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Glacial-Hydrological Investigations at the Vernagtferner Glacier as a Basis for a Discharge Model

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The report gives a review on the glacial-hydrological work carried out since 1974 in the project "Runoff within and from glaciers" of Sonderforschungsbereich 81 of the Technical University Munich with the aim of creating a deterministic discharge model. Since 1974 the runoff of Vernagtferner glacier has been recorded at the gauge station "Pegelstation Vernagtbach" (catchment area 11.44 km^2, mean altitude 3,125 m a.s.l., 81% glaciated). The discharge hydrographs for the years 1974-1980 are discussed and characteristic time intervals with characteristic discharge components are pointed out. Using the different discharge patterns exhibited by different parts of the glacier, a spatial classification for the discharge formation is given, and the different hydraulic conditions are described. The mathematical model which is proposed uses four parallel linear reservoirs for which the storage constants were determined by former experiments. For a fortnight period with dry and sunny weather the discharge is calculated with the energy balance on the glacier surface as input data.

Introduction

In the hydrological year 1965 the Commission for Glaciology of the Bavarian Academy of Sciences started mass-balance investigations at the Vernagtferner glacier in the Oetztal Alps (Reinwarth 1972). At that time it was possible to measure the total amount of precipitation, accumulation and ablation integrated over a time period of one year. No information was available on the time distribution of the ablation processes. Therefore in 1973 the gauge station "Pegelstation

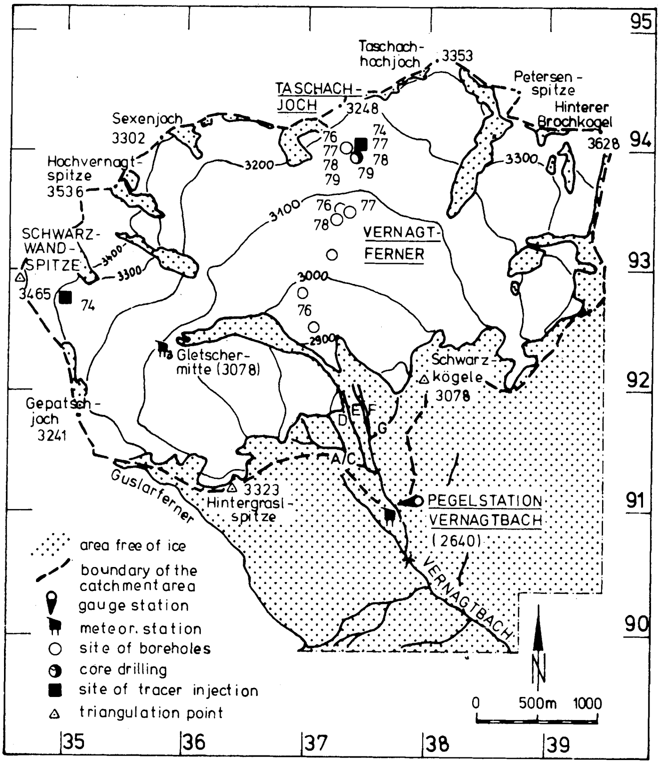


Fig. 1. The catchment area of the gauge station Pegelstation Vernagtbach (Oetztal Alps/Austria). The catchment area extends over an area of $F_N = 11.44$ km^2 which is 81% glaciated by Vernagtferner glacier (9.30 km^2). The map shows the location of boreholes and tracer injection points together with the years in which these investigations were carried out.

Table 1 – Data of the catchment area of the gauge station "Pegelstation Vernagtbach"

Country	Austria (Tyrol)
Longitude	10° 49' E
Latitude	46° 52' N
Catchment area	11.44 km^2
Glacier area	9.30 km^2
Altitude of the catchment area	
Highest point	3628 m a.s.l.
Lowest point	2635 m a.s.l.
Mean altitude	3125 m a.s.l.

Vernagtbach" was constructed (Bergmann and Reinwarth 1976). At this gauge station (for data of the catchment area see Table 1 and Fig. 1) the total runoff of Vernagtferner glacier is continuously recorded during the ablation period and it is measured with interruptions during winter time. Because of the geological situation at the site of the gauge, where the creek cuts into the rock, one can assume that really the whole glacier runoff is recorded. Since 1974 the hydro-glaciological investigations at the Vernagtferner have been carried out in cooperation with the GSF-Institute for Radiohydrometry within the frame work of "Sonderforschungsbereich 81" of the Technical University Munich.

