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Glaciological Research at Vernagtferner/Oetztal Alps: Database and Results of a Hydrological Subprogramme

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Abstract The behaviour of the Vernagtferner is qualitatively well known since 1599, quantitatively it can be described by changes of area and volume since 1889, by mass balance data since 1965 and from 1974 onward also by hydrological data. The relationship of this information to different sections of the processes which link climatic changes to glacier variations, is briefly outlined. Hydrological studies at Vernagtferner aiming to model glacier runoff are explained in detail. The modelling procedure consists of a two-step approach: first, to compute the melt energy available at the glacier surface, second, to calculate travel times of melt water originating from the snow-, firn- and bare ice parts of the glacier. Each of these parts is mathematically treated as a separate linear reservoir with the total runoff resulting from the superposition of the outflow of the three systems. Modelled and measured runoff proved to be in good agreement, regarding amount as well as temporal variations.

INTRODUCTION

The Vernagtferner (ferner=glacier) in the Oetztal Alps (Tyrol) is well known for its behaviour which is characterized by repeated surge-like advances between 1599 and 1848 (Hoinkes, 1969) as well as for the scientific work carried out on this glacier, which began in 1888, when for the first time an entire glacier was mapped with the method of terrestrial photogrammetry. The cartographic representation of this surveying finally yielded the famous map "Der Vernagt Ferner im Jahr 1889" (The Vernagtglacier in the year 1889) at the scale 1:10 000 by Finsterwalder (1897).

VOLUME, MASS AND WATER BALANCES

From this first survey and seven later mappings up to 1990, it was possible to compute changes in area, volume and mean altitude (Brunner & Rentsch, 1972) by comparing exact contour line maps or more recently using digital terrain models (Reinhardt & Rentsch, 1986). As a result, the volume balance of

Vernagtferner is known since 1889 for time intervals of 15 years on an average.

In 1965, the Vernagtferner became included in a combined balances project of the International Hydrological Decade (IHD) 1965-74, which covered the Rofental drainage basin (Oetztal Alps). This project, initiated by H. Hoinkes (1970), demanded the control of at least the large glaciers within this basin of 98 km², which is 43% glacierized. Accordingly, in addition to the already observed glaciers Hintereisferner and Kesselwandferner, ablation and accumulation measurements were carried out at Vernagtferner since that time. For reasons of comparison, determination of mass balance is related to the fixed date system (balance year: 01.10.-30.09) for all these glaciers.

Completed in 1973, the stream gauging station "Pegelstation Vernagtbach" (2640 m asl) was constructed, 1.3 km in front of the glacier terminus, recording the discharge of the Vernagt drainage basin (11.44 km², 84% glacierized) from May to October (Bergmann & Reinwarth, 1976). Together with precipitation data, an attempt was made to compute annual water balances for the period 1974-86. The results proved a rather small contribution of glacier mass change to total runoff at least up to 1981 (Moser *et al.*, 1986).

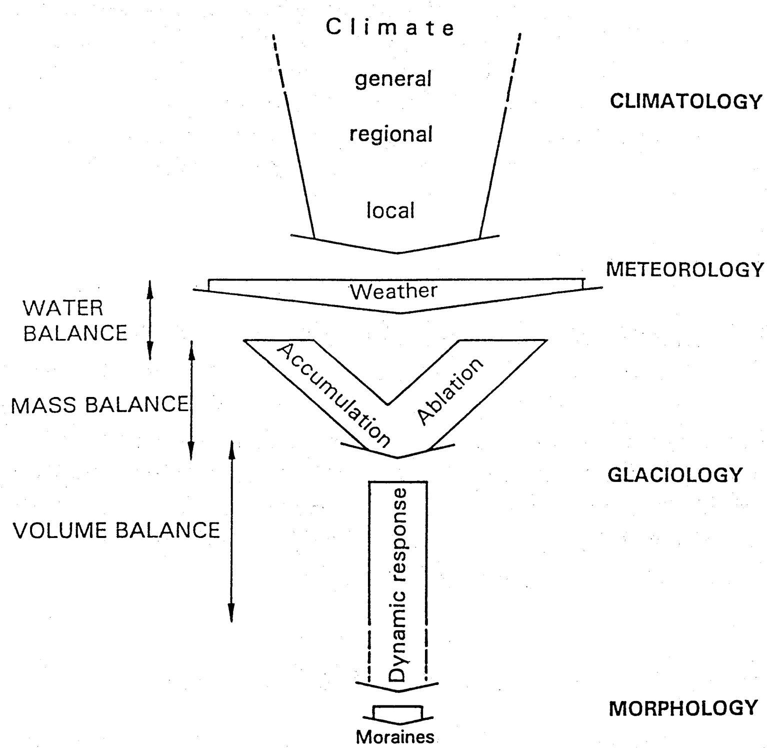

Fig. 1 Processes linking climatic conditions with glacier behaviour. Additionally indicated are "balances", controlling different sections of the chain, equivalent to methods for determination of these balances, i.e. hydrological-meteorological method for water balance, glaciological method for mass balance and geodetic method for volume balance.

