

Origin of shallow saline groundwater on the Island of Læsø, Denmark

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Received 29 November 2000; accepted 7 September 2001

Abstract

Shallow saline groundwater has a patchy occurrence in superficial postglacial marine sediments beneath coastal meadows and salt marshes on the southern shores of the Island of Læsø, Denmark. The postglacial sequence consists of 1–2 m of marine sands and gravels resting on a slightly undulating platform of practically impermeable interglacial marine clay, which makes up a confining layer or aquiclude. The saline groundwater primarily occurs beneath the vegetated fringe and associated minor unvegetated sand pans of coastal meadows and salt marshes. The salinity varies from 2% to approximately 17% and analyses of major ions indicate a prevailing marine composition. The saline groundwater is supersaturated with respect to carbonates in the entire salinity range and slightly supersaturated with respect to gypsum with salinities above 10%. However, aragonite is the only precipitate recorded so far. Stable isotope analyses (^2H and ^{18}O) plot fairly well along the local groundwater–seawater mixing line indicating mixing of seawater with fresh meteoric groundwater in the proportion 0–50%. In contrast, the stable isotopic compositions show no correlation to the wide range of salinities recorded. It is proposed that the thin cover of superficial deposits resting on a clay platform results in a relatively closed hydrochemical system in which increasing concentration of dissolved solids in the interstitial water is caused by transpiration which is known to abstract water from groundwater without leading to isotopic fractionation. Periodical precipitation/dissolution of salt in topsoils of sand pans and from salt secreting halophytes may also be contributory causes of increasing salinity in the groundwater. The spatial distribution of the saline groundwater most likely depends on the microtopography of the slightly undulating clay platform. The dense, saline shallow groundwater, emerging from the vegetated fringe and sand pans and flowing toward the depressions in the clay platform, percolates downward displacing lower salinity seawater and groundwater. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Saline groundwater; Stable isotopes; Transpiration; Authigenic carbonates

1. Introduction

1.1. Shallow near-coastal saline groundwater and brines

Shallow saline groundwater and brines in the near-coastal environment are primarily described from marine sabkhas in the Arabian Gulf (Patterson and Kinsman, 1977). The occurrences of this saline

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groundwater are attributed to evaporation under arid climatic conditions of recharging continental groundwater and flooding seawater (see Robinson and Gunttilaka, 1991). However, examples of shallow saline groundwater have also been reported from the coastal plains and wetlands, La Plata, Argentina in a temperate climate with excess of precipitation over evaporation (Logan and Rudolph, 1997; Logan et al, 1999). A diversity of saline water types is attributed to seawater intrusion, evapotranspiration and complex geochemistry and hydrochemistry in the aquifers.

The current work presents a unique occurrence of shallow saline groundwater in the fresh water/seawater transition zone in a temperate climate regime on the south coast of the Island of Læsø, Denmark.

1.2. Historical background

Shallow saline groundwater has been known for several hundred years at the southern shores of the Island of Læsø (Vellev, 1991). The saline groundwater, with salinities up to 17‰, was suitable for large-scale