The Discharge at the Gauge Station "Pegelstation Vernagtbach"

The Discharge in the Years 1974-1980

The discharge data for the years 1974-1980 has been compiled by Oerter (1981a). A selection of characteristic data is given in Table 2 and the monthly mean values of the discharge are shown in Fig. 2. The typical glacial runoff regime with minimum discharge during the winter months January to April and maximum during the months July or August is clearly recognizable. During the months June to September, 90% of the total yearly runoff passes through the gauge station. Especially the years 1976 and 1980 were remarkable: In 1976 we find the maximum monthly value since 1974 for July (2.51 m^3/s) and the minimum for August (0.743 m^3/s). In 1980 it was just the opposite with the minimum discharge in July (0.643 m^3/s) and the maximum in August (2.68 m^3/s).

The discharge during single months in different years varies considerably. The standard deviations of the monthly means MQ lie between ± 54% for May and ± 37% for August. These big differences in the meltwater runoff disappear largely if one only compares the mean summer values (May to September) for the different years. This mean MQ for the ablation periods 1974-1980 of 0.970 m^3/s shows only a standard deviation of ± 12%.

Table 2 – Mean daily discharge values for gauge station "Pegelstation Vernagtbach" (catchment area 11.44 km^2, 81% glaciated) for the years 1974-1980.

		May	June	July	August	Sept.	Summer
NQ	(m^3/s)	0.015	0.038	0.111	0.418	0.125	0.015
MNQ	(m^3/s)	0.015	0.175	0.445	0.829	0.215	0.015
MQ	(m^3/s)	0.123	0.600	1.47	1.74	0.918	0.970
MHQ	(m^3/s)	0.373	1.36	2.92	3.11	1.50	3.68
HQ	(m^3/s)	0.822	2.40	4.76	4.46	2.04	4.76
A	(mm)	29	136	344	407	208	1.124

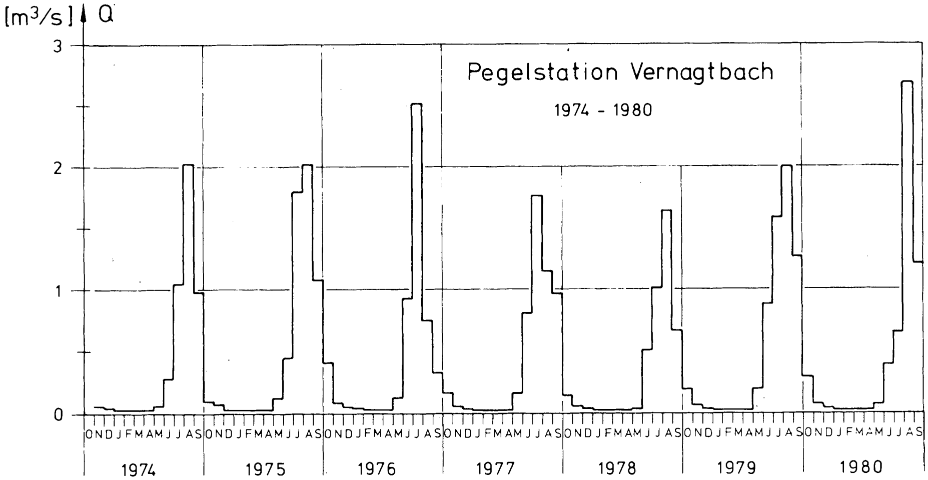


Fig. 2. Monthly mean values of the runoff Q at the gauge station »Pegelstation Vernagtbach« (Oetztal Alps/Austria) in the years 1974-1980.

