Salt Groundwater in Sweden - Occurrence and Origin

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Abstract

The aims of this paper are to give a general regional description of the distribution of salt groundwater in Sweden and to discuss the origin of the salt. Data from the Well Record Section at the Geological Survey of Sweden (SGU) has been compiled, expecially from six counties in central Sweden. Pore water from marine clays has been chemically compared to salt groundwater from drilled wells. The project shows that more than 20% of all wells in the six counties in central Sweden have an increased content of chloride in relation to the natural deposition from precipitation. A strict correlation between salinization and areas beneath the highest marine shore level from previous stages of the development of the Baltic sea, clearly points out fossil seawater trapped in marine clays or in rock fractures beneath the clays as the main natural source of salt in crystalline rock areas. This type of salinization is probably restricted to the upper part (<700 m) of the rock. Locally, other sources of salt water are prevailing, such as salt water intrusion from the sea within a narrow zone, usually less than 100 m from the shore, and formation salts in some sedimentary rock areas. At deep levels in crystalline rock (>1000 m) salt brines are found, probably at increasing depth with increasing distance from the present sea. Such brines may be of hydrothermal origin. In addition to these natural salt sources, locally a considerable salinization of groundwater from anthropogenic sources occur, especially from de-icing road salts. A raised chloride content and an increased hardness of the groundwater can be seen along major roads in Sweden.

Introduction

Salt groundwater is a wellknown problem in the world, usually along the coastal areas. Before nineteen-seventies salt groundwater was sporadically described in Swedish literature. Most notes of salt groundwater concern sedimentary basins (Erdmann, 1911, Tullström, 1955, Pousette & Möller, 1972, Möller et al, 1981). However, such areas only cover a minor part of Sweden. From old crystalline rock areas, salt groundwater was early reported by Olberg (1854), who described salt springs in western Sweden and Svenonius (1918) who noticed salt groundwater in a drilled well not far from Lake Vänern, southwestern Sweden.

Valuable information of the occurrence of deep salt groundwater in sweden has been collected from about ten sites in Sweden, which have been investigated within the Swedish nuclear waste repository project (Laurent, 1982, Smellie & Wikberg, 1989, Arad, 1991).

More comprehensive studies of the occurrence of salt groundwater in Sweden, based on information from the well record section at the Geological Survey of Sweden (SGU) are given by Knutsson & Fagerlind (1977), Lindewald (1985) and Olofsson (1994).

The aims of this paper are to give additional data regarding the occurrence of salt groundwater wells in Sweden and to discuss possibly sources of the salt in relation to recently carried out investigations.

Methods of investigation

From the middle of the nineteen-seventies information from the construction of drilled wells in Sweden regarding capacity, localization, depth and geology have been stored at SGU. Some of these well records include chemical analyses of the groundwater. Analysis of 13 000 well records in Sweden has recently been carried out (Olofsson, 1994). The present project comprises analyses of chemistry using

5-6000 of the chemical analyses stored at SGU. Data has been compiled from 6 different counties in south and central Sweden; the counties of Stockholm, Uppland, Östergötland, Gotland, Örebro and Göteborg-Bohuslän. Among the well records, analyses with a chloride content exceeding 100 mg/l were selected and information regarding geology, topography and distance from seashore and de-icing salted roads were collected from maps for these sites in order to evaluate the chemical variations in relation to natural geological and hydrogeological conditions. In order to evaluate the contribution of salts to the bedrock aquifers from marine clays, pore water in clays in the vicinity of some salt wells, have been pressed out and chemically compared to the well water. Sampling of groundwater has also been carried out in 93 wells within 300 m from roads in the county of Västmanland, central Sweden, on which de-icing salts have been used, in order to clarify the impact on groundwater from roads.

