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Spring Discharge and Aquifer Characteristics in a Sandy Till Area in Southeastern Sweden

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Spring discharge and groundwater levels were used to study groundwater outflow recessions, groundwater reservoir sizes, water yielding properties and saturated hydraulic conductivities in a sandy till area in southeastern Sweden. Water chemistry was used as an indicator of flow paths. The catchment areas of the five springs, ranging from approximately 0.01 km^2 to 0.2 km^2 in size, were all mainly covered with coniferous forest. The maximum active groundwater storages of the catchment areas of the springs varied from 75 to 145 mm. As a comparison the maximum total groundwater storage of the till in the catchment area of the largest spring was estimated to 1,250 mm. Two springs were chosen for detailed studies. The highest peak discharge of the smallest of these springs was 1.7 mm/day and it usually dried up in summer. The discharge from the largest spring was evenly distributed and varied between 0.2 and 0.8 mm/day. Frequent analyses of water chemistry during a spring with intense snowmelt revealed no change of water composition in spite of a great increase in discharge; for the smallest spring by more than 30 times. Integrated values of the specific water release from the unsaturated zone to the groundwater reservoir were calculated from runoff volumes and decreasing groundwater levels for the catchment area of the largest spring. The different values obtained from dry summer and winter periods, 0.024 and 0.047 respectively, indicated a strong influence from evapotranspiration. It the same spring, an areally integrated value of the saturated hydraulic conductivity was estimated to 6×10^{-5} m/s from a linearized solution of the Boussinesq equation.

Introduction

Groundwater studies in the coarse till aquifers, which are frequent in former glaciated hardrock areas, meet several methodological problems. The tills are heterogeneous and lenses of well-sorted coarse material are common. The representativity of point measurements is, consequently, a major problem. Stones and boulders are frequent and the matrix is often very compact, meaning that the installation of measuring devices and the extraction of undisturbed samples are difficult tasks. The tills are well-graded and the porosity is comparatively low. The saturated hydraulic conductivity is also low. Little water is released from the unsaturated zone at moderate tensions. The shallow water tables and the relatively high capillarity of the tills imply a strong interaction between evapotranspiration, the unsaturated zone and the groundwater zone.

Surface water and groundwater divides are generally assumed to coincide in this type of moraine terrain, if no specific indications on the contrary are obtained. Due to the small-scale topography, most aquifers are very small (0.01-1 km^2) and the water is not usually transported over long distances in the till. The terrain may be divided into groundwater recharge and discharge areas. The sizes of these areas vary during the year. The thickness of the aquifers are a few metres or less and the annual fluctuations of the groundwater level are 2-3 m in groundwater recharge areas. The infiltration capacity in the recharge areas usually exceeds the rainfall and snowmelt intensity. However, overland flow appears over shorter distances, especially in connection with intense snowmelt and frozen ground. Temporarily saturated horizons, due to low-permeability layers, may cause lateral flow. Little is known about the significance of macro pores in the percolation process.

The above-mentioned features mean that the application of a two- or three-dimensional integrated soil water and groundwater flow model should be desirable for studies of the relations between groundwater recharge, hydraulic properties and discharge. However, the application of such a model would be very complicated, measurements of input and calibration data laborious and costly, and the representativity of the gathered data questionable. There is a need for simplified models and a careful selection of important processes and parameters for such models.

Scope

In this study, measurements of discharge in some springs and groundwater levels in their catchment areas were used to study groundwater outflow recessions, groundwater reservoir sizes, water yielding properties and saturated hydraulic conductivities. The basic idea was that discharge from small springs, with catchment areas constituting almost entirely recharge areas of uniform geology and vegetation,

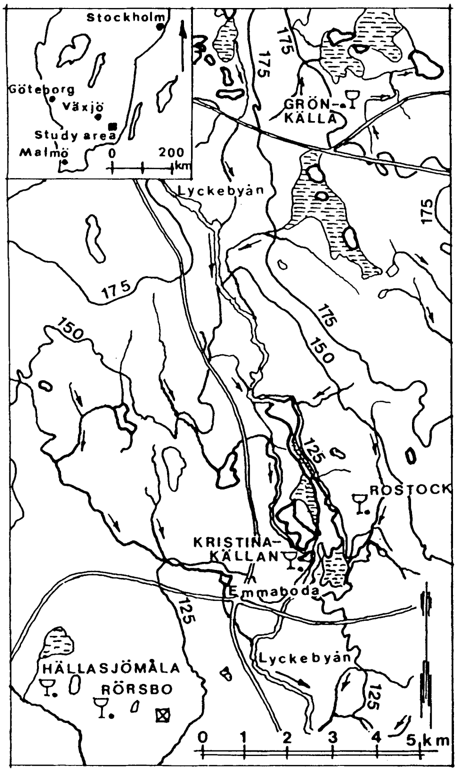


Fig. 1. Map of the study area

(·Ÿ spring; ⊠ meteorological station).

should enable derivation of areally integrated values of hydraulic properties of the till aquifers. From analyses of the chemical composition of the spring discharges, during periods of great variations in discharge, indications of water flow paths might also be obtained.

