

3.21 Description of the Forsmark site case study, Sweden

Title of Case Study	The Forsmark site
Location (region, Country)	Northeastern Uppland, Sweden
Other information	The evaluation of ground water age is restricted to groundwaters in the bedrock.

Description of Case Study (background information on the region)

The Forsmark site is located north-east of Forsmark village (approx. 100 km north-east of Stockholm) along the Baltic Sea coast. In the area (ten square kilometres in size), where a final repository for spent nuclear fuel is proposed to be located, extensive site investigations have been conducted since 2002. These investigations include, among others, hydrogeochemical characterisation of groundwaters (e.g. groundwater age assessments) down to 1,000 metres depth in the bedrock. The ground surface is characterised by low relief with small-scale topography and is almost entirely located below 20 metres above sea level. The Quaternary till deposits that characterise the surface are less than 20 m thick and cover around 90 percent of the ground surface; rock outcrops are common. The bedrock is dominated by different types of Precambrian crystalline rock types (mainly granite and granodiorite), formed between 1.89 and 1.85 billion years ago (1.89-1.85 Ga). The annual precipitation and runoff are 560 mm and 160 mm, respectively. Simulated annual groundwater recharge in bedrock ranges from 29 to 53 mm, depending on depth and methodologies used. The groundwater level in the soil layers is located less than a metre below the ground surface for most of the year. Groundwater levels in rock are very equalized and lie just below sea level. The equalized and low levels can be assumed to be due to the highly penetrative horizontal and sub-horizontal fractures present in the uppermost parts of the rock. Several groundwater types which are now present in the bedrock can be associated with past climatic events in the late Pleistocene and Holocene. Among these, the last glaciation and post glacial period is the most important for the groundwater development.

Description of problem (why is this location chosen for a Cases Study)

The site investigations for a possible final repository for spent nuclear fuel have generated a good hydrogeochemical understanding of the site, both of present and past conditions. Numerous reports have been produced, approximately 800 dealing with the site investigations, and can be downloaded from SKBs (the Swedish Nuclear Fuel and Waste Management Company) website: www.skb.se. The Case Study reveals the groundwater development in the area over a very long time period (1.5 Ma – present) and groundwater age assessments are carried out for groundwaters down to great depth (~ 1.000 m) in the bedrock.

Methods to be used in the Case Study (analytical and isotope techniques, modelling)

Explorative analyses and modelling of groundwater chemistry data have been used to evaluate the hydrogeochemical conditions at the site in terms of origin of the groundwater and the processes that control the groundwater composition. The occurrence of old groundwater is evident from analyses of the isotopes carbon-14 and chlorine-36 (^{36}Cl), as well as the presence of ^4He , which is formed in the Earth's crust and mantle and is transported upward. Low oxygen-18 values ($\delta^{18}\text{O}$) indicate admixture of water originating from a very cold climate, which is interpreted as being meltwater from the continental ice sheet. Admixture of very young surface

water – from the 1950s and younger – is revealed by detectable quantities of the hydrogen isotope tritium (^3H). The following stable and radioactive isotopes have been analysed in the water: ^2H , ^3H , ^{18}O , ^{36}Cl , ^{37}Cl , ^{13}C , ^{14}C (pmC), ^{10}B , ^{11}B , $^{87}\text{Sr}/^{86}\text{Sr}$, ^{34}S , ^{238}U , ^{234}U , ^{230}Th , ^{226}Ra , ^{222}Rn .

Results from this Case Study

The groundwater in the bedrock consists of different mixtures of 1) modern or old surface water, 2) meltwater from the continental ice sheet, 3) water from the Littorina Sea (7,500 BC-present) and 4) extremely old and saline “deep water” from the deep bedrock.