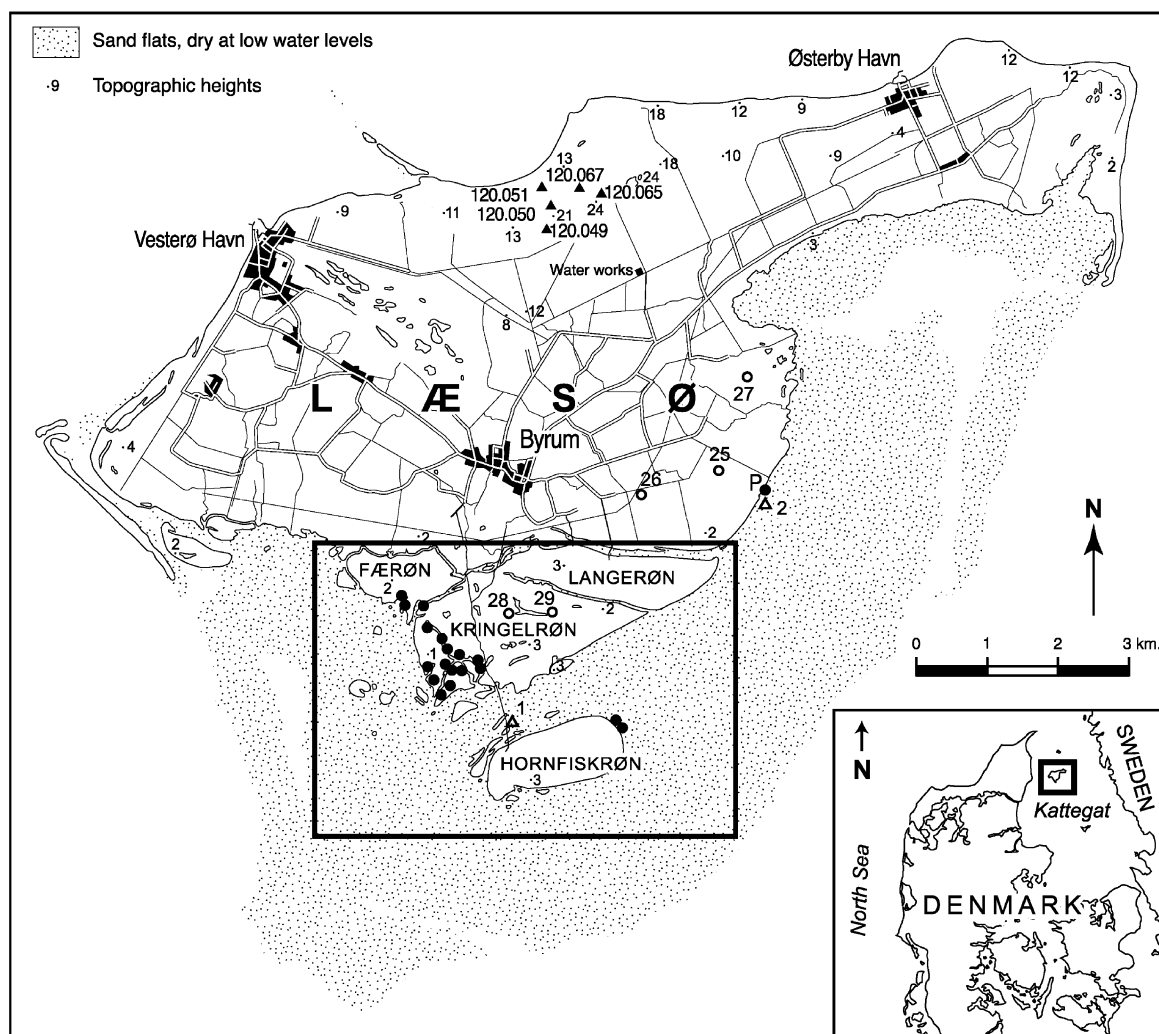


Fig. 1. Map of the Island of Læsø showing the locations of studied water wells (▲), dug wells (○), sample sites of saline groundwater (●) and normal seawater (△). P: location of pan experiment. The frame delineates the field area for the occurrences of saline groundwater. See Fig. 2 for details.

commercial salt production that was mentioned in the annals back to the Middle Ages. The days of glory for the salt production were the 12th–15th century when several hundreds of small salt works were established in the coastal meadows and salt marshes at the south coast of the Island of Læsø. Groundwater was extracted from dug wells and the salt was extracted from the brine by a process of fizzing. However, huge amounts of firewood were consumed in connection with the salt production, which led to increasing deforestation of the island and sand drift as a consequence. For that reason, the salt production was forbidden by law in the year 1652 (Vellev, 1991).

1.3. Natural history

The Island of Læsø is situated in the northern part of the normal marine to brackish, low-tide transition

region in Denmark including Kattegat, the Belt Sea and the Baltic Sea (Fig. 1). The water balance in the Kattegat depends on the exchange of highly saline marine water from the North Sea and brackish water from the Baltic Sea (Dietrich, 1950). The salinity in the northern part of the Kattegat at the Island of Læsø generally ranges from 2.2‰ to 2.8‰. The spring tide amplitude is insignificant, less than 30 cm, and high as well as low water levels are mainly governed by wind pressure, especially water pileup by strong northwesterly winds. This may also result in the observed variation in salinity (Stigbrandt, 1983).

The study area is the marine foreland at the south coast of the island (Fig. 2). The marine foreland is primarily composed of four minor low islands called *Rønnerne* (*Færø*, *Langerøn*, *Kringelrøn* and *Hornfiskerøn*), a belt of coastal meadows and salt marshes on the seaward side and large sand flats which stretch

