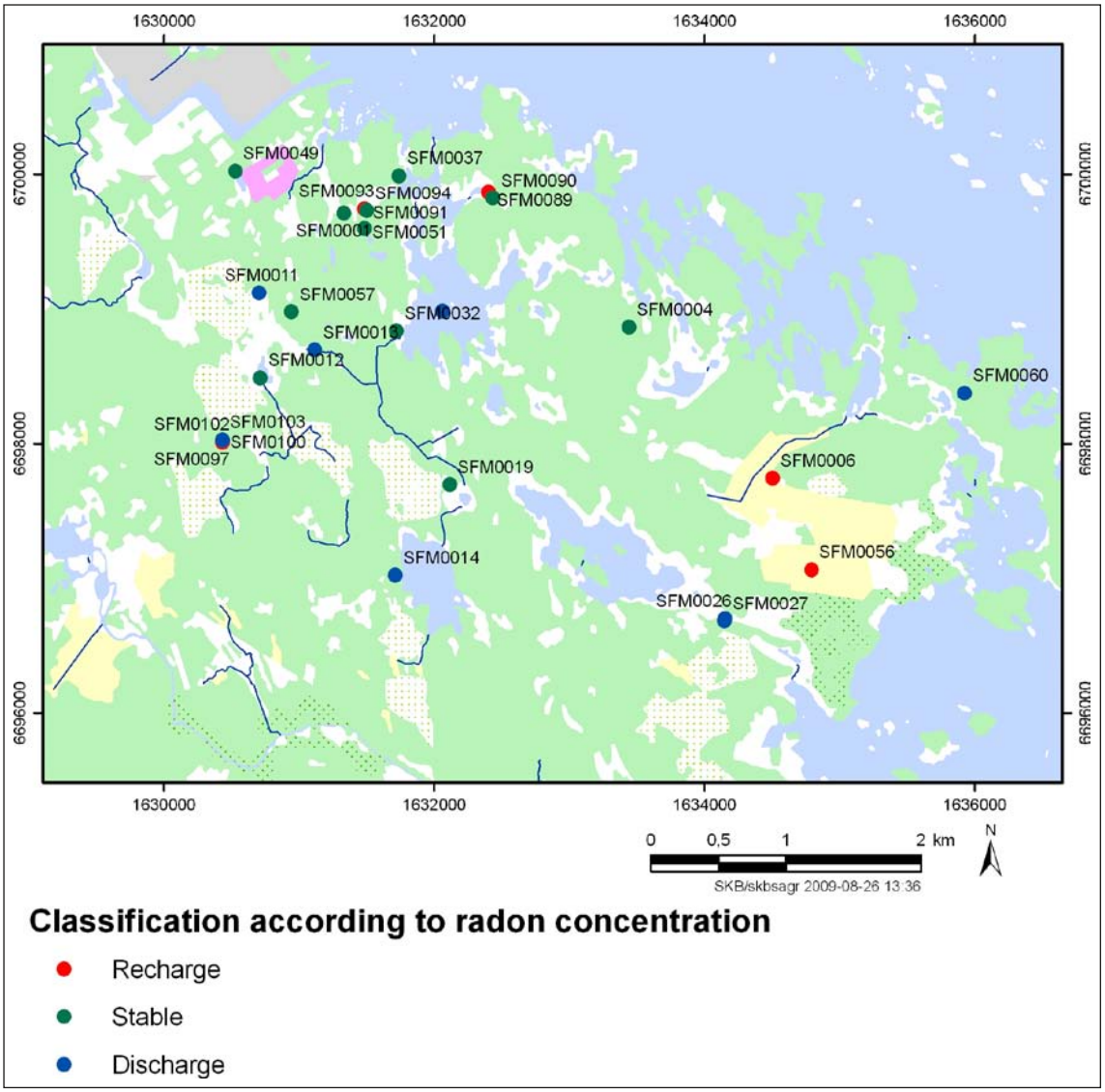

Figure 4-15. *The map shows the distribution of the wells classified based on radon concentration.*

5 Summary and conclusions

5.1 Evaluation of the RAD-7 measurement technique

Radon measurements were done in near surface groundwater with the RAD-7 radon detector within this study. The results of the measurements were evaluated and proven to be reliable and of good quality. RAD-7 is also portable and easy to use in field. This makes the RAD-7 a reliable and cost effective technique for radon measurements.

5.2 Radon in natural waters in Laxemar and Forsmark

Radon concentrations in different water types were investigated in Forsmark and Laxemar during the site investigation and within this study. The radon concentration in surface water was low at both sites even if elevated radon concentration was found in a stream in Laxemar. The elevated radon concentration can be caused by inflow of groundwater with higher radon concentration.

The radon concentration in near surface groundwater is much higher than in surface water at both sites. The radon concentrations measured in near surface groundwater in Laxemar within this study were low and quite homogenous. The concentrations were significantly higher and more variable in the Forsmark area.

