University of Alaska

INSTITUTE OF WATER RESOURCES

HYDROLOGIC PROPERTIES OF SUBARCTIC ORGANIC SOILS

by

Douglas L. Kane
Richard D. Seifert
George S. Taylor

IWR-88

Hydrologic properties of subarcic organic soils

HYDROLOGIC PROPERTIES OF SUBARCTIC ORGANIC SOILS

Richard D. Seifert, Douglas L. Kane, George S. Taylor

Completion Report

for

U. S. Forest Service
Institute of Northern Forestry

Cooperative Agreement No. 16 USC 581; 581a-581i

by

Douglas L. Kane
Richard D. Seifert

Institute of Water Resources
University of Alaska

and

George S. Taylor

Agronomy Department
Ohio State University

Institute of Water Resources
University of Alaska
Fairbanks, Alaska 99701

Report No. IWR-88

January, 1978

ACKNOWLEDGMENTS

The work upon which this report is based was made possible by a cooperative aid agreement funded by the U. S. Forest Service, Institute of Northern Forestry, Fairbanks, Alaska. Contribution to this study was also made by Ohio State University. The authors appreciate the help of Roberta Jones, Lalitha Rao, and Charlotte Hok in collecting and compiling the data.

The modeling work discussed in this paper was also presented in a paper entitled "Two Dimensional Flow Model with Application to Near-Surface Water Movement in Cold Regions" by Douglas L. Kane and George S. Taylor, in *Proceedings: Second Conference on Soil-Water Problems in Cold Regions*, American Geophysical Union, Edmonton, Alberta, September 1-2, 1976, pp. 123-136. Data from the prescribed burns is included in a manuscript entitled "Preliminary Results of Experimental Fires in the Black Spruce Type of Interior Alaska" by Viereck et al. (1978). It is expected that this report will be published by the U. S. Forest Service.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The need for understanding the natural system and how it responds to various stresses is important; this is especially so in an environment where the climate not only sustains permafrost, but develops massive seasonal frost as well. Consequently, the role of the shallow surface organic layer is also quite important. Since a slight change in the soil thermal regime may bring about a phase change in the water or ice, therefore, the system response to surface alterations such as burning can be quite severe. The need for a better understanding of the behavior and properties of the organic layer is, therefore, accentuated.

The central theme of this study was the examination of the hydrologic and hydraulic properties of subarctic organic soils. Summarized in this paper are the results of three aspects of subarctic organic soil examinations conducted during the duration of the project. First, a field site was set up in Washington Creek with the major emphasis on measuring numerous variables of that soil system during the summer. The greatest variations in moisture content occur in the thick organic soils that exist at this site. Our major emphasis was to study the soil moisture levels in these soils. This topic is covered in the first major section, including associated laboratory studies. Those laboratory studies include investigations of several hydraulic and hydrologic properties of taiga organic and mineral soils. Second, some field data on organic moisture levels was collected at the site of prescribed burns in Washington Creek to ascertain the sustainability of fires as a function of moisture levels. This portion of the study is described under the second major heading. The last element of this study was a continued application of the two-dimensional flow model that was developed in an earlier study funded by the U. S. Forest Service, Institute of Northern Forestry, and reported by Kane, Luthin, and Taylor (1975a).

Many of the results and concepts gathered in the field work were integrated into the modeling effort, which is aimed at producing better estimates of the hydrologic effects of surface disturbances in the black spruce taiga subarctic ecosystem. This knowledge should also contribute to better fire management decisions of the same system.

FIELD DATA COLLECTION AND INTERPRETATION

During the 1976 field season, the following data were gathered at the Washington Creek Fire Ecology study site: average depth to frost (by probing), soil temperature, soil moisture (by sampling), and soil moisture tension. Soil temperature, depth of frost, and soil moisture samples were taken weekly from July 7 through September 15. Soil tension was measured with continuous recording tensiometers as well as standard tensiometers. Data were gathered on transect 10 of the surveyed study site (see Figure 1).

During the course of this study data were collected at two sites. Most of the measurements were made at the intensive study site; however, several measurements were made at the prescribed burn site. Although both sites are located in a permafrost environment, considerable variation exists in depth of the active layer, thickness of organic material, and slope. The prescribed burn site is located on a south-facing slope near the ridge, while the intensive study site is located about one-half the distance between the ridge and the valley bottom. Some preliminary results from the prescribed burns are given by Viereck et al. (1977), while selected climatic data for intensive study site is reported by Hoch (1976).

Soil temperature was measured using a bank of eleven YSI thermistors mounted on a vertical dowel in the soil. The thermistors were mounted at 10-cm intervals placed at depths of 0 to 100 cm and were installed in early summer. Care was taken to install them with as little disturbance as possible to the area. Once the thermistors were in place, soil was replaced around them to ensure the minimum amount of infiltration around the hole made for the thermistors. This is a very important consideration, since rainwater and meltwater can rapidly destroy the natural thermal regime which was to be measured.

Soil samples were taken at weekly intervals to measure the soil moisture as a function of depth and time. The samples were nearly all organic in nature, due to the very shallow active layer at the transect 10 site (<60 cm). These organic samples were cut from the mat layer

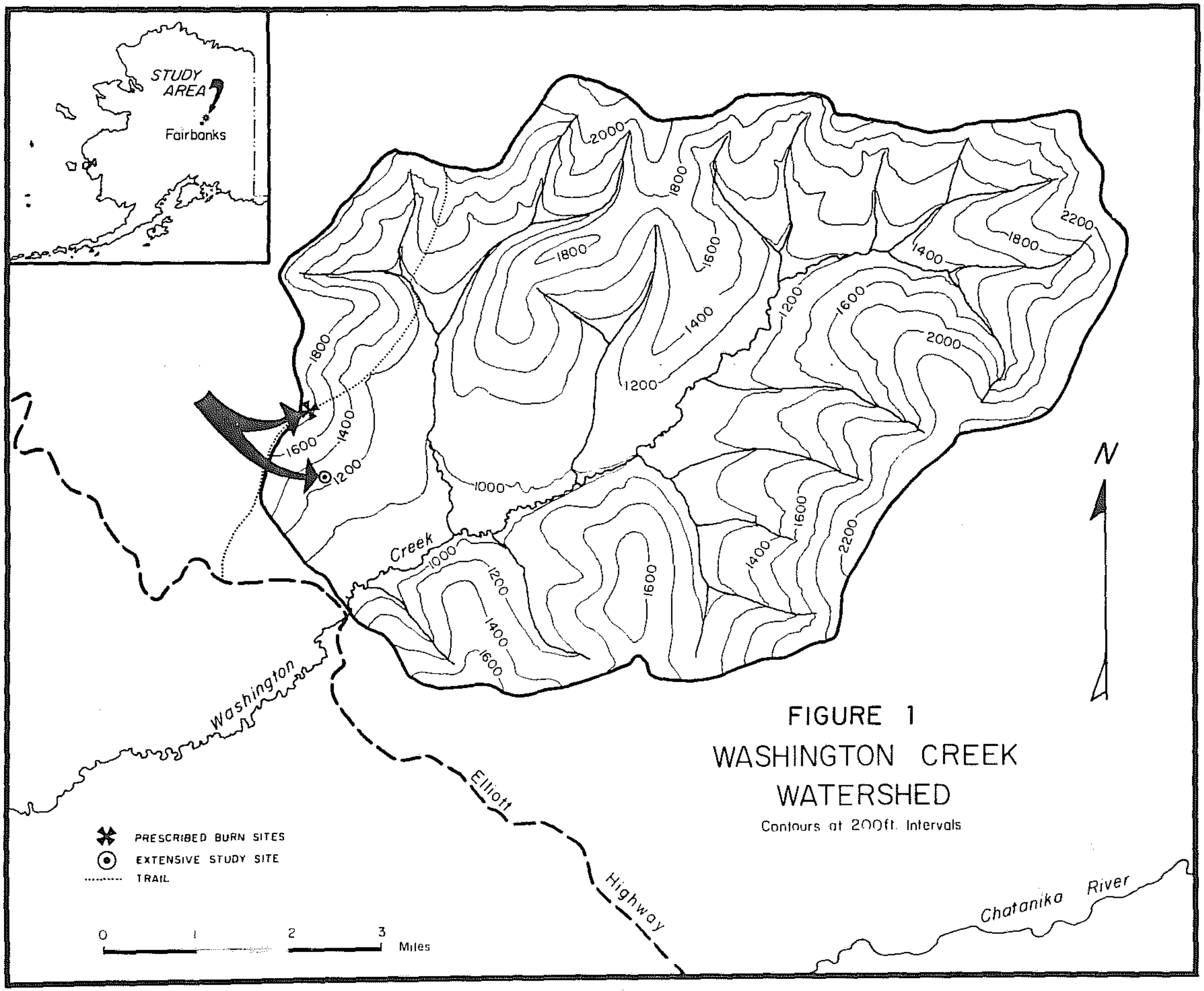


FIGURE 1
WASHINGTON CREEK
WATERSHED
Contours at 200ft. Intervals

using a large knife. A sample about 20 cm by 20 cm was cut and then sliced into sections 2 cm thick for the first 10 cm, then every 5 cm until frozen soil was encountered. Normally frozen soil was encountered from 35 to 60 cm from the surface of the mat layer depending upon time of year and thickness of the mat layer. Samples were placed in 8-inch by 10-inch sample bags, labelled, and brought back to the universtiy for drying and weighing. Since the samples were organic and large, drying was done in a microwave oven so that samples could be weighed immediately after a brief drying period (∿6-8 minutes).

Soil tensiometers used were of two types: continuous recording and standard gauge. The constant recording tensiometers were made according to the specifications of Walkotten (1972). Using the constant recording tensiometers, soil tension was recorded on a battery-powered rotating drum on which tension is indicated by the deflection of a needle attached to a float in a mercury manometer. The standard tensiometers are Soil-Moisture Equipment Company models which consist of a vacuum pressure gauge, plexiglass shaft, and a porous ceramic cup which serves as a medium to link soil water tensions to the pressure system. The four standard tensiometers were placed at depths of 10, 20, 30, and 40 cm, and the three constant recording tensiometers were placed at depths of 10, 20, and 30 cm.

A problem was encountered in maintaining a physical link between the water in the organic material and the porous ceramic cup of the tensiometer. This was partly overcome by affixing pieces of organic material to the cup with cotton twine, which provided better contact between the cup and the suspended water. Organic sphagnum and peat are extremely porous and it was difficult to maintain an adequate contact between the ceramic cup and the soil water.

Special measurements were taken during the prescribed burns on July 22, 1976, and August 26, 1976. These are reported in the sections on burn documentation. Preceding the burns, the depth of the organic layer at each site was probed using the probing tool. Soil samples were taken only to mineral soil, since the parameter of interest for fire sustainability was soil moisture level in the organic layer. A metal stake was also placed at each sample site to measure the depth of burn in the organic layer. Photographs were taken during the burn and any pertinent observations were noted. The same procedure was used both days on which burns occurred. Bagged organic samples were returned to the laboratory at the University of Alaska for analysis. The metal stake burn depth indicators were measured at a later date when each burn site had cooled sufficiently.

An attempt was made to measure the vertical conduction of heat to the lower layers of soil during a burn. To accomplish this, two thermistors, conductor cables, and extensions were buried approximately 18 m from the northeast corner of the plot at depths of 15 and 30 cm respectively. The intensity of fire during the August 26 burn consumed both these thermistors and the test was unsuccessful. The thermistors had been installed earlier when a prescribed burn was cancelled; at that time the moisture levels were much higher and it was anticipated that the severity of the burn would be minimal.

Soil Tension Data

Soil water tensions for mineral soils are a good indicator of the effect of evaporation and drying of soil at a given depth. A comparison of changes in soil tension in response to precipitation can be thought of as a test of the sensitivity of the tensiometers. Rain will moisten the upper levels of the organic mat and decrease soil tension. During July, 1976, there were only three days when more than 10 mm of rain fell--July 14, 15, and 17, with 10, 18, and 11 mm respectively. However, the tensiometers recorded no substantial change during any of the three days. In general, the tensiometers of both types did not fluctuate more than 3 centibars during the entire summer. It is likely that the 20-, 30-, and 40-cm tensiometers remained near saturation conditions during the summer, but the organic layer at 10 cm underwent drying, especially during the weeks of July 7-14 and August 1-7. It should be noted that the soil moisture levels at the intensive study site remained much higher throughout the summer than the levels at the prescribed burn site. This can, in part, be attributed to the deeper active layer and steeper slope at the prescribed burn site.

Because of the limited fluctuations in the measured pore pressures of the organic soils, it was questioned whether these tensiometers were behaving properly. By developing characteristic curves (pore pressure vs. moisture content) for these organic soils in the laboratory, this could be checked. An apparatus was assembled to hold an organic sample 6 cm high and 5.3 cm in diameter. The procedure followed is similar to that used for mineral soils, except that the time to reach equilibrium may be greater due to the height of the sample. Starting with a saturated sample, the weight was determined. This sample was then allowed to set for several days while undergoing gravity drainage. Then the extraction pressure was increased in increments with the water loss being noted.

It appears from the limited data that very large changes occurred in the moisture content with very little change in the pore pressure. Results from one run are shown in Table 1. The weight of this organic sample was 17 g and the bulk density was .128 g/cm^3. This sample was taken from the top 6 cm of the organic column, and the bulk density appears to be somewhat higher than typical values reported in a latter section. Just from gravity drainage alone, the moisture content on a per cent-by-volume basis changed 24%. When the extraction pressure was increased to .04 bars ($\sim$40 cm of H_2O), there was an additional drop in the moisture content from 35% to 12%. In the work with organic soils by Plamondon, Black, and Goodell (1972), a fairly large change in the moisture content was demonstrated ($\sim$50 percent reduction, depending upon the depth of the sample) over the pressure range we are discussing here. Their minimum moisture content was never as low as we measured.

If it is true that a large change in the moisture content produces a small change in the pore pressure, then we can ssume that the tensiometers we installed were working properly. For this case, tensiometers are of restricted use because of the insensitivity of the measurement.

The pressure plate apparatus used in this experiment had an air entry pressure near one atmosphere so this represented the upper limit of extraction. Very minor water losses were observed from the .04 bar level to the 1 bar level of extraction.

TABLE 1: Moisture Content--Pore Pressure Relationship for Organic Soil

Extraction Pressure bars	Weight of Water (g)	Moisture Content by volume (%)
0*	78.3	59
0**	46.6	35
.04	16	12
.08	14.4	11
.12	14.0	10.5
.16	14.0	10.5
.20	14.0	10.5
.24	13.9	10.5
.28	13.8	10.4
.32	13.4	10.1
.42	13.3	10.0
.52	13.3	10.0
.70	13.3	10.0

*saturated
**gravity drainage allowed

Soil Temperature Data

The soil temperatures for the study site on transect 10 are shown in Table 2 for the dates July 1 through September 15 (weekly data). These data show the strong temperature differential between the surface and 100-cm depth. The temperatures below the 60-cm depth did not change more than 0.2°C during the entire period. The lower temperatures near the soil surface on August 18 and September 1 and 8 are likely due to precipitation which fell during these days. It is interesting to note that the effect of the rain on the temperatures in the organic layer can be clearly traced to a depth of 40 cm on each day.

