HYDRAULIC CONDUCTIVITY OF MOUNTAIN SOILS

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Owen R. Williams
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Owen R. Williams, Stanley L. Ponce, James R. Meiman and Mark Spearnak

Department of Earth Resources

Colorado State University

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COLORADO WATER RESOURCES RESEARCH INSTITUTE
Environmental Resources Center
Colorado State University
Fort Collins, Colorado

Norman A. Evans, Director

ABSTRACT

Pathways and rates of delivery of snowmelt runoff from a subalpine coniferous forest watershed were studied through the examination of saturated hydraulic conductivity, soil moisture tension and litterflow measurements. Measurements were taken from litterflow collectors and four soil pits 2.5 meters deep located on north and south aspects.

During the period of snowmelt, runoff was carried as surface and near-surface flow in the litter layer and upper 4-5 cm of mineral soil. Saturated or near-saturated flow occurred at the base of the soil pits. The majority of the soil profile transmitted soil moisture as unsaturated flow. Hydraulic conductivity determinations indicated that under saturated conditions the potential percolation through the soil mass would generally be in excess of the normal snowmelt rate.

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INTRODUCTION

The demand on the natural resources of the subalpine coniferous forest is ever increasing. This area is being subjected to environmental manipulation through timber harvesting recreational development, road construction and increased human activity. Numerous watershed models have been developed to predict the impacts of land management on the hydrologic system (Anderson, 1973; Carlson, et al., 1956; Crawford and Linsley, 1966; Leaf and Alexander, 1975; Leaf and Brink, 1973a, b, 1975; U. S. Army, 1972; Weeks, et al., 1974).

While these models generally serve their intended purposes, there is a need to better understand and describe the various processes operative within the watershed system as a whole. Such understanding and description can improve the theoretical basis and the adaptability of these models. An inherent difficulty in many models is that of extrapolation to different watersheds or regions. By improving the adequacy of the descriptions of the processes involved, the potential for such extrapolation is facilitated.

An essential aspect of most watershed models is the movement of moisture from its location on the soil surface to its ultimate position in the stream channel. Numerous studies have been directed toward this area (Alexeev, et al., 1972; Anderson, 1968; Colbeck, 1974; Freeze, 1971, 1972a, b, c; Harlan, 1972; Hunt, 1970). Most, however, have considered input in the form of rainstorm events. In the high mountain regions, the input is more likely to be a melting snowpack. This provides input at rates and durations which may be greater than record rainfall events.

The objectives of this study were to identify soil moisture pathways and to quantify the rate of water movement in selected subalpine soils during the period of snowmelt runoff.

PAST WORK

In a study of the melting of late lying snow patches in Colorado, DeWalle (1969) observed that percolation accounted for 57 percent of melt at a soil depth of 40 cm, 57 percent at 65 cm and 40 percent at 103 cm. He noted that localized zones of saturation developed in the soil profile and that the zones did not extend throughout the profile. Lower portions of the profile showed moisture tension while upper showed positive pressure. Saturated lateral flow was observed on the steep slopes studied. The role of moisture impeding layers was concluded to be significant in the movement of soil moisture through the soil profile.

The importance of impeding layers in the movement of soil moisture was also noted by Anderson (1970). He stated that traditional concepts of surface runoff, infiltration capacity and surface detention bear little relation to the way water is actually delivered on a forested watershed. He observed that water usually tends to enter the soil readily and then travel by a variety of paths to reach stream channels. Further, such movement frequently occurs in a vertical direction to a layer of different texture and then laterally along the interface downhill to its point of discharge.

In a study in the Idaho Batholith of subsurface flow interception by roadcuts. Megahan (1972) also noted the importance of impeding layers. He observed that the saturated hydraulic conductivity for bedrock is almost always less than that of soil; in his study he found a difference of two orders of magnitude. This difference would then act as a substantial impediment to downward flow and, he felt, could assume a role such as described by Whipkey (1965).

In Megahan's work the seepage from a roadcut was intercepted and collected in a trough and compared to moisture input to the watershed above the collection point. He observed that no overland flow occurred at any time and that significant subsurface flow was measured only during the spring snowmelt period. In addition, peaks of subsurface flow were found to lag about 1.5 days behind those of inflow. It was concluded that approximately 65 percent of subsurface flow passed beneath the level of the roadcut, i.e. within bedrock.

In north-central Alberta, Holecek and Noujaim (1972) studied runoff from a six ha snow covered plot which they contaminated with Iodine-125. The tracer was applied to the snow cover from a helicopter over a period of four years during which the relative contributions of surface and subsurface flows to runoff were evaluated. This tracer was found to be trapped in the soil when carried by subsurface flow but retained in overland flow.

They found that under undisturbed soil conditions the contribution of overland flow to total runoff varied between 45 and 75 percent with subsurface varying between 55 and 25 percent. They observed that these values depended upon the degree of soil saturation, the amount of water in the snowpack and the thaw pattern. Further, they stated that when basin storage requirements are satisfied, the volume of recharge from snowmelt is approximately equal to the volume of subsurface flow, i.e. snowmelt subsurface runoff is old basin storage replaced by new recharge.

Martinec (1975) studied snowmelt runoff through examination of tritium concentrations. He found that a substantial portion of the meltwater did not leave the basin. For the 1,000 meter travel distance studied, normal subsurface flow velocities (e.g., 0.7 meter/day) were in reasonable agreement with observed tritium residence times (e.g., 4 years). As a result, he proposed a mechanism to reconcile the low velocity of infiltrated meltwater and the quick response of the storm hydrograph. He stated, "The massive infiltration of meltwater causes a corresponding increase of outflow from groundwater reserves. The infiltrated water, while slowly moving underground, appears already 'in substitution' in the hydrograph represented by water stored hitherto in the subsurface reservoir." He also observed that such substitution does not result from piston flow entirely, but rather is accompanied by dispersion and mixing.

Reid (1973) made a study relating runoff to slope aspect in Britain. He used north- and south-facing slopes of the Caydell drainage and noted that while groundwater seepage and spring effluent are more characteristic of north-facing slopes, cumulative annual differences in evaporative water loss between slopes of different aspect were not large.

In another study involving similar factors affecting runoff, a statistical evaluation of soil moisture was made on data from Colorado and New Mexico (Engelen, 1972). It was found that, for moisture content as a percentage of total maximum water holding capacity and for the coefficient of variation there was no relation between fluctuation patterns and slope angle, there was no relation between fluctuation patterns and soil type, no station ever became fully saturated or at field capacity as a mean condition and absolute soil moisture content and percentage soil moisture decreased with increasing elevation.

Snow and ice have also been found to affect soil water movement. Alexeev and others (1972) gave consideration to the movement of water into frozen soil. In developing formulae to describe infiltration under such circumstances, it was found that infiltration was directly affected by the cold content of the soil mass. A parameter, "critical temperature," was developed which described the negative soil temperature at which the cold content is sufficient for ice to block all the free pores. This value was found to be a function of soil weight and the amount of bound water not freezing at the negative temperature considered.

A similar study by Komarov and Makarova (1973) determined that ice content and depth of freezing were the main factors determining soil permeability prior to snowmelt. In addition, although the effect of temperature was unknown, it was regarded as significant.

It was observed by Peck (1974) that soil moisture beneath a snow cover increased during winter. The primary mechanism responsible was felt to be the upward movement of moisture, both liquid and vapor. Such movement was found to occur with or without the presence of frozen conditions when induced by a temperature gradient.

Colbeck (1974), in considering water flow from a snowpack over frozen soil, presented a two-layer model in which there occurs vertical unsaturated flow to a layer of saturated horizontal Darcian flow.

The importance of snow in modifying watershed runoff was also noted by Sturges (1975). In his study he described the phenomenon of oversnow runoff. This form of water delivery was found to occur in windswept areas where snow had been compacted and was most likely to be found in intermittent stream channels. The most important factor triggering oversnow runoff was a restriction on flow at the ground-snow interface.

Under conditions of oversnow runoff, it was observed that peak runoff and delivery efficiency increased. In addition, water loss to recharge and deep seepage were minimized. There also occurred an increase in total annual streamflow as a percentage of precipitation input.

In a study of the effects of frost and frozen soil on infiltration, Haupt (1967) identified three types of frost, stalactite, concrete and porous concrete, and found that the movement of moisture into the soil was directly influenced by the type of frost encountered. In applying simulated rainfall to study plots having frozen soil, he also observed that infiltration decreased during the first hour of rainfall and then increased.

The importance of frost was also studied by Harlan (1973). In his study, it was found that the groundwater level lowers and soil water storage in the frost zone increases during winter. The growth of the frost layer was felt to arise from a migration of liquid water in response to a hydraulic gradient caused by a decrease in pore-water pressure at the frozen-unfrozen soil boundary. A rising of the groundwater level in spring was felt to result largely from the redisposition of the moisture from the frost wedge.

Although several investigators have studied subsurface flow in mountain watersheds and the effect of snowmelt on streamflow, little work has been done concerning the pathways and rate of meltwater movement through soils of the Rocky Mountain region.

STUDY AREA

The Deadhorse Creek watershed was selected as the area for this study. It is located within the U. S. Forest Service's Fraser Experimental Forest about 120 km, by road, west of Denver and 8 km southwest of Fraser, Colorado. The watershed covers an area of approximately 370 ha, ranging in elevation from 2,788 to 3,512 mmsl. Deadhorse Creek has a drainage lenght of about 3.6 km.

The climate of the study area is characterized by long, cold winters and short, cool summers. The average annual temperature is about 0.5^{o}C with average monthly temperatures below freezing six months of the year. Prevailing winds are westerly and carry much of the 38 to 76 cm of annual precipitation, two-thirds of which occurs as snow (Retzer, 1962).

The study area lies within the subalpine coniferous forest of the west slope of the Colorado Rocky Mountains. Vegetation of the area consists predominantly of Engelmann spruce (Picea engelmannii), subalpine fir (Abies lasiocarpa), lodgepole pine (Pinus contorta) and quaking aspen (Populus tremuloides).

The soils of the study area have been derived from a mixture of gneiss and schist rocks. These rocks have not experienced advanced weathering. Weathering that has occurred has been largely mechanical rather than chemical. The differences displayed in soils of the area are largely a consequence of the effects of variation in aspect and vegetation rather than difference in parent material (Retzer, 1962). The soils on the south-facing slopes are of the Bobtail soil type while those of the north-facing slope are of the Darling soil type.

The Bobtail gravelly sandy loam soil type of the Bobtail series is classified as Sols Bruns Acides. These soils contain large amounts of sand, gravel and stone and are found primarily on steep, south-facing slopes. The Bobtail soils are moderately shallow and coarse textured with large pores. Consequently these soils are rarely saturated. The profile displays a thick layer of weathered rock above bedrock at a depth of 1.5 to 2.4 m and includes a 7.6 cm surface soil over 99 cm of subsoil. The C horizon is about 30 cm thick. The Bobtail soils are very strongly acid at the surface and decrease in acidity with depth in the profile. All profile horizons display moderately rapid to rapid permeability.

The Darling gravelly sandy loam soil type of the Darling Series is classified as a Podzol. This soil, like the Bobtail, is coarse and gravelly producing high porosity and rapid infiltration. The soils of this series are found on steep, north-facing slopes and range in thickness from 76 to 102 cm. They are slightly more acid than the Bobtail soils and have a thick "mor" type litter layer. The profile includes 8 cm of surface soil over a 90 cm subsoil. The substream is nearly 110 cm thick.

The Darling soils are well to somewhat excessively drained with permeabilities within the profile of moderately rapid to rapid. These soils, however, hold more moisture for longer periods than do the Bobtail soils.

METHODS

Soil Pits

Four soil pits were constructed for study of hydraulic conductivity and soil moisture content at various depths in the soil profile. These pits were dug by hand during the summer of 1975 and measured 2.5 m deep, 2.5 m long (parallel to the slope contours) and 1 m wide. Surrounding vegetation and litter upslope and adjacent to the pits were left undisturbed. The pits were reinforced on both the upslope and downslope sides with corrugated steel braced with 10 by 20 cm wooden beams. Excavated material was piled downslope of each pit.

Two pits were located on each of the south-facing and north-facing slopes. The two pits on each slope were located adjacent but above one another and separated by a slope distance of 23 m on the north-facing slope and 10 m on the south-facing slope. The lowest pit was located at a slope distance 62 m from the streambed on the north-facing slope and 39 m on the south-facing slope.

The pits are referenced as 1 and 2, respectively, for the north-facing lower and upper positions and 3 and 4, respectively, for the south-facing lower and upper positions.

Soil Core Sampling

Soil cores were obtained from various depths in the soil pits for the determination of hydraulic conductivity. Samples were collected from three levels in the soil profile in September 1975 while a near-surface core was collected at a later date. With the exception of the near-surface core, core sample location was chosen to monitor the points at which the tensiometers would be inserted. Samples were collected in duplicate separated by 30 to 60 cm within the same soil profile horizon.

A core sampler was designed and constructed at the Porous Media Laboratory of the Engineering Research Center at Colorado State University and was based on the approach of Laliberte and others (1966 and 1967). The sampler was designed to produce an undisturbed cylindrical core sample 5.08 cm long and 2.91 cm in diameter. After the soil cores were extracted, the cylinder containing the soil was removed from the sampler, trimmed and clamped between plexiglass plates. To minimize disturbance, the samples were then packed in loose styrofoam packing material and placed on air bubble packing material for transportation.

Hydraulic Conductivity Determination

Hydraulic conductivity measurements were made at the Colorado State University Engineering Research Center. The samples were removed from the plexiglass clamps and placed between plexiglass discs. These discs were sealed about the sample cylinder to prevent air entry. The sample was then vacuum saturated with tap water under a gas pressure of 50 mm of Hg or less. Once saturated, the vacuum was removed and the samples were allowed to drain with virtually constant head. Air trapped near piezometer tube outlets was bled off and slow, steady flow was established.

When equilibrium was attained, discharge rates and pressure heads were determined. With these data, hydraulic conductivity was then calculated using the Darcy equation.

Tensiometry

Tensiometers were used for the determination of soil moisture tension. Cylindrical holes with a diameter slightly in excess of that of the tensiometer were made in the pit sidewall to allow the tensiometers to be inserted at a slight angle to the horizontal. The base of the hole was then filled with a slurry of fine sand and the tensiometer inserted. Plumber's putty was packed around the in-place tensiometer to prevent the drainage of water into the tensiometer hole. Due to the variations in the soil and rock material in the soil pits, the tensiometers were placed at various depths of penetration and angles of inclination.

During the early part of the study, tensiometers and the adjoining manometers, were filled with water only on the day of observation. This was done to avoid freezing within the system. This attempt, however, was unsuccessful on the north-facing slope during the initial stages of the snowmelt runoff. Some freezing occurred and consequently some early season data loss. The filling of the tensiometer systems with tap water was made in mid-morning on the days of observation and readings were made about three hours later to allow system equilibration.

Later in the study when the likelihood of freezing was minimized, tensiometer systems were maintained full of water. They were refilled only to remove accumulated gas bubbles or reunite a broken mercury column.

