Groundwater transit times in a small coastal aquifer at Esebotn, Sogn og Fjordane, western Norway

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A shallow alluvial aquifer in Esebotn, Sogn og Fjordane, Norway, has been investigated from a hydrological standpoint in order to obtain estimates of groundwater transit times. Water levels, oxygen isotopes, water temperatures and precipitation were monitored over a one-year period. Groundwater transit times were calculated applying a traditional Darcyan approach and by using oxygen isotopes and temperature as tracers. All methods give transit times of 60-90 days. The oxygen isotopes indicate that groundwater recharge due to infiltration from the river Ygleelvi makes up about 80% of the total groundwater recharge in the central parts of the aquifer during the summer season.

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Introduction

Only 13% of the population in Norway use groundwater for drinking water purposes. However, there is an increasing awareness of the utilisation of groundwater; mainly because of better raw-water quality and source protection, and a higher cost-effectiveness of the water supply compared with surface water (Ellingsen & Banks 1993). Moreover, a stronger emphasis has been placed on water quality due to the ratification of the EU directive on drinking water quality. Particularly, the food and beverage industry and all accommodation establishments will have to document water quality according to these regulations. This has strengthened the efforts to locate new groundwater resources. In coastal Norway, many aquifers in small river deposits and deltas have been considered as marginal or second-class with respect to water quality and capacity. The main arguments against the exploitation of these aquifers for drinking water have been the supposed short transit times and the risk for sea water intrusion. However, compared with surface water, which is often bacteriologically contaminated and may also carry humic substances, the exploitation of these marginal groundwater resources may be more cost-effective as it will require less water treatment to obtain high-quality drinking water.

The aquifer in Esebotn is a typical example of this sort of marginal aquifer. The aquifer has earlier been investigated by geophysical and hydrogeological methods (Bergersen et al. 1987, Enes et al. 1992, Soldal et al. 1994). In the following account we will show how the use of simple hydrological methods can give valuable information about the proportion of infiltrated river water in the aquifer, groundwater flow and transit times; which are all important parameters pertaining to aquifer protection and water quality.

Hypothesis

Our hypothesis is that oxygen isotopes provide a useful means of elucidating groundwater transit times in coastal areas where climatic conditions are variable. Temperature measurements and hydraulic calculations are also simple methods which can adequately be applied to calculate groundwater transit times, and the reliability of these methods can be controlled by oxygen isotopes providing that statistical tools are used. We claim that small fluvial deposits are adequate aquifers with respect to water supplies and that they can be protected in a reasonable manner.

The study area

With regard to topography/catchment, climate and geological architecture, the aquifer in Esebotn is typical for many aquifers in coastal Norway. The Esebotn aquifer is centered around the river Ygleelvi, and is an alluvial fan deposit grading into a coastal fluvial delta. It covers an area of about 0.195 km^2, and is located in a small valley bottom surrounded by steep valley sides which reach altitudes of a thousand metres or more (Figs.1&2). The valley alluvium consists mainly of coarse gravel and sands which have been derived from an older ice-marginal deposit near the head of the valley (Fig.4). As a result of the isostatic uplift of the land mass which followed the termination of the last ice age about 10,000 years ago, this ice-marginal deposit was eroded and the sands and gravels were redeposited further downstream on the river plain and in Esefjord (Fig.4).

The investigated part of the aquifer on the eastern side of the river Ygleelvi has an area of about 0.105 km^2. Hydrogeological and geophysical field investigations

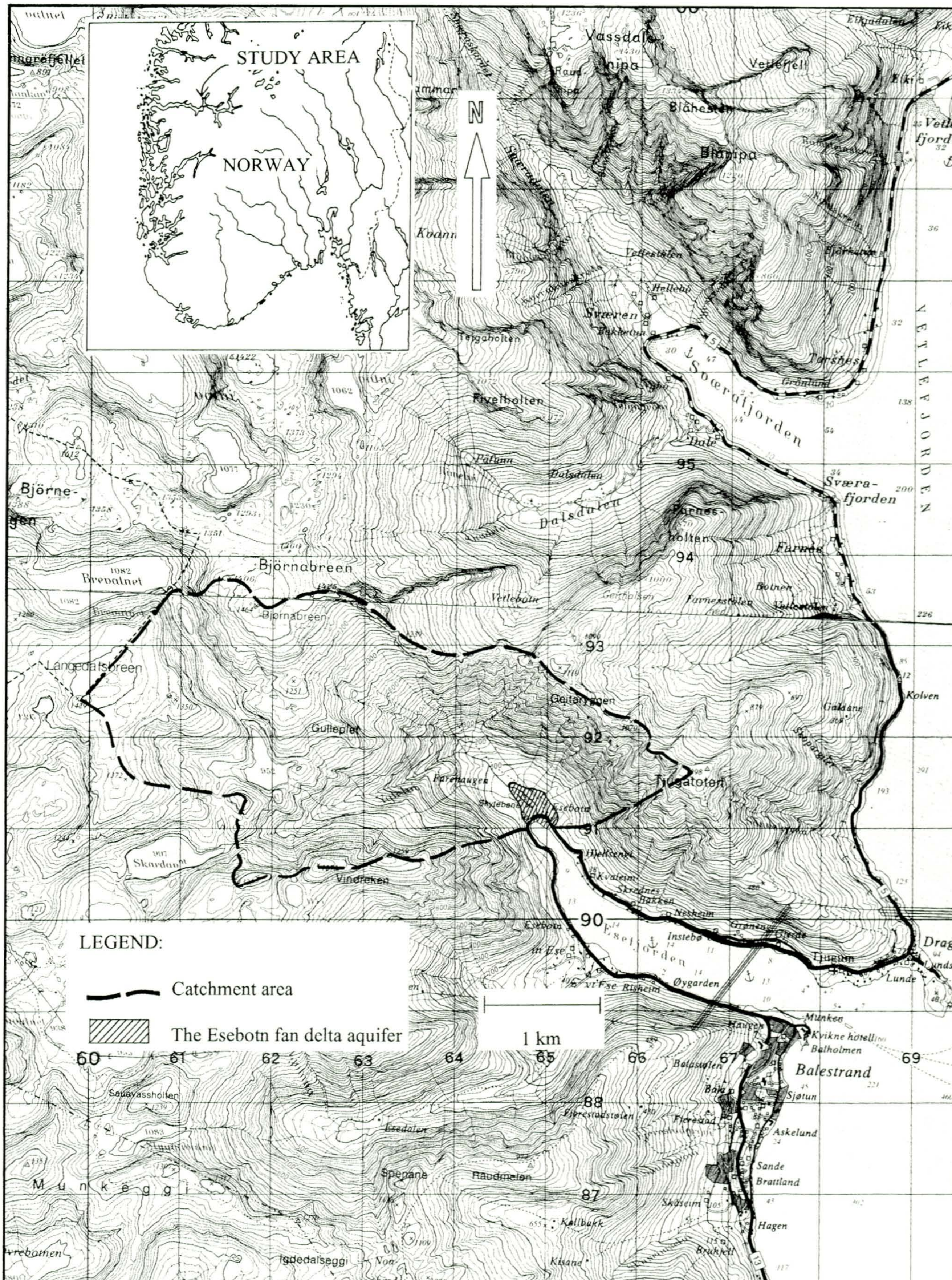

Fig.1. Location map of the study area showing the aquifer in Esebotn and its catchment area.

