STUDY OF THE DISCHARGE OF ALPINE GLACIERS BY MEANS OF ENVIRONMENTAL ISOTOPES AND DYE TRACERS*

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With 12 Figures

SUMMARY

In order to gain a deeper insight into the water budget of temperate glaciers, a model was used in which total discharge of the glacier consists of three runoff components, namely, ice and snow melt water running off during summer ablation, and subglacial water. This model was applied to the runoffs of Kesselwandferner and Hintereisferner in the catchment area of the Rofenache (Ötztal Alps, Austria).

The total runoff was measured by tracer methods using the fluorescent dye Rhodamin WT. It proved advantageous to employ tracer methods particularly on glacier streams, since current meter measurements in these flow channels with their changing flow cross sections and turbulent currents are very difficult. In view of the given terrain conditions and for reasons of expediency, the instantaneous injection of tracer, combined with continuous sampling, must be preferred to a continuous injection of tracer. This method is facilitated in particular by a simple apparatus for continuous sampling during tracer passage at the site of measurement. Comparison between the results of tracer measurements and those of current meter measurements at Vent-Rofenache revealed that the accuracy of tracer measurements is at least equal to that of measurements by current meter.

For determining the runoff portions making up total flow, balance equations were used of the natural isotope contents in the water of tritium and deuterium (or oxygen-18). The isotope contents are subjected to significant annual variations and in the summer ablation period also to daily fluctuations. The premise of this method is that there exists a correlation between the individual runoff portions and specific tritium and deuterium contents, respectively. Thus, melt water from old glacier ice is practically free of tritium, whereas snow melt water and subglacial water are marked by high tritium contents. As regards deuterium levels, subglacial water differs in its low values from the surface melt waters with higher values. It was found, moreover, that spring water and melt water are characterized by distinct conductivity values.

Based on the results obtained for the Hintereisbach, the Kesselwandbach and the Rofenache, the quantitative model calculation of the daily variations of the runoff proportions furnished meaningful glacio-hydrological results. In addition, the discussion of the isotope content of glacier runoffs observed in part for periods of more than five years, provided valuable insight into glacier melting processes, their correlation with weather conditions, and the runoff phenomena of melt water in summer and in winter.

ZUSAMMENFASSUNG: UNTERSUCHUNG DES ABFLUSSES VON ALPENGLETSCHERN MIT UMWELT-ISOTOPEN UND FARBSTOFF-TRACERN

Um einen vertieften Einblick in den Wasserhaushalt von temperierten Gletschern zu gewinnen, wird ein Modell verwendet, bei dem sich der Gesamtabfluß des Gletschers aus drei Abflußanteilen, nämlich dem während der sommerlichen Ablation abfließenden Eis- und Schneeschmelzwasser und dem subglazial abfließenden Quellwasser zusammensetzt. Dieses

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Modell wird auf die Abflüsse des Kesselwandferners und des Hintereisferners im Einzugs-
gebiet der Rofenache (Ötztaler Alpen) angewendet.
Die Messung des Gesamtabflusses erfolgte mit Hilfe von Tracermethoden unter Verwendung
des Fluoreszenzfarbstoffs Rhodamin WT. Tracermethoden werden gerade in Gletscherbächen
mit Vorteil eingesetzt, da Flügelmessungen in solchen Gerinnen mit ihrem wechselnden
Fließquerschnitt und ihrer turbulenten Strömung nur mit Schwierigkeiten durchgeführt
werden können. Bei der Entwicklung der Methodik zeigte sich, daß unter den gegebenen
Geländeverhältnissen die momentane Tracerzugabe mit Sammelprobenentnahme gegenüber
der kontinuierlichen Tracerzugabe mit weniger Aufwand durchzuführen ist. Hierzu trägt
insbesondere ein einfaches Gerät zur Entnahme der Sammelprobe während des Tracerdurch-
gangs an der Meßstelle bei. Vergleiche der Ergebnisse der Tracermessungen mit denen von
Flügelmessungen an der Meßstelle Vent-Rofenache ergaben, daß die Genauigkeit der Tracer-
messungen mindestens der von Flügelmessungen entspricht.
Die Messung der Abflußanteile im Gesamtabfluß erfolgte über Bilanzgleichungen der im
Wasser natürlich vorkommenden Isotopengehalte an Tritium und Deuterium (bzw. Sauer-
stoff-18), welche signifikante jahreszeitliche Variationen und, während der sommerlichen
Ablationsperiode, auch tageszeitliche Variationen zeigen. Dabei wird davon ausgegangen,
daß die einzelnen Abflußanteile mit spezifischen Tritium- bzw. Deuteriumgehalten korre-
liert sind. So ist Schmelzwasser aus altem Gletschereis praktisch tritiumfrei, während das
Schneeschmelzwasser und subglazial austretende Wasser hohe Tritiumgehalte aufweisen.
Im Deuteriumgehalt unterscheidet sich dagegen das subglazial austretende Wasser mit
niedrigen Werten von den übrigen Schmelzwässern, die höhere Werte ergeben. Im übrigen
wurde auch gezeigt, daß Quellwasser und Schmelzwasser auch durch ihre verschiedene Leit-
fähigkeit charakterisiert sind.
Die mit Hilfe der Meßergebnisse am Hintereisbach, Kesselwandbach und an der Rofenache
durchgeführte quantitative Modellrechnung von Tagesgängen der Abflußanteile ergab sinn-
volle glazialhydrologische Ergebnisse. Daneben konnte die Diskussion der teilweise über
5 Jahre beobachteten Isotopengehalte der Gletscherabflüsse wertvolle qualitative Einsichten
in die Abschmelzvorgänge am Gletscher, über deren Korrelation mit der Witterung und über
die Abflußvorgänge des Schmelzwassers im Sommer und Winter erbringen.

I. INTRODUCTION

The present knowledge on the runoff system of a glacier is still unsatisfactory: the
hydraulic behavior (water pressure, flow and seepage) of melt water, and thus the
retention periods in the glacier, remains unexplored to a high degree; nor has the
question been settled whether it is possible to attribute a groundwater system with
subglacial springs to a glacierized Alpine region. Although there exist important
contributions to these glacio-hydrological problems (e. g., Lütschg-Lötscher
(1944), Rudolph (1962, 1963), Lang (1966, 1967, 1968), and Stenborg (1965, 1969,
1970a, 1970b) correlating, e. g., systematic runoff measurements on glacier streams
with meteorological factors. The difficulties mentioned above are mainly due to a lack
of suitable measuring methods. Thus it is difficult to determine the runoff in a glacier
stream with the aid of a current meter, because the sediment load continually
changes the shape of the measurement profile. The flow pattern in the measurement
profile depends on random inflow and outflow conditions. Heavy turbulence fre-
quently causes very pronounced surface waves (Rudolph, 1962). Recording gauges
with a reliable calibration curve have been set up so far only in a few exceptional
cases and usually at a greater distance from the glacier snout (Lang, 1967).
The present study therefore aims at finding new methods of measurement for glacio-
hydrological investigations. It is the main objective in this connection to apply
tracer methods to runoff measurements, and to use the natural isotope content of
the water (i. e., its tritium, deuterium and oxygen-18 contents) for determining the

characteristics of the runoff system of the melt water. It is the particular purpose of these measurements to provide information on the runoff proportions of snow melt water, ice melt water as well as of water running off on the surface and underground. Similarly, Dincer *et al.* (1970) determined the shares of old snow melt water and spring water to the total runoff in a high-altitude non-glacierized drainage area by measuring the natural isotope content. This problem becomes more complex in the case of a glacierized catchment basin, because melt water from old glacier ice contributes decisively to runoff.
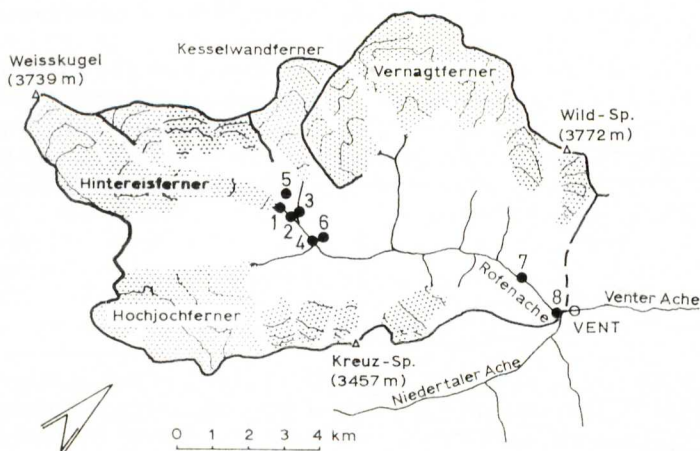

Fig. 1: Map of the drainage area of the Rofenache
  1 Tracer injection point Hintereisbach (2300 m a. s. l.)
  2 Sampling site Hintereisbach
  3 Sampling site Kesselwandferner
  4 Sampling site Hochjochsteg
  5 Spring on a slope near the glacier snout
  6 Hochjoch Spring
  7 Tracer injection point Rofenhöfe
  8 Measuring and sampling site Vent-Rofenache gauge (1890 m a. s. l.)

