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Modelling the runoff from a glaciated drainage basin (Vernagtferner, Oetztal Alps)

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ABSTRACT For the drainage basin of the gauging station Pegelstation Vernagtbach (2640 m a.s.l., 11.44 km²; Oetztal Alps, Austria) which is 84% glacierized by the Vernagtferner, combined discharge and meteorological data are available since 1974. For this catchment a discharge model was developed which takes into account the meteorological and hydrological factors involved in the formation and distribution of runoff in a highly glaciated drainage basin. The discharge model describes the drainage basin as a system of four parallel linear reservoirs which correspond to three different parts of the glacier, and a small groundwater reservoir. The model input is the meltwater produced at the glacier surface and calculated with an energy balance model based on global radiation, longwave radiation, air temperature, relative humidity, wind velocity, and albedo. In addition, input may be caused by liquid precipitation. The paper presents the results for the period 1978-1985. The discharge model yields hourly mean values of the runoff which agree well with the measured runoff data.

NOTATION

A	longwave radiation of the atmosphere
E_0	water vapor saturation pressure for Θ_0
G	global radiation
I	inflow into a linear reservoir
L	sensible heat flux
P_1	liquid precipitation
R	outflow from a linear reservoir
R_1	calculated runoff component from the exposed glacier surface (ice meltwater)
R_2	calculated runoff component from the firn area nearby the temporal equilibrium line
R_3	calculated runoff component from the remaining firn and old snow-covered area, which give no input for R_1 and R_2

R_4	groundwater discharge
R_c	calculated total runoff (including storm runoff)
R_i	runoff component from ith linear reservoir
R_m	measured discharge at Pegelstation Vernagtbach
R_p	storm runoff
S	resulting melting energy
SBK	short wave radiation balance
SBL	longwave radiation balance
T_o	(absolute) temperature of the surface
t	time
V	latent heat flux (in eq. 6)
V	volume of water stored in a linear reservoir (in eqs. 1 and 2)
a	albedo
c_p	specific heat of air
e	base of natural logarithm (in eq. 4)
e_1	water vapor partial pressure corresponding to Θ_1
k	storage coefficient
σ	Stefan-Boltzmann's constant
α_1	heat transfer coefficient
p	air pressure
r	heat of evaporation
Θ_1	air temperature at 2 m above ground
Θ_o	(relative) temperature of the surface

INTRODUCTION

Glacial-hydrological investigations (Moser et al., 1986) have been carried out since 1974 in the drainage basin of the gauging station Pegelstation Vernagtbach, located in the Oetztal Alps (Austria) (Table 1). This station measures the runoff from the glacier Vernagtferner which feeds the glacial stream Vernagtbach (Fig. 1) (Bergmann & Reinwarth, 1976).

The runoff from this high-mountain drainage basin is controlled mainly by the amount of meltwater from the seasonal snow cover and the glacier ice and firn itself. The annual hydrograph of a glacial stream (Table 1, Fig. 2 and Reinwarth & Oerter, this volume, Fig. 3) shows low streamflow values during the winter months November through April, when nearly no melting or liquid precipitation occurs. It rises when the snow melt season starts in May and shows strong daily and seasonal variations due to changing amount of meltwater on the glacier surface. Thus the runoff variations are very sensitive to weather changes. The runoff amount during the summer months May through September adds up to 97% of the total

Table 1 Characteristic data for the drainage basin of the gauge Pegelstation Vernagtbach, located in the Oetztal Alps (Austria) (Moser et al., 1986)

	Drainage Basin		Glacier Vernagtferner (1979)	
Area	11.44	km^2	9.55	km^2
Altitude range	2635-3633	m a.s.l.	2747-3633	m a.s.l.
Mean altitude	3125	m a.s.l.	3130	m a.s.l.
Glacerized	83	%		

Runoff data (1974-1985)

Annual means:		
mean	0.503 m^3/s	1397 mm/a
standard deviation	0.134 m^3/s	373 mm/a
variation coefficient	0.27	0.27

Daily means (May-Sept.)		
lowest observed value	0.015 m^3/s	0.1 mm/d
mean	1.12 m^3/s	8.5 mm/d
highest observed value	5.61 m^3/s	42.4 mm/d

Monthly means:	May	June	July	Aug.	Sept.	Oct.	May-Oct.
mean (mm)	24	144	434	446	245	65	1359
standard deviation (mm)	12	63	201	130	99	42	373
variation coefficient	0.49	0.43	0.46	0.29	0.40	0.65	0.27

annual amount.

