Groundwater chemistry during test-pumping at Sundby, Verdal, Mid-Norway

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The Sundby aquifer, Verdal, Mid-Norway has been evaluated for yield and groundwater quality as a potential water resource for the local municipality. Test-pumping of the aquifer commenced in 1989, after detailed geological investigations. The aquifer's potential yield satisfies the demand, but the observed increase in salinity as function of withdrawal poses a problem.

The geological setting of the aquifer, the distance to the fjord and the ionic ratios observed in groundwater samples indicate that the salinity is not the result of intrusion of present fjord water, but is most likely due to the leaching of salts from relict connate water in the surrounding glaciomarine or marine sediments.

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Introduction

The Sundby aquifer lies by the River Verdalselva in the Verdalen valley, 80 km northeast of Trondheim and approximately 8 km from Trondheimsfjord (Fig. 1). The aquifer has been the subject of intensive studies during the last decade. The main purpose of the investigations was to study the quantity and quality of the available groundwater in order to evaluate the aquifer as a water resource for Verdal municipality.

Test-pumping of the aquifer was initiated in 1989, after detailed geological investigations. The results of these studies are described by Tvedten (1989). The yield of the established well-field satisfied the demand, but the observed increase in salinity as a function of withdrawal posed a quality problem. As a consequence of this, the Geological Survay of Norway (NGU) decided to extend the test-pumping programme and established a new well site in an attempt to lower the salinity of the pumped groundwater (Hilmo 1990).

Fig. 1. Location of the Sundby aquifer in Verdalen, Mid-Norway.

Geological setting

Ice movements during the Quaternary have been reconstructed by Sveian (1989). During the deglaciation, which occurred during the latest Younger Dryas and early Preboreal periods (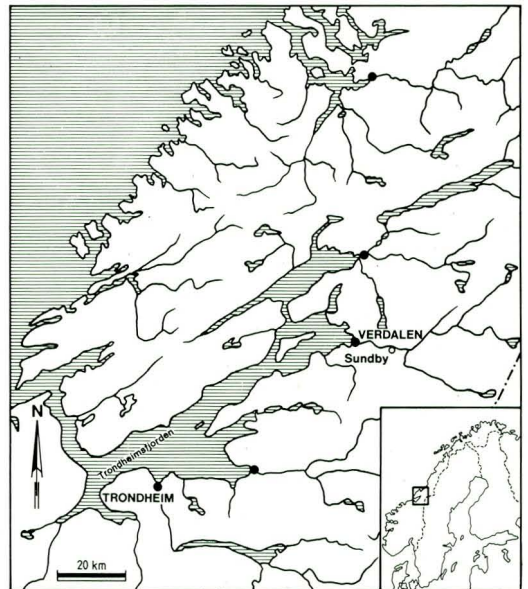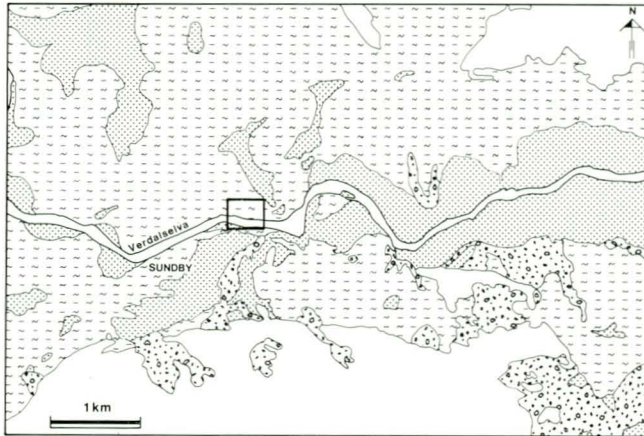c. 10,500-9,800 years B.P.), halts or small advances of the ice-front resulted in several ice-marginal gravel deposits in Verdalen (Fig. 2). The locations of the deposits are strongly influenced by the underlying bedrock topography. The main drainage during deglaciation followed the south side of the Verdalen valley.

Fig. 2. Quaternary geological map, showing ice-marginal and glacifluvial deposits in the lower part of Verdalen (after Sveian 1989).

