Groundwater contribution to a mountain stream channel, Hedmark, Norway.

SYLVI HALDORSEN, JENS-OLAF ENGLUND, PER JØRGENSEN, LARS A. KIRKHUSMO & DAG HONGVE

Haldorsen, S., Englund, J-O., Jørgensen, P., Kirkhusmo, L.A. & Hongve, D. 1992: Groundwater contribution to a mountain stream channel, Hedmark, Norway. *Nor.geol.unders. 422*, 3-14.

The Skvaldra stream in Hedmark, Southern Norway is characterized by a stable baseflow. This baseflow is controlled by a significant groundwater supply from Quaternary deposits. The area was chosen for an attempt at quantification of the baseflow's three groundwater components; (i) groundwater from numerous springs on a spring-horizon at the boundary between permeable sediment-flow deposits in the upper valley side and compact basal till deposited along the lower part of the valley sides and the valley bottom; (ii) groundwater from aquifers in compact basal till, topographically lower than the spring horizon; (iii) deep groundwater from till or underlying bedrock. Flood events in the Skvaldra are due to surface run-off, usually confined to the valley bottom along the stream channel, or due to very shallow subsurface interflow, with very little or no groundwater component. Even when the baseflow is very low ($<$ 0.05 m^3s^{-1}), groundwater from the springs makes up more than 70% of the total flow. Groundwater from the compact till constitutes about 10% of the baseflow, while deep groundwater makes up less than 20%. During the summer the spring component is higher. During a year the baseflow varies between 0.03 and 0.1 m^3s^{-1}. Most of this baseflow is due to groundwater, and the groundwater component is at least 1 x 10^6 m^3 per year, corresponding to 10% of the annual precipitation.

Sylvi Haldorsen, Per Jørgensen, Jens-Olaf Englund, Institutt for jordfag, seksjon for geologi, Norges landbrukshøgskole, Postboks 28, 1432 Ås, Norway.
Lars A. Kirkhusmo, Norges geologiske undersøkelse, Postboks 3813 - Ullevål Hageby, 0805-Oslo, Norway.
Dag Hongve, Statens institutt for folkehelse, Geitmyrsveien 75, 0462 Oslo 4, Norway.

Introduction

Terrain covered by till or with a surface of strongly frost-weathered bedrock characterizes the mountainous regions of south central Norway. In some mountain areas the groundwater contribution to streams and rivers is considerable. It gives a stable and significant baseflow and has an important influence upon the chemical composition of these waters. The routing of water along surface and sub-surface flow paths in such mountainous areas is important because it influences the timing of stream flow and the chemical composition of water reaching the stream. In a catchment consisting of fractured bedrock overlain by glacial sediments, the rivers may receive water from deep regional groundwater flow paths as well as shallower water from the glacial overburden. Two general approaches have been used to better define the sources and actual flow paths of water in catchments (e.g. Horton 1933, Pinder & Jones 1969, Kirkby 1978, Germann 1986, Kennedy et al. 1986, Sklash et al. 1986); (i) physical observations from field studies, coupled with theoretical flow modelling, and (ii) measurements of changes in chemical and isotopic ratios of flow components. Observations from limnigrammes give some information about the hydrological properties of a catchment, but these cannot be anything but qualified guesses without field studies. Hewlett (1982) stated that «no graphical or mathematical operation performed on a hydrograph will reveal the source or pathway of stormflow». Different combinations of sources and pathways can lead to quite similar hydrographs. This study, therefore, uses chemical data in addition to the volume, rate, and timing of streamflow to clarify the sources of groundwater and the specific pathways along which groundwater moves through a catchment.

The Skvaldra catchment in Hedmark was selected for the study because the Skvaldra stream receives groundwater from thick Quaternary deposits along the valley sides and because human influence is small. It is therefore well suited for an attempt to quantify the different groundwater components which contribute to the Skvaldra's streamflow. The investigation is mainly based on data from the period 1987 to 1991.

Study area

Topography, climate and land use

The study was carried out in the upper part of the Skvaldra catchment, Godlidalen, which covers 13.5 km^2 (Fig. 1). Godlidalen is an asymmetric valley with a rather flat valley floor, bounded by mountainous areas to the north and east, and lower hills between the Skvaldra catchment and the main Åstdalen valley to the west. The altitude varies from 875 m above sea level (a.s.l.) in the valley bottom up to 1090 m at the highest mountain summit in the east. The Skvaldra stream forms a dendritic pattern, with most of the tributary streams coming from the east. In the western part of the catchment there are two small lakes (Fig. 1).

The annual precipitation is about 1100 mm (Fig. 2). Winters are normally cold with temperatures well below 0°C, and the snow falls from the beginning of November. The main snow melt period is usually in the latter part of May. Two of the study years, 1989 and 1990, were exceptionally mild, with little or no snow accumulation until late December and with the main snow melt in late April.

Peatland constitutes about 40 percent of Godlidalen, and dominates completely below the timber line. The Skvaldra catchment is used only for extensive grazing by sheep, hunting and recreation. Other sources of pollution are insignificant.

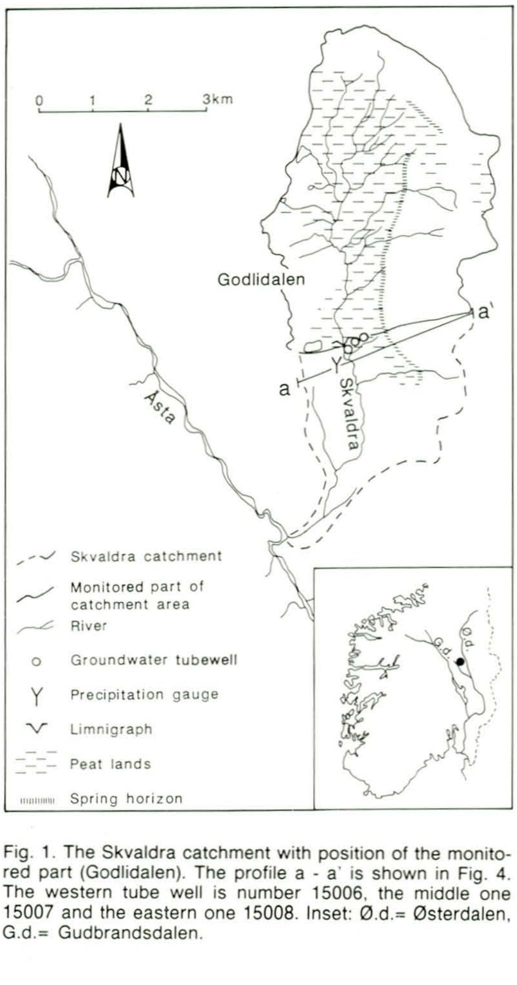

Fig. 1. The Skvaldra catchment with position of the monitored part (Godlidalen). The profile a - a' is shown in Fig. 4. The western tube well is number 15006, the middle one 15007 and the eastern one 15008. Inset: Ø.d.= Østerdalen, G.d.= Gudbrandsdalen.

