Saline groundwater extraction from the fjord delta aquifer, Sunndalsøra, Møre og Romsdal, Norway

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The fjord delta at Sunndalsøra has been investigated by geophysical measurements, drilling and pumping in order to examine the possibilities for abstraction of saline groundwater for use in fish farming. A geological model of the delta's lithostratigraphy is presented. The hydraulic conductivity shows a cyclicity with the highest values on the landward side in each cycle. In the outer part of the delta the saline groundwater is located at shallower depths than along the river and on the landward side. The freshwater layer in the fjord and in the aquifer, the hydraulic gradient and the distribution of hydraulic conductivity in the delta all contribute to a reduction in salinity during pumping of the groundwater. It is estimated that lateral, freshwater-induced recharge from the river to the wells along coarse-grained layers contributes about 18% of the total yield. By means of two-level pumping in the outer area of the aquifer, the salinity of the abstracted water may be increased to at least 20 per mille.

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Introduction

In many fish farms infectious diseases have caused great problems. These are transmitted through the sale of infected fry or by the escape of infected fish from other farms. Such escapees may also infect natural fish stocks. In order to reduce these problems, sterile, saline groundwater may be an important resource for on-shore fish farms.

Fjord deltas can be important aquifers for both saline and fresh groundwater. Lowering of piezometric heads in coastal areas due to pumping has lead to salinization of many aquifers throughout the world (e.g. Inouchi et al. 1990). It is not known to what extent this effect operates in a fjord delta, mainly because the variation in hydraulic conductivity and the groundwater flow regime is poorly understood. Fjord deltas are usually of Gilbert type (Gilbert 1885), characterized by coarse top-sets, steep sandy fore-sets and fine grained bottom-set layers (e.g. Corner et al. 1990). Fjord deltas have previously been investigated by Prior et al. (1981), Bogen (1983), Syvitski and Farrow (1983), Kostaschuk and McCann (1987), Prior and Bornhold (1986,1988) and Corner et al. (1990).

It is to be expected that deltas located in sheltered areas with high relief will have a large supply of sediments and that the wave-energy will be relatively low (e.g. Colella et al. 1987). A progressive lowering of sea-level in postglacial times in Norway has typically led to erosion of older delta deposits and redeposition of coarser material on the delta front. Such erosion and redeposition leads to an unconformity between the top-sets and fore-sets, and to the coarsest sediments usually being found on the part of the delta closest to the fjord (Corner et al. 1990). Alluvial fans which are constricted laterally have a large potential for build-out. They have a relatively small facies gradient downwards along the deposit (Nemec and Steel 1988, Rachocki 1981). It is likely that the same is true for a fjord delta. These sedimentological factors govern the grain-size distribution and hydraulic conductivity and are probably important for the hydrogeology of the delta.

Fjord deltas constitute a special type of coastal aquifer because of the stratification of the fjord water. For example, at the delta front at Sunndalsøra, Møre og Romsdal county, the upper brackish layer of the fjord water