Fig.2. The aquifer in Esebotn with parts of its catchment area. Esefjord is seen in the foreground, and the surrounding mountains reach altitudes of about 1100 - 1200 metres above sea level.

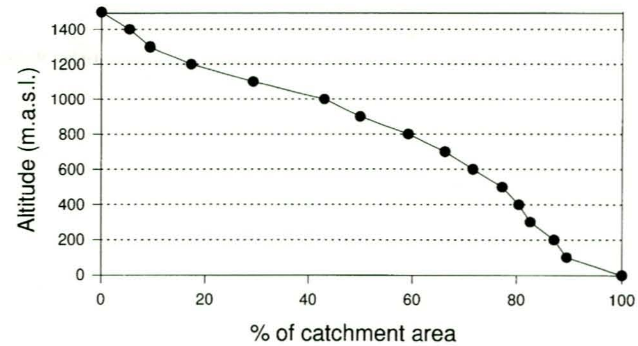

Fig.3. Graph showing percentage of catchment area situated above a specified altitude.

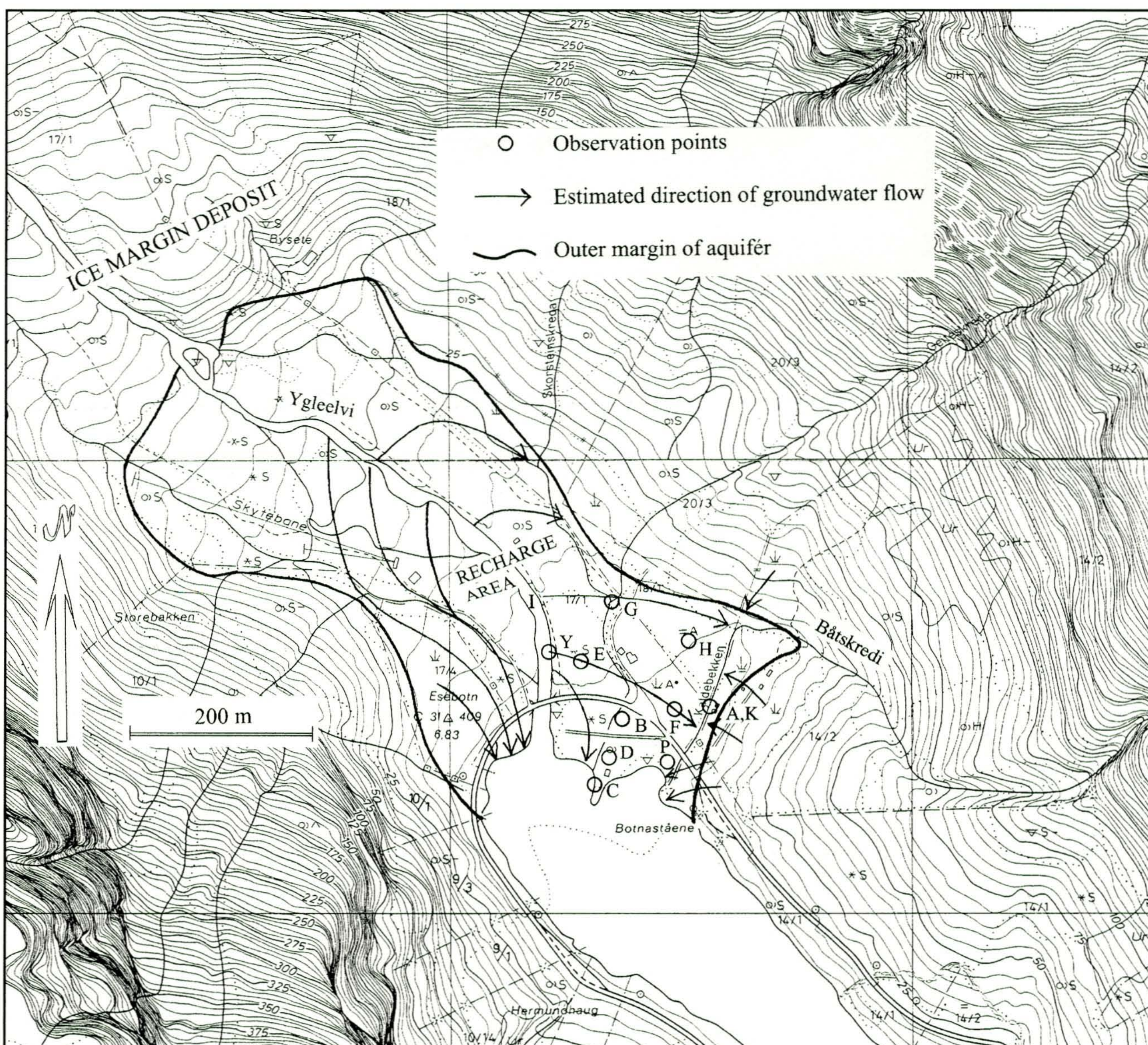

Fig.4. Map showing observation points and deduced groundwater flow directions based on penetration depth of georadar signals from Soldal et al. (1994).

(Soldal et al. 1994) show that the aquifer in this area is built up of gently seaward-dipping layers of sand and gravel with a total thickness of about 10 metres, underlain by at least 40 metres of silt and clay (Bergersen et al. 1987). At the lower boundary of the aquifer, organic material is encountered in the fine-grained sediments. Dating of roots and plant remains encountered during installation of piezometer B (Fig. 4) gave an ^{14}C age of 1085±85 years B.P. (TUa-615, Trondheim). In such a young deposit we consider it likely that organic material was also originally present in the overlying coarse-grained sediments. However, a rapid throughflow caused by a high permeability and hydraulic gradient must have enhanced the decomposition of the organic matter leading to the present-day oxidising conditions that prevent the dissolution of iron and manganese oxides. In the fine-

