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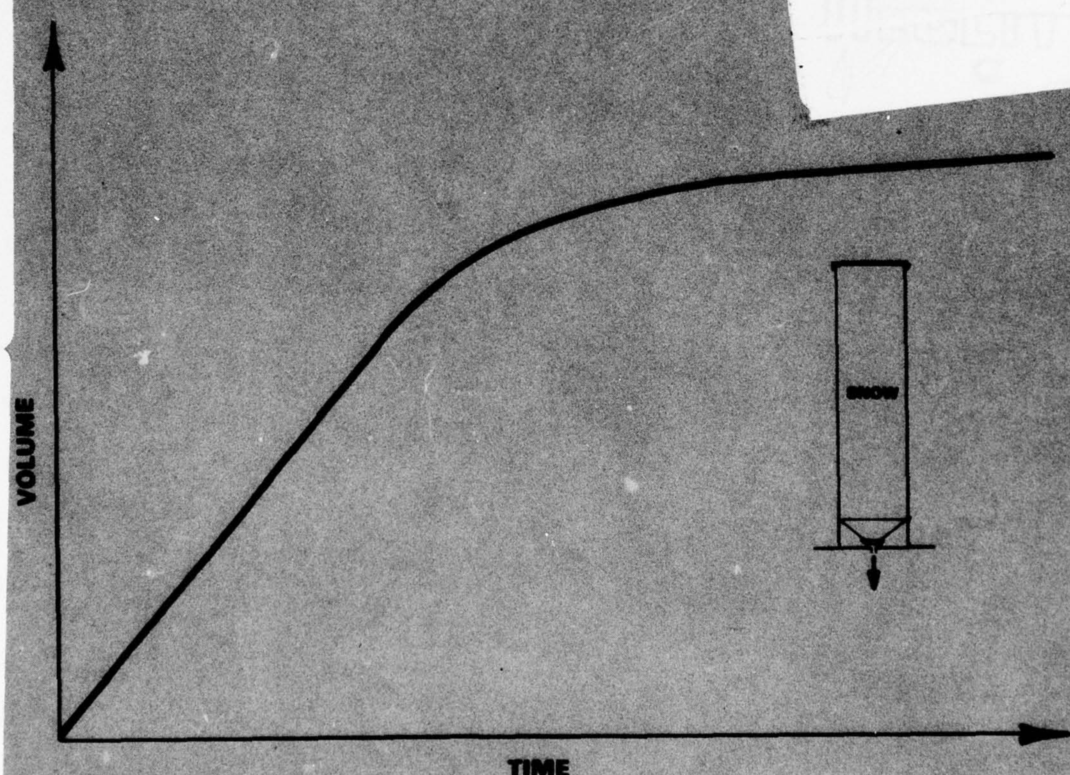
Study of water drainage from columns of snow



Cover: The test setup for drainage of snow columns and the character of the discharge versus time.

CRREL Report 79-1

Study of water drainage from columns of snow

A. Denoth, W. Seidenbusch, M. Blumthaler, P. Kirchlechner,
W. Ambach and S.C. Colbeck

January 1979

UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

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Experiments were conducted to study the flow of water through columns of homogeneous, repacked snow. The gravity flow theory of water flow through snow was verified, although possibly there is some dependence of the relative permeability on the state of metamorphism of the snow. Also, at very large values of saturation there may be some additional flow in saturated channels.

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PREFACE

This report was prepared by Dr. A. Denoth, Dr. W. Seidenbusch, Mr. M. Blumthaler, Mr. P. Kirchlechner and Univ. Prof. Dr. W. Ambach, of the Institute of Experimental Physics, University of Innsbruck, Innsbruck, Austria; and by Dr. S.C. Colbeck, Geophysicist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The participation of Dr. Denoth, Dr. Seidenbusch, Mr. Blumthaler, Mr. Kirchlechner, and Dr. Ambach was supported by a grant of U.S. ARO (Europe), under Project DAERO-76-G-038. The participation of Dr. Colbeck was funded by DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground*; Task A1, *Properties of Cold Regions Materials*; Work Unit 001, *Properties of Snow and Ice.*

Dr. G.D. Ashton and Dr. W.F. St. Lawrence of CRREL reviewed the technical content of this report.

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ILLUSTRATIONS

TABLES

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SYMBOLS

a	Abbreviation for $A\alpha k S_0^{*n}$, m^3/s (rise in the linear part of the *V-t* diagram)
A	Cross sectional area of the drainage pipes, m^2
d	Grain size, mm
g	Acceleration due to gravity, m/sec^2
h	Height of the saturation layer, m
k	Intrinsic permeability of snow, m^2
L	Length of the drainage pipe, m
n	Exponent
$\bar{n}$	Value of the exponent derived by interpolation
p	Fluid pressure, N/m^2
S	Liquid saturation (water volume/pore volume)
S_i	Irreducible saturation
S^*	Effective saturation, $S^* = (S-S_i)/(1-S_i)$
t	Time, sec
u	Volume flux (water volume/area·time), m/sec
u_0	Maximum flux, m/sec
V	Volume of the escaping water, m^3
V_∞	Maximum water volume which can escape, m^3
V_s	Water volume in the saturation layer, m^3
V_c	Captured water volume, m^3
W	Liquid water content (water volume/total volume)
W_i	Irreducible water content
z	Vertical coordinate, measured positively downward from the snow surface, m
α	Constant, $5.47 \cdot 10^6$ m^{-1} sec^{-1}
ϕ	Porosity (pore volume/total volume)
ϕ_e	$\phi(1-S_i)$
ρ	Density of wet snow, kg/m^3
ρ_d	Dry density of snow, kg/m^3
ρ_w	Density of water, kg/m^3
ρ_i	Density of ice, kg/m^3
μ	Fluid viscosity, kg/m-sec

Subscripts

a	Air
c	Capillary
d	Dry
E	End of experiment
s	Saturated
v	Delay
w	Water
0	Initial values

STUDY OF WATER DRAINAGE FROM COLUMNS OF SNOW

A. Denoth, W. Seidenbusch, M. Blumthaler
P. Kirchlechner, W. Ambach and S.C. Colbeck

INTRODUCTION

Previous studies of the flow of water through snow (e.g., Colbeck 1971) have shown that gravity forces dominate the flow, at least in well metamorphosed, ripe snowpacks. Colbeck and Davidson (1973) found that water flow through repacked, homogeneous snow could be characterized by a power-law dependence of relative permeability on liquid water saturation; in particular, the relative permeability of the snow to the liquid increased as the liquid saturation rose to the 3.3 power. For simplicity, Colbeck and Davidson (1973) suggested that a third power relationship be used for routing meltwater through snow.