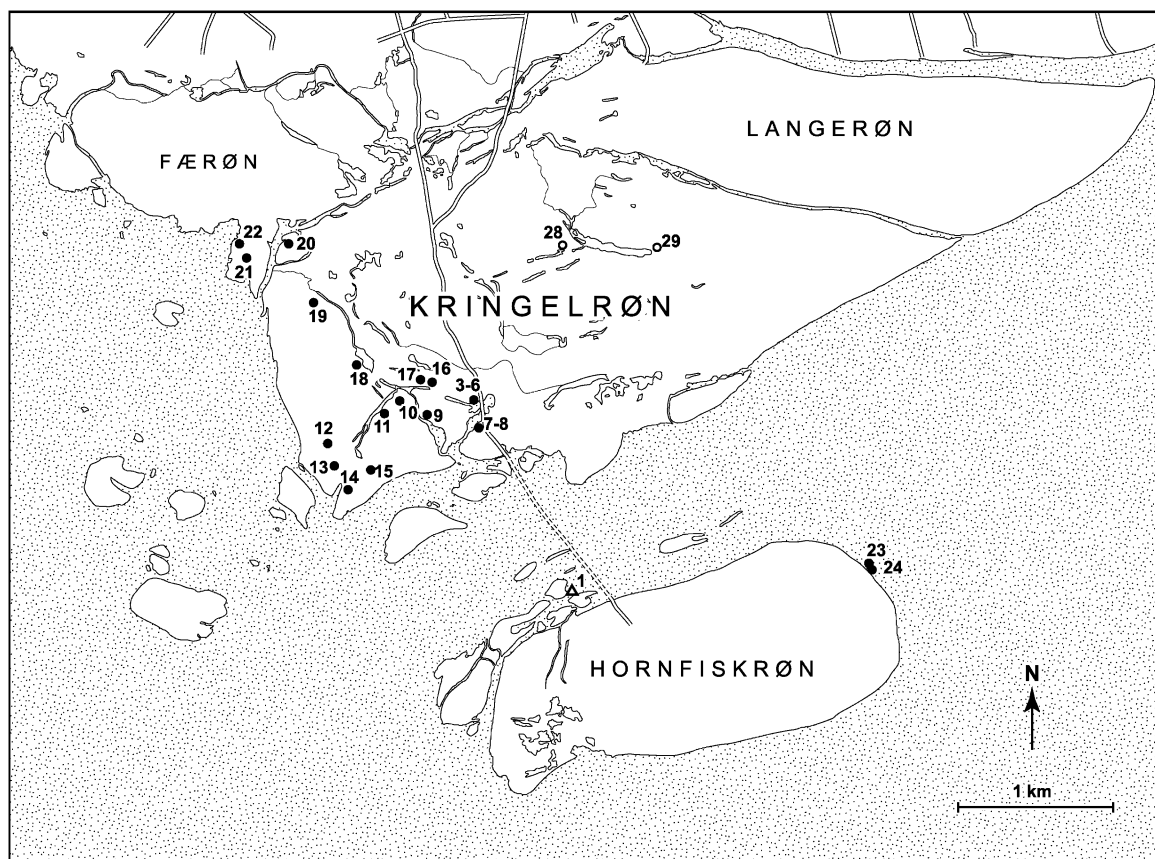


Fig. 2. Map of study area showing the locations of sample sites of saline groundwater. Legend as in Fig. 1.

almost 5 km south of Læsø on the which the water depth seldom exceeds 50 cm and may be dry at low water level (Figs. 1 and 2).

The four major islands are separated by natural channels (Danish: *floder*) that also cut the coastal meadows and the sand flats. The channels are not proper tidal channels since the tide is insignificant, but they do drain the marine foreland during sea-level fluctuations due to wind pressure.

The islands of the marine foreland are characterized by extremely low relief and only lie 3 m above sea level at the highest points. They are overgrown by a variety of grasses, *Calluna* sp. and scattered occurrences of *Juniperus* sp., *Betula* sp. and *Pinus* sp. The vegetation shows a typical zonation depending on elevation above mean seawater level and degree of seawater inundation (Vestergaard, 1998). The inner part, the coastal meadows, which are seldom inundated by the sea, is dominated by plant communities of a variety of grasses and a microtopography characterized by the presence of hillocks and anthills. The coastal meadow gradually transitions into salt marshes dominated by *Limonium* sp., *Armeria* sp., *Salicornia* sp. and *Suaeda* sp. (Hansen, 1995).

2. Geology and hydrogeologic setting

The geology of the study area consists of a thin cover of postglacial marine sediments with a thickness of 1–3 m resting on a slightly undulating platform of interglacial marine clays (Hansen, 1977). The postglacial marine sequence consists primarily of well-sorted sands and silts intercalated by thin storm layers of very coarse-grained sands and gravels. The base of the sequence consists of a 10- to 20-cm-thick residual layer of gravel or pebbles. The underlying interglacial marine clay is a grey-to-light blue stiff clay. The thickness of the interglacial marine clay sequence is not known but exceeds 30 m (Bahnsen et al., 1986).

Recharge by infiltrating rainfall takes place at the low islands of the marine foreland forming thin unconfined freshwater lenses that to some extent may displace the more dense brackish water in the postglacial marine sediments. The subjacent clay platform makes up a confining layer or aquiclude. The potentiometric surface is generally 20–40 cm below

the ground surface and coincides with the topography of the islands (Hansen, 1995). Shallow dug wells and ponds have been established to water livestock.

Shallow saline groundwater with salinities up to 17‰ have a patchy occurrence in the lowermost part of the aquifer of postglacial marine sediments close to the vegetated fringe of the salt marshes and beneath unvegetated sand pans (locs. 3–22, Fig. 2). The unvegetated sand pans are irregular in outline, generally 20–50 m in diameter and fringed by *Limonium* sp., *Armeria* sp. and *Salicornia* sp. Salt marsh communities may periodically be exposed to and able to tolerate high salinities in excess of those in seawater (Adam, 1990). Generally, the salinity in the topsoil and the uppermost part of the aquifer is close to or only slightly above that of local seawater (Hansen, 1995). However, salinity increases with depth and the vegetation apparently avoids the sand pans most likely as a result of the extraordinary high salinity in the interstitial soil water. The pans are periodically flooded by seawater in wintertime but are generally dry during summertime (Hansen, 1995). A very thin salt crust or powder-like salt precipitate may be observed during periods of prolonged dryness (Hansen, 1995). Saline groundwater is also found in the transition zone between salt marshes and sand flat (locs. 23–24, Fig. 2).

It is the objective of this study to identify the sources and processes involved in the formation of the saline groundwater and in the groundwater–seawater interactions.

3. Methodology

Stable isotope (^2H and ^{18}O) and major ion analyses were carried out on interstitial water samples, which were collected in the lower part of the aquifer from a number of vegetated and unvegetated locations (Fig. 1). Additionally, depth-determined samples were collected at two sites (locs. 23 and 24, Fig. 2, Table 1) characterized by extraordinarily high salinities of the pore water. Local groundwater samples were collected from dug wells on the islands of the marine foreland and regional groundwater samples were obtained from dug wells and boreholes on the mainland. Rainwater samples were collected at the local water works in the period July–September 1999. A pan experiment was

Table 1

Hydrochemistry and isotopic compositions of seawater, saline groundwater and water samples from pan experiment, the Island of Læsø