It was decided to perform the scheduled studies in the drainage area of the Rofenache (Ötztal, Austria) for the following two reasons: first, intensive glaciological research on mass balance was conducted in this area (cf., e. g., the comprehensive representation by Hoinkes (1970)), secondly, a fully developed gauging station is available at Vent. The area drained by the Rofenache (see Fig. 1) extends over 98 km², 44 per cent being glacierized; its mean altitude is about 2920 m a. s. l. The measurements were made on the glacier streams of Hintereisferner (9 km²) and Kesselwandferner (4 km²) and on the Rofenache. The differences in exposure, steepness and extent of the accumulation and ablation areas of the two glaciers make such a parallel investigation meaningful.

2. METHODOLOGY AND RESULTS

2.1. Outline

Tracer methods with continuous or instantaneous injection of the fluorescent dye Rhodamin WT were used to measure the total runoff. The measuring procedure described in Section 2.2.1 had been tested in several preliminary runs in the summer and autumn of 1969 and was subsequently adopted for the summer 1970 tests on the glacier stream of Hintereisferner and Rofenache (with a duration of up to 36 hours). Total runoff from the drainage area of the Rofenache was checked by a current meter at the measurement site of Vent-Rofenache, where a recording stream gauge is operating.

The isotope content was measured for tritium, deuterium and, in some cases, also for oxygen-18. At the same time, the tritium measurements initiated at Kesselwandferner in 1966 by Ambach et al. (1969) were continued in 1970. Further results exist also for the Hintereisferner, the Rofenache at Vent and for several springs in the vicinity of the glaciers. A total of about 250 tritium, 600 deuterium and 125 oxygen-18 determinations were made.

2.2 Measurements of Total Runoff

2.2.1 Measuring procedure

In the tracer methods employed to measure the total runoff, a dosed amount of tracer is added to the water at the point of injection. After sufficient mixing, the tracer is detected at the downstream measuring site. Runoff (m^3/sec) is calculated in the case of instantaneous injection from the integral of the measured concentration-time distribution of the tracer, and in the case of continuous injection, from the temporarily constant tracer concentration. Determining runoff from such measurements has the advantage, among others, that the cross section of the flow channel need not be known; the method is therefore particularly suited for channels whose cross section is difficult to measure, such as mountain streams with a large sediment load (for details, c. f. British Standard 3680 (1964) and André (1964). The following requirements, however, must be fulfilled:

First, the tracer has to be well mixed in the current. Preliminary experiments in the Hintereisbach revealed that such an intermixing takes place after a flow distance of about 300 m, because of the great water turbulence.

Secondly, the tracer must not be lost along the measuring section by adsorption, chemical precipitation, seepage or similar processes. In the course of the preliminary experiments and during the main test in July 1970 no loss of the fluorescent dye Rhodamin WT[1] used as tracer was observed in the Rofenache along a fairly short measuring section (Rofenhöfe-Vent, about 1,5 km; see Fig. 1). A comparative runoff measurement with the current meter at Vent-Rofenache confirms this result (see also Fig. 3). It should be noted in this connection that the rate of suspended particles in the Rofenache is high. Rudolph (1962) observed a content of suspended particles at the sampling site Hochjochsteg of up to 3,5 g/ltr. Tracer losses became evident along the measuring section from the Hintereisferner to Vent (about 10 km long). Under the conditions prevailing in July 1970, an apparent runoff increase of the Rofenache at Vent up to some 20 per cent was observed. Hence it is concluded that in the case

of the measurements conducted over a short measuring section (300 m) along the Hintereisbach, the probability is high that no tracer adsorption worth mentioning occured. Though tracer losses through seepage of a substantial portion of the glacier stream are not to be expected for the measuring section chosen on the Hintereisbach, they cannot be excluded with certainty.

Thirdly: When using continuous injection, conditions of steady-state flow must be given along the measuring section if the simple relations for runoff determination described in literature (e. g., André (1964)) are to furnish correct results. It is essential in this respect that the tracer solution at the site of measurement is constant in the case of continuous injection of tracer. Unsteady runoff in the flow channel, however, will vary the flow time between the points of injection and measurement. If this variation occurs during measurement, the tracer runoff at the site of measurement will consequently also change inversely, producing too low runoff values if flow time diminishes, and vice versa.

This effect may be corrected by measuring continuously flow time with the aid of time marks set, for example, by injecting instantaneously a second tracer into the flow channel at the point of the continuous tracer injection. The correction factor for determining the accurate flow value results from the ratio between the time mark intervals registered at the measuring site and at the site of injection, respectively (Behrens 1971 b). For short mixing distances with a flow time during which the steady-state conditions do not change significantly (e. g., the 300 m section on the Hintereisbach), the correction factor is negligible. If longer flow times are involved, however, e. g. between Hintereisferner and the Vent-Rofenache measuring site (10 km) with a flow time of about two hours, evaluation must allow for the correction factor.

To decide whether a continuous or an instantaneous tracer addition is more favorable for solving the problems under study, both methods were applied in the field. Continuous tracer injection was done at a constant injection rate using a Mariotte vessel. In the tests in July 1970 a 12-hour labeling of the Hintereisbach was carried out with a 10 ltr filling of dye solution which could still be detected quantitatively at Vent by direct measurement in the flow cuvette of a fluorimeter. For this purpose the original dye solution (see footnote[1]) was diluted with an equal volume of water. At measuring sites that were not easily accessible (in the glacier forefield, for example), the tracer was detected by taking samples (50 ml plastic bottles) which were later measured by a fluorimeter in the laboratory.

In contrast, the easily executed instantaneous tracer injection requires sampling at the measuring site that covers the entire concentration-time integral of the tracer passage. This may be accomplished, for instance, by taking instantaneous single samples at defined time intervals. The concentration-time-distribution is constructed from those samples. For runoff measurements, however, it is sufficient to take continuous samples at constant withdrawal rate during tracer passage. As an example, Fig. 2 shows the easily transportable equipment for this sampling; the required battery-operated motor pump can be timed by an electronic switch so that one operator is sufficient for injection and sampling. If the head is sufficiently high, the

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[1] Rhodamin WT is supplied by Du Pont de Nemours Co., Wilmington, Delaware, USA in 20% solution. Its properties as dye tracer (spectral absorption, temperature and pH-dependence, sensitivity to light, are equal to those of rhodamin B extra, available in the form of water-soluble powder (Behrens 1971 a), commonly used as hydrological tracer.

water may also be drawn from the channel by a hose, being conducted directly into the overflow vessel.
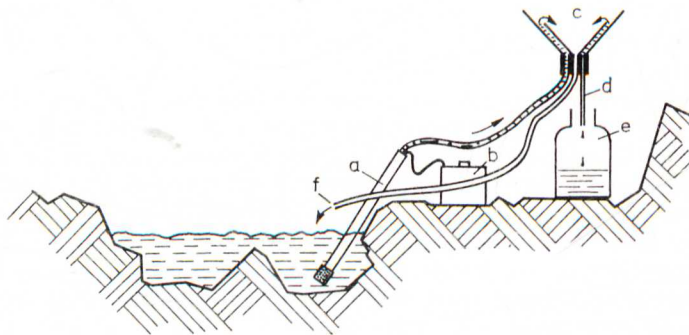

Fig. 2: Continuous sampling equipment for runoff measurements using instantaneous injection of tracer
a   Battery-operated pump
b   Power supply
c   Constant head
d   Capillary
e   Sampling bottle
f   Overflow runoff.

Experience to date has shown that the measuring method with instantaneous injection and continuous sampling is simpler and cheaper for measuring glacier runoffs in rugged terrain. The shortest time intervals possible between the injections are given by the dispersion of tracer clouds at the site of measurement which should not overlap in successive measurements. In general, however, measurements at intervals of one to two hours are sufficient for hydrographic recording. This method requires a lower tracer amount than is needed for continuous injection of the same duration. The following equipment is necessary: tracer portions dosed in bottles plus sampling outfit which in the simplest case consists of a hose, overflow vessel and sampling bottles.

For measuring sites which are accessible by car and may be supplied with electricity, it is favorable to install a fluorimeter with flow cuvette directly recording the trend of the tracer curve. Such an installation was used on the Rofenache near Vent in July 1970. Two fluorimeters (Turner, Type 111) were set up in a VW transporter which, by appropriate lamp and filter combinations, allowed the independent detection of two dye tracers (see Behrens 1971a). In this manner, the daily flow time fluctuations were observed by instantaneous injection of the dye Uranin.