The experiments reported here were carried out with snow having various grain sizes, densities and porosities in order to check on the use of this gravity flow theory under different conditions. In addition, an attempt was made to determine the upper and lower limits of water flow rates for which this theory might be applicable. At very low flow rates, tension gradients may have an important effect, whereas at very high flow rates, unstable channelized flow may occur.

TEST PROCEDURE

The field studies were carried out in spring on the Seegrube and Hafelekar areas (1900 m above sea level or 2200 m above sea level), near Innsbruck, Austria, and in the summer months in the glacier region of the Stubaier Alps (Schaufelferner/Daunferner, 3000 m above sea level), during the period April 1976 to September 1977. The percolation of meltwater was studied by using cylindrical tubes filled with sieved snow. Initially the free water content W_0 and density ρ_0 of the snow were measured and the grain size d_0 was estimated with a lens reticule. After being filled with the sieved snow, the tubes were set upright in deep snow to guarantee isothermal conditions during the experiment.

The tops of the tubes were closed off with waterproof covers so that it would be possible to study the process of drainage of the free water already present. The tubes were covered with a snow layer 0.5 to 0.75 m thick to prevent radiation-induced melting in the snow columns.

Each snow column was supported by a wire net at the bottom and a funnel was firmly attached to the bottom. After several days of drainage, the tubes were weighed to determine the mean density of the show and then opened to allow measurement of the water content, grain size and density of the snow at various heights of the tube, thus permitting the determination of a complete water balance. A sketch of the test arrangement is given in Figure 1.

The water content was measured with a device developed and proven in the Institute of Experimental Physics of the University of Innsbruck. This device was used first with the aid of a plate condenser to measure the dielectric constant of the snow; the free water content was then determined from a calibration curve while taking into account the snow density derived by weighing (Ambach and Denoth 1975).

To record the outflowing water volume precisely and continuously for long periods, the outflowing water was captured in a measuring cylinder; there the water level was measured with a pressure probe or a capacitative pickup. The measured signal was used to record the water volume (pen record) and to activate the controls of a magnetic valve. In this way, starting from a preselected height to which the snow was filled, it was possible to achieve an automatic emptying of the measuring cylinder down to a preselected lower

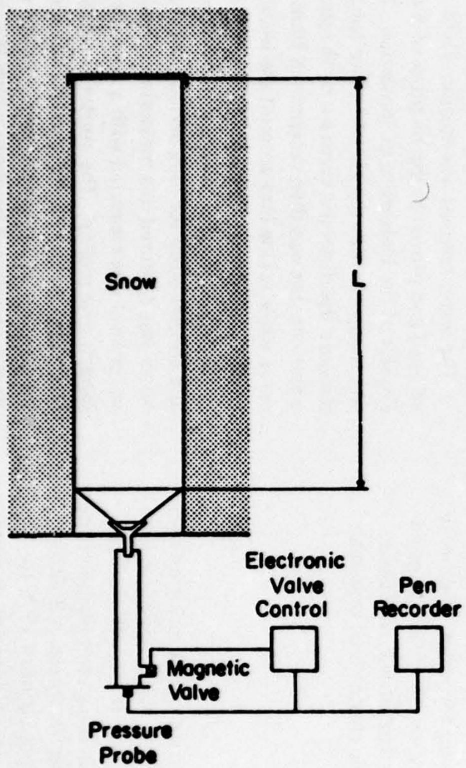

Figure 1. Test setup.

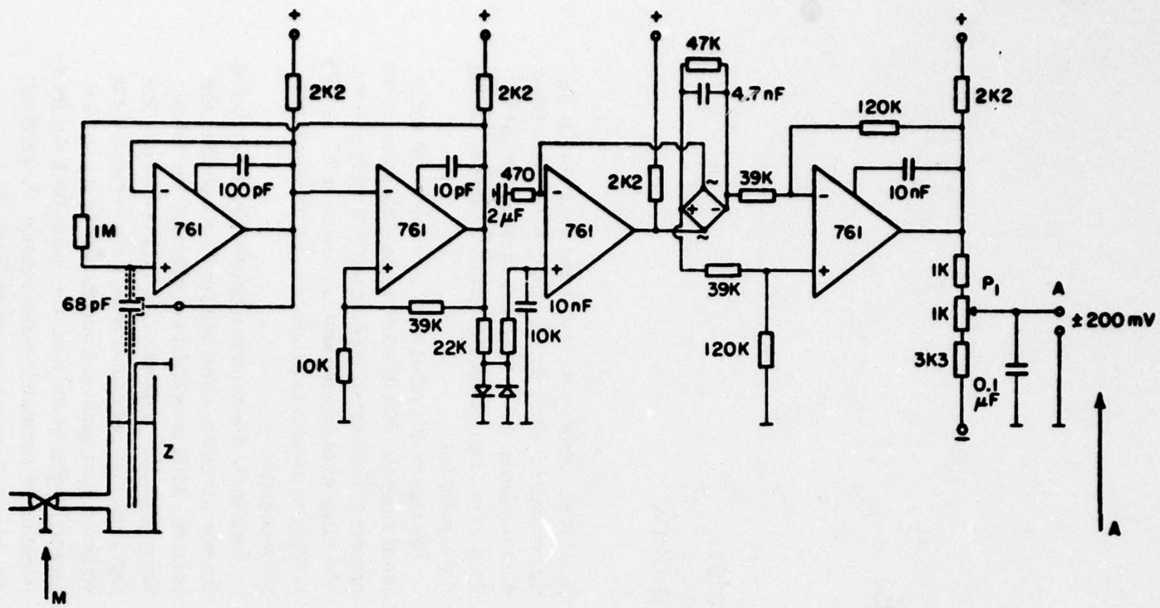

Figure 2a. Circuit diagram of the capacitative level pickup: A—output of the level pickup (pen recorder connection; connection with the threshold switch); M—magnetic valve; P_1—upper switch level; Z—measuring cylinder.