For a better coordination and interpretation of these data sets, the chain of processes connecting climatic changes with the dynamic response of a glacier is demonstrated schematically in Fig. 1. This scheme, which was first presented by Meier (1965) and which is rather generalized, neglecting possible feed back effects, is shown here in a considerably modified way, attempting to indicate qualitatively by varying length and width of the arrows characteristic time scales and variability of the parameters defining or dominating the different processes. Dashed lines mean that the length of an arrow should be expanded to reach a proper relation.

The chain originates from general climatic conditions, which are regionally modified due to topographical and orographical effects. Weather with a greater variability than climate is standing for mass and energy transfer between atmosphere and glacier surface. These exchanges govern accumulation and ablation, meaning that atmospheric and glaciological processes interfere within the time scale of synoptic processes.

Deviations from steady state mass balance conditions cause a dynamic response of the glacier, resulting in a change of flow rate, leading finally to an advance or retreat of the glacier terminus. Without any delay, these effects again induce the formation of moraines and other morphological features, which allow delineation of the former extent of glaciers.

The greater variability of ablation as compared to accumulation corresponds to the situation experienced in the central part of the Eastern Alps, where ablation normally dominates the resulting mass balance. The overall narrowing of the arrows following the forcing atmospheric processes should symbolize a low pass filtering effect of the climatological information stored in glacier variations as pointed out by Kuhn (1981).

Those links of the chain, which determine the different balances with respect to defining the methods applied for their computation, i.e. the hydrological-meteorological method for water balance, direct glaciological method for mass balance and geodetic method for volume balance are marked at the left side by arrows too. The length of these arrows should also arbitrarily indicate a time scale, here with relation to the averaging effect of the applied method, i.e. hourly values for runoff and precipitation (water balance), annual values of net accumulation and net ablation (mass balance) and multiannual values of elevation changes (volume balance).

Results illustrating the different time resolution as derived for Vernagtferner are combined in Fig. 2. Volume balance in the uppermost part of Fig. 2, expressed as mean annual elevation change (m a^{-1}) between consecutive mappings, proves quantitatively the overall shrinkage of the glacier since 1889 with the only exception being the decade 1969-79. This statement does not correspond well with the period of glacier growth beginning already in 1965 and lasting until 1980 as it is derived from annual mass balance values shown in the middle of Fig. 2. The limited time resolution of elevation changes together with the linear interpolation between the states of the glacier, defined