The quantitative runoff measurement with the flow cuvette still presented difficulties owing to the high rate of suspended particles in the Rofenache: disturbance of the direct fluorescence measurement by light being diffused by the high concentration of opaque matter in the glacier water was eliminated by improving the measuring technique (Behrens 1971a). Changing light absorption in the measuring cuvette due to the fluctuating content of suspended particles still made calibration difficult. These difficulties have not yet been solved satisfactorily. The runoff values for the measuring site Vent-Rofenache given in the following section have thus been determined from measurements on continuous samples.

For comparison with runoff values obtained by tracer methods, current meter measurements were also performed at Vent-Rofenache in a preliminary experiment on 8 October 1969 and during the tests in July 1970. In these cases, 15 measuring plumbs each with a maximum of 4 measuring points were measured in rectangular measuring cross section (width, 6.50 m) with a current meter, type V, Arkansas, delivered by Ott, Kempten, Fed. Rep. of Germany. Because of the mostly high flow velocity (up to 4.5 m/sec) and wave formation, the water depth was determined by leveling.

2.2.2. Measurement results

After the preliminary experiments in autumn 1969, whose results have been described qualitatively in section 2.2.1., the following runoff measurements were carried out in July 1970: From 22 July, 12.00 h, to 23 July, 24.00 h, instantaneous injections were made at two-hour intervals into the Hintereisbach at the terminus of the glacier
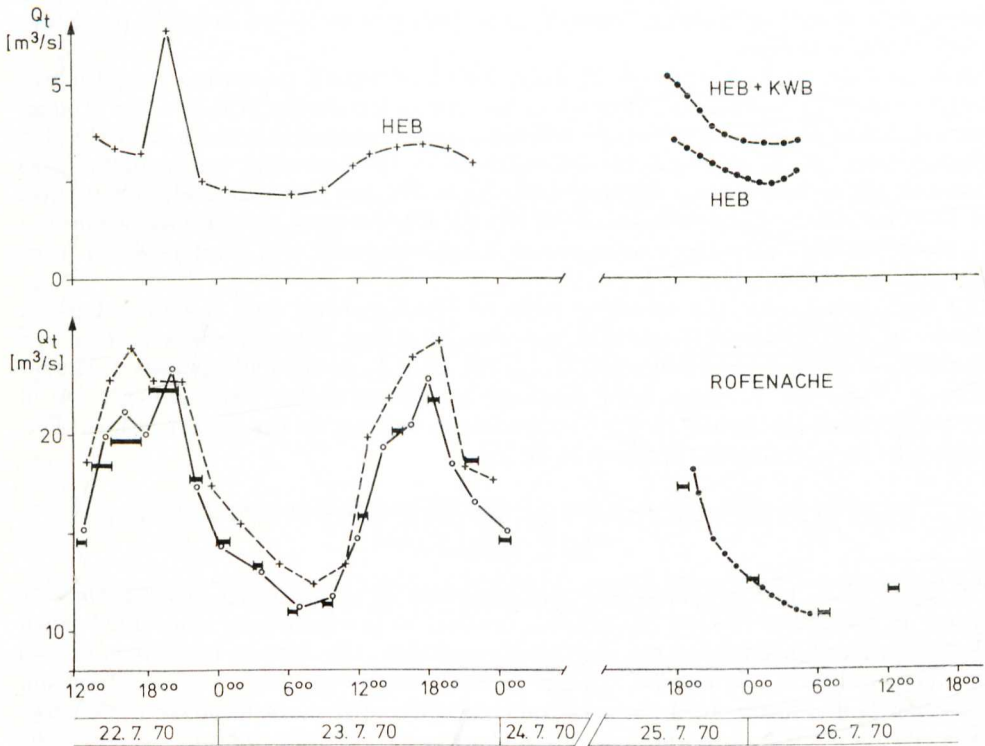

Fig. 3: Runoff Q_t at the measuring sites Hintereisbach (HEB), Hochjochsteg (HEB + KWB) and Vent—Rofenache on 22 to 23 July 1970 and 25 to 26 July 1970
o = Values measured with instantaneous injection of tracer at Rofenhöfe
+ = Values measured with instantaneous injection of tracer into Hintereisbach
● = Values measured with continuous injection of tracer into Hintereisbach
H = Current meter
The peak value in the evening of 22 July 1970 was caused by a heavy thunderstorm,

and into the Rofenache at the Rofenhöfe. The tracer (Rhodamin WT) was detected by continuous sampling at the measuring site on Hintereisbach 300 m downstream from the point of injection and at the measuring site Vent-Rofenache (see Fig. 1). There, tracer passage was also determined directly by measurement in the flow cuvette of the fluorimeter, the runoff being measured with the current meter.

The upper part of Fig. 3 shows the hydrograph for the Hintereisbach. The high flow value measured on 22 July, 19.50 h, was due to a heavy thunderstorm shortly before, with high runoff from the slopes.

The lower part of Fig. 3 shows a comparison of the hydrographs for the Rofenache at Vent which were obtained by the tracer method and by measurements with the current meter. As in the preliminary experiments, again good agreement was observed within the error limits of 3 to 5 per cent between the results of tracer measurements over the short measuring distance Rofenhöfe-Vent (about 1.5 km) and the values furnished by the current meter.

The data of dye labeling on Hintereisbach indicate a runoff apparently higher by about 10 per cent. This suggests that also in this test tracer losses were caused by adsorption along the Hintereisferner-Vent section (about 10 km long), in particular when runoff was high.

From 25 July, 17.00 h, through 26 July, 5.00 h, a second measuring program was carried out with continuous injection of the tracer Rhodamin WT into the Hintereisbach below the glacier snout. In addition, instantaneous injections with the dye Uranin were made at 75-minute intervals. As in the preceding test, samples were taken at the measuring site Hintereisbach (flow distance approximately 300 m) and at Vent-Rofenache (flow distance about 10 km). Furthermore, samples were collected at Hochjochsteg below the confluence of Kesselwandbach and Hintereisbach (flow distance approximately 2 km).

The hydrographs for the sampling sites of Hintereisbach and Hochjochsteg are shown in Fig. 3, the difference of the runoffs giving the respective momentary discharge of the Kesselwandbach (1 to 1.5 m^3/sec.). As to the hydrographs of Rofenache at Vent, the discharge data obtained by current meter measurements are in agreement with the results of dye measurements as long as the runoff is low. This holds also for a measuring distance of 10 km.

2.3 Measurement of the Tritium Content

2.3.1. Methods[2]

The application of tritium content measurements in glaciological investigations is based on the steep rise of the tritium content in precipitations since 1952 when thermonuclear weapons testing started. Even today, the tritium content is one to two powers above the natural tritium content originating from cosmic radiation. In consequence, the snow in the accumulation areas of glaciers dating from the time after the beginning of nuclear weapons tests are labeled by tritium, whereas the "old" glacier ice formed before this period is almost free of tritium. Consequently the mingling of melt waters of varying origins, of subglacial spring water and rain water running off directly, produces daily and seasonally different tritium concentrations, depending on the melting conditions.

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[2] The measuring method for determining the tritium content in water samples has been comprehensively presented by Rauert (1971), for example.

To calculate the components of total runoff from the daily variations, the following balance may be established:

$$T_i\, Q_i + T_s\, Q_s + T_r\, Q_r + T_g\, Q_g = T_t\, Q_t \tag{1}$$

where Q represents the runoff proportions and T the tritium contents of these proportions, the subscripts referring to ice (i), snow (s), rain (r), subglacial spring water (g), and total flow of the glacier stream (t). In the studies to date (Ambach *et al.*, 1969, 1970a, 1971), Q_r was put equal to zero (rainless days of measurement) and $T_i = 0$ (old glacier ice being practically free of tritium) so that equation (1) becomes

$$T_s\, Q_s + T_g\, Q_g = T_t\, Q_t \tag{2}$$

Equation (2) contains four measured values (Q_t, T_s, T_g, T_t) and two unknown quantities (Q_s, Q_g). It must therefore be supplemented by a second balance equation that is set forth in section 2.4.1.
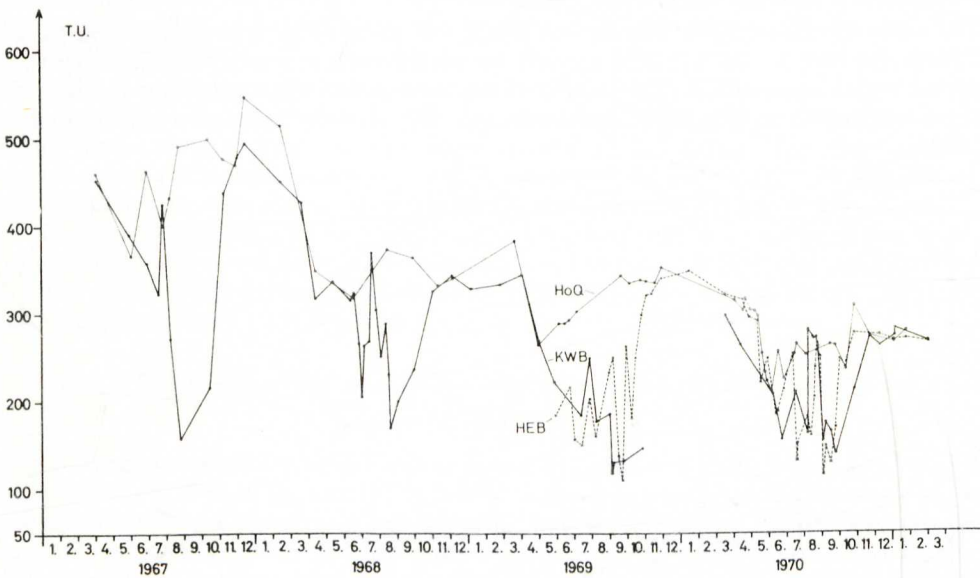

Fig. 4: Annual variations of tritium content in the runoffs of the Kesselwandferner (KWB), the Hintereisferner (HEB), and the Hochjoch Spring (HoQ).