The occurrence of salt groundwater wells in Sweden

A compilation of chloride analyses from almost 13 000 well records stored at SGU indicates that the salt groundwater occurs along the whole Swedish coastline as well as within a 200 km wide zone in central Sweden, from Lake Mälaren in eastern Sweden, through Lake Vättern and Lake Vänern to the Swedish west coast, **figure 1.**

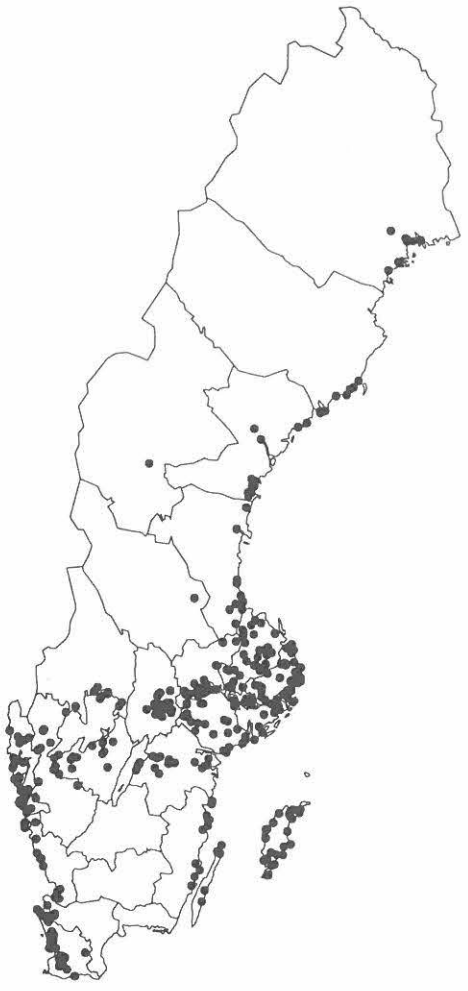

Figure 1 *Salt groundwater (>300 mg Cl/l) in Sweden (data collected from SGU)*

In total approximately 17% of the wells at SGU show a raised content of chloride, which here is defined as a chloride content exceeding 50 mg Cl/l. The chloride content of the precipitation, which is the main natural chloride source in Sweden, varies between 0.2 mg/l in the northernmost part of Sweden, where the wet deposition is small, to 10 mg/l at the Swedish west coast (Granat, 1990). The dry deposition of chloride is much more difficult to estimate. However, measurements of throughfall in a forested terrain, compared to open terrain show that the value of dry deposition is 50-100% of the wet deposition in the northern Sweden and 100-300% of the wet deposition in southern Sweden (Lövblad et al, 1992).

A rough estimation of the present situation in Sweden shows that more than 60 000 wells in Sweden may be affected by other salt sources than from precipitation (Olofsson, 1994). The salt content in 13 000 of these wells may exceed the taste limit of salt (app. 300 mg Cl/l). However, these figures give not a true picture of the present situation, since they principally only reflect the chemical composition of the aquifer at the time of the construction of the wells. Analyses of well records stored at the health administrations of the municipalities, indicate an increased number of salt affected wells (in total 20-30%), compared to the well record section at SGU (Lindell, 1987, Olofsson, 1990).

In the six counties, which have been more closely studied, the percentage of salt affected wells varies from 17% in the county of Örebro to as much as 61% on the island of Gotland, **table 1**. Taste of salt

usually occurs in 2-6% of the wells, except on the island of Gotland where the taste limit exceeds in as much as 25% of the wells. As can be seen in **figure 2**, the distribution of the salt affected wells is highly varying. In the county of Uppland, which consists of a flat crystalline bedrock surface, partly covered by a thin layer of clay, the distribution of salt wells is spread over the whole county, whereas in the county of Örebro, the salt affected wells are more concentrated to the eastern part where the area consists of clays covering a flat surface of sedimentary rocks.