An overview on glacial hydrology was recently given by Röthlisberger & Lang (1987). Techniques for prediction of runoff from glacierized areas were compiled by Young (1985). The first version of the discharge model described in this paper appears in Baker et al. (1982) and its improved version in Escher-Vetter et al. (1986).

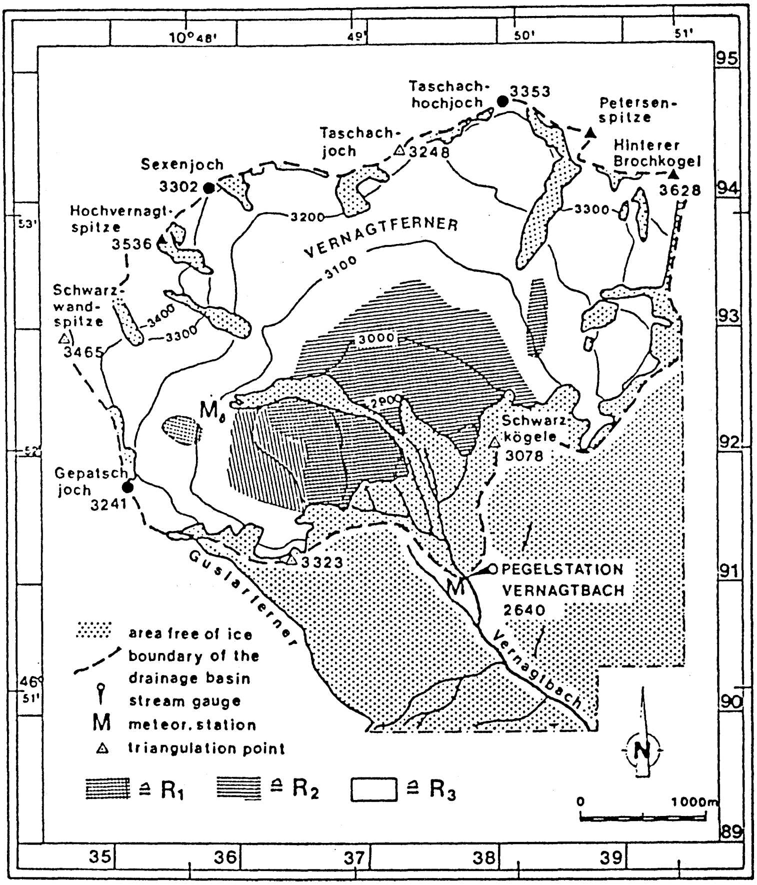

Fig. 1 The drainage basin of the gauge Pegelstation Vernagtbach in the Oetztal Alps. Shown are the ice, firn and snow areas from which the runoff components R_1, R_2, and R_3 originate.

A SCHEME FOR RUNOFF FROM A GLACIATED DRAINAGE BASIN

Fig. 3 shows a scheme for the generation of runoff in a glaciated drainage basin, used as a basis for the runoff model discussed later (Oerter et al., 1981). The given times are mean travel times and mean residence times of the meltwater in the different glacier regions (reservoirs) as calculated for the Vernagt area by dye tracer tests, isotope and electrical conductivity investigations, and statistical analysis of the runoff data.

