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# Deep Groundwater Contribution to a Small Stream

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The contribution of surface water and groundwater were studied in a small stream in the central part of Sweden using electrical conductivity of water as a tracer. The portion of deep groundwater increases in the downstream direction from approx. 5 % to 20 %.

## Introduction

Within the drainage basin of the River Kassjöån, which is one of the former Representative Basins established during the International Hydrological Decade (IHD), a subcatchment was selected for studies of runoff. The subcatchment of Kilmyrbäcken was chosen in order to make the geomorphological conditions as homogeneous as possible.

The working hypothesis used for the investigation was that the contribution of water that reaches a stream is a mixture of a shallow, easily transportible component with low salinity and a deep groundwater component that moves slowly and has a higher salinity. The proportion of the deep component increases downstream in the basin. This paper first presents a study of the variation in discharge along the stream. The increase in discharge in the downstream direction is caused by a lateral inflow of water. The electrical conductivity of water was used as a tracer to study the composition of the lateral inflow.

The theories concerning runoff processes have been modified since Horton's theory of overland flow have been questioned. A great number of authors have shown that Horton's theory does not have a general applicability. The influence of the contributing components has been shown to be much more complex than was suggested by him. Toth (1962) presented a theory of groundwater motion where the stream lines were directed downward in the upper part of a hill side and toward the surface in the lower part. Gustafsson (1970) developed Toth's theories further and applied them to Swedish conditions using for terminology recharge and discharge areas for the groundwater. The influence of local topography on the distribution of these areas on a hillside was stressed. Field work under both natural and experimental conditions carried out by Dunne and Black (1970) showed that a large position of storm runoff was produced by precipitation falling on saturated areas that only occupied a minor portion of the hillside. Using mathematical models, Freeze (1972) extended the theories, and modelling work by Beven and Wood (1983) stressed the dynamic character of the runoff contributing areas and the importance of the geomorphological structure of the drainage basin.

For an extensive summary and comparison of different theories the works of Dunne (1983) and Bonell et al (1984) should be consulted.

## The Investigation Area

The drainage basin of the stream Kilmyrbäcken is situated in the central part of Sweden at 62°42′N, 16°02′E. The basin is a subcatchment of the Kassjöån basin and covers 2.0 km$^2$. All parts of the drainage basin are above the highest postglacial shore-line at altitudes ranging from 375 to 495 m a.s.l. (Fig. 1).

The basin is almost rectangular. The surface water divide is easily distinguished especially along the northern and eastern limits where the highest altitudes are encountered. The area occupied by bogs (hatched in Fig. 1) is 0.26 km$^2$ or 13 % of the total basin area, and there are no lakes. The entire basin is covered by till. Bedrock is exposed only near the northern and northeastern limits of the basin. Recent clear-cutting has removed all but a few trees from the basin. Forestry is the only human activity in the area.

The main stream, Kilmyrbäcken, runs in a northsouth direction near to the center of the basin with its head water situated some 200 m south of the surface water divide. Only two tributaries exist. One emanates from the western bog area and joins the main stream immediately upstream of the main bog area in the central part of the basin. The second tributary comes from the east and joins the main stream within the main bog area. The channel is ill defined within the bog area.

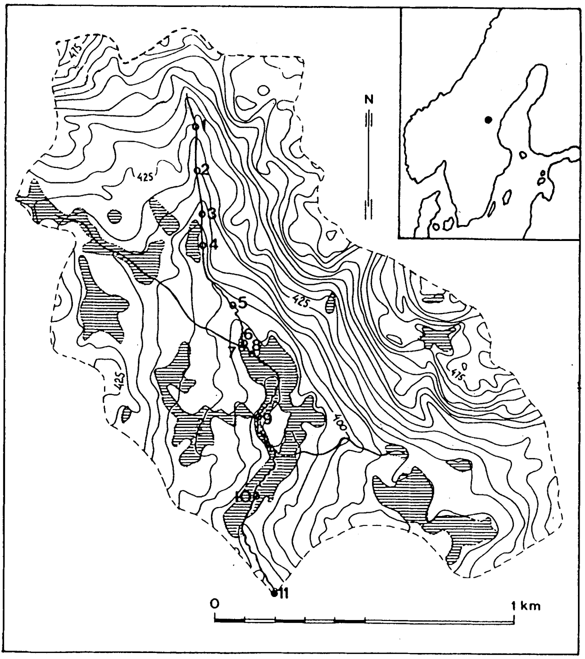

Fig. 1.
The basin of Kilmyrbäcken. Location of observation sites, distribution of bogs (hatched areas). Contour interval 5 m.