Description of the Study Area

The studies were located to moraine terrain in southeastern Sweden (Fig. 1). This area was chosen because till is the totally dominating soil type and different morphological moraine types are well-developed. Hydrogeological studies of till aquifers were earlier performed in this area by Knutsson (1971) and within the groundwater networks of the Geological Survey of Sweden (SGU).

The study area is situated within the catchment area of River Lyckebyån. The precipitation is 550-600 mm/year according to SMHI's stations situated within the catchment area. Eriksson (1983) suggested an increase of these values by 15-25% due to losses at the measuring devices caused by wind, evaporation and wetting. Snow constitutes 25-30% of the annual precipitation. The average annual potential evapotranspiration has been estimated to about 500 mm from the Penman equation (Wallén 1966). The average annual runoff of the catchment area of River Lyckebyån (785 km^2) is about 200 mm.

The entire study area is situated above the highest shore line and sandy till is the dominating soil type. The till cover is on average 4 m deep and underlain by granitic bedrock. The moraine landscape may be divided into drumlin and hummocky terrain (Knutsson 1971). The drumlin terrain is found in the higher parts of the landscape and consists of elongated hills of basal till, oriented in the direction of the glacial movement and formed around mostly outcropping rock cores. The till is often very compact. Lenses of sorted sand and gravel within the till can be continuous over rather long distances. Hummocky moraine dominates in the lower parts of the landscape. Here rock outcrops are scarce and the topography is usually not influenced by the bedrock morphology. The orientation of the moraine hills is irregular. The till is often comparatively loose. The lenses of sorted material are usually short and unconnected. Small fens, constituting discharge areas, are common.

The predominant sandy till is well-graded with comparatively low porosity and permeability. The porosity, the saturated hydraulic conductivity and the water release at moderate tensions are higher in the upper part of the profile due to the soil forming processes (see Fig. 6). The groundwater table is shallow, 0.5-4 m below the ground surface in most areas, and the capillary rise and transport are considerable.

Methodology

Five springs were chosen for the study after a field reconnaissance of about 25 (Fig. 1). A topographically well-defined catchment area and a distinct outlet were main criteria for the choice. The desire to have the different types of moraine represented and to use previous measurements of water chemistry performed by SGU were also taken into account.

Small weirs were installed at the five springs in Sep. 1981. The discharge measurements were performed manually once a week for all of the springs and in addition with continuously recording gauges for two of the springs. Detailed topographical mapping of the surroundings of the springs was carried out and preliminary catchment areas were determined based on the topography.

After approximately a year of discharge measurements a preliminary evaluation of the results was made. The evaluation revealed that the catchment areas of the springs at Hällasjömåla and Kristinakällan, determined from the topography, were considerably underestimated. The need for a survey of groundwater levels in the surroundings of the springs by installation of observation tubes was obvious. Due to economical reasons, continued studies had to be concentrated to two of the springs. The springs at Rostock and Grön källa were chosen, representing a small spring in hummocky moraine and a larger spring in drumlin terrain respectively. The measurements in the other springs were stopped in Dec. 1983.

Geophysical investigations (seismics and geoelectrical sounding) were conducted to elucidate the soil layer and bedrock morphology in the vicinity of the spring outlets at Rostock and Grön källa. Groundwater observation tubes were installed in the catchment areas of the two springs. Considerable difficulties were met due to the very compact and stony tills. Additional tubes would have been desirable at Rostock. At Grön källa undisturbed samples for measurements of water retention and saturated hydraulic conductivity were taken on different depths (length: 5-10 cm, diam: 7.2 cm).

The weekly spring discharge measurements continued at Rostock and Grön källa until late autumn 1985. At Rostock, daily measurements were conducted during intense snowmelt and rainy periods to check the variability in discharge. Measurements recorded continuously were taken at Grön källa during the first 8 months. Groundwater levels were measured weekly at Rostock and every 14 days at Grön källa and in addition recorded continuously for several months in observation tubes R11 and R15 at Grön källa.

In a measuring campaign March-May 1985, discharge and groundwater levels were measured and water samples taken every second day. The samples were analysed for macro constituents, pH, conductivity and oxygen-18. Oxygen-18 was supposed to be a good tracer of the origin of the discharging water (see for example Rodhe 1987).

Periods of aquifer emptying were chosen to study the relationship between spring discharge and aquifer characteristics such as groundwater outflow recessions, groundwater reservoir sizes, water yielding properties and saturated hydraulic conductivities. Boussinesq derived a differential equation describing transient groundwater flow in an unconfined, homogeneous and isotropic aquifer. In the case of an impervious base, same flow in all vertical parallel planes and no groundwater recharge, the cross-sectional flow is given by

$$\frac{\delta h}{\delta t} = \frac{K}{S}\frac{\delta}{\delta x}\left(h\frac{\delta h}{\delta x}\right) \tag{1}$$

where

h – height of groundwater table from the base
t – time
K – hydraulic conductivity
S – specific yield
x – distance from the water divide towards the outlet

Based on a linearized solution of Eq. (1), Boussinesq studied the emptying of aquifers and derived the following expression for the discharge at the outlet

$$Q_t = Q_0 e^{-\alpha t}, \qquad \text{for} \qquad \alpha = \frac{\pi^2 K \bar{h}}{4 L^2 S} \tag{2}$$

where

Q_t – discharge at time t
Q_0 – discharge at $t = 0$
α – recession coefficient
$\bar{h}$ – estimated average saturated thickness
L – distance from the water divide to the outlet.