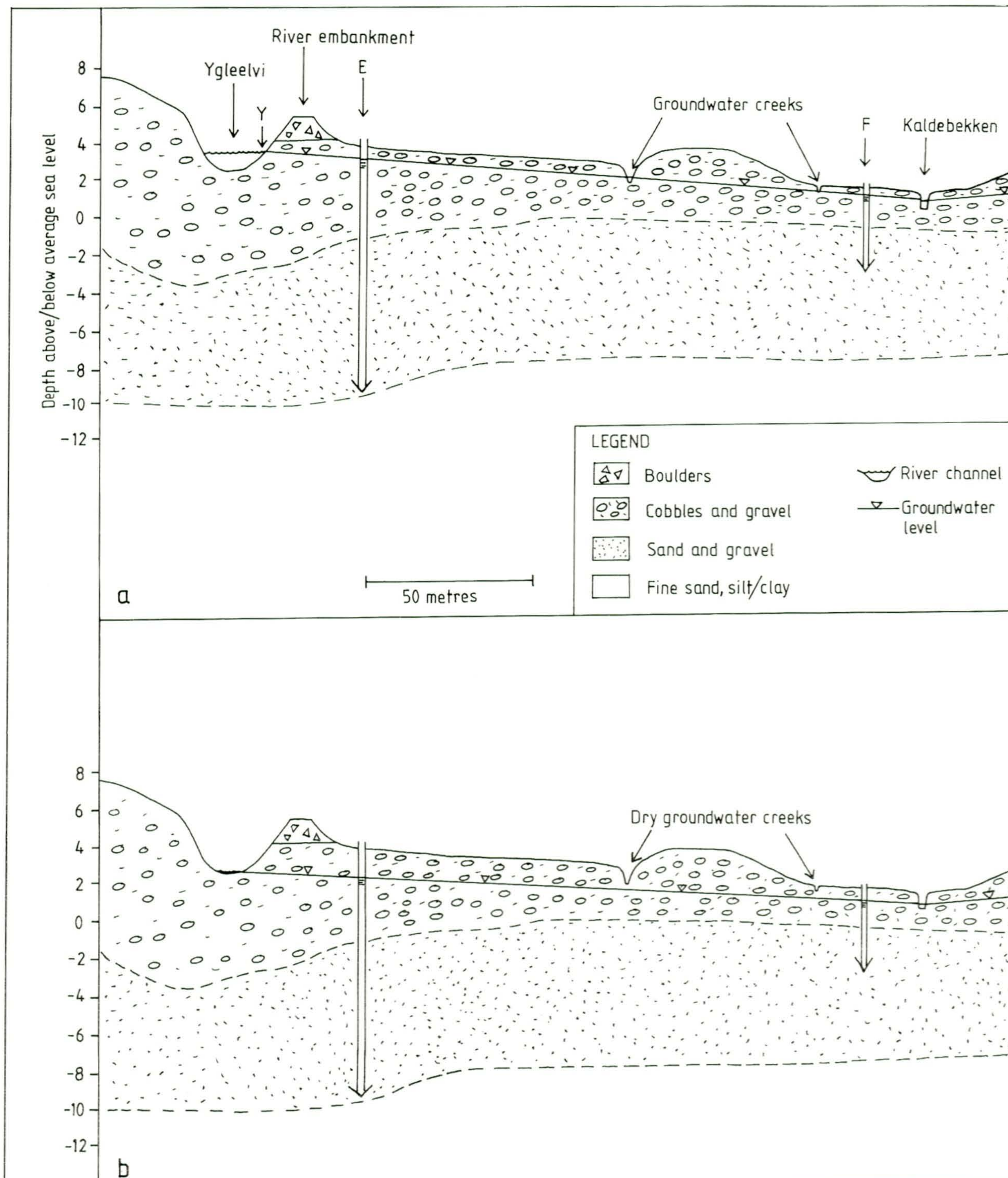

Fig.5. (a) Profile from Ygleelvi to Kaldebekken in late spring/early summer when the discharge in Ygleelvi is high. (b) The same profile when the discharge in Ygleelvi is low.

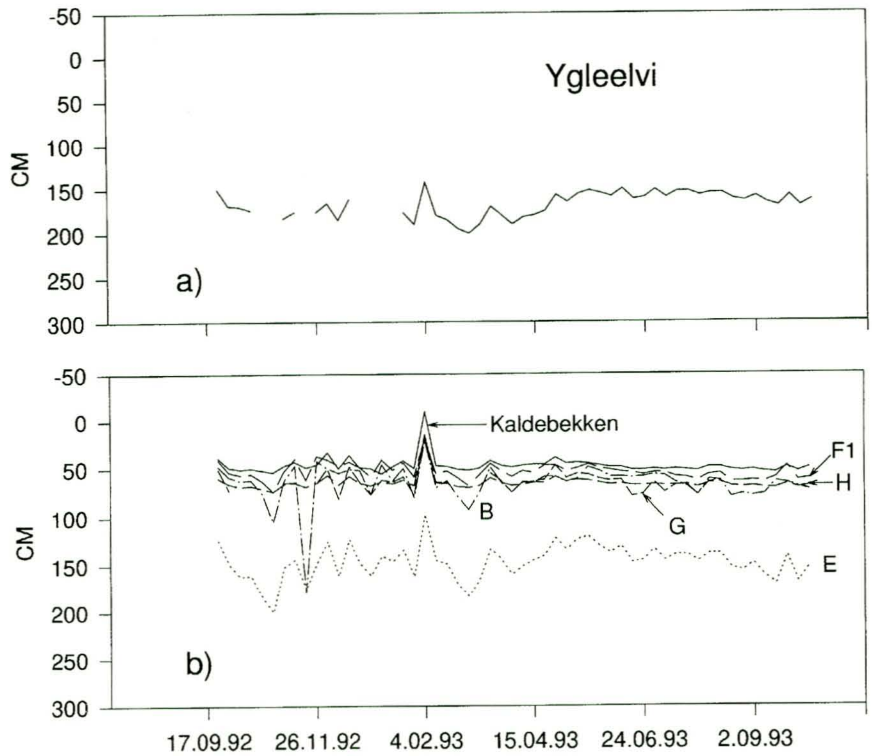

Fig.6. Depths to water level from arbitrary datums at (a) Ygleelvi; (b) observation points B, E, H, F1 and Kaldebekken.

grained sediments organic material still remains due to a slower throughflow, and reducing conditions exist with possibilities for mobilisation of Fe and Mn.

The catchment has a total area of about 12 km^2. The lower part in the valley bottom comprises only about 5% of this area, and most of the catchment is situated at high-altitude elevations (Fig.3). The main drainage of surface water is through Ygleelvi, supplemented by seasonal drainage through some valley side meltwater and floodwater streams. The average annual precipitation for the nearest precipitation station at Skarestad in Fjærland, about 25 km further north, is 1905 mm (Norsk Meteorologisk Institutt 1987). In our observation period, from October 1992 to October 1993, the precipitation in Fjærland was 2190 mm. There was a marked precipitation maximum in the late autumn/early winter months (November-January). In the low-lying parts of the catchment much of the winter precipitation was rainfall, while the area above approximately 800 metres made up a considerable snow-pack wherein much of the winter precipitation was temporarily stored.

Geophysical investigations (Soldal et al. 1994) indicate that groundwater recharge takes place mainly by infiltration of river water through an eastward-facing bend in the Ygleelvi (Fig.4, area I) about 200 metres upstream from its outlet into the Esefjord . Precipitation and surface water which infiltrates the aquifer from the valley sides in the east is considered to form only a small contribution to the groundwater recharge. Groundwater discharge takes place in a marshy area on the western side of Kaldebekken (Fig.4), attested by the water levels in a piezometer-nest (F1-F2-F3) in this area. The discharge takes place from natural springs and from various dug ditches and river-canals, in particular by the groundwater dominated stream Kaldebekken (Fig.4). Surface runoff from the stream Båtskredi and the mountain sides in the east is estimated to make up 0 - 15% of the total discharge of Kaldebekken. In dry and cold periods, Båtskredi has practically no discharge. In short periods of heavy rainfall, however, the discharge of Båtskredi may make up a significant component of the discharge in Kaldebekken.