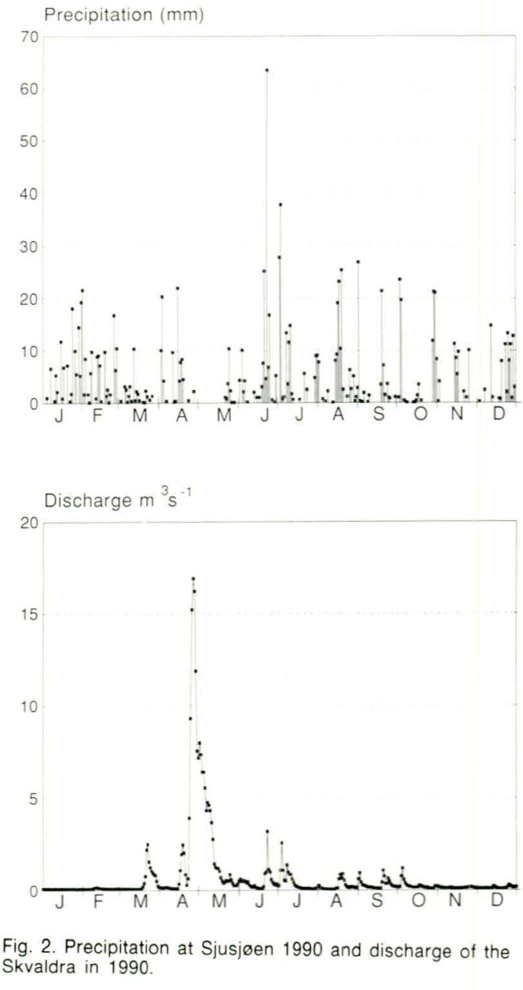

Fig. 2. Precipitation at Sjusjøen 1990 and discharge of the Skvaldra in 1990.

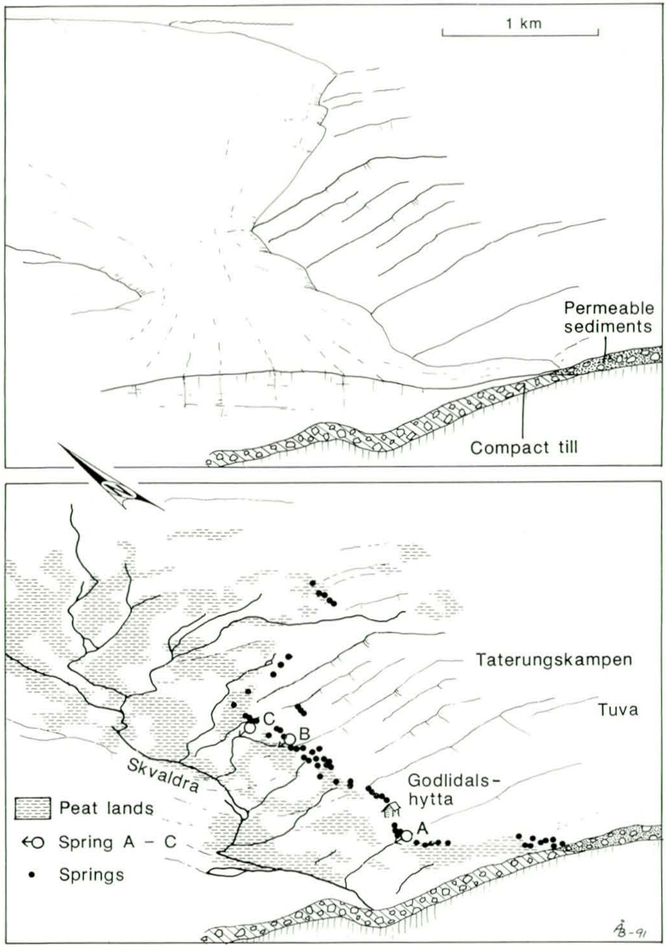

Fig. 3. Depositional model for the Quaternary sediments in the Skvaldra catchment.
Top: Relation to the glacier during glaciation.
Bottom: Present day, showing positions of the springs & peatlands.

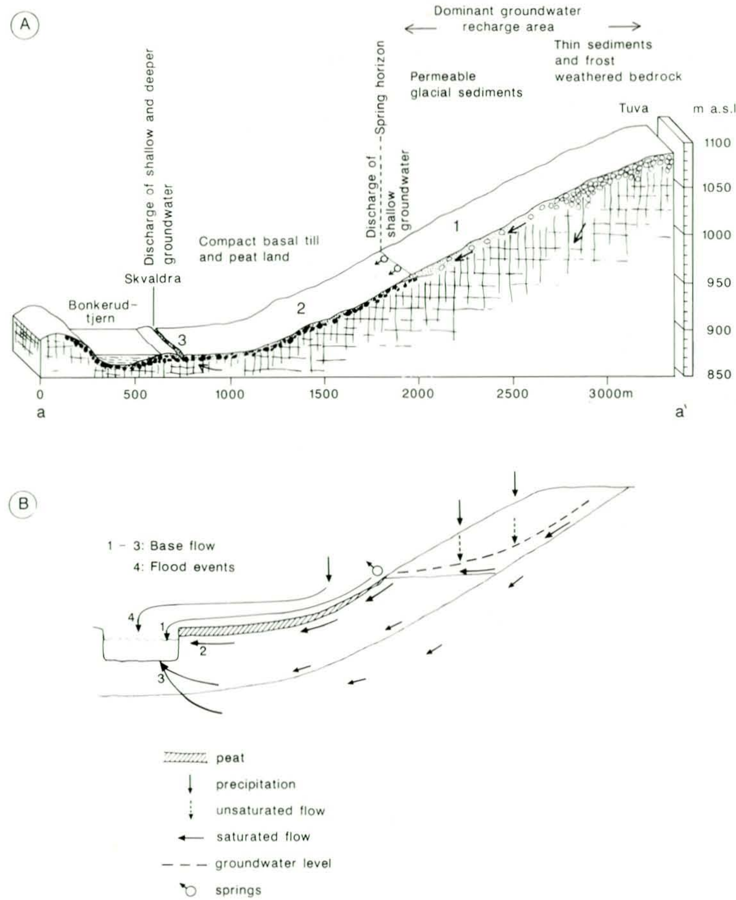

Fig. 4. (a) WSW-ENE geological and hydrogeological profile a - a' through the southern part of the Godlidalen based on the seismic investigations of Hillestad (1990). Position of profile is shown in Fig. 1. (b) Main hydrological budget of the Skvaldra.