Tensiometers were read every few days. On 28/29 May, tensiometers were monitored for 24 hours to evaluate diurnal soil moisture fluctuation.

Litter Layer Moisture Content and Flow Pathway Determination

During the course of study it was observed that surface or near-surface runoff had occurred in the study area. It was therefore determined that samples of the forest litter should be evaluated for water content. A small snow patch on a north-facing slope was selected for study and a 3 m transect was laid out immediately downslope. Litter samples were removed at the snow patch edge and at 30 cm intervals for the length of the transcent during the mid-afternoon of May 29, 1976. No significant precipitation had occurred for a period of 48 hours prior to sampling. Samples were placed into air tight containers as they were removed and frozen shortly thereafter. These samples were transported frozen to the Department of Earth Resources at Colorado State University where water content was evaluated gravimetrically according to procedures outlined by Gardner (1965).

During the 1977 snowmelt season the flow of meltwater from snow to litter, litter to soil and litter to downslope litter was measured with galvanized steel collection pans. Five different types of collectors enabled separation of vertical and downslope litterflow components (Figure 1).

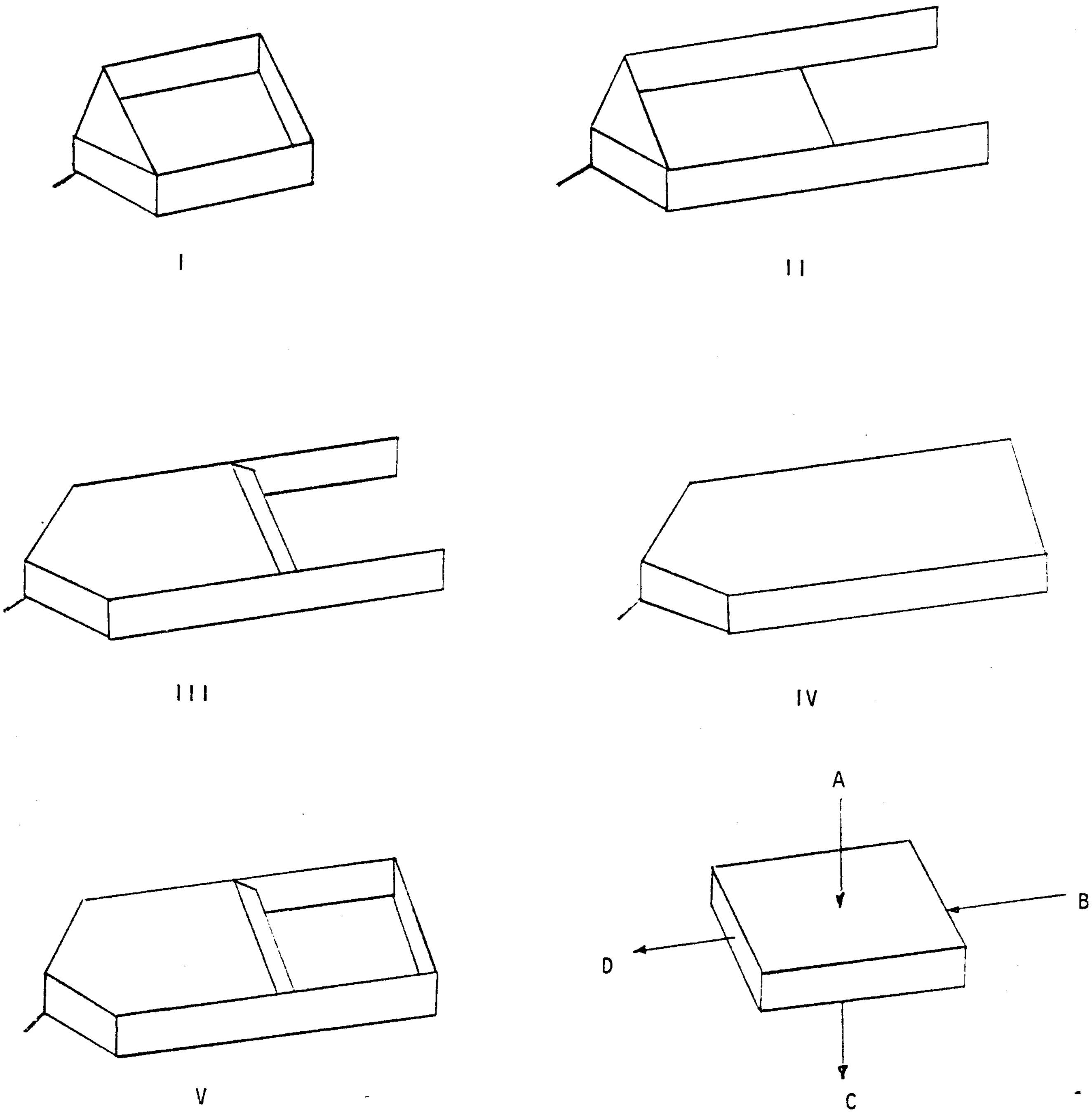


Figure 1. Collector types and litterflow components.

Collector Type I, a box 30 cm X 30 cm X 8 cm deep, open at the top with a tapered downslope end and a drain for water collection was designed to measure flow of meltwater to litter (component A) from snow directly above the collector (Figure 1).

Collector Type II was essentially Type I with the upslope wall removed and sides extended 30 cm upslope. It measured combined flows of meltwater directly above the collector (component A) and meltwater flowing downslope through the litter (component B).

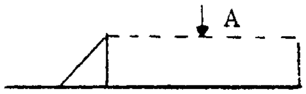
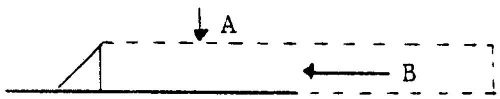
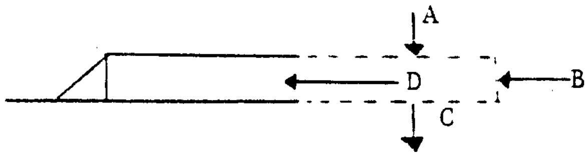
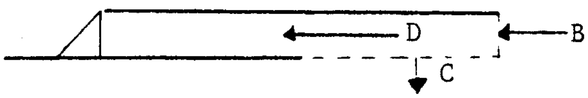
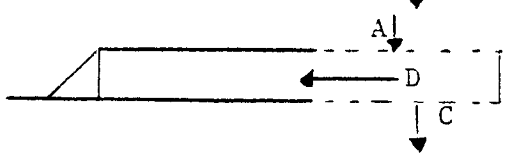
Collector Type III resembled Type II but had a top 30 cm X 30 cm X 35 cm long, which is extended 5 cm on the upslope end. The extension could be bent downward to exclude meltwater from above which would pass vertically through the litter and into the sampler as a result of slope. Type III measured the downslope component (component D) of litterflow.

Collector Type IV is basically Type III with a top 60 cm long instead of 35 cm. It measured downslope litterflow (component D) minus meltwater input from above for 30 cm upslope (component A).

Collector Type V is like Type III only with an upslope sidewall. It measured downslope litterflow (component D) minus downslope litterflow input from 30 cm upslope (component B).

Water volumes recovered over a known time period were used to resolve litterflow pathways and rates in the following manner. It was assumed that a 30 cm square of the litter layer has only four pathways for water flow (Figure 1, components A, B, C, D). It was also assumed that no lateral flow or evaporation occurred and conservation of mass exists so that the sum of litterflow components A and B equals C and D during steady state. If X_i represents the volume sampled by collector type i then the various collectors measured the components summarized in Table 1.

Table 1. Flow components measured by the litterflow collectors.

Collector Type	Side View	Volume Measured	Components Measured
I		X_1	A = C+D-B
II		X_2	A+B = C+D
III		X_3	D = A+B-C
IV		X_4	D-A = B-C
V		X_5	D-B = A-C

Solving for each component in terms of X_i results in the following equations.

$A = X_1$ (1)

$A = X_5 + X_3$ (30 cm upslope) $- X_4$ (2)

$B = X_2 - X_1$ (3)

$B = X_3$ (30 cm upslope) (4)

$C = X_2 - X_1 - X_4$ (5)

$C = X_3$ (30 cm upslope) $- X_4$ (6)

$C = X_1 - X_5$ (7)

$D = X_4 + X_1$ (8)

$D = X_5 + X_2 - X_1$ (9)

$D = X_5 + X_3$ (30 cm upslope) (10)

There are at least two independent ways to measure each component.

One set of five collector types was installed at approximately 62, 73 and 84 m, slope distance, from the streambed on the north-facing slope adjacent to the soil pits. At the 62 and 84 meter sites an extra Type III was included.

RESULTS AND DISCUSSION

The results of the sand sieve analysis are given in Table 2. It is obvious that there is a preponderance of coarse fragments. This results in a soil with an excess of large pores that tends to be droughty. Generally, the soils of the Fraser area are relatively dry in the fall when precipitation and low temperatures resume. This normally results in the formation of a deep snowpack over a dry soil. The snowpack tends to insulate the soil profile from severe heat losses during the winter. However, when heavy precipitation resumed during the fall preceding this study, an unseasonably warm period forestalled the development of the insulating snowpack which permitted an unusual increase in moisture content of the upper soil profile. This period was followed by a period of low temperatures and as a consequence, the upper portion of the soil profile of the south-facing slope developed concrete frost.

The soils of the north-facing slope did not exhibit frost development. The colder air temperatures of this aspect resulted in the earlier establishment of the snowpack which prevented soil freezing.

An early spring snowmelt on the north-facing slope resulted in moisture precolation through the snowpack and accumulation and melt at the soil/snow interface. This was followed by low temperatures, in which an ice layer 3-5 cm thick developed. Later, this ice layer inhibited the movement of moisture through the snowpack to the soil surface during

Table 2. Sand sieve analysis (values in percent by weight).

Sample		Diameter Range (mm)*						
No.**	Depth (cm)	2	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.10	0.10-0.05	0.05
1-7	8	56.8	14.5	9.4	5.0	6.3	3.9	4.1
1-1	100	34.2	11.6	11.3	8.1	13.0	7.2	14.6
1-2	125	39.4	7.4	9.0	7.9	15.5	7.3	13.7
1-3	180	65.5	14.3	7.2	3.0	3.1	1.4	5.5
2-7	12	56.7	13.3	11.0	5.6	6.4	3.9	3.1
2-1	63	47.0	9.4	6.6	4.5	8.3	6.1	18.1
2-2	97	52.0	12.0	9.8	6.0	8.4	3.8	8.0
2-3	177	59.3	8.4	7.2	4.9	8.1	3.9	8.2
3-7	8	43.9	17.7	14.4	7.0	8.2	4.6	4.2
3-1	60	51.1	12.1	8.0	3.6	5.9	4.8	14.5
3-5	130	68.6	9.9	6.4	2.7	3.4	1.7	7.3
3-3	175	56.5	8.2	6.5	3.6	6.0	4.2	15.0
4-7	12	50.8	8.5	6.0	3.1	5.4	4.3	21.9
4-1	34	49.2	11.8	6.9	3.4	5.8	5.0	17.9
4-2	109	74.6	4.6	4.5	2.2	3.6	2.3	8.2
4-3	177	60.4	8.2	8.2	4.3	5.9	3.2	9.8

*2.0 - 1.0 mm - Very coarse sand
1.0 - 0.5 - Coarse sand
0.5 - 0.25 - Medium sand
0.25 - 0.10 mm - Fine Sand
0.10 - 0.05 - Very fine sand

**Samples identified by the following: 1st digit - pit number; 2nd digit - sample number.

snowpack ripening. There resulted a period of moisture movement along the upper surface of the ice lens after snowpack maturation.

Attempts made to secure data prior to and during the early part of the runoff period proved fruitless. Air and soil temperatures within soil pits, especially those of the north-facing slope, were sufficiently low to result in the formation of ice within tensiometers. This condition persisted rendering the data collected during this early period of little value. Consequently, only data in which the effects of ice are not evident were used in the analysis procedures.

Pathways of Soil Moisture Movement

The evaluation of pathways of soil moisture movement was made through the consideration of tensiometer data. These data, which describe matric suction (tension) at a point in the soil profile, were coupled with an elevation head determination for each tensiometer. The elevation of the tensiometer cup, referenced to an arbitrary zero datum, coupled with suction (negative pressure) head, produced a value of hydraulic head (piezometric head assuming negligible effects of velocity). This was used to evaluate the hydraulic gradient of the soil profile.

The elevation head determination was made using alidade and stadia. This technique is limited in accuracy in the determination of vertical distances to a range of $\pm$ 3 cm. Small changes in soil moisture tension could be observed by this inaccuracy when combined with the elevation head data.

Figures 2 through 10 represent portions of the data collected. The data in total are presented in Table 3.

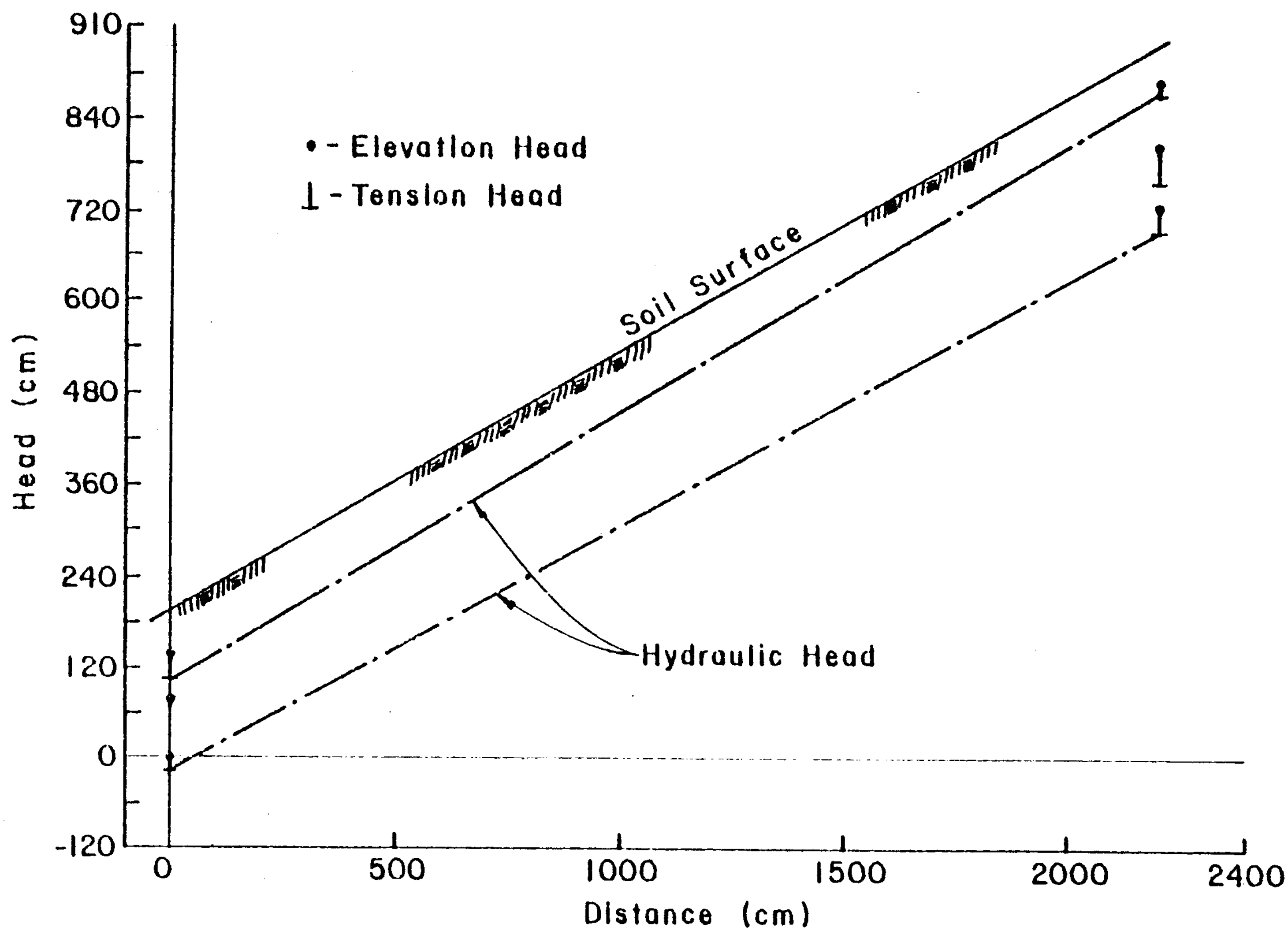


Figure 2. Average hydraulic gradient between the same levels of pits (Pits 1 and 2 for the 35th day, cm water).