The radon concentrations in deep groundwater were generally higher than in the near surface groundwater at both sites. The same pattern was found in deep groundwater with lower radon concentrations in deep groundwater in Laxemar in comparison to the measurements done in Forsmark.

Radon concentrations were also measured at different depths in the bedrock in both Laxemar and Forsmark. Measurements were done at different depths within the same bore hole and the radon concentrations showed large variations with depth. The variation was generally larger within the bore holes in Forsmark than for the bore holes in Laxemar. This variation can be caused by hydraulically conductive fracture zones. In bore hole sections with conductive fractures zones water from the fractures with high radon concentration is constantly replacing the water in the bore hole section and keeps the radon concentration high. In bore hole sections were there are no conductive fracture zones and the water is stagnant, the radon in the groundwater will decay away which gives low radon concentration. This pattern was also confirmed in the report by /Smeilie et al. 2008/ who observed a correlation with high radon concentrations and highly conductive fracture zones.

It can be concluded that large differences between radon concentrations in surface water, near surface groundwater and deep groundwater can be found in Laxemar and Forsmark. It can also be concluded that large variation in radon concentration with depth in deep groundwater exist. These differences in radon concentrations are used in this study to detect interactions between surface water, near surface water and deep groundwater.

5.3 Factors affecting radon concentration in near surface groundwater

The focus of this study has been the radon concentrations of near surface groundwater. The variation in radon concentration in near surface groundwater has been analyses and compared to other parameters in order to try to explain the observed patters. Since the hypothesis of this study has been that there will be differences in radon concentrations between recharging and discharging groundwater, the most important parameter to consider is the recharge/discharge field classification of the wells.

In Laxemar the flow patterns of the near surface groundwater are distinct and the classification of wells as recharge and discharge wells is therefore reliable. There were no correlation between the recharge/discharge classifications of wells and the radon concentrations. The lack of correlation can be caused by the fact that there are just a few wells in recharge areas. The lack of correlation can also

be caused by the homogenous radon concentrations in the Laxemar area. One possible explanation to this is the low radon concentrations in deep groundwater which makes inflow of deep groundwater to the near surface groundwater hard to detect since the signal will be weak.

In Forsmark the radon concentrations in near surface groundwater showed large variability with both low and high radon concentrations. Even if there were large variability in radon concentration the patterns could not be explained by the flow pattern of the groundwater since no clear correlation between radon concentration and recharge/discharge classification was found.

The lack of correlation between groundwater flow patterns and radon concentration in both Laxemar and Forsmark means that it is not possible to use radon to detect flow patterns in near surface groundwater and it is hard to draw any conclusions of the groundwater flow patterns using radon as a tracer in these areas.

To investigate which factors that affect radon concentration the radon concentrations measured in the near surface groundwater in Laxemar and Forsmark were compared to location factors, bedrock and soil properties and chemical parameters measured in the groundwater. This comparison showed no correlation to any of the parameters. This means that none of these factors can explain the variations in radon concentration in groundwater.

The radon measurements done within this study at Site 1, Site 2 and Site 3 in Forsmark showed large differences with increasing radon concentration with increasing depth. These differences can be used to understand the main factors affecting the radon concentration since there were clear signals showing the effect of the local soil on radon concentrations. Soils with high organic content as peat and gyttja can be expected to have lower radon emanation potential due to lower radium content; these wells also had low radon concentrations. High radon concentrations were found in wells in till and bedrock which have higher emanation potential. These observations showed the importance of the emanation potential of the local soil for the radon concentration in groundwater. These results are discussed in more detail below.

At Site 1 and Site 3 the radon concentrations in clay were measured. These concentrations are likely to reflect the steady state radon concentration for clay in the area since clay has low hydraulic conductivity and the groundwater in clay is almost stagnant which means that the groundwater most likely has been in contact with the clay for at least 30 days and the steady state radon concentration has been reached.

At Site 3 the radon concentration in the sand layer was low which indicates an inflow of radon free recharge water since a higher radon concentration in sand than the measured concentration can be expected.

At Site 2 and Site 3 the radon concentrations were higher in the till than in the till/bedrock interface. This could indicate that the groundwater is not influenced by high radon discharge from the bedrock but it can also be an effect of the fact that the wells at the till/bedrock interface were pumping wells with a wider diameter. It may be that the wells were not purged enough to replace the whole water volume of the well which would give lower radon concentrations at these wells.

Even if the radon concentration of the natural water is not only determined by the emanation potential of the soil and bedrock, it seems to be the emanation potential of the local soil that is the main factor affecting the radon concentration in groundwater. The radon concentration also depends on the pore volume of the soil or bedrock, the outgassing to the atmosphere and groundwater flow patterns but these factors do not affect the radon concentration to the same extent as the emanation potential of the soil.