- **Recent to young fresh groundwaters**, some showing signs of mixing with Littorina-type groundwaters, characterise the upper approximately 100-150 m of the bedrock. At these depths, because the hydraulic system is more dynamic, climatic changes have resulted in the cyclic introduction and flushing out of different groundwater types over tens of thousands of years such that residence times for individual groundwater types seem relatively short (i.e. probably some hundreds to a few thousand years). This is shown by tritium (^3H) and ^{14}C which indicate that near-surface groundwaters have short residence times in the order of only a few decades to a few hundred years.
- **Older groundwaters** with a heavy contribution from the Littorina Sea occur from approximately 150 m to depths of around 300-600 m (depending on the location and fracture transmissivity). The radiocarbon analyses (^{14}C) support a postglacial origin of brackish marine groundwater. This is in accordance with palaeohydrogeological estimations, which suggests an age of approximately 5,000 to 6,000 years, covering the period of maximum salinity during the Littorina stage (4,500-3,000 BC).
- **Significantly older groundwaters**, found at depths greater than around 300-600 m (depending on the location and the fracture transmissivity) to around 1,000 m, are characterised initially by brackish non-marine groundwaters which become successively more mineralised with increasing depth (to saline in type) by water-rock interaction, mixing with deep saline groundwater, and exchange with the rock matrix porewater. Hydraulic conditions at these depths indicate low groundwater flow to stagnant conditions and suggest residence times that appear to be considerable. From ^{36}Cl the residence time of the brackish to saline non-marine groundwaters can be shown to extend back to at least 1,5 Ma, which is in accordance with the ^4He systematics.

Impact - how this Case Study contributes to the overall project aims

The Case Study depicts extensive site investigations, described in numerous reports (in English) that are readily available for the public. A significant amount of age tracers has been used to describe the groundwater development over a long time period and to great depth in the bedrock.

Name of pilot area / aquifers / type: The Forsmark site / Precambrian crystalline bedrock aquifers / fissured		Country: Sweden Region: Uppland, 100 km north-east of Stockholm	
Study level	Transboundary: ☐ Regional: ☐ Local: ☒ Single well(s): ☐		
Type of observations <i>(choose one of the options, create separate template if needed for each type if each type need specific information)</i>	☐ Short screened observation wells (not pumped) ☐ Long screened observation wells (not pumped) ☐ Pumped wells, long screens in one aquifer ☐ Pumped wells, long screens over multiple aquifers ☐ Springs ☒ Other (research wells; not pumped)		
Approximate location of pilot:			
Geological cross section / conceptual model of the pilot area:	<i>Conceptual model for Forsmark illustrating present hydraulic conditions and distribution of the different groundwater types. Modified from Follin et al. 2007.</i>		

Name of Shape- / Geopackage file defining the area:		Projection to be used: WGS84 (Epsg4326)		
Hydrological parameters:	Mean annual precipitation (mm or range in mm)	Mean annual groundwater recharge (mm or range in mm)	Mean annual groundwater recharge temperature (°C)	Thickness of unsaturated zone (range in m)
	560	≤ 50 * * simulated groundwater recharge in bedrock	6-7	0-10
Pumped wells only		Typical pump discharge of sampled individual well (m ³ /day):	Typical pump discharge of complete well field (m ³ /day): <i>If relevant</i>	
List of aquifers and aquitards in pilot area		No. of confined or semiconfined aquifers in pilot area: 1* * Aqf-1a, Aqf-1b and Aqf-1c	No. of unconfined aquifers in pilot area: 0	
Aquifer no. (aqf): 1 (aqf-1a, aqf-1b & aqf-1c) Aquitard no. (aqt): 0 Aquiclude no. (aqc): 0	Aquifer/aquitard type and/or name	Lithology (Resource WP6 terminology)	Depth range (m)	GW age range (yr)
Aqf-1a:	Precambrian crystalline rocks (recent to young fresh groundwaters)	Crystalline rocks	0 – 150	<60 – 5,000
Porosity type	Porous: ☐	Fissured: X	Karst: ☐	Fissured and porous / dual porosity: ☐
Aqf-1b:	Precambrian crystalline rocks (old groundwaters)	Crystalline rocks	150 – 300/600 (depending on location)	5000 – 10,000
Porosity type	Porous: ☐	Fissured: X	Karst: ☐	Fissured and porous / dual porosity: ☐
Aqf-1c:	Precambrian crystalline rocks (significantly older groundwaters)	Crystalline rocks	300/600 – 1.000	> 10,000 – 1.5 x 10 ⁶
Porosity type	Porous: ☐	Fissured: X	Karst: ☐	Fissured and porous / dual porosity: ☐
Applied tracer age indicators (³ H, ³ H/ ³ He, ⁸⁵ Kr, ³⁹ Ar, ¹⁴ C, ³⁶ Cl, ⁸¹ Kr, ⁴ He, CFCs, SF ₆ , etc.)		Aquifer-1a ³ H, ¹⁴ C, ³⁶ Cl, ⁴ He, ¹⁸ O, noble gases		
		Aquifer-1b		