The discharge of Ygleelvi controls the water table in the aquifer, which fluctuates with the water level in Ygleelvi (Figs. 5&6). The hydraulic gradient in the direction from the recharge area to the discharge area at Kaldebekken is roughly the same as the gradient of the fan-delta, i.e. about 0.06. If we take the water levels in Ygleelvi and Kaldebekken to represent the hydraulic heads in the recharge and discharge areas, respectively, the hydraulic gradient is found to vary between 0.03 and 0.05. The hydraulic gradient reaches its highest value during the main snow melting in late spring and early summer.

The pressure of the groundwater flowing through the deposit clearly overprints the tidal effect of the sea water; which influences the water levels in the aquifer in a noticeable manner only in the observation wells D and P close to the shoreline (Enes et al. 1992). Geoelectric measurements (Soldal et al. 1994) clearly show that sea-water intrusion is least pronounced during the spring and early summer when the aquifer is flushed with large volumes of freshwater from the snowmelt.

Methods

Studies of residence times can be carried out by the use of hydraulic calculations or by environmental or artificial tracers.

The hydraulic approach is dependent on gathered field data such as grain size and piezometric heads in order to estimate hydraulic conductivity, porosity and hydraulic gradient. From these data, average linear velocity and hence residence times can be estimated. It has been claimed that the accuracy of this method is limited, mainly due to the uncertainties in the estimates of the aquifer properties. The use of tracing techniques has therefore been recommended (e.g. Freeze & Cherry 1979, p.427).

Naturally occurring tracers such as oxygen isotopes or physical parameters such as temperature have proven to be applicable in studies of residence times in aquifers where the residence time is short (< 1 year) (e.g. Walton 1970, Haldorsen et al. 1993), providing that there exists a seasonal variation for the measured parameter in precipitation or infiltrating surface water. By monitoring the time of propagation of the seasonal maxima or minima from recharge area to discharge area, information about transit times can be obtained. The advantages of using oxygen isotopes and temperature are many: they are inexpensive and simple to measure and move as integral parts of the normal groundwater flow without retardation due to adsorption, etc. In Norway, the use of oxygen isotopes in groundwater studies has yielded fruitful results in small aquifers situated in inland areas with stable climatic conditions and well defined catchments (Haldorsen 1994).

Natural water initially formed by evaporation of oceanic water contains the oxygen isotopes ^{16}O and ^{18}O. The isotopic composition of oxygen in a water sample is normally characterised by the isotopic ratio ^{18}O / ^{16}O relative to the same ratio in a known standard water sample. Usually this is 'standard mean ocean water' or 'SMOW' (Craig 1961). The relative difference in the isotopic ratios is defined as:

$$\delta^{18}O = \frac{[^{18}O/^{16}O]_{\text{SAMPLE}} - [^{18}O/^{16}O]_{\text{SMOW}}}{[^{18}O/^{16}O]_{\text{SMOW}}}$$

As the relative difference between the isotopic ratios is small, it is often given in per mille:

$$\delta^{18}‰ = \delta^{18}O \cdot 1000$$

The water vapour in the atmosphere which later condenses to form precipitation is depleted in ^{18}O relative to oceanic water. The $\delta^{18}O$ ‰ values will thus normally be negative. For a given geographic area, the $\delta^{18}O$ ‰ values of precipitation will depend on air temperature, the amount and intensity of precipitation, distance from the ocean, altitude and prevailing wind direction. One would consequently expect both regional and seasonal variations in the $\delta^{18}O$ ‰ values.

Table 1. Observation points in the study area and types of parameters measured. Observation point F is a piezometer nest where three piezometers F1, F2 and F3 are installed at different depths.

Observation point		Parameter
Y	Ygleelvi	Water level, temperature, $\delta^{18}O$ ‰
G	Spring	Water level, temperature, $\delta^{18}O$ ‰
K	Kaldebekken	Water level, temperature, $\delta^{18}O$ ‰
B	Piezometer	Groundwater level
F	Piezometer nest (F1, F2, F3)	Groundwater level
H	Piezometer	Groundwater level
A	Precipitation station	Air temperature, precipitation, $\delta^{18}O$ ‰
E	Piezometer	Groundwater level
C	Piezometer	Sea water level
D	Piezometer	Groundwater level
P	Piezometer	Groundwater level

Data and sampling

In this study 11 observation points were established (Fig.4, Table 1). Once a week, water levels, water temperatures, air temperature and precipitation were measured. At four of the obervation points, water samples were collected for determination of $\delta^{18}O$ ‰. The samples collected at the precipitation station were accumulated samples from the preceding week. The observation period lasted one year, from October 1992 to October 1993. In addition, precipitation and evaporation data from the nearest meteorological observation station, Skarestad in Fjærland, were available (Norsk Meteorologisk Institutt 1992a, 1992b, 1993a, 1993b). At observation points B and F and at several other locations, observation wells have been drilled and aquifer samples gathered at various depths for estimation of hydraulic conductivity from grain-size gradation curves (Enes et al. 1992). Water-level data for estimation of hydraulic gradients were also recorded.

Results and discussion

Darcian approach

Based on the groundwater flow directions deduced by Soldal et al. (1994), the groundwater residence time from the recharge area I to the discharge area at Kaldebekken can be calculated from the equation :

$$t\,(d) = \frac{n_e \cdot L\,(m)}{K\,(m/d) \cdot i}$$

Table 2. Calculated groundwater residence times from recharge area (I) to discharge area at Kaldebekken for different hydraulic gradients and effective porosities.

K(m/d)	14.6	14.6	14.6	14.6	14.6	14.6
L(m)	225	225	225	225	225	225
I	0.03	0.04	0.05	0.03	0.04	0.05
n_e	0.30	0.30	0.30	0.20	0.20	0.20
t(d)	154	115	92	102	77	62

where t is the residence time in days and L is the distance in metres. The hydraulic conductivity K is an average value of a number of K-values determined by Enes et al. (1992). The residence times calculated (Table 2) are considered to represent the dominant water throughflow, ignoring lesser inhomogeneties in the aquifer. The residence time is shortest (62- 92 days) in the spring and early summer when the hydraulic gradient is high (about 0.05).