5.4 Evaluation of radon as a tracer for groundwater flow patterns

5.4.1 Evaluation of the method

The main purpose of this study has been to evaluate the use of radon as a tracer for groundwater flow patterns. The method is based on the ingrowth of radon from its progenitor radium according to the law of radioactive decay. If the equilibrium concentration (or steady state concentration) of radon

in the groundwater is known the resident time and even the flow patterns of groundwater can be assessed since the time it takes for the equilibrium to be reached is known to be 30 days.

The steady state radon concentration was measured at four sites in the Forsmark area. The range of steady state radon concentrations calculated from these measurements was used as an approximation for steady state radon concentration for the whole area. It was then used to evaluate radon concentrations measured in wells in Quaternary deposits in the area. In order to make this comparison the assumption that the steady state radon concentration is homogenous in the area has to be made. For the steady state radon concentration to be homogenous several additional assumptions have to be made;

1) The emanation potential of the soil in the area has to be homogenous.
2) The pore volume of the soil has to be homogenous.
3) The losses of radon through outgassing to the atmosphere are not significant and can be excluded from the assessment.

These assumptions are discussed here to be able to evaluate the method. The emanation potential is as described earlier determined by the radium content of the soil and the area to volume ration of the soil or bedrock. The radium content of the soil can be both radium that is present in the soil particles due to decay of uranium in the soil particles or the radium that is deposited on the soil particles through secondary deposition.

In general the radium inside the soil particles can be assumed to be homogenous since the till in the area has the same origin and is formed during the same time period. There is no reason to expect systematic differences in radium content in the soil that formed the till. On the other hand there are reasons to expect differences regarding the secondary deposition of radium since the deposition processes are governed by chemical processes that can differ in different chemical environments. This means that radium can be concentrated in some parts of the soil and depleted in other parts. The secondary deposited radium contributes directly to radon emanation since it is located on the surface of the soil particles and all radon formed by decay of these radium atoms will enter the surrounding environment. The radium content of the soil has not been measured which means that no data can be used to assess the radium content. The radium content of the soil is for these reasons hard to assess and contributes to the uncertainties of the method.

The second factor affecting the emanation potential of the soil is the area to volume ratio of the soil. The ratio is determined by the particle size of the soil which differs at different sites in the investigated areas. Fine grained soils like clay and silt have a higher area to volume ratio and therefore higher radon emanation potential.

The second assumption that has to be made is that the pore volume of the soil is uniform in the area. The pore volume of the soil affects the radon concentration of the groundwater since a large pore volume means more water and more diluted radon concentrations. The pore volume of the soil depends on the range of grain sizes and the shape of the particles of the soil but not on the actual particle size. Fine grained soils are often well sorted and therefore have a large pore volume in comparison to unsorted soils like till where the pore volume is small. The distribution of the pore volume is not known for the area which make the steady state radon concentrations uncertain.

The outgassing of the radon to the atmosphere is assumed to be small and not influence the radon concentration of the groundwater measured in the Quaternary deposits or in the bedrock. This can be assumed since most of the groundwater samples are taken at a depth below the groundwater table. This means that the groundwater at this depth is not in direct contact with the unsaturated zone of the soil and the atmosphere.

In conclusion the assumption of a homogenous steady state radon concentration in the area contributes to the uncertainties of the method. But since the measured steady state radon concentration was found to be within the same range at the four measured location this assumption is made in this study. To lower the uncertainties of this assumption more measurements of the steady state radon concentration could be made in the area.

5.4.2 Site specific conclusions

In Forsmark recharge/discharge classification of the wells was done using the measured steady state radon concentration and radon concentrations measured in near surface groundwater. All wells with radon concentration below the steady state radon concentration were classified as recharge wells and all wells with radon concentrations above the steady state radon concentration were classified as discharge wells. The wells with radon concentrations within the range of steady state concentrations were classified as wells with groundwater that had been stagnant for at least 30 days.

Most of the classified wells were classified as stagnant wells with concentrations within the range of steady state radon concentration. The groundwater in these wells is likely not influenced by recharging or discharging water in a significant way.

Some of the wells classified as recharge wells were located in soil types such as peat, gyttja and clay, and therefore these wells could be expected to have low radon concentration despite the groundwater flow patterns. The only wells located in till or sand that were classified as recharge wells were SFM0056, SFM0006 and SFM0087. Well SFM0087 is located at Site 3 and is overlayed by gyttja and open water. This makes the infiltration of recharge water fast and a low radon concentration can be expected. The radon concentration in well SFM0056 is uncertain due to difficulties during sampling and the reason for the low radon concentration is uncertain. Well SFM0006 is the only well where a low radon concentration can be considered an indication of recharging groundwater.