LEGEND

- MARINE DEPOSITS
- FLUVIAL DEPOSITS
- GLACIOFLUVIAL DEPOSITS
- EXPOSED BEDROCK OR THIN COVER OF HUMUS ON BEDROCK
- AREA OF Fig. 3

The ice-marginal sand and gravel deposit which constitutes the Sundby aquifer does not extend up to the marine limit during deglaciation (c. 180 m above present sea level). Later river terraces are cut into the deposit at different levels, and the present level of the River Verdalselva is 5-8 m above sea level (Fig. 3). It was not until c. 1500 years ago that the sea had regressed to this level (Sveian 1989), but it is conceivable that freshwater under hydrostatic pressure may have flowed through the aquifer earlier than 1500 yrs. B.P., displacing saline waters.

The structure of the Sundby aquifer is well known, and is based on geological data from 36 boreholes, measurements of groundwater level in 15 observation wells, three seismic refraction profiles and electrical resistivity measurements (lateral profiling and depth profiling). The aquifer is distally (i.e. the western side) covered by clay, and in this part of the aquifer sand and gravel beds interfinger with marine and glaciomarine clays (Fig. 3). Upstream of the aquifer, one can observe exposed bedrock in the riverbank. In the investigated area, the aquifer is largely overlain by mudslide sediments. In a small area in the eastern part of the aquifer, as a result of postglacial erosion, hydraulic communication between the river and aquifer is possible. The top of the gravel deposit dips towards the north. How

far the aquifer extends in a northerly direction is uncertain.

The aquifer appears to be recharged by run-off from the hillside (from the south), and discharges into the river under non-pumping conditions. Infiltration from the river to the aquifer may be possible during flood periods, but only in a limited area by the southern river bank in the vicinity of observation well no.3 (Fig. 3).

The bedrock in Verdalen consists of Palaeozoic phyllites, greywacke, limestones and greenstones (Wolff 1979), and these lithologies are also common in the overlying Quarternary sediments. Occasionally one can find pebbles and clasts of biotite-rich micagneiss and granite in the Quaternary gravel deposits. These are derived from basement rocks located further to the east. X-ray diffraction analyses of sediment samples show that the main minerals in the gravel deposits are quartz, plagioclase, mica, amphibole, calcite and chlorite (Tvedten 1989).

Test-pumping procedure

Test pumping at Sundby was carried out during two periods, the first period (Aug.-Dec. 1989) utilizing the wells in well area W1 and the second period (Mar.-Jul. 1990) utilizing the wells in well area W2 (see below). The total
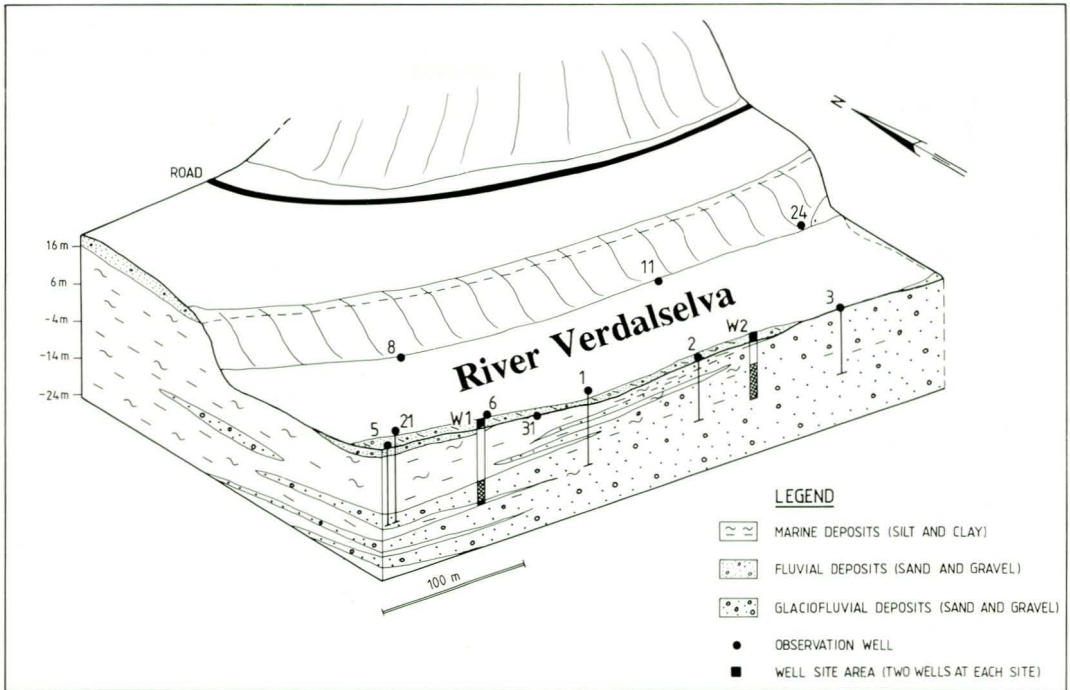
Fig. 3. Block-diagram showing the stratigraphy of the aquifer and the location of the well sites at Sundby.