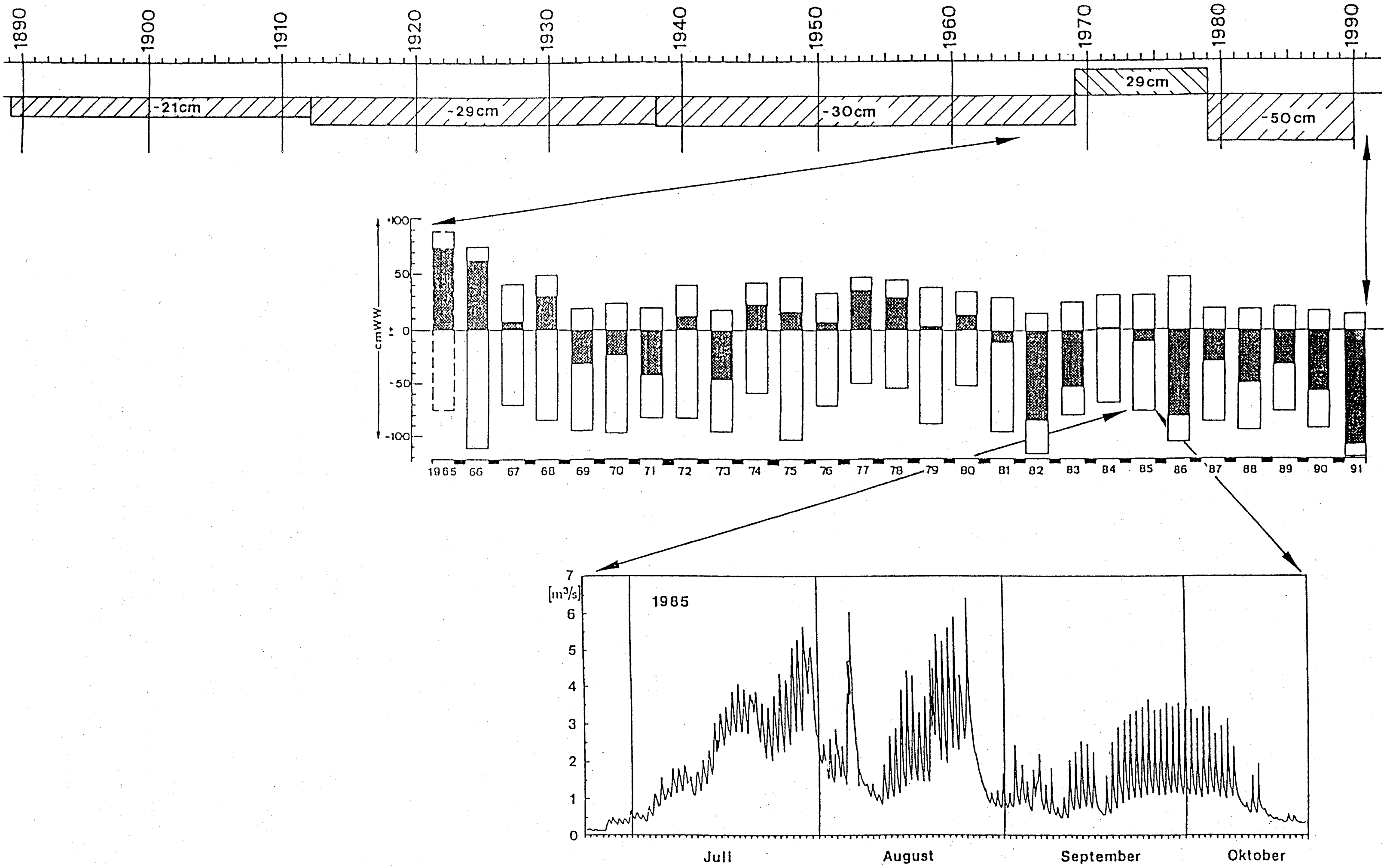

Fig. 2 Changes of the Vernagtferner as derived by geodetic, glaciological and hydrological measurements:
above: mean annual elevation changes in the time 1889-1990 (cm a^{-1});
middle: specific annual net accumulation (upwards), net ablation (downwards) and net mass balance (shaded) in cm water equivalent;
below: runoff hydrograph for the ablation season 1985 (m^3 s^{-1}).

by the arbitrary dates of the mappings, also obscure other climatically induced short term variations of the glacier as for instance the pronounced advance at the turn of the century and the growth around the twenties.

In addition to the specific values of net balance B/S, net ablation B_a/S_a and net accumulation B_c/S_c (B, B_a, B_c = net mass balance, net ablation, net accumulation; S, S_a, S_c = total glacier area, ablation area, accumulation area) shown in Fig. 2, the areal and altitudinal distribution of these values is also derived, yielding the ratio of accumulation area to total glacier area (AAR) and the mean equilibrium line altitude (ELA) as two characteristic quantities, which allow a fairly satisfactory parameterization of mass balance if the situation is not too far from equilibrium conditions.

The principal results of mass balance investigations are demonstrated more impressively by the summation curve of Fig. 3, showing the twin peaked period of mass increase from 1965 up to 1980 with an average amount of 11.2 cm water equivalent/year (w.e. a^{-1}) and the consecutive series of years with drastic mass loss, reaching an average value of −48.3 cm w.e. a^{-1} until 1992.