Bedrock geology

The Skvaldra catchment is situated in the middle of a Late Precambrian sedimentary rock basin. The bedrock belongs to the upper part of the Brøttum formation and consists of alternating fine-grained conglomerates and arkosic sandstones (Siedlecka et al. 1987). Seismic studies (Hillestad 1990) showed that the bedrock underlying the Quaternary sediments can be regarded as only moderately fractured, i.e. with seismic velocities between 4500 and 5500 ms^{-1}.

Quaternary geology

The valley bottom and the lowest part of the valley sides (about 6.5 km^2) are covered by a compact silty basal till of thickness c. 10 m (Køhler 1985, Hillestad 1990) (Figs. 3 & 4). Its petrographic and granulometric composition is very homogeneous because it was formed by comminution of the arkosic bedrock alone (Haldorsen 1982, 1983). Glaciofluvial material is found locally along the Skvaldra and this is probably underlain by till. Bedrock exposures are almost absent.

The upper part of the valley sides (about 7 km^2) is covered by a 5 - 10 m thick layer of more permeable and less compact material, much of it unsorted. Debris flow deposits dominate. The sediments as a whole are inhomogeneous and form a hummocky surface. Meltwater channels are frequent, and in many of these only coarse boulder lags remain. Some of the channels extend deep into the till.

The distinct boundary between compact till and more permeable material can be followed at an altitude of 950 m in the south up to about 1000 m in the northern part of Godlidalen, where it continues into a prominent moraine ridge. The boundary marks the upper limit of an active glacier during the Weichselian period (Fig. 3). Compact till was then deposited subglacially, while the material along the ice-free valley sides was exposed to water sorting, flow and frost activity.

Above an altitude of about 1050 m the cover of Quaternary sediments becomes thinner and the summits are characterized by boulder fields, formed by intensive frost activity, probably during a period of periglacial climate.

General hydrology of the Skvaldra

The baseflow of the Skvaldra is defined as the lowest discharge which is observed between clearly separated flood events, and it is normally between 0.03 and 0.1 m^3s^{-1} (Fig. 2). The annual baseflow is 1 - 3 x 10^6 m^3, corresponding to 110 - 220 mm (i.e. 10 - 20%) of the precipitation. During snowmelt floods, the discharge in the Skvaldra can reach 20 m^3s^{-1}. During the summer, stormflows of more than 2 m^3s^{-1} have been measured.

Monitoring

The precipitation in summer was measured with a Plumatic precipitation gauge (Fig. 1) and the data was processed by the Norwegian Meteorological Institute (DNMI Station 0676 Åstdalen - Skvaldra). During the winter, precipitation data from the meteorological station at Sjusjøen, 30 km west of Godlidalen, were used (DNMI Station 1296 Sjusjøen - Storåsen). The precipitation data from Sjusjøen are almost the same as those from Godlidalen during the summer and fall, and it is therefore assumed that they are also representative for the winter period.

The discharge of the Skvaldra was measured with an Ott limnigraph (Fig. 1). Glaamen og Laagen Brugseierforening was responsible for the instrumentation, and the limnigrammes were analysed by the Norwegian Water Resources and Energy Administration (NVE 2673-0).

For spring A (Fig. 3) the discharge was measured each time a water sample was collected, while for spring B (Fig. 3) the discharge was monitored closely only during two shorter summer periods. The discharges of these springs were measured with a tipping bucket or a bucket and a stop watch.

Three groundwater monitoring tubewells of 5/4'' diameter and with a filter tip of one metre length were placed in the till by the Geological Survey of Norway (Fig. 1) (LGN Station 24/Åstdalen 15006, 15007 and 15008). Groundwater levels in these were measured with a manual measuring tape.

Groundwater types and groundwater chemistry

The main groundwater recharge areas are the area of frost weathered bedrock at the top of the mountains and the permeable sediments along the valley sides (Fig. 4). Lower