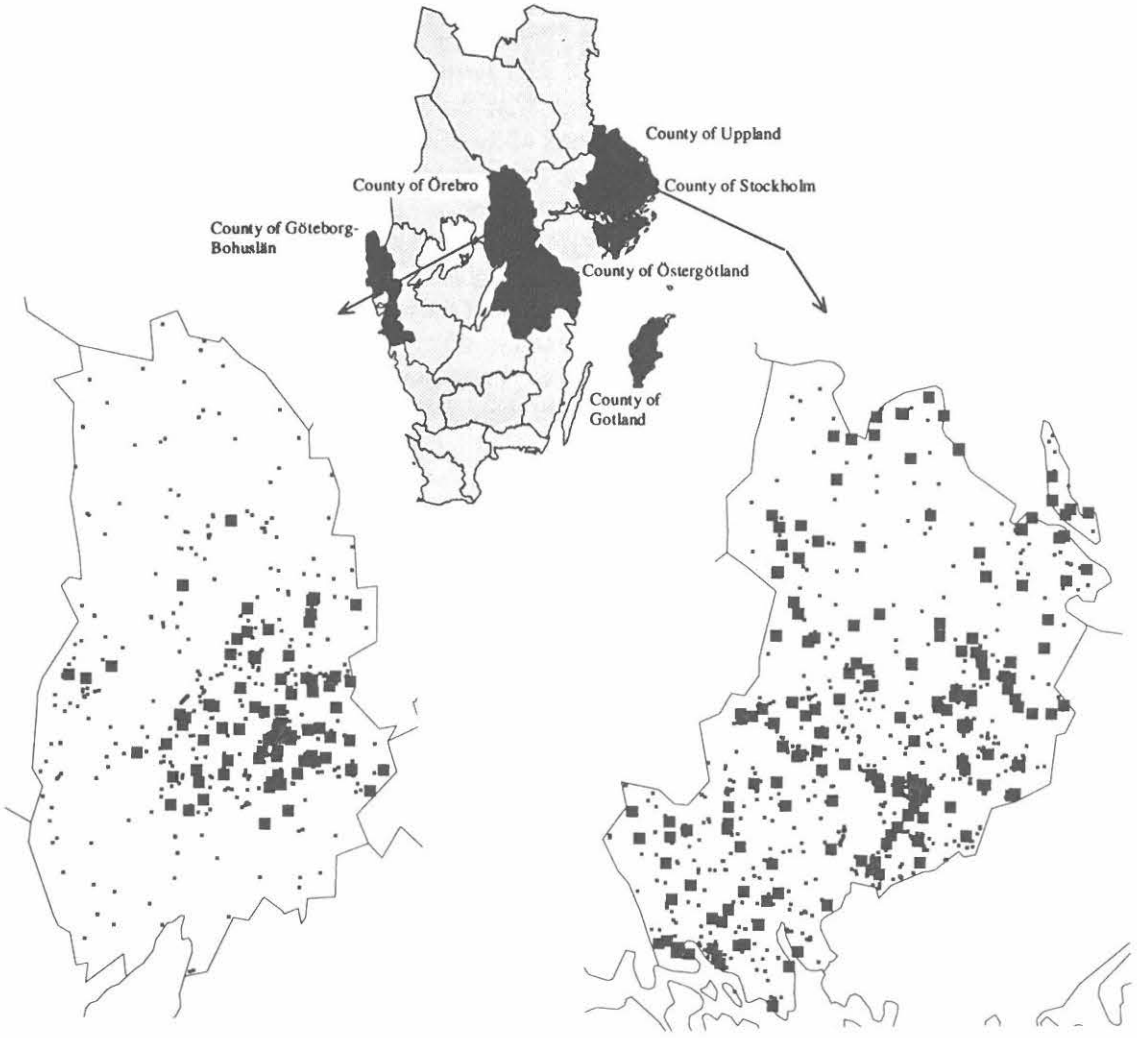

Figure 2 *Location of six detailed studied counties in the south and central Sweden as well as examples of distribution of salt water affected wells (>50 mg Cl/l, black boxes) compared to all wells with chemical analyses at SGU (small black dots) from two of these counties (Uppsala and Örebro).*

