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Spring Flood
Meltwater or Groundwater?

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The environmental isotope oxygen-18 was used as a tracer to separate stream discharge into flows originating from groundwater and fresh meltwater. Two, mainly forested, watersheds (areas 6.6 and 4.0 km^2) in southern Sweden were studied during snowmelt 1979. The seasonal variation of $\delta^{18}O$ in precipitation makes the $\delta^{18}O$ of meltwater different from that of groundwater, hence making the separation possible.

The major part of the streamflow this spring originated from groundwater. Of the total water volumes that left the areas, during the two periods of snowmelt that occurred this year, the fraction of groundwater ranged between 0.7 ± 0.2 and $0.9^{(\pm)}$ 0.2 The volume of meltwater in the streams corresponded to the volume of snowmelt and precipitation over 10-15% of the catchments. A field survey indicated that these percentages reasonably well describe the extension of the saturated areas, i.e. the effluent areas for groundwater where no infiltration can take place.

Introduction

The process by which streamflow is generated from precipitation is not yet understood. It is evident that groundwater plays a key role in streamflow generation in the Swedish moraines, but it is not known how this role is played. The problem is of great importance for a further development of mathematical runoff models and for an understanding of the chemical processes encountered during water flow through the basin to the first draining stream.

In this paper, the process of streamflow generation is studied through estimates of the contributions of groundwater and fresh meltwater to stream discharge. The estimates are made using the stable isotope ^{18}O as a tracer.

Background

According to the traditional picture of streamflow generation, formulated by Horton (1933), stormflow in streams is caused by overland flow from the whole drainage basin. This overland flow occurs when the intensity of rain or snowmelt exceeds the infiltration capacity of the soil. Streamflow between discharge peaks is often called base-flow, originating from groundwater. The base-flow is assumed to be affected in varying degrees by infiltration and percolation from the rain that caused the discharge peak.

This picture has been found to be in poor agreement with reality in humid areas. The concept of »partial area« was developed in the early sixties in the United States (Betson 1964, Tennessee Valley Authority 1965). According to this view, rainfall intensity exceeds infiltration capacity of the soil only over a small fraction of the drainage basin, more precisely in areas adjacent to the stream with high soil moisture content or with a groundwater table up to or above ground level, and also in the stream itself. In Sweden Gustafsson (1970) formulated the theory of influent and effluent areas for groundwater. Rainwater that falls on the upper parts of the hillslopes infiltrates and raises the groundwater table there (influent areas), which increases the outflow of groundwater below the slopes and in the streams (effluent areas). Overland flow is supposed to occur only in effluent areas, where the soil is saturated to the ground level.

To distinguish this overland flow from the traditional, basinwide Hortonian overland flow, it is convenient to call it saturated overland flow. This flow partly consists of rainwater that has fallen on the saturated areas and partly of outflowing groundwater (sometimes called return flow).

In most studies of streamflow generation in humid areas that have been published during the last few years, some type of »partial area« on which rainwater creates saturated overland flow is advocated. The importance of groundwater outflow, on the other hand, has been subjected to an animated discussion (see for instance Freeze 1974 and Martinec 1975). Meanwhile, several studies on the chemical or isotopic composition of streamwater have shown that the main contribution to stormflow peaks is from groundwater (Dinçer, Payne, Florkowski, Martinec and Tongiorgi 1970, Fritz, Cherry, Weyer and Sklash 1976 and Sklash and Farvolden 1979).

Method

About 0.2% of the water molecules in natural waters contain the stable oxygen isotope ^{18}O. The concentration of ^{18}O in precipitation in non-tropical areas has a considerable seasonal variation, which to some extent is caused by variations in temperature when water vapour are condensed in the atmosphere, and also due to different origins of the air masses. During winter the concentration of ^{18}O in precipitation is low as compared to the summer values. In groundwater the concentration of ^{18}O is comparatively constant during the year, probably because of intermixing of water molecules that takes place in the unsaturated and saturated zones and more so as the active groundwater reservoir is fairly large compared to the yearly groundwater recharge. The concentration of ^{18}O in groundwater lies in between the winter and summer values of precipitation. Therefore, groundwater and precipitation have different concentrations of ^{18}O during certain periods of the year. This difference is a necessary condition for the method used in this study.