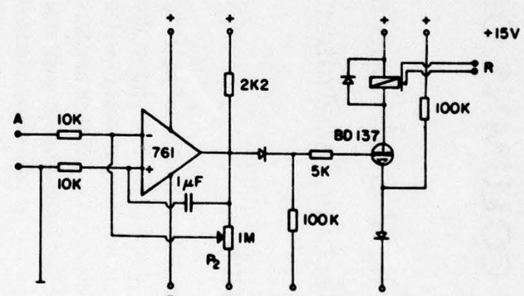

Figure 2b. Circuit diagram of the threshold switch for controlling the magnetic valve; P_2 is the lower switch level and R is the relay for controlling the magnetic valve.

level. Figure 2 shows the circuit diagram of the control electronics with the threshold circuitry for a capacitative pickup. A heater was provided to ensure constant temperature conditions for the electronics.

Because the device used for liquid content measurements had been calibrated in the laboratory calormetrically, the free water content values given for the individual experiments were subject to an absolute error of ± 0.5% by volume. The snow density ρ was determined by weighing with a relative error of ± 1%.

THEORY

From Darcy's law, the vertical flow of air and water through a porous medium can be described by (Scheidegger 1957)

$$u_a = -\frac{k_a}{\mu_a}\left(\frac{\partial P_a}{\partial z} - \rho_a g\right) \tag{1}$$

and

$$u_w = -\frac{k_w}{\mu_w}\left(\frac{\partial P_w}{\partial z} - \rho_w g\right) \tag{2}$$

where the subscripts "a" and "w" stand for air and water, respectively. In these equations, k_a and k_w are the permeabilities relative to the fluids, μ_a and μ_w are the fluid viscosities, P_a and P_w are the fluid pressures, z is the vertical coordinate measured downward from the snow surface, and g is the acceleration due to gravity. For the vertical percolation of meltwater through snow, these equations can be approximated by (Colbeck 1971)

$$u = \frac{k_w}{\mu_w}\left(\frac{\partial P_c}{\partial z} + \rho_w g\right) \tag{3}$$

where P_c, the capillary pressure, is normally a function of liquid saturation and porosity.

Colbeck (1971) wrote

$$u = \frac{k_w}{\mu_w}\left(\frac{\partial P_c}{\partial S}\frac{\partial S}{\partial z} + \frac{\partial P_c}{\partial \phi}\frac{\partial \phi}{\partial z} + \rho_w g\right) \tag{4}$$

where u is now taken as positive in the downward direction and S is the liquid saturation. The first two terms are generally small compared with the gravity term for large grained materials like snow. Hence, for snow

$$u = \alpha k_w \tag{5}$$

where

$$\alpha = \frac{\rho_w g}{\mu_w}. \tag{6}$$

The permeability relative to the water phase k_w depends upon the intrinsic permeability of the snow k and the liquid saturation S. k_w approaches zero as liquid saturation approaches its irreducible value S_i and k_w approaches k as the pore spaces approach complete liquid saturation.

Averjanov (1950) showed that for porous media k_w can be approximately represented as

$$k_w = kS^{*n} \tag{7}$$

where

$$S^* = (S - S_i)/(1 - S_i) \tag{8}$$

and S* is the effective saturation. It follows that

$$u = \alpha k S^{*n}. \tag{9}$$

The continuity equation is

$$\frac{\partial u}{\partial z} + \phi_e \frac{\partial S^*}{\partial t} = 0 \tag{10}$$

where

$$\phi_e = \phi(1 - S_i) \tag{11}$$

and ϕ is the snow porosity. Combining eqs 9 and 10

$$n(\alpha k)^{1/n}\frac{\partial u}{\partial z} + \phi_e u^{(n-1)/n}\frac{\partial u}{\partial t} = 0 \tag{12}$$

which describes water flow through snow for the case where the snow properties do not change significantly over the time and space scales.

The solution to this equation can be given in the form of characteristic slopes where the speed (dz/dt) at specific values of u is (Colbeck and Davidson 1973)

$$\left.\frac{dz}{dt}\right|_u = n\frac{(\alpha k)^{1/n}}{\phi_e}u^{(n-1)/n} \tag{13}$$

where d is the snow grain size. For decreasing flux as in these experiments, it follows that the flux at any given depth is given by

$$u = \left(\frac{\phi_e z}{n(\alpha k)^{1/n}}\right)^{(n/n-1)} t^{n/(1-n)} \tag{14}$$

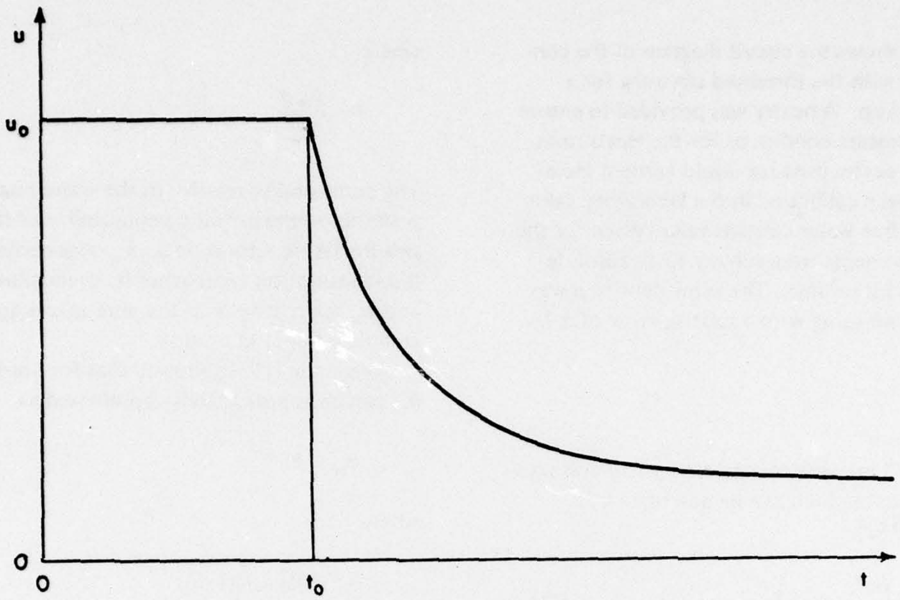

Figure 3. The theoretical profile of discharge rate versus time.