NQ = minimum daily discharge for each month in the years 1974-1980
MNQ = mean minimum discharge for each month
MQ = mean discharge value for each month, calculated from daily data in the years 1974-1980
MHQ = mean maximum discharge for each month
HQ = maximum daily discharge for each month in the years 1974-1980
A - runoff

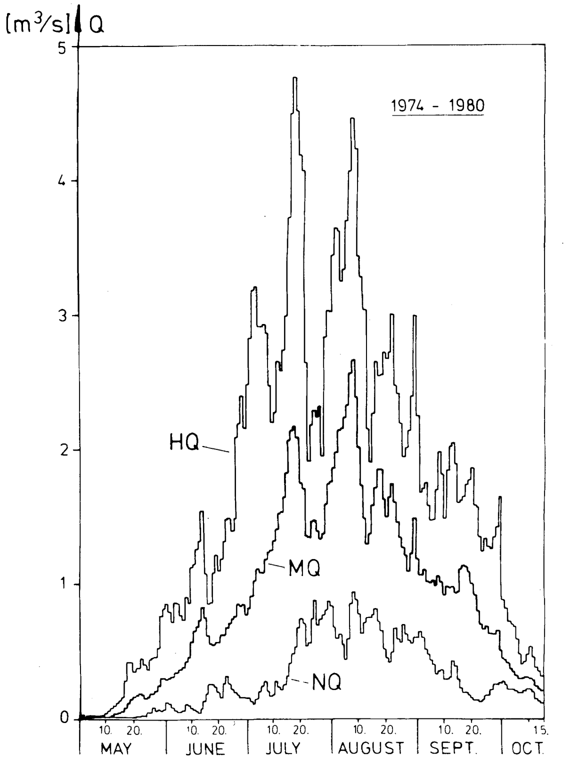
Fig. 3 shows the daily mean values of the discharge for the period 1974-1980, the minimum (NQ) and the maximum (HQ) discharge recorded for each day and the mean (MQ) over the seven years. One can see the wide differences between minimum and maximum discharges for the same day in different years and the unperiodic variations of the discharge hydrograph caused by the weather conditions.

Characteristic Time Intervals for the Runoff and its Characteristic Runoff Components

We tried to describe the runoff by a mathematical model consisting of so-called linear reservoirs, which are characterized by linearity between the water volume within the reservoir $S(t)$ and the outflow $Q(t)$. The proportionality constant k is called the storage constant and is a measure of how quickly water flows out of the reservoir.

$$S(t) = k\,Q(t) \tag{1}$$

Conservation of mass requires that the difference of the inflow $p(t)$ into the



MQ – average of daily mean values
HQ – maximum daily mean values
NQ – minimum daily mean values

Fig. 3. Discharge hydrograph of daily mean values in the years 1974-1980.

reservoir and the outflow $Q(t)$ is equal to the instantaneous rate of change in water volume

$$p(t) - Q(t) = \frac{dS}{dt} \tag{2}$$

From Eqs. (1) and (2), the differential equation for the linear reservoir (Eq. 3) can be derived

$$p(t) = Q(t) + k\frac{d\,Q(t)}{dt} \tag{3}$$

The aim of our investigations was to look for such reservoir systems in the catchment area and to find values for the storage constant k. One possible procedure is to analyse the discharge hydrograph. Another way, described later, is to try to directly determine the hydraulic conditions in the glacier itself.

For analysing the discharge hydrograph, we consider first the case when the input $p(t) = 0$. In this case, Eq. (3) has the solution

$$Q(t) = Q_0 \exp\left(-\frac{t-t_0}{k}\right) \tag{4}$$

where $t = t_0$ is an arbitrary starting time with $Q_0 = Qt_0$.

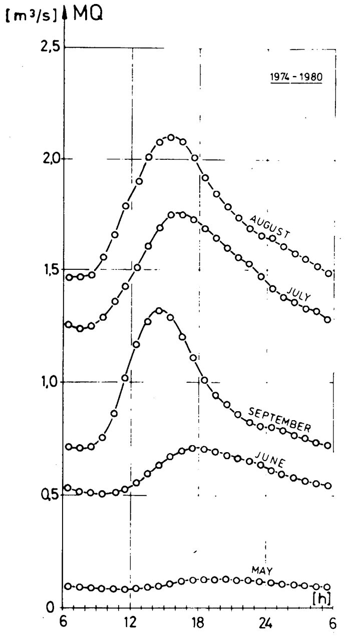


Fig. 4. Diurnal variation of the runoff at the gauge station »Pegelstation Vernagtbach« (Oetztal Alps, Austria) calculated as an average in the years 1974-1980 for the months of ablation period.

