MODELS FOR THE RUNOFF FROM A GLACIATED CATCHMENT AREA USING MEASUREMENTS OF ENVIRONMENTAL ISOTOPE CONTENTS

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Abstract

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For several years, in the glaciated catchment area of the Rofenache (Oetztal Alps, Austria), measurements have been made of the environmental isotopes ^{2}H, ^{18}O and ^{3}H in precipitation, snow and ice samples and in the runoff. Furthermore, the electrolytic conductivity of runoff samples was measured and tracing experiments were made with fluorescent dyes. From core samples drilled in the accumulation area of the Vernagtferner, the gross beta activity was investigated and compared with the data from ^{2}H, ^{3}H and ^{18}O analyses and the data from mass balance studies. It is shown that the annual net balance from previous years can be recovered on temperate glaciers using environmental isotope techniques. From the diurnal variations of the ^{2}H and ^{3}H contents and the elctrolytic conductivity, the following proportions in the runoff of the Vernagtferner catchment area were obtained during a 24-hour interval at a time of strong ablation (August 1976): about 50% ice meltwater, 25% direct runoff of firn and snow meltwater, and 7% of mineralized groundwater. The rest of the runoff consists of non-mineralized meltwater seeping from the glacier body. The annual variations of the ^{2}H and ^{3}H contents in the runoff of the glaciated catchment area permit conclusions on the time sequence of the individual ablation periods, and on the residence time, on the basis of model concepts. The residence times of approximately 100 days or four years, respectively, are obtained from the decrease in the ^{2}H content at the end of the ablation period and from the variation of the ^{3}H content in the winter discharge.

1. INTRODUCTION

1.1. Investigation area and studies to date

The Rofenache catchment area in Oetztal Alps (Austria) is 96.2 km^2, 44% of which is covered by glaciers. Figure 1 shows the catchment area with its

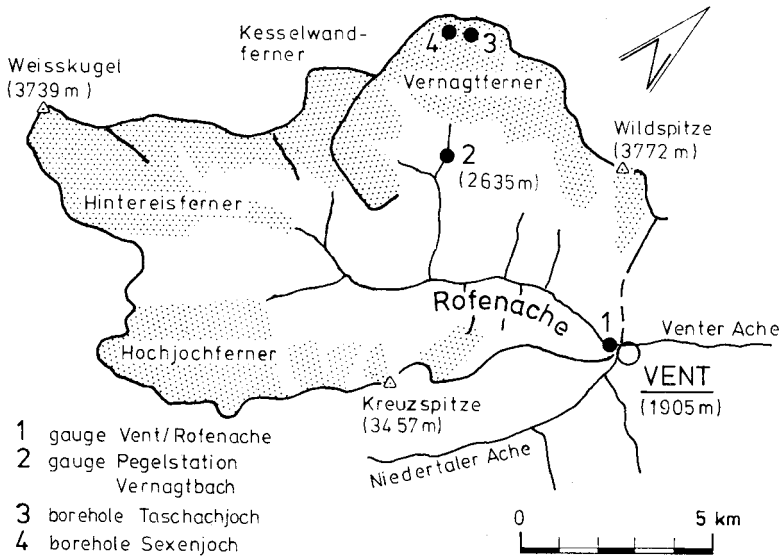

FIG. 1. Catchment area of Rofenache creek in the Oetztal Alps (Austria). The glaciated area (44%) is dotted, with 1 being the Vent/Rofenache gauge station; 2 the Pegelstation Vernagtbach gauge station; 3 the Taschachjoch borehole; and 4 the Sexenjoch borehole.

glaciers and creeks. The discharge of the catchment area is measured at the runoff gauge station of Vent/Rofenache (built in 1963 and operated by the Hydrogeographischer Dienst Tirol[1]). Vent has also a precipitation gauging station (mean precipitation 706 mm/a) providing precipitation samples for isotope measurements. Figure 1 also shows the runoff gauge station, Pegelstation Vernagtbach, run by the Kommission für Glaziologie der Bayrischen Akademie der Wissenschaften, together with the Institut für Radiohydrometrie [1]. In this part of the catchment area, covering 11.44 km^2, is the 9.03-km^2 Vernagtferner glacier. The gauge station thus comprises a catchment area, 82% of which is glaciated.

In this catchment area, isotope hydrological studies were made from 1968 to 1977 by the Institut für Radiohydrometrie together with the Physikalisches Institut der Universität Innsbruck. The content of environmental isotopes ^{2}H, ^{18}O and ^{3}H in the precipitation, in the runoff and in snow and ice samples, was determined; furthermore, the gross beta activity was determined in drill cores. The results of these studies have been published in, among others, Refs [3–5]. By comparison with the isotope hydrological studies, tracer

[1] The measured data have been published in the various yearbooks of Ref.[2].