Over the non-glaciated part of the basin, the snow-meltwater and the rainwater flow on the surface or, after infiltration, in the aquifer. Depending on the depth of the snow cover, the mean residence time lies between one and twelve hours. In the glaciated part of the basin, the ice meltwater shows the smallest residence time between one and four hours. The direct runoff from snow and firn meltwater has a residence time between 0.5 and 1.5 days. The longest residence times are found in the upper parts of the firn

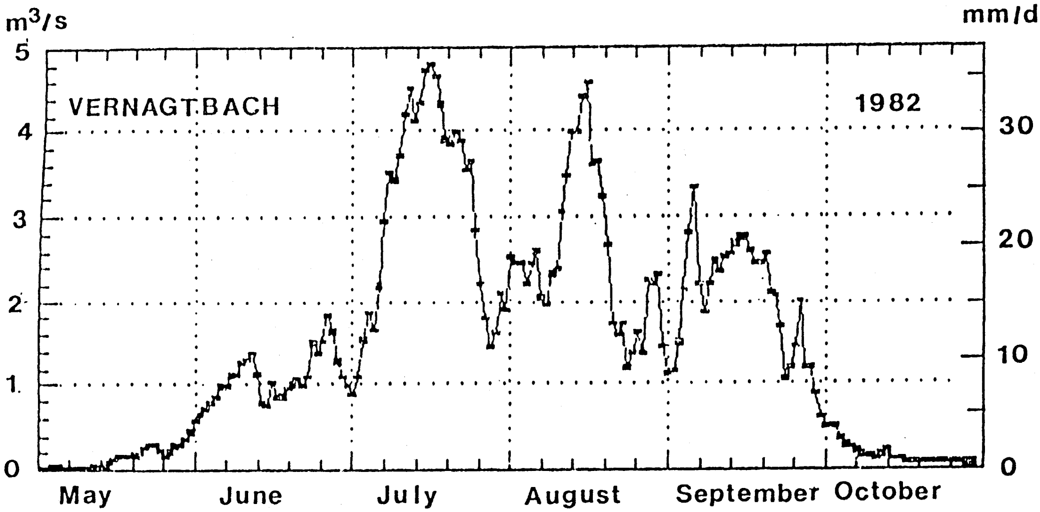

Fig. 2 Hydrograph at the gauge Pegelstation Vernagtbach in 1982, the year which yielded the maximum runoff amount (2148 mm) through the period of observation 1974-1987. The runoff depth (mm/d) is related to the basin area of 11.44 km^2.

area. The travel time for the percolation of snow and firn is, depending on the depth of the snow and firn cover, one to seven days. After the meltwater reaches the firn aquifer it remains in the intraglacial reservoir for seven to sixteen days.

THE RUNOFF MODEL

Linear reservoir model

A linear reservoir model was used to calculate the changes in water storage in the glacier. In this model, the instantaneous runoff $R(t)$ is proportional to the volume of water stored, $V(t)$, and k is a constant, i.e.

$$V(t) = k\, R(t) \qquad (1)$$

This system is analogous to a water-filled container with a hole in which k is related to the size and shape of the hole and the viscosity of the liquid. The change in storage volume is equal to the inflow, I(t), minus the outflow, R(t),