Table 1 *Chloride contents of groundwater in six counties in Sweden.*

County	No of wells	>50 mg Cl/l	>100 mg Cl/l	>300 mg Cl/l	>1000 mg Cl/l
All six counties	4980	20.7 %	11.2 %	4.1 %	1.0 %
Stockholm	2046	18.9 %	9.7 %	2.9 %	0.7 %
Uppsala	887	21.2 %	12.0 %	4.2 %	0.7 %
Östergötland	787	17.4 %	7.8 %	2.2 %	0.6 %
Gotland	149	61.1 %	43.0 %	25.5 %	9.4 %
Göteborg-Bohuslän	570	23.5 %	13.2 %	5.8 %	1.4 %
Örebro	540	17.8 %	9.6 %	3.7 %	0.7 %

Origin of salt groundwater

The origin of the salt groundwater in Sweden has been discussed among others by Lindewald (1981,1985), Nordstrom et al (1989), Arad (1991), Kökeritz (1993) and Olofsson (1994). Several sources have been proposed such as intrusion of seawater in coastal areas, fossil seawater, water-rock interaction, freezing of seawater as well as anthropogenic sources (e.g. leakage from waste deposits and de-icing salts on roads).

Recent seawater intrusion

Due to an extremely heterogeneity of hard crystalline rocks, intrusion of recent seawater into freshwater aquifers usually only occurs in a narrow zone (<100 m) along the coastline. However, in the sedimentary rock areas, such as in the southernmost part of Sweden and on the island of Öland and Gotland, seawater intrusion may occur at a far distance from the shore. This type of a highly fractured limestone aquifer in combination with karstic structures may be one plausible explanation for the very high amount of salt affected wells (61%) in the county of Gotland. In areas where sandy sediments are hydraulically connected to the sea, extraction of freshwater for municipal water supply, has led to intrusion of seawater. Such examples are given from Stafsnäs (Tilly-Leander, 1994, Huber & Lundqvist, 1995) and Dalarö in the archipelago of Stockholm. Many examples of private wells in coastal areas with a raised content of salinity are described in literature (Sund & Bergman, 1980, Gewers & Håkansson, 1988, Hallberg, 1986). In many of these wells, the salinity is probably derived from fossil seawater.

Fossil seawater

Sweden has been covered by salt or brackish seawater during several geological periods. Widespread sedimentation with interstitial salt pore water occurred during the Paleozoic period 570-400 m.y. However, the sedimentary rocks from this period have been eroded away except in some minor areas where faulting or covering with harder rocks effectively have protected the sediments from erosion. Sandstone-filled fractures now indicate the areal distribution of the Paleozoic sedimentary rocks. In Scania, the southernmost part of Sweden, Mesozoic sedimentary rocks also indicate salt water stages. Nordstrom (1983) points out that the general characteristics of the very salt groundwater found in Scania (Brotzen, 1949) and at the island of Gotland, is similar to the groundwater in other sedimentary basins in the world.

Almost all salt wells (>300 mg Cl/l) reported to the Well Record Section at SGU fall within the areas in Sweden, which have been covered by brackish water (the Yoldia sea, 10000-9000 y.b.p) or salt water (the Litorina sea, 7000-3000 y.b.p) after the latest glaciation period. Analyses of chemical data from four municipalities at Lake Mälaren, west of Stockholm, far from the coastline, show a similar amount of salt affected wells as in coastal municipalities within the county of Stockholm (Assad & Salih, 1989).

Areas below the highest marine shore level have a large frequency of marine clays. In order to evaluate a correlation between pore water in clays and the chemical composition of the groundwater in some very salt drilled wells (>1000 mg Cl/l) in eastern central Sweden, the pore water from different depths was pressed out of the clay. The chemical composition of the pore water has been compared to the salt groundwater pumped up from the wells, **figure 3 A-C**.