(For derivation of the Boussinesq equation and linearized solutions see e.g. Bear, Zaslavsky and Irmay 1968; Singh 1968 and 1969). The expression of receding discharge in Eq. (2) gives the emptying of a single linear reservoir often used in hydrological modelling (see for example Bergström 1976).

The difference in groundwater storage between peak discharge and zero discharge may be calculated from

$$V = \int_{t_0}^{\infty} Q_0 e^{-\alpha t} \, dt \rightarrow V = \frac{Q_0}{\alpha} , \quad \text{if} \quad t_0 = 0 \tag{3}$$

where

V – volume of discharge
t_0 – starting time of recession

(see for example Englund and Meyer 1980). The difference in groundwater storage between highest peak discharge and zero discharge will here be called maximum active groundwater storage.

Besides the Boussinesq equation, the hydraulic conductivity was calculated for steady-state situations. In the catchment area of the largest of the springs, one-dimensional flow was assumed through a section perpendicular to the slope towards the spring outlet

$$K = \frac{Q}{b\,h\,I} \tag{4}$$

where

b – width of flow section
h – saturated thickness
I – hydraulic gradient

b was obtained from the determination of the catchment area while h and I were determined from the geophysical investigations and the groundwater observation tubes.

The specific yield concept is used in groundwater hydrology as a measure of the water yielding properties of the aquifer. Bear (1972, p. 485) defined specific yield as the average amount of water per unit volume of soil drained from a soil column extending from the water table to the ground surface, per unit lowering of the water table. The problem of applying the specific yield concept in the sandy till aquifers of the study area, with vertical heterogeneities, shallow groundwater tables and a considerable capillary rise, was discussed in detail by Johansson (1987 a,b). Under the prevailing conditions, the water release could be supposed to be affected by evapotranspiration. Here the intention was to test the applicability of the specific yield concept in an area where the conditions should be comparatively favorable, due to a groundwater table deeper than 2 m below the ground surface.

Integrated values of the water release from the unsaturated zone caused by the receding groundwater levels were obtained from measured discharge and groundwater levels during periods of insignificant rainfall and snowmelt

$$SWR = \frac{V_t}{\Delta h_t A} \tag{5}$$

where

SWR – specific water release
V_t – volume of spring discharge during the time period t
Δh_t – decrease in groundwater level during time period t
A – size of catchment area.

The term specific water release is used to avoid confusion, since the specific yield by definition is supposed to be independent of evapotranspiration.

Description of the Catchment Areas of the Springs

The catchment areas of the three springs, abandoned after two years of discharge measurements, will just be briefly described while more extensive descriptions will be given for the other two.

The Hällasjömåla Spring

The spring is located at the foot of a rather straight slope, which is about 250 m long and with an elevation difference of 15-20 m. The moraine is of the drumlin type. Rock outcrops are frequent at the crest of the slope. Immediately above the spring outlet there is a local discharge area (about 1,000 m^2) where the groundwater level reaches the ground surface during wet conditions. This area is drained towards the spring. The entire catchment area is covered by mature coniferous forest with spruce as dominating specie.

The Rörsbo Spring

The spring is located about 50 m down a slope from a small moraine plateau. The catchment area is topographically not very well-defined. The outlet is distinct. The moraine is of the drumlin type. The area, in immediate vicinity of the spring, is covered by mature spruce forest while the plateau is dominated by a 15-20 year old pine forest (the spring is included in SGU's groundwater networks).

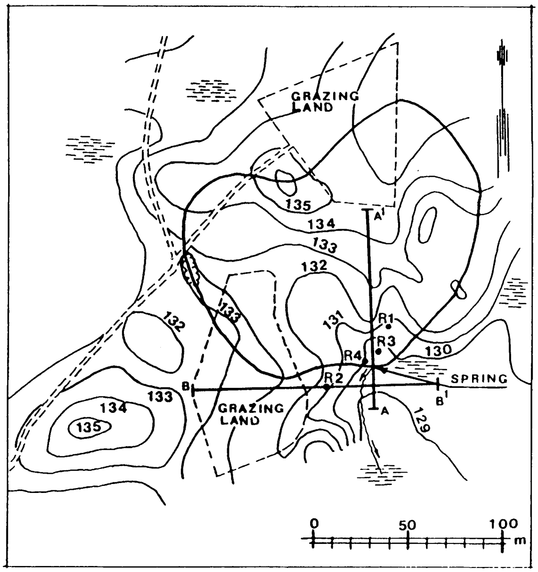
Kristinakällan

The spring is located at the foot of a local hill. The height of the small hill is about 10 m. The landscape is neither of a pronounced drumlin nor hummocky moraine type. From the preliminary evaluation of discharged volumes, it was obvious that the catchment area extended far beyond this local hill, which was topographically very well-defined. Close to the outlet there is a mature spruce forest while most of the local hill is covered by mature pine forest. Possibly a main road and a housing area are also included in the catchment area (the spring is included in SGU's groundwater networks).