Locality/type	Salinity (%)	pH	Ca (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	HCO ₃ (ppm)	SO ₄ (ppm)	Cl (ppm)	Log SI(arag)	Log SI(cal)	Log SI(gyp)	δ ¹⁸ O (‰)	δ ² H (‰)
<i>Seawater</i>														
loc. 1	2.1	7.9	260	775	6500	265	157	1610	11900	0.21	0.41	−0.86	−1.44	−19.6
loc. 2	2.7	8.0	300	1040	8200	310	175	2000	14900	0.19	0.38	−0.79	−1.81	−20.5
<i>Brine</i>														
loc. 3	10.2	8.1	990	3610	30500	1070	228	8300	51000	0.80	0.99	−0.12	−2.27	−27.7
loc. 4	8.2	8.0	920	2880	23600	840	290	5660	41700	0.82	1.01	−0.23	−2.33	−21.3
loc. 5	11.6	8.1	1090	3740	32700	1200	253	7650	57500	0.94	1.13	−0.09	−2.12	−26.4
loc. 6	4.4	7.9	510	1640	12400	450	364	3660	23000	0.59	0.79	−0.47	−1.91	−22.8
loc. 7	15.7	7.9	1450	4980	37600	1540	283	12400	75300	0.86	1.05	0.21	−1.93	−25.0
loc. 8	13.7	7.9	1300	4740	39200	1390	295	8680	66800	0.96	1.15	0.00	−1.86	−25.7
loc. 9	4.7	8.0	470	1690	14700	520	282	3020	31200	0.58	0.77	−0.61	−3.38	−27.1
loc. 10	8.3	7.9	845	3120	25400	860	233	6300	48600	0.64	0.83	−0.22	−2.02	−23.6
loc. 11	3.3	7.8	370	1160	9700	360	350	2480	17400	0.38	0.57	−0.67	−3.97	−31.9
loc. 12	5.6	8.0	630	2050	15300	590	400	4620	29100	0.81	1.00	−0.35	−2.14	−22.5
loc. 13	4.3	7.9	500	1590	11900	480	256	3210	22500	0.44	0.64	−0.52	−1.49	−15.7
loc. 14	3.3	8.0	390	1240	9500	340	295	2190	17400	0.52	0.71	−0.70	−4.28	−33.6
loc. 15	8.7	7.9	920	2950	26800	930	325	7470	44000	0.77	0.96	−0.15	−3.59	−33.9
loc. 16	17.7	8.0	1540	6200	40000	1670	262	11070	76000	1.04	1.23	0.15	−2.08	−28.8
loc. 17	15.3	7.8	1370	5170	41500	1500	374	10000	73800	1.02	1.21	0.07	−1.22	−28.7
loc. 18	2.8	7.9	330	1060	8200	310	352	2220	14900	0.45	0.64	−0.71	−4.29	−31.8
loc. 19	4.2	7.8	480	1570	11800	460	275	3130	22000	0.36	0.55	−0.54	−1.86	−26.3
loc. 20	2.4	7.9	280	910	7100	250	375	1820	12800	0.41	0.61	−0.82	−2.27	−22.9
loc. 21	6.7	8.0	720	2350	19900	720	220	5570	34500	0.58	0.77	−0.29	−1.52	−19.9
loc. 22	3.4	8.0	390	1280	10200	380	360	2560	18000	0.59	0.78	−0.65	−1.86	−23.7
<i>loc. 23, profile</i>														
5 cm bs	3.9	7.9	400	1370	11600	360	271	3560	21300	0.37	0.56	−0.55	−2.96	−26.5
10 cm bs	6.0	7.9	680	2320	16200	620	253	5850	36400	0.59	0.78	−0.24	−2.87	−27.6
15 cm bs	10.5	8.0	1210	4340	33200	1060	212	13100	62800	0.88	1.07	0.20	−2.65	−26.8
40 cm bs	14.5	7.9	1390	4990	31000	1440	320	10100	60600	0.99	1.19	0.11	−2.36	−27.6
50 cm bs	15.0	7.9	1480	5590	36500	1450	247	11760	70300	0.94	1.13	0.19	−2.66	−26.5
<i>loc. 24, profile</i>														
15 cm bs	9.7	7.9	1170	3790	30800	910	350	10820	64500	1.02	1.21	0.12	−1.52	−20.9
20 cm bs	12.8	8.0	1250	4780	31600	1280	278	12140	58000	0.93	1.13	0.13	−1.93	−23.8
50 cm bs	15.0	7.9	1510	5360	37900	1470	340	13890	70800	1.12	1.31	0.29	−3.24	−25.7
<i>Pan experiment</i>														
	2.7												−1.52	−19.9
	7.6												6.8	4.1
	10.5												10.25	14.4
	14.7												17.53	37.3

carried out in July–August 1999 to study the effect of evaporation upon the isotope compositions of local seawater.

Electric conductivity and salinity of groundwater, seawater and saline groundwater were measured in the

field with a WTW conductivity meter LF 197 and salinity refractometer. Water samples were collected in prerinsed polyethylene bottles. Water samples for major and minor ion analyses were filtered through 0.45-μm-pore diameter filters.

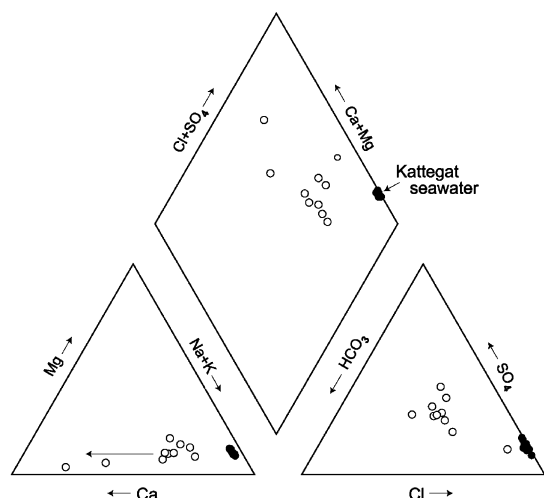


Fig. 3. Piper (1944) diagram showing the hydrochemical compositions of studied water types. Regional groundwater (○); saline groundwater (●). Note that the hydrochemical compositions of saline groundwater are similar to that of Kattegat seawater.