$$\frac{dV}{dt} = I(t) - R(t) \tag{2}$$

Substituting eq. (1) into eq. (2) yields

$$k \frac{dR}{dt} = I(t) - R(t) \tag{3}$$

which has a general solution

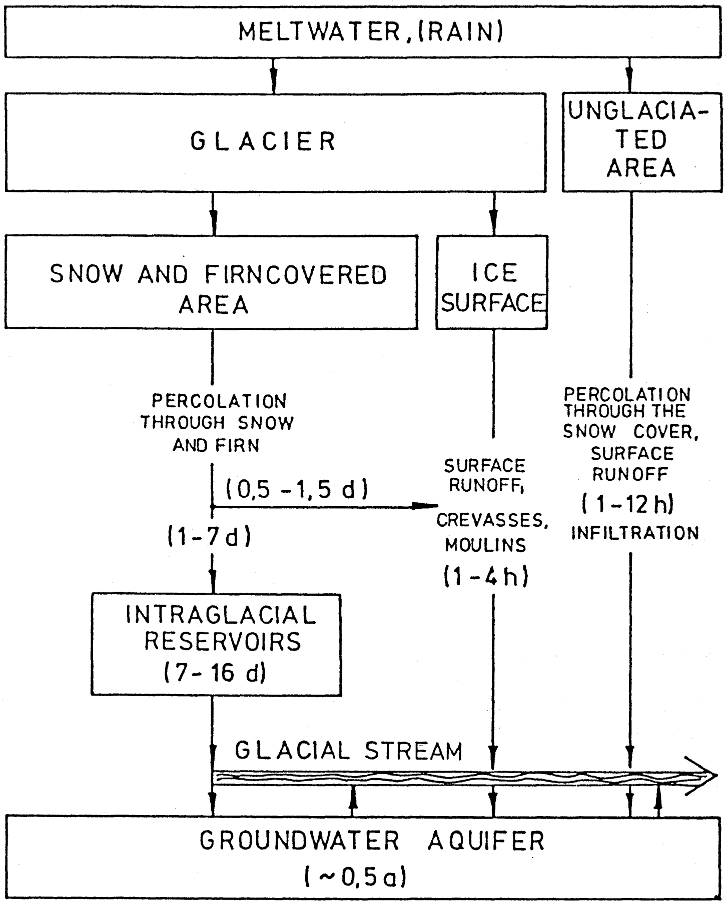

Fig. 3 Runoff generation scheme in the glaciated drainage basin (11.44 km²) of the gauge Pegelstation Vernagtbach (2640 m a.s.l., Oetztal Alps/Austria). The given times are mean travel times and mean residence times of the meltwater in the different reservoirs of the basin.

$$R(t) = \int_0^t \frac{I(\tau)}{k} e^{(\tau-t)/k} d\tau + R(0)\, e^{-t/k} \qquad (4)$$

For the discharge model the glacier is divided into three zones, each of which displays its own characteristic storage and discharge behaviour: exposed ice of the tongue of the glacier, firn next to the exposed ice, and snow in the upper region of the glacier. A linear reservoir is assumed for each zone and the outflow from all three reservoirs is combined to estimate runoff; each reservoir acts independently but total glacier runoff is the sum of all three. A small constant discharge was also added to account for groundwater flow from the basin so that

$$R_c(t) = \Sigma_{i=1}^{3} R_i(t) + R_4 \qquad (5)$$

Calculation of meltwater production

The basic equation to calculate the energy balance at the glacier surface (the calculation will be done for every grid point of a digital terrain model, DTM, of Vernagtferner) is eq. (6) or (7) (see e.g. Escher-Vetter, 1985).

$$SBK + SBL + L + V + S = 0 \qquad (6)$$

$$(1-a)G + (A-\sigma T_o^4) + \alpha_1(\Theta_1-\Theta_o) + \alpha_1 \frac{0.623\ r}{p\ c_p} (e_1-E_o) + S = 0 \qquad (7)$$

The meteorological data measured at the Vernagtbach gauging station are solar radiation, longwave radiation, air temperature, relative humidity of the air, wind direction and velocity, and precipitation. Another important piece of data is the albedo of the glacier surface. As it is difficult to record this quantity continuously during the ablation period, another method was applied in this study: once each day, a large part of the glacier was photographed by an automatic camera, thus recording the distribution of newly fallen snow and of firn and ice. With typical albedo values - snow 80%, firn 60%, ice 40% - the short wave radiation balance is calculated for each point of the glacier surface, which is represented by a digital terrain model. In doing this, the solar radiation measurements at the Vernagtbach gauging station are adapted to the glacier surface with the aid of a radiation distribution model.

Wind velocity, air temperature, and relative humidity, which are needed to calculate the sensible and latent heat fluxes, are also calculated for the altitude of each grid point of the terrain model. The energy balance model (eqs. 6, 7) then makes it possible to calculate the whole energy budget at any point of the glacier surface and thus the meltwater production.