2.3.2. Measurement results

To determine the measurement values of eq. (2), the daily and seasonal variations of tritium content in the runoff of the Kesselwandferner and of the Hintereisferner were measured at two springs in the vicinity of both glaciers. In addition, ice, snow and melt water samples were examined that had been taken on Hintereisferner itself. Furthermore, the daily variation of the tritium content of the Rofenache at Vent was logged in various seasons.

The results represented in Fig. 4, 5 and 6 are given in tritium units (TU), 1 TU corresponding to a concentration of 3.2 pCi/ltr.

The seasonal and daily ice melts are clearly marked by low tritium content in the glacier runoffs (Figs. 4 and 5), whereas snow melt water and subglacial spring water produce higher tritium values. Ambach *et al.* (1969) has already mentioned that isolated maximum values of tritium content appearing in summer may be attributed to an interruption of ice ablation caused by weather conditions (cf. section 3.2). Part of these summer variations are also due to daily fluctuations made evident by samples taken at different times of the day. In the seasonal trend, the end of the ablation period is characterized by an increased tritium content. This increase was found to extend into late autumn, indicating a gradual decline in low-tritium melt water from old glacier ice due to slow seepage from the glacier.

In spring, the tritium content of the glacier runoff drops considerably. From April to June, this is mainly due to melting of last winter's snow in the ablation area, since winter precipitations have a comparatively low tritium content. Later, in midsummer, a low tritium content in the glacier runoff is caused solely by the ablation of practically tritiumfree glacier ice.

The curve of annual variations for the Hochjoch spring (Fig. 4) contains maxima of tritium content in summer and minima in winter with a general decline over the period under observation. The winter value corresponds approximately to that of the two glacier runoffs and of Rofenache (see Fig. 5, daily trend of 1—2 February 1970).
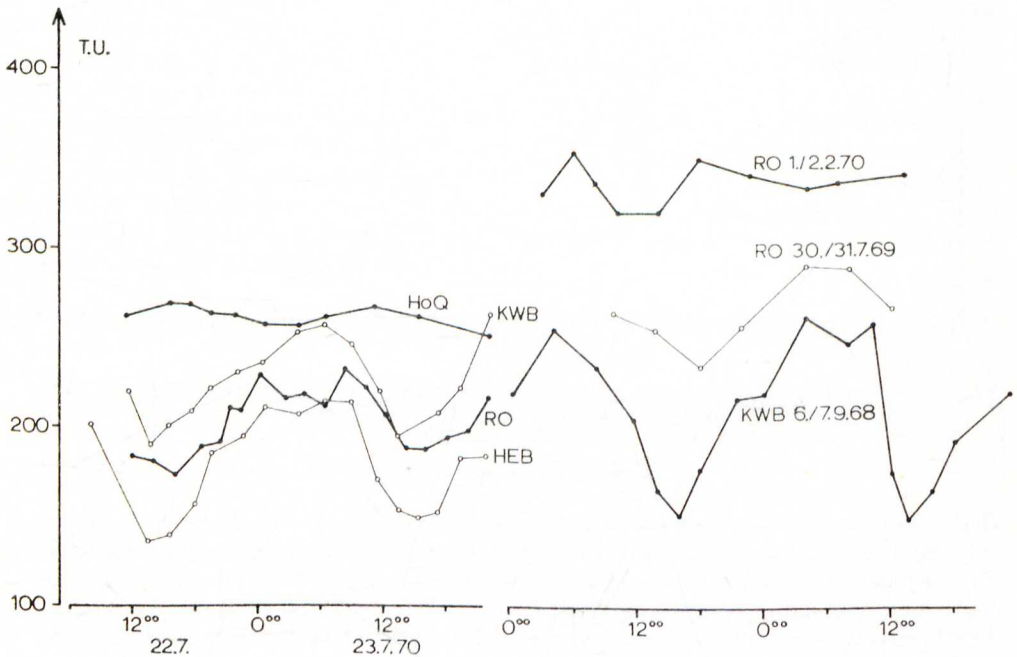

Fig. 5: Daily variations of tritium content in the runoffs of the Kesselwandferner (KWB), the Hintereisferner (HEB), the Hochjoch Spring (HoQ), and the Rofenache at Vent (RO)

Compared to the annual variations of the Kesselwandbach and Hintereisbach there are no significant differences (Fig. 4). The curves of daily variations for 22—23 July 1970 (Fig. 5), however, show the average tritium values for the Kesselwandbach to be about 40 to 50 TU higher than those of the Hintereisbach, indicating that the relative portion of ice ablation of Hintereisferner during this period is higher (due to lower altitude) than that of Kesselwandferner. The values measured at Hochjoch-steg, below the confluence of the two glacier streams, cannot be distinguished from the values for the Hintereisbach within measuring accuracy ($1\sigma = \pm 10$ TU). It is therefore impossible to estimate the runoff share of the Kesselwandbach from these measurements.

So far, the following fluctuations of the daily tritium trends have been measured for the Kesselwandbach: about 70 TU for 22—23 July 1970 and about 110 TU for the period from 5 to 7 September 1968. This increase of the variation amplitude may be explained by a higher ice ablation toward late summer. Finally it should be mentioned that the spring on a slope near the glacier snout showed tritium contents between 350 and 395 TU on 30—31 July 1969 and between 295 and 320 TU on 22—23 July 1970.

Fig. 6 shows tritium and deuterium values measured for the snow, ice and melt water samples taken at Hintereisferner from 22 to 24 July 1970, as well as for some spring water samples taken in the closer vicinity of the glacier. The snow sample values show considerable scattering with a noticeable dependence on the altitude of the sampling site; this phenomenon will be discussed in section 3.3. The tritium values of the spring water samples (except for one sample) lie within the range of the mean value for the snow and melt water samples, i. e. between 195 TU and 240 TU. The tritium values of the ice and ice melt water samples indicate a more or less pronounced addition of snow melt water to the melt water from old glacier ice.

2.4. Measurement of the Deuterium and Oxygen-18 Contents
2.4.1. Methods[3]

The measurements of deuterium and oxygen-18 contents in glaciological studies are based on the fact that the content of heavy isotopes in precipitations decreases with rising altitude and decreasing condensation temperature. The isotope content of precipitations thus shows an altitude dependence and periodic seasonal fluctuations. If precipitation occurs as snow, the metamorphism of snow and phase transformations (by melting, evaporation, freezing, sublimation) lead to further changes in the isotope content which enrich heavy isotopes in the snow cover and in the ice (cf. Moser and Stichler (1970, 1971)). These complicated processes have the effect that the runoff of a glacier shows deuterium and oxygen-18 contents varying daily and seasonally (Ambach et al. 1970b) with subglacial spring water and rain water running off directly.