Major cations were determined by ICP-MS and conventional atomic absorption spectrophotometry (AAS). Alkalinity was measured using a Hach titration unit and is reported as milligrams per liter HCO_3^- . Chloride was measured by titration using the mercury nitrate method. Sulphate was determined by precipitation with barium chloride. The results are listed in Tables 1 and 2. Saturation indices were calculated using PHRQPITZ (Plummer et al., 1988).

Oxygen isotope ratios were determined by acidification with 100% phosphoric acid and equilibration

of 5 ml of sample with CO_2 gas as described by Epstein and Mayeda (1953), followed by analysis on a VG Sira 10 mass spectrometer with automatic inlet. The water samples for hydrogen isotope analyses were reduced to H_2 by use of zinc in quartz ampoules at 700 °C (Colemann et al., 1982). The analyses were carried out on a Finnigan MAT 250 triple collector mass spectrometer. The results for both isotopes are expressed in per mil (‰) deviation from the VSMOW standard using the δ -scale (Gonfiantini, 1978). Reproducibility is better than 0.1‰ for $\delta^{18}\text{O}$ and about 1‰ for $\delta^2\text{H}$.

Authigenic mineral precipitates from the lower part of the aquifer were studied by use of the scanning electron microscopy (SEM). Sediment samples were flushed with distilled water to prevent further precipitation during the process of drying. The dry samples were sieved through 63 μm and the residue was studied in the scanning electron microscope. Mineral identification was carried out by X-ray diffraction (XRD).

4. Results

4.1. Hydrochemistry

Regional groundwater is characterized by relatively low conductivity and low alkalinity and major ion trends $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ and $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ (Fig. 3, Table 2).

The saline groundwater shows salinities in the range from 2‰ to 17‰ (Table 1). The lower end of

Table 2
Hydrochemistry of fresh groundwater, the Island of Læsø

Wells GEUS file no.	EC ($\mu\text{S}/\text{cm}$)	pH	Ca (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	HCO_3^- (ppm)	SO_4 (ppm)	Cl (ppm)
120.046	176	6.2	9	3	16	1.5	22	19	28
120.049	243	6.3	9	4	30	2.0	25	18	47
120.050	183	5.8	9	3	15	1.5	15	28	25
120.051	174	6.2	8	3	16	1.6	15	24	28
120.067	215	6.2	9	6	18	1.4	24	22	33
<i>Dug wells</i>									
loc. 25	429	6.3	66	3	16	1.9	21	22	26
loc. 26	820	6.6	83	18	140	2.5	29	38	257
loc. 27	210	6.3	21	2	11	1.9	26	18	20
loc. 28	256	6.2	9	6	29	1.4	28	25	46
loc. 29	278	6.2	8	5	20	1.4	25	26	39

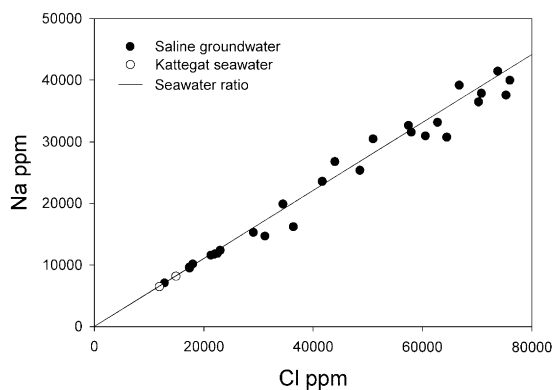


Fig. 4. Diagram showing the Cl and Na concentrations in saline groundwater from the Island of Læsø, Denmark. The seawater composition line is shown for reference.

this range is equal to the salinity of seawater from the surrounding Kattegat. The water body in the aquifer is significantly stratified and the more saline waters are found in the lower part of the aquifer (locs. 23 and 24, Table 1). The hydrochemical composition is similar to that of seawater (Figs. 3 and 4, Table 1). The alkalinity is relatively high compared to normal marine environments. Significantly, the most highly saline water samples appear to be slightly modified by showing a tendency of lower Ca/salinity ratio than the ratio for normal seawater as salinity increases (Fig. 5) Furthermore, the rise in salinity is accompanied by

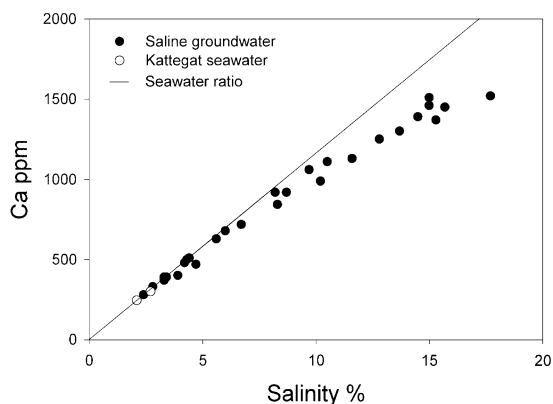


Fig. 5. Diagram showing the relationship between Ca and salinity in the saline groundwater from the Island of Læsø, Denmark. The seawater composition line is shown for reference.