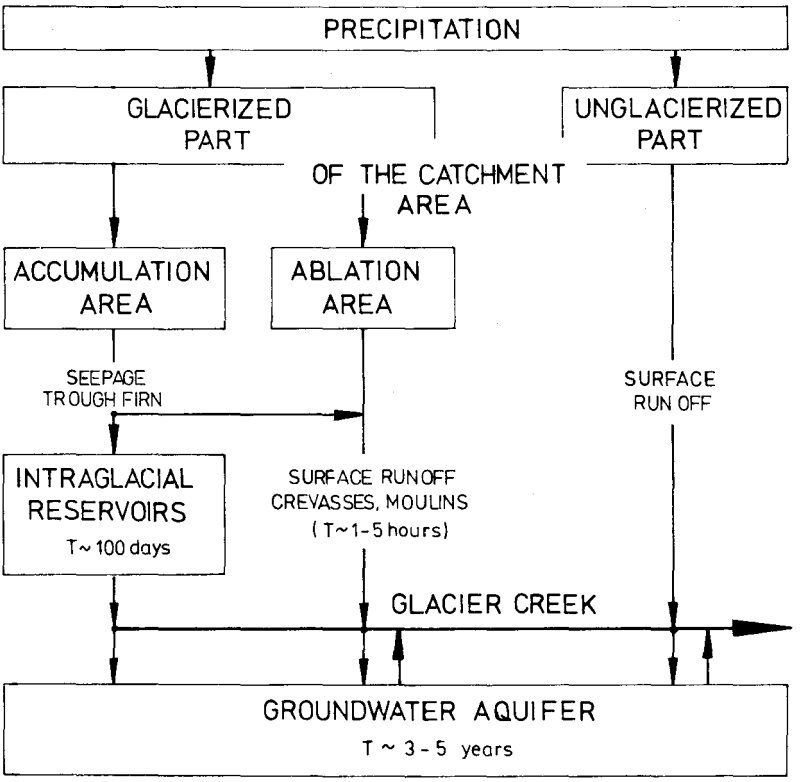

FIG. 2. Schema of the runoff within the catchment area of Rofenache. The mean residence time T is explained in Section 4.

experiments with fluorescent dyes have been made [6, 7] and the electrolytic conductivity of the runoff was determined [3, 8]. The results of all these studies up to 1975 have been reviewed [9].

1.2. Runoff from a glaciated catchment area

The Rofenache catchment area consists of glaciated and non-glaciated parts (Fig. 2). In the non-glaciated part, groundwater discharge is accompanied by a surface water runoff after snow melt and after rainfall. The non-glaciated part, however, shall not be described here. The glaciers located in the catchment area decisively influence the discharge characteristics by the change of the precipitation stored and by snow and ice melt.

The runoff from the glaciated part is mainly governed by the melting conditions on the glacier. The ice meltwater runs off on the ice surface of the

ablation area until it flows through crevasses or moulins into an intraglacial or subglacial discharge system. The ice body of the ablation area has a low retention capacity so that only short residence times of the ice meltwater may be expected. The snow meltwater, however, percolates through the firn body. The path of percolation is strongly affected by intermediate ice horizons. At the depth of the firn-to-ice transition the existence of a water-saturated layer was also proved on Vernagtferner [8]. The firn body certainly has the highest retention capacity of all the glacier parts so that the residence time of the meltwater there must be expected to be longer. The moraine material beneath the glacier offers only limited space for a groundwater system fed by meltwater. The amount of groundwater in the total runoff is only small as is shown in Section 4.

When studying the hydrology of glaciated catchment areas, the snow accumulation as well as the runoff and storage of meltwater must be taken into account. In this paper, the application of isotope hydrological methods to this problem is described.

2. ENVIRONMENTAL ISOTOPE CONTENT OF PRECIPITATION IN THE CATCHMENT AREA

Precipitations in the catchment area are labelled by their content of environmental isotopes. Figure 3 shows the monthly means of ^{2}H content in the precipitations at Vent (for location see Fig.1) in 1972–1977. The typical seasonal variation is evident. The amplitudes of the summer/winter periodicity were roughly equal each year throughout the whole measurement period. The isotope contents of the individual precipitations vary considerably owing to specific weather situations (cf. Ref.[10]) but are largely smoothed out by averaging over one month.

In Fig.4, the time fluctuation of the monthly mean values of the ^{3}H content in the precipitations at Vent is shown for the years 1970–1977. Here, too, the seasonal fluctuations are evident. The decrease in the ^{3}H contents, which has been generally observed since the nuclear weapon test ban, has not been evident since about 1972. Of note is the occurrence of some individual ^{3}H content peaks in the winter, which we also found at other measuring stations for the same periods [11].

3. RETENTION SYSTEMS IN THE CATCHMENT AREA

3.1. Retention in the glacier

When snow is being deposited on the glacier surface, the snow layers that correspond to the individual precipitations are largely preserved and labelled

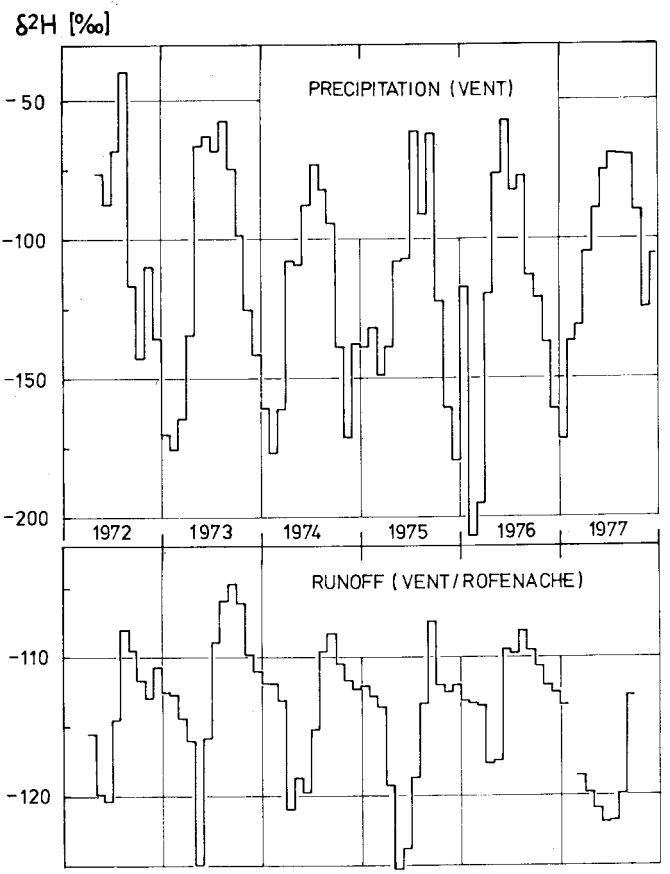

FIG.3. Variation of the ^{2}H content (monthly means) in the precipitation at Vent and in the Rofenache runoff.

by their original environmental isotope content, at least until the onset of ablation, sometimes also longer. Possibly the stratified structure of the varying amounts of net accumulation of former years may be traced back in drill cores by means of their isotope contents.