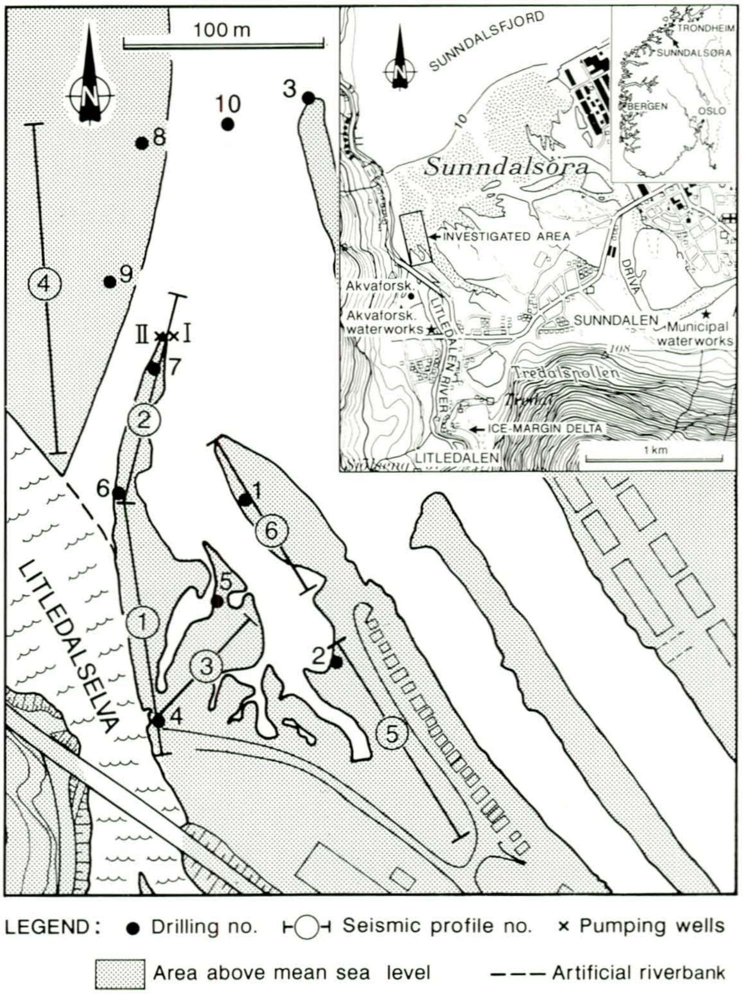

Fig.1. Location of the investigated area (inset). Location sites of boreholes, seismic profiles and pumping wells.

is up to 2-4 m in thickness, while at 40 m depth the salinity is 31-32 per mille (A.Kittelsen, pers. comm.). The thickness of the brackish layer varies with the freshwater discharge from incoming rivers. The salinity of bottom water in Norwegian fjords is close to 35 per mille (Sælen 1976).

The investigated area

The delta at Sunndalsøra is situated between the mouths of two rivers, the Driva and the Litledalen rivers, and is built out into the Sunndalsfjord which is up to 200 m deep in its inner basin (Fig.1). Geological investigations on the delta have been carried out by Andersen (1984), Follestad (1984, 1987), Hillestad (1984), Kummeneje (1985, 1989), Rønning (1985), Storrø (1986), Nielsen (1988) and Soldal et al. (1990).

Both in the Sunndalen valley (containing the river Driva) and in the Litledalen valley there exist ice-margin deltas of Younger Dryas age (10,000-11,000 yrs BP). These sand and gravel deposits were built up to c.140 m above present sea-level and indicate the upper marine limit in the area (Follestad 1987).

The surface sediments in the valley floor consist of coarse, fluvial deposits. Centrally in the delta there is at least 500 m of Quaternary deposits (Hillestad 1984), probably dominantly fine-grained marine sediments (Follestad 1987).

The western portion of the fjord delta, which is located at the mouth of Litledalen (Fig.1), has been investigated. The investigated area lies within the tidal zone. The investigation is part of a project to evaluate the possibilities for abstraction of saline groundwater for use at Akvaforsk fish farm.

Two water-works supplying fresh groundwater are situated at Sunndalsøra (Fig.1). One is for municipal supply and one supplies Akvaforsk, a research station for aquaculture, where salmon fry and halibut are reared. The nearest water-works is located 400 m to the south of the investigated area.

Methods

Ten boreholes were drilled and sampled. Test-pumping was carried out in two pumping wells over a three months period. 600 m of seismic reflection profiles were measured (Fig.1).

The wells were drilled using a Borros hammer-rotation mobile rig employing water as the drilling fluid. Penetration rates, water pressures and sound-response were recorded during boring. These data were used to interpret sediment type. After boring, 5/4" diameter cast-iron well-points, with elongated slots at the tip, were temporarily installed to the desired depth. Samples of sediment and water were collected and the water temperature was measured. The borehole logs are shown in Fig.2. The water samples were analyzed for cations by atomic emission spectroscopy and anions by ion-chromatography. Alkalinity was measured by Gran titration, pH with a glass-electrode, and electrical conductivity (E.C.) by conductivimeter. A field refractometer was used for the majority of the measurements of salinity, a subset of which were controlled by measuring osmotic pressure with a 'Semimikro osmometer, type M'. Salinity is directly related to dissolved solids (1 per mille = 1000 ppm) and electrical conductivity (salinity = 0.68 x E.C. (in mS/cm)). The results of these analyses are presented in Soldal et al. (1990).

