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Water storage and drainage within the firn of a temperate glacier (Vernagtferner, Oetztal Alps, Austria)

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ABSTRACT This paper deals with the flow of meltwater in water-saturated firn of a temperate glacier. The firn is treated as a porous medium according to Darcy's law. The storage of meltwater in the firn was studied in boreholes by measuring the water level. At a depth of about 20 m below the glacier surface a water-bearing layer exists every year which shows strong annual variations. The hydraulic conductivity of firn determined by two pumping tests is 5×10^{-5} m s^{-1}. One can assume that the water-bearing firn layer within the glacier extends over the whole firn area during the ablation period, that water flow takes place there, and that the water body must be interrupted at distances of about 100 m by drainage systems.

INTRODUCTION

In the drainage basin of the gauging station "Pegelstation Vernagtbach" (see Fig.1) in the Oetztal Alps (Austria) various glacial-hydrological works have been carried out in recent years. These activities were done within the framework of Sonderforschungsbereich 81 of the Technische Universität München. In 1973 the gauging station, which is described by Bergmann & Reinwarth (1976), was constructed. Since then it has been possible to record the total runoff from the glacier Vernagtferner (9.30 km^2; lat.46° 52'N, long.10° 49'E). The area of the total drainage basin is 11.44 km^2 and 81% of it is glacierized. The contribution of snow and firn meltwater to the total runoff reaches 80% of the discharge during the ablation period, as was shown for example for summer 1978 by environmental isotope measurements (Oerter *et al.*, 1980, Oerter, 1981). Because of this large amount of snow and firn meltwater it seemed desirable to get more knowledge on the behaviour of meltwater in the firn. Some investigations on the meltwater flow in the firn area of Alpine glaciers have already been carried out, for example by Schommer (1976, 1978) and Lang *et al.* (1979) on Grosser Aletschgletscher (Switzerland). Investigations on the glaciers Hintereisferner and Kesselwandferner (Austria) were carried out and described by Behrens *et al.* (1976, 1979) and Ambach *et al.* (1978).

METHODS OF INVESTIGATIONS

The investigations described in this paper are based on water-table measurements in boreholes in the accumulation area of Vernagtferner (see Fig.1). The boreholes with diameters between 35 to 100 mm and depths between 25 to 30 m have been melted by electrically heated hotpoints constructed for this project (see, e.g., Oerter 1981). Additional boreholes (maximum depth 85 m) and their cores have been available from core drilling in 1979*. The boreholes were made fast in their topmost parts by pipes at least 2 m long. Their tops (well mouth) above the glacier surface served as reference points for the measurements.

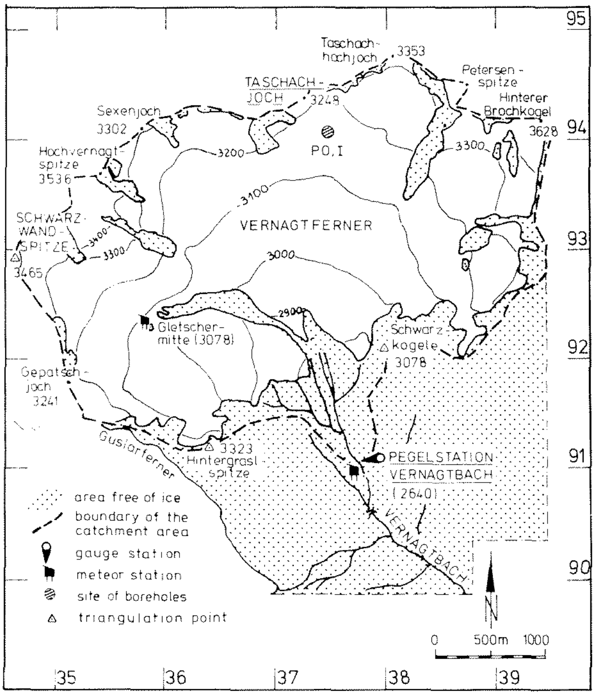

FIG.1 The drainage basin of the gauging station "Pegelstation Vernagtbach" (Oetztal Alps, Austria). The map shows the location of the boreholes PO and I on Vernagtferner.

The water-table measurements have been carried out by measurements at discrete time intervals for one borehole by an automatic water-stage recorder. For special purposes, e.g. during a pumping test, electrical pressure probes were available, either with a recording facility or a digital display.