For this purpose, core samples were taken on Taschachjoch, 17 May 1976, and on Sexenjoch, 9 June 1976 (for location see Fig.1) by means of a core drill described in Ref.[12]. The drilling sites were positioned at an altitude of about 3160 m above sea level, with drilling depths at 14.10 and 15.14 m, respectively. The cores were cut into 10-cm pieces, on which the density, gross beta activity and content of environmental isotopes ^{2}H, ^{18}O and ^{3}H, were determined.

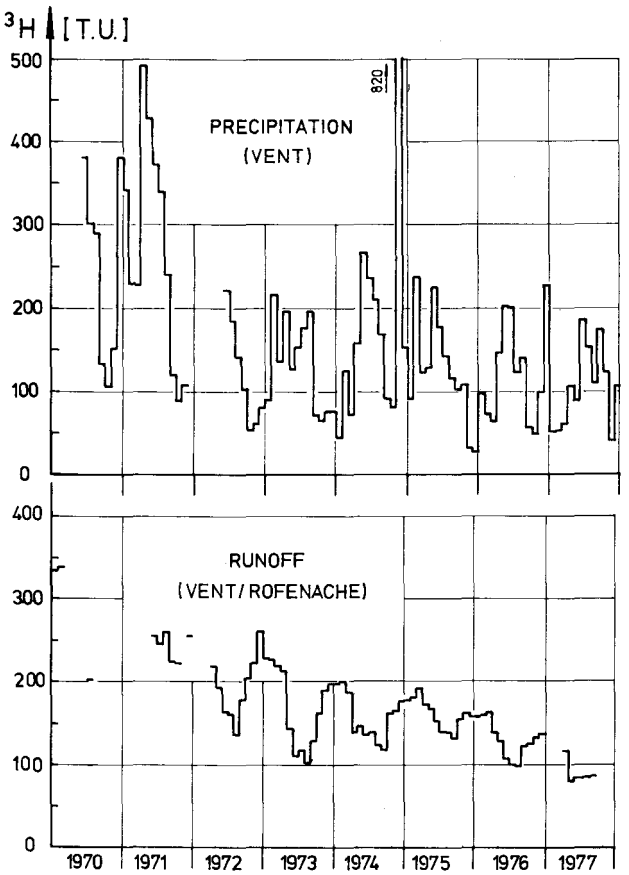

FIG. 4. Variation of the ^{3}H content (monthly means) in the precipitation at Vent and in the Rofenache runoff.

The results measured on the Sexenjoch samples are given in Fig.5. For a time assignment of the individual layers the amount of net accumulation in the neighbourhood of the drilling sites is also plotted. From the mass budget studies on Vernagtferner [13, 14][2], these net accumulation values have been traced as far back as the summer horizon of 1966. From 1966 back to 1953, the net accumulations were extrapolated from mass budget studies on the adjacent Hintereisferner glacier [15], the horizons of reference being the peaks of the gross beta activity (cf. below). These summer horizons of Fig.5 are plotted in

[2] Dipl.-Met. O. Reinwarth, Kommission für Glaziologie der Bayerischen Akademie der Wissenschaften, is thanked for making unpublished data available.

dashed lines. From the position of the summer horizons it may be seen that hardly any net accumulation exists from 1958–1959, 1962–1964 and 1969–1971, which makes an assignment of these layers difficult on account of their gross beta activity or their ^3H contents.

The gross beta activity reaches its maximum at a depth of slightly more than 10 m. The profiles of gross beta activity described in Ref.[12] on drill cores from Kesselwandferner glacier show that, above the summer horizon of 1964, no high values of gross beta activity occur. Hence, it was assumed that also the peak in the Sexenjoch profile, where the summer horizons of 1964 and of 1963 almost coincide, indicates the radioactive fallout of 1963. In comparison with precipitation fallout values, the observed value of 385 pCi/kg is high, being, however, of the same order of magnitude as the maximum values of the gross beta activity measured on core samples from Kesselwandferner. The fallout of several summer horizons must be assumed to have accumulated in the layer of maximum gross beta activity; indeed, the dry residue of the sample showing the peak yields a mass about ten times that of samples collected from the layer above it, although their activity values are also high. Similarly, the peak of gross beta activity found at a depth of 12 m (134 pCi/kg) suggested that the summer horizons of 1957 and 1958 also coincide.

The main peak of the ^3H profile differs only slightly from that of the gross beta activity by its greater depth and width. If one assigns the ^3H peak to the period from 1962 to 19[illegible], an original concentration of about 1700 TU is obtained which agrees well with the mean ^3H contents of precipitation during the winter halves of 1962/63 and 1964/65 in the Davos area 80 km west of the Rofenache catchment area [illegible] As a result the ^3H peak would cover an accumulation period abo[illegible]rs less than that which corresponds to the time scale shown in Fig[illegible] if one keeps to this time scale then it must be assumed that the gr[illegible] tritium deposited in 1962 and 1963 was removed by the melt[illegible] g into the firn, and was then fixed in the form of ice layers. Th[illegible] precipitations of the years 1958 and 1959 cannot be found[illegible] obably owing to the low accumulation and high ablation duri[illegible] On the other hand, comparatively high accumulations of winte[illegible] nmer snow are reflected in the ^3H contents of the 1966 and 1967 l[illegible]