Measurements indicate that the depth of the permafrost table at the site is between 70 and 80 cm, and it may, in fact, be shallower. The disturbance to the temperature regime introduced by the bank of thermistors could have added additional heat to the system and caused the permafrost table to appear to be deeper than it is. Probes indicate that, in the vicinity of the experimental site, the permafrost depth is

TABLE 2: Ground Temperatures-Washington Creek Study Area (°C)*

Date 1976	Depth (cm) 0	10	20	30	40	50	60	70	80	90	100
7/01	16.1	3.8	1.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
7/07	25.5	5.0	2.0	0.7	0.3	0.2	0.1	0.0	0.0	0.0	-0.1
7/14	26.5	5.5	2.7	1.2	0.6	0.2	0.1	0.0	0.0	-0.1	-0.1
7/21	30.0	5.8	3.0	1.8	1.0	0.2	0.1	0.0	0.0	-0.1	-0.1
7/28	25.5	5.9	3.4	2.0	1.2	0.4	0.2	0.1	0.0	-0.1	-0.1
8/04	18.0	6.4	4.1	2.5	1.4	0.6	0.2	0.0	0.0	-0.1	-0.1
8/12	21.2	6.2	4.0	2.5	1.7	0.9	0.2	0.1	0.0	0.0	0.0
8/18	6.3	4.3	3.4	2.2	1.5	0.9	0.2	0.1	0.0	0.0	0.0
8/25	22.8	5.8	3.4	2.1	1.3	0.8	0.3	0.1	0.1	0.0	0.0
9/01	14.8	3.7	2.4	1.5	1.0	0.6	0.2	0.1	0.0	-0.1	-0.1
9/08	8.0	1.8	1.2	0.8	0.4	0.2	0.2	0.1	0.0	0.0	-0.1
9/15	6.9	2.0	1.9	1.1	0.9	0.5	0.3	0.1	0.1	0.0	-0.1

*Thermistors installed 1 July 1976

between 50 and 65 cm. This is also reaffirmed when obtaining soil samples. Rarely was it possible to get an unfrozen sample below the 50-cm depth.

A comparison was made between the hourly data taken by other investigators (Hoch, 1976) on transects 4 and 8 at the Washington Creek site and the weekly measurements of this study. The measurements of this study were done near noon on the date given. The surface temperatures recorded in this study were comparable to the maximum hourly temperatures at the surface. Below the surface however, temperatures were often closer to the mean daily temperatures determined from the hourly data as expected.

Soil Moisture Data

Moisture content in the top 10 cm of the organic soils is extremely variable due to the high porosity and low bulk density of the organic layer of the taiga soils, as well as the climatic variability. Methods used for sampling and analyzing soil samples are described earlier in the field data collection section. Samples were taken at 2-cm intervals in the top 10 cm for the very reason mentioned: to ensure documentation of any rapid changes in moisture content in the vertical column of organic soil. In the remaining soil column, samples were collected at 5-cm intervals. The reported moistures (Table 3) are given as per cent by weight of water divided by the weight of the dried organic material. Consequently moisture percentages frequently are in excess of 100% and are often several hundred per cent of the organic weight.

Although quite variable, there does appear to be a pattern to the soil moisture in the thick organic mat soils. The greatest variability is near the surface. This layer is subjected to rapid and severe drying during rainless, hot weather periods. A sample taken on June 14 shows only 12% moisture content by weight in the 0- to 2-cm layer. The weather preceding this sampling was extremely dry with only 1 mm of rain in the preceding 2 weeks. However, even with this dry weather, the moisture content at 2 to 4 cm was 99% and at 6 to 8 cm it was still 164% by weight. During July, the organic layer continued to dry at greater depths. Moisture content was 52% at 0 to 2 cm on July 21, but increased steadily to 179% at 15 to 20 cm. On July 28, moisture contents were high, since precipitation occurred on four of six days preceding the

TABLE 3: Per Cent Moisture Content by Weight

Depth	Date					
	6/14	7/08	7/14	7/21	7/28	8/04
0- 2	12	292	22	52	289	444
2- 4	49	138	26	96	239	522
4- 6	93	94	187	82	309	537
6- 8	164	98	140	96	237	521
8-10		87	169	85	241	557
10-15		80	195	155	629	493
15-20		117	359	179	855	595
20-25		108	225	*158*	533	681
25-30			*95*	*98*	513	840
30-35		715	*132*	*125*	*156*	380
35-40				*85*	*71*	*276*
40-45					*39*	
45-50					*37*	
50-55					*51*	
55-60					*39*	
	8/12	8/18	8/25	9/01	9/08	9/15
0- 2	206	155	21	240	130	122
2- 4	258	109	73	196	94	134
4- 6	206	105	115	158	83	145
6- 8	160	150	142	179	77	136
8-10	160	282	206	191	82	215
10-15	189	626	360	256	77	341
15-20	317	863	676	362	159	563
20-25	262	1088	456	412	*254*	546
25-30	*219*	846	*287*	488	*179*	503
30-35	*92*	588	*109*	527	*93*	*67*
35-40	*46*	*305*		*80*	*42*	*34*
40-45	*36*	*82*			*52*	
45-50	*60*				*35*	
50-55	*56*				*61*	
55-60					*64*	

*Italicized numbers represent moisture content of mineral soils sampling. Moisture levels were above 200% at all depths less than 30 cm and the moisture reached 855% (near saturation) at 15 to 20 cm. Throughout August, the soil at depth continued to dry and the surface layer reflects precipitation patterns.

The average moisture profile for organic soils at Washington Creek can be characterized as post-snowmelt drying at the surface, with moisture content progressively increasing with depth to the range of 150 to 200% moisture by weight at 15 to 20 cm. Summer moisture levels range over values from 12 to 292% by weight and reflect antecedent precipitation. The layers between the surface (0-2 cm) and the 25- to 30-cm layer continue to dry as the summer progresses, but may be wetted by a heavy rainfall. This is best shown by the July 28 data where antecedent precipitation was 26 mm, which occurred over 6 days preceding the sampling. Moisture levels in the soil, as stated earlier, ranged from 289% at the surface to 855% at 15 to 20 cm. On August 25, moisture increased steadily from the surface (21%) to the 15- to 20-cm layer where it was 676%. Mineral soils are only accessible for thawed moisture content measurements during the latter part of the summer. These soils are also highly variable in moisture content, but generally decrease in moisture with depth below the organic-mineral soil interface. At this interface, the change in the hydraulic conductivity due to the mineral soil tends to block rapid drainage to the soil below, and moisture builds up slightly at the interface, accounting for the higher moisture levels near the bottom of the organic layer, commonly at the depth range of 20 to 35 cm. Moisture content in the frozen mineral soils usually declines with depth, the occurrence of the ice lenses being greater near the surface of the mineral layer.

Due to the spatial variations in moisture content and the problem of using new sampling points for collecting each sample, it is difficult to make concise conclusions conerning natural moisture variation. Obviously in a permafrost setting, the ablation of the snowpack is responsible for the high initial moisture content. Both evapotranspiration and the lateral flow downslope through a saturated zone are accountable for the gradual depletion in moisture content. Without further precipitation input, the upper slopes reach a drier condition at depth before lower regions. Much drier conditions existed both near the surface and at depth in the prescribed burn sites that were located near the ridge top than at the intensive study site located near the center of the slope. Either the existence of permafrost or the large variation in hydraulic conductivity between the two divergent soils are liable for the saturated conditions that develop, resulting in flow down the slope.

Bulk Density and Porosity

In order to get an accurate measurement of the water content by volume it is necessary to know the bulk density of the soil samples. An attempt was made to develop a relationship between the dry bulk density and the depth of the sample. While the dry bulk density was being determined, the porosity was also found. Thirteen vertical profiles were taken at the Washington Creek site--five from transect 4 and eight from transect 10. Five vertical profiles were tested for porosity; all were from transect 10.

Dry bulk density measurements were made on both organic and mineral soils using the standard method of weighing a fixed volume of cored, undisturbed soil. Mineral soil samples were obtained at Silver Creek in the Goldstream Valley, a site with similar permafrost conditions.

Since the bulk density of the organic material varies over a wide range of values, moisture contents by weight are of little value when comparing samples. This problem can be alleviated by determining the moisture content on a volume basis. Several samples were collected to determine an average value for the dry bulk density at each given depth. However, it quickly became evident that the bulk density at a given depth is also related to the overall thickness of the organic layer. A family of representative curves (Figure 2) for the bulk density at various depths was developed based on the total thickness of the organic material. By utilizing these curves, we arrived at values of moisture content as a volume fraction. It can be seen from the plotted data that, for statistical significant results, a larger number of samples should be collected and the plot should show either an appropriate confidence limit or the range of values for a given depth.

Porosity was measured using the following technique. Undisturbed soil samples were taken to the lab and dried at 78°C for 48 hours. The soil sample of known volume was then saturated with a measured volume of water. Calgonite was used as a wetting agent. The saturated soil was

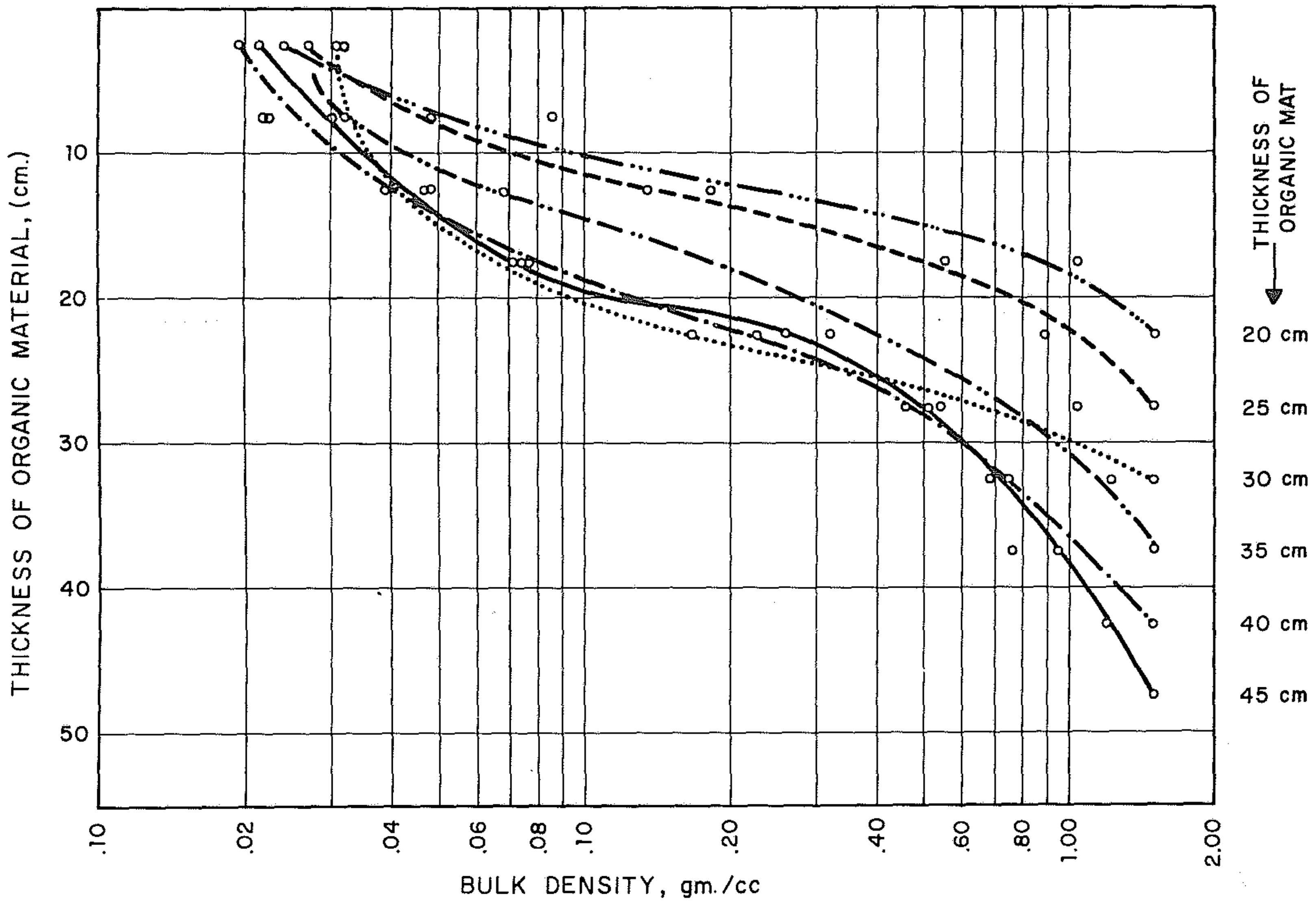


FIGURE 2: BULK DENSITY vs. DEPTH OF ORGANIC LAYER

allowed to soak for 1/2 hour and then put under a small vacuum pressure to extract any remaining air in the soil. The air space was kept small so that the vacuum would draw air from the mixture. Styrofoam was used as a cover so as not to make an excessively tight seal. In this way a low vacuum pressure was guaranteed. A high vacuum would remove water and organic mineral. The volume of voids is then determined by the following relation:

$$V_v = V_T - V_{solids} = V_{H_2O} \tag{1}$$

where

V_v = volume of voids
V_T = total volume
V_{solids} = volume of solids
V_{H_2O} = volume of added water

and

$$\eta = \frac{V_v}{V_T} \tag{2}$$

where

η = porosity

Saturated Hydraulic Conductivity

The hydraulic conductivity of organic and mineral soils in the test areas was measured using standard laboratory instrumentation for this purpose. First, for mineral soils, cores were taken with an earth auger and placed in an aluminum mold in order to preserve as closely as possible its *in situ* conditions. For organic samples, a 25-cm^2 section was cut from the ground surface with a machete and divided into three 10-cm sections which were carefully packed and taken to the laboratory.

The device used for hydraulic conductivity measurement requires that the sample be cut and fitted snuggly into a lucite cylinder. A variable water pressure head is then applied to the soil and the flow rate is measured. The data is plotted (Figures 3 and 4) as a function of the hydraulic gradient. The hydraulic gradient is the ratio of heat loss through the sample (h) over the length of the sample (L).