The comparison shows that moderate saline water from the wells (<700 mg Cl/l) can be partly explained by leakage from the marine clays, whereas the deeper and strongly saline groundwater, which was mobilized by pumping, indicates another source. The chloride content was also three times higher (up to 9000 mg/l) than the chloride content of the present Baltic sea.

Water-rock interaction

Water-rock interaction has been proposed as a source of the salt groundwater. The Br/Cl-ratio of the solutes in fluid inclusions matches the ratio of the groundwater in the granite at the research mine

Stripa, central Sweden (Nordström et al, 1989, a,b) and at Finnsjön, central eastern Sweden (Puigdomènech & Nordstrom, 1987).

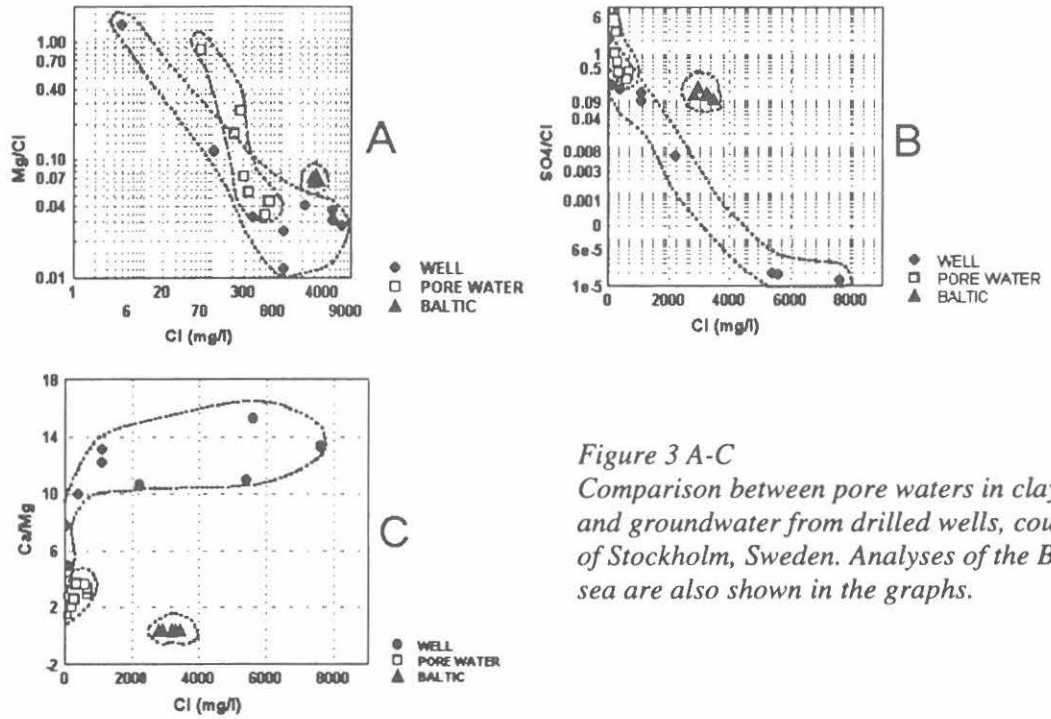

Figure 3 A-C
Comparison between pore waters in clays and groundwater from drilled wells, county of Stockholm, Sweden. Analyses of the Baltic sea are also shown in the graphs.

Freezing of seawater

Herud et al (1990) and Bein & Arad(1992) have suggested freezing of seawater as a conceivable explanation for the formation of deep salt groundwater in Sweden.

Anthropogenic sources

De-icing salts on road have been suggested as an important chloride-source in groundwater supply in Finland and Canada. In Sweden some early investigations on the impact of de-icing salts on groundwater were carried out around the nineteen-eighties (Bäckman, 1980). Locally, unprotected storages of road salts have caused salinization of wells (Müllern & Eriksson, 1981). Comprehensive studies of a municipal well, located in the vicinity of the main road E4 at Upplands Väsby, north of Stockholm, have revealed that the groundwater in the sandy aquifer is strongly affected by infiltrated de-icing salts (Maxe et al, 1993). Water sampling and analyses of groundwater along major roads in the county of Västmanland, central Sweden, have shown that almost 40% of the wells exhibit an increased content of chloride. This figure is much higher than data regarding the chloride content collected from the Well Record Section at SGU, which represents the situation when the well was constructed (Fabricius & Olofsson, 1996). The hardness of the groundwater close to roads is also usually much higher, which can be explained by intensive ion exchange with release of calcium when large amount of sodium-chloride is added to the soils.