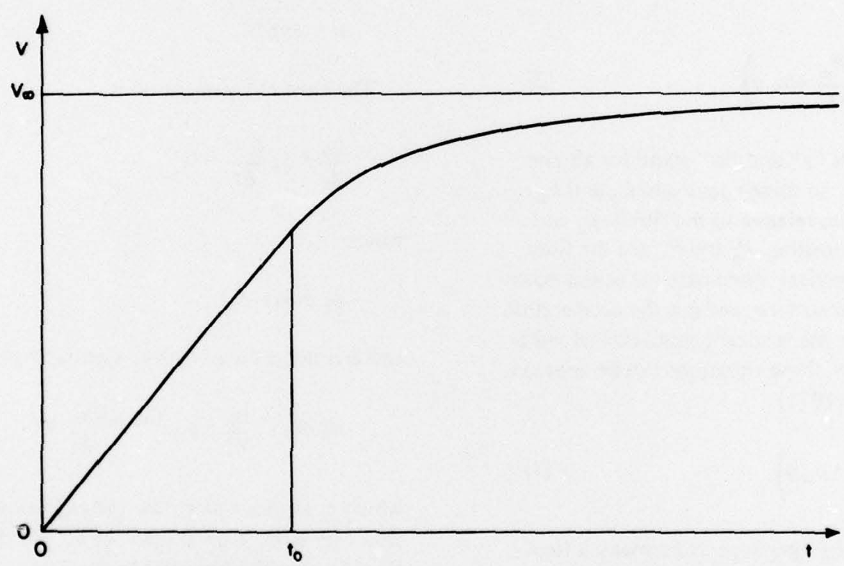

Figure 4. The theoretical discharge profile of total discharge versus time.

where t is the elapsed time since that value of flux u left the surface of the snow.

At the start of each experiment, the saturation throughout the snow is approximately uniform S_0. The initial flux of water is u_0; thus the initial discharge from the tube of snow should be equal to u_0 for a period given by

$$t_0 = \frac{L\phi_e}{n(\alpha k)S_0^{*n-1}} \tag{15}$$

where S_0^* is related to u by

$$u_0 = \alpha k S_0^{*n} \tag{16}$$

and L is the length of drainage pipe (Fig. 1). The theoretical profile of $u(t)$ according to eq 14 is shown in Figure 3.

The volume discharge of water V from the tube is given by

$$V = \begin{cases} A u_0 t & t < t_0 \\ A\left(u_0 t_0 + \int_{t_0}^{t} u dt\right) & t > t_0 \end{cases} \tag{17}$$

where A is the cross-sectional area of the tube. It follows that the total discharge is

$$V = \begin{cases} A u_0 t & t \leq t_0 \\ A\left\{\alpha k S_0^{*n} t_0 + \left[\dfrac{L\phi_e}{(\alpha k)^{1/n} n}\right]^{n/(n-1)} (n-1) \right. & \\ \left. \left(t_0^{1/(1-n)} - t^{1/(1-n)}\right)\right\} & t > t_0. \end{cases} \tag{18}$$

This theoretical discharge is illustrated in Figure 4 where, in the limit,

$$V_\infty = A\,L\,\phi(S_0 - S_i). \tag{19}$$

EVALUATION OF THE EXPERIMENTAL RESULTS

One object of this data analysis is to determine the best value of the exponent n in eq 7, which relates the relative permeability to the liquid and the liquid saturation. The sensitivity of this exponent to such snow parameters as grain size, density and porosity is examined as is the general nature of the usefulness of the theory of flow through porous media for explaining the nature of water flow through snow.

The advantages and disadvantages of two possible methods of evaluation are considered. In the *first* method, which was used in the evaluation of the experimental data, eq 18 is rewritten

$$V = \begin{cases} a t & t \leq t_0 \\ A\,L(W_0 - W_i) - (n-1)\left[\dfrac{AL(W_0 - W_i)}{n}\right]^{n/(n-1)} \times & \\ a^{1/(1-n)} t^{1/(1-n)} & t > t_0 \end{cases} \tag{20}$$

with

$$t_0 = \frac{AL(W_0 - W_i)}{na}$$

and

$$a = A\alpha k S_0^{*n}. \tag{21}$$

The measured volume of discharge with time is compared directly with the theoretical profiles calculated from eq 20, where A, L, W_0 and W_i are measured quantities and a represents the slope of the measured discharge curve at the beginning of the flow ($t < t_0$). The best value for the exponent n, the only unknown in eq 20, is determined by interpolation between calculated profiles for two selected values of n, bracketing all of the measured points. The advantages of this method are *first* that the measured volume of discharge is used directly in the comparison and *second* that the permeability k can be determined from eq 21 with high accuracy.

In the *second* method, used by Colbeck and Davidson (1973), eq 14 is rewritten,

$$\ln u = \frac{n}{n-1} \frac{\phi_e L}{n(\alpha k)^{1/n}} + \frac{n}{1-n} \ln t. \tag{22}$$

The use of eq 22 to evaluate the experimental data plotted on a log-log scale has the advantage that the important snow parameters affect only the intersect of the plot whereas the exponent n can be determined solely from the slope of the plot. But the disadvantage of using eq 22 is that the flux of water u must be determined from the slope of the discharge curve, a procedure which may lead to large errors. However, it is necessary to measure W_0 and W_i to calculate n with the first method whereas these data are not used in the evaluation according to the second method. In the current set of experiments, the first method is preferred in order to avoid the calculation of the rate of discharge.

EXAMPLE EVALUATION

Of the 10 experiments in this study, experiment no. 8 is used as an example in this data analysis because it is typical of the other sets of experiments. In all of the experiments, the outflow was initially delayed because of the formation of a saturated layer at the base of the snow column. The volume of the saturated layer is given by

$$V_s = a t_v \tag{23}$$

where a is the slope of the discharge curve initially and t_v is the delay time before the onset of discharge. Because of the limited capillary effect in snow, it is assumed that the formation of the saturated layer did not affect the flow in the remainder of the column; hence, the initial flux u_0 prevailed throughout the column at first. The water volume V_s of the saturated layer was added to the measured discharge.

The measured profile of water discharge versus time for experiment no. 8 is shown in Figure 5. Profiles calculated from eq 20 for $n = 2$ and $n = 3$ are shown to bracket all of the measured points. By interpolation, the best value of n is found to be 2.38.