The seismic reflection profiling was carried out using the «optimum offset» method (Hunter et al. 1988, Hunter and Pullan 1989) and recorded with a digital seismograph (Scintrex S-2 'Echo' with 24 channels). Six profiles were measured. The distance between the energy source (in-hole shotgun with 12 gauge shells) and the first geophone was 18 m. The geophones were placed with three metre intervals for profiles number 1 and 2, and two-metre intervals for profiles 3 to 6. Seismic processing included static corrections and bandpass filtering. Velocity analysis of multichannel records was used to convert two-way travel time. Processed records are shown in Fig.3.

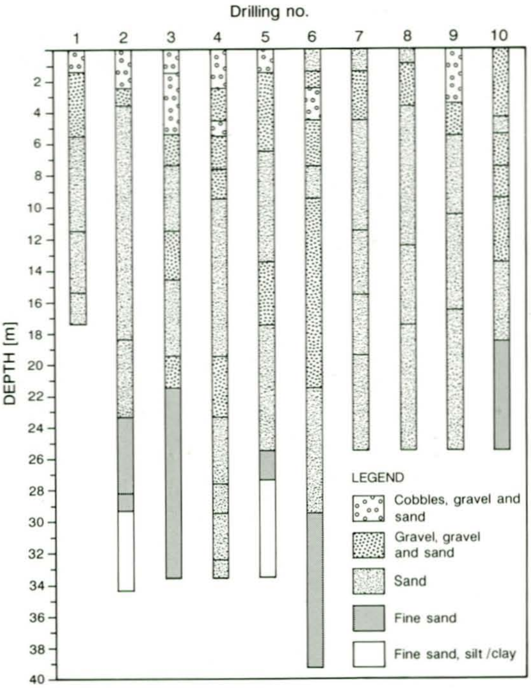

Fig.2. Simplified drilling logs (see Fig. 1 for location). The marked boundaries indicate differences in sediment type, although not necessarily in observed grain-size.

Results

Sedimentology

Inspection of aerial photographs taken in different years reveals rapid changes in the river outlet at the delta front. This is in agreement with Follestad (1987), who states that the delta is river dominated. The Litledal River has probably only contributed to the construction of the western part of the delta. The delta associated with the Litledal River is constricted by the mountain cliffs on the west and the delta of the River Driva to the east (Fig.1).

The postglacial uplift of this area was most rapid between 10,000 and 9,000 years BP, with an estimated rate of 50 mm per year. Between 9,000 yrs and the present, the avera-

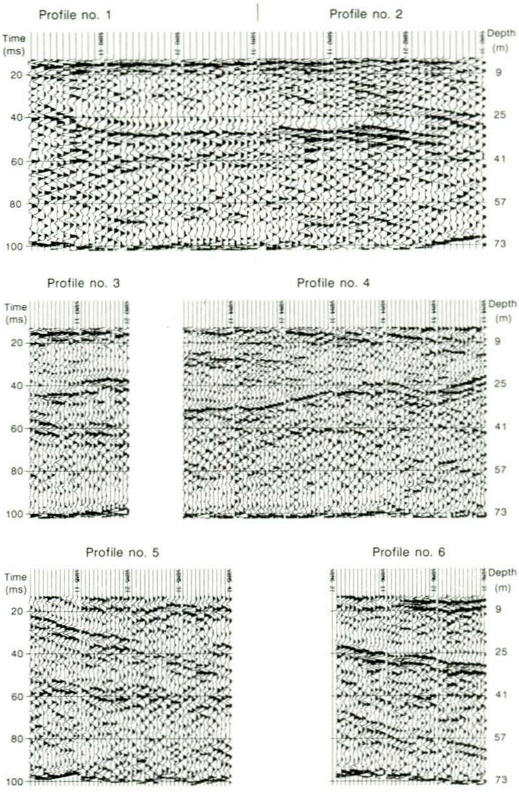

Fig.3. Processed seismic reflection profiles, see Fig. 1 for locations.

ge emergence rate was about 4 mm per yr (Svendsen & Mangerud 1987). The current rate of uplift is 3-4 mm per yr (Sørensen et al. 1987). The emergence, erosion and subsequent sediment supply from the ice-margin delta has been of great importance in governing the postglacial construction of the fjord delta.