The Rostock Spring

The spring is located in a typically hummocky moraine terrain with a small-scale irregular topography. The catchment area is, however, topographically well-defined and the size was estimated to 0.016 km^2 (Fig. 2). Approximately 85 % of the catchment area is covered with mature coniferous forest, spruce completely dominating with exception of a small area in northeast with pine forest. The remaining 15 % is agricultural land used for grazing.

Soil layer and bedrock morphology and groundwater level along the profiles indicated in Fig. 2 are shown in Fig. 3. No geological features, such as outcropping bedrock, are indicated as cause of the location of the spring outlet.



• R1 groundwater observation tube; A—A' seismic profile.

Fig. 2. Topographical map of the catchment area of the Rostock spring.

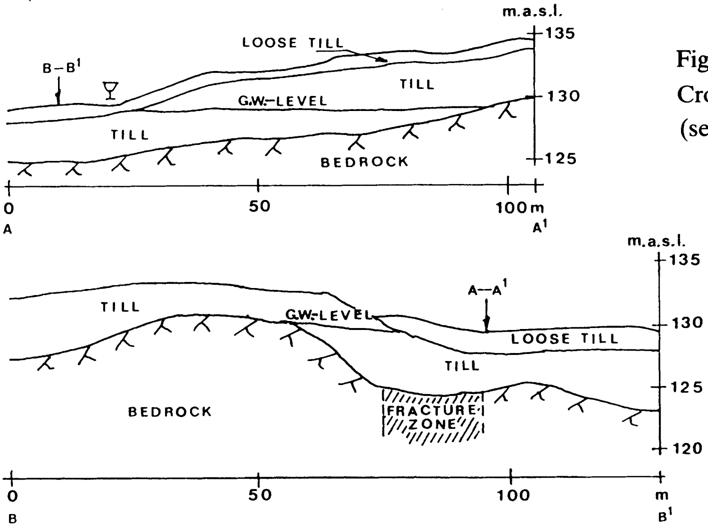
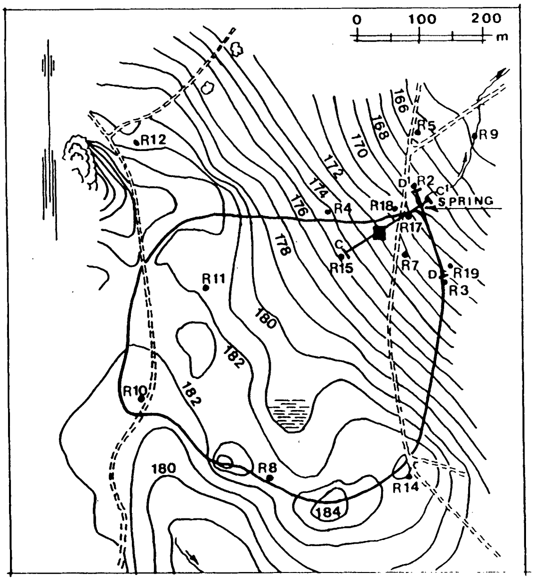


Fig. 3.
Cross-sections at Rostock (see Fig. 2 for location).

The till is sandy and the bedrock is reached at 2-3 m depth. The upper 0.5 of the bedrock is fractured and probably permeable.

Grön Källa

The spring is located in the lower part of a gentle, straight slope in drumlin terrain (Fig. 4). The size of the catchment area was determined to 0.19 km^2 from topography and measured groundwater levels. The entire area is covered with mature



- R11 groundwater observation tube;

C —C' seismic profile;

■ pit for soil sampling.

Fig. 4. Topographical map of the catchment area of Grön källa.

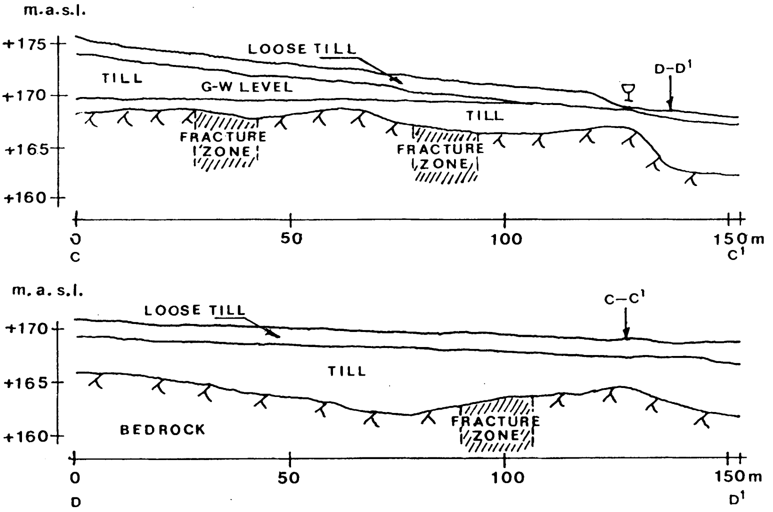


Fig. 5. Cross-sections at Grön källa (see Fig. 4 for location).

mixed coniferous forest with a predomination of spruce close to the spring and pine dominating further up along the slope. The seismic profiles indicated that the location of the spring outlet is governed by a bedrock threshold (Fig. 5). The thickness of the quarternary deposits is 6-7 m in most of the catchment area and the deposits consist of sandy till.