If the streamwater is supposed to orginate only from two reservoirs, groundwater and precipitation, each with uniform concentration of a conservative tracer, then the contributions from these reservoirs can be estimated from measurements of the concentrations in the stream and in the reservoirs. Continuity conditions for the flow of water and tracer give the fraction of groundwater, X, in the stream such that

$$X = \frac{c_s - c_p}{c_g - c_p} \qquad (1)$$

where c_s, c_g and c_p are the concentrations in streamwater, groundwater and precipitation (rain or meltwater) respectively (Dinçer et al. 1970).

In this study, Eq. (1) was used for daily estimates of the groundwater fraction of the stream runoff from two catchments in southern Sweden during snowmelt of 1979. The tracer was the $H_2{}^{18}O$ molecule.

Description of the Sites

The studies were carried out in the Nåsten basin, 5 km SW of Uppsala city, and in the Stormyra basin, 20 km SE of Stockholm city. The Nåsten basin has been described by Bergqvist (1971a and b) and the Stormyra basin by Liljeqvist and Sterner (1975). Both areas are situated below the highest postglacial shoreline. The granite bedrock is frequently bare, the morainic soils are shallow and the valleys are covered with clay. The Stormyra basin has a very thin soil cover. The Nåsten basin is rather flat with a slightly undulating terrain, while the Stormyra basin is comparatively hilly. The discharges in the streams that drain the basins are measured by The Swedish Meteorological and Hydrological Institute by means of triangular weirs, fitted with recording gauges.

Table 1 – Descriptions of the basins

		Nåsten	Stormyra
Latitude		59° 48'N	59° 12'N
Longitude		17° 15'E	18° 20'E
Area (km^2)		6.8	4.0
Fraction of	forest or clearcutting	83	89
(%)	agricultural land	13	8
	bogs	4	3
	lake	0.0	0.0
Fraction of	outcrop	25	67
(%)	moraine	55	13
	clay	16	12
	peat	4	8
Dominating bedrock		precambrian granite	gneiss-granite
Altitude	lowest	18	10
(m a s l)	mean	35	42
	highest	55	77

The figures given for land use and geology have been obtained from topographical and geological maps, scale 1:50,000. An area is classified as rock outcrop if the soil is shallower than 0.5 m.

Measurements Schedule

Daily samples of streamwater were collected at the discharge stations. The isotopic composition of snow was measured after melting of snowcores taken with snow tubes. Snow sampling was undertaken at 2-6 stations within the basins, with intervals of 1-3 weeks. A few groundwater samples were collected from springs and domestic wells, penetrating to depths varying between 0.5 and 50 m.

The ^{18}O content of the samples was measured at the Mass spectrometer laboratory at the Division of Hydrology, University of Uppsala. The isotopic composition is given as $\delta^{18}O$. This value gives the relative deviation of the isotopic ratio $^{18}O/^{16}O$ of the sample from that of the standard water SMOW (Standard mean ocean water), and is commonly expressed in permil (Craig 1961). The samples were also analysed for electrical conductivity, i.e. salt content.

Results

This spring the snowmelt in the two basins occurred during two distinct periods, about March 1 to 25 and March 26 to April 20, respectively. At the beginning of snowmelt the water equivalent of the snowpack was about 90 mm in Nåsten and 125 mm in Stormyra. Frost depth was not measured. The forest ground probably remained unfrozen this year because snow fell early and formed a continuous cover.

In late winter, before snowmelt had started, the water in the streams was assumed to be exclusively groundwater. This is a safe assumption, since the two basins have no lakes and also the air temperature this winter remained below 0°C continuously for more than three months, until the onset of the first melting period. Thus melting cannot be expected to have occurred earlier. The few groundwater samples that were analysed indicate small variations in $\delta^{18}O$, with values close to the $\delta^{18}O$ of the streams before snowmelt had started.

The meltwater $\delta^{18}O$ was assumed to be equal to that of the snowpack. Daily δ-values of the snowpack were estimated through interpolation between the measured values.

Fig. 1 shows total discharge and the contributions from groundwater and meltwater (including fresh rainwater) estimated from Eq. (1). The diagrams also show $\delta^{18}O$ of streamwater and snowpack.