The seismic profiles (Fig.3) reveal several reflectors beneath the fine-grained sediments. These are, however, of little relevance to this investigation. Interpretation of shallower structures (0-15 m) from the profiles alone is difficult, but in combination with observations from the boreholes, a model can be deduced (Fig.4). In the investigated portion of the delta the coarse topset (cobbles, gravel and sand) is underlain by a c. 20 m thick sequence of sand which wedges out towards the ice-margin delta (E. Danielsen, pers. comm.). Under these layers there is a sequence of fine sand and silt/clay with a low hydraulic conductivity. The upper boundary of these sediments is a strong reflector which can be recognized in most of the seismic profiles. The fine-grained deposits are near horizontal and can be interpreted as distal bottom sediments.

Seismic profiles 1 and 2 (Fig.4) show inclined reflectors which flatten out to the north. In the area with more steeply-dipping layers, the sediments encountered in the boreholes are at their coarsest (Fig.2). The preferred interpretation is, therefore, that the coarse, gravelly sands were deposited as foreset beds. The coarsest sediments are thought to have had their origin in submarine channels at the river mouth (e.g. Prior and Bornhold 1988). The finer, sandy sediments were probably either deposited somewhat more distally from the river mouth or laterally, at the sides of the river mouth channels. In front of the river mouth, where the sediment supply was greatest, the delta advanced rapidly with transport along subaquatic channels.

Fig. 4 reveals the cyclicity of sedimentation, which we interpret as being due to erosion of older deposits followed by deposition of new foresets, due to meandering of the two rivers. This resulted in step-wise changes in grain-size. Within each cycle the coarsest sediments are located nearest land.

Hydrogeology

The uppermost part of the delta is an unconfined aquifer, limited by the fjord and the Litledal River. Test pumping has been carried out in the two pumping wells (Fig.1) over a three month period. The transmissivity was calculated as 1.6 x 10^{-2} m^2/s (1382 m^2/d) and the storage coefficient as approximately 0.3 (Soldal et al. 1990).

The salinity of the groundwater in the investigated area varies between 1 and 32 per mille. The measurements reveal that the freshest groundwater is located along the Litledal River and within the southern part of the delta. The salinity increases with depth and towards the fjord. The investigated part of the delta is flooded by water with a salinity of up to 5 per mille during high tide. The average difference between low and high tide in the fjord is 1.5 m. Groundwater levels in the delta change as a function of the tides in the fjord. Consequently there is also a change in hydraulic gradient in the outer part of the aquifer. The net effect