GLACIAL HYDROLOGICAL INVESTIGATIONS

The most informative insight into the processes depending on mass and energy fluxes between atmosphere and glacier surface is provided by the hydrological-meteorological method. In this paper, the interest is focused on

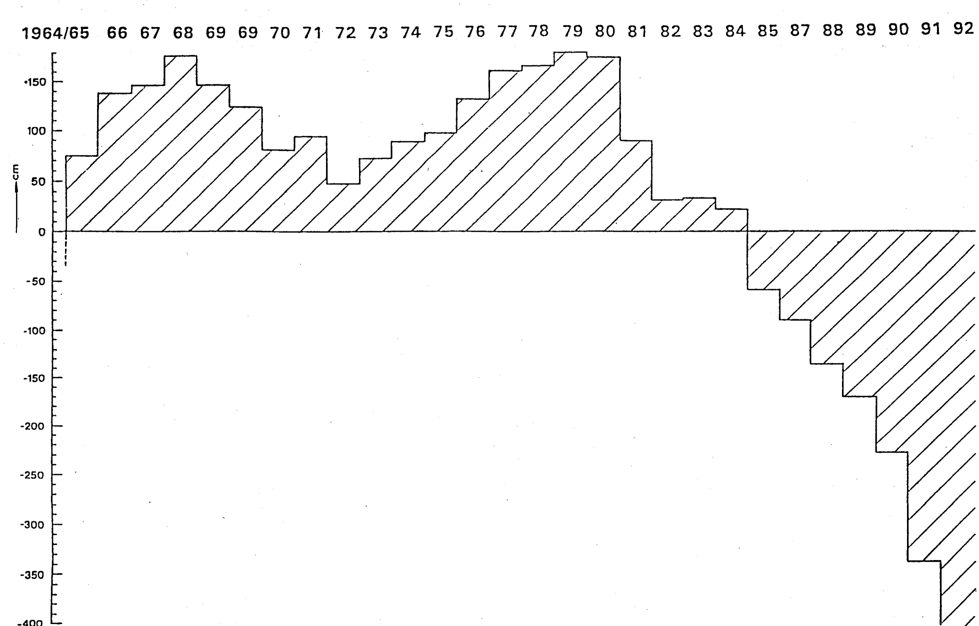

Fig. 3 Summation curve of specific net mass balance values for the period 1965-92 (cm w.e.).

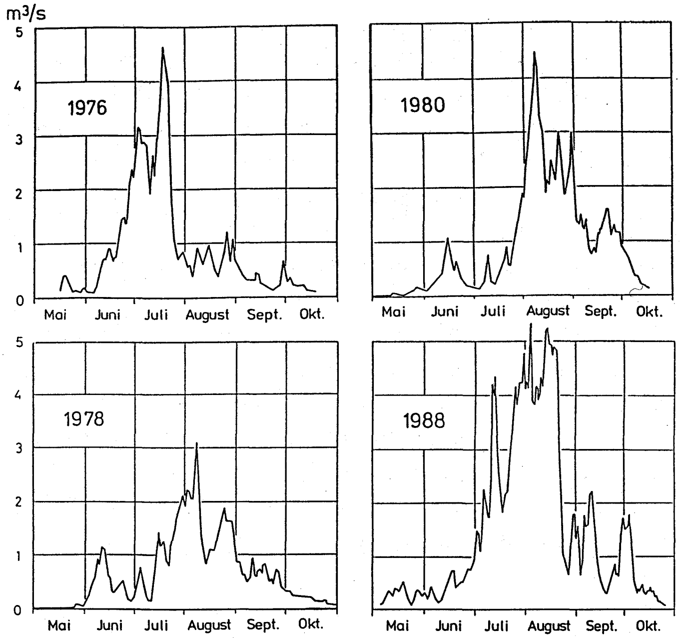

Fig. 4 Daily mean values of runoff ($m^3 s^{-1}$) for selected years, with markedly deviating temporal distribution (1976, 1980) and amount (1978, 1988) of meltwater discharge during the ablation season.

runoff, depicted in the lowest part of Fig. 2 with the hourly hydrograph for 1985 as an example. Daily mean values for four selected ablation seasons, representing different types with respect to distribution and amount of runoff, are shown in Fig. 4, the entire series, given by monthly mean values, is reproduced in Fig. 5.

From the hydrographs of Figs 2, 4 and 5, the pronounced diurnal and annual variations of runoff as well as distinct aperiodic disturbances, caused by fresh snow fall, which interrupts immediately the production of melt water, can clearly be recognized.

Modelling of glacier runoff

Analysis of these characteristics with the aim of modelling glacier runoff requires the understanding of two independent processes:

- production of meltwater, depending on the melt energy available at the snow and ice surface, the amount of which is determined by the heat balance at the glacier surface;
- drainage within and beneath the glacier, mainly depending on the material conveying the water. In this case, snow is treated as an unsaturated porous medium, firn corresponds to a karst-like medium with the water draining through small cracks and narrow crevasses, finally reaching the ice body.