To calculate the changing contributions to runoff in the course of a day, a balance equation analogous to eq. (1) may be written:

$$\delta_i \, Q_i + \delta_s \, Q_s + \delta_r \, Q_r + \delta_g \, Q_g = \delta_t \, Q_t, \tag{3}$$

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[3] A comprehensive presentation of measuring methods to determine deuterium and oxygen-18 contents has been given, for example, by Moser and Stichler (1971).

where Q, as in eq. (1), represents the runoff proportions and δ the corresponding deuterium and oxygen-18 contents, respectively; the subscripts have the same meaning as in eq. (1). Putting $Q_r = 0$ (rainless days of measurement) gives

$$\delta_i\, Q_i + \delta_s\, Q_s + \delta_g Q_g = \delta_t\, Q_1$$

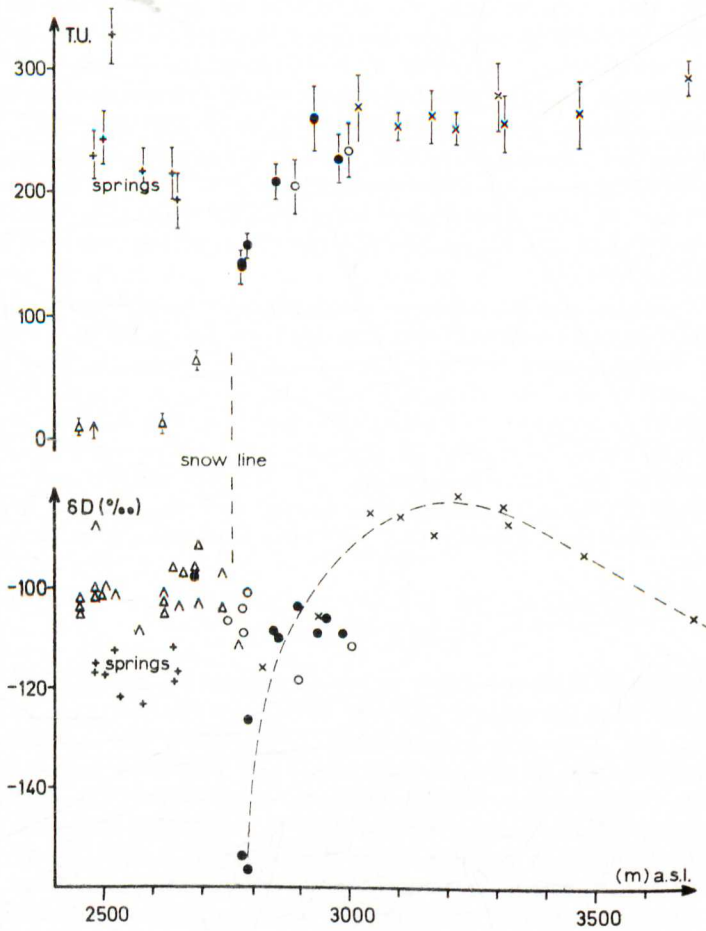Eqs. (2) and (4) are evaluated in Section 3. 1.

Fig. 6: Tritium and deuterium contents of snow, ice and melt water samples collected from 22 to 24 July 1970 at the Hintereisferner, as a function of the elevation a. s. l. of the sampling sites

∧ = Ice
△ = Melt water from ice
✕ = New snow
● = Old snow
○ = Melt water from snow
+ = Springs.

2.4.2. Measurement results

To determine the quantities δ_i, δ_s, δ_g, δ_t of eq. (4), the deuterium content of the same samples was analyzed as in the tritium program (section 2.3.2). In part, parallel oxygen-18 analyses were carried out[4] which may give some clues on rapidly progressing (kinetic) evaporation effects (see, for example, Moser and Stichler (1971)).
The measured results are given by the δD and $\delta^{18}O$ values, respectively, defined by the relation

$$\delta D \text{ and } \delta^{18}O, \text{ resp.} = \frac{R_{sample} - R_{st}}{R_{st}} \cdot 1000\,^0/_{00}$$

where R_{sample} and R_{st} are the deuterium and oxygen-18 isotope ratios in the sample or in a standard. As usual, the standard is an ocean water sample (SMOW according to Craig (1961)). Measuring errors are $\pm 1^0/_{00}$ for the δD-values and $\pm 0.2^0/_{00}$ for the $\delta^{18}O$-values.
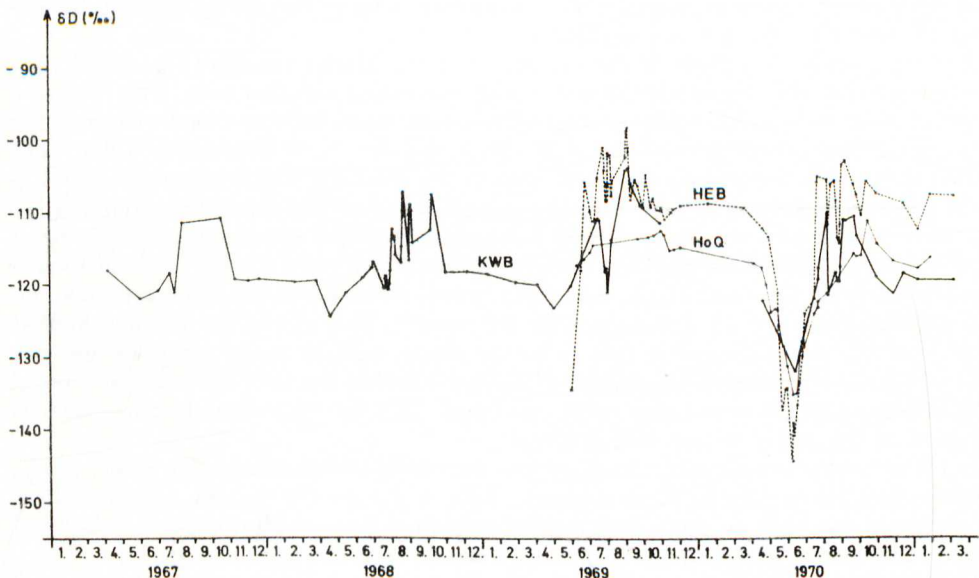

Fig. 7: Annual variations of deuterium content in the runoffs of the Kesselwandferner (KWB), the Hintereisferner (HEB) and the Hochjoch Spring (HoQ).

The annual trend of the δD-values was observed over a period of 5 years on the Kesselwandbach and 2 years on the Hintereisbach (Fig. 7). Both glacier streams show a similar periodic course of the seasonal variations of the deuterium content: after constant winter runoff values (Kesselwandbach about -118 to $-120^0/_{00}$, Hintereisbach about $-109^0/_{00}$) the deuterium content decreases considerably during the snow melt between April and June, because the snow melt water is "lighter"

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[4] The oxygen-18 measurements were performed by Mr. P. Trimborn in connection with the thesis for his diploma.

with respect to its isotopic composition. As the melting of the glaciers increases, the deuterium content rises in midsummer. The heavy variations during this season are mainly due to the weather accompanying fluctuations of the zero-degree (centigrade) level, accumulation and melting of new snow (cf. section 3.2), but also to sampling done at different times of the day. A constant value is obtained only in autumn and throughout winter. The curve of variations for Hintereisbach generally is about $8-10^0/_{00}$ higher than that for the Kesselwandbach. Since the altitude of the snout of the Kesselwandferner is some 300 m higher than that of the Hintereisferner, this corresponds to an "isotope altitude effect" of δD being $-3^0/_{00}$ per 100 m. A similar isotope altitude effect has been measured in the German Mittelgebirge ($-3^0/_{00}$ per 100 m (Eichler, 1964)) and on samples of new snow from the Alpine region (($-4 \pm 2)^0/_{00}$ per 100 m (Moser and Stichler, 1970)).

The annual trend of the δD-values for the Hochjoch Spring shows fewer variations than those of glacier streams. The pronounced drop in early summer, however, evidences a strong and direct influence by snow melt water. Due to the isotope altitude effect, the data suggest that the drainage area of this spring and the Kesselwandferner have the same mean altitude.

As to the daily variations of the δD-values of the glacier runoffs (Fig. 8a), it was observed that the amplitude increases with extending ablation area. This was also observed in connection with the tritium measurements (cf. the trend of curves for the Kesselwandbach for 22—23 July 1970 and for 6—8 September 1968). The δD-values were low during the night and in the morning, and high at noon and in the afternoon. In accordance with the annual trend of the deuterium content, the mean δD-values of the daily trends increase as autumn comes nearer. This must be due to the higher ice ablation and lower melting of snow having a lower δ-value particularly at higher altitudes. The daily trends recorded on the Hintereisbach and Kesselwandbach for 22—23 July 1970 are similar. This allows the conclusion that the time the water needed to flow from the glacier surface to the sampling site was equal for the Hintereisbach and Kesselwandbach within the error limits of the curves. In this case samples were taken every two hours. This flow time includes the residence period of the water within the glacier.

In the above measurements, the δD-values for the Kesselwandbach are about $12\ ^0/_{00}$ lower than those for the Hintereisbach. This is due to the isotope altitude effect mentioned and to particular conditions different from those at Hintereisferner, influencing the melting during the days of measurement with existing snow patches.

The trend of the deuterium content in the Hintereisbach for the period from 4 to 7 September 1969 was measured when the new-snow cover melted, the δD-value being high due to the season. The melting process is thus expressed by the isotope content: up to the beginning of ice ablation on 5 September, the observed δD-values of the new-snow melt water were largely constant. Recurring ice ablation, however, produces an increasing periodic fluctuation of the curve of δD-values. In contrast to the other daily trends, the latter is modified in amplitude and phase by the retention capacity of the partly existing snow cover and by the unusual relations of the δ-values of ice melt water, snow melt water and running-off subglacial seepage water.