This means that radon probably is a poor tracer for recharging groundwater in the Forsmark area since recharge is only identified at one site. This can be caused by the dilution effect caused by small amount of recharging water in comparison to the existing groundwater volume. This can also be caused by the short half-life of radon which makes the signal of recharge water disappear fast and it is likely to be almost gone by the time it reaches the screening depth of the wells. In any case, it can be concluded that it is not likely that high radon groundwater from the bedrock discharges at these sites with low radon concentrations.

Eight of the wells were classified as discharging wells: SFM0091, SFM0060, SFM0011, SFM0014, SFM0026, SFM0023, SFM0103, SFM0027, SFM0095 and SFM0013. To be able to draw the conclusion that these wells are affected by discharging groundwater from the bedrock the assumptions discussed above have to be made but since there are known uncertainties in these assumptions it is hard to draw conclusions unless the differences between the steady state radon concentration and the measured radon concentrations in the groundwater are large, in the order of one magnitude.

This is true for the wells SFM0027, SFM0103, SFM0095 and SFM0013 with the highest radon concentrations. The high radon concentrations at these four wells are one order of magnitude higher than the measured steady state radon concentrations in the area which indicates an inflow of radon from discharging groundwater from conductive fracture zones in the bedrock.

Three of the four wells, SFM0013, SFM0095 and SFM0103, are found in the catchment of Gällsboträsket where signs of discharging deep groundwater have been found in both groundwater chemisty signals and measured groundwater levels in previous investigations. This shows that the results can be used to support the conclusions from previos studies where it has been suggested that inflow of deep groundwater exists in the catchment of Gällsboträsket.

Well SFM027 is located at the outflow of Lake Fiskarfjärden, close to well SFM0026. At well SFM0026 heavily fractured rock was found at the screening depth of the well which could be a sign of conductive fracture zones.

In Laxemar the radon concentration showed low variability which means that the signals of groundwater flow were vague and no conclusions about the flow patterns could be drawn. The differences between radon concentration in the shallow and deep groundwater were not large enough to make signals of discharging deep groundwater detectable in the shallow groundwater. Therefore the lack of elevated radon concentration in the shallow groundwater cannot be interpreted as lack of discharging deep groundwater.

The steady state radon concentration was not determined in the Laxemar area but even if it had been determined the uncertainties of the method would probably give a range of the steady state radon concentration that would be large in comparison to the low variability of the radon concentration in groundwater. This would have made it impossible to use the steady state radon concentration to classify the groundwater based on radon concentration. This means that the use of radon as a tracer for recharge and discharge of shallow groundwater is not straightforward and the method cannot be used to identify groundwater flow in the Laxemar area.

In general this study showed that there were no systematic differences in radon concentrations of groundwater between recharge areas and discharge areas. Even if discharging groundwater was detected in the catchment of Gällsboträsket in Forsmark the usefulness of radon as a tracer was proven to be limited in this study since no general conclusions of the groundwater flow in Laxemar and Forsmark could be drawn from the radon measurements in the shallow groundwater. This may be due to the short half-life of radon that makes the signals of recharge and discharge waters disappear quickly. The time scale of the groundwater flow that we try to trace is too long in comparison to the half-life of the tracer. The lack of correlation can also be caused by the fact that signals from deep groundwater are diluted by the much larger volume of near surface groundwater. This makes the high radon signal weak and hard to detect.

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Appendix 1

Radon concentration measured in Forsmark and Laxemar

The available radon measurements from Laxemar and Forsmark are presented in this Appendix. The table consists of; the idcode of the well or sampling location in surface water, the sampling date and the sampling depth in wells. The fourth and fifth column gives the radon measurement and the standard deviation of the measurement.

Laxemar

Table A-1. Radon concentrations in deep groundwater in Laxemar.