The soil profile at the soil sampling pit (see Fig. 4) is of podzol type. Water retention properties and saturated hydraulic conductivities are shown in Fig. 6.

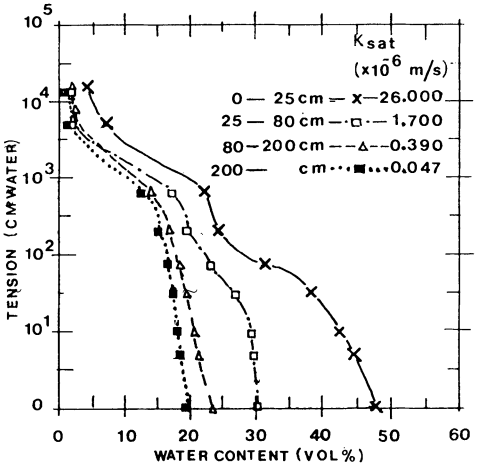


Fig. 6. Water retention properties and saturated hydraulic conductivities from a pit 100 m upstream from the spring outlet at Grön källa (see Fig. 4 for location).

Results

Weekly measurements of the spring discharge seemed to be satisfactory for calculations of discharge quantities. As an example, the differences in discharge between measurements every second and every eighth day were less than 1% at Rostock and Grön källa during March-May, 1985.

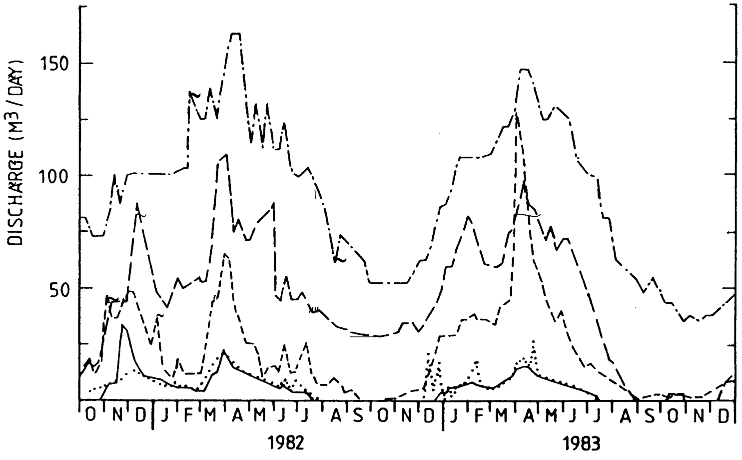


Fig. 7. Discharge of the five springs, Oct. 1981-Dec. 1983.
(—Rörsbo; -----Hällasjömåla; – – –Kristinakällan; ....Rostock; –.–.Grön källa)

Discharge of the Five Springs Oct. 1981-Dec. 1983

The discharge from the five springs are shown in Fig. 7. The discharge from the largest spring (Grön källa) was evenly distributed with a quotient of Q_{max}/Q_{min} during the measured period of 4.4, while the smallest springs at Rörsbo and Rostock showed larger relative variations and became dry during both summers.

If the conditions for the derived expression in Eq. (2) for emptying of aquifers were fulfilled, the recessions of the spring discharges should be linear in a semi-logarithmic plot. The recessions from summer 1982 are shown in Fig. 8. Despite that the summer was drier than normal, obviously the results were disturbed by precipitation. From this point of view the derived recession coefficients must be regarded as minimum values (Table 1). In Table 1, maximum active groundwater storages are also presented. Rough estimates on specific storages are also given for the springs, where the catchment areas were not independently determined. These estimates are based on the assumption that the average specific discharges in these springs during Oct. 1981-Dec. 1983 were equal to the mean of the specific discharges at Rostock and Grön källa.