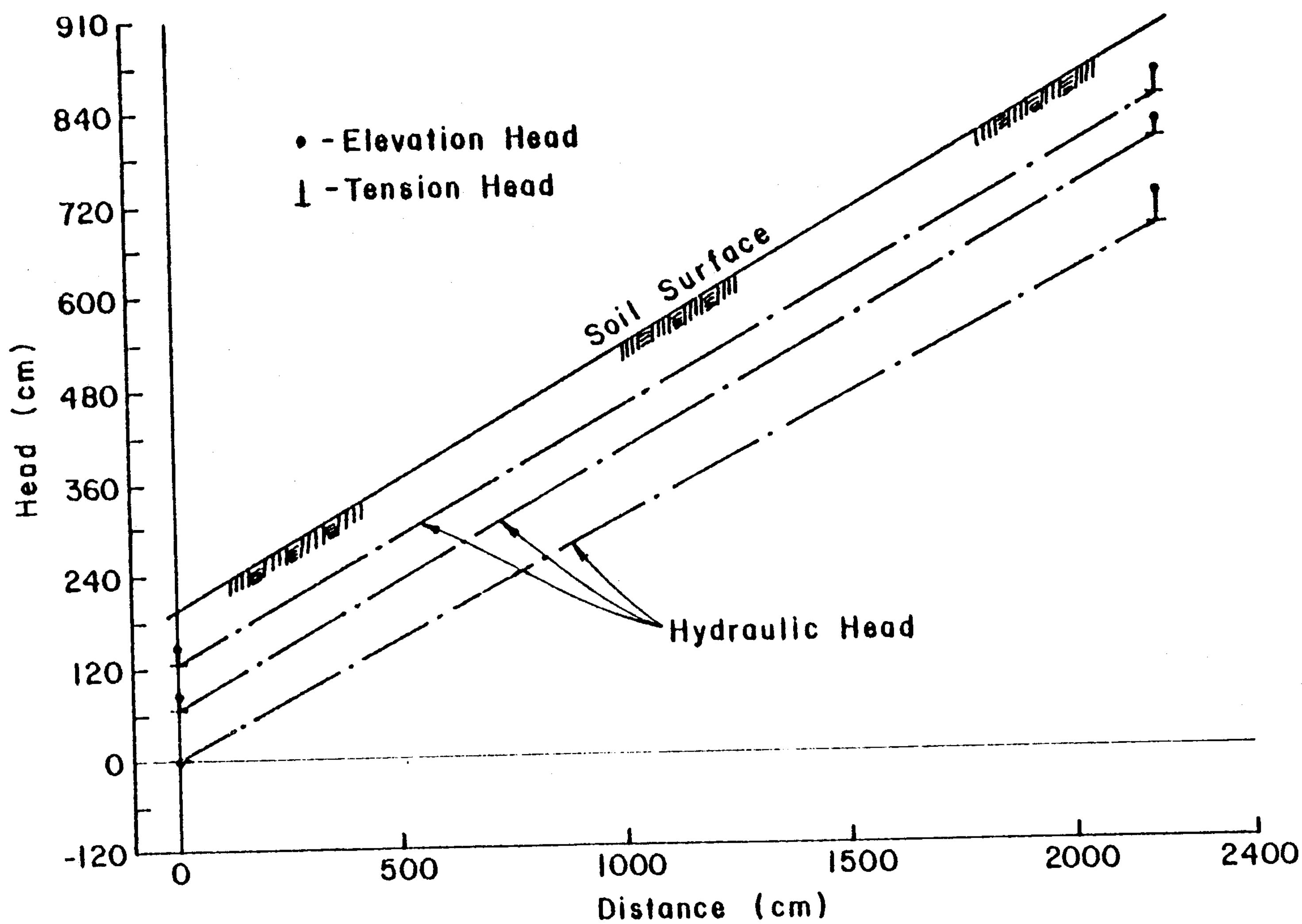


Figure 3. Average hydraulic gradient between the same levels of pits (Pits 1 and 2 for 42nd day, cm water).

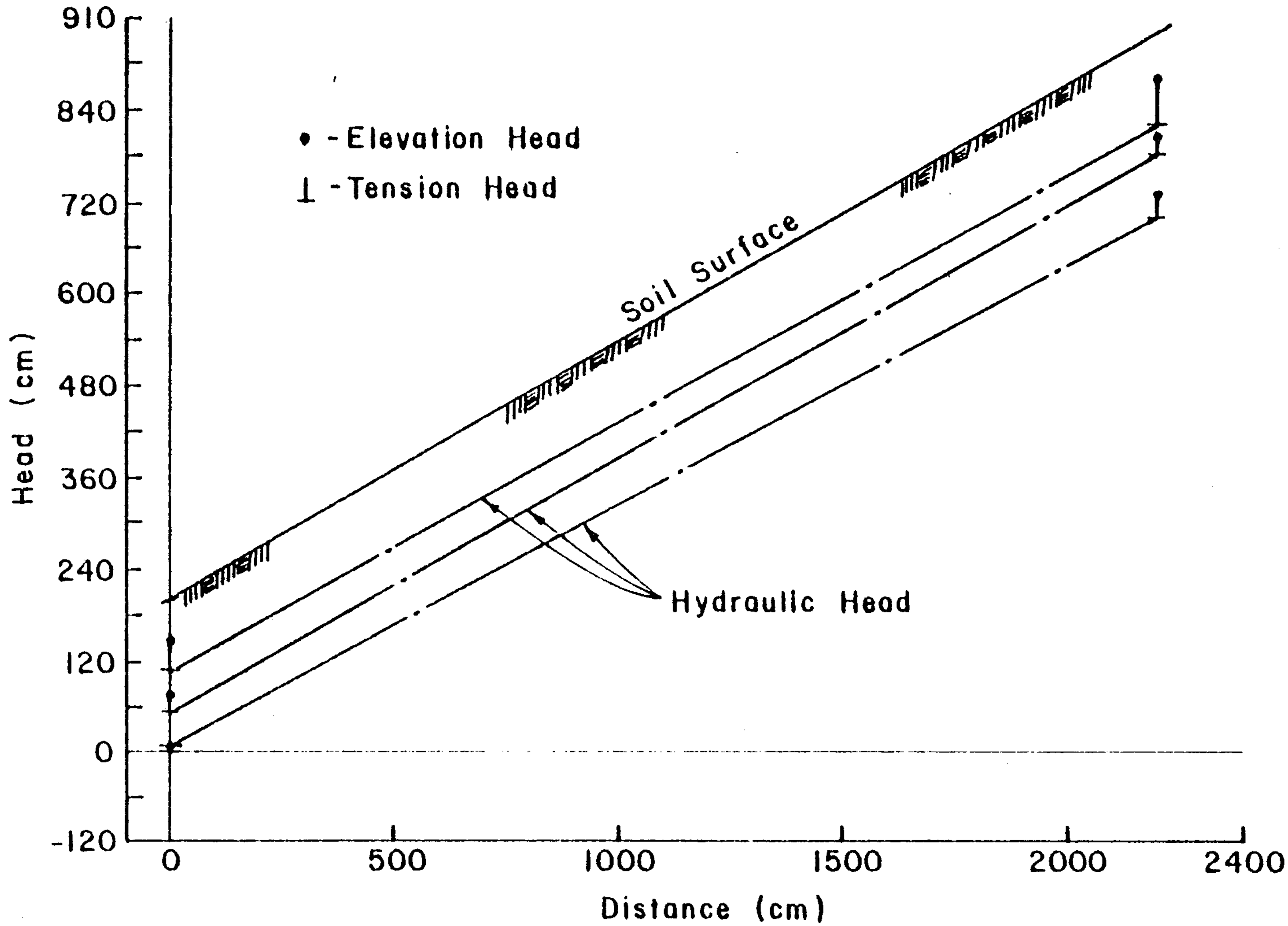


Figure 4. Average hydraulic gradient between the same levels of pits (Pits 1 and 2 for 49th day, cm water).

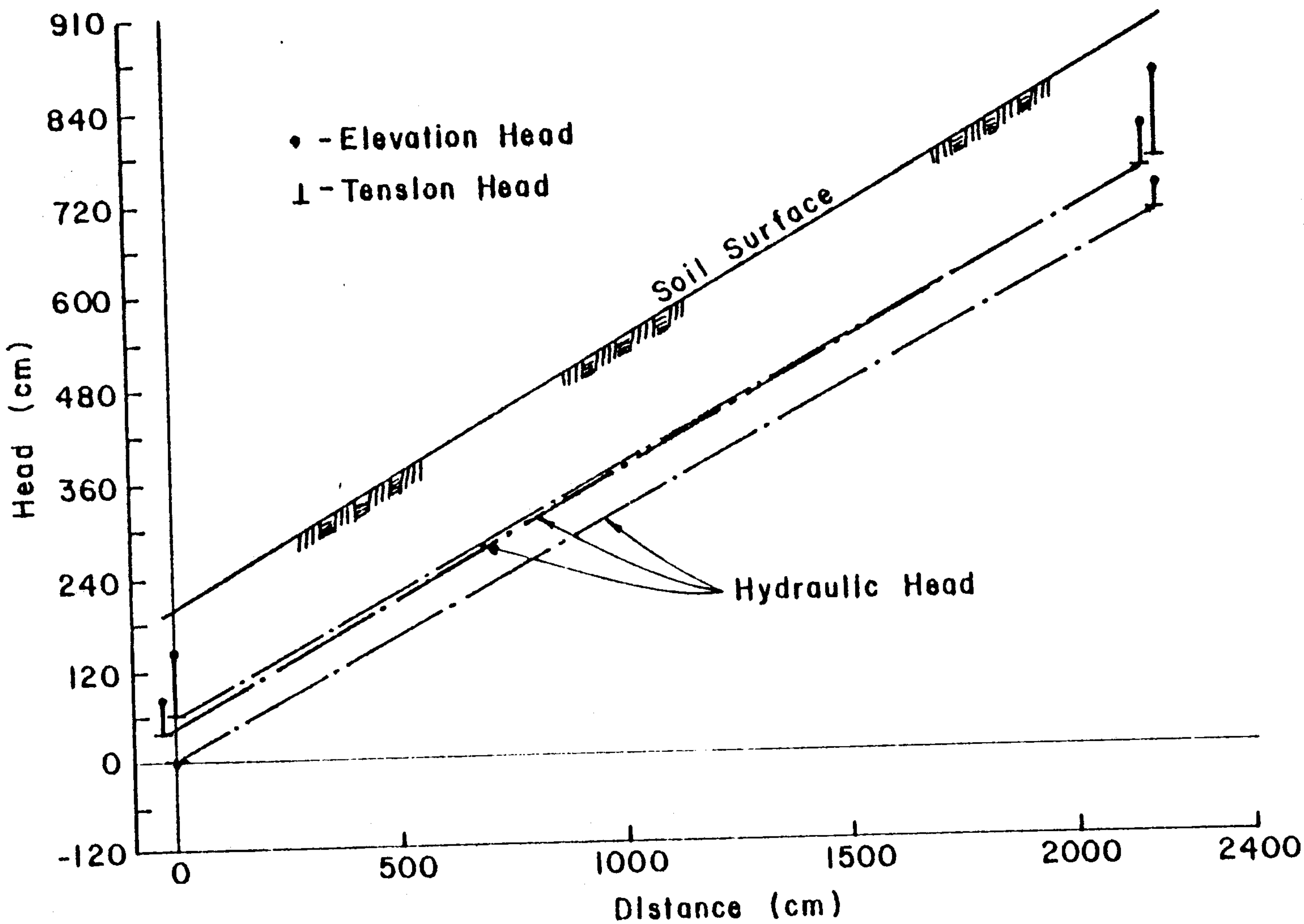


Figure 5. Average hydraulic gradient between the same levels of pits (Pits 1 and 2 for 60th day, cm water).