The annual variation[illegible] H content in the precipitation (cf. Fig.3) cannot be traced so clearly [illegible] ^2H profile of the core as it can in ice cores from Greenland (e.g. Ref.[16]) or in a firn core from Mont Blanc [17], which covers a depth of 16 m, but comprises only three years of accumulation. This is because the stratification sequence of winter and summer precipitations is sometimes largely disturbed by ablation processes. Thus, either it may happen that the entire summer precipitation melts away, which would cause an absence of the δ^2H maximum of that year's accumulation, or that the winter precipitation

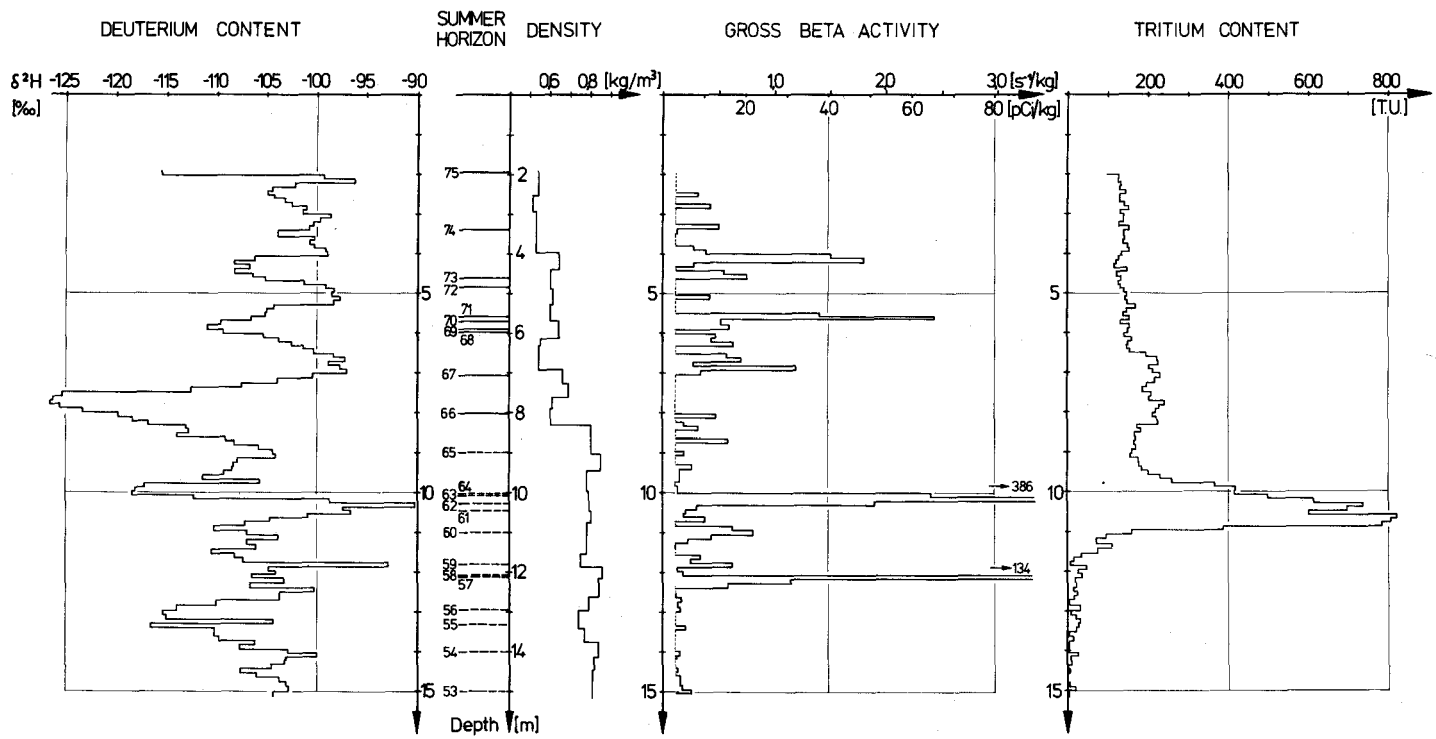

FIG. 5. Drill core Vernagtferner (Sexenjoch) June 1976 (see Fig. 1): Profile of the ^{2}H content, the summer horizons, the density, the gross beta activity and the ^{3}H content. The drilling depth is given for the glacier surface on 9 June 1976. The ^{3}H content corresponds with the time of drilling. The gross beta activity values below 3 pCi/kg are marked by a dotted line.