## Measuring Programme

Measurements of the water's electrical conductivity, temperature, and discharge revealed a clear pattern of variation. The electrical conductivity varied both with distance along the stream and with time. In addition to the normal variation of electrical conductivity, which is opposite to discharge, a diurnal pattern of variation was noted that may be caused by evaporation or earth-tide effects (Calles 1982).

Eleven measuring sites were established along the stream. Four of them were equipped with recording instruments for electrical conductivity, water temperature, and water stage. Stage data were converted to discharge data using V-notch weirs.

After the first field season the investigations were concentrated on the part of the catchment situated upstream of the central bog. Due to a shortage of instruments the recording equipment was placed at varying sites during the three years of study. The locations of the measuring sites are shown in Fig. 1. For easy reference the measuring sites are referred to by their distance from the beginning of the stream in the downstream direction.

Examples of the observed variation of electrical conductivity of water along the stream are shown in Fig. 2. The two sets of measurements were made under

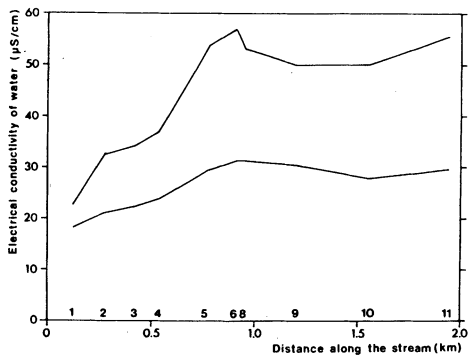

Fig. 2. Variation in electrical conductivity of water along the stream at conditions of high (lower curve) and low (upper curve) runoff. The positions of the measuring sites along the stream are presented in the figure.

different runoff conditions. In both cases, a continuous increase in electrical conductivity in the downstream direction was observed. This pattern was broken at measuring site 8 (950 m) where the first tributary joins the main stream, immediately upstream of the main bog area. The lower curve in the figure, for conditions of high runoff, shows a dilution of the salt content in the water within the bog area. For conditions of low runoff the stream retained its original salt content during the passage through the bog. Downstream of the bog, conductivity again increased progessively.

## Variations of Discharge

The total volumes of water discharged in the stream was studied and variations in discharge are illustrated in Fig. 3, with data for measuring sites 2 (270 m), 4 (530 m), and 8 (950 m) for July 18-August 10, 1979. Precipitation data for the same period of time are also shown. Precipitation was measured by a recording rain gauge located within the drainage basin. Between stations located on either side of the bog, discharge increased linearly downstream. The effect of water storage within the bog is shown by an ellipsoidal relation between discharges at station 8 (950 m) and station 11 (1,940 m).

During the time for which the comparison between sites 2 (270 m) and 4 (530 m) was made, the mean discharge at site 4 (530 m) was 5 l/s. The amount of lateral inflow of water between the sites was 2.7 l/s. The distance between the sites is 260 m which gives an increase of approx. 0.01 l/s for each meter of the stream.

To test if these calculations are realistic, computations based on Darcy's law

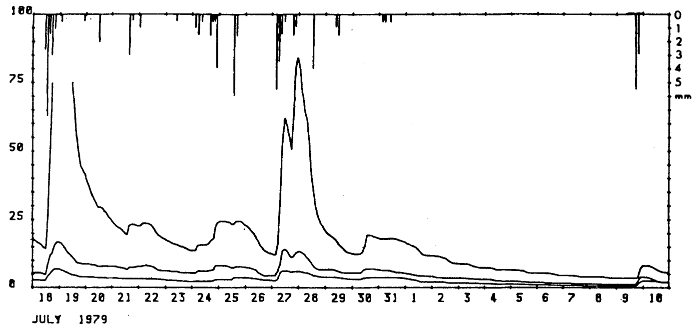

Fig. 3. Precipitation and discharge at sites 2 (270 m) (lower curve), 4 (530 m) (middle curve), and 8 (950 m) (upper curve) during the period in 1979.