This means that, in those time intervals with $p(t) = 0$, it is easy to calculate the storage constant k. Therefore we have to look for such characteristic time intervals.

The Diurnal Runoff Variations

The discharge hydrograph of a glacier creek shows diurnal variations (see e.g. Lang 1967). These diurnal variations (Fig. 4) are due to the direct runoff of meltwater from snow and especially from ice. The greatest diurnal variations appear in the months July, August and September during which normally parts of the glacier are free of snow and the glacier ice appears at the surface. According to various studies using isotope contents and electrical conductivity in the glacier creek Vernagtbach, these diurnal variations are due to ice-melt runoff (Behrens et al. 1979, Oerter et al. 1980 a and b). Therefore we assume the glacier ice area is one reservoir and we separate the runoff of ice-meltwater from the total runoff.

During the night hours the input $p(t)$ can be assumed equal to zero because there is no melting. Thus the decrease of the hydrograph is caused by the drainage of ice-meltwater from the ablation area and of snow meltwater from the accumulation area. If we use two reservoirs to describe the total runoff, with the runoff Q_1 (ice-meltwater) and Q_2 (snow-meltwater and groundwater), we can calculate two storage constants from which k_1 refers to the ice area, k_2 to the rest of the catchment area. Table 3 gives numerical values for these time constants calculated for the years 1977 and 1978 (Hibsch 1979).

Table 3 – Storage constants k_1 and k_2 for the night hours in the summer months in 1977 and 1978 (Hibsch 1979).

Month	Storage constants [h]			
	1977		1978	
	k_1	k_2	k_1	k_2
May	6	44	13	15
June	4	24	6	18
July	6	23	4	26
August	6	30	3	41
September	4	21	5	34
October	2	121	6	40

The Seasonal Runoff Variations

Other characteristic time periods without meltwater input are cold weather periods during summer, periods with a cover of fresh snow on the glacier surface, and the time after the end of the ablation period. The runoff in the glacier creek during such periods is fed from water stored in the glacier and the underground. Because these periods have minimum duration of several days, ice-meltwater does not contribute substantially to the runoff. This is because the stored ice-meltwater drains so quickly, usually within hours.

For a first approximation again two reservoirs have been assumed and two storage constants were calculated (Table 4) which give the best fitting for the calculated discharge to the measured hydrograph (Hibsch 1979).

One can see that the storage constants k_2 from Table 3 and k_3 from Table 4 are of the same order of magnitude. This tends to imply that at least three reservoirs

Table 4 – Storage constants for cold weather periods during 1976, 1977 and 1978 (Hibsch 1979).

time	storage constants [h]	
	k_3	k_4
22.07.-05.08.76	33	515
01.10.-15.10.76	47	641
19.08.-24.08.77	13	161
19.09.-27.09.77	45	621
13.06.-17.06.78	87	149
05.07.-09.07.78	15	91
08.08.-11.08.78	8	113
30.08.-07.09.78	19	282

exist: one reservoir for the ice area with ice-meltwater runoff, and two reservoirs for the firn area with snow-meltwater runoff. The two firn area reservoirs describe meltwater near the firnline and meltwater from the higher areas. The meltwater from the firn area nearby the firnline passes the gauge station during the night hours and immediately after a snow fall, whereas the snow-meltwater from the upper firn areas arrives some days later.

The Meltwater in the Firn

The Water Table in Boreholes

The meltwater from snow and firn in the accumulation zone percolates first through the unsaturated porous medium firn. When the meltwater reaches the depth within the glacier at which the firn changes to ice, the vertical path of percolation is interrupted and the meltwater collects over the ice body. Therefore an aquifer exists during the ablation period (Oerter 1981b). The thickness of this aquifer varies according to the meltwater production on the glacier surface (Fig. 5). Since 1976 many boreholes were melted and used to measure the water table of the water saturated firn in the accumulation area of Vernagtferner. Fig. 5 gives an example of results of such measurements in 10 boreholes spread over an area of 200 × 300 m^2. Data are also available from boreholes in 1979 and from one borehole in which the water table hydrograph was recorded in 1979 and 1980. A comparison of the recorded water table hydrograph in the boreholes with the discharge hydrograph at "Pegelstation Vernagtbach" shows that the maxima of the water table follow with a time lag of 4 to 5 days the maxima of the discharge (Oerter 1981b).