Before the melting began, snowpack $\delta^{18}O$ differed clearly from that of the streams, which is a prerequisite for meaningful estimates using Eq. (1). The diagrams show the increasing $\delta^{18}O$ of the snowpack during the spring. This increase is probably caused by molecular exchange with atmospheric water vapour during the ongoing recrystallization of the snowpack.

The contribution of meltwater with low $\delta^{18}O$ results in a decrease in the streamwater $\delta^{18}O$. Except for the very early days of melting in Nåsten, groundwater was dominating the flows in the two streams during the whole spring flood. During the two melting periods, groundwater fraction of the total flow volume was 0.67 and 0.78 in the Nåsten basin and 0.88 and 0.78 in the Stormyra basin, respectively. The accuracy of these figures is estimated to be ± 0.15 as is discussed below.

Error Estimate

The uncertainity in the calculations using Eq. (1) mainly depends upon the accuracy in the $\delta^{18}O$ of groundwater and meltwater, both of which vary within a basin. The sensitivity of the calculated groundwater fraction to errors in these $\delta^{18}O$-values is shown in Table 2.

Groundwater samples were collected during snowmelt in four wells and springs in Nåsten basin and at three locations in Stormyra basin. The largest observed deviation from »streamwater before melting«, i.e. from the δ-values that were used for groundwater in the calculations was 0.5%. The range of $\delta^{18}O$ in the snowcores can be seen in Fig. 1. From these values and from Table 2, the accuracy of the fractions of groundwater is estimated to ± 0.15.

Precipitation during the melting periods might cause an additional error in the estimated groundwater fractions. If the $\delta^{18}O$ of the precipitation is the same as that of meltwater, the estimated groundwater fraction will be correct; the term meltwater then will include fresh rainwater. If, on the other hand, the $\delta^{18}O$ of rainwater differs from that of the snowpack, it will cause an error. This error has

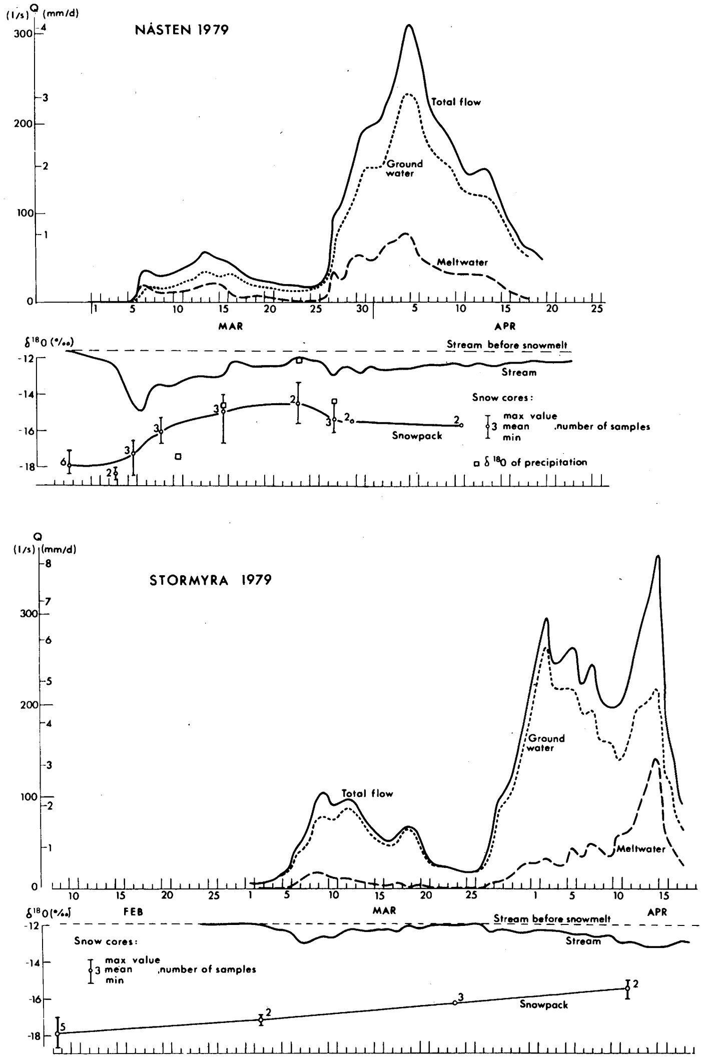

Fig. 1. $\delta^{18}O$ of streamwater and snowpack and total stream discharge, with fractions of groundwater and meltwater estimated from Eq. (1) using ^{18}O as a tracer.