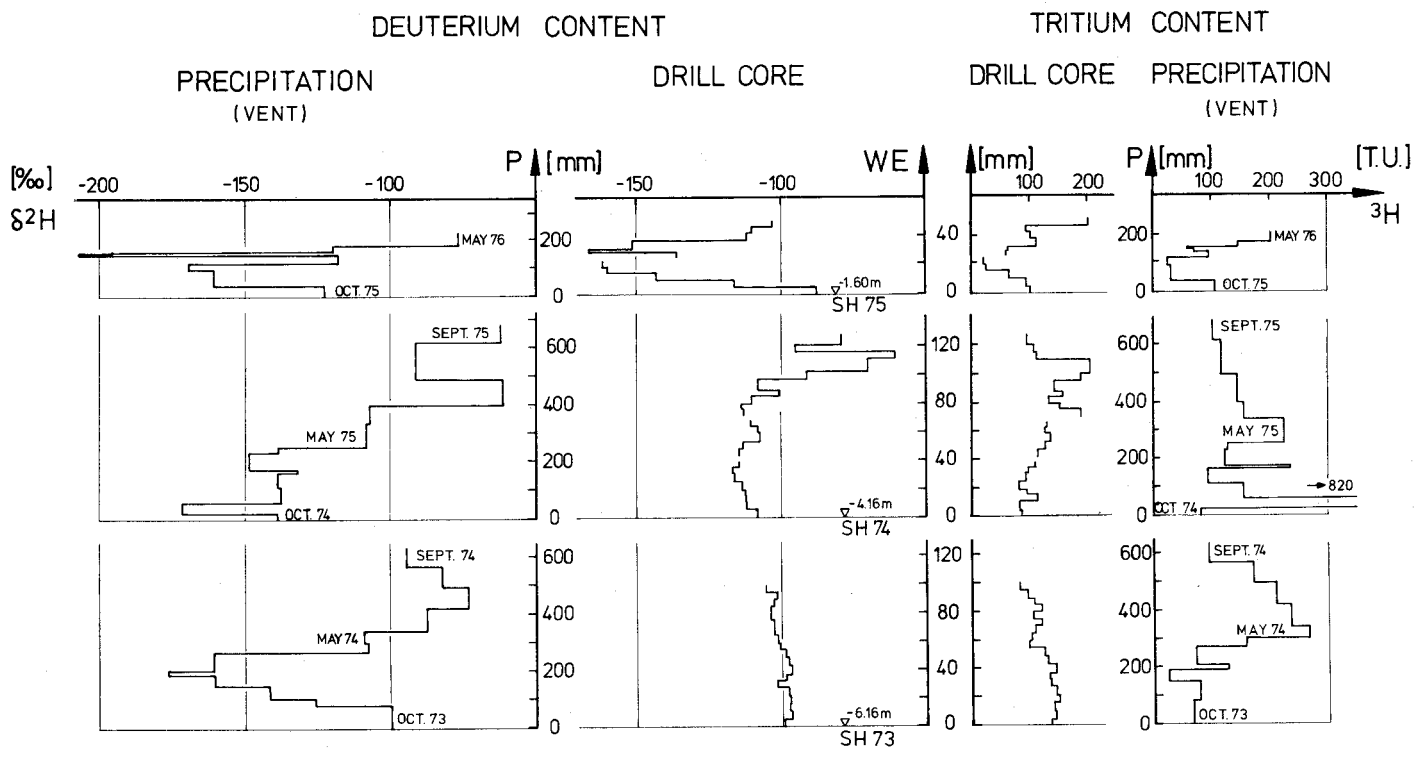

FIG. 6. Drill core Vernagtferner (Taschachjoch) May 1976 (cf. Fig. 1): Comparison of ^{2}H and ^{3}H contents in the precipitation of Vent (October 1973 – May 1976) and in the core (summer horizon 1973 – summer horizon 1974) with respect to the precipitation depth (P) and the water equivalent (WE) of firn layers, given separately for three hydrological years. Regarding precipitation, one stage always corresponds to the precipitation of one month. The depths given for the drill cores refer to the glacier surface on 17 May 1976. The ^{3}H contents given for the boreholes refer to the time of drilling.

may be almost completely melted by early summer ablation so that only summer precipitation is accumulated, thus causing an absence of the winter minimum in ^2H contents. This rare phenomenon was observed on Vernagtferner in summer 1977. It is remarkable that the absolute minimum in the δ^2H value of this drill core which was $-126.5‰$ in the winter of 1966/67, was found to be repeated in a drilling sample of Taschachjoch with the same order of magnitude. This minimum might be due to a special meteorological situation, e.g., precipitations of largely polar origin.

The drilling site on Taschachjoch shows higher accumulation rates, approximating the summer horizon of 1966, which was determined only from accumulation values obtained from mass balance studies. The ^3H contents in the 1973–1976 layers show the same slightly increasing tendency (about 150 TU) as those obtained on Sexenjoch. In contrast to the latter, however, the ^2H profile of the Taschachjoch drill samples at 0–7 m depth, showed the annual variation of the ^2H content in the precipitations to be traceable also in the snow layers (Fig.6). The seasonal amplitude of the ^2H contents in the precipitations here is maintained so long as there was no ablation. This seasonal variation is also revealed in the ^3H profile.

What has been said about the ^2H content is also valid for the ^{18}O content in the two drill cores. The slope of the $\delta^{18}O/\delta^2H$ relation is approximately 7.5, which might be due to an enrichment caused by melting and evaporation.

3.2. Retention in the groundwater reservoir

Apart from the glacier, the groundwater aquifer also acts as a reservoir. In the winter months, when there is no surface water runoff and when the runoff from the glaciated area is fed only by the groundwater and by the meltwater retained in the ice and firn body of the glacier, the groundwater reservoir has a decisive effect on the discharge.

3.3. Labelling of the discharge components

Discharge from a glaciated catchment area consists of various components, depending on the state of ablation: snow meltwater, ice meltwater, immediately running-off rainwater and emerging groundwater. These components may be characterized by their content of environmental isotopes and their electrolytic conductivity; their quantitative proportion in the total runoff can be thus determined (cf. Section 4). In this way, the ^3H content helps to distinguish between ice meltwater from old glacier ice formed long before the nuclear weapon tests, and therefore practically free of tritium, and other discharge components. The ^2H content and ^{18}O content differentiates immediately running-off snow meltwater from meltwater with longer retention, because these two