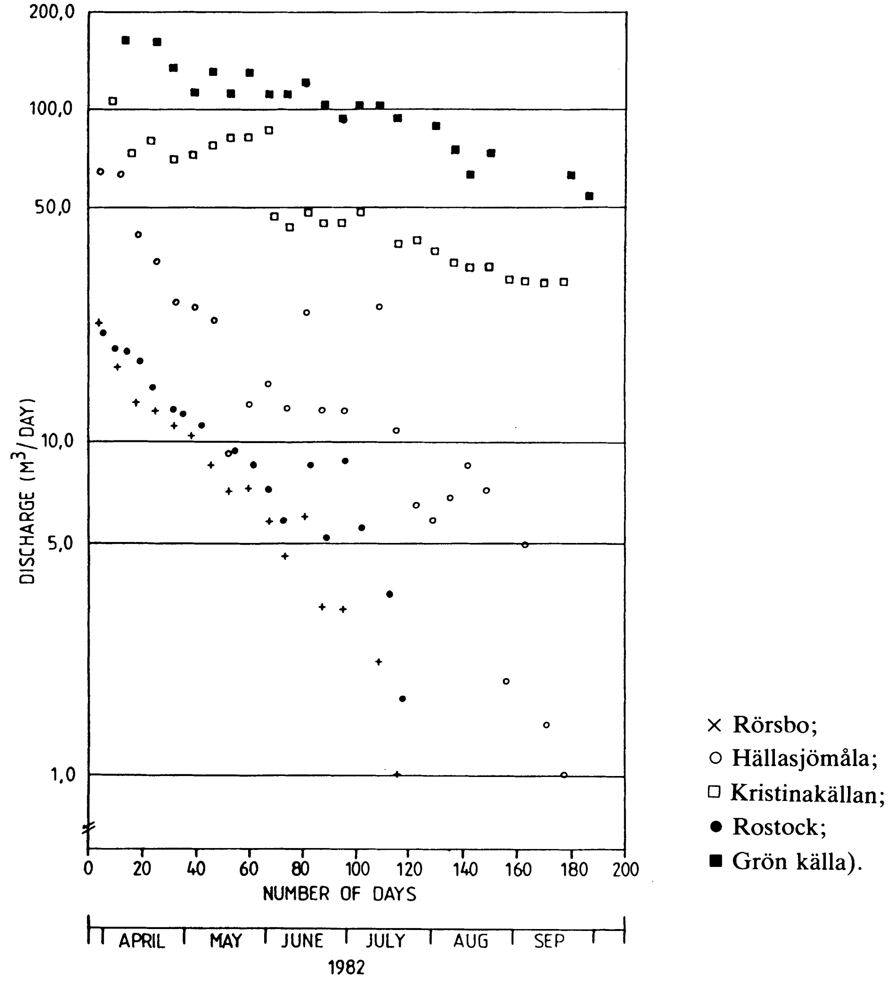


Fig. 8. Spring discharge recessions during 1982 starting from March 29.

Table 1 – Recession coefficients and maximum active groundwater storages based on the summer recession 1982.

	rec. coeff.	max. active storage	
	(day^{-1})	m^3	mm
Rörsbo	0.023	980	85
Hällasjömåla	0.017	3 800	75
Kristinakällan	0.007	15 530	145
Rostock	0.016	1 320	80
Grön källa	0.007	24 200	125

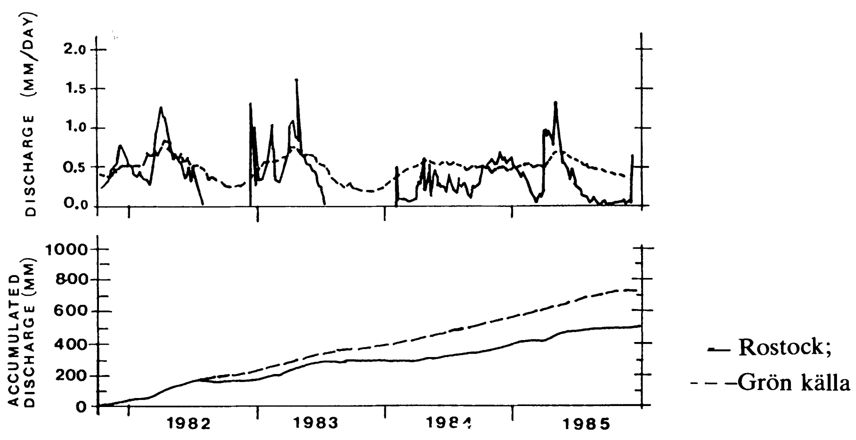


Fig. 9. Spring discharge at Rostock and Grön källa, Oct. 1981-Dec. 1985.

Prolonged and Expanded Investigations at Rostock and Grön Källa

At Rostock and Grön källa the discharge measurements continued until the end of 1985 (Fig. 9). The ratio of discharge and precipitation was considerably lower 1983/84 than the other years for both springs (Table 2). This was partly an inter-annual feature due to the dry summer 1983 resulting in a very low groundwater level at the start of the hydrological year 83/84. The extreme situation was accentuated by a comparatively low precipitation in the autumn and winter 83/84, which could not be compensated by abundant rainfall in the following summer.

From autumn 1983 groundwater levels were measured. At Grön källa the depth to the groundwater table and its fluctuations were very similar in all the area except for a very small part in the immediate vicinity of the spring (Fig. 10). The continuous recordings of the groundwater levels at R11 and R15 showed smooth changes and no diurnal variations were obtained as observed in another part of the study area (Johansson 1986). Spring discharge and groundwater level showed high linear correlation for both springs (Rostock: discharge-R2, r^2 = 0.79; Grön källa: discharge-R15, r^2 = 0.81).

Table 2 - Ratio between spring discharge and uncorrected precipitation at Rostock and Grön källa, Oct. 1981-Sep. 1985.