pumping rate varied between 25 and 50 L/s. Before test-pumping commenced, fifteen observation wells (diameter 5/4") were established in order to monitor changes in groundwater level during pumping.

Four groundwater abstraction boreholes were drilled. Two 4" diameter boreholes were established at well area W1, with well- screen at 10-19 m depth. From one to four months after the start of the test-pumping at well area W1, a consistent increase in the content of total dissolved solids of the pumped groundwater was noted (Tab. 1).

Later, in March 1990, two 3" boreholes were drilled further upstream at well area W2 (Fig. 3), in order to increase the contribution from river-bed infiltration and thus to reduce the content of total dissolved solids. The well screens here were placed between 8-18 m depth.

Groundwater quality monitoring

Groundwater samples for chemical analysis were collected from the observation wells prior to test-pumping. During the two periods

of test-pumping, water was sampled from the abstraction boreholes initially once per day and later once every week. Electrical conductivity, alkalinity, pH and major ions in the water samples were analysed by standard procedures at the Geological Survey of Norway (Ødegård & Andreassen 1987).

At 5 m below ground level in the vicinity of well area W1, a marine clay was sampled and later subjected to pore-water analysis and determination of the adsorbed cation content. This was done to evaluate whether the rather high content of total dissolved solids in the groundwater could be due to leaching of relict salts from marine clays. The content of exchangable cations was determined by shaking 10 g clay in 50 ml 0.2 M $BaCl_2$ solution buffered with NH_4Cl to pH = 8.5, for 3 periods of 15 min. before final rinsing in 50 ml deionized water (Grim 1953 and Hilmo 1989).

In addition to inorganic chemical analysis, water samples were collected from W1 for determination of microbiological parameters. These analyses indicated that the biological quality of the water satisfies Norwegian drinking water standards (SIFF 1987).

After two months of pumping at W2 a 240 litre sample of groundwater was collected on May 23rd, 1990, and analysed for its content of ^{13}C and ^{14}C. The CO_2 gas generated from the sample by adding acid was stored for six weeks prior to analysis in order to avoid contamination from radon.

Results and discussion

Aquifer hydrogeology
Data from the test-pumping at W1 gave the the following hydrogeological parameters:

Transmissitivity (T) : 0.058 m²/s (5000 m²/day)

Specific storage (S) : 0.15 - 0.2 in the eastern part of the aquifer and < 0.1 in the western part.

Hydraulic conductivity : c. 3.8 x 10⁻³ m/s (330 m/day)

Measurements during test-pumping indicate that the groundwater level in the aquifer adjusts quickly to water-level variations in the river. During autumn 1989 net variation in the in river stage was measured to be 1.5 m (Tvedten 1989). The groundwater level in observation well no. 6 (Fig. 3) was drawn down by only 0.55 m, after correction for river level variation, during three months of test-pumping from W1.

Groundwater temperature
The groundwater temperature measured in the well area W1 was found to be stable at 5.6°C during the four-month test-pumping period, while the temperature in the river varied from 16°C to 6°C. The annual mean air temperature is 4.6°C. The groundwater temperature was measured in several observation wells at different depths and at various distances (8, 38, 54 and 130 m) from W1. There was no significant change in temperature with depth in the aquifer, nor with distance from the most likely area of river water infiltration, during the pumping period.