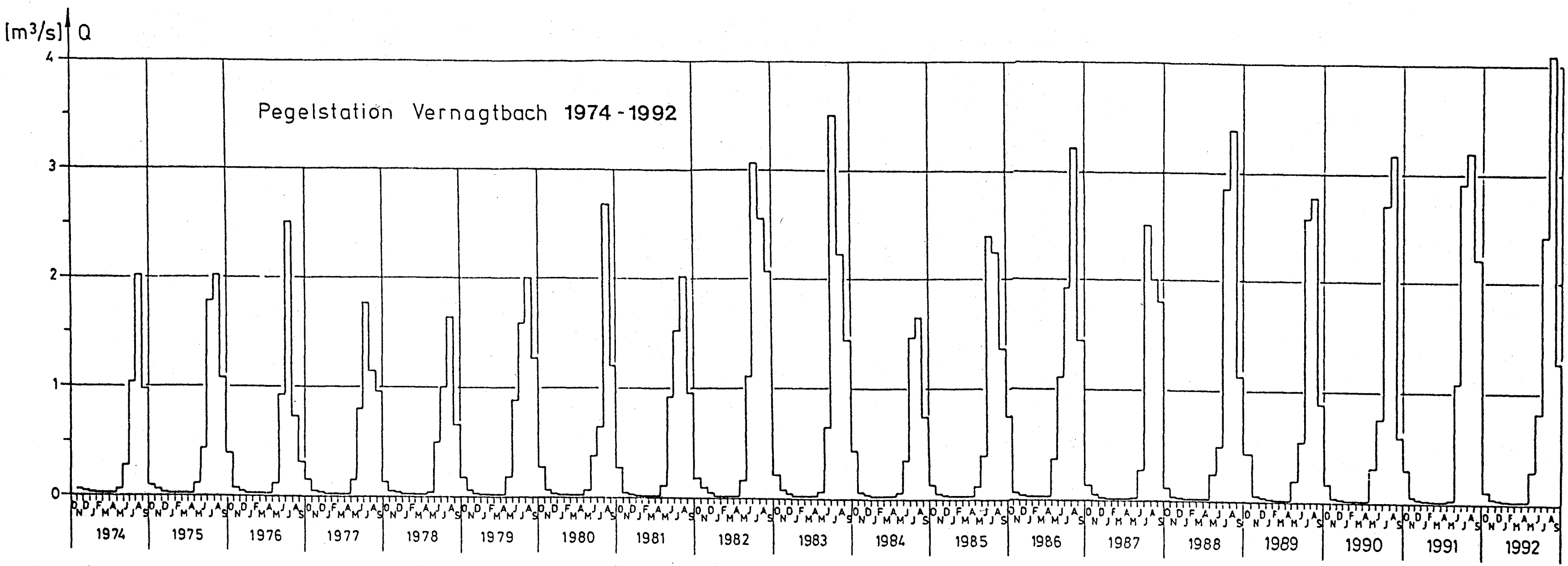

Fig. 5 Monthly mean values of runoff ($m^3 s^{-1}$) for the period 1974-92. The increase in runoff amount for the ablation seasons since 1981, due to distinct negative mass balances, becomes evident.

The tongue region with bare ice is hydraulically characterized by water flow in supra- as well as intraglacial conduits or channels (Röthlisberger & Lang, 1987).

Both complexes have been intensively studied at Vernagtferner from 1974 to 1986 in a joint programme of the Commission for Glaciology, Bavarian Academy of Sciences and the GSF-Institut for Radiohydrometry, Munich (Oerter *et al.*, 1981; Baker *et al.*, 1982; Moser *et al.*, 1986).

Computation of energy available for melt

In order to reproduce the pronounced daily amplitudes in the discharge hydrograph when modelling runoff, the parameterization of energy input at the surface has to provide the same time resolution as the runoff record. For this reason the frequently used parameterization by positive temperature sums was not applicable here. On the other hand, positive degree day computations proved most successful for modelling net ablation within the time scale of mass balance studies (Kraul *et al.*, 1992).