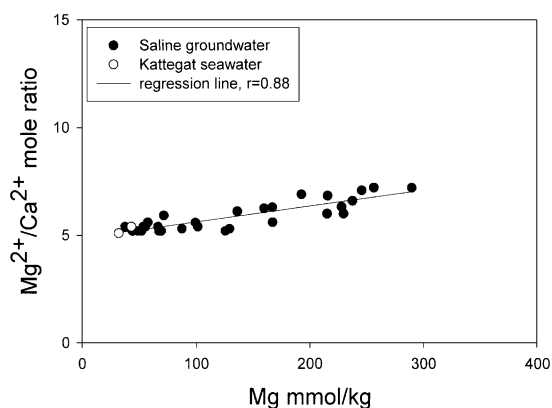


Fig. 6. Diagram showing $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratios as a function of Mg concentrations for saline groundwater from the Island of Læsø, Denmark.

an increase in $\text{Mg}^{2+}/\text{Ca}^{2+}$ mole ratios from 5 to approximately 7 (Fig. 6).

4.2. Hydrogen and oxygen isotopes

The stable isotopic compositions of precipitation are in the range from -5.6‰ to -10.7‰ $\delta^{18}\text{O}$ and from -34‰ to -84‰ $\delta^2\text{H}$. The isotopic compositions of groundwater obtained from water wells and dug wells are in the range from -7.5‰ to -9.6‰ and from -54‰ to -66‰ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively (Fig. 7, Table 3). The values are repre-

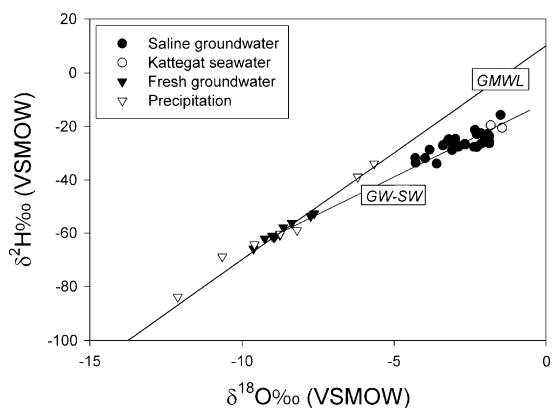


Fig. 7. Diagram showing the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ distributions in natural water from the Island of Læsø, Denmark. The global meteoric water line (GMWL) and the local seawater-groundwater line (GW-SW) are shown for reference.

Table 3
Isotopic compositions of fresh groundwater and precipitation, the Island of Læsø

Locality/type	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)
<i>Well, GEUS file no.</i>		
120.046	−9.01	−61.3
120.049	−9.01	−62.1
120.050	−8.95	−61.8
120.051	−9.05	−61.1
120.067	−8.75	−60.9
<i>Dug wells</i>		
loc. 25	−8.64	−57.9
loc. 26	−8.36	−56.3
loc. 27	−9.62	−66.0
loc. 28	−7.62	−52.7
loc. 29	−7.74	−53.8
<i>Precipitation/date</i>		
20.7.1999	−5.65	−34.0
11.8.1999	−9.59	−64.4
16.8.1999	−12.12	−83.9
19.8.1999	−10.65	−68.9
30.8.1999	−8.19	−59.0
20.9.1999	−6.19	−38.9
28.9.1999	−8.74	−60.4

sentative for the isotopic compositions of precipitation in Denmark and normal Danish groundwater (Dansgaard, 1964; Jørgensen and Holm, 1994) and are close to the global meteoric water line described by the equation (Craig, 1961):

$$\delta^2\text{H} = 8\delta^{18}\text{O} + 10 \quad (1)$$

The isotopic composition of local seawater from Kattegat is approximately -1.5‰ $\delta^{18}\text{O}$ and -20‰ $\delta^2\text{H}$ (Fig. 7, Table 1). The isotope composition is in agreement with the deuterium–salinity relationship reported by Ehhalt (1969) and Friedman et al. (1964) in their studies of the isotope compositions of Baltic seawater.

The isotope distributions in the saline groundwater samples range from -4.3‰ to -1.2‰ $\delta^{18}\text{O}$ and from -34‰ to -16‰ $\delta^2\text{H}$ (Fig. 7, Table 1). The values fit to the local groundwater–seawater mixing line described by the equation:

$$\delta^2\text{H} = 3\delta^{18}\text{O} - 55 \quad (r^2 = 0.82) \quad (2)$$

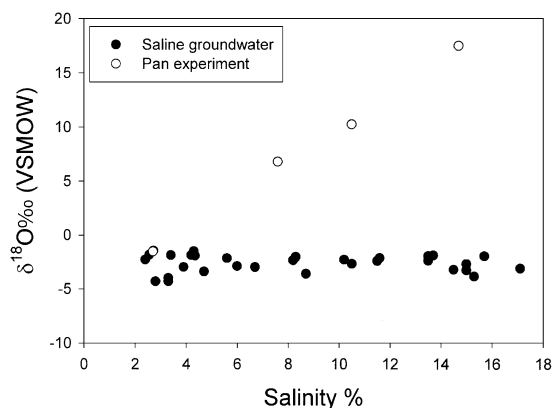


Fig. 8. Diagram showing the relationship between salinity and $\delta^{18}\text{O}$ in saline groundwater and samples obtained from pan experiment.

However, the isotope distributions show no coherence with the salinity variations observed and, therefore, rule out evaporation of seawater as a leading process in the formation of the saline groundwater (Fig. 8).