Groundwater chemistry
Groundwater in Norway contains, in general, low amounts of total dissolved solids. This is to be expected in a temperate climate with a long winter season and a short residence time for most natural waters including groundwaters. Processes such as hydrolysis, redox-reactions, ion-exchange, dissolution and precipitation can however cause large variations in the chemistry of the groundwater. The effect of the various reactions on the chemistry of the water in the aquifer depends on temperature, pH, Eh, residence time and mineralogical composition of the surrounding bedrock and sediments.

Ion concentrations during test-pumping of well area W2 are considerably lower than those of waters pumped from well area W1 (Table 1). The lower amounts of total dissolved solids in W2 may be due to a higher degree of infiltration from the river. pH-values of around 8 and alkalinities varying from 3.5 to 4.1 mmoles/L in W1 and 2.0. to 3.0 mmoles/L in W2 were recorded.

The electrical conductivity and ion-content of the analysed samples are shown versus time of pumping in Fig. 4 and Table 1. The first samples of water collected at W1 and W2 are best characterised as a calcium-bicarbonate type with moderate amounts of total dissolved solids. After almost two months of pumping at W1 the salinity increased drastically. The increases in chloride and sodium concentrations were most significant (Table 1). After an interruption of the pumping, the electrical conductivity is reduced (Fig. 4). This suggests that the aquifer receives a significant influx of freshwater when pumping stops.

Sources of salinity in groundwater
The low concentrations of Cl⁻ and Na⁺ at the start of the test-pumping indicate that the initial groundwater composition is only marginally influenced by marine waters. The drastic increase in salinity after a period of pumping, is presumably an indication of marine influence. Topography, distance from present shoreline (c. 8 km) and the Ghyben - Herzberg-equation, however, indicate that direct infiltration of saline fjord water is not likely to occur. Possible sources for the salinity in the groundwater are thus assumed to be:

Tables 1: Chemical analyses of groundwater samples from (Table 1a) well area W1 and (Table 1b) well area W2. Table 1c shows analyses of pore water squeezed from a clay sample and adsorbed cations in clay samples. "-" = not analysed.

Table 1a: Well area W1

Date	Electrical Cond. µS/cm	pH	Alkalinity mmol/L	F^- mg/L	Cl^- mg/L	Br^- mg/L	$SO_4^=$ mg/L	Na^+ mg/L	K^+ mg/L	Mg^{2+} mg/L	Ca^{2+} mg/L	Fe mg/L	Mn mg/L
10/8	426	7.8	3.5	0.3	13	0.03	45	8	7	8	69	0.1	0.1
11/8	459	7.8	3.7	0.3	14	0.06	53	9	8	9	75	0.2	0.1
12/8	472	7.8	3.8	0.4	15	0.04	56	9	8	9	78	0.3	0.1
13/8	487	7.8	3.8	0.6	17	0.37	57	10	8	10	79	0.3	0.1
17/8	502	7.8	4.1	-	-	-	-	11	8	10	80	0.4	0.1
24/8 stop	525	8.0	4.1	0.4	16	0.01	60	-	-	-	-	-	-
12/9	543	7.9	4.1	0.4	22	0.07	69	12	8	10	83	0.0	0.1
20/9	819	8.0	4.0	0.3	111	0.48	85	36	8	14	105	0.6	0.2
26/9	1114	7.7	3.9	<0.5	195	0.53	97	65	9	17	115	0.7	0.2
5/10 stop	2220	8.0	3.7	<0.5	657	1.82	158	197	13	33	151	1.1	0.2
12/10	1880	7.6	3.8	<0.5	526	1.31	149	167	11	27	129	0.9	0.2
27/11	4080	8.0	3.8	<2.5	1200	-	268	529	15	78	153	1.4	0.3
19/12	4500	7.6	3.7	<2.5	1300	-	300	603	17	85	136	0.0	0.2