Two pumping tests were carried out to calculate the hydraulic conductivity of firn in 1979 and another one in 1981 (the interpretation of this last one is not yet complete). The interpretation of the pumping-test data follows the method of analysis given by Kruseman & De Ridder (1970).

* *This drilling was done in cooperation with Universität Bern (Prof. Oeschger, H. Rufli).*

THE WELL HYDROGRAPHS IN THE BOREHOLES

The meltwater from snow and firn in the accumulation zone of a glacier 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. Figure 2 shows the record of the water level (well hydrograph) in well number I (see Fig.1) in the years 1979-1981. One sees here that the water-saturated layer starts to increase in the early ablation period. During the

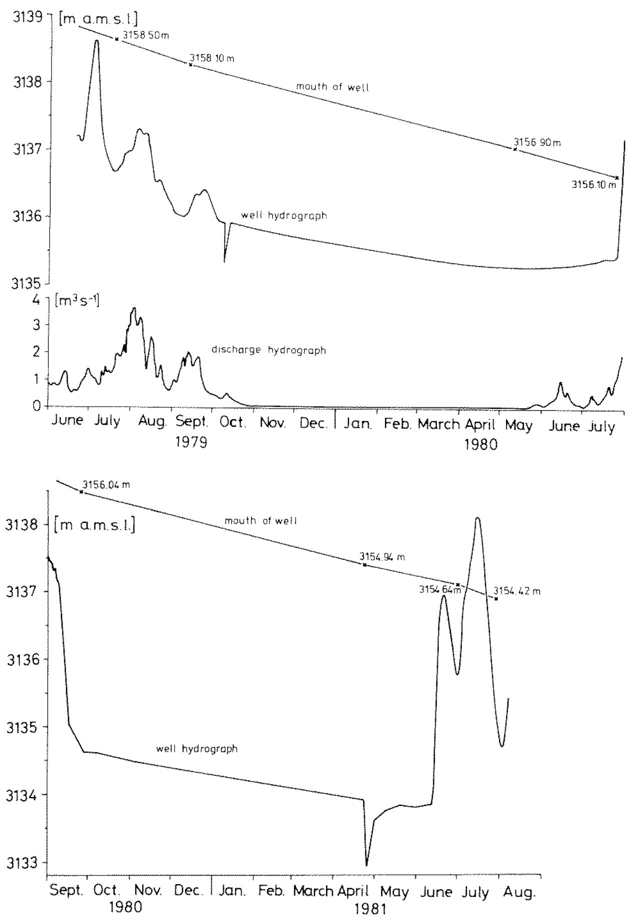

FIG.2 Record of water level (well hydrograph) in borehole I. In addition the change of elevation of the mouth of the well is plotted and also the discharge hydrograph at the Vernagtbach gauging station for the time period 1979-1980.

ablation period the hydrograph shows strong variations due to meltwater production, during which the thickness of the water-bearing layer reaches 4 m. At the end of the ablation period one sees the depletion of the water table. During winter this water-bearing layer almost completely disappears. In October 1979 and April 1981 electrical drilling was carried out in the borehole to keep it at its original diameter of approximately 100 mm. This caused the water level to drop to 0.6 m and 0.85 m respectively, probably below the bottom of the formerly water-bearing layer. To replenish these losses of about 7 l and 10 l of water respectively it took 5 days in October 1979 and 20 days in April 1981.

A comparison of the well hydrograph with the discharge hydrograph at the Vernagtbach gauging station shows that the maxima of the water table follow with a time lag of 4 to 5 days the maxima of discharge. This must be the time needed for the percolation of water through the unsaturated layer, which at this site is about 20 m thick.

To get an idea of the residence time of the meltwater in the firn aquifer we analysed the well hydrograph during periods without meltwater production on the glacier surface, i.e. during periods with a depletion of the water table in the firn. In a porous medium the discharge is proportional to the thickness of the aquifer if the hydraulic gradient remains constant. Therefore we may handle the water-bearing firn layer as a linear reservoir and try to describe the drawdown of the water level by an exponential fit. During periods without meltwater input, starting with a thickness H_o at the time $t = 0$, the thickness H is:

$$H = H_o \exp(-t/K) \qquad (1)$$

The time constant K is a measure of the residence time of the meltwater in the firn aquifer, i.e. the time for a discharge of e^{-1} of the amount of water. Thus the well hydrograph of Fig.2 shows that the meltwater cannot remain inside this aquifer for a very long time. The mean time constant, averaged from different observation periods and boreholes in Table 1 is about 13 days.