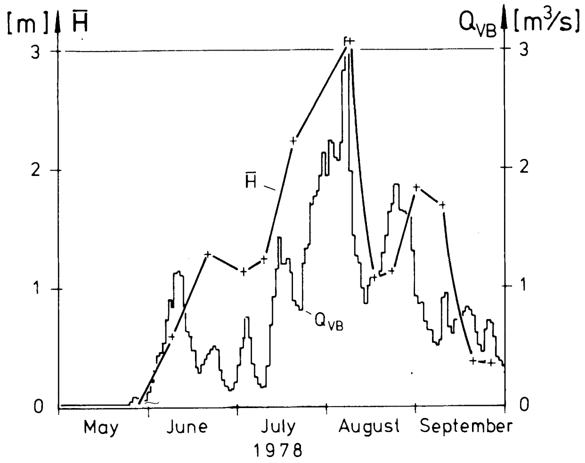


Fig. 5.

Well hydrograph for the water table $\bar{H}$ in the firn of Vernagtferner (Oetztal Alps/Austria). The stage of the water table was calculated for an area of 200 × 300 m^2 from water table measurements in 10 boreholes. The discharge hydrograph Q_{VB} at the gauge station Pegelstation Vernagtbach is also shown.

This time is therefore needed to percolate through the firn layer, which is approximately 20 m thick at this site. For the period without meltwater production it is possible to calculate an exponential fit for the water table hydrograph according to Eq. (5)

$$H(t) = H_0 \exp\left(-\frac{t}{k}\right) \tag{5}$$

H – height of the aquifer and $H_o = H\ (t_o)$

In this way we also get a storage constant k_5 which describes the water outflow from the firn area. The calculated values are given in Table 5.

Table 5 – Storage constants k_5 for running out of firn aquifer during periods without meltwater production (Oerter 1981b)

time 1979	H_o (m)	K_5 (h)
04.07.-18.07.	2.90	280
10.08.-16.08.	1.60	275
21.09.-04.09.	0.80	395
25.09.-08.10.	0.80	320

H_o – thickness of the firn aquifer at the beginning of the given period

Tracer Tests

The best way to measure the travel time of the meltwater is to use fluorescent dye tracers. During the years 1974-1980 several tracer tests were carried out (Behrens et al. in preparation). One example is given here. On 9 August 1978 4 kg Uranin were injected into a borehole at the site of Taschachjoch (Fig. 1). As one can recognize in Fig. 6, at this date there was a maximum discharge and in the following days the discharge as well as the firnwater aquifer came to a minimum. This was caused by a snowfall and by bad weather conditions. The amount of tracer in the discharge shows seven days after the injection time a clear maximum. It is not possible to correlate this main peak of the tracer load to a peak of meltwater production. The rising tracer load occurs at the same time that the discharge and the firnwater aquifer are decreasing. That means that meltwater transport within the glacier takes place in this time without meltwater production at the glacier surface. The firnwater aquifer is thus draining. The tracer load shows another peak between 24 and 28 september; the amount of tracer in this peak is only 1/10 of the amount in the first peak. During this tracer test 81% of the injected tracer was recovered.

The tracer test from Vernagtferner shows that it is possible for the meltwater to flow out of the firn area within a few days. From this and another tracer test at the