Table 1b: Well area W2

Date	Electrical Cond. µS/cm	pH	Alkalinity mmol/L	F^- mg/L	Cl^- mg/L	Br^- mg/L	$SO_4^=$ mg/L	Na^+ mg/L	K^+ mg/L	Mg^{2+} mg/L	Ca^{2+} mg/L	Fe mg/L	Mn mg/L
7/3	255	8.0	2.3	0.3	4	0.02	19	8	2	5	40	0.2	0.1
9/3	270	8.0	2.4	0.4	5	0.02	23	10	2	5	40	0.1	0.1
22/3	394	8.0	2.6	0.5	27	0.10	34	31	3	7	42	0.3	0.1
28/3	518	7.9	2.8	0.6	30	0.17	46	44	3	9	46	0.2	0.1
6/4	619	7.9	3.0	0.7	68	0.33	56	66	4	11	50	0.4	0.1
17/4 stop	801	7.8	2.9	0.9	116	0.43	62	82	4	14	51	0.5	0.1
8/6	896	8.3	2.9	0.6	276	0.74	90	91	4	18	55	0.0	0.1
14/6	1149	8.0	3.1	5.7	244	0.86	97	120	5	24	63	0.0	0.1
28/6 stop	1260	7.8	3.0	-	271	1.05	111	137	4	27	63	0.3	0.1
3/7 stop	871	7.7	3.0	0.3	158	0.55	75	84	4	18	55	0.1	0.1
17/7A	160	8.1	1.3	0.1	5	0.01	14	4	1	5	22	0.0	0.1
17/7B	300	8.0	2.0	0.2	17	0.07	39	16	2	8	34	0.0	0.1
27/7	488	7.9	2.8	0.2	40	0.16	61	33	3	12	48	0.1	0.1
1/8	667	7.8	2.9	0.2	102	0.34	68	58	3	16	50	0.1	0.1

Table 1c: Marine Clay Sample

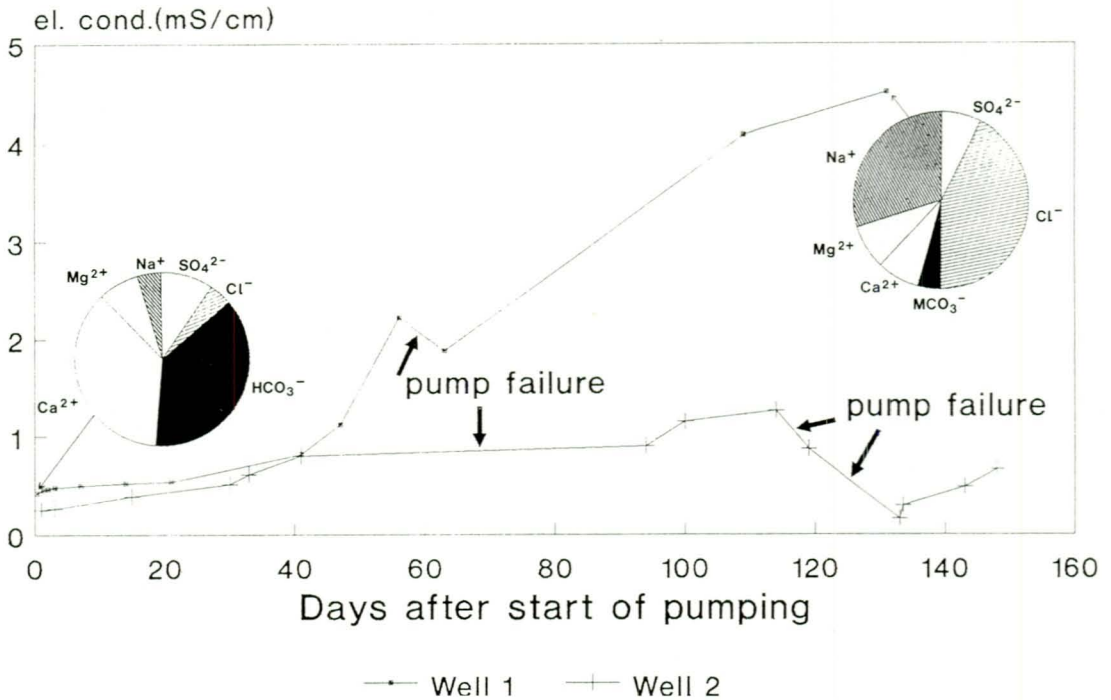| Sample	F^-	Cl^-	Br^-	$SO_4^=$	Na^+	K^+	Mg^{2+}	Ca^{2+}	Fe	Mn
Pore water squeezed from clay (mg/L)	7.7	900	-	448	743	29	43	36	0.1	
(meq/L)	0.4	25		9.3	32	0.7	3.5	1.8	0	
Adsorbed cations in meq/100 g clay	-	-	-	-	1.2	0.9	1.8	6.9	-	

el. cond.(mS/cm)

Fig. 4. Electrical conductivity plotted as a function of pumping-time (Pie diagrams: ion-distribution at the start of test-pumping and at time of maximum total dissolved solids).