Packing the organic samples in the lucite cylinder posed a problem. If the samples were placed with minimal compaction, then it was felt the values for the determined hydraulic conductivity may be too high due to

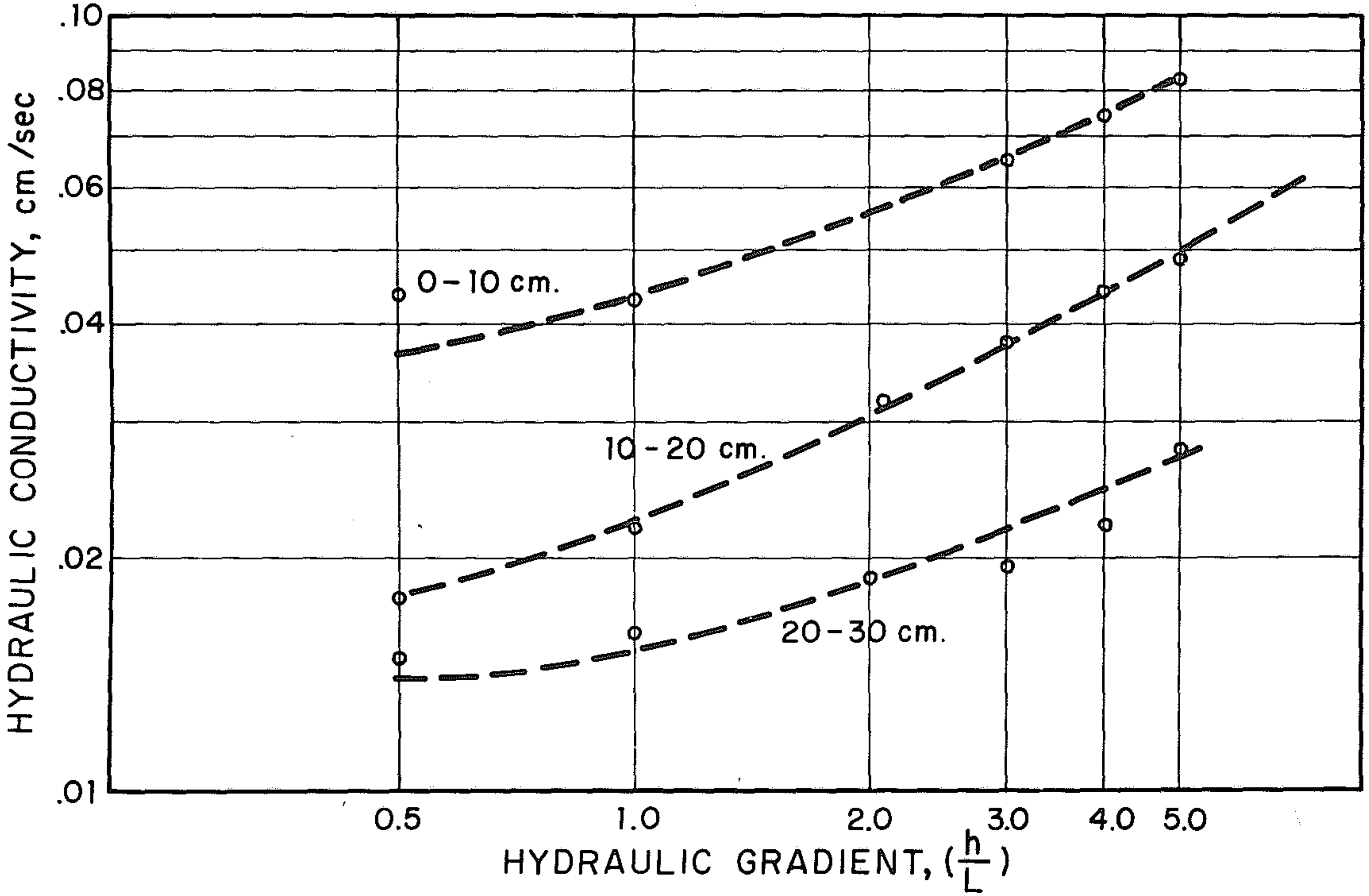


FIGURE 3: SATURATED HYDRAULIC CONDUCTIVITY AS A FUNCTION OF HYDRAULIC GRADIENT, WHERE h IS THE HEAD LOSS THROUGH A SAMPLE OF LENGTH L (SAMPLE 1).

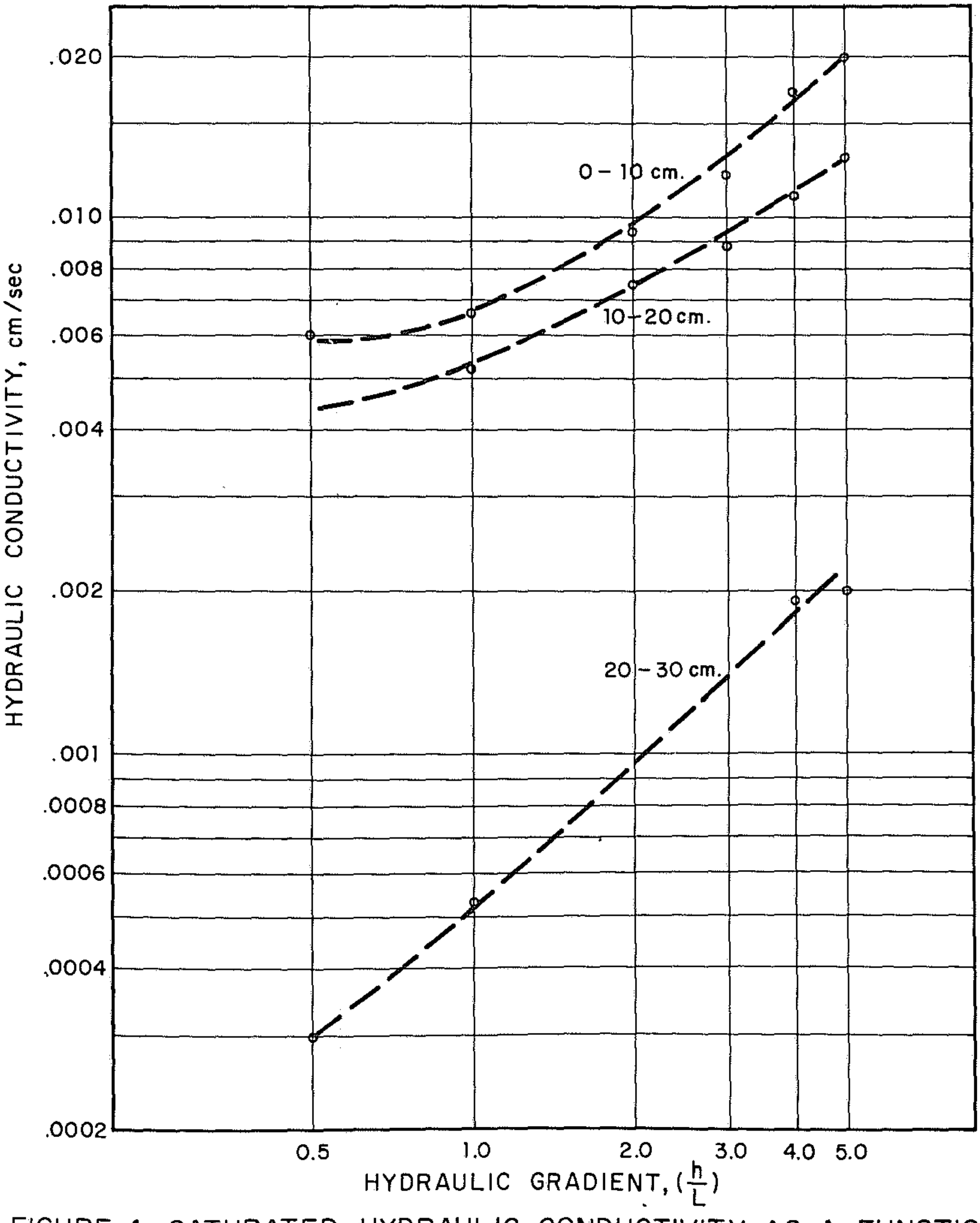


FIGURE 4: SATURATED HYDRAULIC CONDUCTIVITY AS A FUNCTION OF HYDRAULIC GRADIENT, WHERE h IS THE HEAD LOSS THROUGH THE SAMPLE OF LENGTH L (SAMPLE 2)

water flowing along the cyclinder walls. To obtain a firmer fit with the walls, it was necessary to compact the sample slightly, also undesirable. The laboratory runs were made under both conditions--sample 1 was observed under no compaction, whereas sample 2 was tested under slight compaction. The true hydraulic conductivity rests between the two values reported; these differ by an order of magnitude.

The saturated hydraulic conductivity was determined for only one hydraulic gradient, with the average conductivity of our tests equal to 3.4×10^{-4} cm/sec. This is typical of silt loam soils.

Determination of unsaturated hydraulic conductivity from characteristic curves.

It is convenient in modeling flow systems through the use of computer simulation that the relationship be established between the two variables: unsaturated hydraulic conductivity and soil tension (pore pressure). Because of the difficulty in measuring the unsaturated hydraulic conductivity, alternate methods have been used.

First, it is possible to determine the relationship in the laboratory between moisture content (% by volume) and pore pressure. This is accomplished through the use of a pressure extraction device. This device allows a constant fixed pressure to be applied to soil samples for long periods of time. This enables a precise measurement of the moisture content retained in the soil as a function of the extraction pressure. This relationship is called the "characteristic curve". A characteristic curve is plotted in Figure 5 for the Washington Creek mineral soils. These soils are very similar in every way to the Fairbanks silt loams (USDA Soil Conservation Service, 1963) and are described in detail in a publication entitled "Soils of the Wickersham Dome Experimental Forest, Alaska (Furbush and Schoephoester, 1974).

Next, in order to determine the calculated unsaturated hydraulic conductivity as a function of moisture content, we refer to the work of Green and Corey (1971). In their paper, which deals with the calculation of hydraulic conductivities at different water contents, these authors give the relationship which was used here to calculate, using a computer program, the relationship between the unsaturated hydraulic conductivity and moisture content by volume. It is as follows:

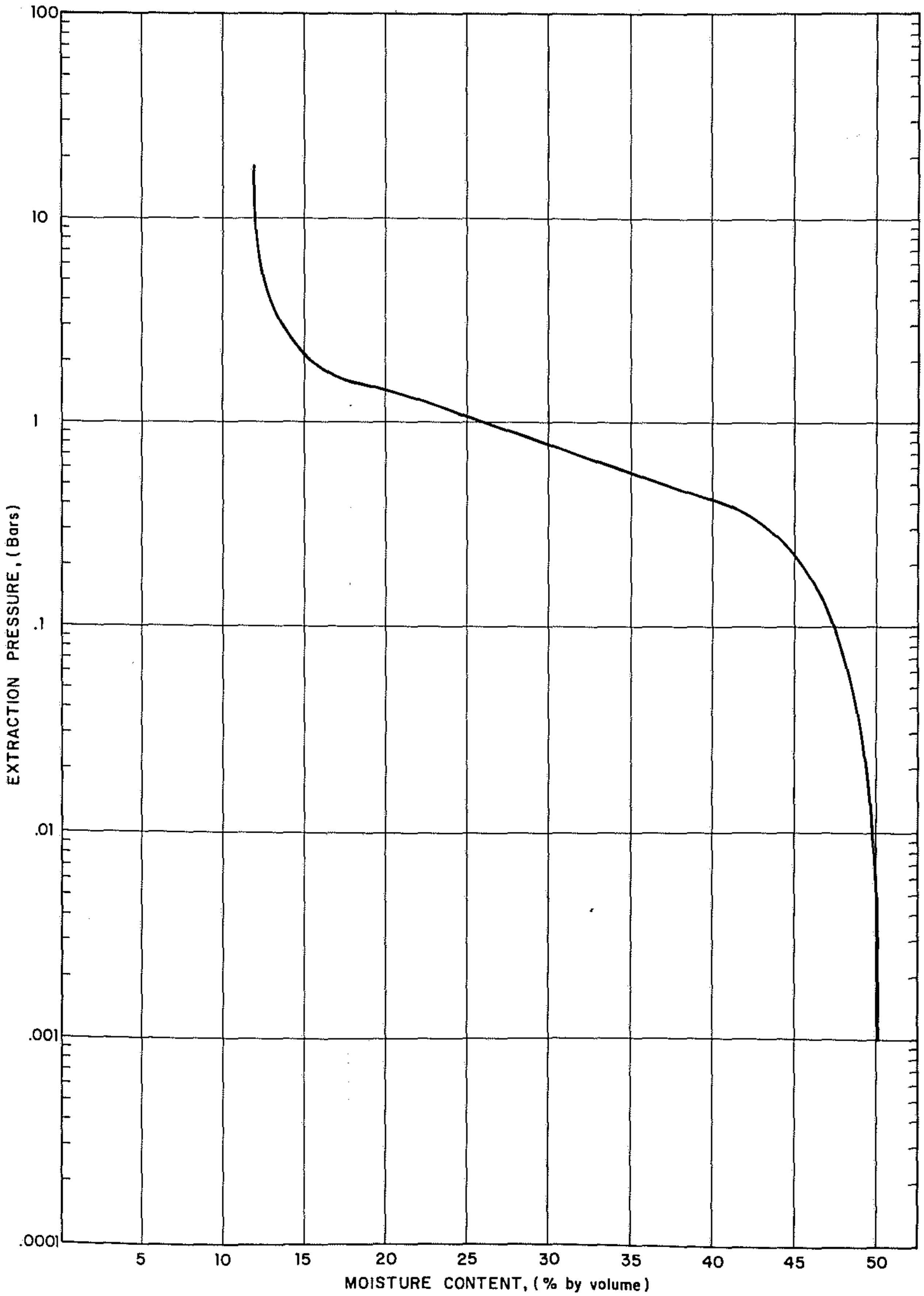


FIGURE 5: CHARACTERISTIC CURVE FOR FAIRBANKS SILT LOAM.

$$K(\theta)_i = \frac{K_s}{K_{sc}} \cdot \frac{30\gamma^2}{\rho g n} \cdot \frac{\varepsilon^p}{m^2} \sum_{j=1}^{m} [(2j + 1 - 2i)h_j^{-2}] \tag{3}$$

$i = 1, 2, \ldots m.$

where

$K(\theta)_i$ = the calculated conductivity for a specified water content or extraction pressure (cm/min).

θ = the water content by volume (cm^3/cm^3),

i denotes the last water content class on the wet end, e.g., $i = 1$ identifies the pore class corresponding to the saturated water content, and $i = m$ identifies the pore class corresponding to the lowest water content for which conductivity is calculated,

K_s/K_{sc} = the matching factor (measured saturated conductivity/calculated saturated conductivity) when $K_s/K(\theta)_i = 1$,

γ = the surface tension of water (dynes/cm),

ρ = the density of water (g/cm^3),

g = the gravitational constant (cm/sec^2),

η = the viscosity of water ($g/cm\ sec^{-1}$),

ε = the porosity (cm^3/cm^3), defined in various ways depending on the method of calculation,

p = a parameter that accounts for interaction of pore classes,

n = the total number of pore classes between $\theta = 0$ and θ_s, the saturated water content: $n \geq m$

h_j = the pressure for a given class of water-filled pores (cm of H_2O).