TABLE 1 Time constants K for the depletion of the water table in the firn for different boreholes and times. H is the original thickness, r^2 the coefficient of determination of the exponential fit

Date	Borehole	H(m)	K(days)	r^2
4.7.79-18. 7.79	I	2.90	11.6	0.922
10.8.79-16. 8.79	I	1.60	11.4	0.970
21.9.79- 4. 9.79	I	0.80	16.4	0.989
25.9.79- 8.10.79	I	0.80	13.3	0.962
22.6.81- 2. 7.81	I	3.20	17.2	0.989
18.7.81- 3. 8.81	I	4.40	9.3	0.994
10.8.79-16. 8.79	PO-P12	2.20	10.0	0.995
mean			12.7±3	

HYDRAULIC CONDUCTIVITY OF FIRN

In groundwater hydrology the hydraulic conductivity of an aquifer will usually be determined by a pumping test. We tried to determine the hydraulic conductivity of water-saturated firn in the same way. In the literature only a few values are available (Table 2). For

TABLE 2 Hydraulic conductivity k_f for the water bearing firn layer calculated for different glaciers

Author	*Method*	*Location, date*	*k_f(m s^{-1})*
Schommer (1978)	*pumping test*	*Aletschgletscher 6-8.7.1977*	*1.2×10^{-5}*
Behrens et al. (1979)	*tracer dilution in a firn pit*	*Kesselwandferner 10-30.7.1976*	*3.0×10^{-5}*
own investigation	*pumping test*	*Vernagtferner 1-2.8.1979*	*5.0×10^{-5}*

the pumping tests on Vernagtferner, Fig.3 shows the location of the pumped well PO and the various observation wells. All boreholes extended into the impermeable ice, i.e. below the bottom of the aquifer. The pumping tests were performed on 1 and 2 August 1979. During the first pumping test the pumping rate was 26.6 l min^{-1} over a period of 54 min. During the second pumping test the pumping rate was 25.1 l min^{-1} over a period of 120 min. For the second

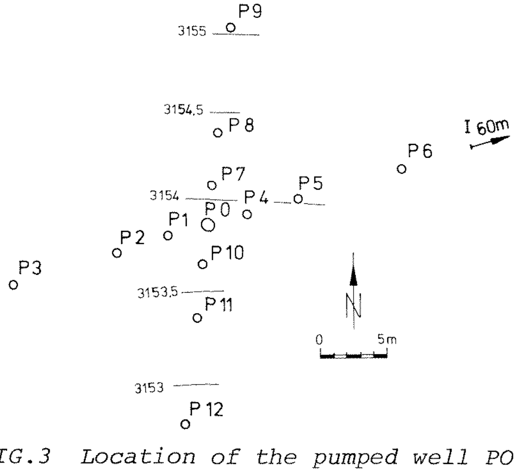

FIG.3 Location of the pumped well PO and the observation wells for the pumping tests on Vernagtferner in August 1979. The altitude data are related to the glacier surface. The site of borehole I is also indicated (see Fig.1).

pumping test the pumping rate and drawdown s of the water level in the pumped well during pumping as well as the residual drawdown s" after pumping, when the water level rises again, are shown in Fig.4. The thickness of the aquifer was 2.70 m.

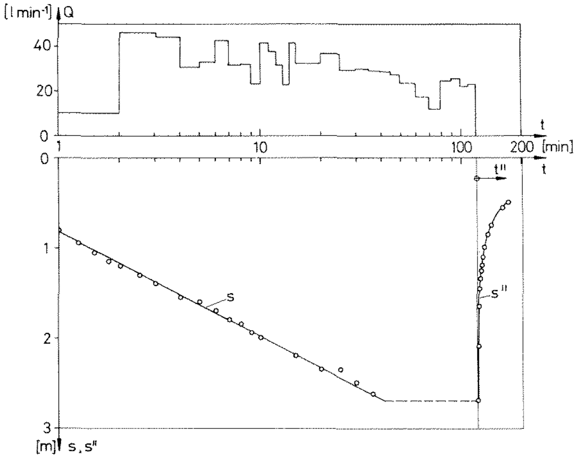

FIG.4 Pumping test Vernagtferner 1979. Pumping rate Q of the pumped well PO and drawdown s of the water level in the pumped well as well as the residual drawdown s" during the recovery period (time t") after pumping.