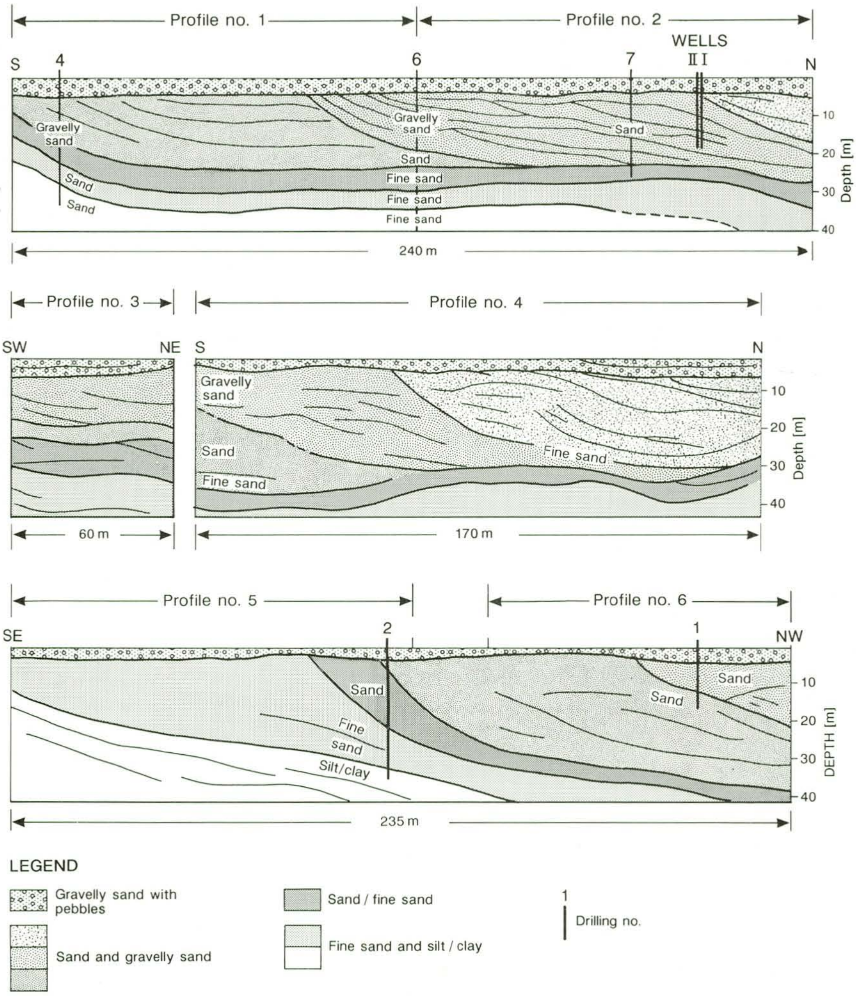

Fig.4. Interpretation of the seismic profiles and borehole data. Hydrogeological observations are also used in the interpretations. Some of the boreholes show no changes in sediment type across the seismic reflectors. The maximum depth to the groundwater level is 1.5 m below the surface.

of the tidal fluctuations (Serfes 1991) is a hydraulic gradient from the river towards the aquifer, as illustrated by the saline water distribution.

Many studies have shown that sedimentary facies is a determining factor for the hydraulic conductivity (permeability) of clastic rocks (e.g. Dreyer et al. 1990), because there is a known correlation between grain size and hydraulic conductivity in a porous aquifer (e.g. Shepherd 1989). If the presented sedimentological model is correct, there must be stepwise changes in the hydraulic conductivity of the delta, within each step the highest values being on the landward side.

The zone of mixing between fresh and salt water is wide and the overall distribution is independent of the sedimentology (Soldal et al. 1990). Boreholes 2 and 4 (Fig.5) provide an exception to the overall picture of a general increase in groundwater salinity downwards in the aquifer. Decreases in salinity (E.C.) are detected between 17 and 19 m depth in borehole 2 and between 11 and 15 m depth in borehole 4. In borehole 3, groundwater becomes gradually more saline downwards in the aquifer, but the measurements of Br^- and alkalinity show a considerable vertical variation in the profile (Fig.6). The large increase in alkalinity at 21 m depth in borehole 3 is probably due to analytical error because electrical conductivity, pH and Ca-content do not exhibit a similar variance (Soldal et al. 1990). Bromide ions are good indicators of sea water intrusion (Morell et al. 1986). The local decreases in salinity, alkalinity & bromide at some levels in boreholes no. 2, 3 and 4 are interpreted as due to inflow of fresher water along coarse foresets.

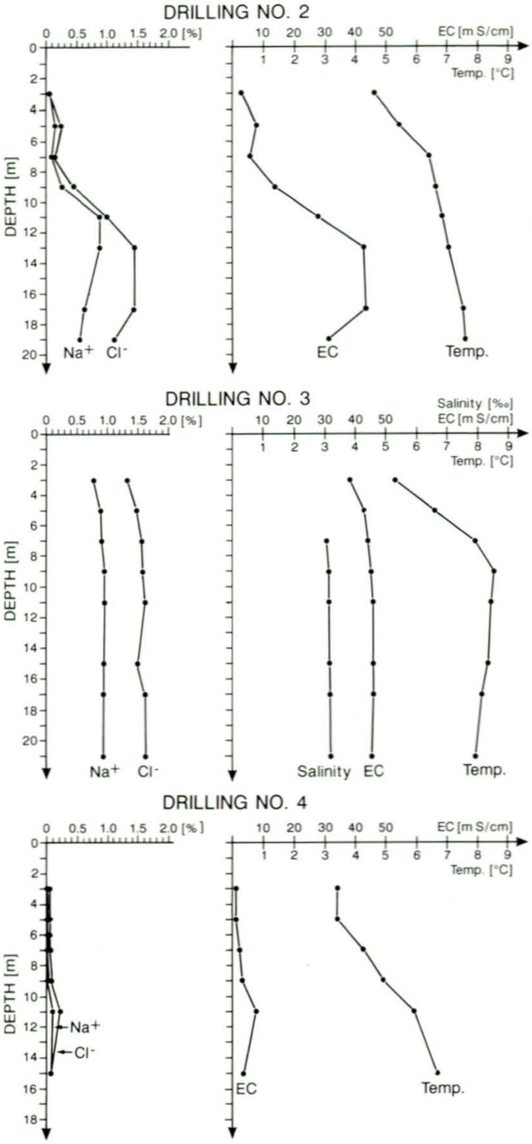

Fig.5. Changes in different parameters in three boreholes located at the margins of the investigated area. Plotted points are located in the centre of the 1 m sampling interval.