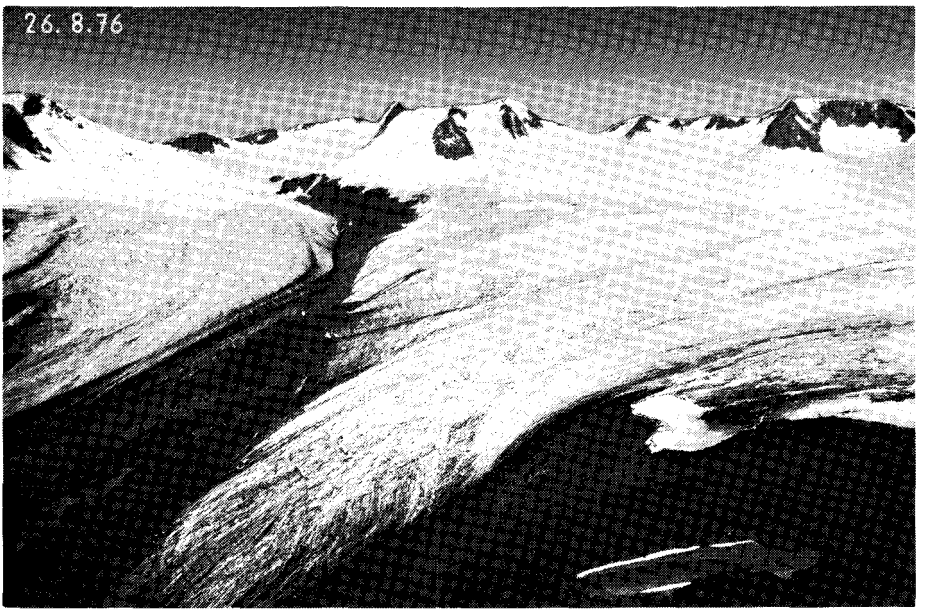

FIG. 7. Photograph of Vernagtferner glacier on 26 August 1976, taken with an automatic camera set up at the edge of the glacier by O. Reinwarth.

originate from precipitations of different seasons and have a different exposure time on the glacier surface in the form of snow. Finally, groundwater in contact with mineral rock is characterized by a higher electrolytic conductivity than meltwater running off within the glacier or on its surface.

4. RUNOFF FROM THE GLACIATED CATCHMENT AREA

4.1. Runoff from an entirely glaciated part

The total runoff of Vernagtferner is measured at the Vernagtbach gauge station (location, see Fig. 1). As 82% of the catchment area of this gauge is glaciated, the influence of the non-glaciated part is negligible, especially at times with no precipitation runoff and no snow melt in that area; the runoff there may thus be considered as a specific glacier runoff. Figure 7 shows a photograph of Vernagtferner taken on 26 August 1976. The dark ice surface contrasts well with the lighter firn and the white snow surface. The picture, taken after a week of fine weather, shows that ice ablation, firn and snow ablation took place simultaneously on that day.

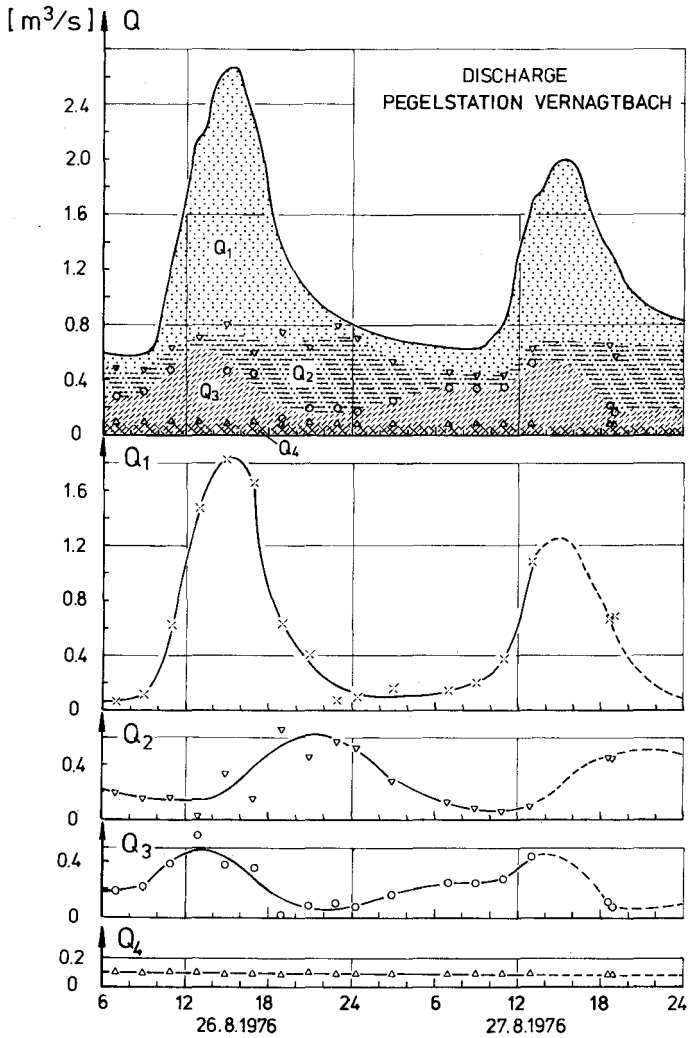

FIG. 8. Variation of the total runoff Q at the Vernagtbach gauge station (cf. Fig. 1) on 26/27 August 1976 and variations of the individual runoff components such as ice meltwater (Q_1), directly running-off snow meltwater (Q_2), longer retained meltwater (Q_3), and groundwater parts (Q_4), marked by different patterns.