were done. Conductivity values were chosen in accordance with Lundin's (1982) investigations in comparable soils. Lundin measured the conductivity in three profiles, showing that the part of the soil situated deeper than 1 m had very low conductivity compared to the overlying parts of the profile. The mean values of conductivity for the first meter ranged from $0.68\times10^{-4}$ to $0.24\times10^{-4}$. The slope of the groundwater surface was obtained from groundwater tubes placed along a line perpendicular to the stream on the western slope at site 2 (270 m). The gradient was approx. 0.1 which gives a proable range of groundwater flow under saturated conditions of 0.005-0.014 l/s for each meter of the stream, indicating that the observed values are realistic.

## Variations of Electrical Conductivity of Water

Measurements of the electrical conductivity of the stream water give information on the salt content of the water added between two sites in the stream. This information can be used to divide the lateral inflow into one shallow and one deep component. Variations in electrical conductivity of the water during the investigated period for sites 2 (270 m), 4 (530 m), and 8 (950 m) are shown in Fig. 4. Since the electrical conductivity varies along the stream, a simple mixing model can be formulated to show the composition of the lateral inflow. Models of this kind have previously been presented by e.g. Pinder and Jones (1969), Martinec (1975), Fritz et al. (1976) and Rodhe (1981) and can be written

$$Qd = Qu + Qc$$

$$Cd\,Qd = Cu\,Qu + Cc\,Qc$$

where $Qd$ and $Qu$ represent discharges at the downstream and upstream measur-

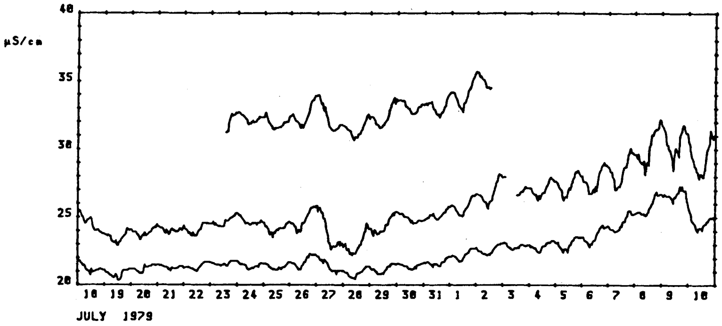

Fig. 4. Variation in electrical conducitivity of water at sites 2 (270 m) (lower curve), 4 (530 m (middle curve), and 8 (950 m) (upper curve) during the period in 1979.

ing site and *Cd* and *Cu* are the corresponding concentration values. *Qc* represents the amount of water added between the two sites and *Cc* is the electrical conductivity of the added water. If the observed values are used in the equations, we find the salt concentrations in the added water shown in Fig. 5.

The complicated picture of increasing electrical conductivity with increasing depth below the ground surface can be simplified into a system in which only one shallow and one deep body of water contribute to the discharge. In this investigation, the proportion of the deep groundwater was of major interest. Under the conditions given, the following statement can be used in the model

$$Qc = Qs + Qg$$

where *Qs* is the shallow groundwater component and *Qg* is the discharge from the

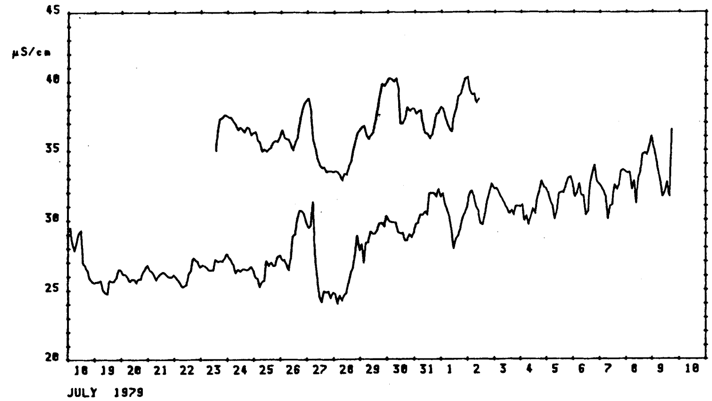

Fig. 5. Variation in the electrical conducitivy of water in the added water between sites 2 (270 m) and 4 (530 m) (lower curve) and between 4 (530 m) and 8 (950 m) (upper curve) during the period in 1979.