4.3. Pan experiment

To study the effect of evaporation on seawater, a pan experiment was carried out by leaving natural local seawater at a salinity of 2.1‰ in a pan to evaporate in the salt marshes close to field station Lyngholt in the period July–August 1999, the driest period of the year (Fig. 1). The local humidity, temperature and wind shear are considered to be

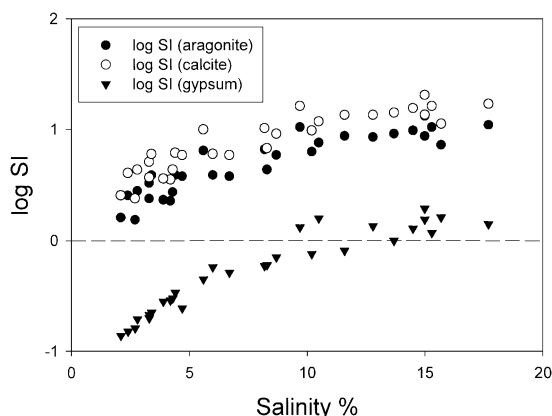


Fig. 9. Graph of log SI vs. salinity showing calculated saturation indices (Plummer et al., 1988) for aragonite, calcite and gypsum in saline groundwater.

comparable to the climatic conditions at the salt marsh. Samples for isotope analyses were collected at salinities of 5.6%, 11.5% and 14.0%, respectively, and the results are shown in Table 1 and Fig. 8. The isotopic relationship is described by the equation:

$$\delta^2\text{H} = 3.2\delta^{18}\text{O} - 33 \quad (r^2 = 0.99) \quad (3)$$

4.4. Authigenic mineral precipitation

Precipitation of authigenic carbonates and sulphates are to be expected within the wide range of salinities recorded in the saline groundwater. The calculated saturation indices (Plummer et al., 1988) show increasing supersaturation with respect to both calcite and aragonite with increasing salinities (Table 1 and Fig. 9). Therefore, calcium carbonate is expected to start precipitation soon after concentration of seawater commences. Gypsum may start to precipitate after a concentration of normal seawater by a factor 3.5–5 (Drever, 1997). The calculated saturation indices indicate that the saline groundwater reaches saturation with respect to gypsum approximately at salinity of 10%, but the brine is only slightly supersaturated in the range of 10–17% salinity (Fig. 9).

Mineral precipitates were studied by means of SEM in sediment samples collected from the lower part of the aquifer of postglacial marine sediments yielding highly saline pore water up to 17%. The electron micrographs reveal patchy occurrences on the surfaces of the quartz grains of needle-like crystals identified to be aragonite by use of X-ray diffractom-

etry (Fig. 10). It was not possible to identify the presence of any other precipitates, carbonates or sulphates, in the sediment samples studied.

5. Discussion

The saline groundwater found on the Island of Læsø has only received minor attention since salt production collapsed at the beginning of the 17th century. The salt production is mentioned in a few local historical descriptions (see Vellev, 1991) and for a long time, the occurrences of saline groundwater were primarily considered to be the result of seawater evaporation.

However, Hansen (1995) discussed thoroughly the occurrences and possible origin of the saline groundwater in his natural history of the Island of Læsø. Hansen (1995) found a significant correlation between major ions and salinity which was interpreted as the result of physical concentration, that is, evaporation of seawater. The distribution of the brine was related to vegetation zones and to different plant communities; the highest salinities apparently occur beneath *Limonium* sp. communities and minor unvegetated sand pans. Hansen (1995) suggested a number of mechanisms to be involved in the brine formation, for example, seawater evaporation, “freshwater pumping”, osmosis and physiological effects.

The hydrochemical data from the present study also indicate that the saline water and brines have a marine origin. However, the hydrogen and oxygen isotope signatures reveal a significant correlation to the local groundwater–seawater mixing line demonstrating influence of meteoric groundwater. The end members of the mixing line are the arithmetic means of the isotopic compositions for seawater and the local shallow groundwater. The proportion f of mixing for a given sample can be calculated according to the equation:

$$f = ((\delta_{\text{sample}} - \delta_{\text{groundwater}}) / (\delta_{\text{seawater}} - \delta_{\text{groundwater}})) \times 100\% \quad (4)$$

which yields a proportion factor f in the range of 0–50%. Although some mixing has taken place with meteoric groundwater, the ion strength of the saline water is considerable larger than in the fresh groundwater so that the overall marine signature remains unaffected.

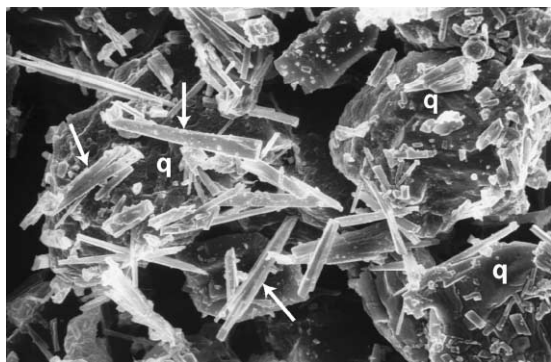


Fig. 10. Scanning electron micrograph (SEM) of quartz sand showing quartz grains (q) and intergranular authigenic aragonite needles (arrows). $\times 800$.

The relatively large ranges in salinity, that is, 2–17‰, do not show corresponding enrichments in hydrogen and oxygen isotopes (Fig. 8). Transpiration from vegetation is known to abstract water without causing isotopic fractionation (Dincer et al., 1981; Gat, 1981; McCarthy et al., 1991; Logan and Rudolph, 1997), which suggests that transpiration predominates over evaporation in the study area. It is believed that the dense plant communities of the salt marshes selectively remove water by transpiration causing a progressive enrichment in total dissolved solids. Furthermore, the dominant species in the salt marsh, that is, *Limonium* sp. and *Armeria* sp., are typical salt-secreting halophytes (Batanouny et al., 1992; Salisbury and Ross, 1992), which may lead to the enrichment of the salinity in the interstitial water by leaching during rainfall and/or flooding. Likewise, it is noteworthy that the desiccation of the sand pans that particularly takes place in the summertime periodically leads to the observed salt accumulation caused by capillary-driven evaporation in the topsoil. The consequence of subsequent dissolutions by flooding seawater (or meteoric water) would lead to enhanced salinity in the pore water without isotopic fractionation. However, repeated precipitation and dissolution of salt minerals (from topsoil as well as from vegetation) may also lead to changing hydrochemistry of the resulting brine in comparison to normal marine composition, and such trends have not been observed in the present study. Other but a minor contributor to the enrichment of total dissolved solids in the interstitial water is dry deposition of aerosols.