	Rostock		*Grön källa*	
	Prec. mm	Discharge/ Prec.	Prec. mm	Discharge/ Prec.
1981/82	559	0.26	580	0.31
1982/83	550	0.22	571	0.27
1983/84	643	0.09	682	0.22
1984/85	544	0.26	628	0.27

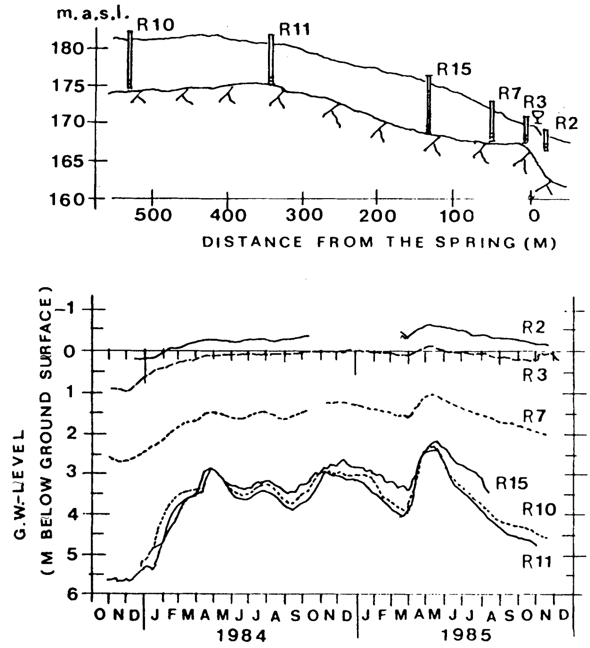


Fig. 10. Cross-section from the catchment area of Grön källa and groundwater level fluctuations, Oct. 1983-Dec. 1985.

Results from the every-second-day measurements of discharge, groundwater level and water chemistry at Rostock and Grön källa during the spring 1985 are presented in Fig. 11. The water equivalents in the snowpacks were 40 and 70 mm on Apr. 1-2 at Rostock and Grön källa respectively. At that time almost nothing had melted in the Grön källa catchment area, which is located in a slope facing NE, while a considerable melt had occurred at Rostock. The total amounts of rainfall during the studied period were 75 and 90 mm respectively at the meteorological stations representative for Rostock and Grön källa. It is notable that the strongly increased discharges are not reflected in changes in water chemistry. Also the chemical parameters, not presented here, were more or less constant over the studied period. The oxygen-18 concentrations in the discharges were almost constant (Rostock: −11.0 – −10.8‰; Grön källa: −10.8 – −10.7‰ given as deviation from Standard Mean Ocean Water) and no influence from oxygen-18 depleted meltwater was noticed. The snow samples had with one exception oxygen-18 concentrations of −13‰ or less at the start of the intense snowmelt.

Water Releasing Properties and Saturated Hydraulic Conductivity at Grön Källa

The runoff volumes from the summer recessions of the dry years 1982 and 1983 at Grön källa were used, together with measured and extrapolated values of groundwater levels, to estimate integrated values of the specific water release from the

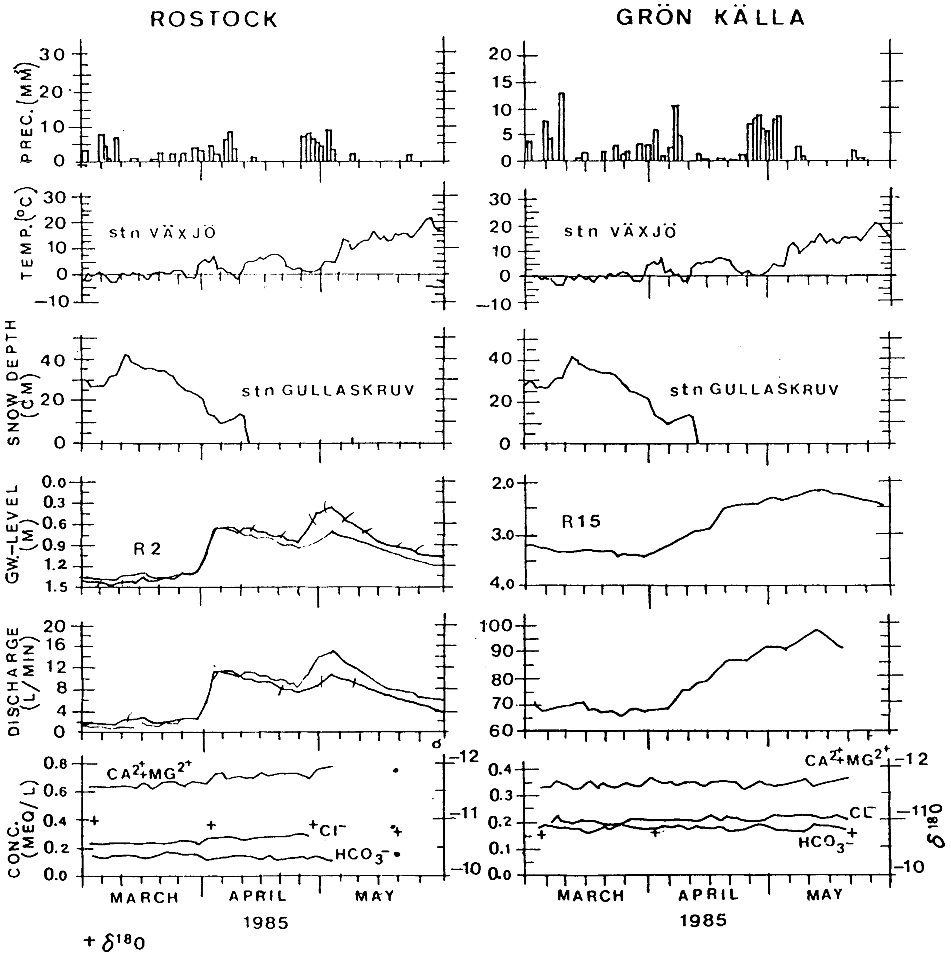


Fig. 11. Climatical, hydrogeological and chemical data from Rostock and Grön källa, March-May 1985.

unsaturated zone to the groundwater reservoir during periods of receding groundwater levels.