Figure 8 gives the runoff Q of the Vernagtbach gauge station on 26/27 August 1976, which actually shows a considerable daily variation. To determine the daily variations of ice meltwater, (Q_1), directly running-off firn and snow meltwater, (Q_2), meltwater of longer retention in the glacier, (Q_3), and groundwater, (Q_4), the fluctuations were measured of the isotope contents and the electrolytic conductivity marking these components (Fig. 9). It can be seen

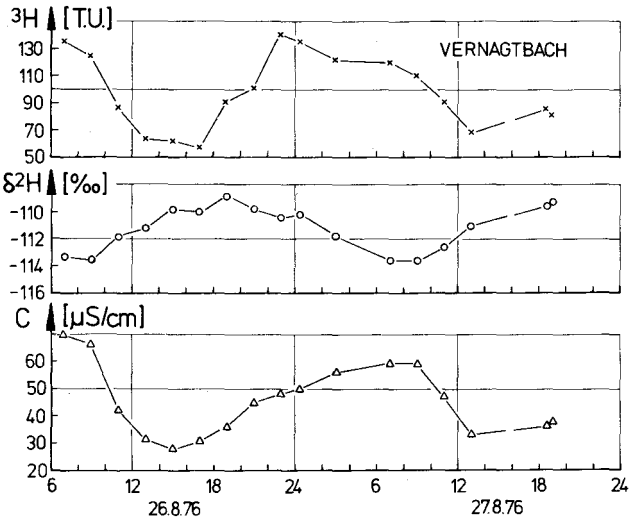

FIG. 9. Variation of the ^2H and ^3H contents and of the electrolytic conductivity in the runoff at the Vernagtbach gauge station (cf. Fig. 1) on 26/27 August 1976.

that all three measuring quantities show diurnal fluctuations. Expecially significant are the variations in ^3H content owing to the changing admixture of ice meltwater in the total runoff.

The mixing proportion of the runoff components at a certain time was calculated from the individual isotope contents and electrolytic conductivity, respectively, by using the following balance equation (cf. [3]):

$$\Sigma\, Q_i \cdot c_{iK} = Q \cdot c$$

with Q_i = runoff portion of the component i,
c_{iK} = isotope content or value of electrolytic conductivity of the component i for the tracer K (^3H, ^2H, mineralization) and
c = isotope content or value of the electrolytic conductivity of the total runoff Q.

The following values were used for the quantities c_i:

(a) ^3H: $c_1 = 0$; $c_2 = c_3 = c_4 = 150$ TU corresponding to the ^3H content in the discharge of Vernagtferner in winter and the mean value of the ^3H contents in the precipitations between April and August 1976 (cf. Figs 10 and 3).

(b) ^2H: $c_1 = c_2 = -108‰$ corresponding to the δ^2H value of a surface runoff on the glacier snout; $c_3 = c_4 = -118‰$ corresponding to the mean δ^2H value in the discharge of Vernagtbach in winter [5].

(c) Electrolytic conductivity: $c_1 = c_2 = c_3 = 20\ \mu S$ corresponding to values measured on meltwater from Vernagtferner $c_4 = 350\ \mu S$, corresponding to the average value measured on groundwater from springs in the catchment area.

Figure 8 reviews the variations of the individual runoff components determined from balance equations by using the above values and the variations of the total runoff and its ^3H and ^2H contents as well as its electrolytic conductivity.

The direct runoff of firn and snow meltwater (Q_2) has a time lag of about six hours as compared with the ice meltwater (Q_1). The peak of this meltwater wave from glacier areas of higher altitudes passed through the Vernagtbach gauge station at about 21.00 hours (9 p.m.). The fluctuations of the residual amount, Q_3, cannot be clearly interpreted. The increase in Q_3 in the morning hours may be due to onsetting ablation, which certainly activates the entire hydraulic system in and below the glacier so that the meltwater with longer residence times runs off more intensively.

The total quantitative balance for the 24-hour interval from 26 August 1976 (6 a.m.) to 27 August 1976 (6 a.m.) is given in Table I, clearly showing the specific influence of the ice meltwater on the amount of the total runoff and on the shape of diurnal variations.

TABLE I. BALANCE OF THE RUNOFF COMPONENTS IN VERNAGTBACH CREEK FROM 6 a.m., 26 AUGUST 1976 TO 6 a.m., 27 AUGUST 1976

		Q	Q_1	Q_2	Q_3	Q_4
Mean runoff	(m^3/s)	1.23	0.60	0.33	0.21	0.09
	(%)	100	49	27	17	7

4.2. Total runoff of the catchment area

The runoffs of the individual claciers (location: Fig.1) in the catchment area are characterized by different seasonal fluctuations of the ^2H values. In this respect, detailed studies were made between 1968 and 1974, with the results published in Ref.[5]. The elements are the ^2H and ^3H values (Figs 3 and 4) measured in the Rofenache runoff at the Vent/Rofenache gauge, and in the precipitation of the sampling site of Vent, during a period of several years.

The variations of the isotope contents in the runoff, together with those in the precipitations, demonstrate what runoff components prevail at what times:

(1) The onset of snow melt in spring, beginning at lower altitudes and gradually growing upwards, is clearly marked by a sudden decrease of the δ^2H values in the runoff. In the period thereafter, the runoff mainly consists of melting winter snow. The decrease in ^3H content in the runoff of spring is also due to the melting winter snow.

(2) The period of ice ablation on the glaciers is marked by minimum ^3H contents. Such ^3H minima, however, occur only during fairly long periods of fine weather since, in a period of precipitation, the surface runoff from the non-glaciated part of the catchment area, causes an increased ^3H content. Thus, two mechanisms are activated during the summer. Furthermore, the period of heavy ablation is characterized by maximum ^2H contents.

By means of fluorescent dye tracers the residence time of ice meltwater in the glacier was found to be several hours, and the percolation time in firn was found to take up to several weeks [6, 7].

(3) After the end of the ablation period, which is usually set by new snow falls down to lower altitudes of the catchment area, runoff no longer consists of directly running-off ice meltwater, firn and snow meltwater, or of rain running off directly. Normally, the catchment area is covered with snow from November to March. The runoff is then fed only by water retained in the catchment area. During this period, the ^2H content decreases until the beginning of snow melt in the following spring. The ^3H content behaves conversely: it increases up to a winter maximum. Figure 10 shows the trend of these maximum ^3H contents in the Rofenache catchment area from 1968 to 1977/78 and the annual mean values of the ^3H contents in the precipitation of various stations. All precipitation values are lower than the corresponding winter runoff values, which shows that the winter runoff is fed from precipitations of former years.