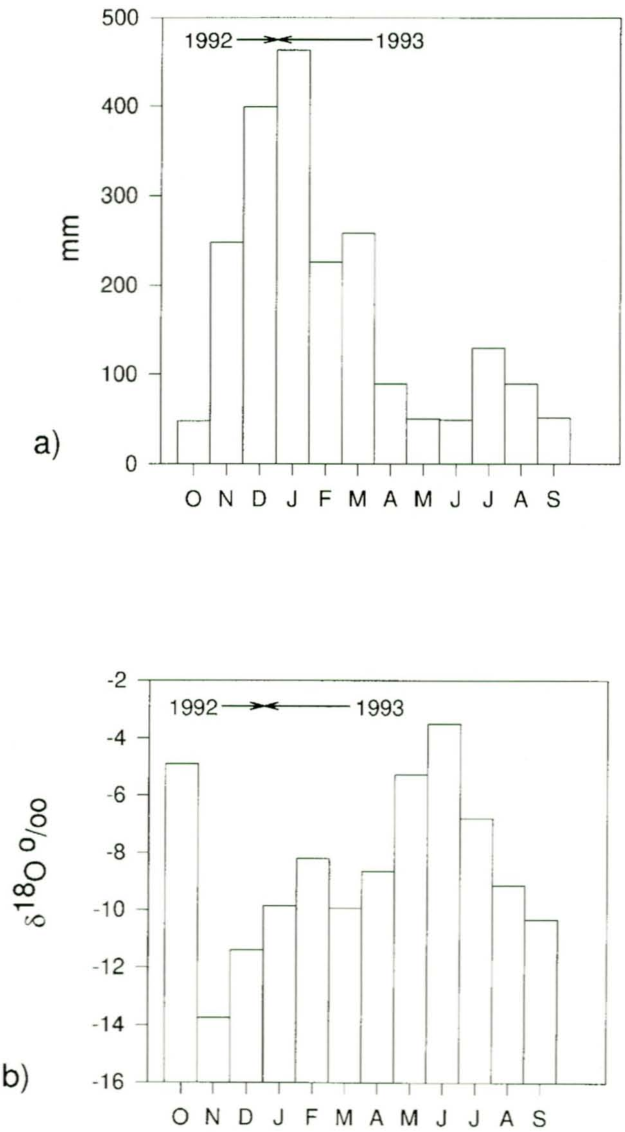

Fig.7. (a) Monthly precipitation data from the nearest meteorological observation station, Skarestad in Fjærland, during the observation period; (b) Monthly weighted means of $\delta^{18}O$ ‰ at Esebotn against the precipitation data from Skarestad.

Oxygen isotopes δ^{18} O ‰

The precipitation has an annual mean δ^{18} O value of -8.58 ‰, with maximum and minimum values of 1.17 and -17.40. The winter 1992/93 had periods with unusually high air temperatures, strong southwesterly winds and large amounts of precipitation. Several high δ^{18} O ‰ values indicate that the isotopic composition was influenced by airborne sea-water aerosols during episodes of extreme weather conditions. Nevertheless, the monthly weighted means show a distinct seasonal variation, with rising values from December to June, and decreasing values from July to November (Fig.7). One important condition for applying oxygen isotopes in studies of transit times was thus present. Our assumption is that recharge of groundwater takes place mainly by infiltration of river water from Ygleelvi. If seasonal variations in the river's δ^{18} O ‰ values are present, this isotopic labelling of the river water should be traceable in the aquifer and thus provide a means of determining the residence time for the water in the aquifer.

In drainage systems controlled by surface runoff one would expect the highest δ^{18} O ‰ values in the summer months and the lowest during the winter. In our area this could be different, because the temporarily stored winter precipitation which melts during the spring and summer months can reverse the isotopic fingerprints in the river water. In Ygleelvi one must expect any seasonal variation in δ^{18} O ‰ to be a result not only of seasonal variations in the δ^{18} O ‰ of the precipitation, but also of the supplies of meltwater carrying with it the low δ^{18} O ‰ isotopic signatures. The δ^{18} O ‰ values also decrease with altitude. This altitude effect will result in a lowering of the δ^{18} O ‰ values of 0.15 - 0.50 ‰ per 100 m (Yurtsever & Gat 1981). A commonly observed altitude gradient appears to be near 0.2 ‰ per 100 m (Eriksson 1983). As much of the drainage area of the Ygleelvi is situated at elevations above 800 - 1000 metres, the altitude effect will give rise to lower δ^{18} O ‰ values than one would expect at this distance from the coast. The water samples from Ygleelvi show an amplitude in their δ^{18} O ‰ values of about 1.5 per. mille about an average value of -11.11.

Compared with the observation points in the discharge area, Ygleelvi has the lowest δ^{18} O ‰ values (Fig.8). Kaldebekken has the highest values (average -10.32), while the values for observation point G (average -10.82) fall between the values for Ygleelvi and Kaldebekken. None of these cited averages are weighted for flows. The difference between the three average values is statistically significant at the 95% confidence level. The pattern of increasing δ^{18} O ‰ values with distance from the recharge area is most prominent in the period from April to September, and supports our view that recharge of groundwater takes place by infiltration of river water