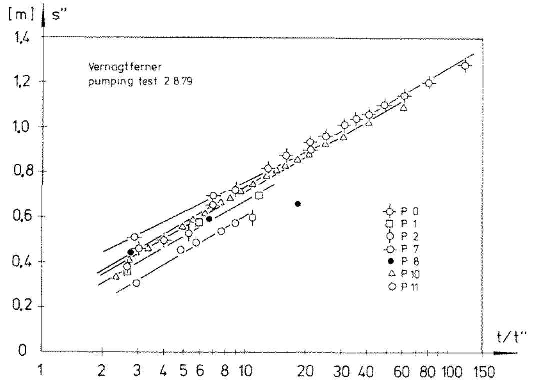

FIG.5 Theis's recovery method: relationship between residual drawdown s" and time (quotient of total time t, i.e. the time since pumping started, and time t", i.e. the time after pumping). The slopes of the regression lines are used for calculating the transmissivity.

For interpretation of the pumping-test data it is necessary to assume the following conditions: Darcy's law is valid, the aquifer is unconfined, the horizontal extension of the aquifer is unlimited, the aquifer is homogeneous, the thickness of the water-bearing layer is constant and almost horizontal and the pumpage is constant. We consider the unsteady flow in the surroundings of the pumped well.

The methods used for the interpretation are described by Kruseman & De Ridder (1970), the most important equations are compiled in an appendix at the end of this paper. As an example, Theis's recovery method can be used with the aid of Fig.5, which plots a water-level/time relationship for the data. One can see that all values of the residual drawdown, except that from borehole P8, lie on straight lines with approximately the same slope. That implies that Equation (8) in the appendix can be used to calculate the transmissivity. Water measurements were not sufficient for calculations for all the boreholes. Therefore only the observation wells P1, P7, P10, P2, P8, P11 and the pumped well P0 were used. Table 3 gives the different k_f values evaluated by the different methods of analysing the two pumping tests. One can see that neither the results from the first nor those from the second pumping test vary considerably from the averaged mean of 5 x 10^{-5} m s^{-1}. This value is in good agreement with the literature (Table 2) when one considers that the field conditions are only an approximation to the theoretical situation on which the methods are based.

TABLE 3 The hydraulic conductivity k_f of firn calculated from pumping-test data on Vernagtferner in 1979

Date	*Borehole*	*P0*	*P1*	*P7*	*P10*	*P2*	*P8*	*P11*	*Mean*
1979		*Hydraulic conductivity k_f (m/s) x 10^{-5}*							
1.8.79	*Jacob*		*6.1*	*5.2*	*4.3*	*7.1*	*6.4*	*6.5*	*6.0 ± 1.0*
2.8.79	*Jacob*		*5.5*	*3.5*	*3.8*	*6.6*	*6.4*	*5.3*	*5.2 ± 1.3*
1.8.79	*Theis*		*5.0*	*4.2*	*4.7*	*3.4*	*5.0*	*3.8*	*4.3 ± 0.7*
2.8.79	*Theis*		*4.2*	*2.9*	*3.2*	*6.5*	*5.1*	*4.4*	*4.4 ± 1.3*
1.8.79	*recovery*	*4.5*	*6.1*	*5.4*	*4.6*	*5.7*			*5.2 ± 0.8*
2.8.79	*recovery*	*5.3*	*5.4*	*6.3*	*5.4*	*5.2*			*5.5 ± 0.4*
2.8.79	*Hantush*			*2.8*	*4.1*				*3.4 ± 0.9*
									5.0 ± 1.1