The δD-values were measured not only on the two glacier streams, but also at Hochjochsteg below the confluence of the Hintereisbach and Kesselwandbach on 22—23 July 1970. As expected, the daily curve of these δD-values lies between those of the two glacier streams. From the δD-values obtained in three simultaneous measurement
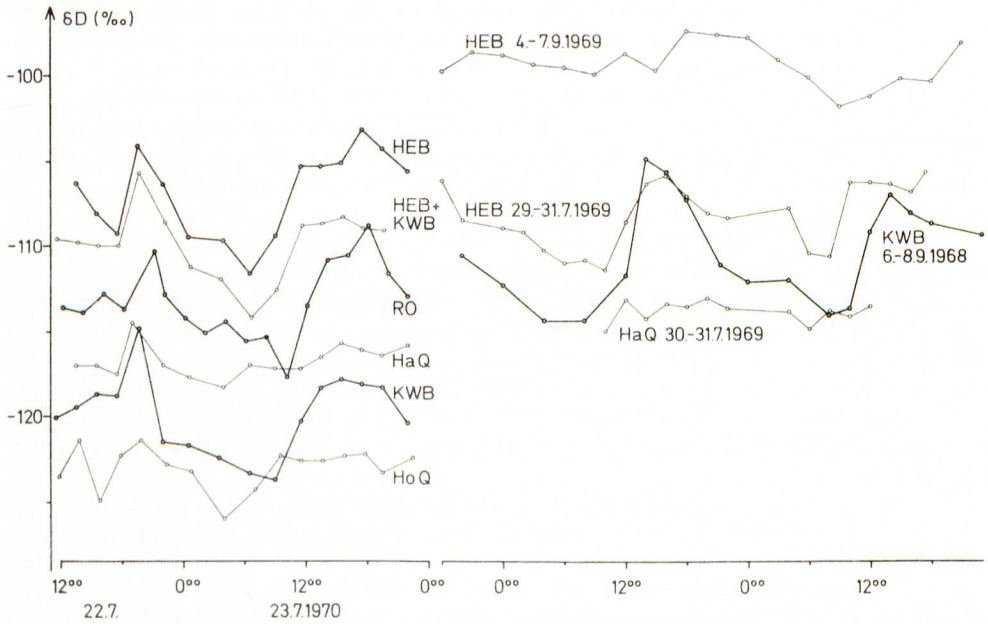
Fig. 8a: Daily variations of deuterium content in the runoffs of the Kesselwandferner (KWB),
the Hintereisferner (HEB), the Hochjoch Spring (HoQ), the slope spring (HaQ),
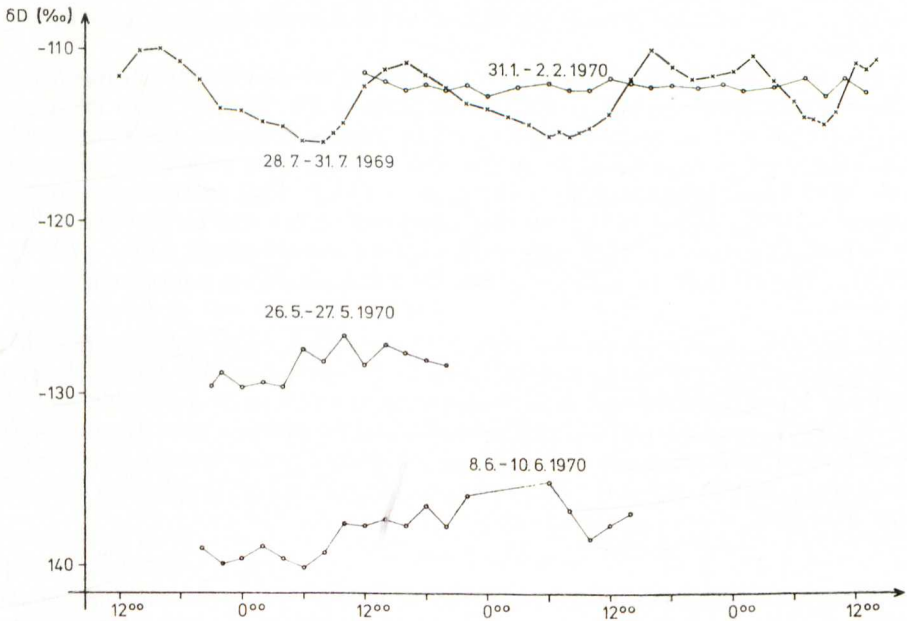the Rofenache at Vent (RO), and at the sampling site of Hochjochsteg (HEB + KWB).

Fig. 8b: Daily variations of deuterium content in the Rofenache at Vent.

series the contributions of the two glacier streams to the total runoff after confluence can be calculated in per cent. It was proved that 60 to 90 per cent of flow at Hoch-jochsteg, depending on the time of day, originate from the Hintereisbach.

The δD-value curves for the two springs (spring on the slope near the glacier snout and Hochjoch Spring) show only a slightly defined periodicity for the two days of measurement, indicating a weak influence by melt water. Also in this case, simul-taneous measurements (22—23 July 1970) showed a difference in the δD-values of about 5 to 6 $^o/_{oo}$ due to the altitude of the drainage area.

On 22 July 1970, around 19.00 h, a short but heavy thunderstorm accompanied by hail struck the observation area; measurements on individual hailstones collected during the storm furnished a δD-value of —44$^o/_{oo}$. It is therefore not surprising that the δ-value had a steep maximum at all sampling sites when precipitation runs off directly (Fig. 8a). This maximum exists also in the daily trend of the δD-values for the Rofenache at Vent for 22—23 July 1970, though as late as 21.00 h. The difference in time corresponds to the flow time of 2 hours determined by tracer measurements between the glacier drainage areas of the stream and the measuring site at Vent-Rofenache.

The remaining daily trends of δD-value for the Rofenache in Fig. 8b as expected show very low δD-values for the period of the snowmelt in May and June without a marked periodicity. A comparison of the two measurement series shows that the layers formed by snowfall in high winter, with a lower δ-value, are melting later than the "heavier" spring snow. During the ice ablation period in the Rofenache there also occurs the periodic daily trend of the δD-values observed in the glacier streams, although with an attenuation to about half the amplitude because of the different flow times of tributaries. As expected, the winter runoff shows constant daily δD-values, which, however, lie above the minima of the daily variations in midsummer. This may be due to a lower mean altitude of the Rofenache drainage area during the winter frost period.

The δD-values of samples of snow, snowmelt water, ice and ice melt water collected at the Hintereisferner in the measuring program of 22—23 July 1970 are given in Fig. 6 together with δD-values of spring water samples from the closer surroundings of the glacier (cf. section 2.3.2). As in the case of the tritium values the snow sample values were found to range from —157$^o/_{oo}$ to —81$/_{oo}^o$. This scattering decreases to between —119$^o/_{oo}$ and —101$^o/_{oo}$ for the snow melt water and to between —106$^o/_{oo}$ and —91$^o/_{oo}$ for the ice melt water. The spring waters range from —124$^o/_{oo}$ to —112$^o/_{oo}$. The altitude dependence of the snow sample values is discussed in section 3.3.

Besides the deuterium content, also oxygen-18 was measured on the samples collected in the course of the day on the Rofenache on 6—7 September 1968 and on the glacier streams of Hintereisferner and Kesselwandferner from 28 to 31 July 1969 as well as in their confluence zone on 22—23 July 1970, and on samples from Hintereisferner. Overall, these measurements furnished no significant supplementary information since it was possible, within the limits of measuring accuracy, to refer the $\delta^{18}O$-values to the δD-values of corresponding samples through the relation

$$\delta D = 8 \, \delta^{18}O + t \qquad (6)$$

The quantity t in eq. (6) assumes a value of approx. 10 in the measurements on samples of glacier runoff, ice and melt water, whereas the value resulting from snow

samples is 13. This shift in connection with the phase transformation of snow into ice has not been explained satisfactorily.

2.5. Conductivity measurements

The tests in July 1970 included preliminary orientation experiments to determine the conductivity of ice and snow melt water and various spring waters. Ice and snow melt water showed a very low conductivity (2.5 to about 10 μmho/cm at 20° C). The springs seeping out of the slope gravel adjacent to the glacier, were found to have the highest conductivity of all samples (about 80 μmho/cm). While the conductivity of these slope springs did not change throughout a day, a characteristic daily variation pattern was recorded for the runoff of the Hintereisferner (Fig. 9), showing an inverse phase compared to water flow and thus indicating the diurnal variation of the glacier discharge consisting of various runoff portions. Changes in conductivity corresponding to those for the Hintereisbach were observed also at the measuring site of Rofenache-Vent.

These measurements prove the conductivity of a glacier stream to be a suitable indicator in runoff studies; on the other hand, the daily variations in natural conductivity of glacier stream water must be observed carefully for making runoff determinations by conductivity measurements on salt tracers.