to be added to the errors in Table 2. The $\delta^{18}O$ of precipitation was measured only in the Nåsten basin (see Fig. 1). These δ-values, together with the rainfall or snowfall amounts in the two basins, show that this error can be neglected in both basins during the first period. During the second period, rainwater has probably caused an overestimate of the groundwater fraction in Stormyra, particularly during the early days of this period. It has, however, not been possible to quantify these errors.

Table 2 – Influence of errors in the $\delta^{18}O$ of groundwater and meltwater on the calculated groundwater fraction of the total flow volume

Assigned deviation from the δ-values that were used in the calculations (‰)		Calculated groundwater fraction Nåsten		Calculated groundwater fraction Stormyra	
		period		period	
Groundwater	Meltwater	I	II	I	II
+0.5	0	0.59	0.69	0.80	0.69
0	0	0.67	0.78	0.88	0.78
-0.5[1)]	0	0.77	0.89	0.99	0.91
0	+1.0	0.55	0.71	0.76	0.70
0	0	0.67	0.78	0.88	0.78
0	-1.0	0.73	0.82	0.90	0.83

1) This value is unrealistic during certain days with high δ-values in the streamwater, because the δ-values of the stream then will be higher than those of groundwater and meltwater both.

Mixing Diagrams

It should also be possible to use Eq. (1) for estimating the groundwater fraction from electrical conductivity. But for this tracer (salt concentration) the prerequisites for the equation are less fulfilled than they are for ^{18}O. Water will get continuously enriched in salts on its way through the unsaturated and saturated zones, causing considerable variations in the salt concentration of groundwater within a basin. Thus the value of the tracer concentration of groundwater in Eq. (1) will be poorly defined. Water might also get enriched in salts during overland flow, Hortonian as well as saturated.

On the other hand, the relation between electrical conductivity and $\delta^{18}O$ gives some information on the validity of the assumptions made enabling the estimates using ^{18}O as a tracer (i.e. two homogeneous reservoirs and meltwater $\delta^{18}O$ equal to that of snowpack). In so-called mixing diagrams the concentrations of two tracers are plotted against each other. Samples from a stream that is fed only from two homogeneous reservoirs will form a straight line in the mixing diagram. The end points of the line will be the points representing the two reservoirs (c.f. the T-S-diagrams that are commonly used in oceanography).

A mixing diagram from Stormyra is shown in Fig. 2. During the early days of the first melting period, i.e. up to March 7, there was an increase of the salt concentration in the stream. (Such an increase is well known and is due to separation of dissolved salts from snow crystals during recrystallization). After the early days, the points roughly follow a straight line up to March 26, i.e. to the end of the first melting period. The points of the second melting period follow another straight line. The two lines might pass through the points that indicate the composition of snow, with the later line tending to pass through points representing later snow sampling dates. This supports the assumption that the meltwater $\delta^{18}O$ is