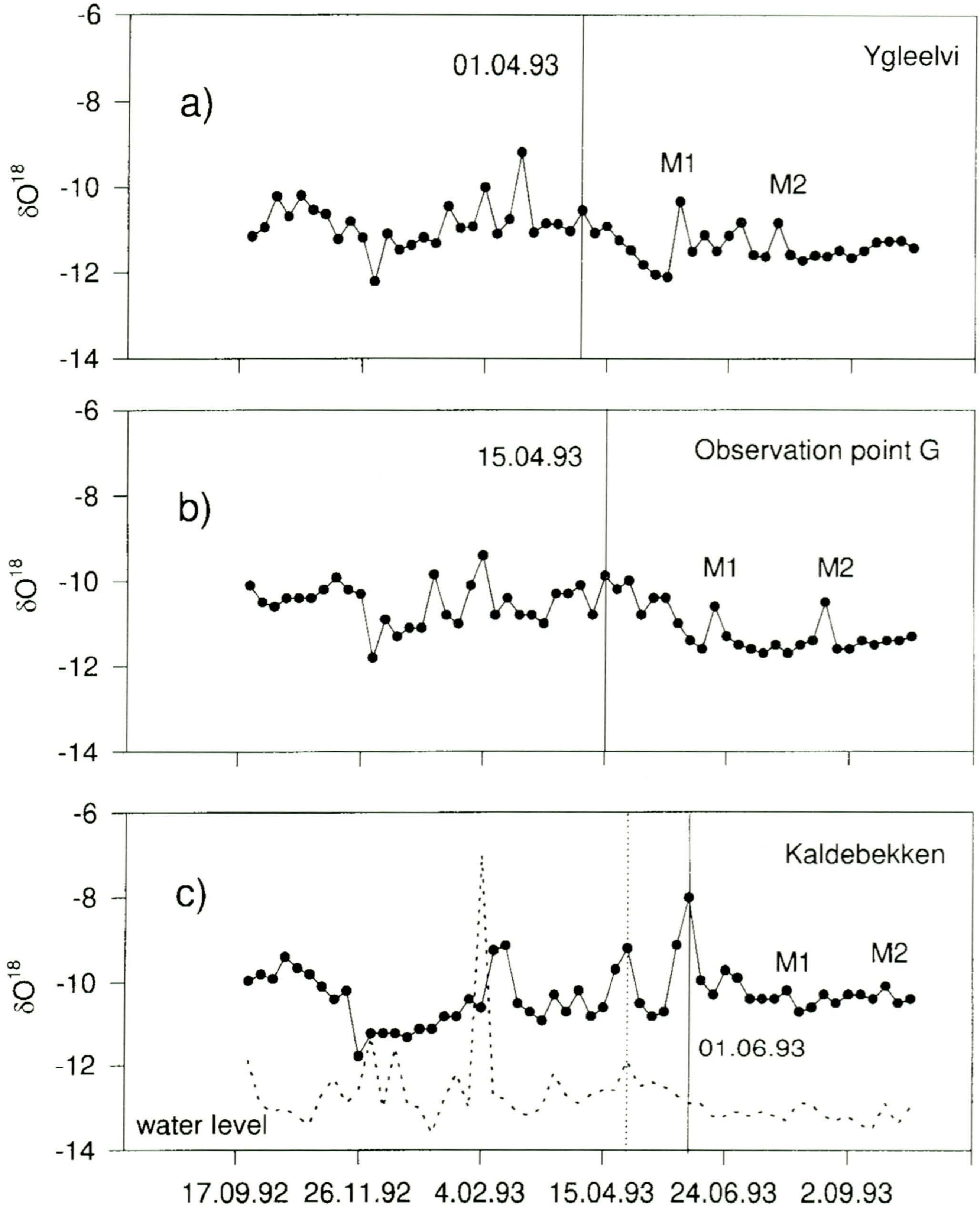

Fig.8. Variations in $\delta^{18}O$ ‰ during the observation period at (a) Ygleelvi; (b) Observation point G ; and (c) Kaldebekken. In Fig. 8c, the water level in Kaldebekken is also depicted. The vertical bars indicate starts of decreasing trends for $\delta^{18}O$‰.

	Mean Annual	Mean Nov. 92-March 93	Mean May 93-Aug. 93	Mean April 93-Sept. 93
$\delta^{18}O$ Ygleelvi	-11.11	-10.93	-11.38	-11.35
$\delta^{18}O$ Precipitation	-8.58	-10.56	-5.13	-7.13
$\delta^{18}O$ Kaldbekken	-10.32	-10.65	-10.04	-10.14
% river infiltrated groundwater	68.55	24.30	78.50	72.50

Table 3. Mean $\delta^{18}O$ values from Ygleelvi, precipitation and Kaldebekken and the calculated contributions of river-infiltrated water leaving the aquifer at Kaldebekken in selected periods from October 1992 to October 1993

from area I. The trend of increasing δ^{18} O ‰ values is considered to reflect direct surface infiltration of local precipitation on the river plain labelled with higher δ^{18} O ‰ values. In April, any infiltration of melted snow on the river plain would, due to the altitude effect, have higher δ^{18} O ‰ values than the meltwater dominating the discharge of Ygleelvi. In the summer months, the δ^{18} O ‰ values in Ygleelvi were rising (Fig.8a), but were still much lower than the δ^{18} O ‰ values (-5 to - 7) of the precipitation on the river plain. In water which is a mixture of water from different sources, the δ^{18} O ‰ value is given by :

$$\delta^{18}\,O\,‰ = \sum x_i\, \delta_i\,^{18}O$$

where x_i is the proportion of water with the isotopic composition $\delta_i{}^{18}O$ (Gonfiantini 1981). By using the average δ^{18} O ‰ value for the period April to September (-11.35) for the river water and the average value of - 7.13 for the precipitation, from Table 3, an estimate of the relative contributions of river and surface water infiltration can be obtained by simple iteration. The result indicates that during this period, the water leaving the aquifer at Kaldebekken was a mixture of 72.5 % river-infiltrated water and 27.5 % water derived by recharge of precipitation on the river plain. In the period May - August the contribution of river-infiltrated water was 80 %. These figures are comparable with figures from a much larger river delta at Sunndalsøra (Soldal et al. 1994).

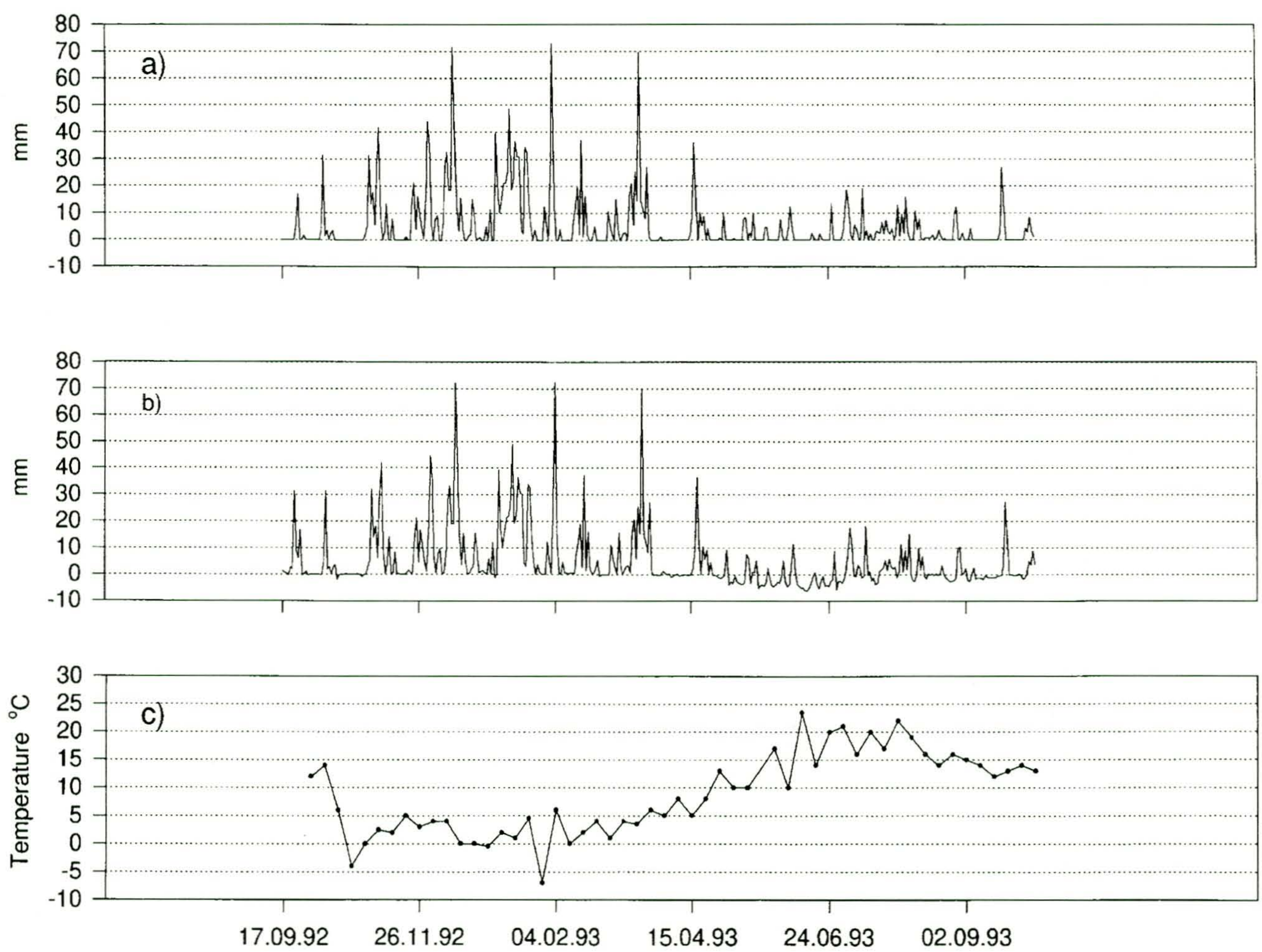

Fig.9. (a) Daily precipitation at the metereological station Skarestad, Fjærland, (b) Difference between daily precipitation and evaporation at Skarestad, Fjærland, (c) Air temperature at Esebotn, weekly measurements.