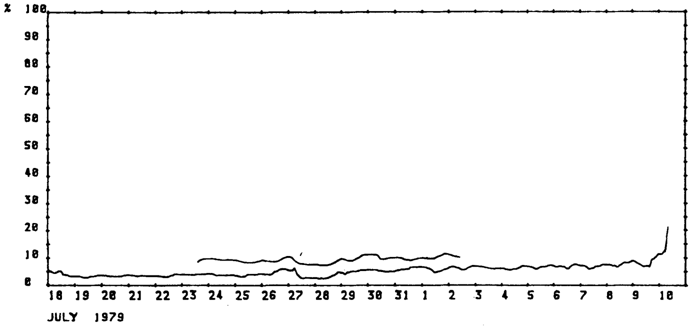

Fig. 6. The percentual proportion of deep groundwater between sites 2 (270 m) and 4 (530 m) (lower curve) and between 4 (530 m) and 8 (950 m) (upper curve) during the period in 1979.

deep groundwater. *Cs* and *Cg* are the electrical conductivity of the shallow and deep components. This gives

$$Cd\ Qd - Cu\ Qu = Cs\ Qs + Cg\ Qg$$

All data on electrical conductivity are given in µS/cm at 20°C. An estimated value of electrical conductivity for the shallow component, which also includes precipitation is 20 µS/cm. The electrical conductivity of pure rain is usually less than 10 µS/cm after reduction for low pH-values. A value of 20 µS/cm corresponds roughly to a mean value for the water in the stream at site 1 (120 m) and also represents the electrical conductivity of water in pits dug in the slopes that filled with shallow groundwater.

The value of electrical conductivity for the deep groundwater is about 200 µS/cm, which is an approximate mean value of the water samples collected from a groundwater tube 7.5 m from site 2 (270 m). The bottom of this tube was situated 1.3 m below the surface equal to approx. 0.5 m below the bottom of the stream. The mean ground water level was 0.25 m below the surface. Use of the model mentioned above results in the division of shallow and deep components shown in Fig. 6. A mean value for the deep component of water added between sites 2 (270 m) and 4 (530 m) is approx. 5 %.

In studying the size of the deep groundwater component further downstream data from sites 4 (530 m) and 8 (950 m) were used. The computed values of the proportion of deep groundwater are included in Fig. 6. The mean value increased to almost 10 %.

Note, however, that site 8 (950 m) also receives water from the western tributary. In order to eliminate this influence the conditions between sites 4 (530 m) and 5 (770 m) were investigated. During the time for which computations of the composition of the lateral inflow between sites 2 (270 m) and 4 (530 m) and

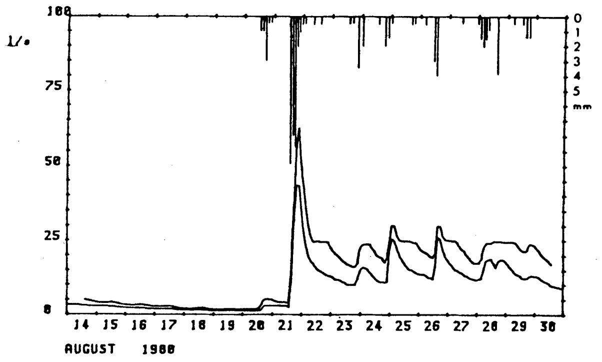

Fig. 7.
Precipitation and discharges sites 4 (530 m) (lower curve) and 5 (770 m) (upper curve) in August 1980.

further downstream to 8 (950 m) were made, no recording equipment was placed at site 5 (770 m). It was necessary, therefore, to choose another period of time for comparison.