Input data of the model

To calculate the runoff by eq. (5) one needs the following input data:

- the storage coefficients k_1, k_2, k_3 of the three reservoirs,
- the amount of the constant groundwater flow, R_4,
- the amount of meltwater I(t) including the amount of liquid precipitation
- the discharge value $R_i(0)$ at time t = 0, as the initial value of a simulation run

Calculation of runoff is started only after most of the snow is melted from the lower unglacierized portion of the basin. As a

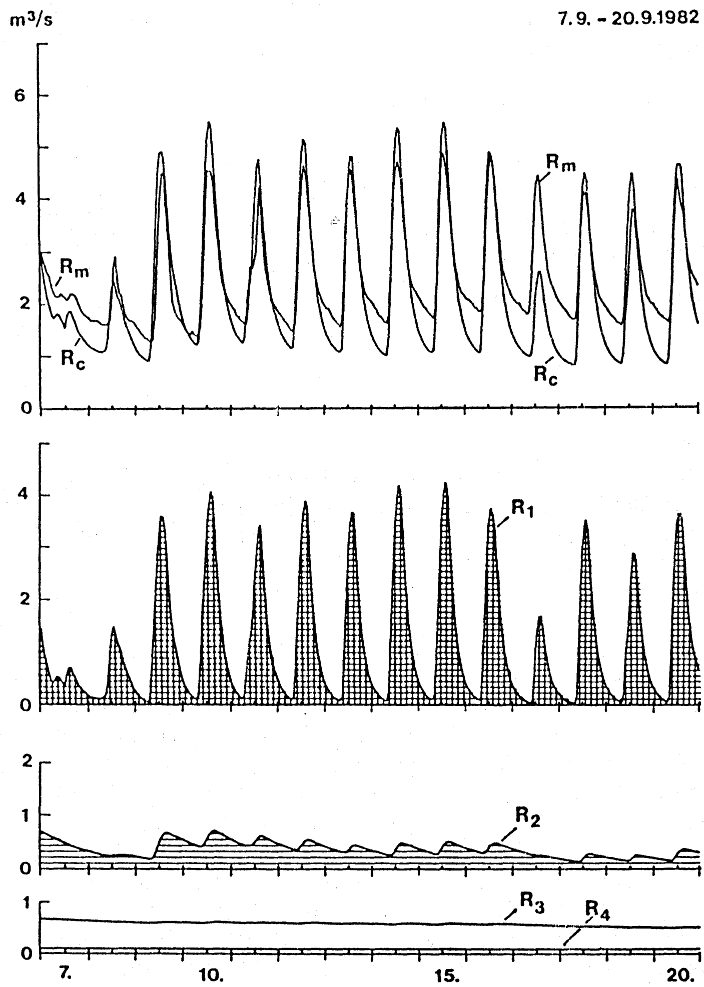

Fig. 4 Calculated (R_c) and measured (R_m) discharge during a good weather period, September 7-20, 1982. The four different runoff components are also shown separately: ice meltwater runoff (R_1), melting firn (R_2), and meltwater from high glacier areas covered by old snow (R_3) as well as the ground water contribution (R_4).

fixed date, June 1st, 0 hours was chosen and it was assumed that $R_1(0) = R_3(0) = 0$, so that $R_2(0) = R_m(0) - R_4$. Here $R_m(0)$ is the measured discharge at the gauge Vernagtbach and the amount of groundwater R_4 was assumed to be 0.1 m³/s.

RESULTS OF MODEL CALCULATIONS

For discussion of the results, three different types of meteorological situations have been chosen. These are "good weather" periods, "bad weather" periods and the night hours.