3. FURTHER GLACIO-HYDROLOGICAL CONCLUSIONS

In this section some conclusions are drawn from the combined application of the results described in the foregoing section.
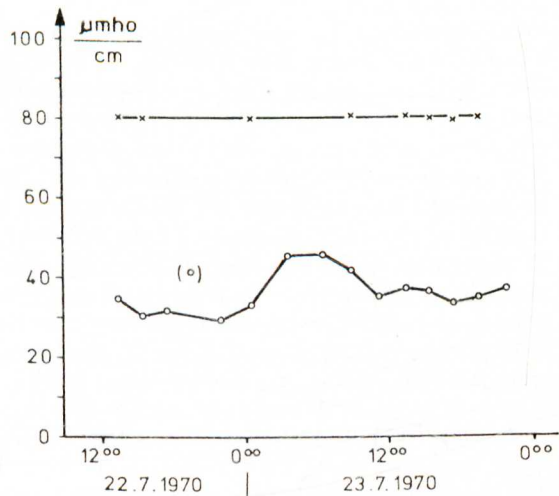

Fig. 9: Daily variations of water conductivity in the Hintereis bach (o—o—o) and in a spring in the drainage area of the Hintereisbach (x—x—x).

3.1. Daily variations of the runoff portions in glacier discharge

For evaluating the isotope balance equations of sections 2.3.1. and 2.4.1., the following simplified model was supposed:

a) Tritium content: some flow portions contain practically no tritium (i. e., melt water from old glacier ice), others showing the mean tritium content of precipitations of

preceding years (i. e. snow melt water running off directly or seeping through the glacier and emerging subglacially).

b) Deuterium and oxygen-18 contents: The following flow portions must be distinguished during the summer ablation period: On the one hand, snow and ice melt water running off directly, with high δD-values, which either originates from summer precipitation or was enriched in heavy isotopes through extended exposure at the glacier surface; on the other hand, the water running off underground through the channel system of the glacier and the ground, characterized by a low δD-value owing to the melt water seeping into the glacier from the winter snow cover.

With this two-component system assumed for the isotopes tritium and deuterium (and oxygen-18), eqs. (2) and (4) read as follows.:

$$T_{sg} (Q_s + Q_g) = T_t Q_t \tag{7}$$

and
$$\delta_{is} (Q_i + Q_g) + \delta_g Q_g = \delta_t Q_t \tag{8}$$

supplemented by the runoff summation relation

$$Q_i + Q_s + Q_g = Q_t \tag{9}$$

as the third equation. The quantities T_t, δ_t and Q_t are obtained from the curves of daily variations. To determine T_{sg}, δ_{is} and δ_g, measurements on precipitation samples, on glacier ice and snow samples, and the winter values of the annual variation curves may be utilized. The relations between the isotope values of the different glacier streams also provide criteria for determining these quantities.

The runoff portions Q_g and Q_i (cf. Fig. 10) were calculated from eqs. (7), (8) and (9) derived from the measurements on the Hintereisbach and on the Rofenache on 22—23 July 1970.

For determining T_{sg}, the suggestion by Ambach et al. (1969) was followed using 330 TU as the winter 1969—1970 value for Hochjoch Spring (see Fig. 4). The values of the tritium contents of snow, ice and melt water samples given in Fig. 6 are lower. This indicates that basically T_{sg} is governed by a subglacial runoff portion Q_g whose tritium content corresponds to that of precipitations during previous years.

More problematic is the determination of δ_{is} and δ_g for which separate values must be assumed for evaluating the measurements on Hintereisbach and on Rofenache, because of the altitude effect and the different altitude levels of the drainage areas. To determine δ_{is} for the Hintereisbach, the mean of the δD-values of the measured ice melt water samples was used (see Fig. 6), which is around $-100^0/_{00}$. For Rofenache $\delta_{is} = -105^0/_{00}$, since the daily curve for the Rofenache referring to 22—23 July 1970 is lower by $5^0/_{00}$ than that for the Hintereisbach. In contrast to T_g, δ_g apparently cannot be taken from the winter values 1969—1970 of the annual trend because the winter flow in its deuterium content does not correspond to the subglacial runoff in summer. This has already been made clear when discussing the δD-values of the daily variation curve for the Rofenache from 31 January to 2 February 1970, and was confirmed by the fact that the minimum δD-values of the diurnal curve for Hintereisbach on 22—23 July 1970 ($-112^0/_{00}$) lie below the winter value (about $-109^0/_{00}$). In determining δ_g it was therefore assumed that the glacier runoff in the early morning hours contains no melt water running off directly, i. e. $Q_s = 0$. δ_g may then be calculated from eqs. (7), (8) and (9), and from the values measured for this point of time, the result being $\delta_g = -118^0/_{00}$ for the Hintereisbach and $\delta_g = -122^0/_{00}$ for the Rofenache. The value of δ_g for Hintereisbach corresponds approximately to
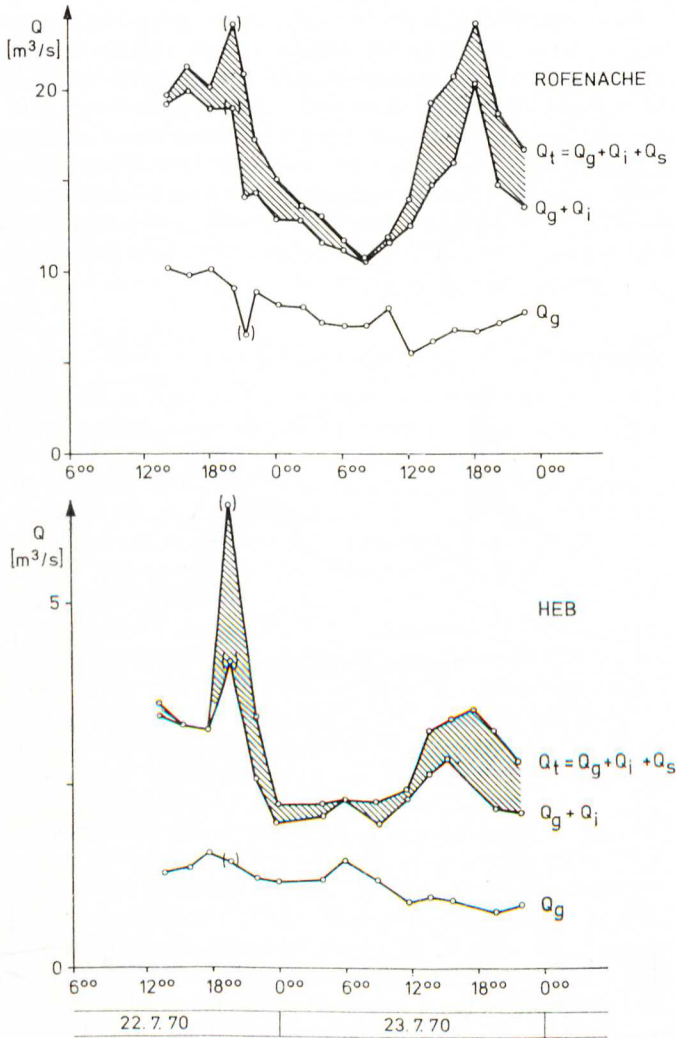
Fig. 10: Daily curves for the Rofenache and the Hintereisbach of the portions of subglacial runoff (Q_g), ice melt water (Q_i) and snow melt water running off directly (Q_s), calculated from measurements of the tritium content, of the deuterium content and of total flow, Q_t, for 22—23 July 1970. See text for suppositions of calculation.

the mean of the δD-values of the spring water samples collected in the vicinity of the glacier (see Fig. 6). Discussing the chronological curves represented in Fig. 10, it should be taken into account that considerable inaccuracies may arise in the evaluation, as erroneous measurement values appear as differences. Yet it may be said that the simple model concept underlying the evaluation is well suited to describe the glacio-hydrological processes involved: it can be recognized that the water discharging subglacially represents the base flow of runoff; this portion is subjected