Applied recharge temperature indicators (^{18}O , D, noble gases)	^3H , ^{14}C , ^{36}Cl , ^4He , ^{18}O , noble gases					
	Aquifer-1c ^3H , ^{14}C , ^{36}Cl , ^4He , ^{18}O , noble gases					
Number of sites (wells/springs) with age indicators	Aquifer-1a 1-5: ☐ 5-10: ☐ 10-25: X >25: ☐					
	Aquifer-1b 1-5: ☐ 5-10: ☐ 10-25: X >25: ☐					
	Aquifer-1c 1-5: ☐ 5-10: ☐ 10-25: X >25: ☐					
GW age range (GAR) GAR-1: Modern (< 60 yr) GAR-2: Old (> 60 yr and 10 kyr) GAR-3: Paleowaters (> 10 kyr)	Aquifer-1a GAR-1: 1-10%: ☐ 10-25%: ☐ 25-50%: X >50%: ☐ GAR-2: 1-10%: ☐ 10-25%: ☐ 25-50%: X >50%: ☐ GAR-3: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: ☐					
	Aquifer-1b GAR-1: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: ☐ GAR-2: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: X GAR-3: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: ☐					
	Aquifer-1c GAR-1: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: ☐ GAR-2: 1-10%: ☐ 10-25%: ☐ 25-50%: X >50%: ☐ GAR-3: 1-10%: ☐ 10-25%: ☐ 25-50%: ☐ >50%: X					
	Tracer based estimates X					
	Flow and age model simulations ☐					
	Combination of model and tracer estimates ☐					
	Expert judgement: X					
	Objective of age dating studies:					
	Basic research or General groundwater management	Assessment of pollutant history		Assessment of the efficiency of remediation and mitigation measures		Indication of vulnerability of aquifers and water supply wells
X						
Water Usage <i>(not relevant for observation wells)</i>	Water supply		Irrigation	Industry	Other	
Geoenergy related activities <i>(not relevant for observation wells)</i>	Shallow Geo-T	Deep Geo-T	Hydrocarbons		Nuclear waste disp.	CO ₂ storage
					X	
Mining activities <i>(not relevant for observation wells)</i>	Construction materials		Minerals / metals	Coal	Other	
REFERENCES						



OPEN Access reports and papers (PDF versions made available in EGD repository making them downloadable via maps and keyword / free text searches):

Follin S., 2008. Bedrock hydrology Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-95, Svensk Kärnbränslehantering AB.

Laaksoharju M., Smellie J., Tullborg E-L., Gimeno M., Hallbek L., Molinero J. & Waber N., 2008. Bedrock hydrogeochemistry Forsmark. Site descriptive modelling SDM-Site Forsmark. SKB R-08-47, Svensk Kärnbränslehantering AB.

Lundin L., Lode E., Stendahl J., Melkerud P-A. Björkvald L. & Thorstensson A., 2004. Soils and site types in the Forsmark area. SKB R-04-08, Svensk Kärnbränslehantering AB.

Nilsson A-C., Tullborg, E-L., Smellie J., Gimeno, M.J., Gomez J.B., Auqué L.F., Sandström B. & Pedersen K., 2011. SRF site investigation Bedrock Hydrogeochemistry. SKB R-11-06. Svensk Kärnbränslehantering AB.

SKB, 2012. Site Investigation, Forsmark, Annual Report 2002-2007. Second edition April 2012. Svensk Kärnbränslehantering AB.

Smellie J. Tullborg E-L., Nilsson A-C., Sandström B., Waber N., Gimeno M. & Gascoyne M., 2008. Explorative analysis of major components and isotopes. SDM-Site Forsmark. SKB R-08-84. Svensk Kärnbränslehantering AB.

Söderbäck B. (ed), 2008. Geological evolution, paleoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling, SDM-Site. SKB R-08-19, Svensk Kärnbränslehantering AB.

Reports and papers with restricted access:

Follin S., Stephens M.B., Laaksoharju M., Nilsson A-C., Smellie J.A.T. & Tullborg, E-L. 2008. Modelling the evolution of hydrochemical conditions in the Fennoscandian Shield during Holocene time using multidisciplinary information. Applied Geochemistry 23, 2004-2020.

Remarks / other relevant information:

The evaluation of ground water age is restricted to groundwaters in the bedrock. The aquifer in the bedrock has been subdivided into three sections (Aqf-1a, Aqf-1b and Aqf-1c), depending on differences in estimated groundwater age with depth.