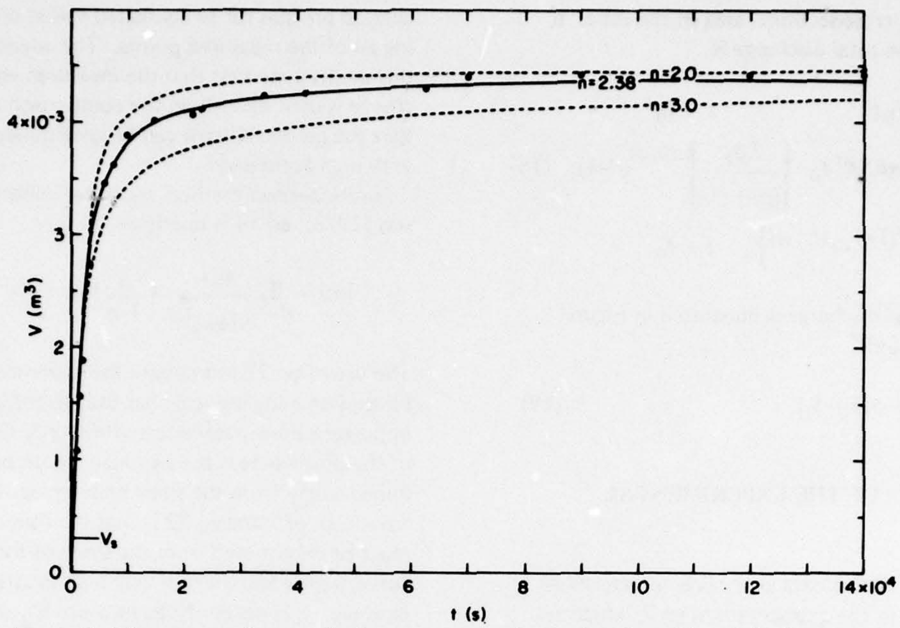

Figure 5. The measured water discharge points and calculated profiles of discharge versus time for various values of n for Experiment no. 8.

RESULTS AND DISCUSSION

All of the experimental results are given graphically in Appendix A in the form of measured volume of discharge versus time. For each experiment, calculated profiles of discharge versus time are shown for different values of the exponent n. A compilation of all of the determined quantities of $\bar{n}$ and k by use of the first method is given in Table I. The values of $\bar{n}$ were found to range from a low of 2.16 to a high of 4.59.

There appears to be a dependence of $\bar{n}$ on the grain sizes or the sizes of clusters of grains and hence upon the age and history of wetness of the snow. For example, experiments no. 1 and 7, where large clusters of crystals were observed, are described by $\bar{n}$ values of 4.59 and 4.31, respectively, whereas for the relatively young snow of experiment no. 10, the grain size was about 0.5 mm and $\bar{n}$ was 2.16. However, no clear relationship exists between any snow parameter and $\bar{n}$.

For experiments no. 10 and 11, the initial flow of water was larger than expected theoretically. In these experiments the comparatively large value of initial saturation (~15%) could have caused the formation of unstable fingers of saturated flow in addition to the unsaturated flow described by the unsaturated flow theory given here. This value of initial saturation corresponds closely to the change from the pendular to the funicular mode of saturation where some of the assumptions used in the derivation of eq 9 might be invalid. It is very important to note that the large values of water flux associated with these large values of saturation are greater than anything normally encountered in nature. The question of unstable flow arising from high saturations may be important in experiments where large flow rates are often encountered although it may not be an important question in naturally-occurring snowpacks.

As shown by the experimental data and computed curves of volume versus time (App. A), the gravity flow theory offers a reasonable explanation of the percolation of water through snow for the wide range of flow rates and snow conditions studied. Also, the values of snow permeability k calculated from eq 21 are compared with the values calculated from Shimizu's (1970) formula,

$$k = 0.077d^2 \exp[-7.8\,(1-\phi)\rho_i/\rho_w] \qquad (24)$$

where the mean grain size and the porosity are shown in Table I. These two methods result in generally good agreement, suggesting that Shimizu's formula can be extended to a grain size of about 3 mm.

Further investigations of these phenomena should concentrate on developing an understanding of the unstable flow of saturated fingers and the mode of water flow through fresh snow. In both cases, the

Table 1. List of measured and computed values.

Experiment	w_0 (%)	ρ_0 (kg/m^3)	ϕ_0 (%)	S_0 (%)	d (mm)	A (m^2)	L (m)	h_s (m)	V_s (m^3)	V_c (m^3)
1	5.9	500	51.9	11.4	–	0.0625	1.17	7.7×10^{-3}	2.5×10^{-4}	1.9×10^{-3}
2	2.8	500	48.5	5.77	1-2	0.0625	1.12	2×10^{-2}	5.5×10^{-5}	5.976×10^{-4}
3	8.7	520	52.8	16.5	1.5	0.073	1.4	1.21×10^{-2}	4.67×10^{-4}	4.582×10^{-3}
4	7.0	460	57.5	12.2	0.5	0.073	1.3	1.67×10^{-2}	7×10^{-4}	2.58×10^{-3}
5	7.0	460	57.5	12.2	0.5	0.073	1.4	1.05×10^{-2}	4.4×10^{-4}	3.05×10^{-3}
6	8.7	560	48.4	17.97	1-1.5	0.073	1.4	3.06×10^{-2}	1.08×10^{-3}	3.78×10^{-3}
7	8.0	550	48.7	16.4	1-3	0.073	1.4	2.05×10^{-2}	7.3×10^{-4}	3.36×10^{-3}
8	7.8	550	48.5	16.1	1	0.0625	1.4	1×10^{-2}	3×10^{-4}	4.12×10^{-3}
9	4.7	540	46.2	10.2	1	0.0625	1.34	1.04×10^{-2}	3×10^{-4}	1.57×10^{-3}
10	7.7	524	51.3	15.02	0.5	0.0625	1.4	2.5×10^{-2}	8×10^{-4}	2.3×10^{-3}
11	7.3	528	50.4	14.5	1	0.073	1.4	6×10^{-3}	2.2×10^{-4}	3.091×10^{-3}