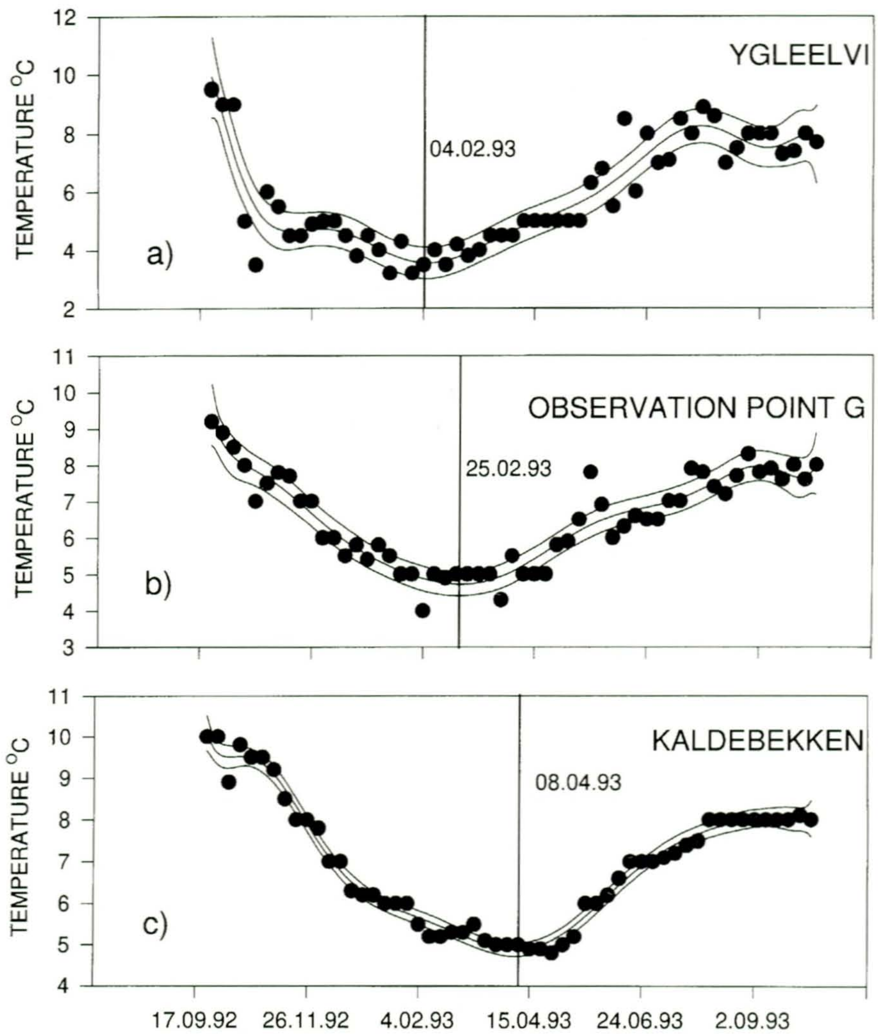

Fig. 10. Temperature trends at (a) Ygleelvi, (b) Observation point G and (c) Kaldebekken depicted by 10 th. order regression curves. The vertical bar indicates the position of the temperature minima at each of the observation sites.

In the period November - March the average δ^{18} O ‰ values were -10.93 (Ygleelvi), - 10.65 (Kaldebekken) and -10.56 (precipitation). These figures indicate that the water in the aquifer during this period was a mixture of 24.3 % river-infiltrated water and 75.7 % water derived by infiltration of precipitation on the river plain. The climatic conditions during this winter were, however, extreme with large amounts of rainfall-precipitation on the river plain. In the higher altitude parts of the catchment the temperatures were lower and the precipitation was in the form of snow. The winter discharge of Ygleelvi was normal, but the amount of precipitation infiltrating on the river plain must have been greater than normal.

In Ygleelvi, a minimum in late November 1992 (Fig.8a) is considered to represent the contribution of large amounts of autumn precipitation with low δ^{18} O ‰ values. It is, however, difficult to trace this isotopic signal to the observation points in the discharge area. The water samples in Kaldebekken have an autumn minimum which occurs before the autumn minimum in Ygleelvi. Although the observation points in the discharge area are predominantly groundwater springs, they receive precipitation as surface water from smaller flood streams during short and intensive periods of heavy rainfall. The late autumn 1992 and the early winter 1993 was characterised by mild weather with large amounts of precipitation (Fig.9a), and several episodes with storms and flooding were recorded. In Kaldebekken, this led to frequent variations in discharge (Fig.8c) and the δ^{18} O ‰ values must have been influenced by precipitation surface water from the flood-stream Båtskredi. This isotopic labelling appears to have been received earlier in Kaldebekken than in Ygleelvi, probably because the latter has a larger discharge and also receives a larger part of its discharge by runoff in the upper soil layers. The autumn 1992 groundwater levels were generally high, and direct ground infiltration of precipitation could also have influenced the isotopic composition at the observation points. We conclude that the extreme climatic conditions that existed at this time of the year were not favourable for studying residence times in the aquifer.

From March to September the weather conditions were more stable. In the valley bottom there was an early snowmelt. The amount of precipitation was small, and represented only about 30% of the total precipitation during our monitoring programme. Over long periods, the evapotranspiraton exceeded precipitation (Fig. 9b). The recharge of groundwater at this time of the year must have taken place mainly by infiltration of river water from Ygleelvi, and the observation points in the discharge area were hardly affected by precipitation derived surface water. This period seemed more promising for studies of transit times on the basis of our environmental tracers.

The measurements from Ygleelvi (Fig.8a) depict the start of a decreasing trend for δ^{18} O ‰ from about 1 April. We consider this trend to represent the input of meltwater from the high-altitude parts of the catchment, labelled with the winter's low isotopic signatures. At observation point G the start of a decreasing trend is recorded around 15 April (Fig.8b). Provided this is the arrival of the same isotopic signal, a transit time of about 15 days from the recharge area to G is indicated.