ID code	Sampling date	Sampling depth (m)	Rn222 (Bq/L)	Rn222Dev (Bq/L)
HLX35	2008-10-28	135.00	58.7	1.7
HLX37	2008-10-15	199.80	168	3
HLX39	2008-10-29	199.30	89.8	2.6
KLX04	2008-03-17	897.00	22.9	0.5
KLX04	2008-03-06	530.00	1,117	24
KLX04	2007-10-30	530.00	1,179	18
KLX05	2007-11-07	255.00	869	27
KLX05	2008-03-17	255.00	742	22
KLX05	2007-08-13	255.00	437	7
KLX07A	2008-03-13	780.00	100	3
KLX07A	2007-12-05	780.00	127	3
KLX07A	2007-06-26	780.00	92.8	2.7
KLX08	2006-05-22	485.62	150	5
KLX08	2006-05-22	485.62	129	4
KLX08	2006-05-22	485.62	137	5
KLX08	2006-02-03	400.87	76	5
KLX08	2006-02-03	400.87	138	7
KLX08	2008-03-11	625.00	78	2
KLX08	2006-06-29	618.51	37	1
KLX08	2006-06-29	618.51	47	1
KLX08	2006-05-22	485.62	124	4
KLX08	2006-02-03	400.87	83	4
KLX08	2006-02-03	400.87	111	6
KLX08	2006-02-03	400.87	91	5
KLX08	2007-11-06	625.00	99.9	2.6
KLX08	2006-05-22	485.62	138	9
KLX08	2005-11-23	206.65	94.8	4
KLX08	2005-11-23	206.65	116	7
KLX08	2006-06-29	618.51	53	1
KLX08	2005-11-23	206.65	107	5
KLX08	2006-02-03	400.87	134	7
KLX08	2006-05-22	485.62	116	4
KLX08	2005-11-23	206.65	118	5.8
KLX08	2008-10-27	625.00	99.4	2.5
KLX11A	2007-05-02	599.00	27.3	0.8
KLX11A	2007-03-28	584.00	24.5	0.7
KLX11A	2007-04-10	519.50	14.17	0.03
KLX11A	2007-03-28	584.00	22.7	0.7
KLX11A	2007-05-02	599.00	26.4	0.8
KLX11A	2007-04-10	519.50	14.13	0.03
KLX12A	2008-03-17	545.00	98.8	2.1
KLX12A	2007-11-07	545.00	77.8	1.6
KLX12A	2007-07-09	545.00	116.3	1.8

ID code	Sampling date	Sampling depth (m)	Rn222 (Bq/L)	Rn222Dev (Bq/L)
KLX12A	2008-10-21	545.00	116	3
KLX13A	2006-12-14	439.16	23.9	0.7
KLX13A	2006-12-14	439.16	17.3	0.5
KLX13A	2006-11-21	506.66	109	3
KLX13A	2006-12-14	439.16	17.8	0.5
KLX15A	2007-06-15	634.51	68.2	0.2
KLX15A	2007-12-04	640.00	132	2
KLX15A	2008-02-26	640.00	121	3
KLX15A	2007-06-15	634.51	92.8	2.8
KLX15A	2007-06-15	634.51	90	1.9
KLX15A	2007-06-15	634.51	79.7	2.5
KLX15A	2007-06-15	634.51	124	4
KLX15A	2007-06-15	634.51	115	2
KLX15A	2007-06-15	634.51	81.1	1.7
KLX15A	2007-06-15	634.51	98.3	0.8
KLX17A	2007-01-31	701.08	41.4	1.3
KLX17A	2007-03-05	437.51	47.6	0.7
KLX17A	2007-01-31	701.08	74.7	2.3
KLX17A	2007-01-31	701.08	40.1	1.3
KLX17A	2007-01-31	701.08	42.6	1.3
KLX17A	2007-01-31	701.08	37.1	1.1
KLX17A	2007-03-05	437.51	99.8	1.3
KLX17A	2007-03-05	437.51	183	1
KLX17A	2007-03-05	437.51	42.9	1.3
KLX17A	2007-03-05	437.51	44.4	0.6
KLX17A	2007-03-05	437.51	60.7	1.6
KLX18A	2008-02-27	489.00	140	2
KLX18A	2007-10-31	489.00	216	3
KLX18A	2008-10-22	489.00	234	6
KLX19A	2008-02-26	517.00	136	2
KLX19A	2007-08-13	517.00	188	6
KLX19A	2007-12-03	517.00	220	7
KLX19A	2008-10-14	517.00	193	3
KLX20A	2008-03-19	293.00	240	7
KLX27A	2008-03-12	650.56	42	1
KLX27A	2008-03-12	650.56	42	1
KLX27A	2008-03-12	650.56	41	1
KLX27A	2008-03-12	650.56	40	1
KLX27A	2008-03-12	650.56	35	1
KLX27A	2008-03-12	650.56	44	1
KLX27A	2008-03-12	650.56	31	1
KLX27A	2008-03-12	650.56	36	1
KLX27A	2008-03-12	650.56	41	1
KLX27A	2008-03-12	650.56	41	1

Table A-2. Radon concentration in near surface groundwater in Laxemar.

ID code	Sampling date	Sampling depth	Rn222 (Bq/L)	Rn222Dev (Bq/L)
SSM0022	2005-09-13	7.00	11.2	0.3
SSM0027	2005-09-08	5.00	12.4	0.5
SSM000029	2005-09-06	7.00	12.8	0.4
SSM000030	2005-09-08	5.00	17.3	0.7
SSM000031	2005-09-06	4.00	27	0.8
SSM000034	2005-09-06	4.00	4.86	0.14
SSM000035	2005-09-13	4.00	17.4	0.5
SSM000037	2005-09-08	4.00	14.2	0.6
SSM000041	2005-09-13	4.00	12.8	0.09
SSM000042	2005-09-13	5.00	17	0.6
SSM000224	2005-09-15	17.00	1.06	0.05
SSM000226	2005-09-20	5.00	13.1	0.4

Table A-3. Radon concentrations in near surface groundwater in Laxemar measured with RAD-7.