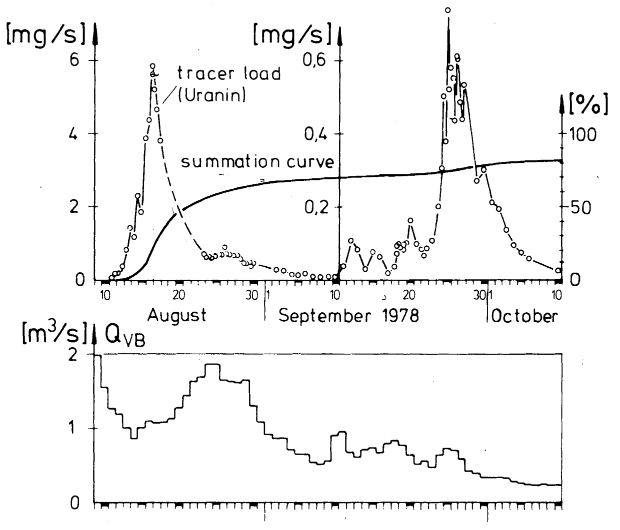


Fig. 6. Tracer test Vernagtferner 1978: hydrograph of the tracer load and summation line of the recovered tracer after a tracer injection into a borehole in the accumulation area on August 9th. The discharge hydrograph Q_{VB} at the gauge station Pegelstation Vernagtbach is also shown.

same site and the same time, where the dye was spread on the glacier surface, the percolation velocity of the meltwater through the firn can be conjectured to be about 4 m/d. This was a result at the site of Taschachjoch where the firnlayer is about 20 m thick. For the total way from the surface in the accumulation area to the glacier snout a mean travel time of 12 days was determined. That means that the meltwater needs about 7 days after it joins the firnwater aquifer to flow out of the glacier. From pumping tests and from the hydraulic gradient (Oerter 1981b) one can conclude that during this relatively short travel time the meltwater cannot pass more than 50 m along a path within the water saturated firn. Therefore the firn must be drained in short distances by draining channels.

A Scheme for the Runoff in a Glaciated Catchment Area

The results of these investigations yield a scheme of the runoff in a glaciated catchment area as it is shown in Fig. 7. The given times are mean travel times, respectively mean residence times, of the meltwater in the different glacier regions (reservoirs) as they were calculated by means of dye tracer tests, isotope and electrical conductivity investigations as well as statistical analysis of the runoff data. They are not real residence times of the precipitation in the catchment area.

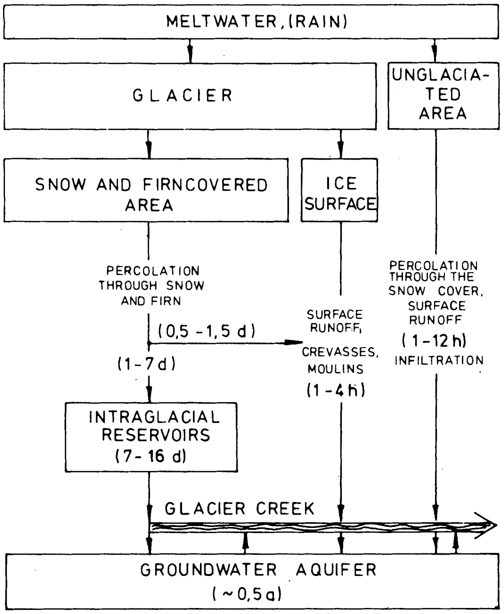


Fig. 7.

The scheme of runoff in a glaciated catchment area according to the catchment area of gauge station »Pegelstation Vernagtbach« (Oetztal Alps/Austria). The given times are mean travel times respectively mean residence times of the meltwater in the different reservoirs of the catchment area.

Over the non-glaciated part of the catchment area the snow-meltwater and the rainwater flow on the surface or, after infiltration, in the aquifer. Depending on the height of the snow cover, the mean residence time lies between 1 and 12 hours (assuming that the snow cover is already a temperate one). In the glaciated part of the catchment area the ice-meltwater shows the smallest residence time between 1 and 4 hours. The direct runoff of snow – and firn – meltwater has a residence time between 0.5 and 1.5 days. The longest residence times are to be found in the upper parts of the firn area. The travel time for the percolation of snow and firn is, depending on the height of the snow or firn cover, 1 to 7 days. After the meltwater reaches the firnwater aquifer it remains 7 to 16 days in the intraglacial reservoir.

The times calculated by different methods show a good agreement. One has to consider that the discharge flows through a glacier and therefore travel times may change throughout the ablation period. In the different methods above one has always comparable but not identical reservoirs, so that one expects some variation in the calculated times, depending on which method is used.