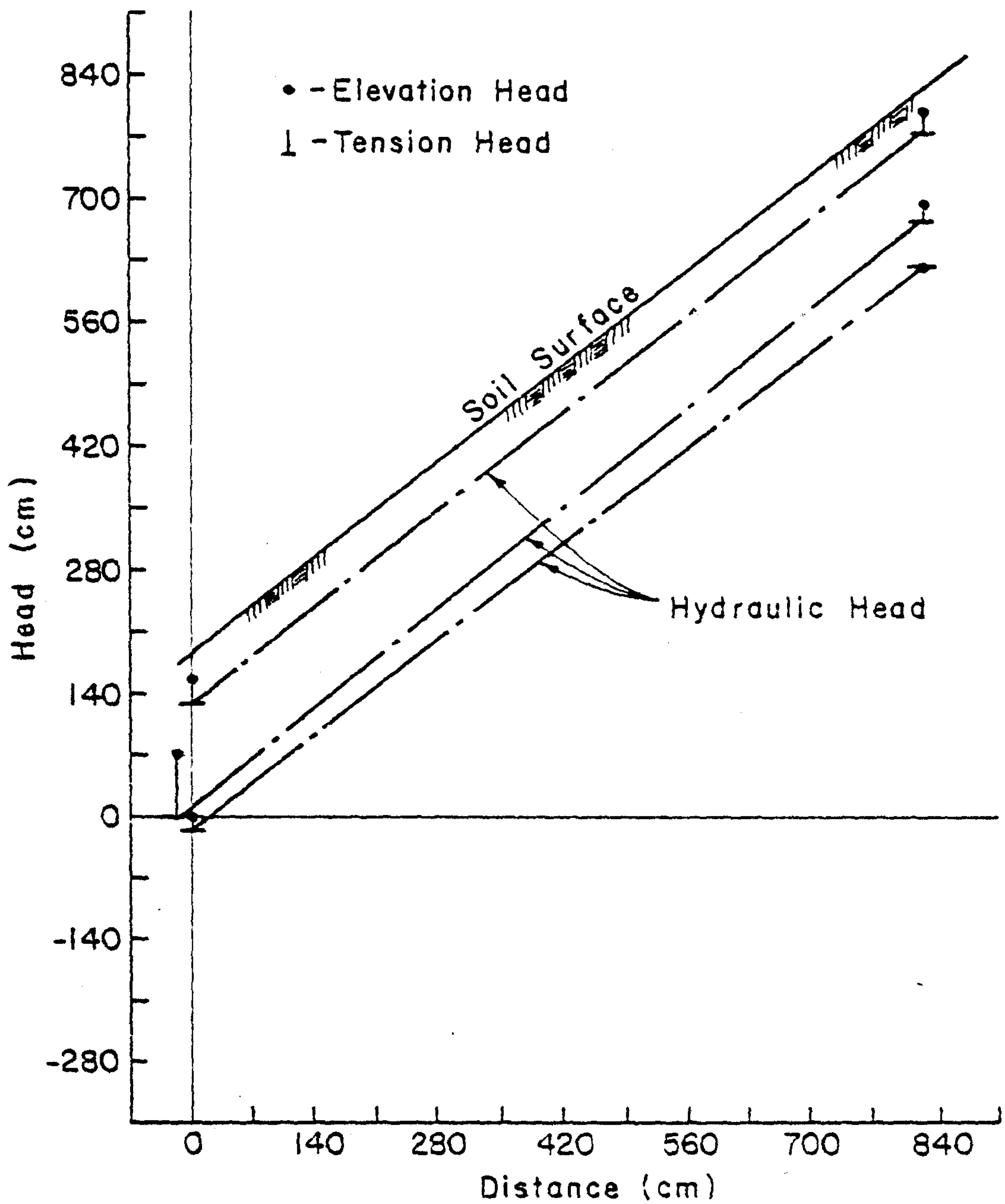


Figure 6. Average hydraulic gradient between the same levels of pits (Pits 3 and 4 for 22nd day, cm water).

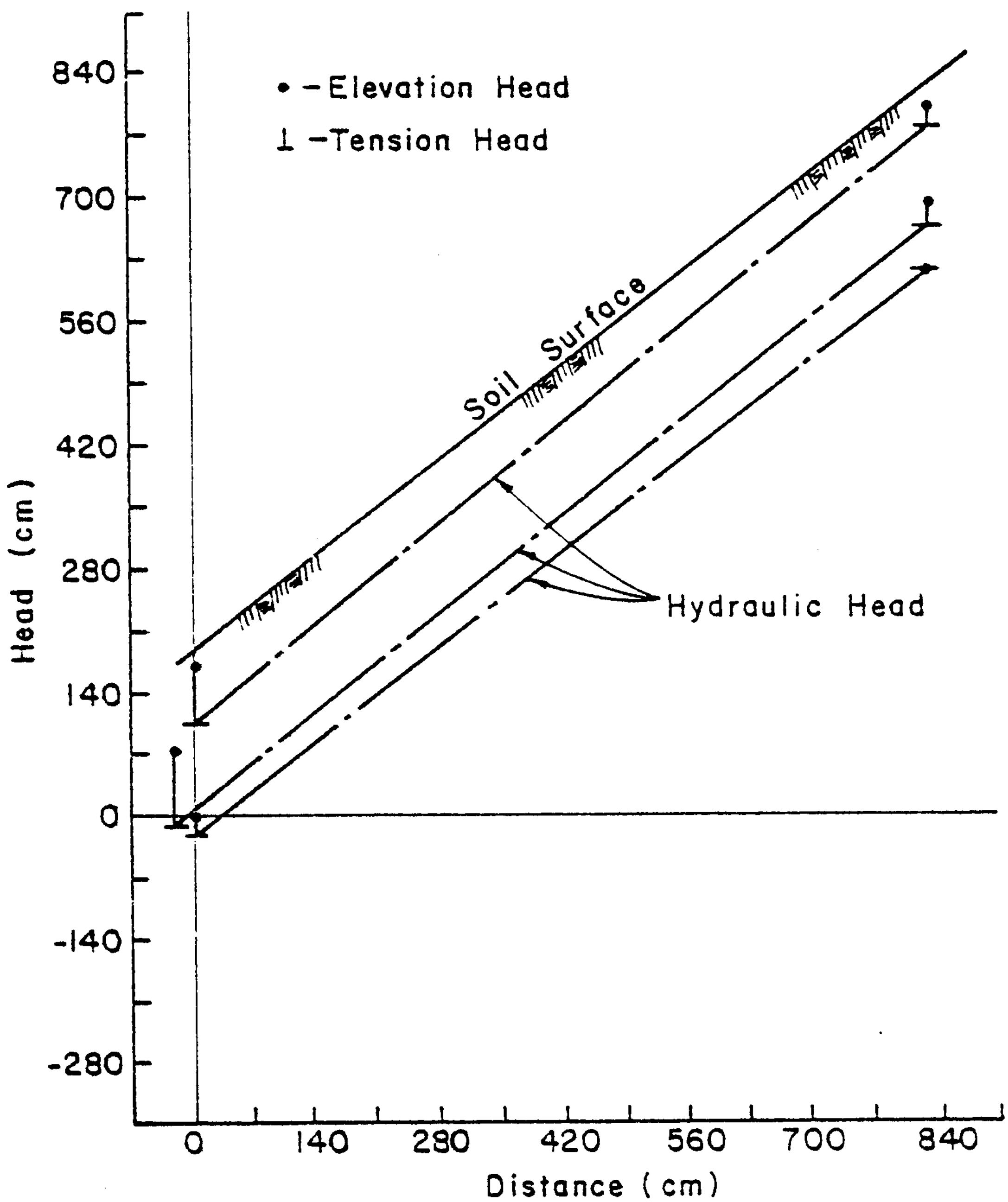


Figure 7. Average hydraulic gradient between the same levels of pits (Pits 3 and 4 for 31st day, cm water).

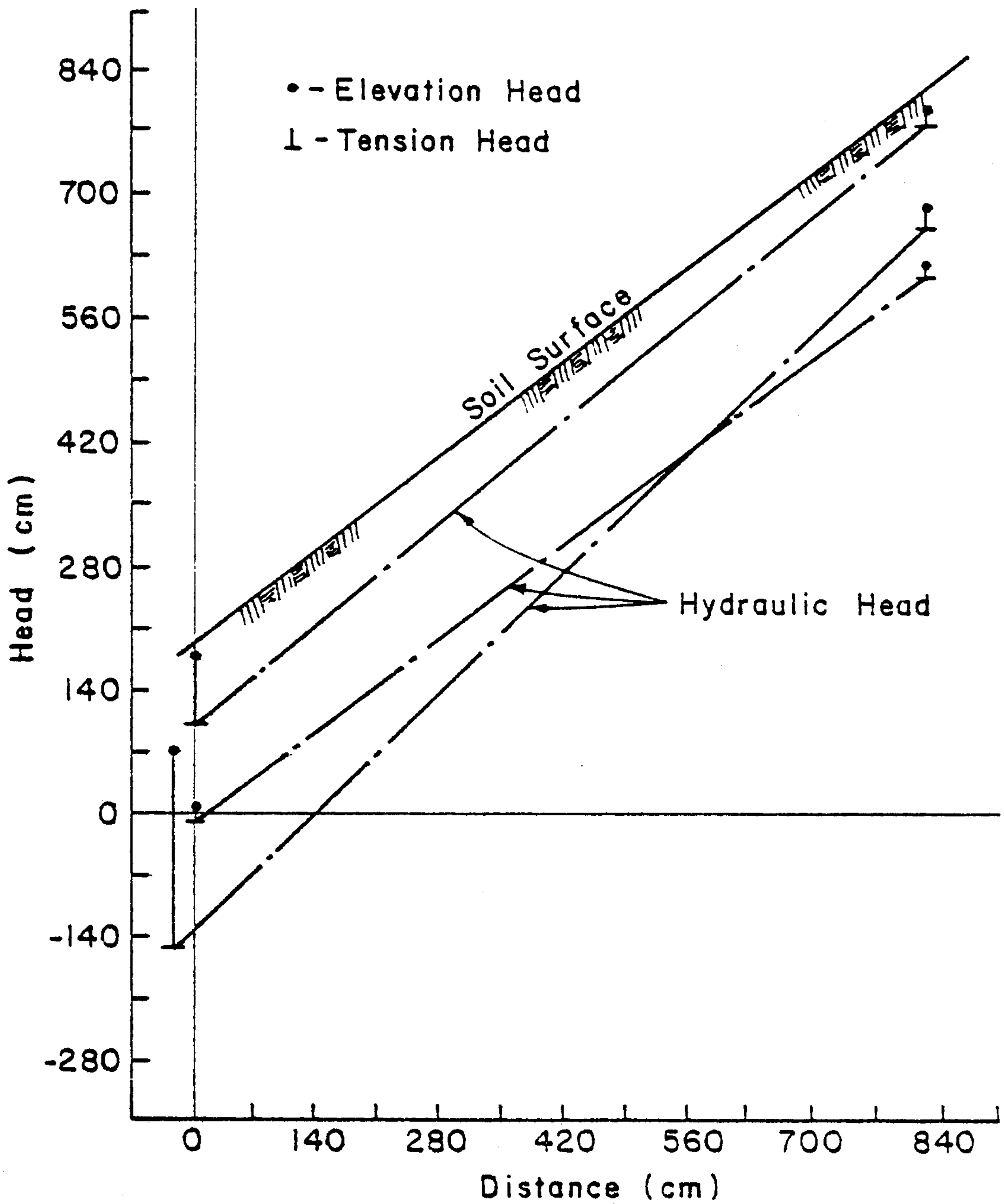


Figure 8. Average hydraulic gradient between the same levels of pits (Pits 3 and 4 for 42nd day, cm water).

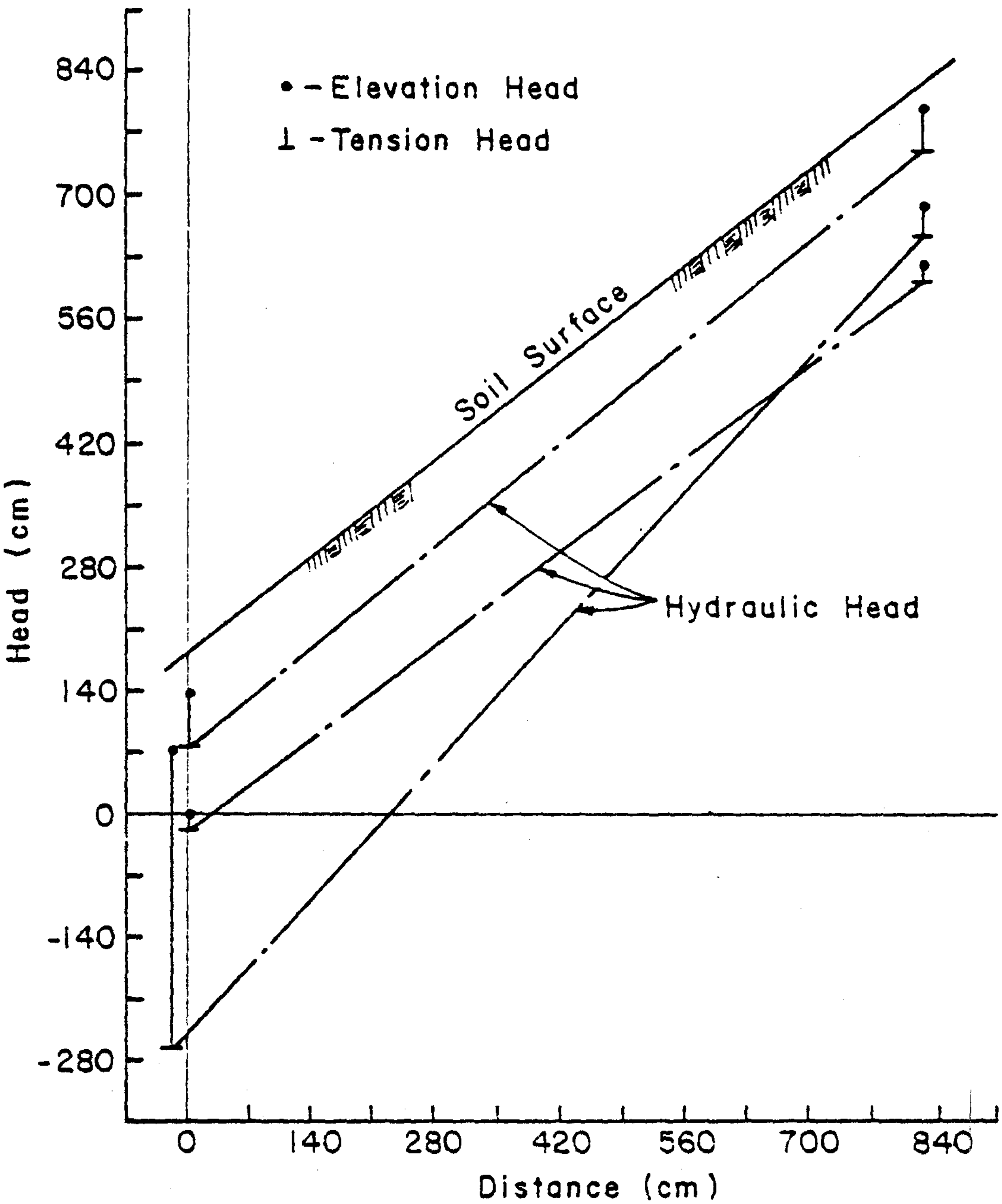


Figure 9. Average hydraulic gradient between the same levels of pits (Pits 3 and 4 for 49th day, cm water).