Experiment	Duration (s)	V_s+V_c (m^3)	ρ_E (kg/m^3)	ϕ_E (%)	S_E (%)	S_i (%)	a (m^3/s)	$\bar{n}$	k (m^2)	V_∞ (m^3)
1	84,000	2.15×10^{-3}	470	51.9	5.7	3.0	1.1×10^{-7}	4.59	2.47×10^{-8}	3.2×10^{-3}
2	99,300	6.526×10^{-4}	490	48.5	3.8	3.0	1.6×10^{-8}	3.07	2.55×10^{-9}	9.41×10^{-4}
3	162,300	5.049×10^{-3}	470	52.8	7.1	5.0	2×10^{-7}	3.29	4.96×10^{-10}	6.19×10^{-3}
4	327,900	3.28×10^{-3}	430	57.5	6.2	5.0	5.5×10^{-8}	2.85	2.13×10^{-10}	3.92×10^{-3}
5	326,520	3.49×10^{-3}	430	57.5	6.2	5.0	4×10^{-8}	2.53	6.58×10^{-11}	4.22×10^{-3}
6	349,800	4.86×10^{-3}	510	48.4	8.1	6.0	2.25×10^{-7}	3.79	1.41×10^{-9}	5.92×10^{-3}
7	255,300	4.09×10^{-3}	510	48.7	8.2	6.0	3×10^{-7}	4.31	9.75×10^{-9}	5.19×10^{-3}
8	514,800	4.42×10^{-3}	499	48.5	5.7	5.5	1.23×10^{-6}	2.38	6.57×10^{-10}	4.49×10^{-3}
9	265,000	1.87×10^{-3}	520	46.2	5.3	5.0	3.05×10^{-7}	2.43	8.72×10^{-10}	2×10^{-3}
10	249,840	3.1×10^{-3}	490	51.3	8.1	8.0	6.2×10^{-7}	2.16	4.58×10^{-10}	3.15×10^{-3}
11	221,400	3.31×10^{-3}	500	50.4	8.06	5.0	4.18×10^{-7}	3.39	2.574×10^{-9}	4.89×10^{-3}

limits of the unsaturated flow theory used here should be examined by labeling the water with tracers and doing experiments under conditions where the snow properties can be observed to change throughout the duration of the experiments.

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APPENDIX A: MEASURED AND COMPUTED DISCHARGE

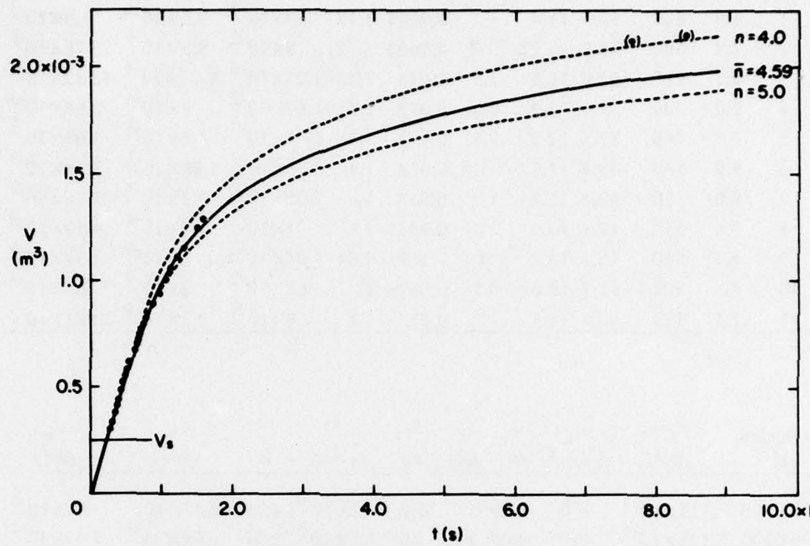

Figure A1. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 1.

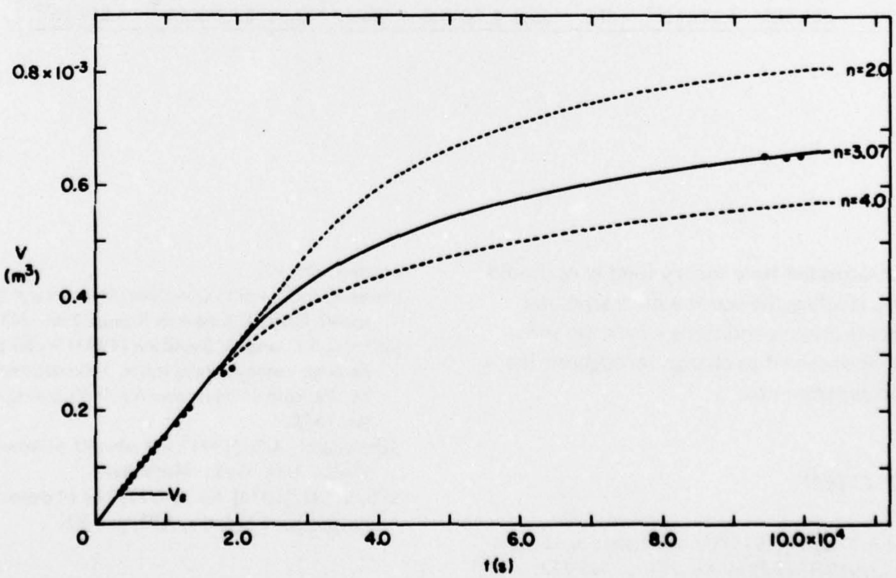

Figure A2. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 2.

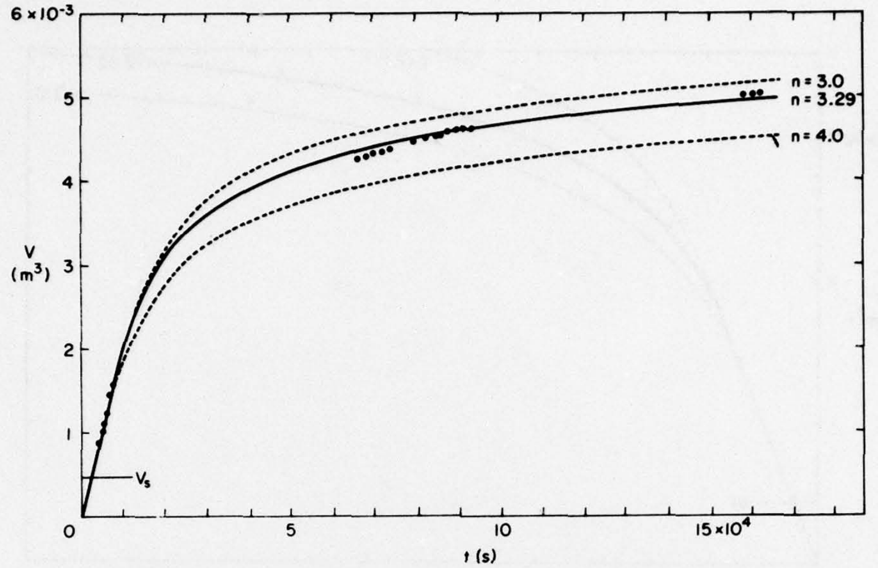

Figure A3. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 3.