The interpretation of the δ^{18} O ‰ values for Kaldebekken is not as straightforward. A decreasing trend during the first weeks of May is succeeded by a rising trend which is followed by a second decreasing trend from about 1 June (Fig.8c). The first period with decreasing δ^{18} O ‰ values coincides in time with a period where the water levels in Kaldebekken are high, but without any precipitation. The lower parts of the drainage area were free of snow at that time, so we consider this trend to represent the input of local high-altitude meltwater from the flood- and meltwater stream Båtskredi (Fig.4). The snow pack drained by Båtskredi, however, is small, as the area available for snow accumulation is very limited because of the steep topography. The isotopic fingerprint from this input of meltwater has probably only resulted in a small lowering of the δ^{18} O ‰ values in Kaldebekken. The second decreasing trend, which is more pronounced, can be related to the propagation of the isotopic signal from the meltwater in Ygleelvi. This interpretation gives a residence time of about 60 days from the recharge area at Ygleelvi to Kaldebekken. In Ygleelvi there are also two subsidiary maxima, M1 and M2, on the 27 May and 22 July. The arrival of these two isotopic signals is recorded at observation point G on 17 June and 19 August, and at Kaldebekken on 29 July and 23 September. Both these signals give a transit time of 64 days from the recharge area I to Kaldebekken.

Temperature

The temperature of the groundwater in shallow aquifers is affected by daily and seasonal variations in the air temperature. The temperature in groundwater formed by infiltration of river water will display roughly the same trend as the river water. There will, however, be a time-lag, and the temperature of the groundwater could also be slightly higher (Walton 1970, Kihlstrøm 1993). By monitoring the propagation in the aquifer of a well-defined temperature maximum or minimum in the river water, it should be possible to obtain an estimate of the residence time in the aquifer. The time-temperature regression curves (Fig.10) depict similar seasonal variation patterns for all three observation points. In Ygleelvi, a well-defined temperature minimum is identified on about 4 February (Fig.10a). Similar temperature lows at observation point G and Kaldebekken are identified around 25 February and 8 April, respectively (Fig.10 b,c). The temperature of the groundwater leaving the aquifer at this time was about 1.5°C higher than the temperature of the cold water entering the aquifer in early February.

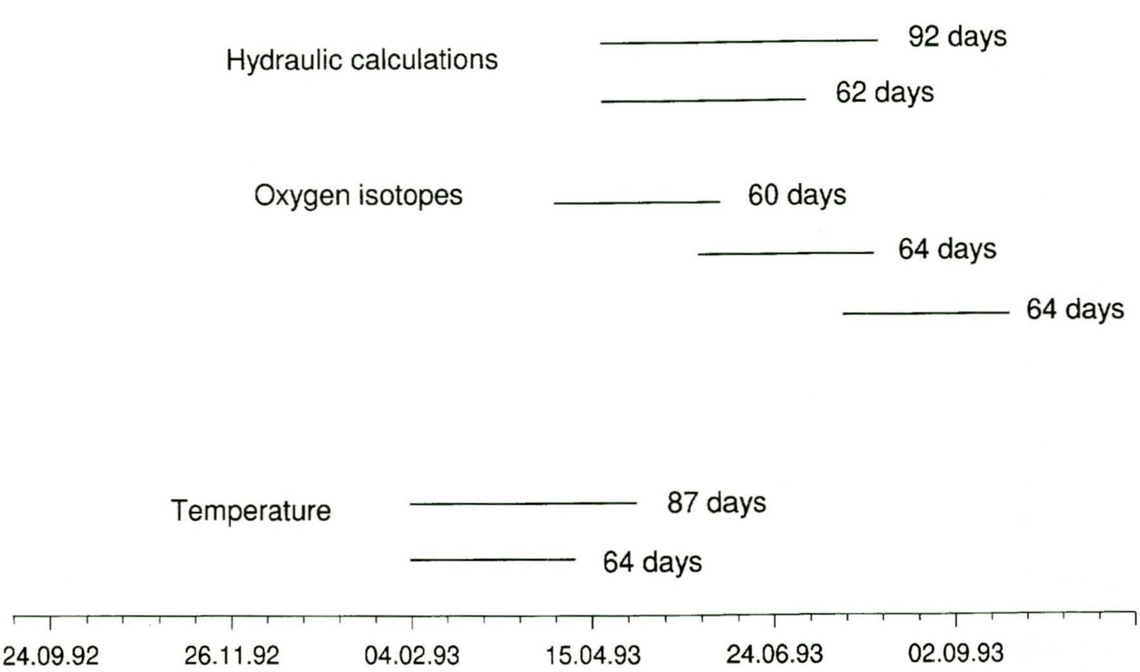

Fig.11. Transit times obtained by the various methods. See text for discussion.

We consider the lows on the time-temperature regression curves to represent the arrival of the temperature signal through the aquifer, thus giving a residence time of about 64 days from the recharge area by the river bed in Ygleelvi to the discharge area in Kaldebekken. If we consider only the data points, a subsidiary minima around 1 May may be associated with the same input of a component of cold meltwater from Båtskredi which caused the lowering of the $\delta^{18}O$ values in Kaldebekken at that time. Alternatively it could be interpreted as a transit time of 87 days.

Comparison of results

Calculated transit times obtained by the different methods are summarised in Fig.11. The three isotopic $\delta^{18}O$ signals from water entering the aquifer in the period 1 April to 22 July give transit times of 60, 64 and 64 days. Hydraulic calculations based on the prevailing hydraulic gradient during that period (i.e. 0.05) give transit times of 62 days (n_e = 0.20) and 92 days (n_e = 0.30). The temperature signal that entered the aquifer around 4 February gives transit times of 64 days or alternatively 87 days. Normally we would expect longer transit times in the winter months due to a smaller hydraulic gradient at that time of the year. However, the winter of 1993 was extremely mild and wet. From early February the temperatures in Esebotn were above 0° C, and there was a considerable amount of precipitation in February and March (Fig.9). Hence, the winter discharge in Ygleelvi in 1993 did not differ much from the snowmelt discharge in the late spring and early summer, and hydraulic gradients and transit times for these two periods would not differ significantly. We thus consider the results obtained from these three methods to be broadly comparable. The consistency in transit times obtained from the $\delta^{18}O$ signals suggests to us that the oxygen isotopes are the most reliable and precise means for calculating transit times.

Conclusions

Simple hydrogeological calculations applying a Darcian approach give transit times of about 60 - 90 days for the river water from Ygleelvi entering the aquifer in late spring and early summer. The use of environmental tracers, oxygen isotopes and temperature give comparable results. We conclude that the environmental tracer approach also has applications in areas where climatic conditions are more extreme and variable than in inland areas. A pre-requisite for such an approach is a thorough monitoring of the total hydrological and climatic system. The monitoring of the propagation of the isotopic signal delivered by the snow-melt in high-altitude areas appears to be the most fruitful approach in studies of residence times. The oxygen isotopes also provide valuable information about the relative contributions of infiltrated river water and more local water derived by recharge of precipitation on the river plain. The proportion of recharge due to river infiltration and precipitation varies in both space and time. Such information is particularly important in the context of groundwater development, as it could be used to select optimum abstraction sites for groundwater with regard to protection and water quality.

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