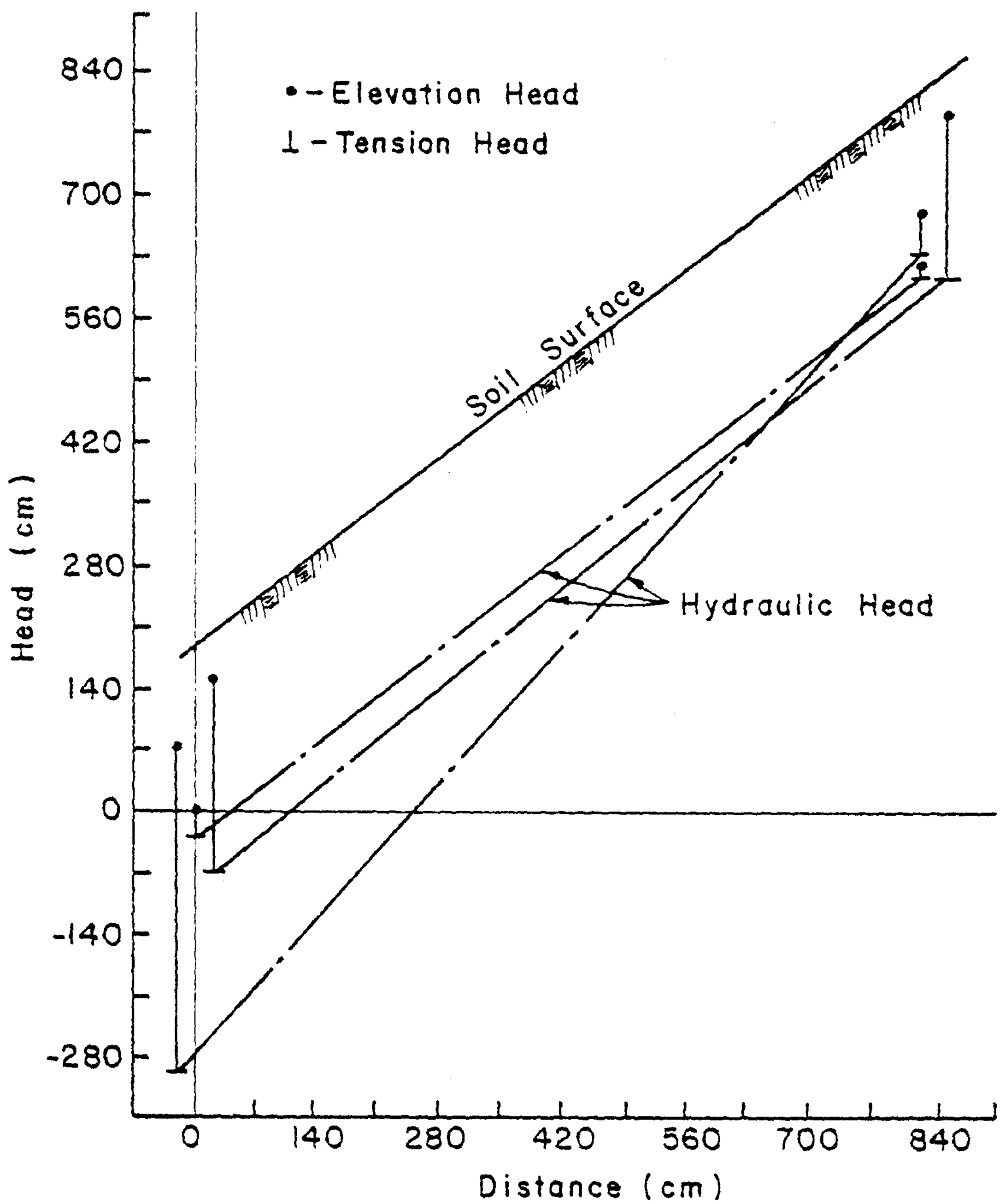


Figure 10. Average hydraulic gradient between the same levels of pits (Pits 3 and 4 for 60th day, cm water).

Table 3. Hydraulic (piezometric) head over time (Elevation Head - Tension) (in cm H_2O) (Day 1 = 15 Apr).

Tensiometer	DAY 1	6	10	17	22	24	29	31	35	37	40	42	45	47	49	54	56	60
2-1.						--	859	878	875	875	856	850	837	828	818	792	782	757
2-2.						--	--	818*	759	802	798	795	789	780	778	772	758	749
2-3.						--	--	708*	689	686	682	674	675	684	697	697	698	692
1-1.						--	151*	55*	100	116	128	127	114	106	98	80	74	53
1-2.						--	--	--*	--		--	65	62	55	45	40	39	31
1-3.						10*	--	-59	-18	-7	-2	0	-1	0	0	-2	0	-2
4-1.	796*	793*	790	781	775	786	796	777	775	775	785	792	769	771	753	718	672	617
4-2.	638*	632*	579	672	675	672	677	679	673	670	667	665	664	662	658	653	650	641
4-3.	640*	617*	614	627	623	619	621	607	654*	619	616	613	611	608	608	606	608	613
3-1.	107	-67*	--	80	121	95	103	104	136	109	117	97	90	82	78	53	-12	-75
3-2.	55	--	64*	67*	-12	-39	-10	-16	61	-17	4	-156	-247	-234	-273	--**	-286	-304
3-3.	-37	-40*	-38	-21	-18	-17	-15	-18	-11	-12	-12	-13	-14	-15	-18	-25	-26	-32

*Values probably erroneous due to ice or lack of equilibrium.

**Value discarded due to air entrapment in manometer.

--All values to the left not used in the computations.

NOTE. Tensiometers identified by the following: 1st digit - pit number; 2nd digit - tensiometer number.

The graphical presentation depicts the hydraulic gradient between tensiometers of the same level in two pits of a slope on an individual day. The end points represent the elevation head (relative to the lowest tensiometer of the lowest pit) to which has been added the suction (negative pressure) head producing the hydraulic head of the point, represented by a horizontal line. Therefore, a point higher on the slope which exhibited a matric suction equal to that of a lower point would have a greater hydraulic head. Although the tensiometers were vertically aligned in the soil profile, they have been displaced where necessary in the graphical presentation to enhance clarity.

An examination of Figures 2 through 10 indicates that a negative hydraulic gradient exists between the pits studied which resembles that of the soil surface. This is especially noticeable on the north-facing slope. The south-facing slope behaves similarly except for the anomaly observed in Pit 3. The extreme tension values measured in the middle tensiometer of this pit, while anamalous, were consistent over time. This creates a question as to the nature of soil moisture behavior at this level.

Figures 11 and 12 indicate a negative hydraulic gradient in the soil profile. This gradient tended to steepen with time. A comparison of hydraulic gradients within pits with those between pits reveals a greater negative gradient in the vertical direction than along the slope.

A further examination of Figure 12 reveals that, in Pit 3, soil moisture would move, in response to tension gradients, towards the middle tensiometer level from points both above and below the middle tensiometer. That is, water would move if the conductivity between these points and the location of the tensiometer was non-zero (i.e. no impermeable layers).

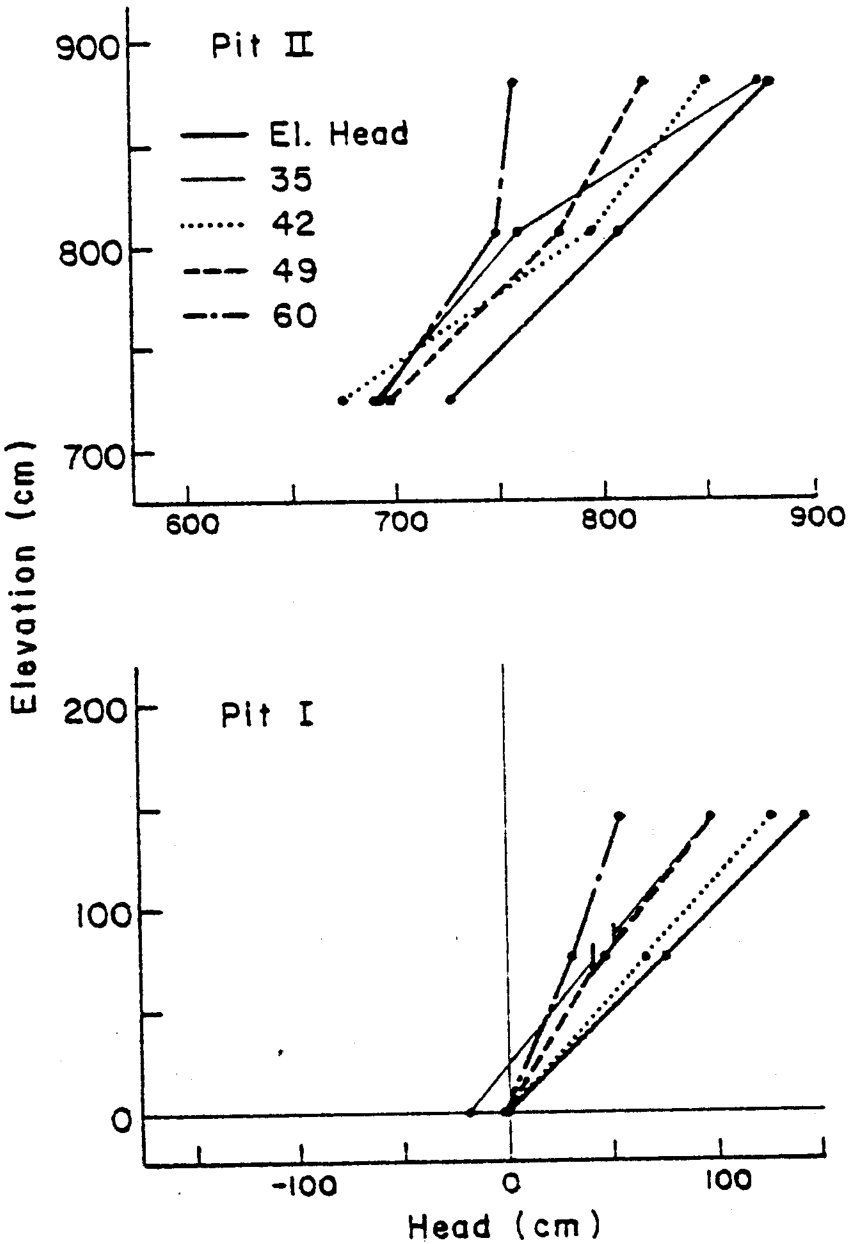


Figure 11. Average hydraulic head within pits at different times (Pits 1 and 2).

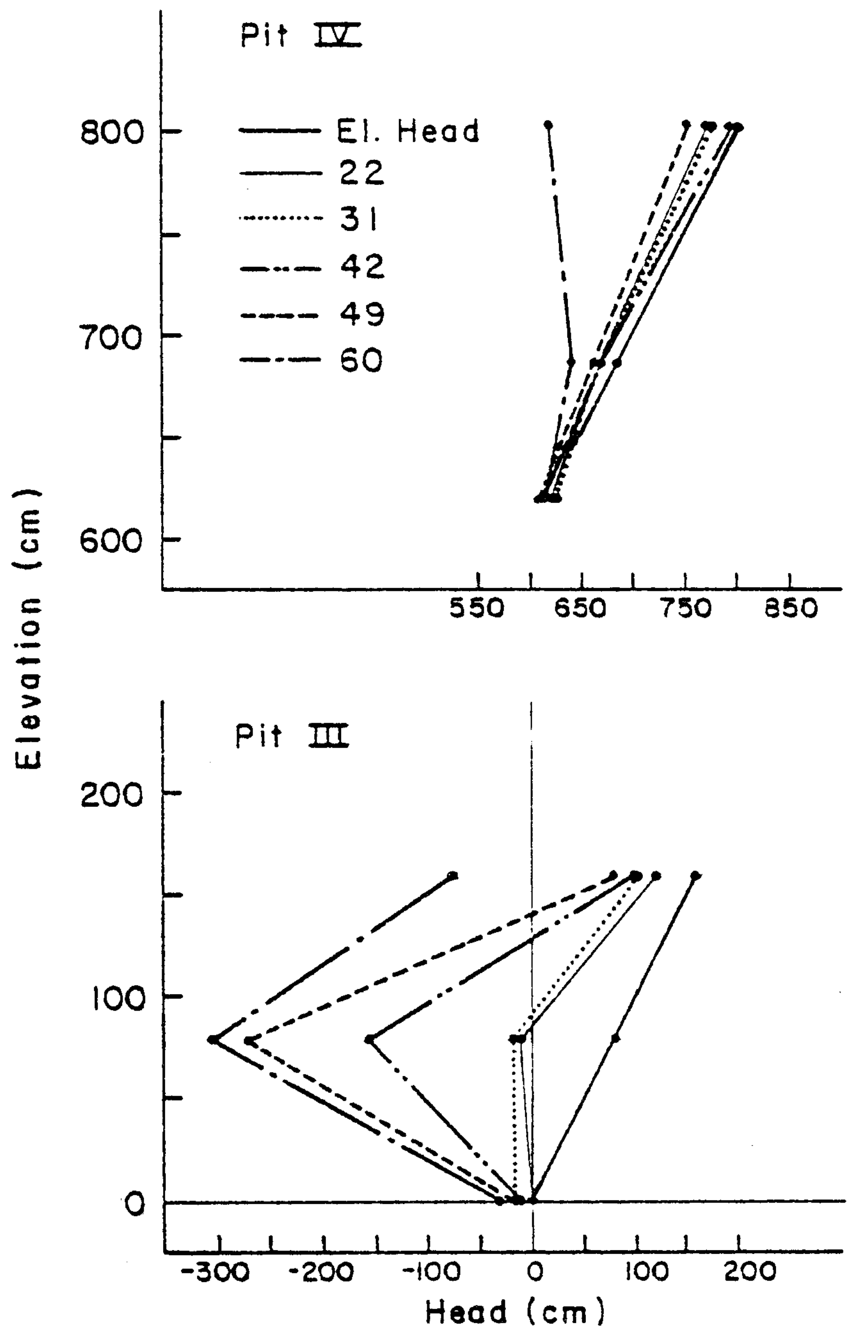


Figure 12. Average hydraulic head within pits at different times (Pits 3 and 4).

The likelihood of impermeability around the middle tensiometer is minimal. Thus it appears that under unsaturated conditions, this level of the soil profile, which may extend upslope or downslope of the pit location, transmits soil moisture at a rate inconsistent with the remainder of the soil profile.

Figures 13 through 16 describe the changes in soil moisture over time. As can be seen, with the exception once again of Pit 3, the entire soil profile tends to dry over time. There is no evidence of transmission of soil moisture in a particular zone while the rest of the profile dries. The data of the south-facing slope (Pits 3 and 4) do indicate that the base of both soil profiles, as studied, remain at or near saturation. This situation (i.e. the base of the upper pit not showing increasing tension relative to the lower) indicates the possibility of a flow restricting layer beneath the base of both soil pits which tends to channel soil moisture downslope. Such a layer could be impermeable or extremely slow in its transmission of soil moisture. The existence of such a flow restricting layer and the nature and extent of the layer of moisture restricted were not determined.

The data of Figures 13 through 16 indicate fairly low values of tension during the period of snowmelt runoff. Tension values were in all cases less than one-third bar during active snowmelt. However, it should be reiterated that the soils of the study area were characterized by coarse material and large pores. Soils of such a nature tend to have minimal moisture content and discharge at any tension much greater than zero. For example, in the soils studied, soil moisture movement may be regarded as virtually inconsequential at tensions of 25 mb insofar as such movement is considered as significant streamflow input.