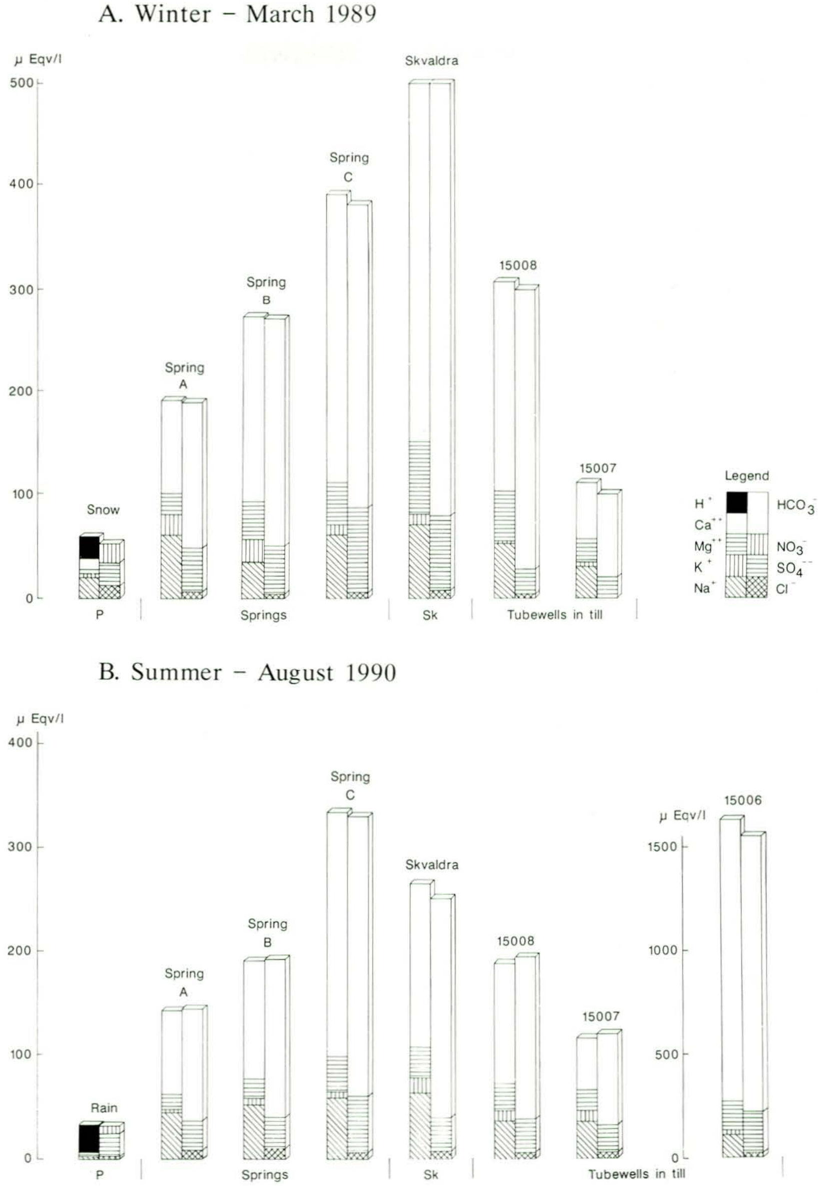

Fig. 5. Ion composition of the main water types in Åstdalen. Precipitation (P), groundwater springs A, B and C, Skvaldra, and groundwater tubewells 15008, 15007 and 15006. Bars on left show cations and bars on right show anions.Winter data are from 1989. Summer data are from 1990.

down, the peatlands form an effective barrier against groundwater recharge. Three main groundwater types dominate (Fig. 4a, 4b):

(i) Groundwater in the inhomogeneous permeable sediments along the upper part of the valley sides. Data from Haldorsen et al. (1983) suggest that the hydraulic conductivities of these sediments may be up to one hundred times higher than those of the compact basal till lower down. The groundwater in these upper sediments discharges via a marked spring horizon (Figs. 1, 3 & 4) (Køhler 1985).

The springs are classified as contact springs, since they occur at the boundary between the permable upper sediments and the compact basal till. The spring water follows numerous small streams from the spring horizon down to the Skvaldra.

(ii) Shallow groundwater in the basal till along the lowest part of the valley sides and in the valley bottom. This water discharges along the valley bottom. Some discharge may occur from the till to the peatlands, but the main part probably flows from the till directly to the Skvaldra.

(iii) Deep groundwater in the lower parts of the till or in the bedrock, with a long residence time, which discharges in the middle of the valley (see Englund 1986).

From a conceptual standpoint, flow systems in catchments can be considered to fall between two end-member extremes; those that are dominated by near-surface flow paths and those that are dominated by deeper groundwater flow paths (e.g. Peters & Murdoch 1985, Parsons et al. 1986, Winter 1986, Baron & Bricker 1987).

The bedrock in Godlidalen is resistant to chemical weathering and most of the groundwater has a rather short residence time. The area is dominated by near-surface flow paths. As a result the groundwater which discharges into the Åsta (Fig. 1) has a low ionic strength (Fig. 5) compared with other types of Norwegian groundwater (Englund 1983).

Calcium, magnesium and sodium are the major cations, with potassium as a minor constituent. Bicarbonate and sulphate are the dominant anions. Calcium, magnesium, sodium and bicarbonate constitute more than 90% of the total ion content. The difference in chemistry for the studied groundwater types is mainly reflected in the different contents of cations and bicarbonate.

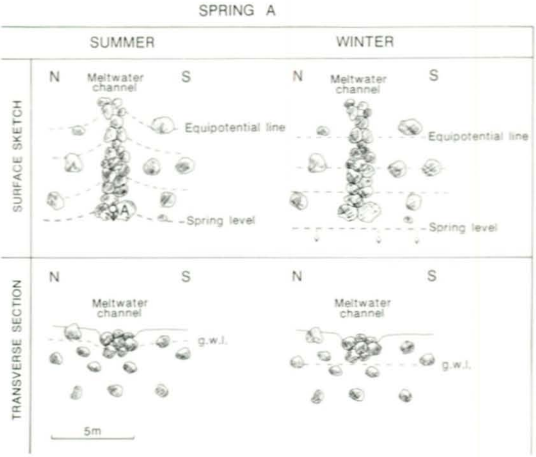

Fig. 6. Model of spring A (shallow groundwater) and its relation to the meltwater channel. For position of spring A see Fig. 3.

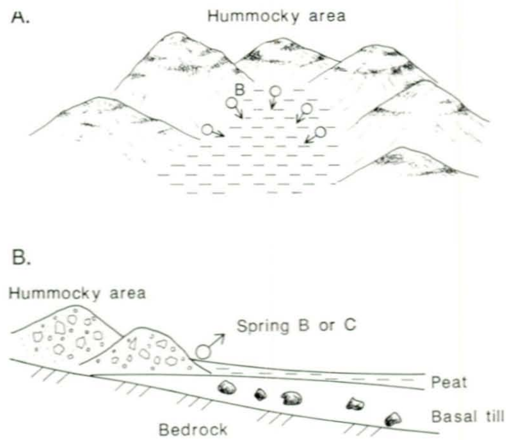

Fig. 7. (a) Position of spring B in a hummocky area. (b) Model of springs B and C. For geographical position of the two springs, see Fig. 3.

Springs

The marked spring horizon along the eastern valley side is found at an altitude of 930 m.a.s.l. in the south, rising to about 1000 m in the north (Figs. 1, 3 & 4). More than 80 distinct springs can be mapped over a distance of three kilometres, with more diffuse seepage faces between them.

The seismic profile indicates that the permeable sediments are mainly unsaturated (Fig. 4b), with seismic velocities between 800 and 1000 ms^{-1}. The saturated zone must be rather thin with a flow parallel to the bedrock surface down towards the spring horizon.

The most typical springs are found in the following positions:

(i) Single springs downslope of meltwater channels which act as confluence areas for the groundwater (Spring A, Figs. 3 & 6).