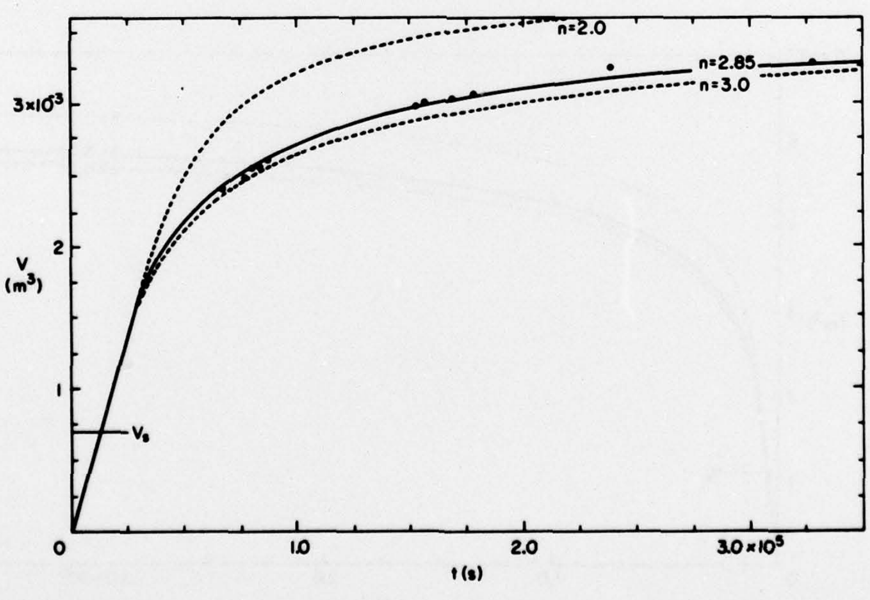

Figure A4. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 4.

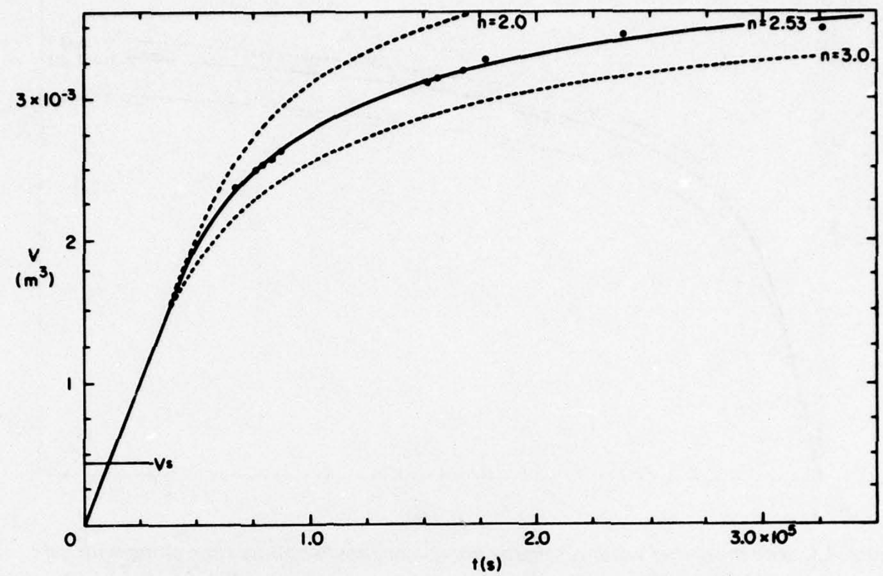

Figure A5. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 5.

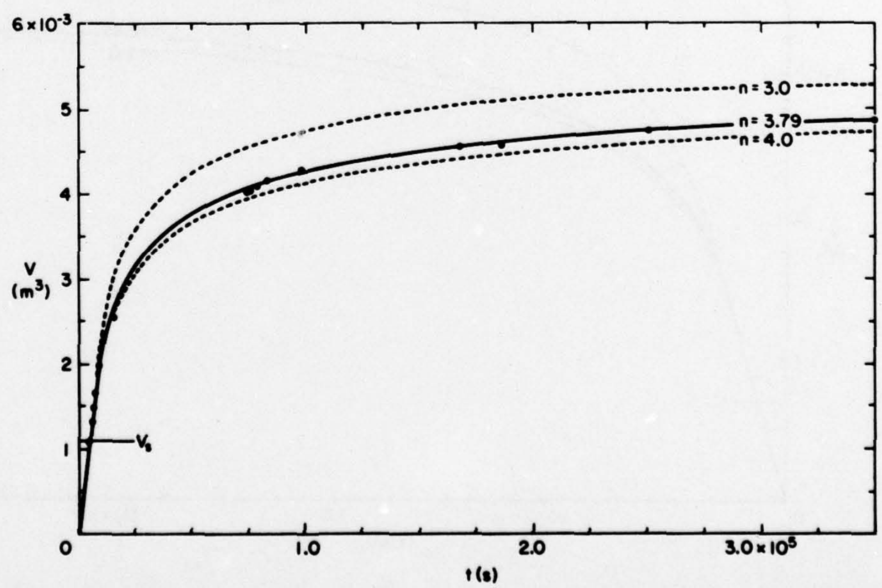

Figure A6. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 6.

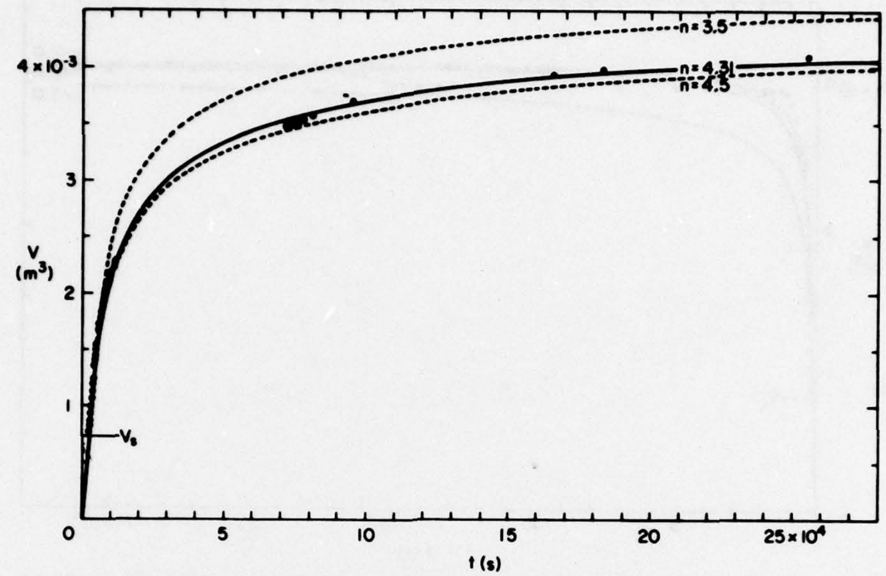

Figure A7. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 7.