Based on the data of two meteorological stations (Fig. 6), the components of energy balance were computed in hourly steps for the entire glacier surface and for the whole ablation period, related to the grid points of a digital terrain model with a 100 m grid. Particular attention was devoted to quantify shortwave net radiation which proved to be the dominating term of the energy balance. Shortwave radiation balance is strongly dependent on surface albedo and demanded therefore the rather difficult determination or at least approximation of the changing areal distribution of surface reflectivity. This problem was solved by analysing pictures of the glacier, taken daily by an automatic camera, in order to delineate the areal share of bare ice, firn and snow to which in turn typical albedo values were attributed. The analyses were also related to the grid points of a digital terrain model.

Drainage of meltwater within the glacier

To describe the internal drainage system of the glacier, different methods have been applied. In particular usage of fluorescent dye and natural isotopes as tracer substances, electrical conductivity measurements as well as special analyses of the discharge hydrographs were the main tools.

The basic concept for modelling is suggested by the glacier itself, showing usually three distinct altitudinal zones, the lowest one comprising bare ice, the highest one with snow of the current balance year and an intermediate one with firn layers consisting of snow from former years. The average extent of these zones for approximately equilibrium conditions, meaning an AAR of close to 0.7, is illustrated in Fig. 6, which additionally shows the different measuring sites in the Vernagt area.

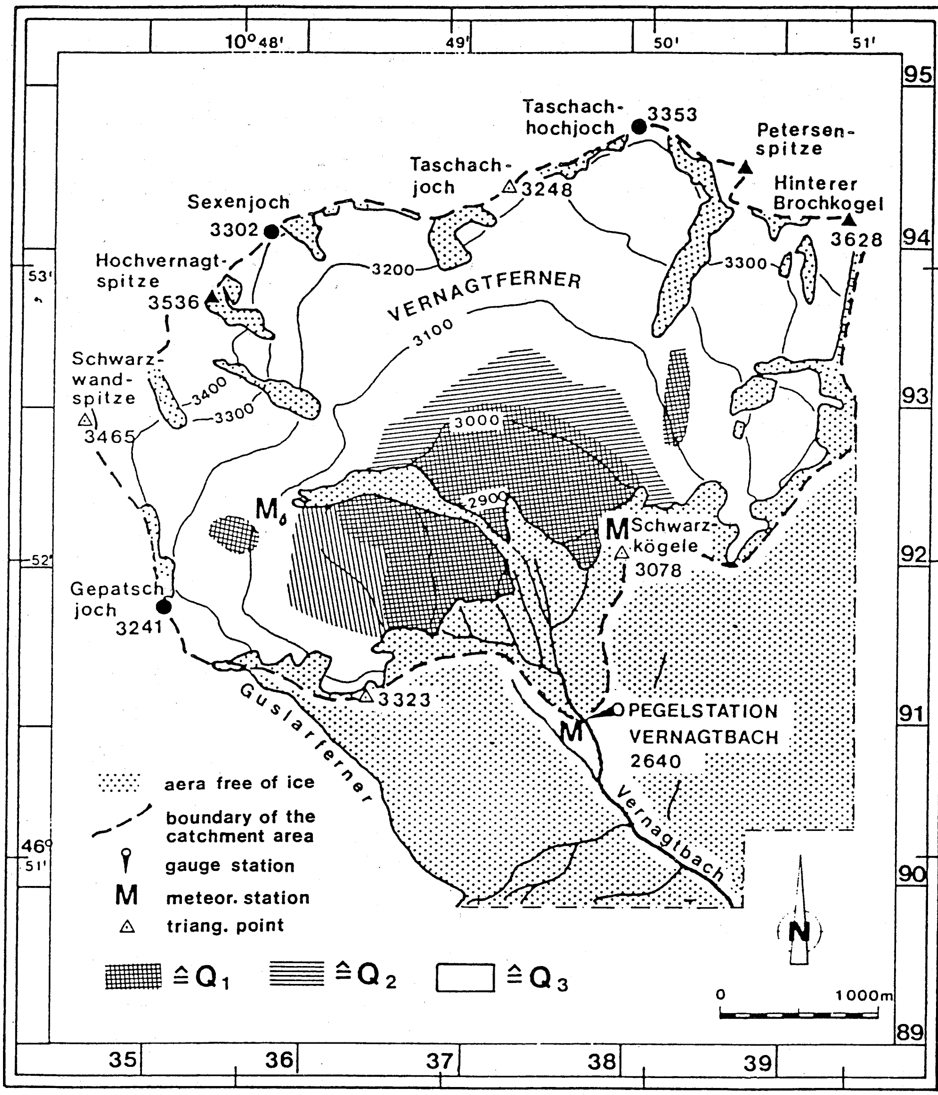

Fig. 6 Sketch map of the Vernagt catchment area extending over 11.44 km² of which 84% are glacierized. The different types of hatching and the unhatched area indicate the zones with deviating hydraulic characteristics, i.e. Q_1 = ice surface, Q_2 = firn, Q_3 = snow. In addition, the meteorological and hydrological measuring sites are inserted.