(a) relict ocean water within isolated sand/ gravel layers.
(b) leaching of fossil salts from marine sediments, primarily clays.

If we consider the increase in the concentration of the different ions and their ratios during test-pumping, it is possible to evaluate the causes of the increasing salinity. Fig. 5 & 6 show the ratios of Br^-/Cl^-, $SO_4^=/Cl^-$ Ca^{2+}/Cl^-, Na^+/Cl^- and Mg^{2+}/Cl^- as a function of the chloride concentration. The results from both well-areas are presented.

The Br^--ions and Cl^- -ions both have a marine source. They are assumed to be products of weathering to a negligible degree. They are unlikely to be precipitated or adsorbed onto clay minerals, and one would thus expect a constant ratio between Br^- and Cl^- independent of salinity and Cl^--concentration (Fig. 5). Despite the inaccuracy in the determination at low Br^--concentrations, this is in fact found to be the case; the ratio is approximately constant and similar to that in Mean Standard Ocean Water.

Sulphate in groundwater originates

(a) from weathering of sulphides and sulphate-minerals
(b) from the marine environment
(c) from infiltration of anthropogenically contaminated precipitation.

Sources (a) and (c) appear to be evident from the high concentrations of sulphate, and therefore high $SO_4^=/Cl^-$-ratios, at low concentrations of Cl^- (Fig. 5). In groundwater with a higher salinity, the $SO_4^=/Cl^-$-ratio approaches the value found in Mean Standard Ocean Water.

The dissolution of aquifer calcite (Paleozoic limestone clasts and marine molluscs) is probably the main source of the Ca^{2+} in the groundwater. However, the Ca^{2+}-concentration increases with increasing salinity (Table 1 and Fig. 6) suggesting an additional marine contribution. All the groundwater samples that are analysed appear to be saturated or slightly supersaturated with respect to calcite (apparent supersaturation of the waters with respect to calcite may, however, be an artifact of using concentrations instead of ion activities in the calculation).
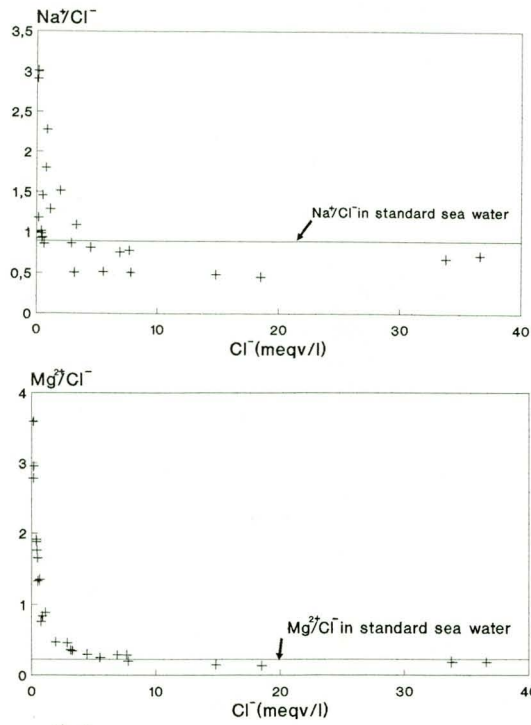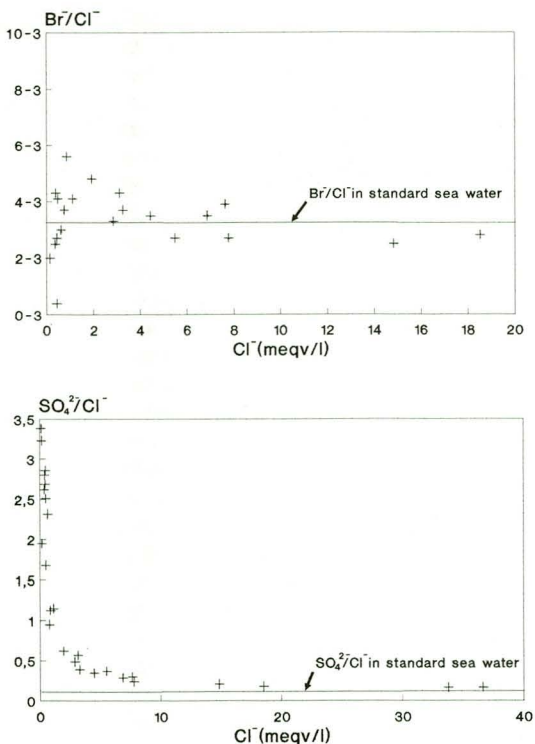
Fig. 5. Ratios of Br⁻/Cl⁻ and SO₄⁼/Cl⁻ as a function of the chloride concentration. The results from both W1 & W2 are presented.