Analysis of variance (ANOVA) using classified well records with a chloride content exceeding 100 mg/l, collected from the six counties, shows that groundwater close to roads represents the group with the highest hardness.

Water chemical sampling and analyses in about 100 wells along the major road E20, east of Lake Vänern, in the county of Skaraborg, central Sweden, have shown that about 50% of the sampled wells within 100 m from the road showed a raised content of chloride (Jansson, 1996).

Locally, leakage from many waste deposits influences the groundwater chemistry giving an increased salinization. This is accentuated in areas where the soils consist of sand or gravel.

Discussion

The correlation between possible chloride sources, using selected well records from SGU which have been classified, and hardness of the water as well as total amount of nitrogen, are shown in **figure 4**. The hardness clearly increases towards major roads. The classification of wells with regard to possible origin of the salt water shows that the hardness/chloride-ratio is highest among the groups classified as road salt and fossil seawater.

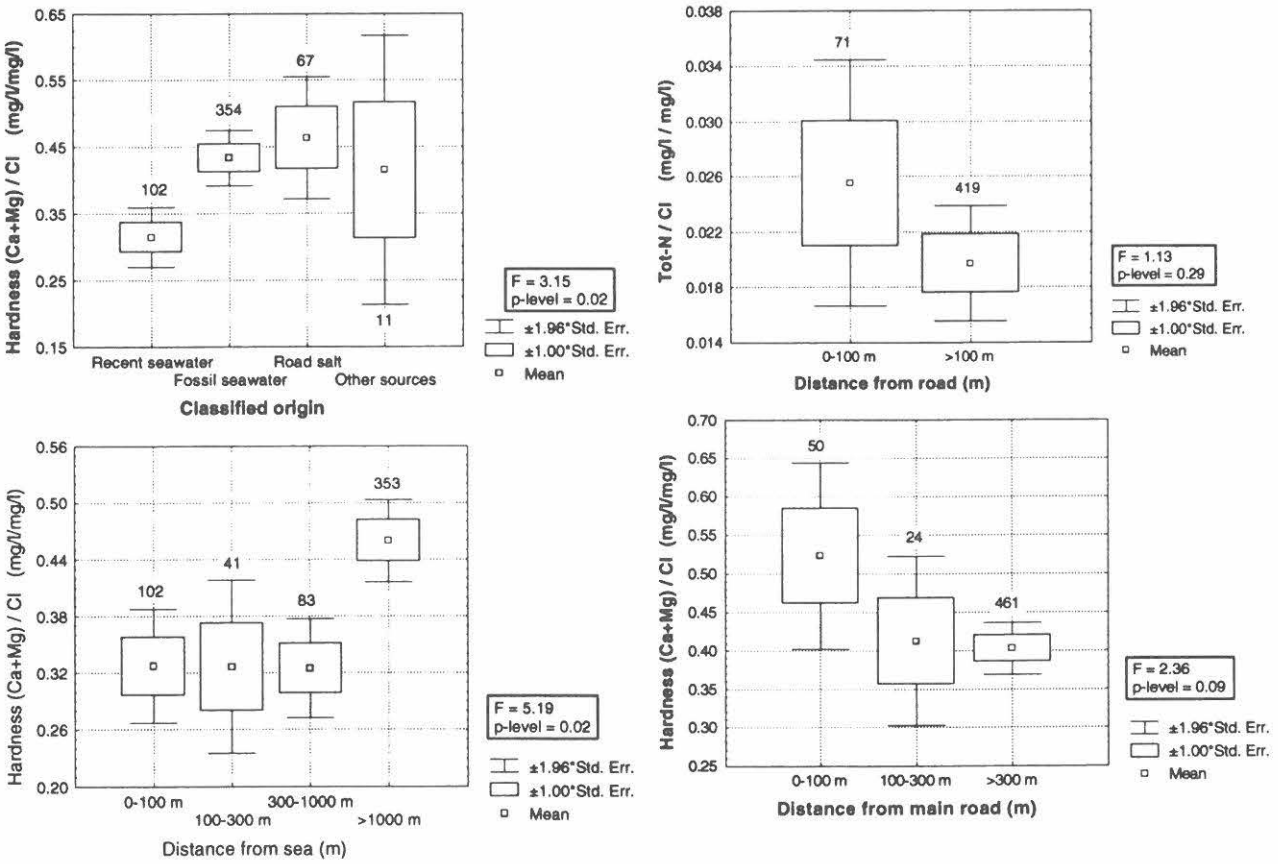

Figure 4 *ANOVA, showing the variation of hardness and nitrogen in relation to some probably sources of chloride. Based on classified well records from SGU.*

The spatial distribution of salt water wells in Sweden, clearly points out a strong connection to the brackish and salt marine environment after the latest glaciation period. The strong correlation (so far without exceptions) can only be explained either by the capture of seawater in rock fractures and pores in marine clays or by the fact that the marine clays act as an effective protection from flushing by fresh water. However, if other major sources of the salts, such as water-rock interaction, which has been proposed a.o. by Nordstrom et al (1989,a ,b) or old Paleozoic pore water could be preserved in crystalline rocks, salt groundwater should have been frequently found also in other areas, such as in the

Storsjön basin, west central Sweden or in central Småland (south Sweden). Also in the many deep drilled wells in Sweden (<800m), which have been carried out within the investigation programme for the final nuclear waste repository, salt groundwater at depth has only been registrered in boreholes below the highest marine shore level. In the three studied areas above this boarder, Taavinunnanen, Svartboberget and Klipperås, only fresh groundwater was found, **figure 5**.