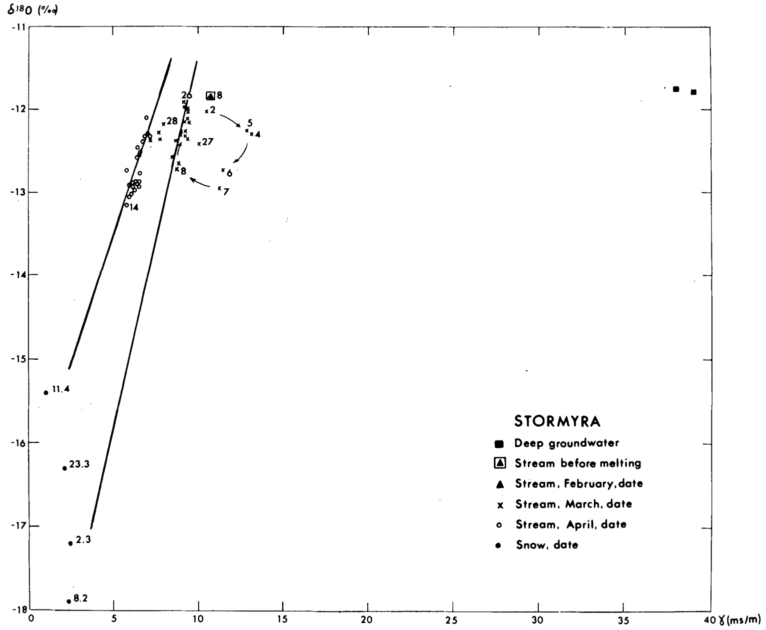

Fig. 2. Mixing diagram. The relation between $\delta^{18}O$ and electrical conductivity (γ) of streamwater, snowpack and deep groundwater during spring flood in the Stormyra basin 1979.

equal to that of snowpack. The contributing groundwater during snowmelt seems to contain somewhat less amounts of salts than that which gave the streamwater before snowmelt, probably because of low salt concentration of the very shallow groundwater. The samples of deep groundwater falls far away from the mixing lines, indicating that this deep groundwater is not contributing to the spring flood. (The deep groundwater is from drilled domestic wells in the rock. No groundwater from the unconsolidated deposits were collected in the Stormyra basin).

The fact that the points in general seem to follow straight lines in the mixing diagram, and that the lines pass through the points of the snow samples, supports the assumptions that were made for the estimates using Eq. (1). But the mixing diagrams from Nåsten, which are not shown here, are more difficult to interpret. In that basin, groundwater with highly varying salt concentration but with uniform $\delta^{18}O$ seems to contribute to the waterflow in the stream.

Extent of Effluent Areas

The extent of effluent areas can be estimated from the total volume of meltwater. If all meltwater on influent areas is assumed to infiltrate and if all meltwater on the effluent areas is assumed to generate overland flow (saturated overland flow) then the effluent area will be

$$A = \frac{V}{P-\Delta S}\,, \qquad (2)$$

where A is total effluent area, V is discharged volume of meltwater, P precipitation and ΔS snow storage (negative during melting).

During the two melting periods this spring, the effluent areas according to Eq. (2) were fractions 0.09 and 0.16 of the Nåsten basin and 0.11 and 0.14 of the Stormyra basin, respectively. The accuracy of these figures is estimated to about 0.08, using the above error discussion and a reasonable accuracy of $P - \Delta S$. The extent of the effluent areas increases as the groundwater level rises and has its maximum close to the time of maximum discharge in the streams. A field survey of the extension of effluent areas was carried out in the Nåsten basin four days after the culmination of the spring flood. Areas with groundwater table shallower than 5 cm were defined as effluent areas. From observations at 544 points, equally distributed along straight lines covering the basin, 23% of the basin was estimated to be effluent area. This ought to represent the maximum extent, and should be somewhat higher than the »mean value« during the second period, 16 ± 8% according to the estimates from ^{18}O.

Conclusions

The spring flood of 1979 from the two basins studied, was mainly originating from groundwater. These findings agree with results from similar studies of snowmelt in Czechoslovakia (Dinçer et al. 1970) and of rainfall events in Canada (Fritz et al. 1976 and Sklash and Farvolden 1979). The estimated volumes of discharged meltwater equalled the total melting over 10-15% of the basins. These figures can be assumed to represent the fraction of effluent area, as no infiltration can take place in areas with the groundwater table at (or above) the ground surface. A field survey indicated that these fractions are not unrealistic.

The results of this study stress the decisive role played by groundwater in the process of streamflow generation and support the theory of influent and effluent areas for groundwater. It should be noted, however, that the study was undertaken in basins with outwashed morainic soils (situated below the highest postglacial shoreline), during a spring when the soil was almost unfrozen. Preliminary results from a similar study in Buskbäcken, situated above the postglacial shoreline (Kloten area in Bergslagen, lat 59°57'N long 15°15'E), indicates a smaller groundwater fraction, about 50% of the total spring-flood volume in 1980.

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