CONCLUSIONS

Hydraulic conductivity gives us an important parameter for the meltwater flow in firn. The observations on Vernagtferner yield an hydraulic gradient of J = 0.1 for the test site. Thus the Darcian or filtration velocity v_f evaluated by Darcy's law, $v_f = k_f J$, is of the order of 5 x 10^{-6} m s^{-1}. The flow velocity v defined as the ratio of distance s and the corresponding travel time t can be calculated from the effective porosity p_e and the filtration velocity v_f:

$$v = \frac{s}{t} = \frac{v_f}{p_e} \qquad (2)$$

The density of the firn at the depth at which the water-bearing layer occurs is about 780 kg m^{-3}. The corresponding porosity is therefore p = 0.15. We know from groundwater hydrology that the effective porosity p_e is considerably smaller than the total porosity p, especially for a porous medium with a hydraulic conductivity of the order of 10^{-5} m s^{-1}. As no measurements for the effective porosity of water-saturated firn are available, we simply make the estimate p_e = 0.5 p. Using this we get a flow velocity v of 6 m day^{-1}.

It would be of interest to know something about the areal dimensions of the firn aquifer. To do this we can combine the flow velocity v of 6 m day^{-1} with the residence time t of the meltwater of about 13 days calculated above and obtain a mean length of meltwater paths within the firn aquifer of about 80 m. This is to be understood as an average travelling distance s of water, before reaching a crevasse and thus draining into an intraglacial drainage system. We emphasize that this is only a rough estimate. However, results of tracer tests which were carried out on Vernagtferner as well as experiences from investigations on Grosser Aletschgletscher (Switzerland)(Lang *et al.*, 1979) are in close agreement with this result.

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APPENDIX

General

All methods of analysing are based on Theis's theorem for a confined aquifer

$$s(r,t) = \frac{Q}{4\pi k_f H} \int_u^\infty \frac{\exp(-y)}{y}\, dy = \frac{Q}{4\pi k_f H} W(u) \qquad (3)$$

with

$$u = \frac{r^2 S}{4k_f Ht} \qquad \text{and} \qquad S = \frac{4k_f Htu}{r^2}$$

s(m) : drawdown in an observation well at the distance r(m) from the pumped well

$Q(m^3/s)$: constant pumpage
$S(-)$: specific yield
$k_fH(m^2/s)$: transmissivity
$H(m)$: thickness of the aquifer
t : time since pumping started

The integral of the exponential function is written in the form of the function W(u) and is called "well function". The numerical values of this function are given e.g. by Kruseman & De Ridder (1970).

For an unconfined aquifer one must substitute the reduced drawdown s' for s:

$$s' = s - \frac{s^2}{2H} \tag{4}$$

Jacob's method

For small values of u, i.e. u < 0.02 equation (3) can be transformed

$$s' = \frac{2.30Q}{4\pi k_f H} \log \frac{2.25 k_f H t}{r^2 S} \tag{5}$$

In a semi-logarithmic scale the plot of s' versus t is a straight line and the transmissivity k_fH can be evaluated with the aid of the slope $\Delta s'$ of this line

$$k_f H = \frac{2.30Q}{4\pi \Delta s'} \tag{6}$$

Theis's method

Theis's method is a graphical interpretation method in which the plot of s' versus (tr^{-2}) is compared with the plot of u^{-1} versus W(u) (see explanation to equation (3)). For a certain point A the transmissivity is evaluated

$$k_f H = \frac{Q}{4\pi s'_A} \cdot W(u)_A \tag{7}$$

Theis's recovery method

The hydrograph of the residual drawdown s" after pumping is described by

$$s'' = \frac{2.30Q}{4\pi k_f H} \log \frac{t}{t''} \tag{8}$$

with t" : time after pumping
t : time since pumping started

A semi-logarithmic plot of s" versus t/t" is a straight line (see Fig.5) and the transmissivity can be evaluated with the aid of the slope $\Delta s''$ of this line

$$k_f H = \frac{2.30Q}{4\pi\Delta s''} \qquad (9)$$

In this way the recharge Q equals the former pumpage.

Hantush's method

Hantush's method considers the real inclination of the water table and is based on the following equation for the drawdown

$$s' \left[= \frac{Q}{4\pi k_f H} \exp(-\frac{r}{\beta}) \cos\theta \right] W(u, \frac{r}{\beta}) \qquad (10)$$

where

θ : angle between flow direction and the connection line between pumped well and observation well

β : $\frac{2H}{J}$

J : hydraulic gradient of the aquifer

This method of analysis is also a purely graphical method.