Sampling date	ID code	Sampling depth (m)	Rn222 (Bq/L)	Rn222 STD (Bq/L)
2009-05-26	SSM009	4.00	49.6	3.6
2009-05-26	SSM009	4.00	50.6	2.2
2009-05-26	SSSM09	4.00	53.0	2.6
2009-05-27	SSM014	3.00	67.3	6.1
2009-05-27	SSM014	3.00	62.4	3.7
2009-05-25	SSM022	7.00	54.7	4.0
2009-05-25	SSM022	7.00	56.4	4.4
2009-05-27	SSM030	5.00	53.6	1.5
2009-05-27	SSM030	5.00	54.6	4.9
2009-05-27	SSM030	5.00	46.9	12.6
2009-05-27	SSM031	4.00	104.2	5.5
2009-05-27	SSM031	4.00	108.8	8.3
2009-05-26	SSM037	4.00	41.5	2.6
2009-05-26	SSM037	4.00	40.6	10.4
2009-05-25	SSM041	4.00	34.6	1.2
2009-05-25	SSM041	4.00	35.1	1.5
2009-05-25	SSM042	5.00	71.9	2.6
2009-05-26	SSM218	3.00	40.7	1.7
2009-05-26	SSM218	3.00	42.7	6.1
2009-05-27	SSM228	7.00	54.0	4.3
2009-05-27	SSM228	7.00	54.4	3.2
2009-05-27	SSM228	7.00	51.7	12.0
2009-05-25	SSM230	5.00	174.2	7.2
2009-05-25	SSM230	5.00	177.6	6.2
2009-05-27	SSM264	5.00	34.7	3.3
2009-05-27	SSM264	5.00	35.7	2.8
2009-05-27	SSM264	5.00	30.8	7.9
2009-05-25	SSM267	6.00	56.0	2.6
2009-05-25	SSM267	6.00	44.3	4.9
2009-05-25	SSM267	6.00	53.7	5.4
2009-06-02	SSM240	6.00	52.2	1.5

Table A-4. Radon concentrations in surface water in Laxemar.

ID code	Sampling date	Sampling location	Rn222 (Bq/L)	Rn222Dev (Bq/L)
PSM002064	2005-08-23	Sea	0.095	0.009
PSM002064	2006-08-22	Sea	< 0.015	
PSM002064	2006-08-22	Sea	< 0.015	
PSM002064	2007-08-21	Sea	< 0.015	
PSM002064	2007-08-21	Sea	0.034	0.005
PSM002064	2008-08-19	Sea	< 0.015	
PSM002064	2008-08-19	Sea	< 0.015	
PSM002065	2005-08-23	Lake	0.204	0.009
PSM002065	2006-08-22	Lake	0.026	0.009
PSM002065	2006-08-22	Lake	0.024	0.008
PSM002065	2007-08-22	Lake	0.081	0.005
PSM002065	2007-08-22	Lake	0.096	0.005
PSM002065	2008-08-19	Lake	0.081	0.005
PSM002065	2008-08-19	Lake	0.057	0.005
PSM002079	2006-08-23	Stream	0.336	0.014
PSM002079	2007-08-22	Stream	1.334	0.019
PSM002079	2008-08-20	Stream	1.26	0.02
PSM002083	2005-08-24	Stream	2.47	0.03
PSM002083	2006-08-23	Stream	4.923	0.082
PSM002083	2007-08-21	Stream	12.42	0.151
PSM002083	2008-08-19	Stream	3.54	0.06
PSM002085	2008-08-19	Stream	0.19	0.01
PSM002086	2008-08-20	Stream	2.69	0.05
PSM002087	2006-08-23	Stream	0.449	0.012
PSM002087	2007-08-22	Stream	1.334	0.019
PSM002087	2008-08-20	Stream	0.92	0.02
PSM007097	2005-08-23	Sea	0.405	0.012
PSM007097	2005-08-23	Sea	0.281	0.011
PSM007097	2006-08-22	Sea	< 0.015	
PSM007097	2006-08-22	Sea	6.28	0.04
PSM007097	2007-08-21	Sea	< 0.015	
PSM007097	2007-08-21	Sea	< 0.015	
PSM007097	2008-08-19	Sea	0.024	0.005
PSM007097	2008-08-19	Sea	< 0.015	
PSM107795	2008-08-20	Stream	1.54	0.03

Forsmark

Table A-5. Radon concentrations in deep groundwater in Forsmark.