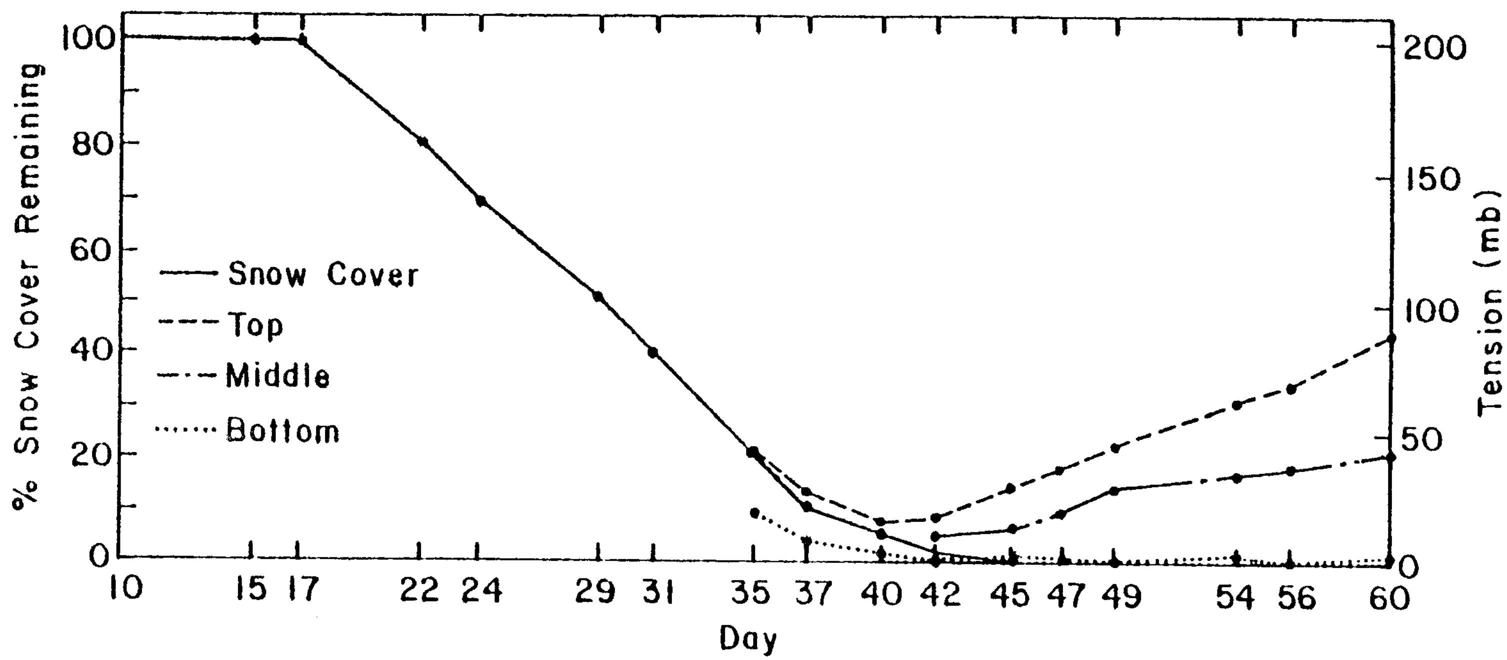


Figure 13. Soil water tension and estimated snow cover over time (North-facing slope, Pit 1) (Day 10 = 24 Apr).

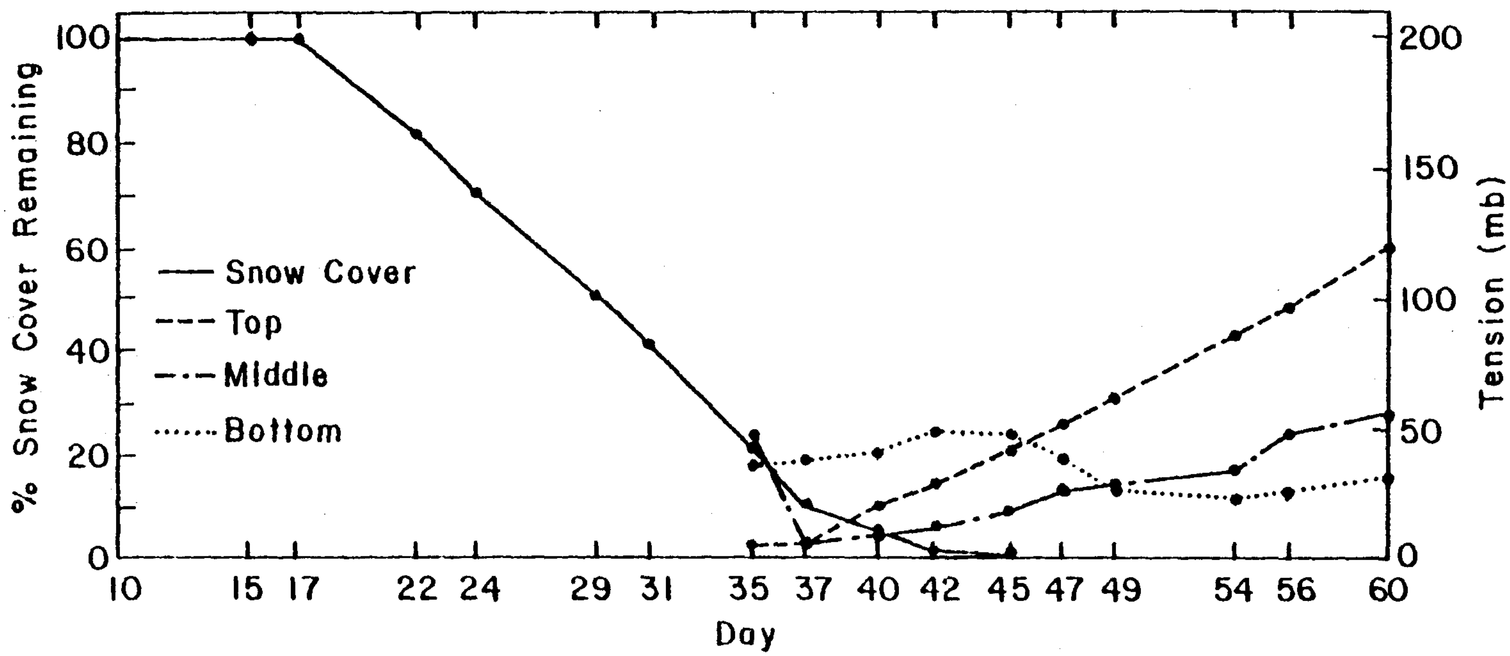


Figure 14. Soil water tension and estimated snow cover over time (North-facing slope, Pit 2) (Day 10 = 24 Apr).

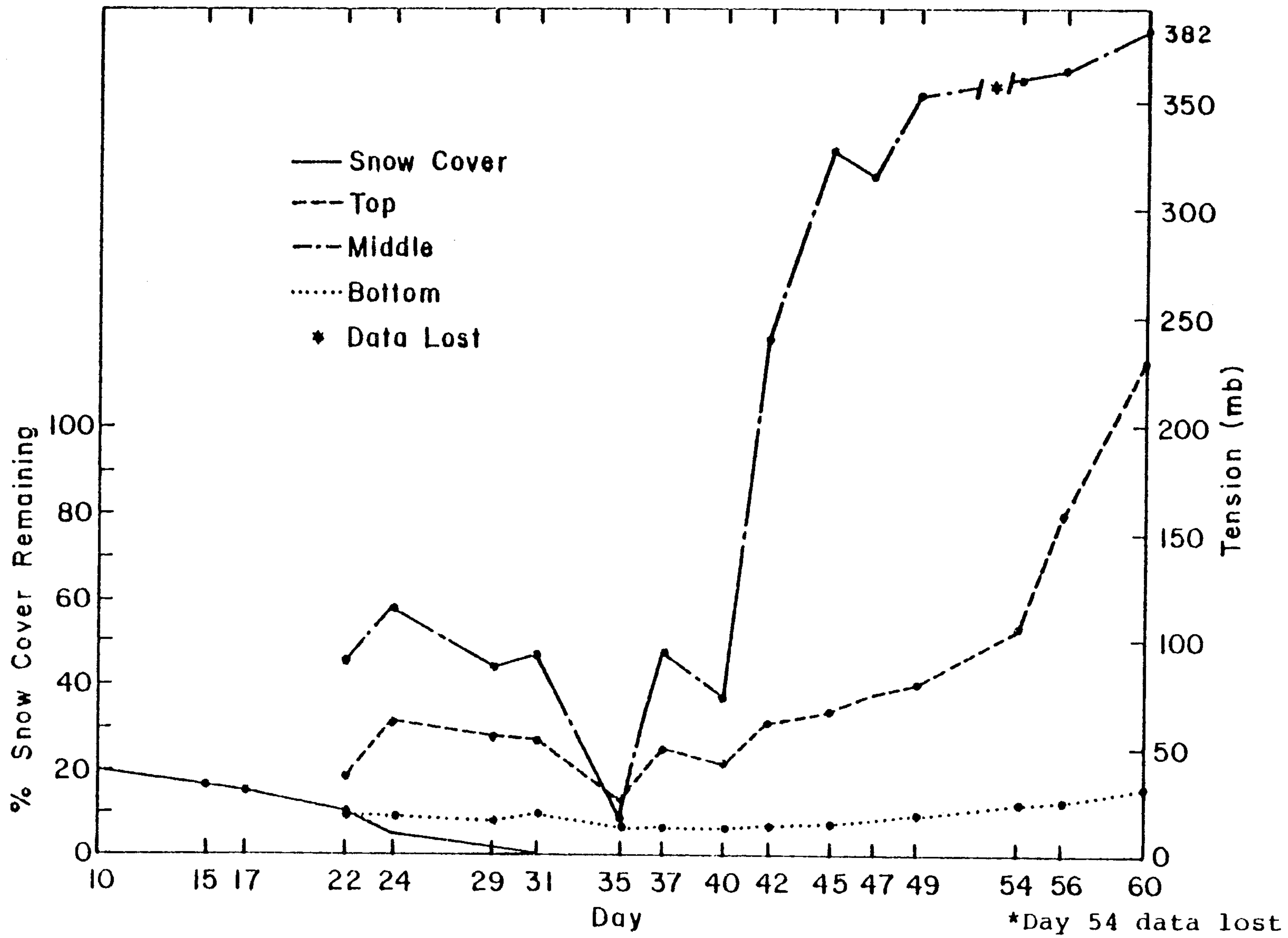


Figure 15. Soil water tension and estimated snow cover over time (South-facing slope, Pit 3) (Day 10 = 24 Apr).

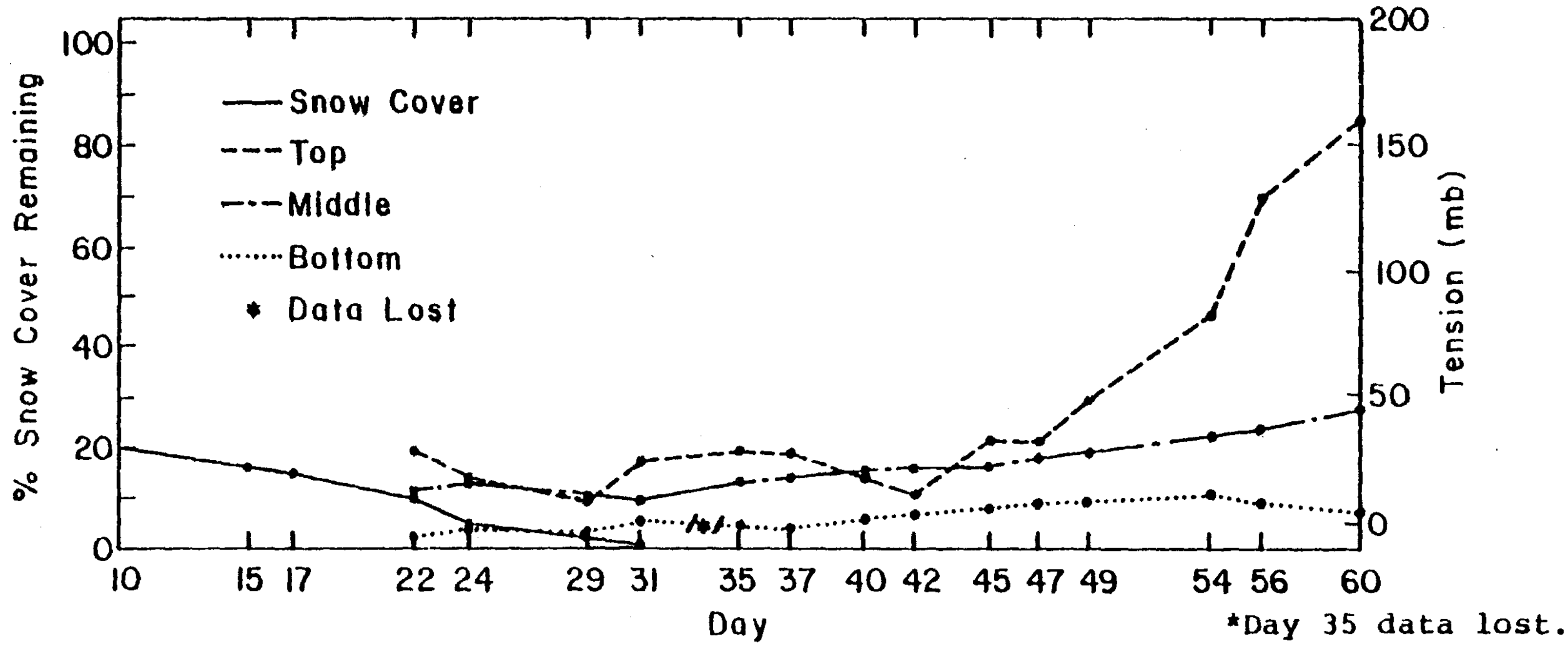


Figure 16. Soil water tension and estimated snow cover over time (South-facing slope, Pit 4) (Day 10 = 24 Apr).

During the course of this study substantial amounts of snowmelt runoff were observed at various times in the litter and surface 4-5 cm of soil. This runoff occurred as surface and near-surface flow, and was transmitted at fairly high rates as has been observed by other authors (Ragan, 1967; Dunne and Black, 1970b). Since such flow could be significant in snowmelt delivery, an evaluation was made of litter layer moisture content for a distance downslope of a melting snow patch. The data of Figure 17 reveal the substantial quantity of water retained in the litter at a distance of 3 m downslope. While these values are presented on a weight basis relative to a light porous medium, the data do indicate that water moved readily downslope through this region of the soil profile.

Runoff volumes measured from each of the litter collectors are presented in Table 4. It appears that the bulk of snowmelt occurred between April 24th and May 15th. Collection pans were subject to blockage by ice and sediment, and sample bottles may have overflowed on occasion.

Calculation of the four litterflow components was completed as previously described. Results of these calculations are presented in Tables 5, 6 and 7. Large differences in calculated component values occurred and suggest litterflow is highly variable and site specific and instrumentation was inadequate. Nevertheless, flow through the litter was detected. Quantification of litterflow rates was not possible.