(ii) Groups of springs inside topographical depressions downslope of greater accumulations of coarse sediments. The latter common-

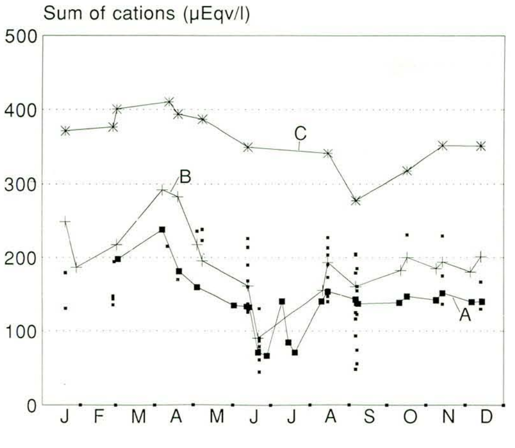

Fig. 8. Cation content (μeq/l) of the springs during the years 1989-1991. Samples from all three years are plotted in the same diagram to show the general annual variation. Springs A, B and C are shown by curves. Small black squares are samples from other springs in the catchment.

ly form a distinct hummocky topography (Spring B, Figs. 3 & 7).

(iii) Single spring outlets in topographical positions some metres below springs of types (i) and (ii) (Spring C, Figs. 3 & 7b).

Between the marked spring outlets, a seepage face extending along the whole valley side feeds the downslope peatland areas with water (Fig. 3). In dry summer periods no streams are found above the spring horizon. The streams leading from the springs have a significant discharge even after long dry summer periods and also during the whole winter.

The ion concentration varies among the springs (Figs. 5 & 8), with the highest concentrations for the springs topographically lowest down in the valley side. The highest concentrations in the springs are found at the end of winter (March-April) (Fig. 8) before the meltwater reaches the water table. Variations in concentration reflect degree of dilution and variations in storage time for the groundwater.

The similarities in groundwater level fluctuation and chemical composition indicate that all the springs are fed by the same type of aquifer, a shallow unconfined aquifer in coarse Quaternary sediments. Since the sediments are rather inhomogeneous they probably form many local, limited aquifer units rather than one single continuous aquifer along the valley side.

Three springs, A, B, and C, have been studied in more detail.

Spring A (Fig. 3) has a relatively low ion content (Figs. 5 & 8). Its upper, main outlet is active only when the groundwater level is high, i.e. from May to the middle of October (Figs. 6 & 9). The rest of the year only a diffuse seepage face is found some metres below the main spring A outlet. The highest groundwater level is established one to two months after the snow melt. After the start of an intensive rainy period during the summer it takes at least two weeks before the discharge from spring A starts to increase (Fig. 10).

Spring B has a medium ion concentration (Figs. 5 & 8). Its discharge is more stable than that of spring A, but spring B also has its highest discharge in the middle of the summer.

Spring C has the highest ion content of all the springs. The lowest values, found in the middle of the summer, are higher than the highest winter values for springs A and B (Figs. 5 & 8). The discharge from spring C is significant even in the late part of the winter.

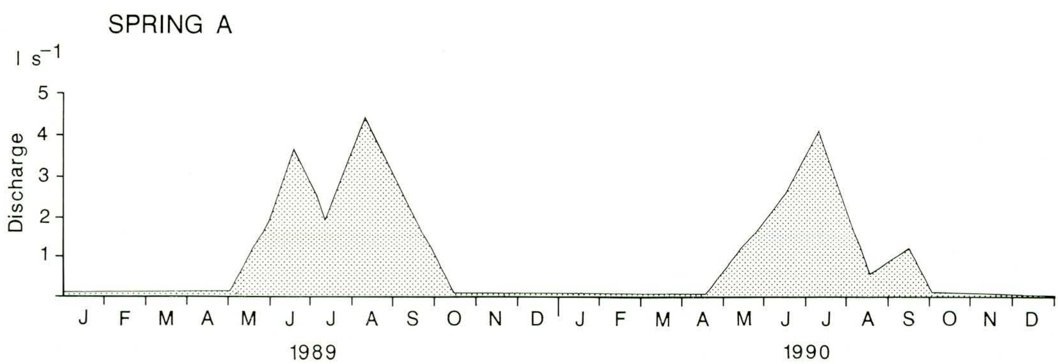

Fig. 9. Discharge of spring A (l/s) in 1989 and 1990.

The change in chemistry along the stream flowing from spring A to the Skvaldra is insignificant during low discharge situations in summer, as well as during winter. The water sampled at the spring outlets is therefore representative of the groundwater that drains into the Skvaldra via the small streams leading from the springs.

The water supply to the Skvaldra from the springs thus has an annual variation with one main maximum in discharge during the summer. This is the same annual variation which is observed for other aquifers in the inland mountain areas of south Norway (Kirkhusmo & Sønsterud 1988).

Groundwater in basal till

About 80% of the compact basal till, stretching from the spring horizon down to the Skvaldra, is covered by peat (Fig. 1). The till forms local unconfined aquifers along the valley side where it is not covered by peat. Along the valley bottom the peat forms a confining layer. Two groundwater tubewells are located in an unconfined part of the compact till in the lower part of the valley side (the two tubewells to the right in Fig. 1). The lower one (NGU 15007) extends to a depth of 2.4 m below the ground surface and the upper (NGU 15008) to a depth of 5.1 m. The distance between them is about 100 m.

Falling head tests (method: Hvorslev 1951) gave hydraulic conductivities of 2×10^{-7} ms^{-1} (tubewell 15007) and 5×10^{-8} ms^{-1} (tubewell 15008), which are typical values for a compact basal till (Lind & Lundin 1990). The till thus has a limited ability to transport water down to the valley bottom. The annual groundwater fluctuation in the two tubewells is about 1.5 m, with the highest values occurring during the summer. This is a typical pattern for groundwate in the mountainous regions of southeastern Norway (Kirkhusmo & Sønsterud 1988).

The contribution of water from the till to the Skvaldra has been calculated in two different ways:

(i) Lowering of the groundwater table. During the winter months there is no recharge to the till, except for some water which may flow into the till from the permeable sediments of the upper area (Fig. 4b). There is no loss of water from the till by evapotranspiration. The

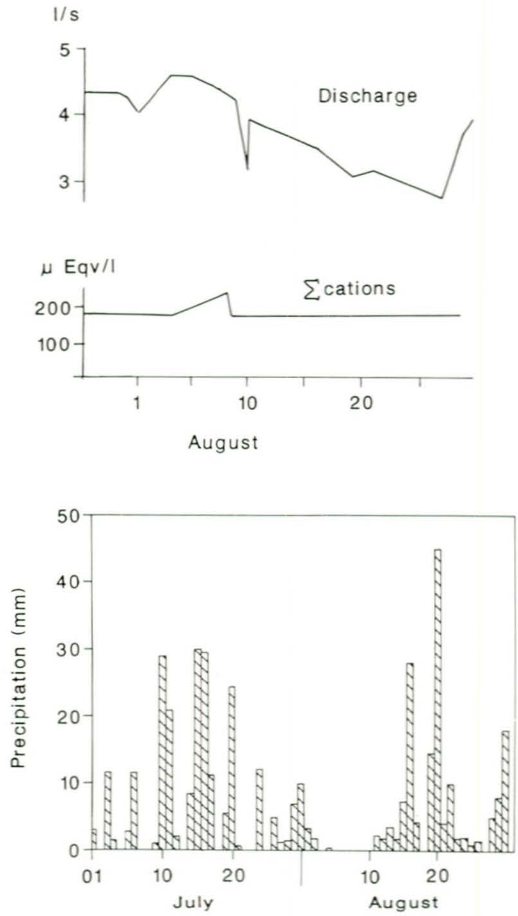

Fig. 10. Variation in discharge and cation content of spring A in August 1988 in relation to precipitation in July and August 1988.