Each of these zones, indicated as Q_3, Q_2 and Q_1 in Fig. 6, is treated as a linear reservoir which is defined by a linear relation between water volume in the reservoir and the change of volume respectively the outflow of the reservoir, with the so-called storage constant as a proportionality factor.

The aim was now to prove numerically the concept of three superimposed linear reservoirs and to determine reliable values of the different storage constants.

These values can be achieved by analysing the discharge hydrograph for situations with zero water input rates, causing an exponential decline of the hydrograph. For the diurnal period, produced by the drainage of ice melt water, this is the case during night time. The decline connected with a fresh snow cover is affecting the runoff from the whole glacier, i.e. the discharge from ice, firn and snow. The runoff decline at the end of the ablation season is due to the water draining from the upper snow area only.

Another rather more important approach is to determine directly the hydraulic conditions by tracer methods. From a great number of dye tracer experiments, carried out in the different parts of Vernagtferner, numerous

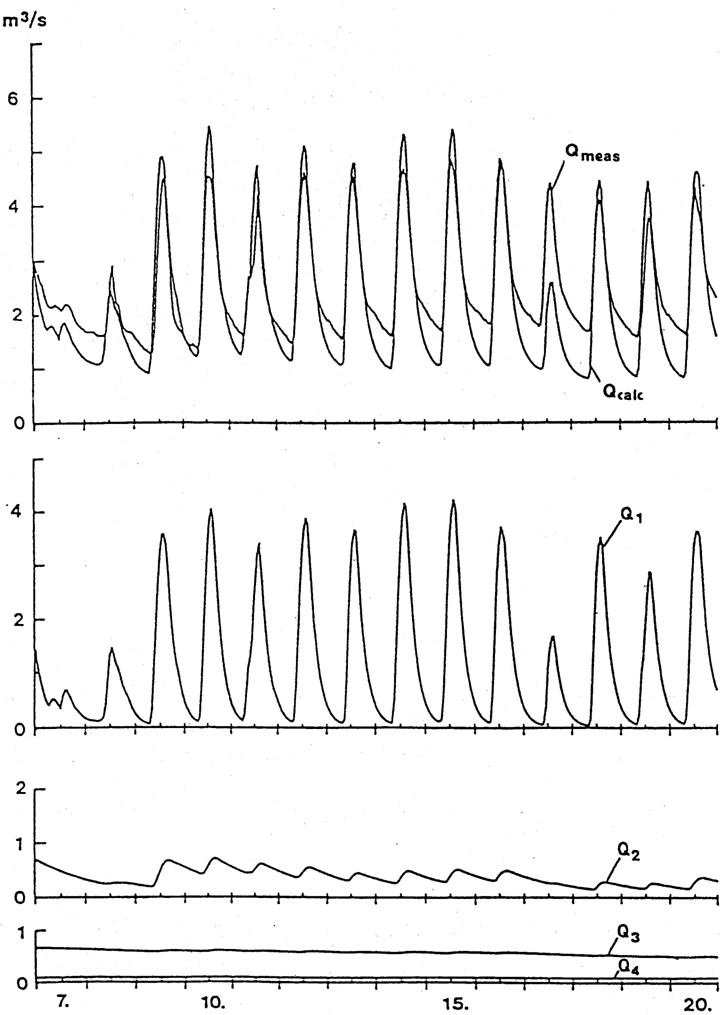

Fig. 7 Computed (Q_{calc}) and measured (Q_{meas}) runoff ($m^3\ s^{-1}$) for the fair weather period 7-20 September 1982. In addition the contribution to runoff from the ice area (Q_1), the firn zone (Q_2) and the snow zone (Q_3) as well as the amount of groundwater (Q_4) as composed for modelling the total runoff are shown.

values of the storage constants were derived (Behrens *et al.*, 1982). They turned out to be allotted to three distinct ranges, thus confirming the three reservoir concept. Moreover, they were in good agreement with the values derived by the hydrograph method. A fourth component of runoff contribution finally is given by a constant and rather small amount accounting for groundwater flow.