Rate of Soil Moisture Movement

The evaluation of the rate of soil moisture movement was made through the measurement of the discharge of water through soil cores under constant head. As described earlier, this determination was made using vacuum

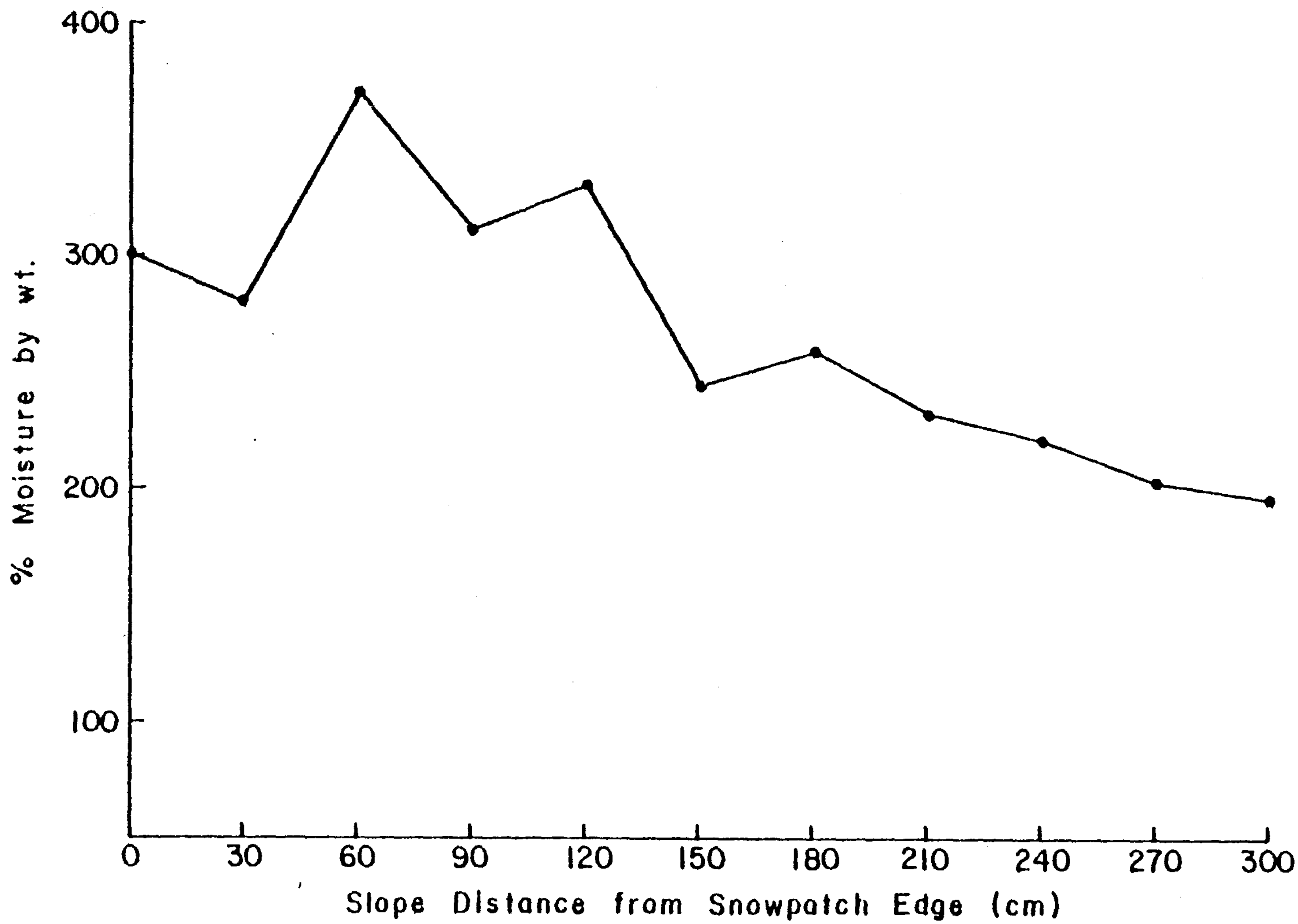


Figure 17. Percentage moisture by weight of litter layer at varying slope distances from a snow patch (Slope inclination = 29 %).

Table 4. Volume of litterflow collected (ml) by galvanized metal samplers.

Sampler	Date of collection/length of sampling period								
	< 24 APR	24 APR	30 APR	30 APR	7 MAY	7 MAY	15 MAY	23 MAY	31 MAY
	2 weeks	2 hours	1 week	4 hours	1 week	5 hours	1 week	1 week	1 week
1-I	trace	0	15	0	655	0	875	110+	0
1-II	2855	115	3730	1175	3785+	645	1125	1325	675
1-IIIA	210	0	320	0	420	frozen*	trace	0	1025
1-IIIB	0	0	380	0	1085	125	0	435	0
1-IV	0	0	235	0	60	32*	115	trace	41
1-V	0	0	1700	0	1855	395*	3785+	1600	0
2-I	0	0	0	0	-	105	395	31	0
2-II	125	0	1540	2520	3785+	225	30	0	0
2-III	0	0	1730	0	1385	0	0	0	0
2-IV	0	375	0	1125*	-	335	1145	11	0
2-V	0	0	0	0	-	0	0	0	0
3-IB	1255	0	450	145	3215	365	100	425	975
3-II	16	0	3750	1375	3425	765	3425	810	350
3-IIIA	125	400	3500	0	2665+	285	1455	105	40
3-IIIB	43	0	1430	1110	3785+	90	0	10	0
3-IV	0	0	370	115	1415	465	3785+	630	82
3-V	0	0	1550	0	3225	440	0	0	500
% Snow Cover	>95	95	60	60	15	15	100	0	0
Snow Depth	18"	18"	12"	12"	<12"	<12"	3"	0"	0"

* Possibly freed ice blockage

+ Possible overflow

- Possible blockage

Table 5. Litterflow components at the 62 meter site (ml).

Component	Method	24 APRIL 2 Weeks	24 APRIL 2 Hours	30 APRIL 1 Week	30 APRIL 4 Hours	7 MAY 1 Week	7 MAY 5 Hours	15 MAY 1 Week	23 MAY 1 Week	31 MAY 1 Week
		DATE/Length of Sampling Period								
A	X_1	Trace	0	15	0	655	0	875	110	0
B	X_2-X_1	2855	115	3715	1175	3130	645	250	1215	675
B	X_3^*	105	0	350	0	753	125	0	218	513
C	$X_2-X_1-X_4$	2855	115	3480	1175	3070	613	135	1215	634
C	X_3-X_4	-2750	0	115	0	693	93	-115	218	472
C	X_1-X_5	0	0	-1685	0	-1200	-395	-2910	-1490	0
D	X_3	105	0	350	0	753	125	0	218	513
D	$X_5+X_2-X_1$	2855	115	5415	1175	4985	1040	4035	2815	675
D	X_5+X_3	105	0	2050	0	2608	520	3785	1818	513
D	X_4+X_1	0	0	250	0	715	32	990	110	41

*Average of two collectors.

Table 6. Litterflow components at the 74 meter site (ml).

Component	Method	DATE/Length of Sampling Period 24 APRIL 2 Weeks	24 APRIL 2 Hours	30 APRIL 1 Week	30 APRIL 4 Hours	7 MAY 1 Week	7 MAY 5 Hours	15 MAY 1 Week	23 MAY 1 Week	31 MAY 1 Week
A	X_1	0	0	0	0	-	105	395	31	0
B	X_2-X_1	125	0	1540	2520	3785	120	-365	-31	0
B	X_3	0	0	1730	0	1385	0	0	0	0
C	$X_2-X_1-X_4$	125	-375	1540	1395	3785	-135	-1510	-42	0
C	X_3-X_4	0	-375	1730	-1125	1385	-355	-1145	-11	0
C	X_1-X_5	0	0	0	0	0	105	395	31	0
D	X_3	0	0	1730	0	1385	0	0	0	0
D	$X_5+X_2-X_1$	125	0	1540	2520	3785	120	-365	-30	0
D	X_5-X_3	0	0	1730	0	1385	0	0	0	0
D	X_4-X_1	0	375	0	1125	0	460	1540	42	0

Table 7. Litterflow components at the 84 meter site (ml).

		DATE/Length of Sampling Period								
Component	Method	24 APRIL 2 Weeks	24 APRIL 2 Hours	30 APRIL 1 Week	30 APRIL 4 Hours	7 MAY 1 Week	7 MAY 5 Hours	15 MAY 1 Week	23 MAY 1 Week	31 MAY 1 Week
A	X_1	1255	0	450	145	3215	365	100	425	975
B	X_2-X_1	-1249	0	3300	1230	210	400	3325	385	-625
B	X_3^*	84	200	2465	555	3225	188	728	58	20
C	$X_2-X_1-X_4$	-1249	0	2930	1115	-1205	-65	-460	-245	-707
C	X_3-X_4	84	200	2095	440	1810	-277	-3057	-572	-62
C	X_1-X_5	1255	0	-1100	145	-10	-75	100	425	475
D	X_3	84	200	2465	555	3225	188	728	58	20
D	$X_5+X_2-X_1$	-1249	0	4850	1230	3435	840	3325	385	-125
D	X_5+X_3	84	200	4015	555	6450	628	728	58	520
D	X_4+X_1	1255	0	820	260	4630	830	3885	1055	1057

*Average of two collectors.

saturated samples. It should be noted that saturation which occurs under field conditions often results in air entrapment which produces conductivity values smaller than those observed in the laboratory. Generally, the field values are approximately one-half of those obtained using the approach herein employed. The technique of vacuum saturation is however consistent and reproducible.

Figures 18 through 21 represent the values of hydraulic conductivity determined in the laboratory. Values are displayed according to their location vertically in the soil profile. Duplicate samples are presented adjacent to each other. An initial examination of these data reveals the extreme variability between samples of the same horizon as well as between horizons and pits. The similarity of conductivities between the pits of the north-facing slope as well as the dissimilarity of pits of the south-facing are also readily apparent.

The conductivity of soil has been shown to be a function of saturation. The highest values of conductivity are those associated with fully saturated soils. As a soil becomes desaturated, the rate of transmission (or conductivity) decreases. The decrease is uniquely associated with the particular soil and is a function of the soil's texture and pore size and distribution.

Similarly, the water content of a soil at a given tension is also a function of the soil's texture and pore size and distribution. In coarse textured soils with large pore spaces, such as those studied, there is substantively less moisture present (and thus available for discharge) at a given tension than in soils of finer textures.

An examination of tension values, as presented in Figures 13 through 16, indicates that for most of the profile for the majority of the period

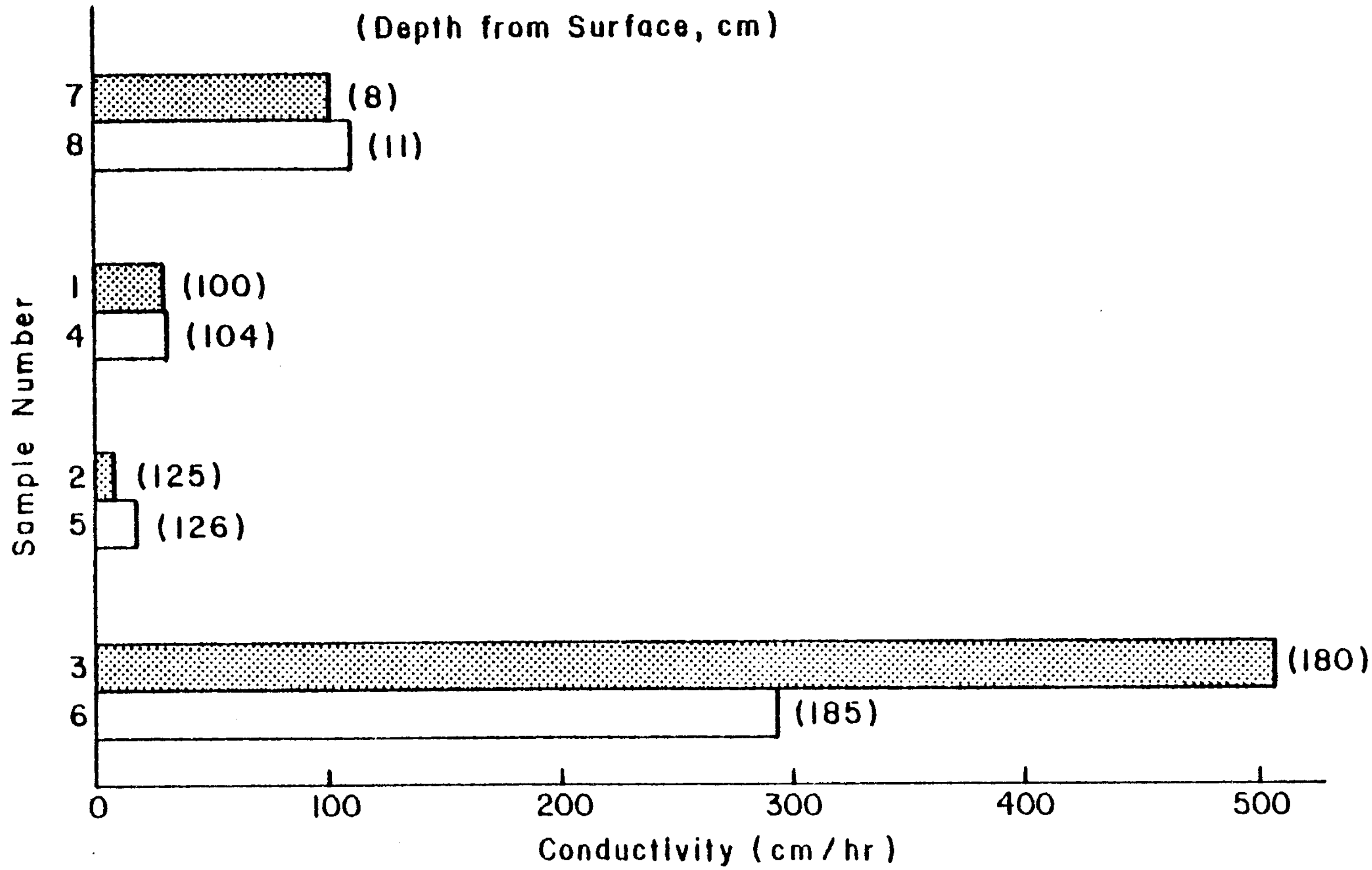


Figure 18. Hydraulic conductivity by depth (Pit 1).