Test pumping

Two abstraction wells were placed 20 m NE of borehole 7 (Fig.1). The distance between them was 2.0 m and they were screened from 8 to 18 m below the surface. The sediments below 18 m depth consisted of fine sand. Well II is located nearest to Litledal River. The total capacity of the wells was 0.02 m^3/s (1200 l/min) and the test-pumping period was three months. In the screened level of the wells, the average salinity of the water was 27 per mille before the pumping started. After two weeks of pumping the salinity of abstracted water had stabilized at 10-14 per mille in well I and at 7-8 per mille in well II. There is a large difference in the salinity of the water from the two wells in spite of their being located adjacent to each other. Nothing in the local geology can explain this difference. One possible explanation is that a natural gravel filter has been developed outside the well screen and casing in well II. This might lead to the introduction of fresher groundwater from the aquifer's coarse top layer down to the slotted screen. In borehole 7, however, which is located between the river and the wells, influx of water with 2 per mille salinity was detected at 11-12 m depth during the test pumping. In addition, the sedimentological model indicates that there is a higher hydraulic conductivity in the part of the aquifer nearer the river than in that part nearer the fjord. Consequently, it appears that the inflow of water from the Litledal River causes the low salinity in well II. Well II, which is located closest to the river, receives a higher proportion of this fresh water than well I, which presumably derives much of its water from the fjord-dominated part of the aquifer.

It is assumed that the fresh/brackish water that reaches the wells has a salinity of 2 per mille, as measured in borehole 7 during the pumping period. The fjord water which covers the area at high tide also has a similar average salinity. The salt water component can be assumed to have an average salinity of 27 per mille, as measured in borehole 7 prior to pumping. A simple relationship between salt and fresh water inflow to the wells is:

$$(A \times F) + (B \times S) = (A + B)W$$

where A= Volume of fresh/brackish water, B= Volume of salt water, F= Salinity of fresh/brackish water, S=Salinity of salt water, W= Salinity of the water in the well, A + B = 1. F = 2 per mille, S = 27 per mille.

After one month's test-pumping, the average salinity in well I was 12.0 per mille, and in well II 7.5 per mille. This gives:

Well I: A = 0.6 (60%) and B = 0.4 (40%)
Well II: A = 0.78 (78%) and B = 0.22 (22%)