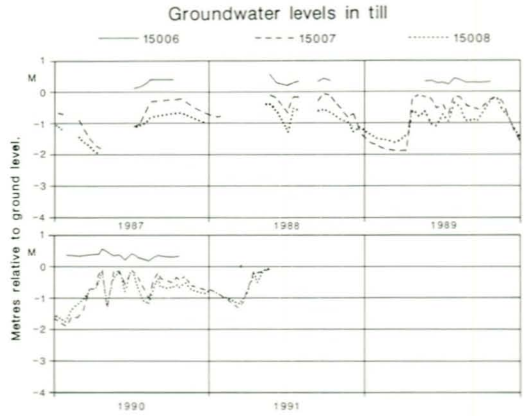

Fig. 11. Fluctuations in groundwater level of tubewells 15006, 15007 and 15008.

lowering of the ground water level (Fig. 11) roughly corresponds, therefore, to the amount of water which has drained from the till to the bottom of the valley and later contributed to the discharge of the Skvaldra. From Dec.12th 1989 to Feb. 25th 1990 (75 days) the groundwater level declined by 50 cm in both tubewells 15007 and 15008. Based on other studies of basal tills (e.g. Haldorsen et al. 1983) specific yield is estimated to about 10% and the length of the till slope from the spring horizon down to the Skvaldra is about 1 km. If the whole till area was an unconfined aquifer, the observed lowering of the water table would correspond to a release of water from the till to the Skvaldra of 8×10^{-3} m^3s^{-1} per km^2. However, much of the till forms a confined aquifer, where the storativity is much less than the specific yield. A general lowering of the piezometric surface by half a metre in the confined parts of the till aquifer would yield a much smaller amount of water to the Skvaldra than calculated for unconfined conditions. Based on typical values of storativities for confined aquifers, the real flux from the whole till area to the Skvaldra is probably not more than a tenth of the calculated value.

(ii) Groundwater flow to Skvaldra. The groundwater gradient between the two tubewells is 1:10 which is equal to the topographical gradient. This is representative for the whole till slope from the tubewell 15007 up to the spring horizon. The flow of groundwater is thought to be mainly one-dimensional and directed down the valley slope. The hydraulic conductivity around tubewell 15007 at 2 m depth was found to be 10^{-7} ms^{-1}. The hydraulic conductivity nearer the till surface is obviously much higher due to the occurrence of fractures and root channels, while the values deeper down probably are lower (as for tubewell 15008). If the hydraulic conductivity value from tubewell 15007 is used, and the average thickness of the till is estimated to be 10 m, Darcy's law implies a water transport of 10^{-4} m^3s^{-1} down to the Skvaldra per km width of the area.

The whole till slope area in Godlidalen is about 7 km^2. If the calculation above is representative, it indicates that the Skvaldra receives a till water component of between 6×10^{-3} and 7×10^{-4} m^3s^{-1} during the middle of winter.

Water samples from the two tubewells in the till have ion concentrations which are similar to many of the springs (Fig. 5). Water samples taken from tubewell 15008 have a higher ion concentration than those from tubewell 15007 because the former is placed deeper down in the till. Samples from the bottom of the peat between the Skvaldra and tubewell 15007 give values in the same range. It is thus not possible to distinguish between water from the till and water from the springs by means of chemistry alone.

The till water has been sampled only in the area between the Skvaldra and tubewell 15008 and only down to 5 metres depth. Till water from other parts of the area has not been studied. However, since the basal till is very uniform, the obtained values are probably representative for other parts of the till down to a depth of 5 metres.

Groundwater with a long residence time

In the middle of the valley bottom, close to the river Skvaldra a groundwater tubewell in till extends to a depth of 3.5 m below ground level (NGU 15006, the tubewell to the left in Fig. 1). The conditions are artesian the whole year, with a pressure surface above ground level (Fig. 11). The ion concentration in water from this tubewell is about ten times higher than that of most of the other studied groundwater types (Fig. 5). The ion concentration has only a small variation throughout the year. The artesian pressure could be caused by the unconfined aquifer in the upper part of the valley sides feeding a confined aquifer lower down. However, the high and rather stable ion concentration indicates that this is a deep groundwater, or a groundwater with a significantly long residence time, which discharges in the centre of the valley, as has earlier been proposed for the main Åsta catchment (Fig. 1) (Englund & Haldorsen 1983, Englund 1986). The small variations in pressure head and chemical composition indicate a nearly constant annual flux of this groundwater type. It is not clear if the water originates from the deepest part of the till or from the bedrock below it.

Tubewell 15006 is the only locality where the deep groundwater has been sampled. Its representativeness for the catchment as a whole has not been verified. However, the bedrock is very homogeneous, as is the overlying till. The topographical gradient of the valley sides in the studied part of the catchment does not vary very much, and the gradient of the valley bottom is very small. There is, therefore, no reason to suppose that the deep groundwater component along the valley should vary significantly. Streamwater samples taken at several places along the Skvaldra in August 1987 and 1988 showed very little variation in water chemistry (Bosch et al. 1988, Anema et al. 1989) indicating a rather uniform distribution of the different water components along the Skvaldra.

The influence of the deep groundwater is clearly seen in the chemistry of the Skvaldra. In the winter the ion concentration in the Skvaldra's streamwater is normally higher than in spring C (Fig. 5). There are no other sources for such water other than the deep groundwater which discharges in the middle of the valley.