Fig. 6. Ratios of Na⁺/Cl⁻, Mg²⁺/Cl⁻ and Ca²⁺/Cl⁻ as a function of the chloride concentration. The results from both W1 & W2 are presented.

In addition to their marine origin, sodium- and magnesium-ions are derived from weathering of rocks and minerals. Thus it might be expected that the Na⁺/Cl⁻- and Mg²⁺ /Cl⁻-ratios in the sampled groundwater would always remain higher than the ratios present in ocean water. In spite of this, the Na⁺ /Cl⁻- and Mg²⁺/ Cl⁻ - ratios in groundwater became less than the same ratios in ocean water as pumping progressed and salinity increased (Fig. 6). This is interpreted as being due to preferential adsorption and ion- exchange of Na⁺ and Mg²⁺ on clay minerals.

Clay minerals have a net negative charge. Cationic attraction to the basal planes of clay particles increases with increasing valence and decreasing hydrated ionic radii. This leads to an enrichment of polyvalent cations in adsorbed positions relative to the ionic composition in the liquid phase (Van Olphen, 1977). Because of repulsion from the clays' basal planes and weak or no attraction to the edges, mono-

valent anions will leach more easily from marine clay than cations and especially polyvalent cations. Water leached from marine clays will therefore have lower Na⁺ /Cl⁻ and Mg²⁺ /Cl⁻ ratios than ocean water. The pore water chemistry and the measured composition of adsorbed cations for the marine clay sampled in the vicinity of W1 supports this hypothesis (Tab. 1). An elevated concentration of Na⁺ in relation to Cl⁻ is found in the pore water squeezed from the clay samples. This is also found in

the pore water of marine sensitive clays samp-
led in other localities in Trøndelag and North
Norway (Hilmo 1989). This pressure-extracted
pore water of the marine clay sample is belie-
ved to reflect the remnant concentration of the
ions after at least 2000 years of fresh water
leaching. In contrast to the ionic composition
of adsorbed cations, the concentration of
Mg^{2+} relative to Na^+ and Cl^- is lower in the
pore water, compared to ocean water. The
net effect appears to be that water leached
from a marine clay with a fossil salt content
is impoverished in cations in comparison to Cl^-.

When abstraction of groundwater exceeds
the amount which can readily be infiltrated
from the surface, an increasing proportion of
the groundwater will originate in sand- and
gravel deposits which are in close contact
with the marine clays. Mapping of the aquifer
revealed several thin sand- and gravel depo-
sits which interfinger with marine clays distal-
ly (Fig. 3). These sediments are presumed to
act as drainage avenues for the leached pore-
waters.

Carbon isotopes
Analyses of the carbon isotopes in water from
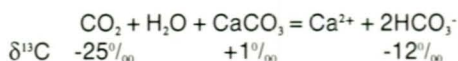well W2 gave the following results:

$\delta^{13}C = -12.2^0/_{00}$

$^{14}C = 12.72 \pm 0.10$ cpm, corresponding to
60.2 ± 0.5 % activity, and an apparent (assu-
ming all carbon is biogenic) age of $4290 \pm$
55 years (Sæther 1990).

The water sample used for the dating had
an alkalinity of 2.84 mmoles/L. It was supersa-
turated with respect to calcite. The alkalinity
was higher than in seawater (2.3 mmol/L). By
comparing the concentrations of chloride and
bromide in the groundwater to those of seawa-
ter, a 'dilution factor' of about one hundred
times is estimated. The contribution of bicar-
bonate from seawater cannot thus be more
than about 0.02 mmoles/L, i.e. less than one
percent of the total bicarbonate.