The Discharge Model: First Results

To calculate the runoff we used a mathematical model (Eq.(6)) consisting of 4 parallel linear reservoirs (Eq. (3)). The runoff Q_i for the i^{th} reservoir is then given by the general solution (Eq.(7)) to the differential Eq. (3), where the meltwater

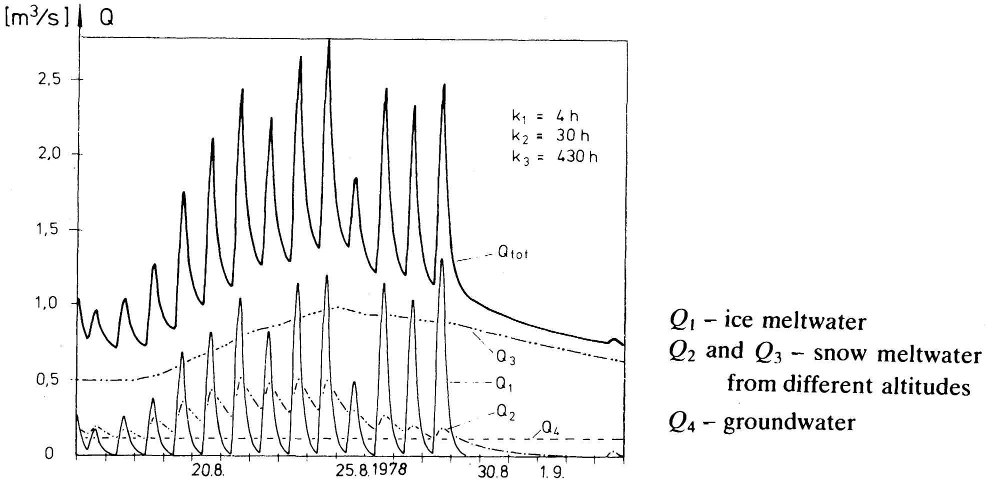


Fig. 8. Calculated runoff at the gauge station »Pegelstation Vernagtbach« (Oetztal Alps/Austria). The diagram shows the total runoff Q_{tot} and the runoff components Q_1, Q_2, Q_3 and Q_4.

input for the i^{th} reservoir, p_i, was calculated by a separate model from meteorological data measured at "Pegelstation Vernagtbach" (Escher-Vetter 1980).

$$Q(t) = \sum_{i=1}^{4} Q_i(t) \tag{6}$$

$$Q_i(t) = Q_{i,0} \exp\left(-\frac{t-t_0}{k_i}\right) + \int_{t_0}^{t} p_i(\tau)\,\frac{1}{k_i}\exp\left(-\frac{t-\tau}{k_i}\right) d\tau \tag{7}$$

The results of the calculation for a period of 19 days (8/16 – 9/3/1978) are given in Fig. 8.

For the runoff component Q_1, representing the runoff of ice-meltwater, a storage constant of $k_1 = 4\ h$ was chosen.

For the runoff component Q_2, consisting of snow-meltwater running off directly from the area immediately over the ice area, a storage constant k_2 of 30 h was chosen. Q_3 consists of meltwater from the higher firn areas, and a storage constant k_3 of 430 h was chosen. The groundwater runoff Q_4 during this period was assumed to be constant, i.e. $k_4 = \infty$.

The calculated runoff was only slightly smaller than the runoff measured at the gauge station: 6.2% smaller in August, 2.2% smaller in September. These deviations constitute a good agreement between calculated and measured data. The proposed method for calculating the runoff is certainly a good basis for further calculations which are already under way.

The runoff component Q_1 shows the strongest variations. This is due to the diurnal variations of the ablation on the ice surface and to the smallest storage constant k_1. The discharge Q_2 shows lower diurnal variations but the amount summed over one day is often equal to the discharge Q_1. The biggest proportion of the runoff is the component Q_3. It shows no more diurnal variations because the input into this third reservoir was assumed to be constant. Q_4 has the constant value 0.1 m^3/s, and constitutes a small part of the total runoff.

The good weather period till August 28th caused a rising discharge hydrograph for Q_3. When a stop of melting occured during the following bad weather period, the discharge hydrograph for Q_3 slowly decreased. The total runoff during this time exists almost entirely of snow-meltwater runoff from the upper accumulation area Q_3, which was already stored within the glacier, and of groundwater Q_4.

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