During "good weather" periods (Fig. 4) we find strong periodic discharge variations due to the runoff of ice meltwater, R_1. The production of ice meltwater is strongly correlated with the diurnal variation of the energy balance and runoff shows only a small time lag, because there is no big storage capacity in the ice area. The storage capacity increases in the firn area near the firn line because of the overlaying firn. Thus the runoff component R_2 shows smaller diurnal variations than R_1. The total amount of R_2 changes within the year and is relatively small in the chosen example, because at that time the firnline was already at a very high elevation. Nearly no diurnal variation remains for the runoff R_3 from the high firn and snow area. At the beginning of the melting season the hydrograph of R_3 shows a rising tendency, during a long good weather period and towards the end of the melting season in September the hydrograph becomes more constant. The limit between the

Table 2 Results of the runoff model for the period 1978 to 1985

Model Component		1978	1979	1980	1981	1982	1983	1984	1985
R_m	$10^6 m$	9.978	14.89	12.58	14.51	23.22	20.79	10.99	16.97
R_c	$10^6 m$	8.243	10.57	11.99	14.09	19.43	16.33	8.54	11.75
R_c/R_m	%	82.6	71.0	95.3	97.1	83.7	78.5	77.7	69.2
R_1/R_c	%	8.6	22.3	11.2	17.5	35.1	36.6	22.8	26.5
R_2/R_c	%	27.3	17.4	38.8	22.1	28.8	36.9	51.9	33.1
R_3/R_c	%	51.7	50.4	41.7	52.9	30.7	20.0	13.8	31.4
R_4/R_c	%	12.4	9.9	8.3	7.5	5.4	6.5	11.5	9.0
P_1/R_c	%	8.2	7.0	4.5	3.8	7.0	7.1	12.5	6.9

catchment of R_3 and R_2 usually was kept constant at an altitude approximately 50 m higher than the elevation of the mean equilibrium line at the end of the previous year. The model gives good results for the chosen period 7/9 - 20/9/1982, because for this period the meteorological input data can be calculated rather well. On average, the time of the maxima and minima is calculated with accuracy of ± 1 hour. The calculated hourly means deviate by ± 15% from the measured ones.

During a "bad weather" period (without liquid precipitation in eq. 5) the runoff R_1 is missing, so that the discharge is calculated by the model only with the aid of two linear reservoirs, R_2 and R_3,

$$R(t) = \Sigma_{i=2}^{3} R_i(0)\, e^{-t/k_i} + R_4$$

Fig. 5 shows that eqs. (5) and (6) calculate the shape of the hydrograph during bad weather periods immediately after good weather periods quite well. However, if a bad weather period is interrupted by a short weather improvement with meltwater production during day time, then the model does not calculate the small runoff maxima correctly (Fig. 6). This may be caused by (among other things) melting of new snow in the unglaciated parts in front of the glacier which would explain the small peaks after September 11.

The runoff peak in the night between September 10 and 11, however, is caused by direct storm runoff (amount of precipitation on 10/9/1982 was 18.5mm) on the wide exposed ice surface. The dashed line in Fig. 6 gives the amount of runoff due to energy balance at the glacier surface without rain, and it is evident that it cannot fit the measured runoff values. The influence of rain and storm runoff peaks becomes greater in the years after 1982, when the exposed ice surface area was increasing from year to year.

During bad weather periods the model results deviate by ± 20% on an average from the measured discharge.

The storage coefficients k are not constant and may slightly vary within the year and also from year to year. At Vernagtferner one finds a period of positive mass-balance between 1975 and 1980 and a period of negative mass balance since 1981 (Reinwarth & Oerter, this volume). The runoff conditions on the glacier changed from the first to the second period due to an increasing ablation area. Therefore the exposed ice surface, and thus the amount of ice meltwater, became larger, and the flow time as well as the storage capacity within this part of the glacier increased. For the model we have to choose greater coefficients k_1 in the later years than in the first years of our investigations. In the hydrological behaviour of the accumulation area we do not notice big changes which may change k_3 values. The transition zone between exposed ice area and firn area covered by old snow becomes smaller. It seems as if this zone was losing the thinner firn layers at lower elevation, and thus we have to deal with a smaller area but thicker layer, and to make k_2 bigger. Fig. 7 shows the results of two calculations with different storage coefficients.