to slight daily variations probably due to differences in hydraulic pressure and subsequent seepage of the water from the aquifer (ice or moraine). Daily fluctuations, however, are mainly caused by ice ablation being overlapped by precipitation water and snow melt water running off directly, depending on snow and precipitation conditions. The onset of a fair weather period during the measurements caused a relatively high percentage of this type of snow melt water. Though the runoff caused by the hail storm is recognizable as precipitation water running off directly, the quantitative evaluation is doubted, since the greatly deviating isotope content of this precipitation (see section 2.4.2) could not be taken into account.
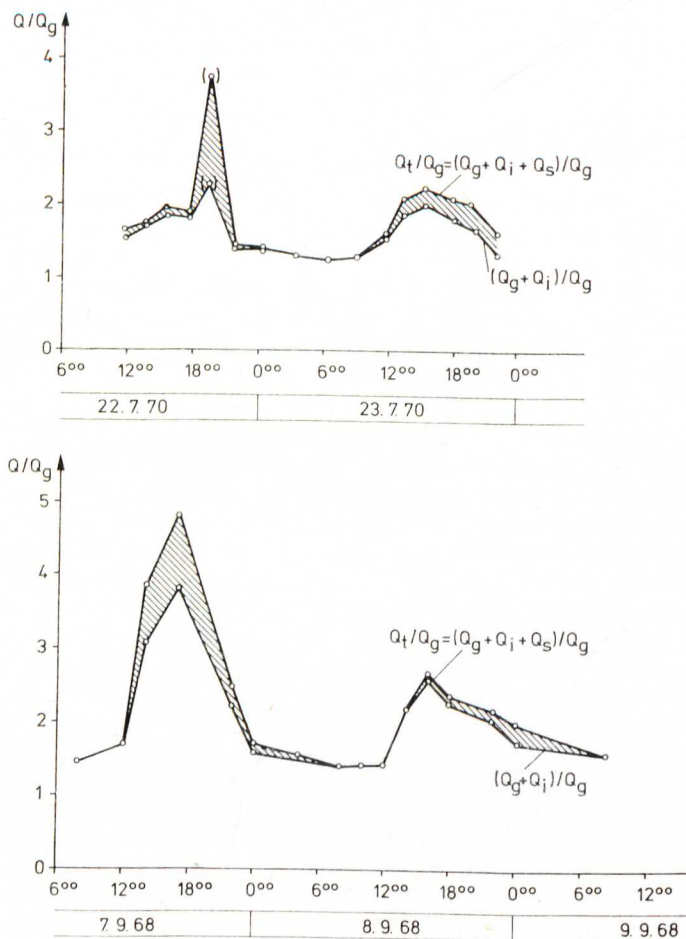

Fig. 11: Daily curves for the Kesselwandbach of the portion of ice melt water (Q_i) and snow melt water running off directly (Q_k) normalized to a constant subglacial runoff (Q_g) and calculated from measurements of tritium and deuterium contents on 22—23 July 1970 and from 7—9 September 1968.

If no runoff measurements are available, relative proportions of the runoff may be calculated from the curve of variations of the δD- and tritium values. Putting $Q_g =$ constant, good approximation of the runoff curve may here be expected judging by the results obtained on the Hintereisbach and on the Rofenache. Figure 11 contains such curves derived from values measured on the Kesselwandbach, 7—9 September 1968 and 22—23 July 1970, where T_{sg}, δ_{is} and δ_g were determined from criteria similar to those of previous measurements. In the curve for 7—9 September 1968, melting of a cover of new snow that fell the days before, is evident, whereas on 22—23 July 1970, the ice ablation at the higher elevated Kesselwandferner commenced very slowly compared to Hintereisferner. Again, the hail storm is clearly marked.

3.2 Weather conditions and isotope content in the glacier runoff

The model developed in Section 3.1. is based on a relationship between the different runoff portions of a glacier and the specific isotope contents which, in turn, may be used for analyzing the individual portions of total runoff.

Apart from the relations discussed in Section 3.1. of the daily trends of the deuterium and tritium contents which lead to an inversely phased trend of the two curves, (see Figs. 5 and 8) the trends of the annual curves also show correlations of the isotope contents typical of the season (cf. Fig. 12, Figs. 4 and 7): at the beginning of the ablation period (April to June), tritium and deuterium contents drop due to the runoff of the winter snow cover. During midsummer, low tritium values and high deuterium values are generally observed caused by the melt water of ice and old snow running off on the glacier surface. In autumn, the tritium content rises slowly up to the winter maximum, whereas the deuterium content remains approximately constant at the value occurring in summer in periods without ablation. Hence, the winter flow is assumed to consist of spring and snow melt water running off sub-glacially which in part gradually seeped from the glacier.

In addition to these daily and seasonal periodic relationships, relations of the isotope contents also become apparent under special weather conditions, in particular during the midsummer ablation period. In Fig. 12, such weather conditions are characterized by the amplitude of the flow of the Rofenache at the measuring site at Vent, since the daily variations in discharge may be attributed mainly to melt water. It can be seen that an interruption of ablation by cold weather (lack of ice ablation) causes the tritium content to increase considerably, whereas the deuterium content decreases (Fig. 12, graph points C—D, H—K—L, R—S). Inversely, recurring ablation causes tritium contents to fall and deuterium values to rise (Fig. 12, graph points B—C, D—E, F—G, N—O). If the cold weather spell was accompanied by snow fall, however, the tritium content increases owing to melting snow, the deuterium content decreases due to snow melt water running off on the surface (Fig. 12, graph points A—B, O—P).

3.3 Remarks on the isotope contents of snow samples from the glacier surface

The deuterium and tritium values of the snow samples taken from the surface of Hintereisferner between 22 and 24 July 1970 are shown in Fig. 6. There exists a significant dependence (differing for both isotopes) of the isotope measurement values on the altitude of the sampling sites: near the transient snow-line at an alti-
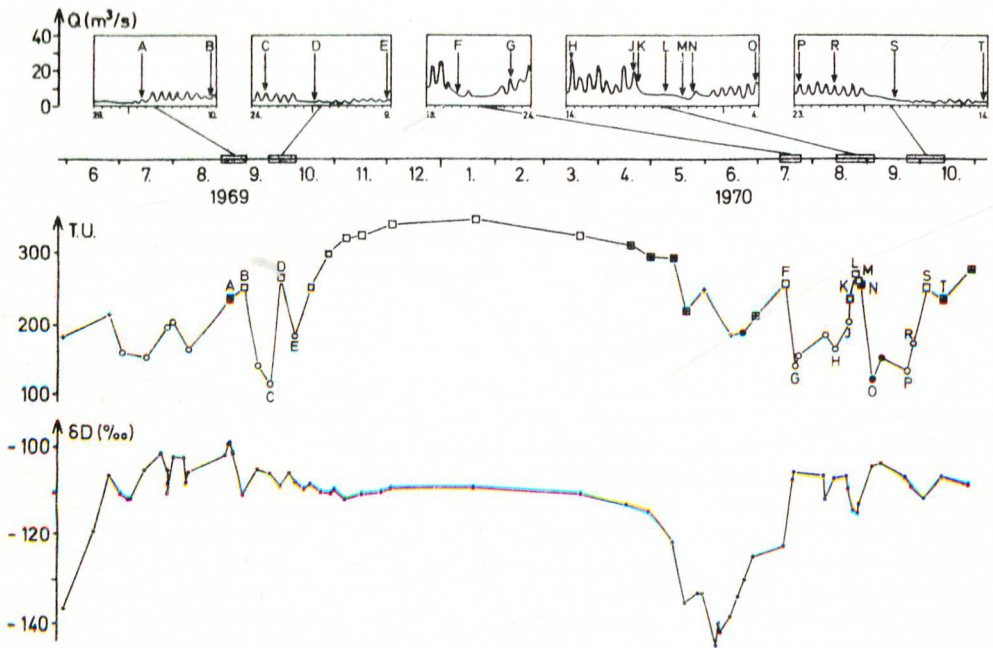
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Fig. 12: Annual curves of tritium and deuterium contents in the runoff of the Hintereisferner. Special weather conditions being characterized by the curve of discharge variations in the Rofenache

□ = Sampling during continuous interruption of ablation for some days or more
o = Sampling during periods of substantial ice ablation
+ = Sampling during periods of substantial snow ablation
● = Sampling during periods of ice- and new snow ablation
◼ = Traces of snow ablation only.

tude of about 2770 m, very low δD- and tritium values are observed, suggesting that the precipitations of high winter, with low isotope contents, again form the surface after spring snow has melted off. The steep rise between 2800 m and 3100 m a. s. l. reflects the increasing isotope content of precipitations toward early summer. Its stratification is revealed by the meltoff decreasing as altitude increases. Above 3100 m, the tritium content remains constant (about 260 TU) within the error limits. This value corresponds to the tritium content of the last snow of early summer that did not melt. The tritium content increases only at the highest sampling site, near the peak of the Weisskugel (3690 m), which might be due to the special meteorological conditions there, but has not been explained so far.

In contrast to tritium, the deuterium content above 3000 m first rises and then, from 3200 m onward, drops linearly up to the highest sampling site. This linear drop is a result of the isotope altitude effect and corresponds in its quantity ($-5^0/_{00}$ per 100 m) to the known values (Moser and Stichler, 1970). Figure 6 thus indicates what part of the snow cover on the glacier still consisted of new snow at the time of sampling, and where the snow fallen in high winter crops out due to melting.

4. FINAL REMARKS

The described qualitative and quantitive conclusions from the measurements of the isotope contents in the glacier runoff in combination with measurements of total runoff, point toward new possibilities in the study of glacier water budgets. Though the investigations so far have not proved sufficient to justify a general application in glaciology, they have confirmed the fact, however, that the discussed isotopic methods may contribute essentially to glacio-hydrological research. Yet, knowledge must still be expanded by continuing research in this field.

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