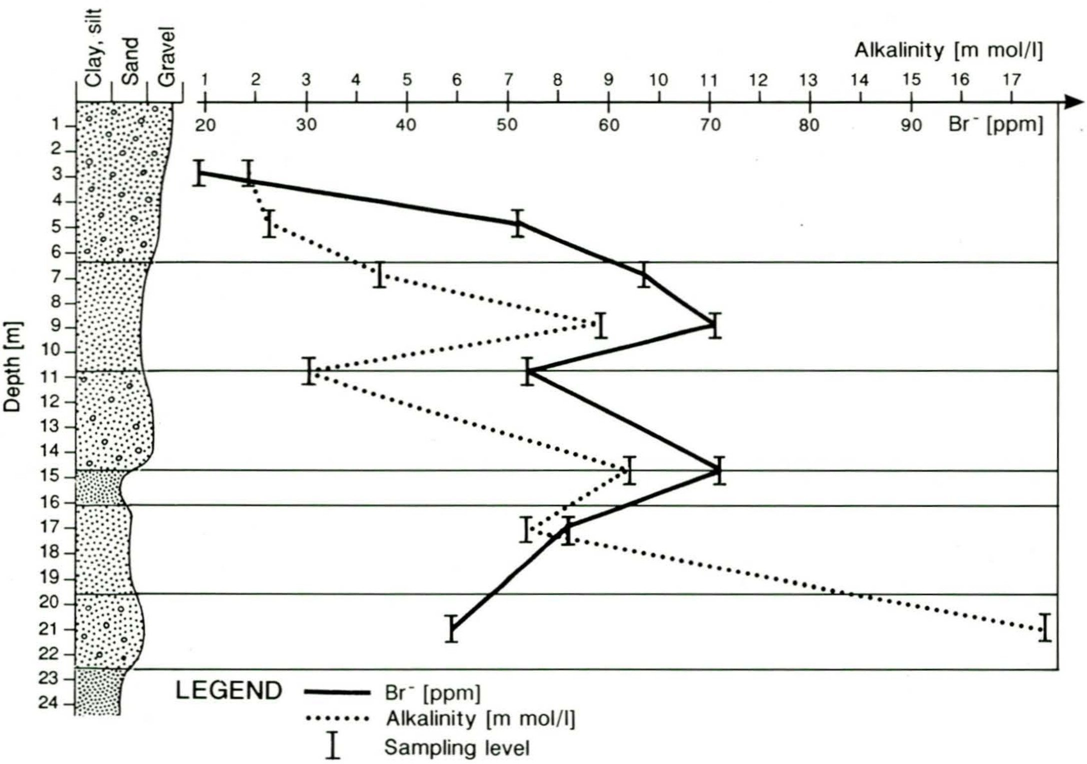

Fig.6. Lithostratigraphy and hydrochemical profiles from borehole no.3. Note the decrease in Br⁻ -content and the change in alkalinity in the coarse layers. The extreme alkalinity at 21 m is probably due to analytical error.

The saline water constitutes 40% of the total yield in well I, and 22% in well II. If it is assumed that any inflow from the top part of the aquifer is similar in the two wells, the 18% difference in salinity is due to the lateral flow of fresh water.

The observations in boreholes 2, 3 and 4 reveal that fresh water mixes with saline water along coarse foresets. Small variations in grain-size lead to great differences in the hydraulic conductivity and thus to an increased interfingering when the groundwater velocity increases (Gillham & Cherry 1982). The hydraulic conductivity, which is highest in the area between the wells and the river, the interfingering effect and the hydraulic gradient from the river to the aquifer cause this lateral flow of fresh water.

After two months of pumping, a test with two-level pumping was performed (Fig.7). The screen level was adjusted to 5-10 m below the surface in well I and to 12-18 m in well II. The total pumping rate remained 0.02 m^3/s. This change caused the salinity in well I to stabilize at 0-5 per mille, whereas in well II it increased to 15-16 per mille. Using the same relationship as above, we estimate that 54% of the yield in well II is saline water. In well I the percentage of saline water is around 2%. It is estimated that 18% of the fresh water in well II was transmitted laterally through coarse layers from the river-dominated area of the aquifer and 28% was due to vertical flow of fresh groundwater from the top of the aquifer. Figure 7 shows a qualitative model of groundwater inflow to the wells.

No drawdown effect was observed in the freshwater wells at the Akvaforsk waterworks during the test-pumping period. The radius of influence around wells I & II is thus small or is limited in the direction of the waterworks.

The salinity of the water obtained from wells I & II is too low to be used by the fish farm. Preliminary investigations indicate that the general stratigraphy of the whole delta front is similar to that in the investigated area. They