Peatland hydrology

The 40% of the Skvaldra catchment which is covered by peatlands (Figs. 1 & 3) plays an important role in its hydrology. The hydraulic conductivity of the peat was measured at three localities between tubewells 15006 and 15007 by falling or increasing head methods (Hvorslev 1951). For the upper part of the peat the value varies between 5×10^{-6} and 3×10^{-5} ms^{-1}, while below 50 cm depth the value drops to $1 - 2 \times 10^{-9}$ ms^{-1}. In the deeper part of the peat the hydraulic conductivity is much lower than in the till. The peatlands clearly act, therefore, as a confining layer overlying the till. The water transport through the deeper part of the peat must be very slow, and therefore of little importance for the hydrological budget of the Skvaldra.

Hydrological budget of the Skvaldra

Flood events

In 1989 and 1990 the snowmelt flood occurred from April to May (Fig. 2). The conclusions above indicate that the groundwater component of the snowmelt flood is insignificant, since the discharge from the springs and the groundwater level in the till are low during the whole snowmelt period. The snowmelt flood is therefore completely dominated by direct supply of melt water, as surface run-off or shallow channelled interflow, down to the Skvaldra.

Marked precipitation events in moist periods give a rapid increase in the discharge of the Skvaldra. After a rainstorm the discharge decreases very rapidly. The corresponding delay in the increase in discharge from spring A, which reacts quickly to rainstorms compared with the other springs, was found to be about two weeks. During this groundwater delay period, the discharge in the Skvaldra has typically nearly returned to baseflow conditions. This means, in the same way as argued for the snowmelt flood, that the groundwater supply is of very little importance for the discharge of the Skvaldra even during the latter parts of flood events. During a rainstorm, water discharges as surface run-off or follows shallow channels in the peat or the soil down to the Skvaldra (Fig. 4b). The peat is very important since it constitutes most of the area along the valley bottom. This is very apparent after heavy rain; the Skvaldra then becomes brownish-coloured due to a high humic content in the water. The water soluble humic substances stored in the peat are partly washed out from it under such conditions.

It is therefore concluded that groundwater flow does not significantly influence flood discharge in the Skvaldra during any part of the year.

Baseflow and groundwater budget

It is difficult to say how much of the baseflow is real groundwater and how much is surface water or shallow interflow water. In the Skvaldra catchment, water from peatlands, as well as from the three small lakes, will certainly contribute to baseflow during dry periods. According to studies by Yasuhara & Storrø (1992) in Trøndelag (mid-Norway) the flux from peatlands is important for the baseflow of rivers, even when the watersheds are rather dry. However, from October/ November and during the winter months, the surface water influence decreases and the baseflow becomes more and more dominated by groundwater. It is thus thought that the lowest discharge values recorded during winter approach the true groundwater baseflow value.

The January baseflow in the Skvaldra during the winters of 1989 and 1990 was about 0.25 m^3s^{-1}. By the latter part of February it had decreased to about 0.05 m^3s^{-1}. In 1991 the minimum discharge was even lower and February discharge values of 0.03 m^3s^{-1} were measured. To make a groundwater budget for these low baseflow situations, the following assumptions, which are based on the discussions above, have been made:

(i) The total baseflow is due to the three groundwater components described earlier in the paper, while the contribution from surface water is insignificant.

(ii) The deep groundwater sampled in tubewell 15006 is representative for the whole catchment.

(iii) The average groundwater component from the springs lies between the observed values for spring A and spring C.

(iv) The shallow till groundwater in the entire area has an average composition close to that of tubewells 15007 and 15008. The discharge from the till is not higher than 5 x 10^{-3} m^3s^{-1}.

(v) There exists no groundwater with a composition between that of spring C and tubewell 15006, i.e. there is a real difference between the deep groundwater component and the shallow groundwater, with no intermediate groundwater types.

Based on these assumptions one can make the following approximation of the groundwater budget for late February 1991. The cation concentrations for spring C, tubewell 15006, tubewell 15008 and the Skvaldra are applied as input data. The relative water contribution from the springs (X) and from deep groundwater (Y) are then calculated as follows:

X * cation concentration spring C
\+ Y * cation concentration tubewell 15006
\+ Z * cation concentration tubewell 15008
= cation concentration of the Skvaldra

Z is the relative water contribution from the till. The total discharge in Skvaldra in late February is 3.6 x 10^{-2} m^3s^{-1}. Thus,
Z = 5 x 10^{-3} / 3.6 x 10^{-2} = 0.14 (i.e. 14%).

The second equation required to solve this problem is,
X + Y + Z = 1 (total discharge is 100%).

The calculation yields a spring water component of 76%, a deep groundwater component of about 10% and a till water component of 14% of the total baseflow (Table 1).

Table 1. Calculated components (%) of different groundwater types contibuting to Skvaldra during winter baseflow periods. Data from spring A gives minimum, and data from spring C gives maximum, spring water components.

PERCENTAGES OF DIFFERENT GROUNDWATER BASEFLOW COMPONENTS

Based on data from		CALCULATED COMPONENTS (%) Spring water	Deep groundwater	Till water
Feb.1991	Spring A	66	20	14
	Spring C	76	10	14
March 1990	Spring B	82	13	5
March 1989	Spring A	70	20	10
	Spring B	72	18	10
	Spring C	79	11	10

If the lower ion concentration found in spring A is regarded as representative for the winter spring flow, the same calculation gives a spring water flux of 66%, a deep groundwater flux of 20% and a till water component of 14%.

A similar calculation for early March 1990, using data from spring B, yields a spring flow component of about 82%, a deep groundwater flux of 13% and a till water component of 5% (Table 1). For early March 1989 (Fig. 5) similar calculations give a spring component of 70, 72 and 79% and a deep component of 20, 18 and 11%, using data from springs A, B and C respectively. The till water component is then calculated to be 10%.

It is concluded, therefore, that the contribution from springs is the most important component of winter baseflow in the Skvaldra, comprising considerably more than 50%. The deep groundwater constitutes less than 20% of the total baseflow. The calculation of the flux from the basal till is based on a series of assumptions which are not verified by field data. However, the till water chemistry is so close to the spring water chemistry that an error in the till water flux would mainly affect the calculated spring water component and would have little effect on the calculated deep groundwater flux. The calculation of the maximum deep groundwater flux is thus regarded as a rather good estimate.

It was difficult to separate the baseflow part of the limnigrammes during the summer periods, because rain events were frequent during most of the observed summers. In addition the groundwater discharge responds very slowly to rain events, with a delay of at least two weeks. Compared with the winter, a calculation of the different groundwater components is complicated to carry out. However, this study does support the following deductions.