Figure 7 presents an example for comparing measured and calculated runoff for a dry fair weather period, which in addition illustrates the runoff contributions of the different reservoirs. For the ice reservoir, runoff was computed with a storage constant of 4 h, for the firn reservoir with 30 h (=1.26 days) and for the snow reservoir with 430 h (=17.9 days). The mean difference between hourly values of measured and computed runoff is about

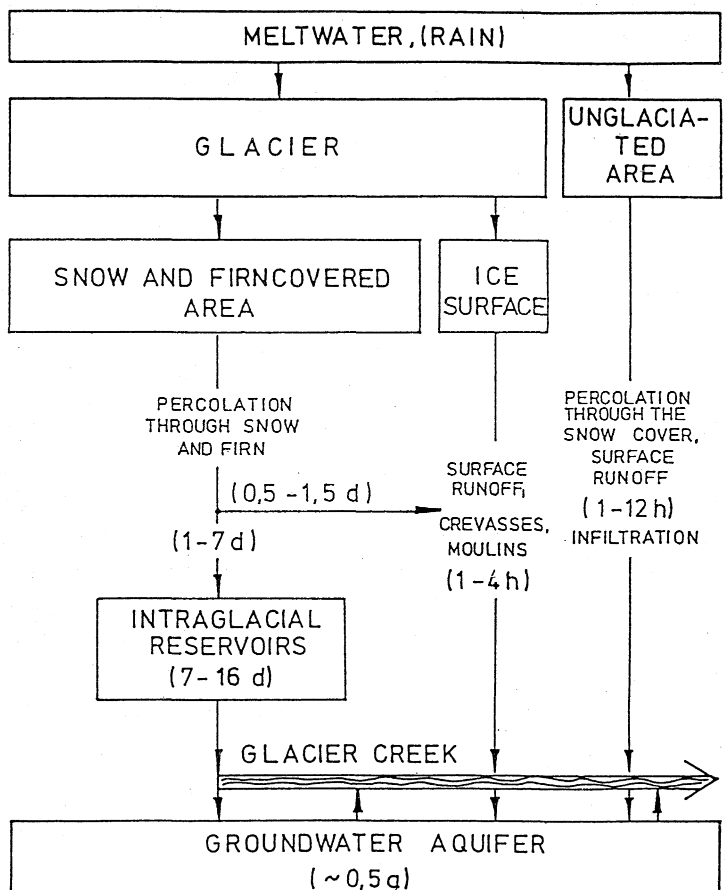

Fig. 8 Scheme of runoff for a glacierized drainage basin, related to the catchment of the gauging station "Pegelstation Vernagtbach". The times inserted in the scheme are mean travel times respectively mean residence times of water draining from the different reservoirs.

15% in the example, for the long term average it amounts to about 6%. The occurrence time of the extreme values fits within ±1 h.

Particular consideration and field work was directed towards the water movement in the snow zone. From tracer tests, it was found that melt water is percolating with about 4 m day^{-1} through the unsaturated part of the snow pack until a water saturated layer is reached. This layer, occurring immediately at the boundary to the underlying solid ice, exists throughout the whole ablation season and has a variable thickness, depending on the melt water input at the surface. The distances which water moves in this firn aquifer until it reaches the more efficient part of the internal glacier drainage system by entering cracks or crevasses in the ice must be rather short, otherwise the mean residence time should be much longer.

The overall results of the hydrological investigations with respect to modelling glacier runoff are summarized in the scheme of Fig. 8. The inserted times are mean travel times respectively mean residence times, ranging from 1 h for water from the lowest tongue area to 23 days for water from the highest snowfields on Vernagtferner.

Finally it can be stated, that the attempt of a two step modelling, first of heat balance to compute melt water production and second of drainage of meltwater within the glacier to simulate the glacial runoff, proved to be very successful for Vernagtferner.

OUTLOOK

In recent years, the climatological and glaciological situation has changed considerably. Recent conditions are characterized by a progressive disappearance of the snow and firn area, meaning a nearly negligible water storage and a minimum runoff contribution of these reservoirs, connected with an increasing total amount and amplifying diurnal amplitudes of runoff, caused by the corresponding expansion of the ice reservoir. These conditions provoke practically flood-like events every afternoon during warm summer periods and imply therefore a rather dangerous situation for the upper valleys in this region.

Further investigations on the hydrological system of Vernagtferner seem therefore indispensable. Attempts to apply the runoff model also to other glacierized drainage basins are regarded as important tasks.

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