To compare the results for the model periods in years 1978 through 1985, the annual sums of the measured and calculated discharge are compiled in Table 2. The calculated runoff amount is

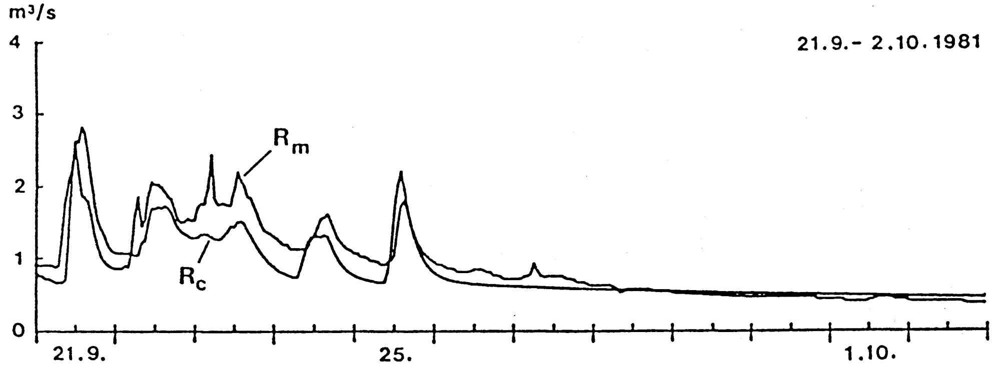

Fig. 5 Calculated (R_c) and measured (R_m) discharge during the bad weather period at the end of the melting season, September 21 to October 2, 1981.

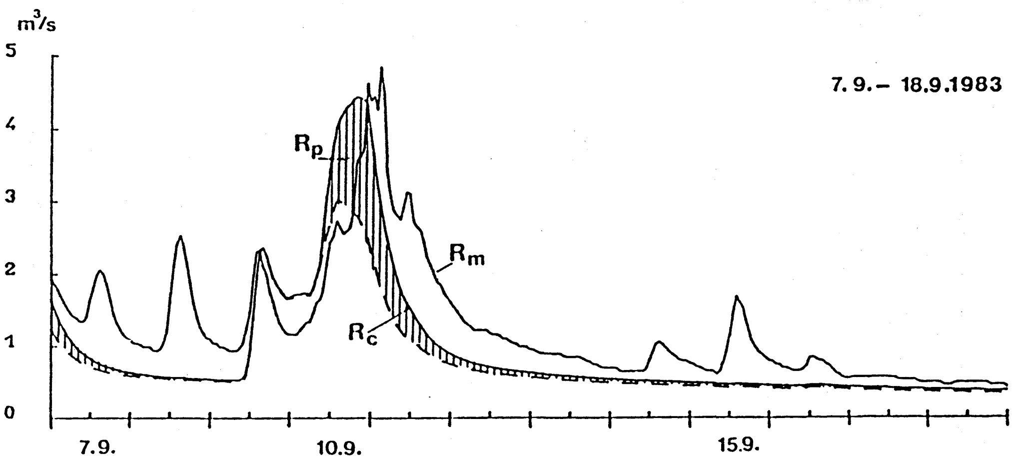

Fig. 6 Calculated (R_c) and measured (R_m) discharge for the period September 7-18, 1983. The dashed line gives the calculated runoff without the storm runoff.

always less than the measured one, because runoff in the unglaciated part of the catchment (1.83 km^2 or 17% of the total catchment) was not taken into account. The annual runoff amount from this area is estimated to be 2×10^6 m^3 on an average, and is mostly contributed by melting of the seasonal snow cover at the beginning of the melting season.

The model gives a good approximation of the glacial meltwater runoff on an hourly basis depending on the quality of the meteorological data, which should be provided with a time resolution of at least half-hourly values. The melt-water input is calculated for each grid point of a digital terrain model of the glacier. It is also necessary to know the distribution of the snow cover or the albedo of the surface.