Typically, meteoric water has a $\delta^{13}C$ of
around $-7^0/_{00}$. As it percolates into the ground,
however, it acquires biogenically derived CO_2
from the soil zone, with a $\delta^{13}C$ of $-25^0/_{00}$. Mari-
ne carbonates typically have a $\delta^{13}C$ value of
$+1^0/_{00}$ (Lloyd & Heathcote 1985). The $\delta^{13}C$ value
obtained for the groundwater is thus typical

for the standard model of bicarbonate generati-
on in groundwater, where 50% of bicarbonate
carbon is biogenic, and 50% is from dissolved
carbonate, leading to a typical $\delta^{13}C$ value of
-12 to $-13^0/_{00}$.

$$CO_2 + H_2O + CaCO_3 = Ca^{2+} + 2HCO_3^-$$
$$\delta^{13}C \quad -25^0/_{00} \qquad +1^0/_{00} \qquad\qquad -12^0/_{00}$$

If one also assumes that 50% of the ^{14}C is
biogenic, and 50% is inorganic (with $^{14}C = 0$,)
the age of the biogenic carbon (the age of
recharge) is calculated as -1540 years. One
can also apply a more complicated correction
method such as that of Wigley (1971), which
yields an age of between -1800 and -2200
years. Such negative ages are plainly meaning-
less, and this may be due to:

(a) The assumption that the ^{14}C content of the
aquifer carbonate is zero being incorrect. This
is the most likely reason. If the aquifer car-
bonate contains young carbonate material
($^{14}C>0$), the above assumption would lead to
overcorrection of the age. In fact, Tvedten
(1989) found that the aquifer material contains
up to 10% calcite. This calcite is composed
both of clasts of Paleozoic bedrock and of
recent marine molluscs (i.e. finite ^{14}C).

(b) Carbon from humic acids in the groundwa-
ter affecting the results.

(c) Exchange of groundwater and aquifer car-
bonate, a phenomeneon noted in saline envi-
ronments by Wendt (1971).

In summary, the carbon isotopes give no conc-
lusive information on the water's age. The
obtained 'negative' dates are not, however,
inconsistent with a modern recharge water
which has been overcorrected for its ^{14}C age
(due to the finite ^{14}C content of the aquifer
carbonate).

Conclusion
Test-pumping of the Sundby aquifer in Verda-
len, Mid-Norway, yielded groundwater with a
higher content of total dissolved solids than
is acceptable for domestic water (SIFF, 1987).
During the first weeks of the pumping period
the groundwater could be characterised as a

calcium bicarbonate water with moderate total dissolved solids. After more than three months of test-pumping at W1, the salinity had increased to approximately 2.5 g/L. The maximum salinity during test-pumping at W2 was 0.7 g/L. The ratios of Br^-/Cl^- and $SO_4^=/Cl^-$ in the saline water samples are close to those found in Standard Mean Ocean Water, and indicate a marine origin for the salinity.

Although the well screens are situated under sea level, it is regarded as unlikely that ocean water can intrude the 8 km from the fjord through thick clay sediments during pumping. The high content of dissolved solids may therefore be due to relict saline water from isolated sand and gravel layers or be leached from marine clays.

The Mg^{2+}/Cl^- and particularly Na^+/Cl^- ratios in the saline groundwater are lower than the corresponding ratios in ocean water. This was rather unexpected, as additional Na^+ and Mg^{2+} ions might be expected to originate from weathering. It is, however, believed that cations such that Na^+ and Mg^{2+} are being adsorbed onto clay particles. Water leached from marine clay will thus have a higher concentration of Cl^- compared to Na^+ and Mg^{2+} than ocean water. Analysis has confirmed that the pore water of a clay sampled in the vicinity of W1 is enriched in Na^+ ions compared to Cl^- ions, and that adsorbed cations are enriched in Mg^{2+} and Ca^{2+} compared with Na^+.

Thin layers of sand and gravel interfingering with clay deposits have been mapped in the distal part of the aquifer. These layers act as drainage avenues for the leached pore water, which becomes an increasingly important component of the abstracted groundwater with time of pumping.

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