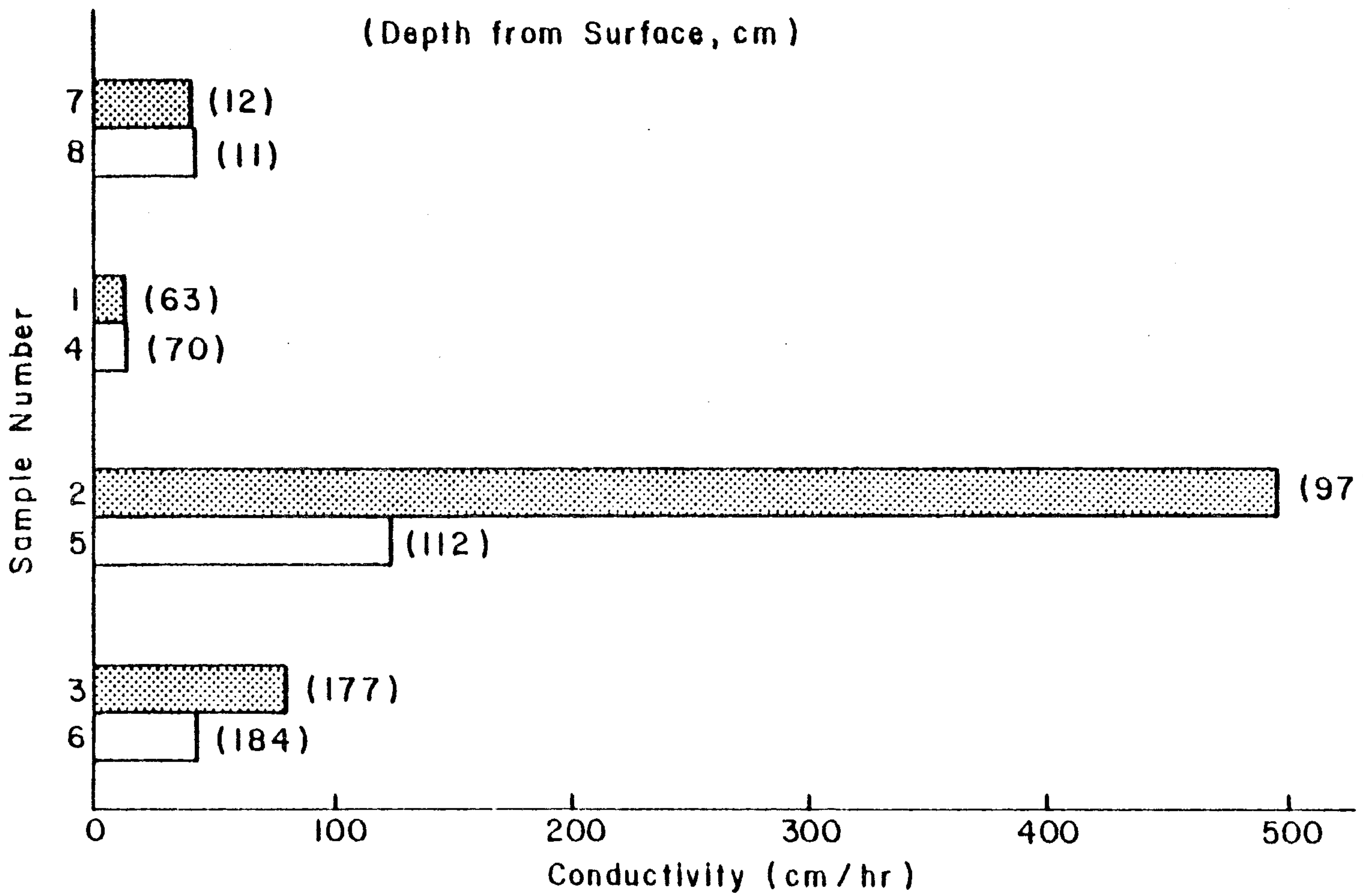


Figure 19. Hydraulic conductivity by depth (Pit 2).

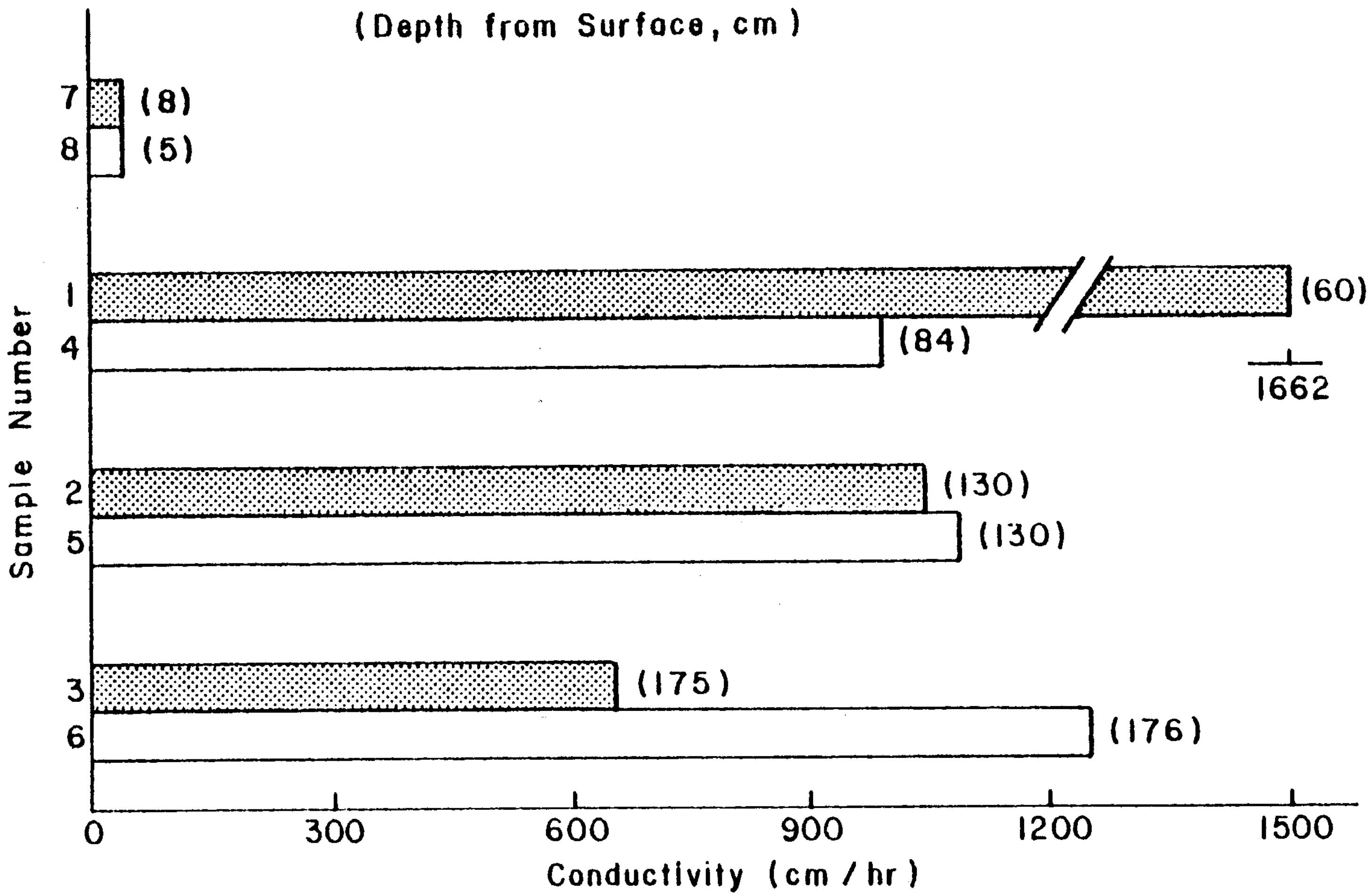


Figure 20. Hydraulic conductivity by depth (Pit 3).

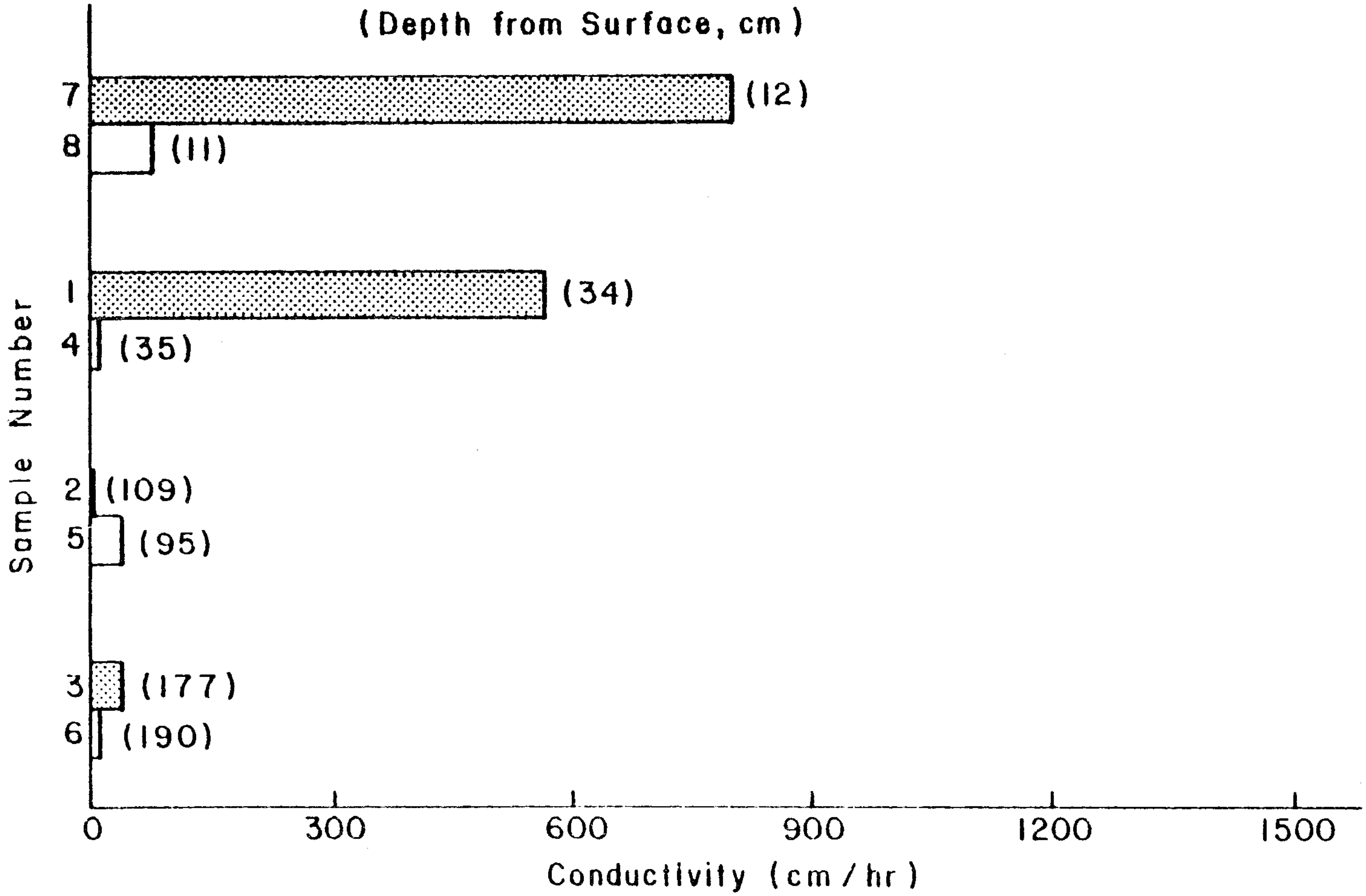


Figure 21. Hydraulic conductivity by depth (Pit 4).

studied there was little movement of water both in terms of quantity and rate. During the period of active snowmelt the pathways described differ substantially in their respective rates of delivery. Specifically, during snowmelt the surface and near-surface delivery was rapid as was the delivery in saturated or near-saturated flow beneath the base of the pits studied (i.e. two meters). Within the two meter depth of the soil profile, the movement of soil moisture occurred in unsaturated flow and thus at a very reduced rate.

The rate of water transmission, as indicated by tension readings, can be seen to change rapidly and in concert with changes in areal snow cover. Examination of Figures 13 through 16 shows that the soil of the slopes studied experienced increasing tension immediately upon or just prior to the disappearance of snow cover. In addition, it can be seen that the south-facing slope began to dry earlier than the north and showed, overall, greater tension over time.

In consideration of delivery rates, it is necessary to note the transmission within the litter layer and near-surface soil. As was mentioned earlier, researchers have found that surface and near-surface flow rates are generally far greater (sometimes by a factor of 100 to 500) than subsurface flow rates (Ragan, 1967; Dunne and Black, 1970b). In light of these findings, it would appear from observations made in this study that delivery of snowmelt runoff, particularly when the snowpack is complete or nearly so, through this means could have significant impact upon snowmelt transmission rates.

An examination of Table 8 reveals minor diurnal variations in soil moisture tension in the soil pits studied with a net increase in tension throughout the profile at the end of 24 hours. These data were obtained

Table 8. Soil moisture tension readings for 24-hour period 28/29 May 1976 (readings in mb).

Tensiometer*	Time					
	20:30-21:00	03:30-04:00	08:00-08:30	10:30-11:00	14:00-14:30	19:30-20:00
1-1.	63	63	65	66	66	68
1-2.	42	42	45	45	45	46
1-3.	40	40	41	41	41	42
2-1.	88	89	91	91	92	94
2-2.	52	52	54	54	54	54
2-3.	78	78	80	80	79	78
3-1.	75	78	91	90	82	82
3-2.	332	348	358	358	353	356
3-3.	51	52	52	52	54	54
4-1.	48	50	53	54	56	56
4-2.	62	63	64	64	66	65
4-3.	54	55	58	60	59	60

*Tensiometers identified by the following: 1st digit - pit number; 2nd digit - tensiometer number.

at the end of snowmelt (28/29 May); consequently, the influence of diurnal variations in melt are not in evidence.

It may also be observed in these data that the highest tension values occurred either in mid-morning or mid-afternnon and that the values of these two periods were essentially equal. This serves to indicate, at least for unsaturated flow, the period during which soil moisture transmission was at its lowest.

CONCLUSIONS

This study was undertaken to evaluate the pathways and rates of delivery of snowmelt runoff from a subalpine coniferous forest zone watershed. The data as presented are, admittedly, incomplete due to early data loss and the necessity for at least one additional season's data. Even within this limitation, however, certain trends may be identified.

1.) Little saturated flow occurred in the soil profile studied other than in the litter and top 4-5 cm. Snowmelt was largely transmitted through unsaturated flow, though during most of the spring run off season very little water moved through the soil profile in any direction. Only at the base of the 2.5 m deep soil pits was any persistent saturated or near-saturated flow indicated. The observations of increased soil moisture early in the snowmelt runoff period indicate the likelihood of flow to this saturated layer during the relatively short lived period of active snowmelt.

2.) Othen than in the litter and top 4-5 cm the magnitude of the negative hydraulic gradient was greater in the vertical direction of the soil profile sampled than along the soil slope during the snowmelt runoff period.

3.) The litter layer and surface 4-5 cm of soil were major pathways for snowmelt delivery, especially during the period of complete or near-complete snowcover. This means of delivery may have been influenced, at least early in the melt period, by the presence of concrete frost in the soil profile.

4.) The rate of percolation through the soil mass is generally in excess of normal rates of snowmelt.

In summary, it was observed that, during the period of melting snow on the Deadhorse Creek drainage, runoff was carried as surface and near-surface flow in the litter layer and upper 4-5 cm of mineral soil. Saturated or near-saturated flow occurred at the base of the soil pits and unsaturated flow was observed in the upper two meters of mineral soil. When snowpack ablation was largely completed, the soil profile displayed increasing tension with a consequent reduction in soil moisture movement.

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