ID code	Sampling date	Sampling depth	Rn222 (Bq/L)	Rn222Dev (Bq/L)
HFM01	2008-10-07	45.5	171.0	3.0
HFM01	2007-10-23	45.5	149.0	4.0
HFM02	2005-11-09	48.0	36.0	1.0
HFM02	2008-10-07	48.0	59.5	1.3
HFM02	2006-10-17	48.0	50.6	1.3
HFM02	2007-10-23	48.0	72.0	2.0
HFM04	2008-09-30	66.0	164.0	3.6
HFM04	2006-10-31	66.0	231.0	6.0
HFM04	2005-11-07	66.0	228.0	6.0
HFM04	2007-11-01	66.0	418.0	14.0
HFM13	2006-10-24	173.0	348.0	5.0
HFM13	2008-09-30	173.0	754.0	17.0
HFM13	2005-11-09	173.0	1,200.0	19.0
HFM13	2007-10-17	173.0	1,120.0	33.0
HFM15	2006-10-24	95.0	44.0	1.0
HFM15	2007-10-17	95.0	72.0	2.0
HFM15	2005-11-09	95.0	154.0	3.0
HFM15	2008-10-28	95.0	172.0	4.0
HFM16	2008-10-17	67.0	37.6	0.6
HFM16	2006-10-06	67.0	47.0	1.0
HFM16	2007-10-23	67.0	83.0	2.0
HFM19	2006-10-25	182.0	58.0	1.0
HFM19	2005-11-09	182.0	95.0	2.0
HFM19	2008-10-28	182.0	81.6	2.1
HFM19	2007-10-17	182.0	200.0	5.0
HFM21	2008-10-22	32.0	233.0	4.0
HFM21	2007-10-23	32.0	201.0	5.0
HFM27	2008-10-07	58.0	270.0	5.0
HFM27	2006-10-17	58.0	194.0	5.0
HFM27	2007-10-26	58.0	248.0	5.0
HFM32	2008-10-14	31.0	110.0	3.0
HFM32	2006-10-30	31.0	148.0	3.0
HFM32	2007-11-12	31.0	225.0	6.0
KFM01A	2005-11-09	130.0	424.0	7.0
KFM01A	2006-10-09	130.0	476.0	10.0
KFM01D	2008-10-03	321.0	298.0	5.0
KFM01D	2006-07-10	575.1	335.0	9.0
KFM01D	2008-10-03	438.0	449.0	9.0
KFM01D	2006-06-12	435.6	534.0	16.0
KFM02A	2008-10-01	442.0	739.0	18.0
KFM02A	2006-10-10	442.0	844.0	20.0
KFM02A	2005-11-07	442.0	914.0	20.0
KFM02A	2008-10-01	518.0	2,330.0	57.0
KFM02A	2007-10-30	518.0	2,460.0	61.0
KFM02A	2005-11-07	518.0	3,310.0	68.0
KFM02A	2006-10-18	518.0	2,570.0	71.0
KFM02A	2006-06-20	518.0	3,350.0	95.0
KFM02B	2007-10-30	506.0	489.0	13.0
KFM02B	2008-10-01	506.0	643.0	15.0
KFM02B	2007-10-30	431.0	1,990.0	48.0
KFM02B	2008-10-01	431.0	2,250.0	50.0
KFM03A	2008-11-07	994.5	24.2	0.9
KFM03A	2006-10-25	994.5	20.0	1.0

ID code	Sampling date	Sampling depth	Rn222 (Bq/L)	Rn222Dev (Bq/L)
KFM03A	2007-10-15	994.5	82.0	2.0
KFM03A	2004-04-15	455.6	238.0	6.0
KFM03A	2006-10-24	650.0	4,460.0	63.0
KFM03A	2007-10-15	650.0	5,010.0	91.0
KFM03A	2008-10-24	650.0	8,310.0	107.0
KFM03A	2005-11-07	650.0	6,110.0	176.0
KFM03A	2005-06-23	650.0		
KFM03A	2004-02-26	946.6		
KFM03A	2005-11-07	994.5		
KFM04A	2008-10-06	245.0	283.0	5.0
KFM04A	2004-04-20	361.1	194.0	6.0
KFM04A	2007-11-01	245.0	612.0	21.0
KFM05A	2004-09-24	722.0	15.0	1.0
KFM06A	2006-10-09	362.0	57.0	1.0
KFM06A	2006-10-09	748.0	52.0	1.0
KFM06A	2005-02-15	360.6	437.0	3.0
KFM06C	2006-10-10	540.0	373.0	9.0
KFM07A	2008-10-29	972.0	17.2	0.8
KFM07A	2007-10-26	972.0	48.4	1.9
KFM07A	2005-03-22	1,001.6	219.0	3.0
KFM08A	2008-10-28	694.0	430.0	10.0
KFM08A	2005-09-13	690.6	458.0	11.0
KFM08A	2008-01-22	694.0	425.0	12.0
KFM08D	2007-04-04	835.5	492.0	13.0
KFM10A	2008-09-30	440.0	237.0	5.0
KFM10A	2006-10-12	487.5	217.0	5.0
KFM10A	2007-10-17	440.0	229.0	7.0
KFM10A	2006-11-03	305.1	578.0	15.0
KFM11A	2008-10-06	710.0	409.0	8.0
KFM11A	2008-10-06	456.0	521.0	10.0
KFM11A	2007-07-11	710.0	527.0	16.0
KFM11A	2007-10-09	710.0	669.0	16.0
KFM11A	2007-10-09	456.0	696.0	17.0
KFM12A	2008-10-07	280.0	51.9	1.2

Table A-6. Radon concentration in near surface groundwater Forsmark.