The isotopic compositions show that the saline groundwater has a prevailing marine signature indicating that the formation of saline water primarily takes place during flooding of the marginal parts of the salt marshes by seawater. The interstitial water gains an increasing salinity during flood events and emerges from the vegetated fringe, slowly flowing toward the depressions in the clay platform and percolates downward, displacing a lower salinity seawater–groundwater mixture (Fig. 11). The thin cover of superficial marine deposits resting on a clay platform and the extremely low relief and low flow regime result in a relatively closed hydrochemical system with a density-stratified water body and stagnant conditions in the depressions in the clay platform, which most likely prevent subsequent flushing and dilution by meteoric water and/or seawater (Fig. 11).

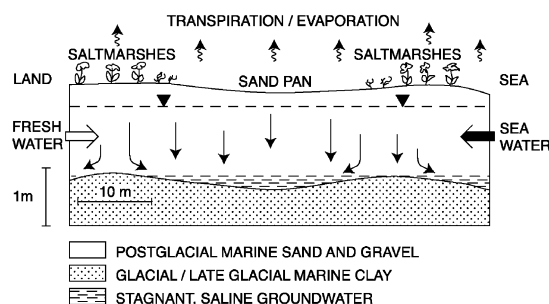


Fig. 11. Schematic cross section showing the formation and preservation of saline groundwater in the vicinity of salt marshes at the south coast of the Island of Læsø. The formation of saline interstitial water takes place in the upper part of the sequence, percolating downward and displaces lower salinity seawater/freshwater mixture. See text for further explanation.

The spatial distribution of the saline groundwater most likely depends on the sites of formation in the marginal rim of the salt marshes and on the micro-topography of the slightly undulating clay platform. The process most likely also led to patchy and local destruction of vegetation is the reason for the formation of the irregular sand pans (Fig. 11).

The saline groundwater and the normal seawater are supersaturated with respect to calcite and aragonite. However, the only carbonate phase identified in this study is the observed patchy occurrences of authigenic aragonite cement in the most saline lower part of the aquifer. The absence of calcite is most likely the result of the inhibiting effect of Mg^{2+} on crystal growth of calcite (Berner, 1975). The aragonite precipitation apparently affects the overall marine composition of the brine leading to a slight decrease in the Ca concentration with increasing salinity and, additionally, an increase in Mg^{2+}/Ca^{2+} mole ratios from 5 to approximately 7 (Fig. 6). The saline groundwater reaches saturation with respect to gypsum at approximately 10‰ salinity and is slightly supersaturated in the salinity range of 10–17‰. However, neither gypsum nor other sulphate solid species have been recorded so far.

6. Conclusions

The hydrochemistry of shallow saline groundwater in the superficial postglacial marine deposits at Røn-

nerne on the Island of Læsø indicates that the saline groundwater and brine predominantly have a marine origin. However, oxygen and hydrogen isotope signatures reveal a significant correlation to the local groundwater–seawater mixing line indicating a contribution of fresh groundwater in the range from 0% to 50%. The salinity of the saline groundwater is in the range from 2% to 17%. Calculated saturation indices indicate significant supersaturation with respect to calcite and aragonite in the entire salinity range and slight supersaturation with respect to gypsum with salinities above 10%. However, authigenic aragonite cement that occurs in the most saline lower part of the aquifer is the only precipitate recorded so far.

The high salinities of up to 17% do not show corresponding enrichments in the isotopic compositions of the saline groundwater and this rules out any kinetic evaporative effect on the formation of the saline water. The isotope distributions suggest that the transpiration that takes place in the dense vegetation on coastal meadows and salt marshes results in increasing concentration of dissolved solids in the shallow groundwater–seawater mixture. Additionally, precipitation/dissolution of salt from salt-secreting halophytes and from the surface of the sand pans may be a contributory cause for salinity enrichment of the groundwater in the shallow stratified aquifer. The dense saline water emerging from the vegetated fringe and flowing toward the depressions in the clay platform, percolates downward displacing lower salinity seawater–groundwater mixtures. The stratified water body, low flow regime and stagnant conditions in the depressions in the clay platform most likely prevent subsequent flushing and dilution of the saline waters by meteoric water and/or seawater (Fig. 11).

The results of this study demonstrate an important biological/physiological interaction between the vegetation of the coastal meadows and salt marshes and the shallow groundwater–seawater system.

Acknowledgements

The author is indebted to Jens Morten Hansen for fruitful discussions and for his inspiring work on the natural history of the Island of Læsø and to Poul Christensen and his colleagues at the Læsø Salt Museum for valuable help and information. Manager

Ivan Petersen and staff members at Læsø Waterworks collected the rainwater samples. ICP-MS analyses were carried out at the Risø National Laboratory, Environmental Science and Technology Department. Oxygen isotope analyses were determined at the Geophysical Institute, University of Copenhagen, whereas the hydrogen isotopes were analysed at the Danish Centre of Isotope Geology, University of Copenhagen. Atomic absorption spectrophotometry analyses and determination of chloride and sulphate took place at the Geochemical Laboratory, Geological Institute, University of Copenhagen. **JD**

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