The average decreases in groundwater level in the catchment area during the recessions April 19 – Sep. 29, 1982 and April 21-Oct. 30, 1983 were approximately 3.5 m which resulted in a specific water release to the groundwater reservoir of 0.024 for both years. The specific water release calculated from the groundwater level recession during the stable winter 1985 (Jan. 27-March 24) was considerably higher, 0.047. The results indicated that the water release during the summer recessions may be strongly influenced by evapotranspiration, in spite of the comparatively deep groundwater table. As a comparison a volume fraction of 0.030 was drained at field capacity (pF = 2) from the undisturbed core samples extracted at 2.5 m below the ground surface.

The expression given in Eq. (2) was used to calculate a value of the hydraulic conductivity at Grön källa. The average saturated thickness was put to 3.5 m and gave together with the derived specific water release (0.024) and α-value (0.007 day^{-1}) a hydraulic conductivity of 6×10^{-5} m/s. The section perpendicular to the slope at R15 was also used to calculate the hydraulic conductivity from presumed steady-state situations (Eq. (4)). The spring discharge was reduced to compensate for the groundwater recharge on the area between the section and the outlet. Hydraulic conductivities of 8×10^{-5} and 7×10^{-5} m/s were obtained for the situations with the minimum and maximum groundwater levels of the period respectively.

Discussion and Conclusions

The comparatively slow discharge dynamics of the springs are due to catchment areas constituting almost entirely recharge areas. Grön källa and Kristinakällan showed a very evenly distributed discharge. The estimated maximum active storages of the aquifers feeding the springs range from about approximately 75 mm for Hällasjömåla to 145 mm for Kristinakällen. The values of the calculated maximum active groundwater storages rely on the assumption that the peak discharges after the winter of 1982 with abundant snow, are good measures of the absolute peak discharges of the springs. It is also presumed that the same α-value may be used throughout the recession. There is a tendency at some springs to a steeper recession at very low discharges (Fig. 8). This behaviour was very clear at Kristinakällan during 1983 when the discharge ceased completely. The steeper recessions at low discharges are probably caused by evapotranspiration, but bedrock thresholds and the low specific yield of the bedrock could also be contributing factors.

The active storage is the storage traditionally used in hydrological, linear reservoir modelling. Regarding hydrochemical modelling, the total groundwater storage is of interest. As an example, the maximum total groundwater storage in the till of the Grön källa area was estimated to approximately 1,250 mm from data of maximum saturated thickness and total porosity.

Since the bedrock underlaying the till is not impervious, some of the water reaching the spring outlet will obviously pass through the bedrock. This behaviour must be correctly described to obtain the transit time distribution of the water. However, the influence on the total groundwater storage will be minor due to the very low storage capacity of the bedrock.

The intense study of discharge and water chemistry during the spring 1985, with a great variation in discharge, revealed no signs of surface flow or shallow, fast flow paths. The supplied amount of water by snowmelt and rainfall (100-150 mm) gave no changes in the chemical composition of the discharge. The concentration of chloride in the discharge clearly indicated that the water had been subjected to evapotranspiration. Obviously the discharge consisted of water already in the ground at the start of the snowmelt, which also was confirmed by its oxygen-18 content.

The determinations of specific water releases from runoff volumes and groundwater level recessions at Grön källa during periods of negligible rainfall or snowmelt gave completely different values for summer and winter; 0.024 and 0.047 respectively. The results indicated that the values obtained in summer were strongly influenced by evapotranspiration. This should also be remembered when the sizes of the above-mentioned active groundwater storages are discussed. The results at Grön källa were obtained in an area where the groundwater table was comparatively deep to be in moraine terrain, which means that the influence of evapotranspiration may be even more accentuated in other areas.

The hydraulic conductivity estimated from the solutions of the linearized Boussinesq equation (Eq. (2)) and the steady-state solutions (Eq. (4)) are marred by considerable uncertainty since the prerequisites for the validity of the equations are only partly fulfilled. However, the solutions gave approximately the same values of the hydraulic conductivity. These values were three orders of magnitude higher than the values of vertical saturated hydraulic conductivity determined in the laboratory for the samples extracted 2.5 m below the ground surface. Compared with hydraulic conductivities of till determined with varying methods in other areas, the derived values are also high (Knutsson and Morfeldt 1973; Engqvist,Olsson and Svensson 1978; Lundin 1982). Field methods, integrating over large volumes, tend to give higher values due to the appearance of structures and well-sorted lenses. Grön källa is located in a well-developed drumlin terrain. The hydraulic conductivity has been shown to be higher in drumlin terrain than in the hummocky moraine terrain (Knutsson 1971; Engqvist *et al.* 1978).

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