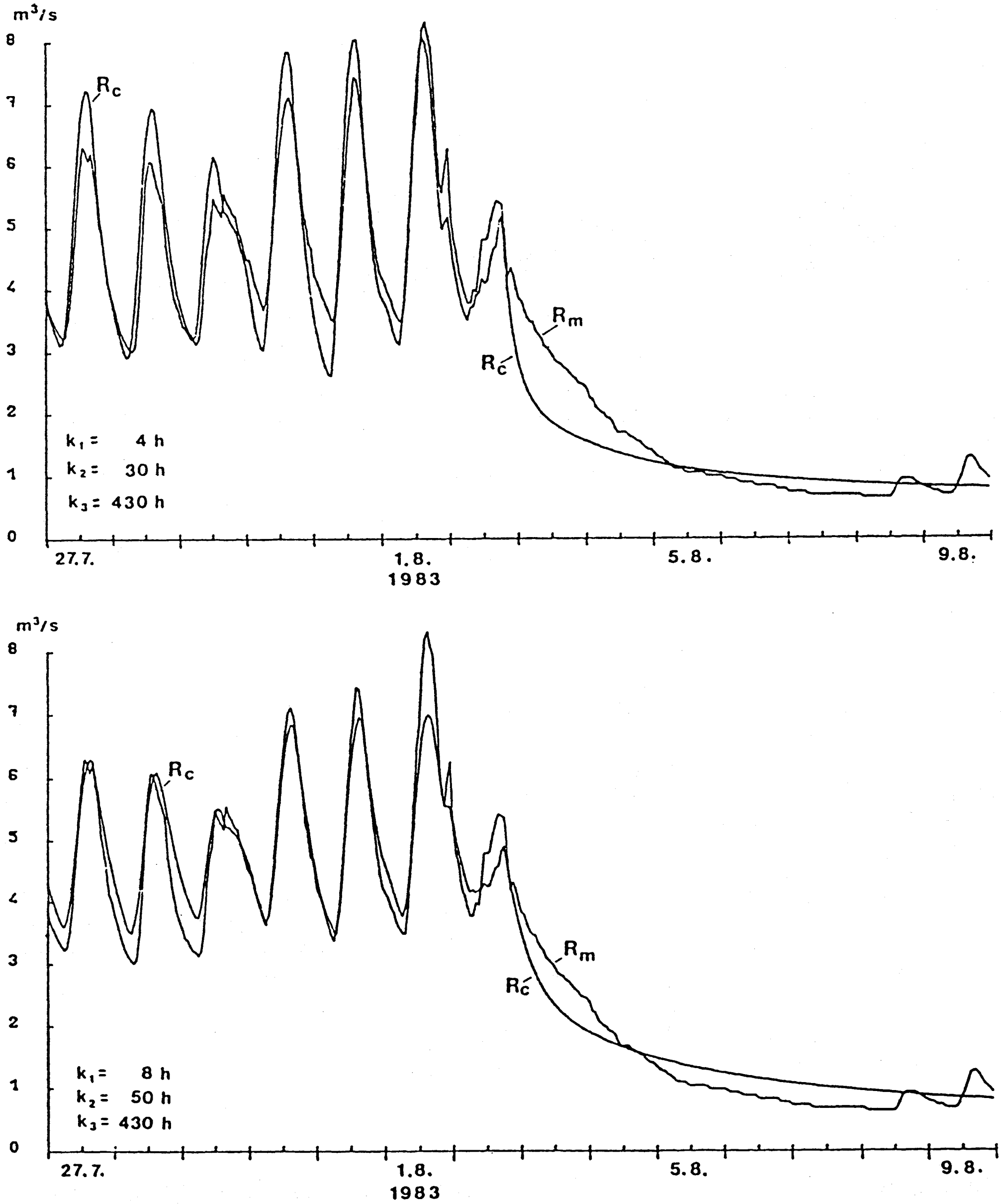

Fig. 7 Influence of the storage coefficients on the calculated discharge hydrograph for the period July 27 to August 9, 1983

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