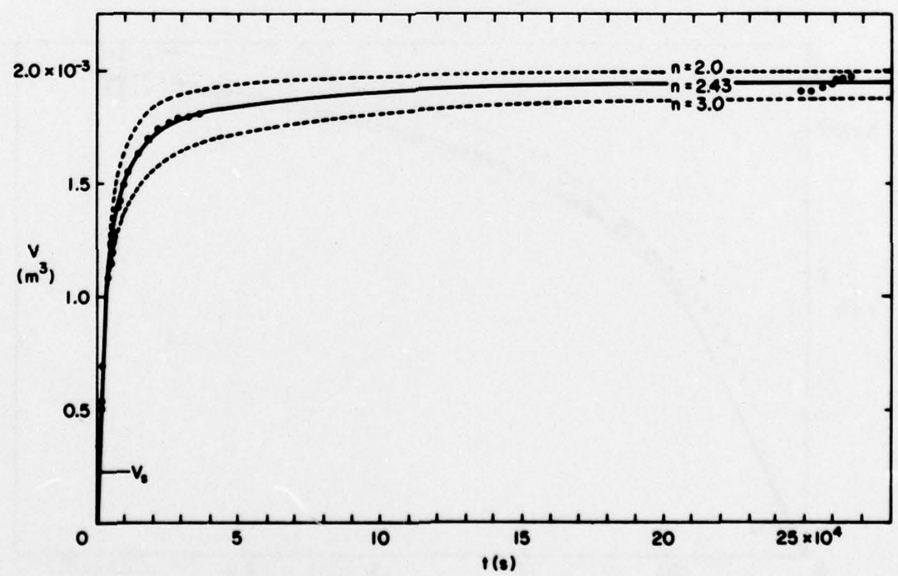

Figure A8. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 9.

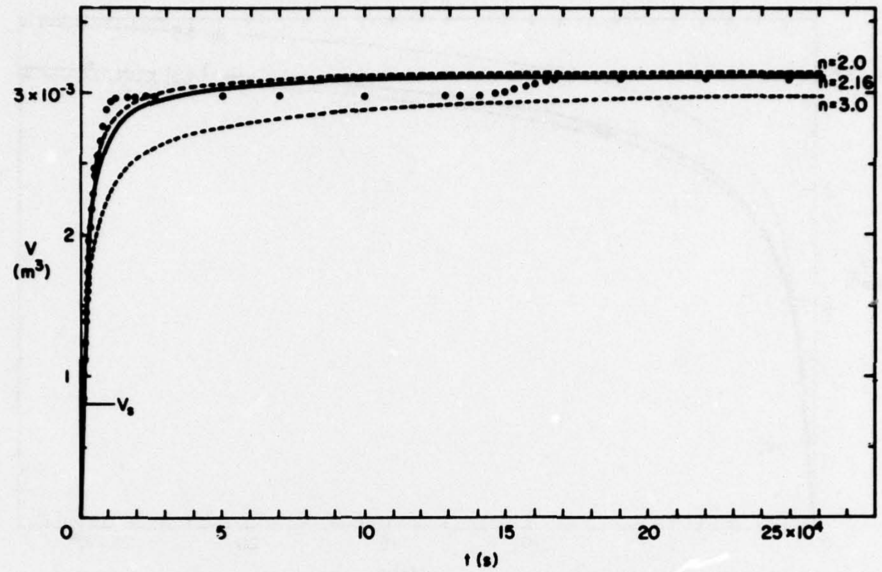

Figure A9. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 10.

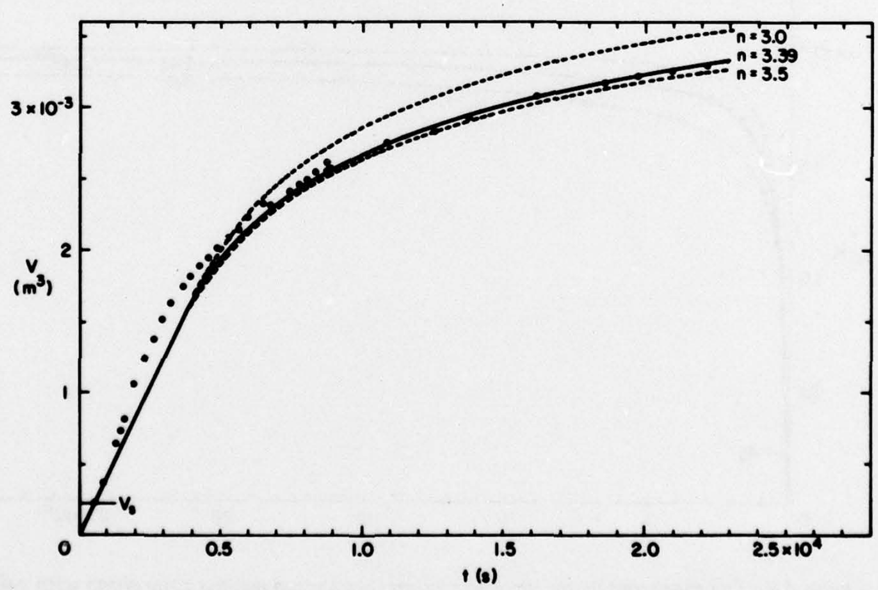

Figure A10. The measured water discharge points are shown against time along with calculated profiles of discharge versus time for various values of n for Experiment no. 11.

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Bibliography: p. 7.

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1. Drainage. 2. Gravity forces. 3. Snow. 4. Water. I. W. Seidenbusch. II. M. Blumthaler. III. P. Kirchlechner. IV. W. Ambach. V. S.C. Colbeck. VI. United States. Army. Corps of Engineers. VII. Series: Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. CRREL Report 79-1.

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