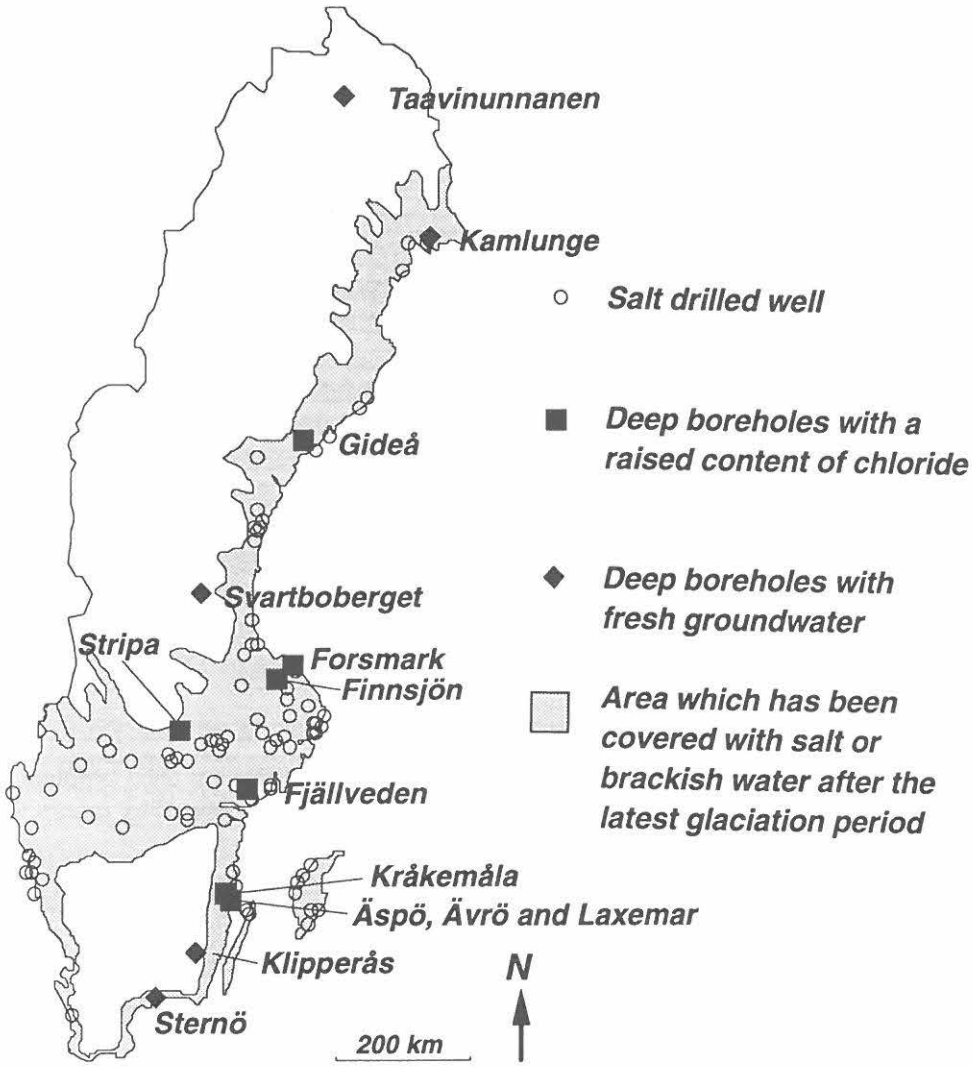

Figure 5 *Localization of deep drilled boreholes within the final nuclear waste repository project in Sweden. The highest marine shore level and the occurrence of salt drilled wells among well records at SGU, is also presented in the graph.*

Although most of the salt wells can be explained by the Holocene marine environment, some other sources of the salt must exist:

The very high salinity on the island of Gotland (>60 000 mg Cl/l) and in Scania (>150 000 mg Cl/l) (Brotzen, 1949) as well as the presence of many salt wells registrered in the southwestern part of Scania, must be a result of formation salts (such as salt minerals or very salt pore waters) connected with the sedimentary rocks prevailing in these areas.

Very high salinity has also been registrered at very deep levels in crystalline rocks (>1000 m) at Laxemar, south eastern Sweden, and at a depth of more than 4000 m in the deep Siljan borehole (central Sweden). Probably, brines exist at increasing depths, from the recent coastline where this type of water is found at depths more than 800 m, to the central part of Scandinavia, where the extremely saline water is found several tousand metres below the land surface. The origin of these brines may be of hydrothermal processes, indicating stagnant flow conditions at these depths.

In addition to these natural salt sources, which probably result in a raised chloride content in about 20% of all drilled wells below the highest marine shore level, a considerable impact from anthropogenic sources occurs. De-icing salts used on major roads in south and central Sweden probably explain additional 15-20% of the salt affected wells. This strong anthropogenic influence is not given by the data from SGU, which represents the conditions at the construction period of the well, but it is mainly shown from two separate investigations carried out in southwestern and central Sweden (Fabricius & Olofsson, 1996, Jansson, 1996).

Conclusions

Analyses of well records stored at SGU indicate that a raised content of salts, in relation to the contribution from the precipitation, exists in 17-25% of the well sites located below the highest marine shore level. Locally, such as on the island of Gotland, the amount of salt affected wells exceeds 61%. Most of the salt wells derive from salt or brackish stages of the development of the Baltic after the latest glaciation period. The salt water has been trapped in fractures in the crystalline rocks or in pores in the marine clays. The clays also act as a protection from flushing with fresh water. Locally, anthropogenic sources of the salts are important, such as de-icing salts used on roads, which may explain 15-20% of the salt water affected wells in the vicinity of major roads. Hence, locally up to 40% of the wells in small aquifers along major roads may be affected by salt water.

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