The calculation results are plotted on Figure 6, for K_s/K_{sc} (matching factor) equal to 1.734. From equation 3 it is possible to get a relationship between the hydraulic conductivity and the pore pressure. In solving equations of flow, it is necessary to know the pore pressure at predetermined points; to determine the flux it is necessary to know the relationship between the pore pressure and hydraulic conductivity (Figure 7). Rather than calculate the hydraulic conductivity from equation 3, computation time can be reduced substantially by substituting in a simple empirical equation of the type:

$$K(\psi) = Ae^{-B\psi} + Ce^{-D\psi} \tag{4}$$

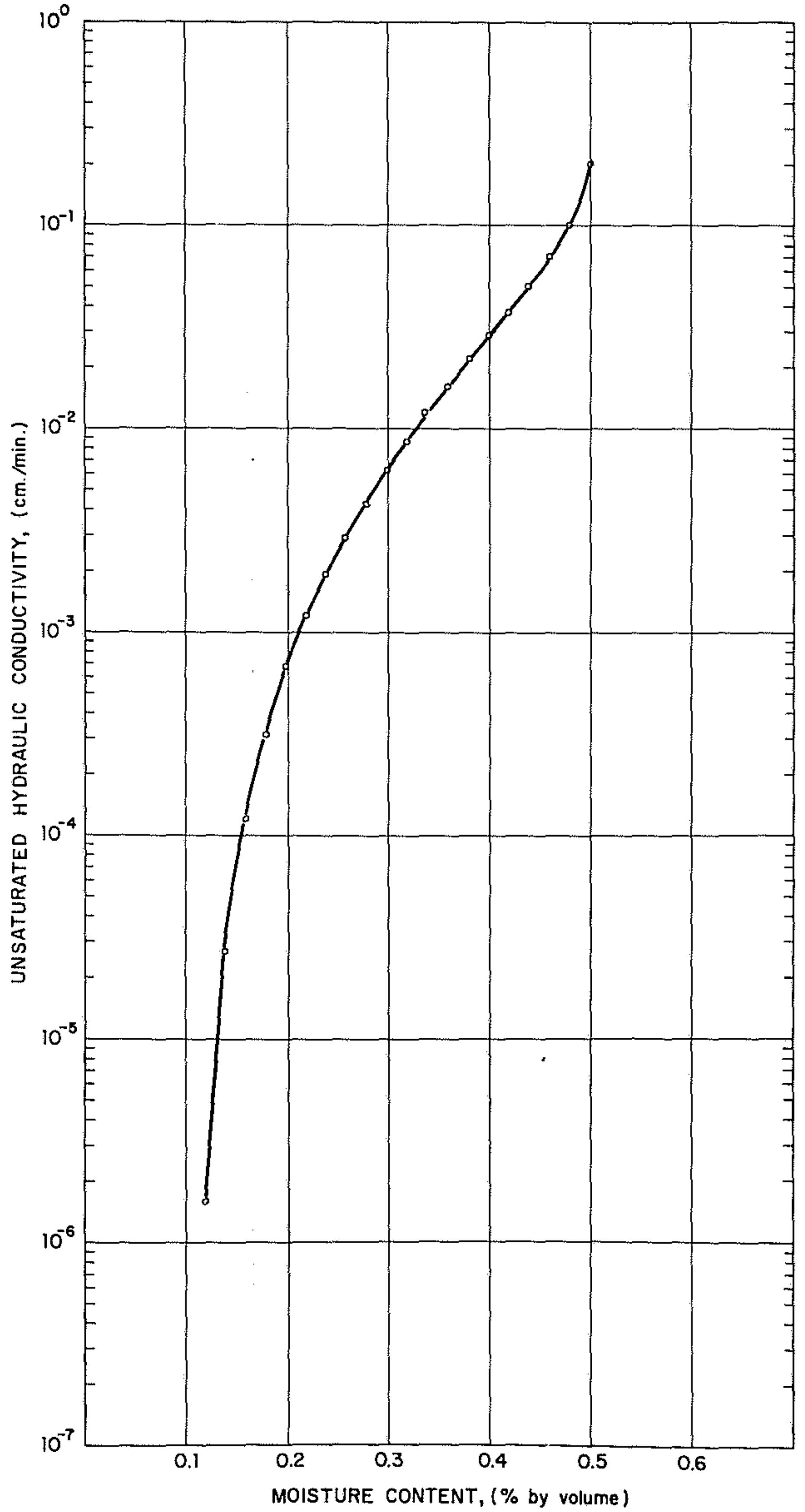


FIGURE 6: CALCULATED UNSATURATED HYDRAULIC CONDUCTIVITY AS A FUNCTION OF MOISTURE CONTENT, FAIRBANKS SILT LOAM.

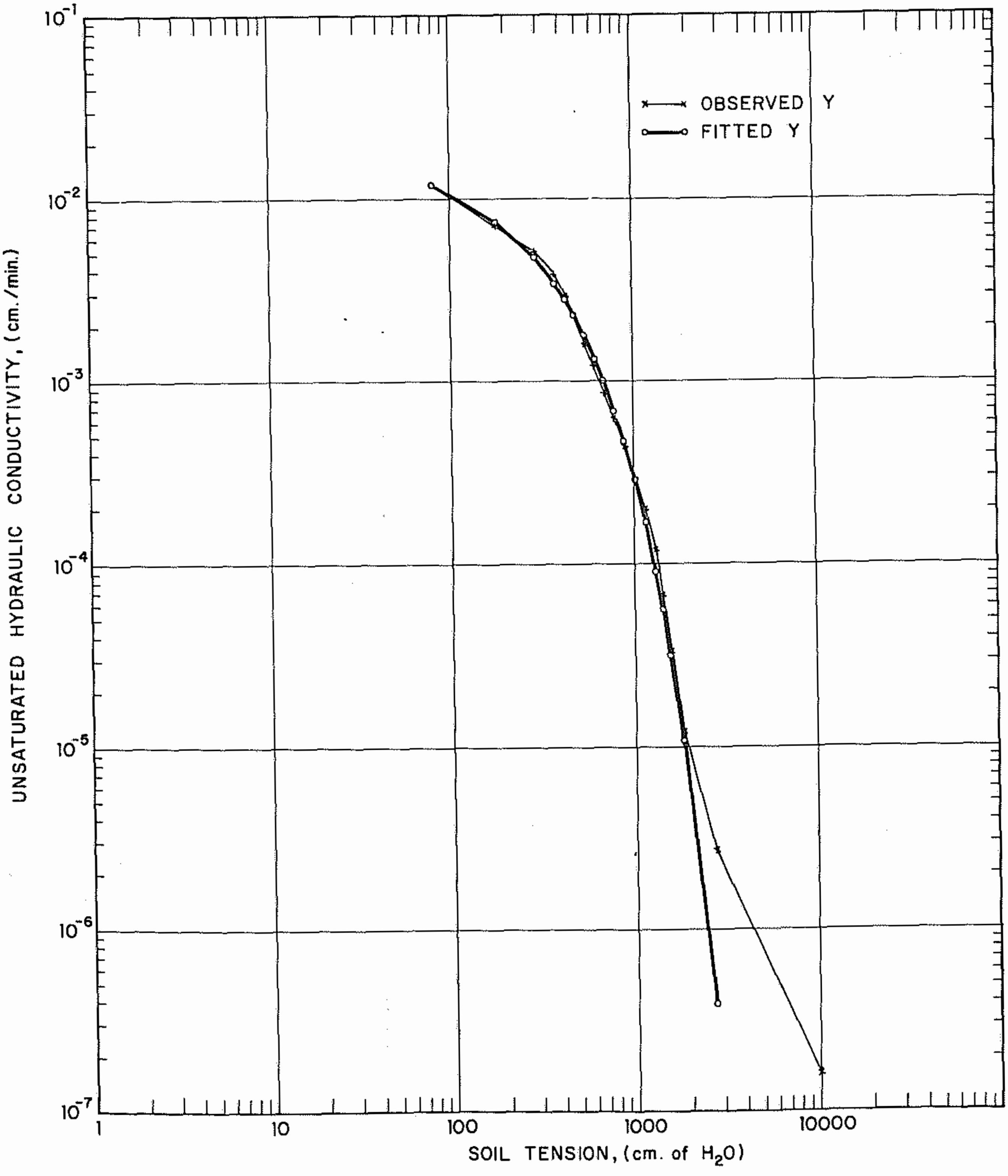


FIGURE 7: RELATIONSHIP BETWEEN UNSATURATED HYDRAULIC CONDUCTIVITY AND PORE PRESSURE, FAIRBANKS SILT LOAM.

where

$K(\psi)$ = unsaturated hydraulic conductivity at various values of pore pressure (ψ)

A nonlinear, least-squares, curve-fitting program yielded the following values:

$A = 5.67 \times 10^{-3}$

$B = 1.75 \times 10^{-2}$

$C = 1.44 \times 10^{-2}$

$D = 3.89 \times 10^{-3}$

The fit for this equation can be compared to calculated values on Figure 7. An excellent prediction is made except when very high soil tensions exist. It should be noted that the sum of A and C equal the saturated hydraulic conductivity.

DOCUMENTATION OF PRESCRIBED BURNS

The original plan of study for this project did not include studying the effect of soil moisture content on burn severity. In that no new methods would be required--only the analysis of additional samples--it was felt that only a small amount of additional work would yield some preliminary useful and interesting information. The following map (Figure 8) shows the layout of the prescribed burns. The reader is referred to the paper by Viereck et al. (1977) for additional detailed information concerning the prescribed burns.

Description of Burn--July 22, 1976

A prescribed burn was planned for the morning of July 22 at Site 2. Before the burn, initial soil moisture conditions were sampled. The soil was sampled at each stake at intervals of 2 cm. Stakes were located next to soil-sampling sites in order to ensure the maximum possible correlation of the samples with depth-of-burn measurements. Samples of the entire organic layer were taken until mineral soil was encountered. Soil depths at each stake are given below.

TABLE 4: Burn Depths at Site 2 (July 22, 1976)

Sample Point	Organic Thickness (cm)	Burn Depth (cm)
A1	13	5.0
A2	27	0
A3	19	4.5
A4	22	5.5

These depths reflect a decrease in the thickness of organic soil which existed toward the west corner (highest in elevation) of the plot. The stakes were randomly placed on the west side of the plot at a point where the fire should have reached its maximum intensity.

Once initial measurements were made, four stakes were placed in the burn plot as designated above. The fire was then ignited at the southeast and northeast boundaries of the plot. The fire burned toward the

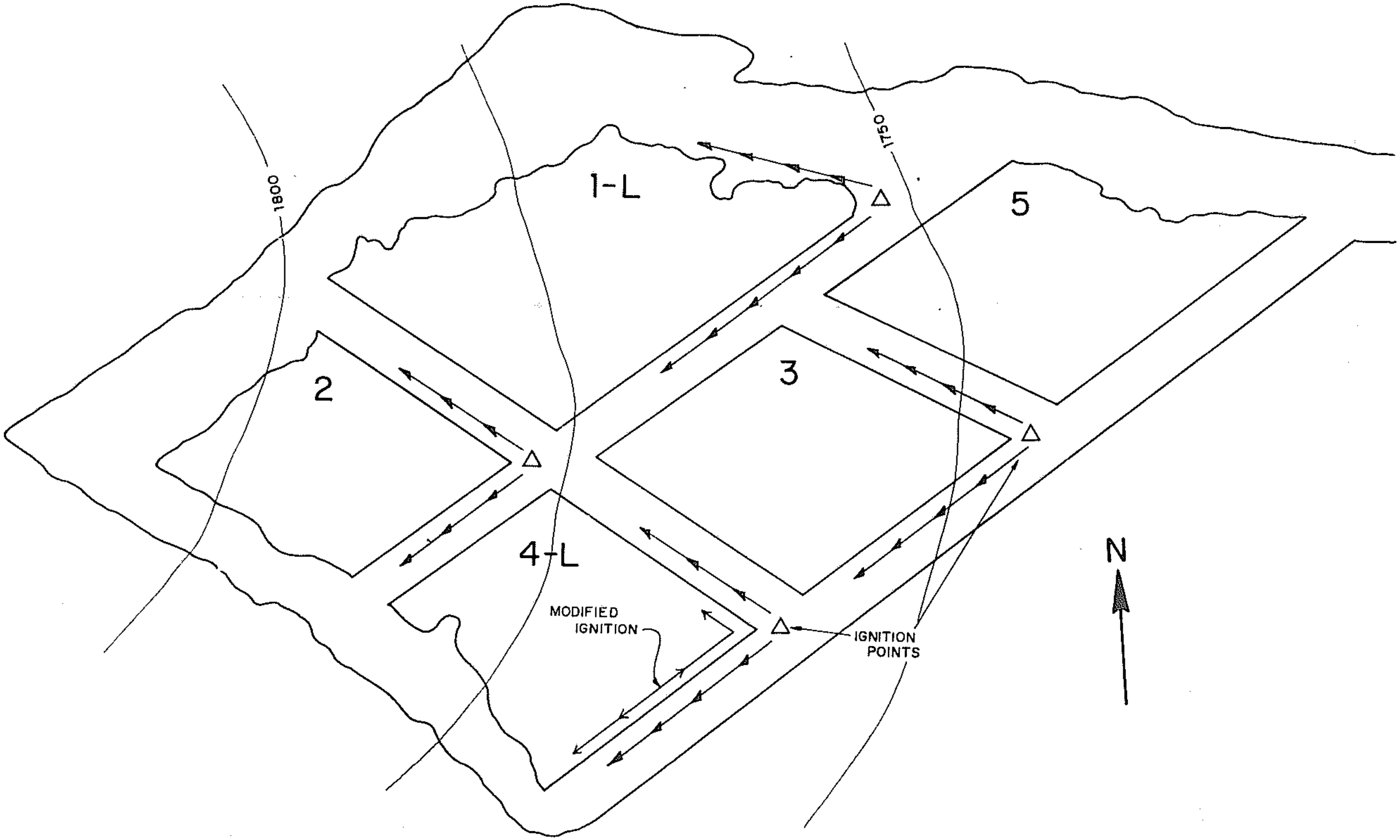


FIGURE 8: WASHINGTON CREEK FIRE ECOLOGY STUDY AREA PRESCRIBED BURN SITES, 1976

ridge to the west of the plot and lasted 8 to 9 minutes. The four stakes were recovered and the depth of burn noted (Table 4) after the area had cooled.

Description of Burns--August 26, 1976

Three plots were burned on this date: site 1L, site 3, and site 4L. The "L" attached to these site designations indicates loading of the plot with additional forest material from the surrounding area in order to determine what effect this might have on the burn intensity.