ID code	Sampling date	Sampling depth	Rn222 (Bq/L)	Rn222Dev (Bq/L)
SFM0001	2008-08-05	4.8	49.9	1.2
SFM0001	2007-08-09	4.8	22.5	0.3
SFM0032	2008-08-06	2.94	35.2	0.9
SFM0032	2007-08-09	2.94	60.5	0.7
SFM0037	2008-08-06	2.1	16.5	0.3
SFM0037	2007-08-08	2.1	29.1	0.3
SFM0049	2007-08-08	3.9	27.7	0.3
SFM0049	2008-08-06	3.9	40.4	1.0
SFM0087	2007-08-08	2.2	27.6	0.3
SFM0095	2007-08-09	6	397.0	4.0

Table A-7. Radon concentrations in near surface groundwater in Forsmark measured with RAD-7.

Sampling date	ID code	Sampling depth (m)	Rn222 (Bq/L)	Rn222 STD (Bq/L)
2008-10-09	SFM0001	4.45	35.67	0.13
2008-10-10	SFM0004	6	23.23	2.51
2008-10-08	SFM0006	4.2	3.86	2.59
2008-10-09	SFM0011	4.5	99.16	1.88
2008-10-10	SFM0012	6.35	33.55	2.19
2009-06-11	SFM0013	4.480	410	14.3
2008-10-09	SFM0013	4.480	430.52	3.12
2009-06-14	SFM0014	2.000	142.19	8.01
2008-10-10	SFM0014	2.000	149	4.62
2009-06-15	SFM0019	4.500	39.6	1.177
2008-10-10	SFM0019	4.500	39.85	6.55
2008-10-09	SFM0023	5.4	94.66	2.9
2009-06-11	SFM0026	16.000	144.35	8.93
2008-10-09	SFM0026	16.000	165.24	0.23
2008-10-09	SFM0027	8	314.37	5.25
2008-10-07	SFM0032	4	51.35	2.27
2008-10-08	SFM0037	3	31.87	4.55
2008-10-07	SFM0049	5	12.52	6.05
2008-10-08	SFM0051	?	53.98	9.06
2008-10-10	SFM0056	?	1.06	13.8
2008-10-09	SFM0057	4.55	66.39	22.771
2008-10-09	SFM0060	7.6	79.6	21.97
2009-06-12	SFM0084	3.700	42.65	3.34
2009-06-16	SFM0086	2.21 (BAT)	23.33	7.15
2009-06-12	SFM0087	2.000	3.64	0.96
2009-06-16	SFM0089	0.95 (BAT)	0.43	0.5
2009-06-12	SFM0090	3.070	53.08	8.01
2009-06-09	SFM0091	1.900	71.28	4.99
2009-06-12	SFM0093	1.01 (BAT)	3.75	1.32
2009-06-09	SFM0094	2.240	32.16	1.56
2009-06-09	SFM0095	5.000	374	19.2
2009-06-10	SFM0097	2.76 (BAT)	19.8	2.61
2009-06-12	SFM0100	1.81 (BAT)	4.25	1.21
2009-06-09	SFM0102	1.26 (BAT)	2.68	0.57
2009-06-09	SFM0103	4.900	230	22.08

Table A-8. Radon concentrations in surface water Forsmark.

Sampling date	ID code	Sampling location	Rn222 (Bq/L)	Rn222Dev (Bq/L)
2006-07-17	PFM000062	Sea	0.11	0.01
2007-08-06	PFM000062	Sea	0.032	0.005
2008-08-05	PFM000062	Sea	> 0.015	
2007-08-07	PFM000074	Lake	0.049	0.004
2008-08-05	PFM000074	Lake	0.036	0.005
2004-07-06	PFM000074	Lake	0.021	0.008
2006-07-17	PFM000074	Lake	0.008	0.023
2007-08-06	PFM000107	Lake	0.25	0.006
2006-07-17	PFM000107	Lake	0.19	0.42
2008-08-04	PFM000107	Lake	0.023	0.004
2007-08-06	PFM000117	Lake	0.032	0.005
2006-07-18	PFM000117	Lake	> 0.015	
2008-08-05	PFM000117	Lake	> 0.015	