A new measurement period was chosen which had precipitation data comparable to the original period. Before the original period, the precipitation was 56 mm. In 1980, when recordings were performed at site 5 (770 m), precipitation from August 1 to August 14 was 49 mm. The discharge values and values of electrical conductivity are comparable. Therefore, it seems reasonable to use the time following August 14 for the study. This period comprises the time August 14 to August 30, 1980. Following a week without precipitation an intensive rain on August 21 made the discharges rise above the values of the 1979 series. Observed values at the two sites are shown in Fig. 7. During the week of drought the values of electrical conductivity rose to approx. 40 µS/cm at site 4 (530 m) and to approx.

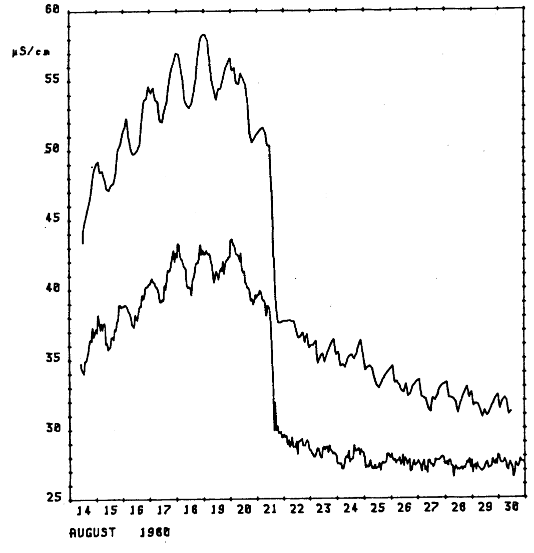

Fig. 8.
Variation in electrical conductivity of water at sites 4 (530 m) (lower curve) and 5 (770 m) (upper curve) in August 1980.

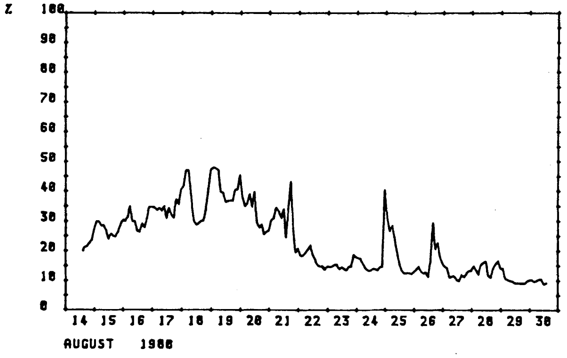

Fig. 9.
Computed proportions of deep groundwater in the laterally added water between sites 4 (530 m) and 5 (770 m) in August 1980.

55 μS/cm at site 5 (770 m). Due to the rain the values dropped rapidly to 27-28 and 30-35 μS/cm. Recorded values are shown in Fig. 8. The computed proportion of deep groundwater in the laterally added water between the sites is shown in Fig. 9. Computations using the presented model reveal a proportion of deep groundwater that is even greater between sites 4 (530 m) and 5 (779 m) than between sites 4 (530 m) and 8 (950 m). It amounts to approx. 20 % of the total water added between the two sites.

The reason why deep groundwater contributes a smaller proportion at site 8 (950 m) can be attributed to the western tributary joining the main stream immediately upstream of site 8 (950 m). This tributary drains a comparatively large bog area close to the stream in its upper parts, resulting in a rapid runoff of surface water. A comparison with the data presented in Fig. 2 shows that, under conditions of high discharge, the values of electrical conductivity are comparable in both the tributary and the main stream, but under drought conditions, the tributary has considerably lower values (42 μS/cm) than the main stream (57 μS/cm).

## Conclusions

In the upper reaches of the brook Kilmyrbäcken, upstream of the main central bog area, the proportion of deep groundwater laterally added to the stream increases downstream. The percentage increased from 5 % between measuring sites located 270 and 530 m from the beginning of the stream to 20 % in the reach between 530 and 770 m. The qualitative results of the investigation are probably also applicable to other first order streams. Conditions become more complex if the central bog area is also considered and when tributaries with variable salt content add to the flow.

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