Each plot was sampled for an organic soil moisture profile. The samples were taken every 2 cm to a depth of 10 cm and then the remaining organic sample was used as the last sample. The number of soil profiles collected and samples dissected was limited because of the short time interval between burns. Because the lower sample in each profile was several centimeters in length, the average moisture content, when plotted, does not adequately depict the soil moisture profile. Generally, the stake for measuring the severity of the burn was located 1 m from where the moisture profile was taken, this is why the depth of burn could exceed the thickness of the organic layer (see Table 5).

TABLE 5: Burn Depths at Sites 1L, 3, and 4L (August 26, 1976)

Site, Sample Point	Sample Number	Organic Thickness (cm)	Burn Depth (cm)
1L, 1	A1	18	20.5
1L, 2	A2	16	21.0
3, 1	B2	23	10.5
3, 2	B2	24	--
4L, 1	C1	18	14.5

As indicated previously, two of the plots (1L and 4L) were loaded with material cut from the fire breaks. On the first burn (22 July), samples were collected from an area that was consumed toward the end of the burn; however, on the latter burn (26 August), the sampling sites were selected 5-8 m in from the ignition boundary. All three plots burned on this date were rapid fires and could be characterized as moderate to severe burns based on the depth of burn in the organic layer.

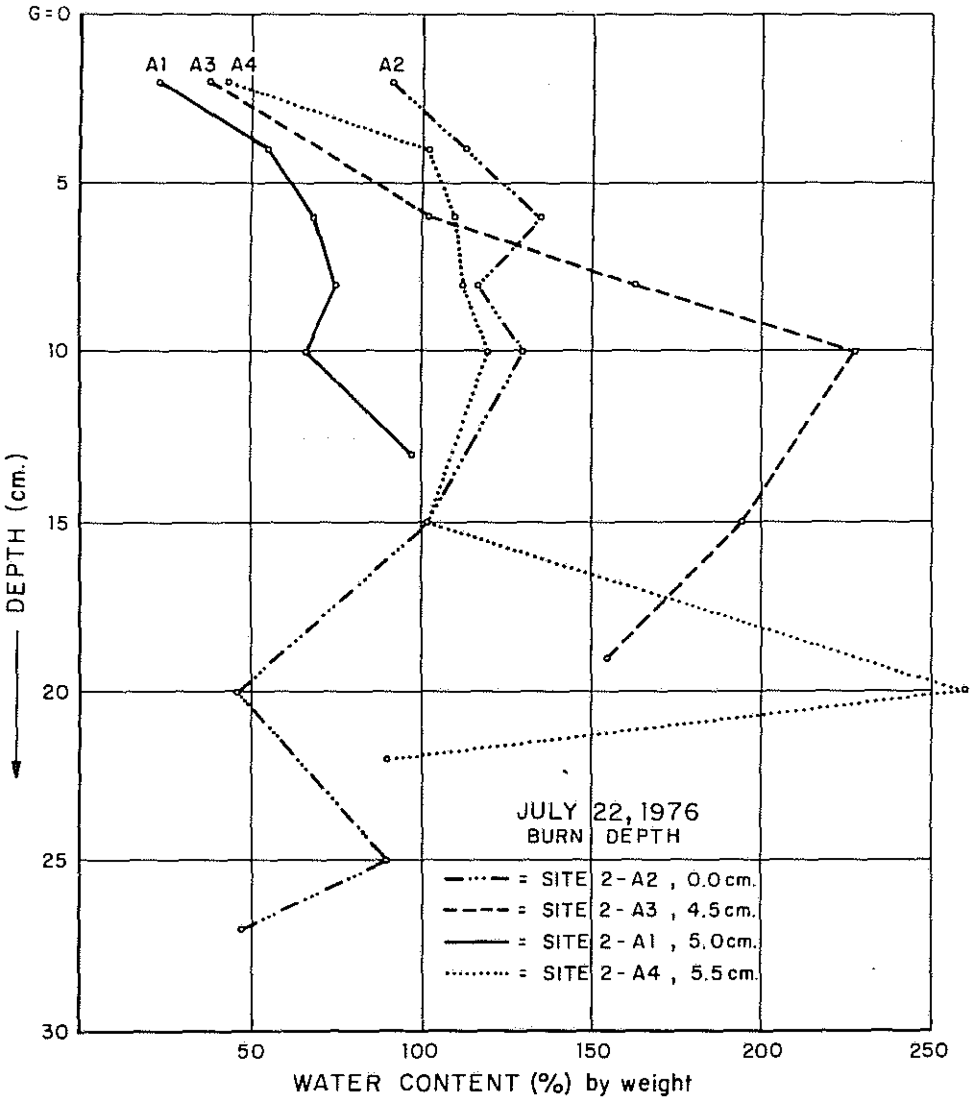
Data Discussion

As mentioned earlier, two pieces of field data were collected: the moisture content by weight and the depth of the burn at selected points (Figure 9). Because of the large variation in the bulk density for a vertical profile, a comparison of the moisture content by weight for different depths is meaningless. However, each plotted moisture profile for the 22 July 1976 burn can be compared with profiles from the 26 August 1976 burn by assuming that bulk density is equal at comparable depths.

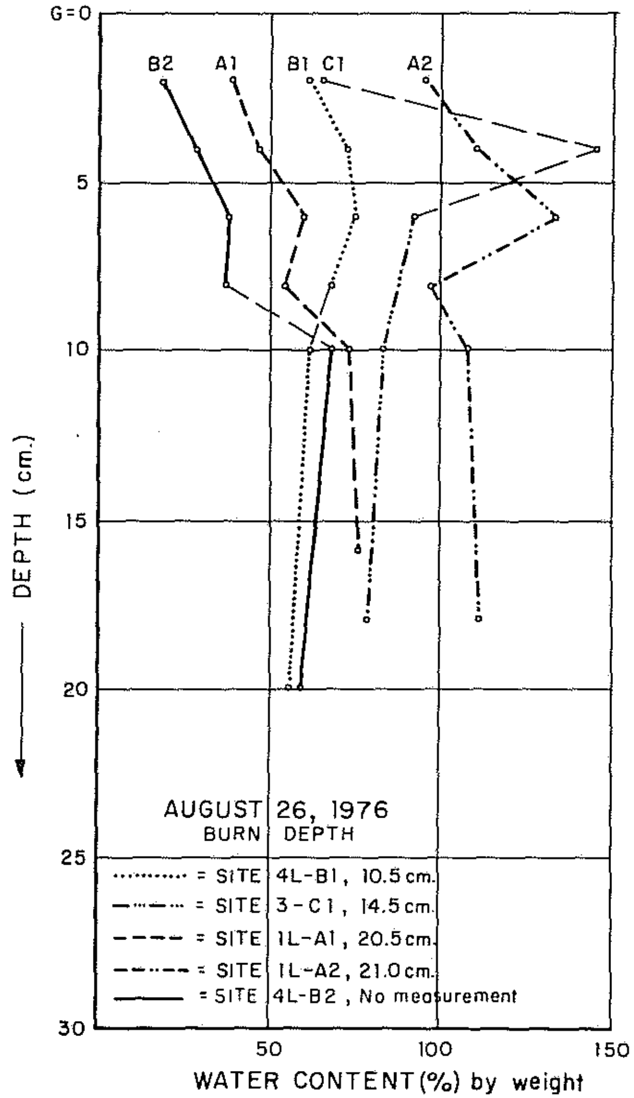
It can be seen from the figure that, in general, the organic layer was much drier during the latter burn period. An examination of the burn depth at each sampled site indicates that the depth of burn was greater during the second set of fires due to the drier conditions. By multiplying the moisture content (expressed as mass) by the bulk density, one obtains the moisture content by volume. Data in this format is more useful because that fraction of the sample that is moisture is seen readily. The moisture content by volume just prior to the burns was less than 10 percent near the ground surface (Figure 10). Typical values of the bulk density in the upper 10 cm vary from .02 gm/cm^3 to .08 gm/cm^3.

Due to the limited number of sampling points at each burn site, coupled with the fact that there is not a wide range of initial moisture conditions for the two dates of burn, it is difficult to arrive at a clear relationship between the depth of burn and the moisture content. However, by examining energy needs and requirements in combination with available combustible material and water, certain generalizations can be made.

This relationship can be examined from the point of view that energy from combustion is required to vaporize water present in the organic material. In order to vaporize water, it first has to be heated to 100°C; this requires one calorie per °C per cm^3 of water. On a volume basis, if the moisture content is 10%, 1/10 of a calorie is required to heat just the water present one degree (°C). After the

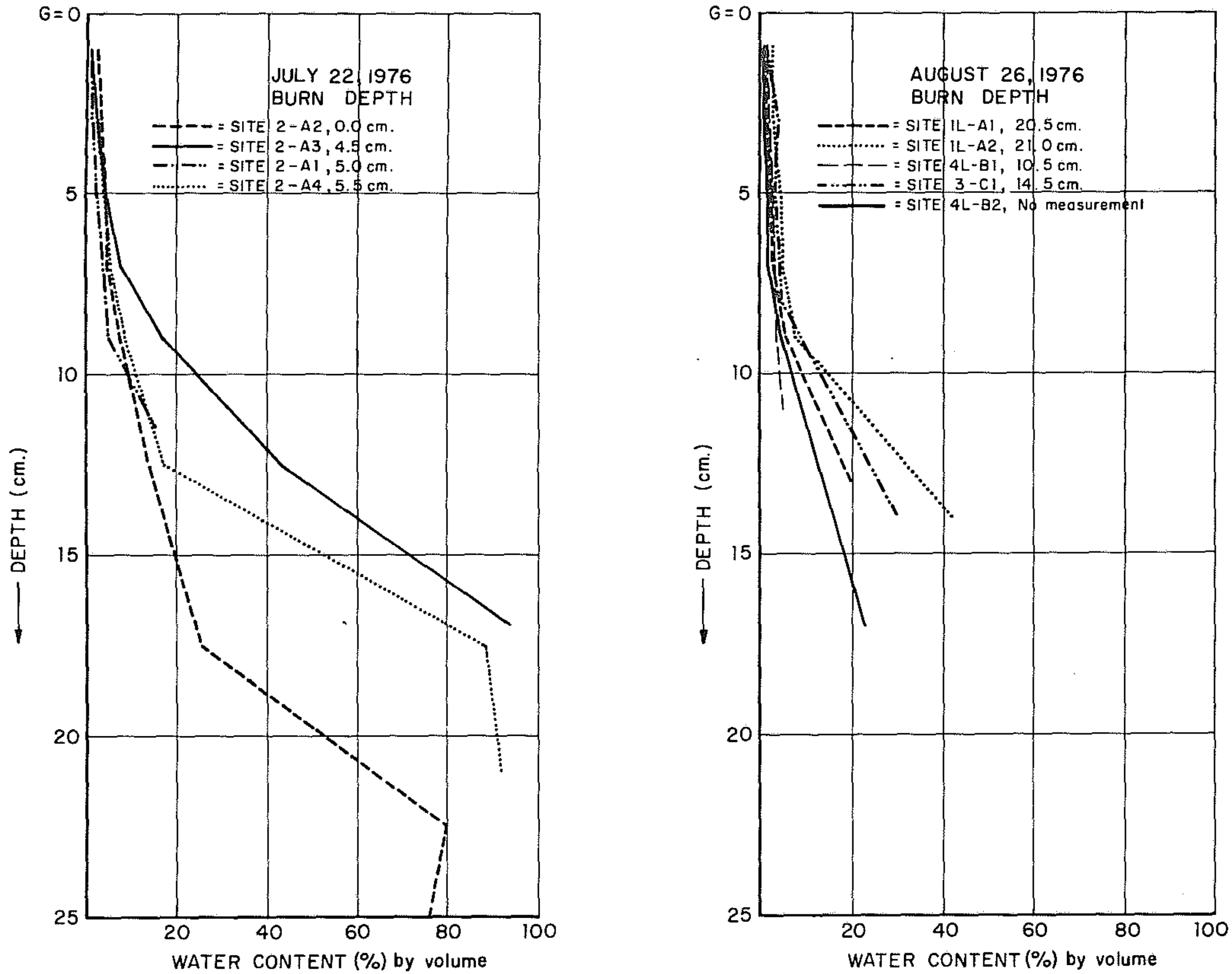


PRESCRIBED BURN - PLOT 2, MOISTURE CONTENT & DEPTH OF BURN. WASHINGTON CREEK BURNSITE No. 2



PRESCRIBED BURN PLOTS 1L, 4L & 3 MOISTURE CONTENT & DEPTH OF BURN WASHINGTON CREEK BURNSITE

FIGURE 9: MOISTURE CONTENT BY WEIGHT AS A FUNCTION OF DEPTH.



WASHINGTON CREEK BURNSITE

FIGURE 10: MOISTURE CONTENT BY VOLUME AS A FUNCTION OF DEPTH.

water has reached 100°C, 539 calories per cm^3 of water are required for vaporization. For various moisture contents and typical soil temperatures, the caloric heat requirement for vaporization is shown in Figure 11.

The next step is to determine the caloric content of combustion. Rowe et al. (1975) and Bliss (1962) report on the caloric content of various ericoids and lichens. Plotted on Figure 11 is the mean value of the caloric contents reported by Bliss (1962) that were adjusted for various bulk densities. The heat required for vaporization may be more than that generated by the burning organic material. If, for example, the bulk density is .02 g/cm^3 and the moisture content by volume exceeds approximately 15%, then the heat required to vaporize the soil water present exceeds that being generated by the burn. It is realized in this simple analysis that other energy processes are occurring, such as generation of heat in the canopy as well as a loss of heat by convective dynamics. It should be noted that, once the bulk density reaches 0.12 g/cm^3, the heat generated from burning is approaching that required to evaporate the moisture from a totally saturated sample.

Where the plots had been loaded with trees and brush from the fire breaks (such as at sites 1L and 4L) it would be expected that the burn would be more severe than anticipated because of the added fuel positioned at the ground surface.

The July 22 burn could be characterized as a light burn. From the few measurements made, it appears that the average depth of burn in the organic material was about 5 cm. As can be seen from Figure 10, the moisture content near the ground surface was about the same during the two fires; however, at the time of the earlier fire, the moisture content increased more rapidly with depth. If the bulk density near the 10-cm depth is 0.02 gm/cm^3, then the moisture content is near the limit at which suppression of additional burning may occur.

At sample point A2, on July 22, the reported depth of burn was 0 cm. This was a lichen-dominated site. Rowe et al. (1975) suggest that post-burn lichen survival may be explained in terms of combustibility and flammability; that is, the difference in the lipid composition of vascular plants and ground lichens is responsible for the observed difference in burnability.