If it is assumed that the runoff after the ablation period is largely fed by two different reservoirs, which are characterized by their respective ^2H and ^3H contents, the residence time of meltwater can be calculated [19] from the decrease of ^2H contents in late autumn (Fig.3) and the decrease in the winter values of the ^3H content over a period of several years. In the former case, a mean residence time of 100 days can be calculated from the ^2H values. It seems reasonable that this residence time should be attributed to the meltwater, which is still retained in the glacier at the end of the ablation period. From the ^3H values of the years 1971/72 to 1974/75 residence times of 3.6 years and 4.8 years, respectively, result, depending on whether the winter runoff is assumed to be

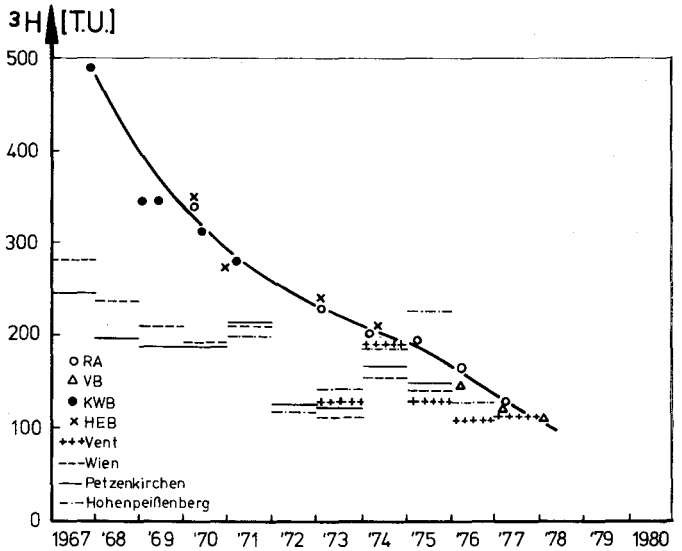

FIG. 10. Decrease in ^3H content in the winter runoff of creeks in the Rofenache catchment area (cf. Fig. 1) and the annual mean values of the ^3H contents in the precipitation of Vent, Vienna, Petzenkirchen (Austria) and Hohenpeißenberg (Bavaria, F.R. Germany). (The ^3H concentrations for Vienna and Petzenkirchen were provided by the IAEA.)
RA = Rofenache creek, VB = Vernagtbach creek, KWB = Kesselwandbach creek, HEB = Hintereisbach creek.

due to the summer or to the winter precipitation. This residence time of about four years is suitably attributed to the outflowing groundwater. From the two residence times of 100 days and 4 years it becomes evident that the winter runoff originates from two different reservoirs. The runoff of meltwater from the glaciated part decreases gradually up to midwinter so that the groundwater portion in the runoff prevails at that time. This can be proved by conductivity measurements.

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DISCUSSION

J. MARTINEC: Were the tritium concentrations in the winter baseflow as illustrated in Fig.10 not affected by the presence of meltwater from glaciers containing practically no tritium? It seems from Fig.2 that part of the groundwater recharge would come from the glacier.

W. AMBACH: Yes, you are right. During the ablation period, a small part of the ice meltwater contributes to groundwater recharge.

P. THEODORSSON: With reference to Fig.5, which shows the isotopic content of the glacier ice core, you ascribe the single pronounced tritium peak

to the summer precipitation of 1963. Judging from my experience with many similar tritium profiles for glaciers in Iceland, something seems to be missing. The sharp peak you show indicates very little vertical mixing from percolating meltwater, especially where there is a sharp decrease in tritium at the lower edge of the peak. Under such circumstances I would certainly also expect the summer peak of the years after 1963 to show up clearly in the ice.

W. AMBACH: The ^{3}H peak covers several years of ^{3}H fallout. In this Alpine region it is mainly winter precipitation that is accumulated, whereas spring and summer precipitation (particularly that of May and June) melts and is not accumulated.

J.Ch. FONTES: How do you explain the fact that the ^{3}H peak attributed to the high level of ^{3}H in precipitation in 1963–4 remained so remarkably sharp in a profile in which processes of melting and recrystallization occur?

W. AMBACH: We assume that the firn layers beneath can store only 1% per volume of meltwater. In such a situation, contamination moving downwards is small.

J. MARTINEC: What was the model used to determine the residence time of groundwater?

W. AMBACH: We used the exponential model described in Ref.[18].

B.R. PAYNE: Could you please indicate the errors in your estimates of the relative amounts of the different runoff components?

W. AMBACH: The values in Table I are integrals of the discharge curves in Fig.8. The scatter in the measurements can also be seen in Fig.8. The isotope concentration values for the discharge components were found from a group of samples (see Ref.[5]).

B.R. PAYNE: I would say that in the case of deuterium the range in delta values is only about 10‰, which would give rise to quite large errors in the estimates.

P. FRITZ: I find it very surprising that the discharge of the fourth component, namely the groundwater, in the runoff you describe is constant in time. If I remember correctly, similar studies also involving measurements of Alpine environments show very great seasonal variations, whereby the groundwater discharge increases with river discharge.

W. AMBACH: The period shown in Fig.8 is only 42 hours. We also observed seasonal variations in groundwater discharge.

J.Ch. FONTES: Did you measure conductivity for the snow profile and, if so, in that case did you observe a relationship between ^{2}H and total dissolved solids (TDS)?

W. AMBACH: We did not measure conductivity.