During the summer the total deep groundwater flux and till water component are probably about the same as in the winter. The spring discharges are at a maximum in the middle of the summer and early fall. The total groundwater flux is therefore expected to be higher in summer than in winter. The ion content of the Skvaldra baseflow is lower during summer than during winter because all the springs have lower ion contents in summer than winter (Fig. 5).

The mean annual groundwater flux to the Skvaldra must be more than 0.03 m^3s^{-1}, equivalent to at least 10% of the annual precipitation. Of this, most is recharged above the spring horizon, while precipitation along the lower part of the catchment mainly contributes to the flood events.

Acknowledgements

Financial support was provided from the Norwegian National Committee of Hydrology. Glaamen & Laagen Brugseierforening and the Norwegian Water Resources and Energy Administration were responsible for the discharge station. The Norwegian Meteorological Institute has been responsible for the precipitation data. Facilities have been placed at our disposal by Pihlske Skogsameie. B.v.d.Weerd, D.J.G. Nota and R.v.d.Berg from the Institute of Soil Science and Geology, Univ. of Wageningen supervised two groups of Dutch students in the field. Valuable comments and constructive criticism have been given by D. Banks, H. Rueslåtten, G. Storrø and an anonymous referee. G. Bloch, L. Jakobsen, B. Sønsteby and R. Sønsterud assisted in the field. Å. Borgan and B. Hopland drafted most of the figures. To these persons and institutions we render our sincere thanks.

References

Anema, D., Janssen, R., Nijssen, B. & Veenis, N. 1989: *A hydrogeological reconnaissance of the Skvaldra catchment, Southeastern Norway.* Agricultural University of Norway - University of Wageningen, 113 pp.

Baron, J. & Bricker, O.P. 1987: Hydrologic and chemical flux in Loch Vale watershed, Rocky Mountain National Park. *In:* Averett, R.C. & McKnight, D.M. (eds.), *Chemical quality of water and the hydrologic cycle.* Lewis Publishers, Chelsea, MI.

Bosch, R.v.d., Eggink, H., Pelgrum, R. & Vermaas, J. 1988: *A hydrogeological reconnaissance of the Skvaldra catchment, Southeast Norway.* Agricultural University of Norway - University of Wageningen, 84 pp.

Englund, J-O. 1983: Chemistry and flow pattern in some groundwaters of Southeastern Norway. *Nor.geol. unders. 380,* 221-234.

Englund, J-O. 1986: Spring characteristics and hydrological models of catchments. *Nord.Hydrol. 17,* 1-20.

Englund J-O. & Haldorsen, S. 1983: The Åstadalen catchment, southeastern Norway, geology and general hydrology. *Rep.Dept. of Geol.Agric.Univ. of Norway 18,* 42 pp.

Germann, P.F. 1986: Rapid drainage response to precipitation. *Hydrol. Processes 1,* 3-13.

Haldorsen, S. 1982: The genesis of tills from Åstadalen, southeastern Norway. *Nor.Geol.Tidsskr. 62,* 17-38.

Haldorsen, S. 1983: Mineralogy and geochemistry of basal till and their relationship to till-forming processes. *Nor. Geol.Tidsskr. 63,* 15-25.

Haldorsen, S., Jenssen, P.D., Køhler, J.Chr. & Myhr, E. 1983: Some hydraulic properties of sandy-silty Norwegian tills. *Acta Geol.Hisp. 18,* 191-198.

Hewlett, J.D. 1982: *Principles of forest hydrology.* The Univ. of Georgia Press. Athens, Georgia, U.S.A., 183 pp.

Hvorslev, M.J. 1951: Time lag and soil permeability in ground water observations. *U.S. Army Corps of Engin. Waterways Experiment.Stat.Bull. 36,* 50 pp.

Hillestad, G. 1990: Seismiske målinger i Åstadalen. *Nor. geol.unders. Report 90.036,* 5 pp.

Horton, R.E. 1933: The role of infiltration in the hydrologic cycle. *Ann.Geophys.Union Trans. 14,* 446- 460.

Kennedy, V.C., Kendall, C., Zellweger, G.W., Wyerman, T.A. & Avanzino, R.J. 1986: Determination of the components of storm flow using water chemistry and environmental isotopes, Mattole River Basin, California. *J. Hydr. 84,* 197-140.

Kirkby, M.J. 1978: *Hillslope hydrology.* John Wiley & Sons, New York, 386 pp.

Kirkhusmo, L. & Sønsterud, R. 1988: Overvåkning av grunnvann. *Nor.geol.unders. Report 88.046,* 15 pp.

Køhler, J.Chr. 1985: *Kvartærgeologisk kart - Godlidalen 1:10 000.* NLVF's inst. for georessurs- og forurensningsforskning (GEFO), Ås, Norway.

Lind, B.B. & Lundin, L. 1990: Saturated hydraulic conductivity of Scandinavian tills. *Nord.hydr. 21,* 107-118.

Parsons, D.J., Stohlgren, T.J. & Graber, D.M. 1986: Long term effects of acid deposition on selected ecosystems of Sequia National Park, California. *U.S. Dept. Interior, Nat. Park Service, Ann. Rep.,* Dec. 1986, Three Rivers, California.

Peters, N.E. & Murdoch, P.S. 1985: Hydrologic comparison of an acidic-lake basin with neutral-lake basin in the west central Adirondack Mountains, New York. *Water, Air & Soil Pollut. 26,* 387-402.

Pinder, G.F. & Jones, J.F. 1969: Determination of the groundwater component of peak discharge from the chemistry of total runoff. *Wat.Res.Res. 5,* 438-445.

Siedlecka, A., Nystuen, J.P., Englund, J.O. & Hossack, J. 1987: Lillehammer - berggrunnskart M. 1:250 000. *Nor. geol.unders.*

Sklash, M.G., Stewart, M.K. & Pearce, A.J. 1986: Storm runoff generation in humid headwater catchments 2. A case study of hillslope and loworder stream response. *Wat.Res.Res. 22,* 1273-1282.

Winter, T.C. 1986: Effect of groundwater recharge and configuration of the water table beneath sand dunes and on seepage in lakes in the Sand Hills of Nebraska, USA. *J.Hydr. 86,* 221-237.

Yasuhara, M. & Storrø, G. 1992: Baseflow production from partially peat-covered watersheds: A case study in middle Norway. *Nor.geol.unders. 422,* (this volume).

Manuscript received October 1991; revised typescript accepted February 1992.