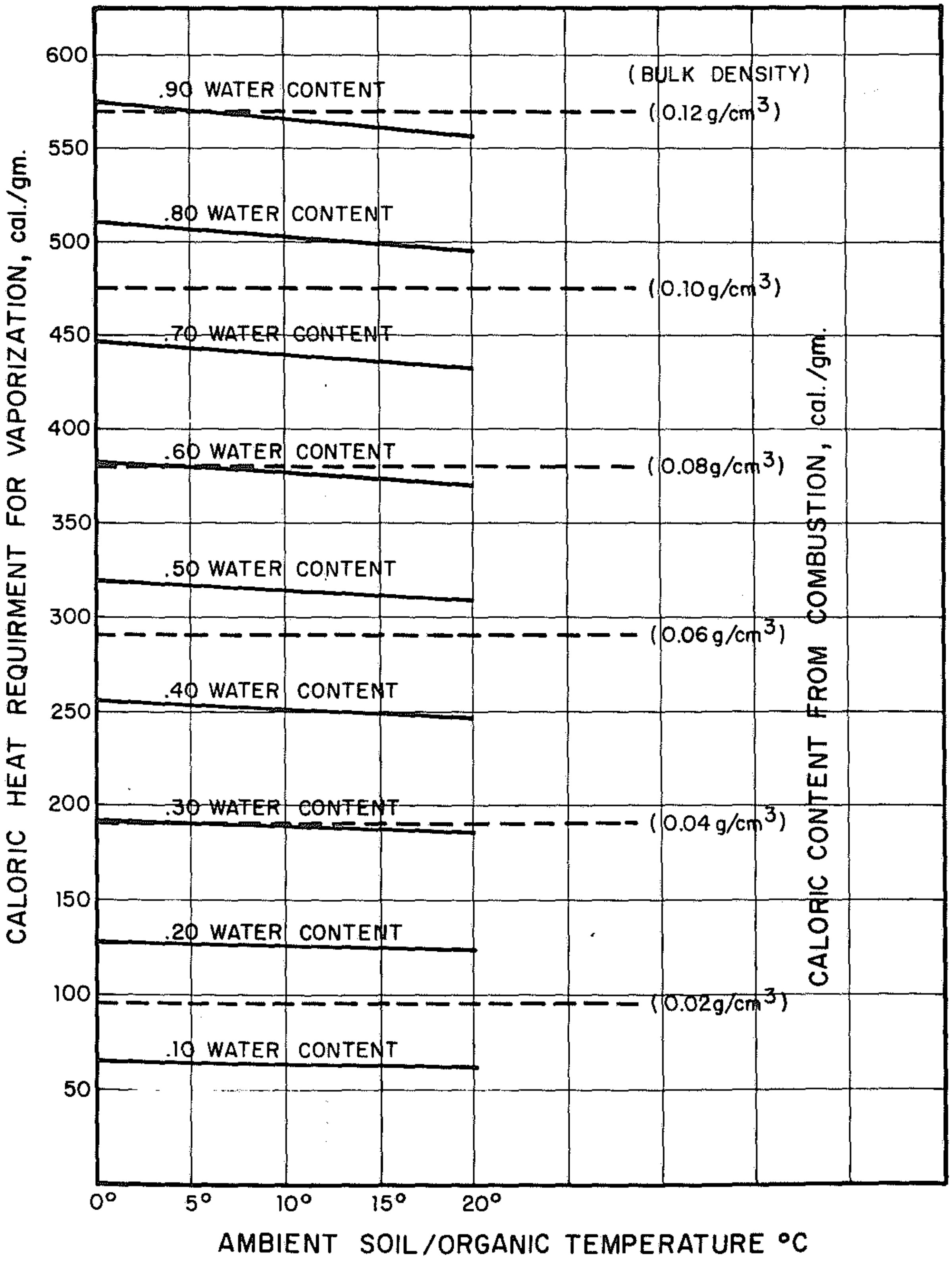


FIGURE 11: CALORIC CONTENT OF COMBUSTION FOR A RANGE OF BULK DENSITIES COMPARED TO THE HEAT OF VAPORIZATION FOR VARIOUS FRACTIONS OF WATER CONTENT.

Conclusions of the Experimental Burn Observations

Several conclusions can be drawn from these few observations, some obvious and expected, some implied. As expected, the dryness of the organic layer is important in sustaining the fire on the ground and in determining the depth of burn. The water content by volume at the surface (<10 cm) is very important in sustaining the ground fire, as indicated in the depths of burn in the two fires of July 22 and August 26. The major physical parameter which varied between the two days was water content by volume below the 10-cm depth, indicating that this was the major control of the depth of burn.

The energy of combustion available to vaporize the water content is only a limitation at bulk densities below 0.12 g/cm^3. At bulk densities less than 0.12 g/cm^3, water content by volume becomes critical to sustaining the burn. The relationship is best illustrated by Figure 11 in which the factors can be viewed in relation to each other.

The burnability of lichens appears to be less than that of woody plants, and may be related to the difference in lipid content of the two types of plants and may not necessarily be related to the water content.

GROUNDWATER TWO-DIMENSIONAL FLOW MODEL WITH APPLICATION TO NEAR-SURFACE WATER MOVEMENT IN COLD REGIONS

Except for the possibility of a thicker-than-normal layer of organic material, permafrost-free soil systems of the north are similar to soil systems found elsewhere. However, superimposed on this system is a climate that is responsible for sustaining permafrost and, during the winter months, drawing large quantitites of heat from the soil, thus producing a seasonal frost layer. The phase change (water to ice) due to freezing causes a reduction in the hydraulic conductivity of these soils. It is this change in hydraulic conductivity, caused by ice crystals or lenses in the soil pores, that produces the shallow groundwater situation.

In general, four flow systems can be identified for northern regions. Criteria for defining these systems are based on determining the influence of snowmelt or rainfall events and ascertaining the existence of permafrost (Figure 12). It is recognized that other physical systems exist; however, on a given watershed, the exception to these classifications is unusual. Three of the four cases are truly shallow-layered systems; while the fourth can vary from shallow to deep depending upon the position of the water table.

First consider case (a) in Figure 12 where permafrost and seasonal frost are absent. The rate of flow through this system is primarily a function of the hydraulic conductivity. As long as the infiltration rate does not exceed the hydraulic conductivities of the organic and mineral soils, essentially vertical flow occurs. Generally, the organic layer is not well developed in nonpermafrost sites where adequate drainage is found. When organic soils with a relatively high hydraulic conductivity overlay fine mineral soils such as silt loam, horizontal component of flow will occur if saturated conditions exist at the interface of the two layers. For a given precipitation event, the amount of infiltration is a function of the duration and intensity of the event as well as the condition of the soil system. This is typical of groundwater recharge to subpermafrost flow systems. This would not depict a shallow flow system, unless the water table were near the surface.

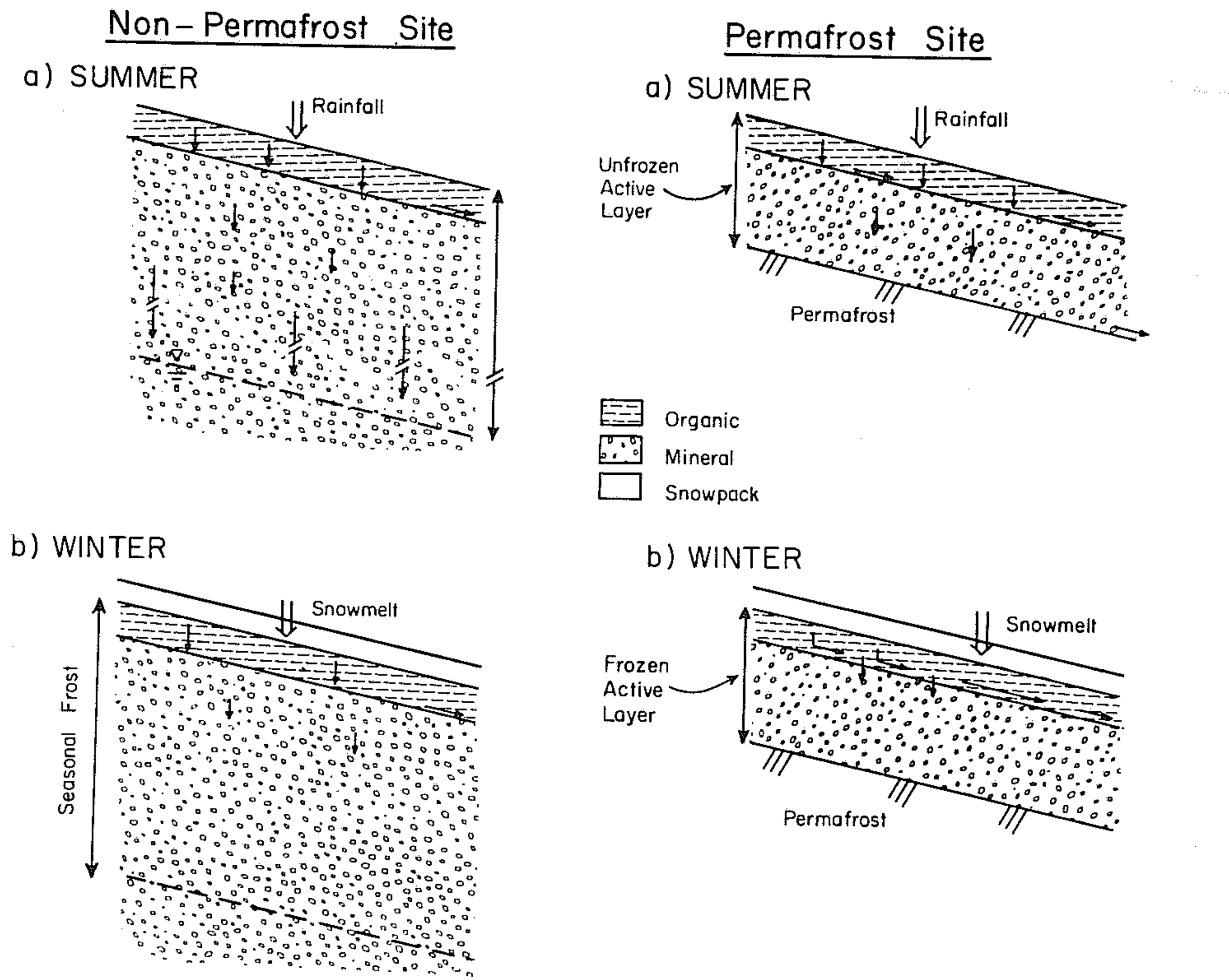


FIGURE 12: REPRESENTATIVE SUBSURFACE FLOW SYSTEMS IN COLD REGIONS FOR RAINFALL AND SNOWMELT EVENTS.

When seasonal frost is present in such a system at the time of snowpack ablation, the hydraulic conductivity of the soil layers is further reduced. The extent of this reduction is a function of the volume of ice crystals within the soil pores. Organic soils generally have such high rates of hydraulic conductivity that they do not seriously impede infiltrated flow when frozen soil conditions exist. It is not until the mineral layer is reached that the hydraulic conductivity is sufficiently reduced by the pore ice to enable saturated conditions to develop. When permafrost is not present, limited field studies indicate that soils in nonpermafrost sites are much drier than similar soils overlying permafrost. The volume of ice is thus reduced in the soil pores; additional drying of these soils is accomplished during the winter months by the movement of soil moisture toward the colder air-ground interface and thus, subsequently, into the snowpack.

For case (b), in the nonpermafrost site (see Figure 12), flow may develop at the interface of the organic and mineral layers if high moisture levels exist in the mineral soil layer and if snowpack ablation is rapid. Groundwater recharge may occur in this case, as well as contributions to peak surface runoff events. If the soils are quite dry, this water may be retained in the near-surface soils and lost over the summer by evapotranspiration processes.

The presence of permafrost ensures that a shallow-flow system will exist; this is depicted in Figure 12 for two cases, summer and winter. The maximum depth of the active layer is a measure of the thickness of this shallow system. Clearly, horizontal flow quickly develops in this system whether seasonal frost exists or not. When high moisture levels are found, this active layer seldom exceeds 1 m in thickness, while in drier soil this thickness may be 2-3 m or more. It is logical that these permafrost areas are responsible for contributing a large percentage of the peak flow for both snowmelt and rainfall runoff events. When permafrost exists, a thick layer of organic material usually can be found. Where the frozen mineral soil beneath this organic material has a high moisture content, the usual case, downslope flow occurs above the mineral soil, through the highly conductive organic material. This is true for both frozen soil conditions that exist during snowmelt and unfrozen summer conditions.

Disregarding the flow properties of the soil system, if the snowmelt rate or rainfall intensities are low, soil water will be transmitted vertically downward until either the water table or an impermeable barrier is reached. Historically, rainfall intensities and snowmelt rates are low in cold regions. Snowmelt events tend to be of several days duration and are directly related to the total snowpack content and climatic conditions. The point to be made here is that, if the rainfall or snowmelt event proceeds slowly, significant near-surface horizontal flow may not develop due to the lack of saturation.

Complementary Research

Various aspects of subsurface flow and subsurface systems in northern areas have been studied to help understand a complete spectrum of problems. Several mathematical flow models with differing degrees of complexity have been developed for application elsewhere; as most of these models are derived using the same basic principles and assumptions, they will not be recapitulated here. Remson, Horberger, and Molz (1971) summarize many of these modeling techniques. Described here is that work relative to an understanding of natural flow systems in cold regions.

In order to understand subsurface flow adequately, it is necessary to have a handle on various hydraulic properties of the soils systems; for this reason we are including consideration of both the organic and mineral layers. Retention and conduction of soil water are the two properties of greatest interest for flow models (this list becomes much longer if heat transfer is included in the calculations). Obtaining retention curves and the saturated hydraulic conductivity of mineral soils is not difficult and, in fact, has been determined in many studies. Methods of obtaining the unsaturated conductivity have been formulated using moisture retention curves and saturated hydraulic conductivities. Unfortunately, similar data for frozen soils are almost completely absent.

Williams and Burt (1974) made some measurements of the saturated hydraulic conductivity of frozen silt as a function of temperature (0 to -0.5°C). Dingman (1975) reviews and synthesizes hydrologic data on frozen ground for relevant research published prior to 1972. Kay, Hons, and Goit (1975) and Plamondon, Black, and Goodell (1972) have examined the hydrologic properties of organic soils, in particular water retention characteristics. Plamondon, Black, and Goodell (1972) also arrived at some values of the unsaturated hydraulic conductivity for negative potentials ranging from -1 to -100 cm of water. Dingman (1971), in the laboratory, found values for the saturated hydraulic conductivity of organic soils for a positive range of hydraulic gradients. Field measurements of moisture content at various sites are included in a report by Kane, Luthin, and Taylor (1975) for a one-year cycle. No attempt was made to separate the frozen and unfrozen portions of the soil moisture content for freezing conditions. Field tensiometer data is reported by Guymon (1975), Luthin and Guymon (1974), and Kane, Luthin, and Taylor (1975). Berg (1975) has used a pressure transducer tensiometer to measure tension in man-made roadway fills where seasonal frost exists.