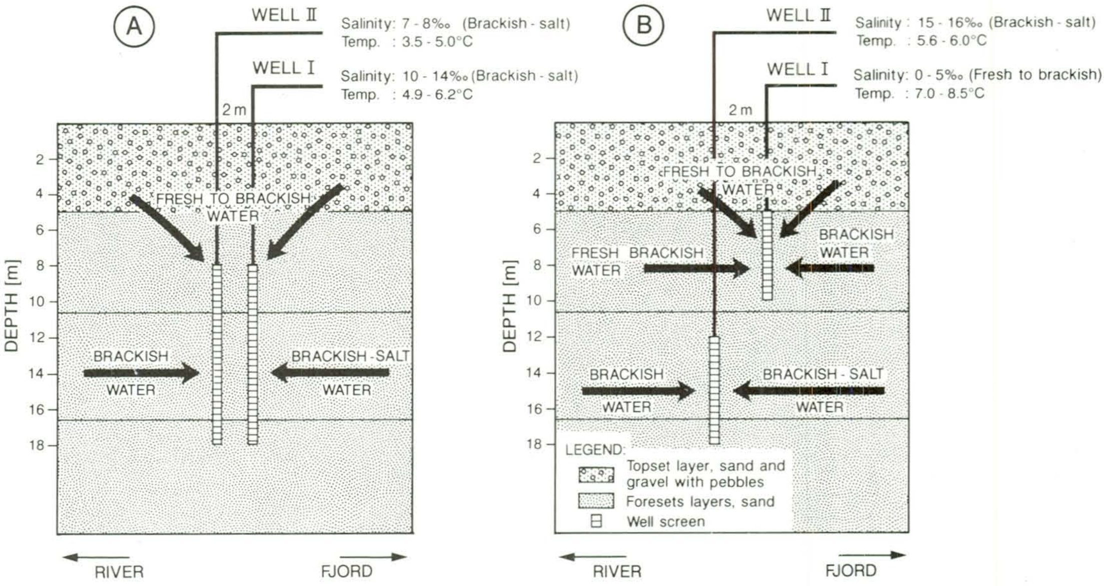

Fig.7. A qualitative model for inflow to the wells. A: pumping from one level, B: two-level pumping. Designation of the water types is in accordance with Stuyfzand, 1986.

also show that the aquifer's coarse top layer carries relatively fresh water throughout the whole delta. Thus, the potential inflow of fresh water from the aquifer's top layer to groundwater wells will probably be large everywhere on the delta. New pumping tests, 200 m to the north of borehole 3, reveal that the salinity of the abstracted water eventually decreases to below 15 per mille with a pumping rate of around 0.04 m^3/s. Preliminary investigations do, however, indicate that a reduction in the pumping rate to c. 0.02 m^3/s may give a stable situation with a salinity of 25-30 per mille (G. Storrø, pers. comm. 1991).

The maximum groundwater salinity will be attained in areas with no lateral flow from the fresh water aquifer. Consequently, wells designed to abstract saline water must be placed far out on the delta. The lateral fresh water flow that constitutes c. 18% of the well yield in the investigated area can then be avoided. If the wells were placed far out on the delta, at locations where the net hydraulic gradient is very small and where coarse foresets with connection to the top of the aquifer are lacking, 72% of the well yield would be saline water. Using the same salinities of fresh and saline waters as above, and the same relationships, we estimate that the salinity would be at least 20 per mille in the water abstracted from the deepest well using two level pumping.

Conclusions

Investigations at the extreme northern edge of the delta (Kummeneje 1985, 1989; E. Danielsen pers.comm. 1991) did not reveal any coarser-grained material than was observed in the investigated area. The absence of a trend towards coarser-grained material outwards in the investigated part of the delta is probably due to the fact that this part of the delta was formed after 9000 yrs BP during a period with little uplift. Uplift may however be responsible for the wedge-shaped form of the coarser-grained sediments between the fjord- and the ice margin deltas.

The wide zone of mixing between fresh and salt groundwater in the aquifer is probably the result of the influence of tidal changes in the fjord on piezometric heads in the delta aquifer. In a dynamic system such as the one described here, the Ghyben-Herzberg principle (Badon Ghyben 1888, Herzberg 1901) is not applicable. Glover (1964) has developed an approximate equation for the shape of the freshwater-saltwater interface in a situation where groundwater dynamics are involved. The internal distribution of hydraulic conductivity, the hydraulic gradient and the tidal fluctuations are probably the most important factors influencing the flow of groundwater in the aquifer. The coarse-grained top layer carries large amounts of fresh water and to a large extent negates the flow of deeper salt groundwater to the investigated wells.

If a high salinity is to be achieved, two-level pumping is the simplest solution. Other possibilities to obtain groundwater with a high salinity are to reduce the pumping rate of the wells, to infiltrate saline water from the fjord into the shallow aquifer, or to search for deeper aquifer horizons. In order to reduce fresh water inflow, it is important to avoid localities with hydraulic gradients from rivers and high-permeability foresets.

Saline groundwater can be pumped out from wells I & II at Sunndalsøra in large amounts without causing conflict with the utilization of fresh groundwater in the existing water-works.

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