The model discussed in this paper is strictly a flow model; eventually, if one is going to predict flow for a system that is partially frozen, a heat component will have to be added to the model. Several coupled models of heat and mass transfer exist, even for a case in which phase change occurs. The emphasis of these models has been directed at the problem of frost-heaving. The justification for a model of the type discussed in this paper is based on the fact that major runoff events occur over a relatively short period of time and the boundaries of the system change very little during this period. For example, the decay of seasonal frost over a week will amount to only a few centimeters.

Flow Model

Because of the sparseness of data verifying coupled heat and moisture models and the need to explore further heat and moisture fluxes in layered soils, particularly during winter, it was felt that a flow model would initially yield more useful information. To pursue this, a subsurface hydrologic model was developed to study water flow in these soils. The model is two dimensional and simulates a flow region having uniform slopes of variable length and inclination. It was developed for a shallow two-layered soil system. Consideration was given only to a one-layer system in earlier modeling. At prescribed time intervals, rainfall or snowmelt can be simulated. The resulting movement of water downslope was then evaluated in terms of hydrostatic pressure head, flow velocity, and moisture content at different soil depths along the slope. The initial model simulates water movement following a single storm and for a given antecedent moisture condition. The shallow flow is one of an organic layer over a mineral layer and represents porous media with highly varying thermal and soil moisture properties. The relative geometry of the various layers is based on measurements made in natural flow systems.

The model is basically developed by utilizing the transient equation for liquid water transport in soil created by hydraulic gradients (Equation 5). This is the expression for Darcian-type flow in two-dimensional coordinates without sources and sinks. For saturated, porous media that is uniform and isotropic, this equation becomes the familiar Laplace-type expression. To solve Equation 5, experimental relationships between soil water content and pore water pressure head and those between soil hydraulic conductivity and pressure head were utilized.

A numerical analysis method is used in the solution of this partial differential equation. First, the derivative terms in Equation 5 are expressed in finite-difference form. The latter equation is applied to each point in a two-dimensional grid that covers the flow region. These equations are then solved for pressure head H at various times t by the alternating-direction-implicit technique. The latter technique is essentially that reported by Douglas, Peaceman, and Rachford (1959) and Rubin (1968). The entire computing operation is programmed for an IBM 375/165 electronic computer.

In the analysis, we assume the mineral layer to be resting on an impermeable floor, the latter due to permafrost or an impervious soil layer. Both organic and mineral layers can be characterized by experimental relationships among media water content, pressure head, and hydraulic conductivity. Estimated values for H are assigned initially to all grid points, then the resulting values are computed at time t by solving Equation 5. A rainfall rate R can be simulated at the ground surface for specified time intervals. Water flow is evaluated following a single storm or snowmelt event and for a sequence of storms. The computed values of H will reveal time patterns of water content and flow velocities at various elevations and for different thickness and water-transmitting properties of the active layer:

$$\frac{\partial}{\partial x}\left(K(\psi)\,\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(\psi)\,\frac{\partial H}{\partial y}\right) = S\,\frac{\partial \psi}{\partial t} \tag{5}$$

where

- ψ = $\frac{P}{\rho g}$ = the hydrostatic pressure head in the porous medium
- P = the hydrostatic pressure, also referred to more appropriately as pore pressure
- H = the hydraulic head ($\psi + y$)
- $K(\psi)$ = the hydraulic conductivity of the medium (for negative values of ψ, K is a function of ψ)
- S = $\frac{\partial \theta}{\partial \psi}$ = the specific moisture capacity of the medium
- θ = the water content of the medium expressed as a total volume fraction
- x, y = the coordinate directions, y being parallel to the earth's gravitational field
- ρ = mass fluid density
- g = gravitational field strength
- t = time

The two experimental relationships between soil water content and pore water pressure head and between hydraulic conductivity and pressure head used in the solution of the partial differential equation are:

$$K = K_o/(A_k\psi^3 + 1) \tag{6}$$

$$\theta = \theta_o/(A_\theta\psi^3 + 1) \tag{7}$$

where

- K = unsaturated hydraulic conductivity
- K_o = saturated hydraulic conductivity
- θ = unsaturated soil moisture content
- θ_o = moisture content under saturated conditions
- A_k, A_θ = constants

Use of these equations and proper selection of the constant A are discussed in a paper by Taylor and Luthin (1969). These constants were selected for an organic soil with a saturated water content of 0.90

cm^3/cm^3 and a hydraulic conductivity of 50 cm/hour. These values of hydraulic conductivity and moisture content under saturated conditions are comparable to the values described by many researchers, particuarly Dingman (1971) in his work on the Glenn Creek watershed just north of Fairbanks. The relationships discussed in an earlier section of this report had not been developed at the time these computer simulations were made, otherwise they would have been used.

In this model the boundary conditions are presented as follows:

1. There is neglible water in the channel
2. There is no moisture flux across the lower boundary or the up-slope vertical boundary
3. No moisture flux exists across the surface boundary.

The stipulation that there is no moisture flux across the surface boundary is flexible. The program is written in order that fluxes can be handled across the boundary; however, because of the variability of this particular flux, it was felt that, for the comparison of cases where the slope and hydraulic properties were varied, a simple approach would be used. This approach assumes that the shallow layer is saturated initially (t=0), then the outflow from this sloping slab is calculated as time progresses. Other than fluid and media properties, the two major variables of importance in any slope drainage problem are the dimensions and per cent of slope. The variability of both of these features in natural settings is well appreciated. Due to the computer cost for each run, only a few runs with selected slope angles and slope lengths were made.

The output from this model is in tabular form with the position of the water table (saturated-unsaturated interface) indicated for various times by the calculated pore pressures. The computer results of four cases are shown in the following figures: two cases for a single-layered system with slopes of 5% and 10% (Figure 13) and two cases of double-layered system with the same slopes (Figure 14). The hydraulic conductivities used in these computer runs were selected with a view to obtaining similar results without the aid of a computer. For example, in Figure 13, the hydraulic conductivity selected was 1 cm/hr. If the actual hydraulic conductivity is 50 cm/hr then the position of the water table at various times could be obtained by dividing the selected times

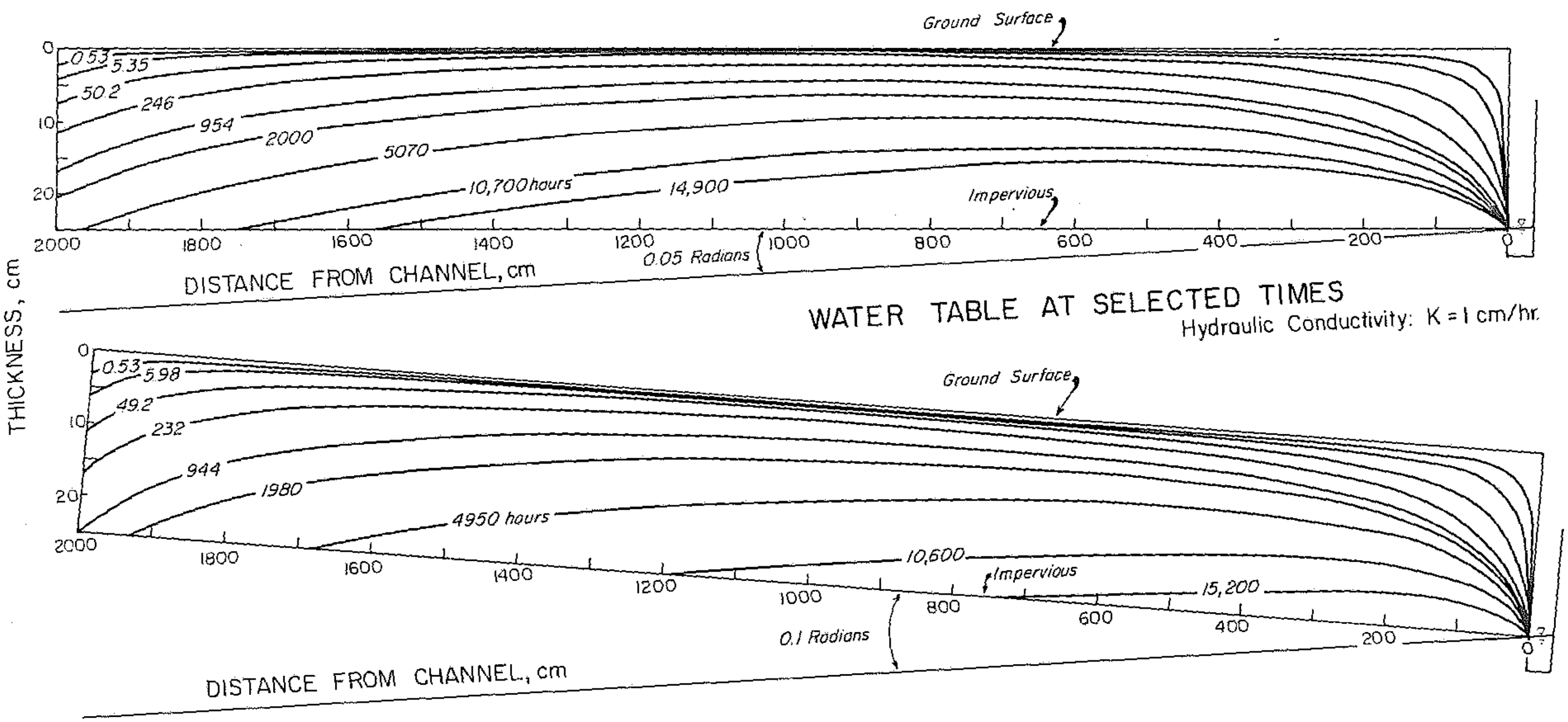


FIGURE 13: POSITION OF WATER TABLE AT VARIOUS TIME INTERVALS FOR A SINGLE-LAYERED SYSTEM.

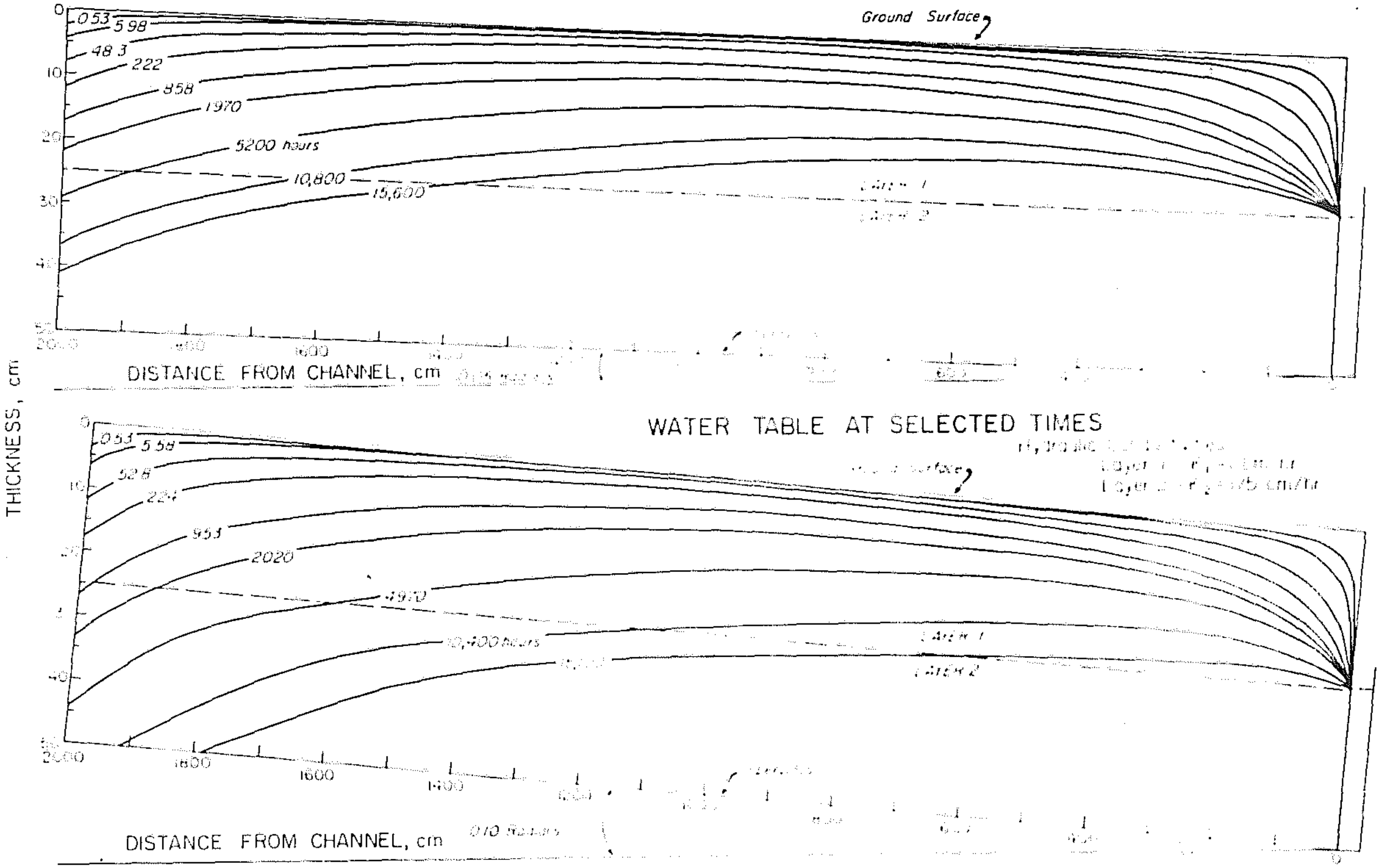


FIGURE 14: THE POSITION OF THE WATER TABLE OF A TWO-LAYERED SYSTEM WITH DIFFERENT HYDRAULIC PROPERTIES.

by 50, for the given slope and slope length. For the two-layered system we have given the hydraulic conductivity of the lower layer as 1/5 the upper layer. Similar manipulation of this data can be made for other conductivities so long as the ratio of the two hydraulic conductivities remain the same.

The next step is to show the channel outflow for these four systems (Figures 15 and 16); the level in the stream channel was maintained at the lower surface of the upper layer for all cases. The outflow results for other hydraulic conductivities (for given slopes and slope lengths) can be obtained by dividing the time scale by the new conductivity (if it is greater than the given conductivity) and multiplying the outflow scale by the same number.

It should be noted in the figures (13 and 14) with the water table shown at selected times that the position of the water table at the upper end of the slope appears to be lower than the water table at points downslope. This is not the case; we have drawn the slopes to scale, while simultaneously introducing vertical exaggeration into the thickness of the element. If everything is drawn to scale, then the elevation of the water table can be seen to decrease as one proceeds downslope.

Conclusions of the Groundwater Modeling Study

The need for better quantitative understanding of the role of subsurface flow in cold regions is apparent. Increased demand for subpermafrost groundwater has resulted in the mining of this water. Water flow in the near-surface soil layers is primarily responsible for the peaks in the surface runoff events. Where alteration of this surface layer occurs, such as burning of the organic layer, significant changes in the magnitude and timing of the runoff may happen. While some of these changes can be measured in the field, it is advantageous to predict by modeling the apparent magnitude of these changes. Developed in this discussion is a two-dimensional flow model that indicates the rate of drainage of a saturated layer given the geometry and hydraulic properties of the slab and the modeling assumptions. If actual values of the moisture flux across the ground surface are incorporated into the model (with the initial moisture contents) the resultant rate of runoff

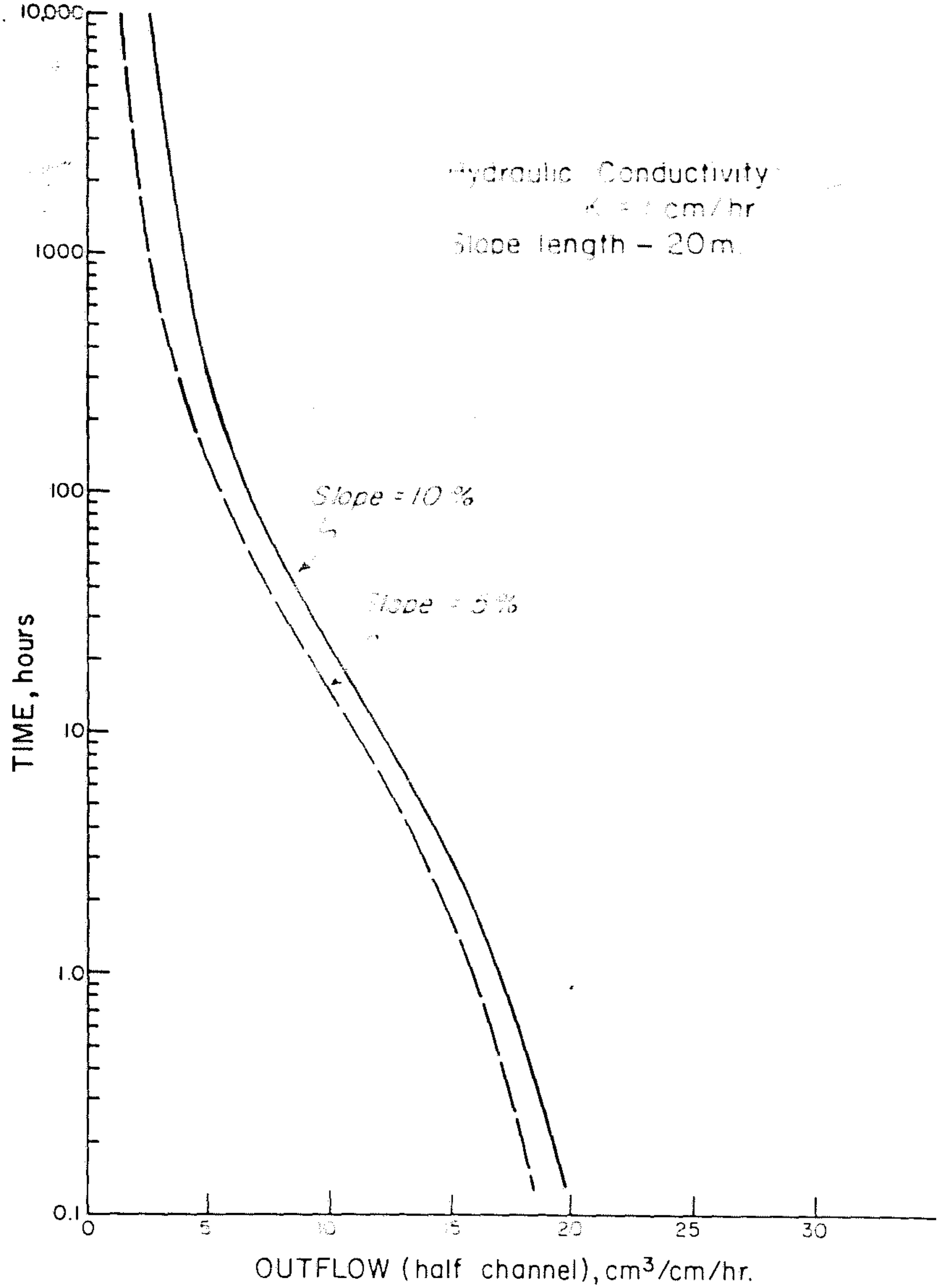


FIGURE 15: A PLOT OF THE OUTFLOW RATES FOLLOWING THE INITIATION OF FLOW FOR VARYING SLOPES OF A SINGLE-LAYERED SYSTEM.

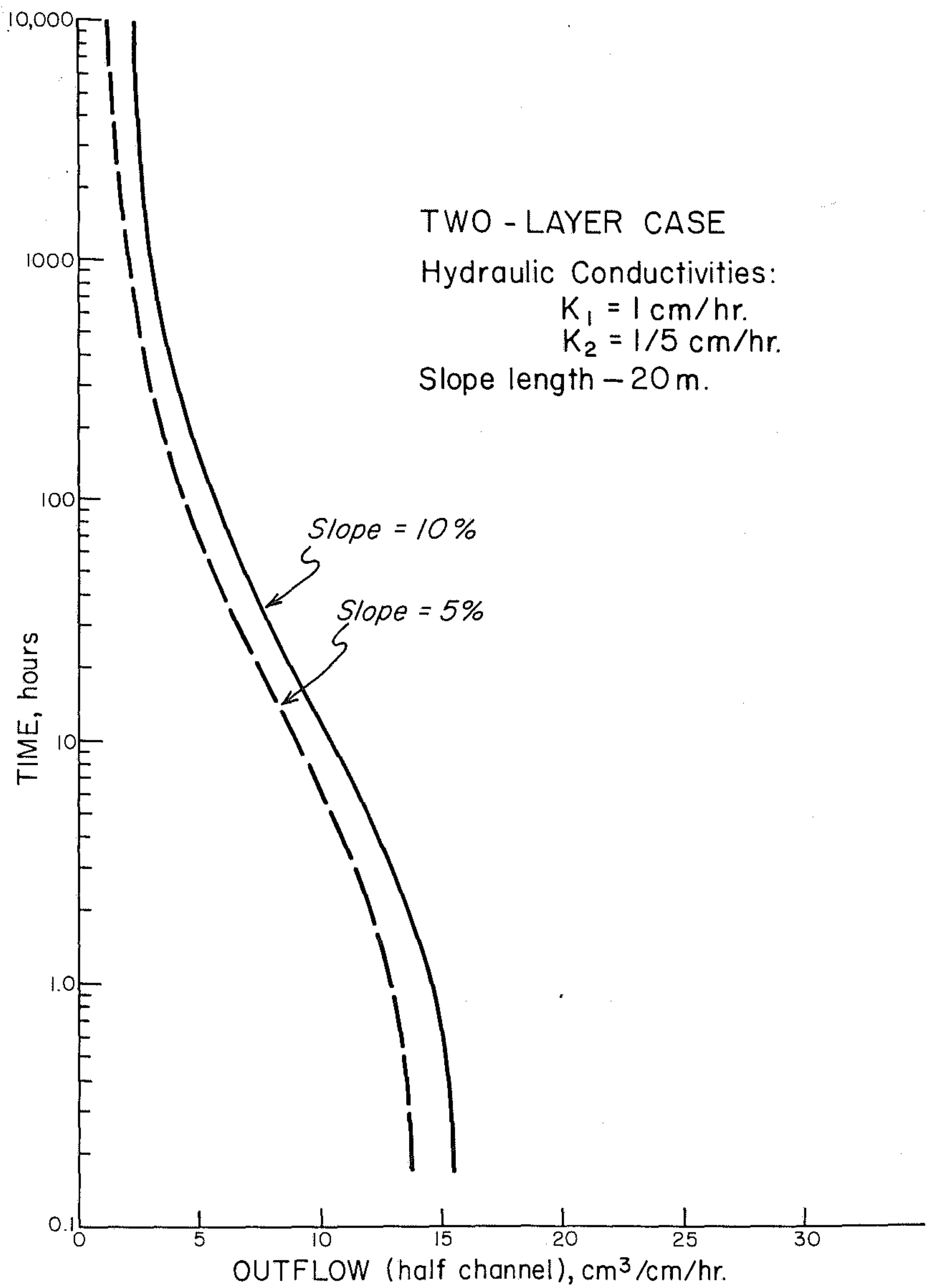


FIGURE 16: A PLOT OF THE OUTFLOW RATES FOR A TWO-LAYERED SYSTEM FOLLOWING INITIATION OF FLOW.

can be determined for different mutations of the system. While the full potential of this model has not been utilized, these results should be useful in understanding the hydrologic processes of surface runoff and groundwater recharge.

CONCLUSIONS

Because of the role that the organic layer plays in controlling the transfer of heat and moisture, it is required that properties of this soil layer be well understood. Several parameters of hydrologic interest were examined in this study with the following conclusions:

1. It appears that major changes in moisture content in the organic layer occur with only a slight change in the pore pressure. This result was concluded from the insensitive measurements made with various field tensiometers and laboratory data collected when developing a characteristic curve of extraction pressure and moisture content. From saturation to an extraction pressure of 0.04 bars ($\sim$40 cm H_2O) the moisture content by volume declined from 59% to 12%. For moisture contents less than 12% by volume, the pore pressure is quite sensitive to changes in moisture content; rarely were measurements of moisture content of less than 12% measured in the field below the 10-cm depth (depth of shallowest tensiometer). These results indicate that for most of the moisture regime, although large fluctuations in moisture content occur, tensiometers are not sensitive enough for use.
2. Moisture content expressed as a volume fraction is more meaningful where there is a large change in the bulk density. To determine the bulk density for each sample to be analyzed is quite time consuming. It was hoped that a relationship between dry bulk density and depth could be developed for all samples. From the limited number of samples used, it was obvious that there was a large variation in dry bulk density at a given depth. Some of this variation can be estimated if the total thickness of the organic layer is considered.
3. The intensity of the prescribed burns was related to the moisture content at depth. Although there were three sites burned on 26 August 1976, the moisture conditions that existed at these sites were similar. During the earlier burn, the

moisture content at depth (>10 cm) was much higher, resulting in less organic material being consumed. Where the dry bulk density is low, such as near the air-ground interface, even low moisture content is capable of limiting the spread of ground fires.

4. The measurement of water downslope through the organic layer is responsible for the generation of high flows in streams, especially in the case where the organic layer is underlain by permafrost. High ice content in the active layer of the mineral soil and near the top of the permafrost is responsible for substantially reducing the hydraulic conductivity that results in near saturation conditions existing near the surface at the intensive study site for most of the summer.

REFERENCES

Berg, R. L. 1975. Heat and moisture flow in freezing and thawing soils--A field study. American Geophysical Union, Calgary, Alberta, May. pp. 148-160.

Bliss, L. C. 1962. Caloric and lipid content in alpine tundra plants. Ecology. 43:753-757.

Dingman, S. L. 1971. Hydrology of the Glenn Creek watershed, Tanana River Basin, Central Alaska. U. S. Army Cold Regions Research and Engineering Laboratory, Research Report 297.

Dingman, S. L. 1975. Hydrologic effects of frozen ground, literature review and synthesis. U. S. Army Cold Regions Research and Engineering Laboratory, Special Report 218.

Douglas, J. D.; Peaceman, W.; and Rachford, H. H. 1959. A method for calculating multi-dimensional immiscible displacement. Amer. Inst. Mining, Met. & Petrol. Eng., Trans. 216:297-308.

Furbush, C. E., and Schoephoerster, D. B. 1974. Soils of the Wickersham Dome Experimental Forest, Alaska. USDA, Soil Cons. Ser.

Green, R. E., and Corey, J. C. 1971. Calculation of hydraulic conductivity: A further evaluation of some predictive methods. Soil Sci. Soc. Amer. Proc. 35:3-8.

Guymon, G. L. 1975. Soil-moisture-temperature for Alaskan lowland. Journal of the Irrigation and Drainage Division, ASCE. 101(1R3): 187-199.

Hoch, D. 1976. Selected climatic characteristics - Washington Creek experimental area intensive study site - summary 1976. U. S. Forest Service, Institute of Northern Forestry.

Kane, D. L.; Luthin, J. N.; and Taylor, G. S. 1975a. Heat and mass transfer in cold regions soils. University of Alaska, Institute of Water Resources, Fairbanks. Report No. IWR-65.

Kane, D. L.; Luthin, J. N.; and Taylor, G. S. 1975b. Physical Transfer processes in subarctic soils influenced by forest fires. IN: Proceedings, Conference on Soil Water Problems, American Geophysical Union, Calgary, Alberta, May. pp. 128-146.

Kay, B. D.; Hons, D. B.; and Goit, J. B. 1975. Thermophysical characterization of the surface tier of an organic soil. IN: Proceedings, Conference on Soil-Water Problems in Cold Regions, American Geophysical Union, Calgary, Alberta, May. pp. 112-127.

Luthin, J. N., and Guymon, G. L. 1974. Soil moisture--vegetation temperature and relationships in central Alaska. Journal of Hydrology. 23:233-246.

Plamondon, P. A.; Black, T. A.; and Goodell, B. C. 1972. The role of hydrologic properties of the forest floor in watershed hydrology. National Symposium on Watersheds in Transition, American Water Resources Association, Ft. Collins, Colorado, June 19-22. pp. 341-348.

Remson, I.; Horberger, G. M.; and Molz, F. J. 1971. Numerical Methods in Subsurface Hydrology. Wiley Interscience.

Rowe, J. S.; Plittlehouse, D.; Johnson, E.; and Jasieniuk, J. 1975. Fire studies in the upper MacKenzie Valley and adjacent Precambrian uplands. Department of Indian Affairs and Northern Development, Report ALUR 74-75-61.

Rubin, J. 1968. Theoretical analysis of two-dimensional transient flow of water in unsaturated and partly saturated soils. Soil Sci. Amer. Proc. 32:607-615.

Taylor, G. S., and Luthin, J. N. 1969. Computer methods for transient analysis of water table aquifers. Water Resources Research, 5(1):144-152.

Viereck, L. A.; Foote, M. J.; Dyrness, C. T.; VanCleve, K.; Kane, D. L.; Seifert, R. D. 1977. Preliminary results of experimental fires in the black spruce type of interior Alaska. Manuscript, U. S. Forest Service, Institute of Northern Forestry, Fairbanks, Alaska.

U. S. Dept. of Agriculture, Soil Conservation Service. 1963. Soil Survey, Fairbanks, Alaska.

Walkotten, W. J. 1972. A recording soil moisture tensiometer. U. S. Dept. of Agriculture, Forest Service, PNW-180.

Williams, P. J., and Burt, T. P. 1974. Measurement of hydraulic conductivity of frozen soils. Canadian Geotechnical Journal 11:647-650.